PROCEEDINGS

OF THE

SIXTH ANNUAL
PRECISE TIME AND TIME INTERVAL
(PTTI) PLANNING MEETING

DECEMBER 3-5, 1974

U. S. NAVAL RESEARCH LABORATORY
WASHINGTON, D. C.

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OF THE SIXTH ANNUAL
PRECISE TIME AND TIME INTERVAL (PTTI) PLANNING MEETING

Held at U.S. Naval Research Laboratory
December 3-5, 1974

Sponsored by

U.S. Naval Electronic Systems Command
NASA Goddard Space Flight Center
U.S. Naval Observatory

Prepared by
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BANQUET SPEAKER

Dr. William T. Keeton
Langmuir Laboratory, Cornell University
Subject: The Continuing Mysteries of Pigeon Homing

CALL TO SESSION

James A. Cauffman, NAVELEX

WELCOME ADDRESS

Dr. Alan Berman, Director of Research, NRL

OPENING COMMENTS

Tecwyn Roberts, Director, Networks Directorate, GSFC

OPENING ADDRESS

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The authors were responsible for the typing and proofing of all manuscripts. The Editorial Committee did not serve as referees but reviewed manuscripts only for gross errors.

FOREWORD

This volume contains the papers presented at the Sixth Annual Precise Time and Time Interval (PTTI) Planning Meeting. The meeting was sponsored jointly by NASA/Goddard Space Flight Center, the U.S. Naval Observatory, and the U.S. Naval Electronic Systems Command. The meeting was held December 3-5, 1974 at the Naval Research Laboratory.

The purposes of this meeting were to:

a. Disseminate, coordinate, and exchange practical information associated with precise time and frequency;

b. Review present and future requirements for PTTI; and

c. Acquaint systems engineers, technicians, and managers with precise time and frequency technology and its problems.

More than 300 people participated in the conference. Attendees came from various U.S. Government agencies, from private industry, and from several foreign countries and international laboratories. Thirty-one papers were presented at the meeting, covering areas of navigation, communications, applications of interferometry, frequency and time standards and synchronization, and radio wave propagation.

It was readily apparent that the close communication and cooperation that was established between various Government agencies, private industry, and international laboratories at previous meetings has been maintained.

Many contributed to the success of the Meeting. On behalf of the Executive Committee of the Sixth PTTI Planning Meeting, I wish to acknowledge the Session Chairmen, speakers and authors, the members of the Technical Program Committee and Editorial Committee and the many others who gave freely of their time.

Copies of the 1972, 1973, and 1974 Proceedings may be obtained for a charge of $5.00 by sending a request to:

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James A. Cauffman
General Chairman

CALL TO SESSION

James A. Cauffman
Naval Electronic Systems Command

MR. CAUFFMAN: I am Jim Cauffman from the Naval Electronic Systems Command, and it is my pleasure to call to session the Sixth Annual PTTI Planning Meeting. I won't say too much about our program since it is pretty well laid out. It is tutorial in nature, and hopefully it will be of benefit to many people.

I believe that the Technical Program Committee, under Dr. Stover, did an excellent job in selecting the papers on the program. However, if anyone feels that certain topics are not adequately covered or that any other changes would be beneficial, please leave your suggestions at the reservation booth so that they can be considered for next year's meeting.

One of the most important benefits of this meeting is the gathering together of many knowledgeable and interested parties. Because of this, I urge all attendees to participate in the discussion period. To facilitate an accurate recording of the discussion period, we have a 5 x 7 card which you can use to write down your questions.

What we would like is the author's name, your name, and the title of the paper, and then the question. This will alleviate the problem we had last year of taking questions off the tape recorder and some people saying, "Gee, that is not really what I said."

These forms will be available at the microphones and should be turned in at the registration desk.

It is also important, I think to take note of the increased participation of representatives of foreign laboratories in this meeting. PTTI is one of those unique fields which not only brings together scientists and engineers of different fields, but also of different countries. Last year, six foreign countries were represented; this year, there are thirteen — Argentina, Australia, Brazil, Canada, Chile, France, Japan, Poland, South Africa, Switzerland, Taiwan, Thailand, and the United Kingdom.

I am sure this broadened international participation will be of great benefit.

It is now with great pleasure that I call upon Dr. Alan Berman, Director of Research of the Naval Research Laboratory for our welcoming address.

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WELCOME ADDRESS

Dr. Alan Berman, Director of Research
Naval Research Laboratory

DR. BERMAN: Good morning. As Director of Research in this laboratory, it is my pleasure to welcome you. I had the privilege of delivering a similar welcoming address approximately three years ago, the last time this group met here at the laboratory.

When one gives a welcoming address, it is usually one's habit to give some anecdotal material to sort of set the tone. And I recall at that time, I recounted the tale of an encounter I had with an Israeli General. He was, for those of you who weren't here, a very pragmatic, hard-headed person as are most Israeli Research Directors. In particular, he got to the point where he was teasing me about work in precision time and frequency. And he made some sort of remark because he was much taken at that time with the interest in tests of general relativity.

If I recall, about three years ago, people were flying cesium clocks around the world in different directions to try to test some of the twin paradox.

And he went on and on and berated me. And I tried to indicate the relevance and importance of precise time and frequency. And he kind of grudgingly conceded that it was worth doing, but in Israel, they don't measure the age of twins.

I met this gentleman some years later after the Arab-Israeli War, and he was very much sobered up. He actually apologized to me and said "Well, we still don't measure the age of twins, but we feel that the work in precise time, time standards, played an immense part in our military applications. We used it for TDOA, coding, navigation, cryptology, and one thing or another." He had finally seen the light and the value of much of the work.

It was sort of amusing to look at it, but I think that one doesn't need a war, and one doesn't need military applications to see the relevance of the sort of work you are doing.

Going through the program here and reviewing the work in the field over the past few years, I am indeed impressed by two things:

First, the broad, international participation in this meeting;

And second, the scope of your applications and interests.

Precise time, and time interval measurements have played a real role in the coming truly of age in the area of communications. Improvements in synchronization and time distribution technique I think are allowing a wide variety of applications, both military and civilian.

We here at NRL are particularly proud and interested in the work of the Navigation Technology Satellite One. And it is very reassuring to us to think we have reached a point where you actually have rubidium clocks functioning in satellites and that we have programs, as you will hear, looking forward into the future to successively install cesium clocks and eventually a hydrogen maser before the end of this decade.

This will open up new frontiers, new abilities to determine time, transfer time, and achieve all the other things one can do.

Aside from the military aspects of what one can achieve with improved navigation, synchronization, cryptology, what have you, I am still enough of a scientist and have enough of a scientific background to be intrigued by the ability to tell the age of twins — namely, one is intrigued by the possibilities that are opened with the availability of precise standards to test many aspects of the theory of relativity.

I am also extremely interested in the applications which I see you will be discussing in your program that are applied to geophysics and astronomy. You have the possibility now of observing crustal movements, possibly even using very long baseline interferometry to determine the possibility of earthquakes, severe tensions building up in continental margins or in continental crust.

I think the possible benefits of your work are only just beginning to become visible, and I look forward to seeing many more in the future.

Thank you, have a good meeting.

MR. CAUFFMAN: At this time, I would like to introduce the representative of our co-sponsor, NASA, Mr. Tecwyn Roberts, Director of the Networks Directorate, Goddard Space Flight Center.

OPENING COMMENTS

Tecwyn Roberts, Director of Networks Directorate
Goddard Space Flight Center

MR. ROBERTS: Good morning, ladies and gentlemen. On behalf of the Goddard Space Flight Center, it is my pleasure to welcome you to the Sixth Annual Precise Time and Time Interval Planning Meeting. Goddard has been a co-sponsor of the PTTI meetings since 1972. It was our pleasure to host the '72 and the '73 meetings.

I am pleased that NRL is this year's host because it gives me the chance to visit this great facility which is known to us all. At Goddard, we have so many people who were at one time with NRL that I am not sure for whom they are still working.

The Goddard Space Flight Center is probably best known for its space programs in the fields of science and application. This was highlighted in this past year by the Atmospheric Explorer Satellite and the Applications Technology Satellite. The latter is playing a most exciting role in the area of communications testing and educational television on a global scale.

This, then, brings me to the part in which I am involved — the NASA Worldwide Tracking Satellite Network for which Goddard has the engineering and operational responsibility. In this area, we are indeed indebted to our friends at the Naval Observatory and the Naval Research Laboratory for many cooperative efforts. These run the gambit from cooperation in procurement of our new cesium standards for the NASA Network and visits to our tracking stations by Observatory personnel on their portable clock trips.

The network supports many spacecraft, civilian and DOD as well as foreign. These spacecraft have various missions, as I said, in support of scientific projects. Some of these projects impose stringent time and frequency requirements. Our present worldwide clock synchronization requirement is about 25 microseconds.

Upcoming projects will demand much better than this. The Geodetic Earth-Orbiting Satellite (GEOS) project will require about one microsecond at selected sites and frequency synchronization to a few parts in 10^{12}.

The Earth and Ocean Physics Applications Program (EOPAP), the major goals of which are earthquake hazard assessment and global surveying and mapping, some of the things that Dr. Berman touched on, hopes to ultimately detect crustal motion to within one centimeter a year. To do this requires a station-to-station clock synchronization of better than one microsecond.

Our very long baseline interferometer program is multidisciplinary, providing continental drift, polar motion, and UT1 data to the geophysical community. Observations of the properties of quasars, pulsars and radio galaxies demand frequency stabilities approaching parts in 10^{15}. This effort has drawn heavily on our in-house hydrogen maser development program.

I might add that we hope to track the NRL-developed TIMATION III spacecraft (NTS-1) with our laser tracking network for geodetic work. This is a stepping stone to the Goddard Laser Geodetic Orbiting Satellite Program, perhaps better known as LAGEOS.

We are continually evaluating new techniques to meet our time and frequency requirements. As I mentioned, we have an ongoing hydrogen maser development program. We are also investigating ways to improve our network timing for Loran-C, Omega, and Satellite Time Transfer.

Much of the PTTI work done at Goddard will be summarized in papers presented here during the next three days. So as you can see, Goddard is very much involved in the area of PTTI. It is through meetings such as this with the mutual exchange of information that enables Goddard to remain in the forefront of this very interesting and challenging field.

We look forward to continued cooperation with each of you in furthering PTTI capabilities. I thank you for the opportunity to greet you this morning, and I particularly thank Dr. Berman for permitting the PTTI meeting to be held here. I wish you a very successful three days.

MR. CAUFFMAN: Now, it is with great pleasure that I introduce my boss who will give us the opening address, Rear Admiral Raymond J. Schneider, Commander of the Naval Electronic Systems Command.

OPENING ADDRESS

Rear Adm. Raymond J. Schneider, Commander
Naval Electronic Systems Command

REAR ADM. SCHNEIDER: Good morning, ladies and gentlemen. I have a few prepared remarks. I intend to slightly embellish them with some unprepared ones.

I particularly, as I look at the assembly, am somewhat envious of you in your scientific work. Deep in my heart, I always wanted to be a scientist. And I managed to approximate that by becoming an engineer, but it seems that in the military role, it is not very long after you become an engineer that you are a manager. And from then on, you spend all your time working in fields somewhat less rewarding than scientific or engineering personal performance.

Built on that little thought, I want to drive the community into a little bit of a challenge so that here today on behalf of my command which by its very nature is one of the more, I call it, exotic commands of the Navy, we have the strange capability of dealing with many complicated things that almost none of my peers understand. There is somewhat a tendency, rue the thought, of scorning me if I show some ability to understand. It seems to be unmilitary to know which end of a vacuum tube has the prongs on it.

I have always felt that way since I had my nose rubbed in this business. But I steel myself to believe that you can't hurt yourself by knowing what is going on. And so I insisted on understanding the business in my younger days. And it led to this fate I now pursue.

Let me welcome you then on behalf of the Navy's Electronic Command and the U.S. Navy itself to this Sixth Annual Meeting.

I want to also extend the welcome of the United States to the foreign visitors. We are very proud that you would take the time to come, some from Europe and South America and the Orient. We feel we have a mutual scientific interest here.

And I also note that no one else has remembered to notice that this grand laboratory has a Commanding Officer in the person of my good friend Captain John Geary. I want to thank him, along with Dr. Berman, for hosting our splendid meeting. He and his staff have made these facilities available.

I take particular pleasure in joining you who are somewhat experts in precise measurement of time in this scientific environment. These scientists here at NRL — and they are the laboratory, not the facilities — have put many new scientific theories into operation, tested them, and evolved them into hardware. And remember hardware. Their fields of past renown have included radar communication, navigation, chromatic control, and some secret work that we still don't entirely talk about, and innumerable other disciplines.

The primary purpose of these precision time meetings is to exchange information, preferably scientific, although the social events may be interesting. In conferences such as this, the interchange and exchange of the technical information is probably immensely enhanced by the opportunity to have a face-to-face, eyeball encounter. I think this is most significant as we push against the frontiers here. I heard someone talking 10^{15}. Heck, I am just as willing to talk 10^{24}. Why set your goals low?

I had some of my physics acquaintances bumbling with the thought — and most physicists bumble quite a bit and stumble into results as much as they get them by deep scientific research. I wanted to know whether since everything else that seemed in our life in the ultimate appeared to have a quantum, there was a piece of below which you could get no smaller, I wanted to find out what the quantum of time was. Because it would seem to me that it would make some sense that since everything else has a quantum, why not time. You would finally get down to where there isn't a half of the one you got.

I was informed that, as usual, I didn't know what I was talking about. I haven't given up the thought. Man seems to be put together rather digitally if you really look into it seriously. And it is no wonder the Lord could walk through a wall, see. If you get your digits all lined up, there is one magic microsecond at which you could, indeed, synchronize and get through the wall. And you better do it fast.

And I hope that isn't blasphemous. It is just applying good scientific theory to the problem. You would be stuck forever if you blew it.

Anyway, our little meeting here is really about time — I am emphasizing the word "about." My speech writer is getting better. We realize that of the three fundamental quanities, and I think it is about time we took this very seriously, mass, length and time, the one most significant in the electronic scientific world has to be time.

Then being about right or about accurate is always very relative to what you are doing. Someone talks here that we can get around in milliseconds. Someone said a few microseconds. Well, you couldn't measure a loop mile with a radar, you realize, until you could measure something in the order of 12 microseconds more or less repeatedly, more or less all the time in any temperature condition. And we want to do a lot better than a loop mile.

But there are so many other places I want to do a lot better. As the state of the art in our electronics has advanced, the digital situation is simply overwhelming us. It is going to predominate. There is just no sense having analog voice radio, for example. It is passé. People look at me like I am crazy and still want to push the key.

But you can get so much more done digitally and still maintain voice recognition with a little effort that it is silly to consume the expensive rare band width with the beauties of an analog transmission. Now, once we get to that digital transmission and want to do it in all the circumstances that one might, military or civilian, one has to control the time. And the better you control time, the better your receiver works.

Finally, you end up not having to synchronize at all because you are always synchronized to some level of accuracy. We in the Navy have had a long history of being interested in scientific things. While I sometimes think our silver-plated badge of honor has tarnished somewhat over the last forty or fifty years, I personally belong to the clan that is doing everything it can to revive that place the U.S. Navy once held in the 1800's of being really the leader on the government side in scientific affairs.

And now we have a great partnership to share with the Bureau of Standards and the NASA and several other agencies that have come along and made important claims to the same situation and have not got a warfare role to nag them. Nonetheless, we, the Navy, are a scientific service. We can't operate to a great extent without our lowest-level officer being somewhat scientific and engineeringly inclined, to our detriment if we don't believe it.

We continue to press, therefore, in the study and development of time measurements and all instrumentation. My command assists the Naval Observatory as we execute our responsibilities in time management for the Department of Defense. NAVELEX with the assistance of NRL and the Observatory is itself the basic hardware management support for the entire operation. Our responsibilities have included engineering, procurement, calibration, planning, programming, budgeting, all those workhorse, housekeeping operations, to keep the research and development going and ultimately into the life-cycle support which is the tough part. It is the nagging part. Bits, pieces and part drugstore, I call it.

Our center here in Washington which is a field activity of mine has established depot repair facilities out at the Observatory to hang on to our clocks and keep them in calibration and repair. We have a test bed in Wahiawa — I give up; that one throws me all the time. It is in Hawaii. This site was selected because it was involved and closely proximate to various activities that might benefit from a time standard, and it was itself advantageous.

We are using this to determine operational requirements and help develop requirements, assisting in the implementation of the work you are doing, and create a frequency discipline of other facilities worldwide. We have had this thing running now for 18 months.

NRL here and under the sponsorship and working with NAVELEX has stabilized our VLF transmissions, making them coherent worldwide. Realizing the advantages of a VLF time and phase coherence, frequency shift keying coherence demodulator has been sponsored and developed. This unit at about $2,000 was able to hold up and be installed on operational submarines. So more now are going aboard and giving us a worldwide feasibility and operational test.

With this installation, substantially improved operational capability of the VLF broadcast reception then occurs in both Atlantic and Pacific. On one rare occasion when we did something right, we drew citations from fleet commanders who have cited both TELECOM, the C&O Managing Command, NAVELEX, the Material Support and NRL for this fine job.

In addition, shipboard time and frequency standards are now ready for operational evaluation. We plan to install aboard two tactical Naval ships, and this hopefully is the beginning of perhaps a program that is the mainstay of future fleet shipboard time and frequency distribution.

Looking a little further into the future, time sync and time transfer techniques, using the electronic system characteristics that are essentially fundamental to microwave satellite optical and wired technologies can be developed and easily put into place.

We must go on with processing clock systems for the program which are compact and versatile and can be matched for a specific use or extended to further applications. This processing of the clocks can be used either as a primary or secondary mode, comparison units, work in conjunction with atomic standards, time frequency oscillators, and of course now the maser. They would need to be designed to produce time of day, time of event, delayed time, time difference, coordinated universal time, any number of things. We can go on to infinity.

But you automatically, from the engineering point of view see the applications into the computer and information transfer world, the radio frequency oscillators which if they were accurate to 10^{15}, everybody could sort of automatically navigate by inverse Loran with a tiny computer.

I spoke of this three years ago, and I feel rather futile in that I can't see anything happening. It moves so slow, so to some extent I chide you. Being scientific, I think you want to keep this racket going while you finish your career.

Now, that's why I said make it worthwhile. Let's go for 10^{24} , and then you have got a longer future.

In the meantime, I would like to exhort some innovative individuals to get some of these things ever increasingly small while we on the one hand scientifically push for the best we can ever do, and that in itself is a goal, and that is a scientific goal. And I honor it. Ever increasingly better is the way we make progress.

Yet, there must be a spin-off from time to time. As I talked with Captain Geary for a moment over coffee this morning, it came to my mind if we sit around waiting for God to ordain that the PTTI program is great and should do many, many more things, we will wait a very long time. But if some of you great scientific geniuses, genii, will take ahold and back home at the ranch get something about the size of a shoe box or preferably a pack of cigarettes that will give me something approximately 10^{11} all the time or most all the time so that I can have it as the oscillator of my aircraft radio, for example, from which I build up the frequency synthesization, we begin to have some real application of the wonders of this art.

Indeed, the way to do it is not to announce loudly that you are going to have a PTTI oscillator; you just go do it and sneak it into the next radio. And when nobody is looking, you suddenly have a radio that is basically, by its own oscillator, a time standard. Once that starts to happen, we do the same thing in a computer, and we have a matched computer time standard, the same accuracy as the main oscillator of our radio. Pretty soon, we can talk in spread spectrum and all this sort of thing without this inordinate amount of effort in synchronizing and getting organized.

Now, I admit I don't know what I am talking about, and I don't know what I am dreaming about, but I have a sixth sense I am close to being right and close to being possible. It is my job nowadays to get on; my time is running out; I am getting old fast. I want to see some of these wonders installed in useful equipment

At any rate, let me finish here with the fine work added to it now, the long based interferometer, the things we have discovered there give us encouragement to believe it is really working, and we can go further.

For the future, we now stress having all our ship and shore facilities oriented to PTTI through applying the latest advances in the field of electronics to satisfy in a total system engineered complex. That is not as big a thought as some people think it is — to do everything right for a change in an organized way. Don't put the plumbing in the house after it is five years old. It is better to do it while building.

We can engineer these things in if we start.

I plan to see that my command puts forth its best efforts and provides strong support to this community, working with all their interested parties. Our particular role, of course, is hardware, and to bring the benefits of this expertise down to practical application on an everyday basis and across the ever-increasing number of electronic marvels where precise time actually dictates the speed of technological progress.

A lot of people don't understand that, but all of us here do. It is underlying the whole system.

So once again, now, I welcome you all, national and international visitors, for your participation in what I trust will be a most rewarding and successful meeting this week. Thank you.

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PRECISE TIME AND TIME INTERVAL (PTTI), AN OVERVIEW

Gernot M. R. Winkler
Naval Observatory

ABSTRACT

Present applications of precise time and frequency (T/F) technology can be grouped as follows:

1. Communications systems which require T/F for time division multiplexing and for using spread spectrum techniques.

2. Navigation systems which need T/F for position fixing using a timed signal.

3. Scientific-Metrological applications which use T/F as the most precisely reproducible standard of measurement.

4. Astronomical-Space applications which cover a variety of the most demanding applications such as pulsar research, Very Long Baseline Interferometry (VLBI) and laser/radar ranging. In particular, pulsar time-of-arrival measurements require submicrosecond precision over a period of one-half year referred to an extraterrestrial inertial system, and constitute the most stringent requirements for uniform timekeeping to date.

The standard T/F services which are available to satisfy such requirements are based on an international system of timekeeping coordinated by the Bureau International de l'Heure (BIH). The system utilizes the contributions from the major national services for standard frequency and time (USNO and NBS in the USA), and it is implemented through a variety of electonic systems (HF, T/F signals, VLF, Loran-C, etc.). The performance of these systems will be briefly reviewed. Several

of the user systems (such as VLBI) can, in turn, be used as contributors to the global effort of T/F distribution.

Moreover, PTTI is the one common interface of all time-ordered electronic systems. Time coordination (not necessarily synchronization) is the first necessary step for any wide scale integration and mutual backup of such systems.

OVERVIEW

In this short overview we can only mention the major aspects of time and frequency (T/F) which will be discussed extensively in the papers of the Proceedings. The main concepts are as follows:

1. Time of Day → UT1 (Rotation of Earth)
2. Clock Time at Standard Meridian → UTC
3. Synchronization
4. Accurate Frequency
5. Relativity: Local (Proper) Time, Coordinate Time
6. Coordination: 1 ms → 10 μs progress during the last 10 years.

For economical as well as practical reasons, SYNCHRONIZATION will usually be accomplished via clock time (UTC). Very accurate frequency cannot entirely be handled without also considering time. Relativity aspects must be considered if precision of better than a few hundred nanoseconds is involved. Lastly, the various international time services are coordinated with the BIH to the order of 10 μs - 100 times better than required by pertinent CCIR recommendations.

T/F has become a very active field during the last 10 years, due largely to the availability of commercial atomic clocks. Information is exchanged at a number of regular conferences, including the following:

1. Annual Frequency Control Symposium*, Atlantic City (U.S. Army), May.
2. CPEM, next meeting June 1976, Boulder (NBS-URSI-IEEE, Conference Proceedings in IEEE Trans. IM).
3. PTTI Planning Meeting*, Washington, December (annually), NASA-DoD.
4. URSI Commission 1 (National Meetings).

5. URSI Commission 1 (General Assembly (3 years), next in Lima, August 1975).
6. IAU, Commission 31, General Assembly (3 years) next Grenoble, August 1976.
7. International Congress for Chronometry* (5 years), last September 1974.

*Proceedings available

In addition there are regular training seminars by various groups, e.g., the NBS T/F seminars.

Let us consider the uses of T/F:

1. UT1 (mean solar or sidereal time) which is related to angular orientation of the Earth is needed for navigation, space tracking and geodesy. Essentially this application group is concerned with the orientation of the Earth in space and its rotation around its axis.

2. Other major uses deal directly with clock time. These applications come from a variety of time-ordered electronic systems:

a. Communications Technology

1) Time division multiplexing - channel packing, many stations on one frequency.
2) Reducing spread spectrum acquisition window.

b. Electronic Navigation in TOA Mode (Absolute)

1) For improved geometry of position determination (RHO-RHO).
2) For improved coverage - mixed systems.
3) For integration with communication and identification systems.

c. Metrology

Time and frequency are by far the best controllable parameters and can be used for measurement of length, voltage, pressure, temperature, etc.

d. Astronomy - Space Technology. This last application has the most stringent requirements - fractions of a microsecond over 1/2 year related to an inertial system (with relativity corrections for the movement of the Earth in the solar system).

These requirements for precise time are being satisfied in a variety of ways; with time signals, publications and superpositioning of the timing capability on existing electronic systems.

We have available the following time information services:

1. BIH Announcements.
2. U.S. Naval Observatory publications, particularly Time Service Announcements Series 1 through 17, and Almanacs (Ephemerides) (See Appendix).
3. National Bureau of Standards Time & Frequency Bulletins.

These services refer to time as it is disseminated by the following systems:

1. HF Standard T/F Signals: (WWV, CHU, etc.).
2. Timed electronic navigation signals: Loran-C, OMEGA, Transit, and later Global Position System (GPS), etc.
3. Wideband Communication links: Two-way.
4. Portable clocks, Precise Time Reference Stations (PTRS).
5. Special systems, largely under R&D: TV, etc.

The HF signals provide a global capability (including a great number of coordinated foreign services) of 1 ms precision, if propagation and receiver delays (3-5 ms depending mainly on band width used) are taken into account. Item 3 is potentially the most accurate, but portable clocks remain our final "authority" to calibrate services.

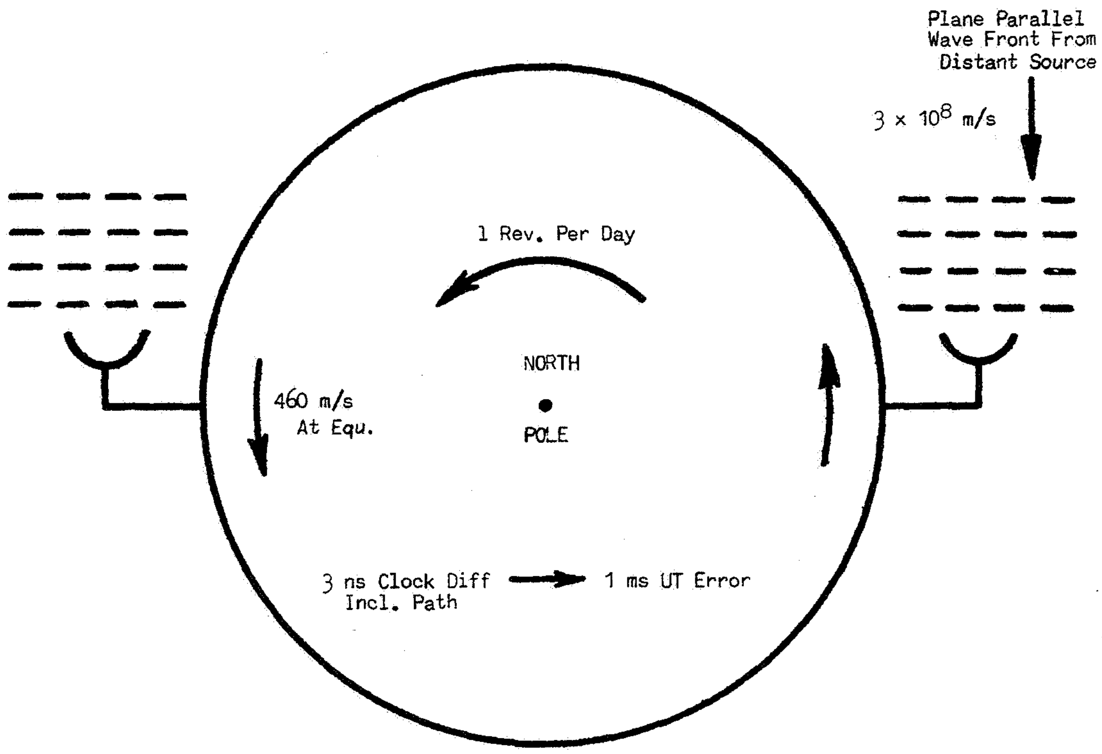
In greater detail, we could summarize the distribution capabilities as follows:

1. HF radio time signals:	1 ms global	
2. Portable clocks:	0.5 μs global	
3. VLF-OMEGA:	1-3 ms phase track (Relative)	
4. Loran-C/D	0.5 μs Northern Hemisphere	
5. Satellites:		
a. DSCS	0.1 μs "trunk line", global	2-way
b. TACSAT	0.5 μs "intermediate"	
c. TRANSIT	10 μs global	Silent (one way)
d. GPS	0.1 μs global	Silent (one way)
6. Television:		
Local:	10 ns	
Long range:	1 μs	

7. Microwave, laser (local): 1 ns
8. Others: (R&D, VLBI, power lines, etc.)

As an example of users who can also help in global timekeeping, we can mention VLBI which, as the following sketch shows, provides both synchronization and UT (also the polar coordinates, x and y).

PRINCIPLE OF VLBI TIME DETERMINATION
UT1 VERSUS SYNCHRONIZATION
A USER AND CONTRIBUTOR



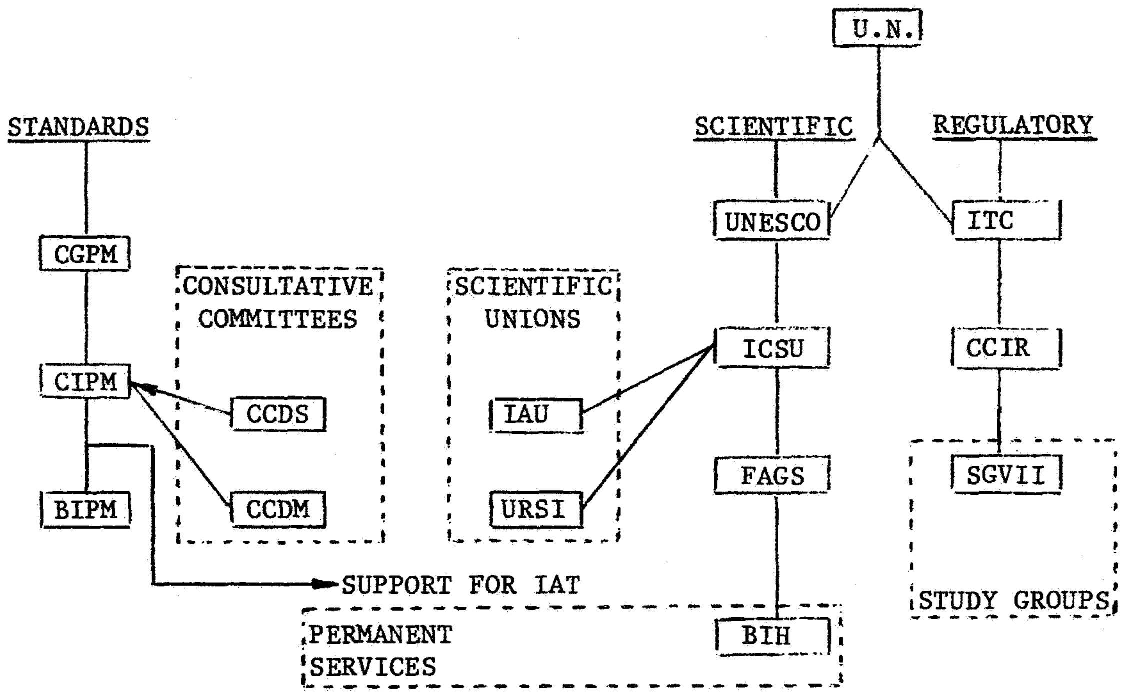
Redundant observations allow determination of time difference, base line, UT1 and polar coordinates.

<u>Coordination of Services</u>:

We have a system of international timekeeping in existence, coordinated by the BIH which is located at the Paris Observatory, and which is operated with some support from various international organizations.

The BIH operates under the auspices of the following organizations:

INTERNATIONAL ORGANIZATIONS INVOLVED WITH STANDARD FREQUENCY AND TIME



Abbreviations for PTTI

BIH	-	Bureau International de l'Heure
BIPM	-	International Bureau of Weights and Measures
CCDM	-	Consultative Committee for the Definition of the Meter
CCDS	-	Consultative Committee for the Definition of the Second
CGPM	-	General Conference of Weights and Measures
CIPM	-	International Committee for Weights and Measures
CCIR	-	International Radio Consultative Committee
IAT	-	International Atomic Time
FAGS	-	Federation of Astronomical and Geophysical Services
IAU	-	International Astronomical Union
ICSU	-	International Council of Scientific Unions
ITU	-	International Telecommunication Union
SGVII	-	Study Group 7
U.N.	-	United Nations

UNESCO - United Nations Education, Scientific and Cultural Organization
URSI - International Union of Radio Science

The national organizations (time services and/or standards laboratories) provide basic data to the BIH. The U.S. contributions from the U. S. Naval Observatory and the National Bureau of Standards are given in detail in NBS Technical Note 649, "The Standards of Time and Frequency in the USA".

In the United States, the division of responsibilities can be briefly summarized as follows:

T/F Responsibilities

NBS	USNO
National Standard of Frequency	National Standard of Time (Epoch, Date)
Standard Frequency (and time) Broadcast	Control of DoD T/F Transmissions
Fundamental Research in T/F as Related to Clock Time, Frequency Measurements	Applied Research in Time as Related to Clock Applications, Astronomy, Geophysics, and Navigation
Synchronization	Consultation and Management of PTTI Activities as Related to DoD
Consultation and Education	
PTRS for USNO	

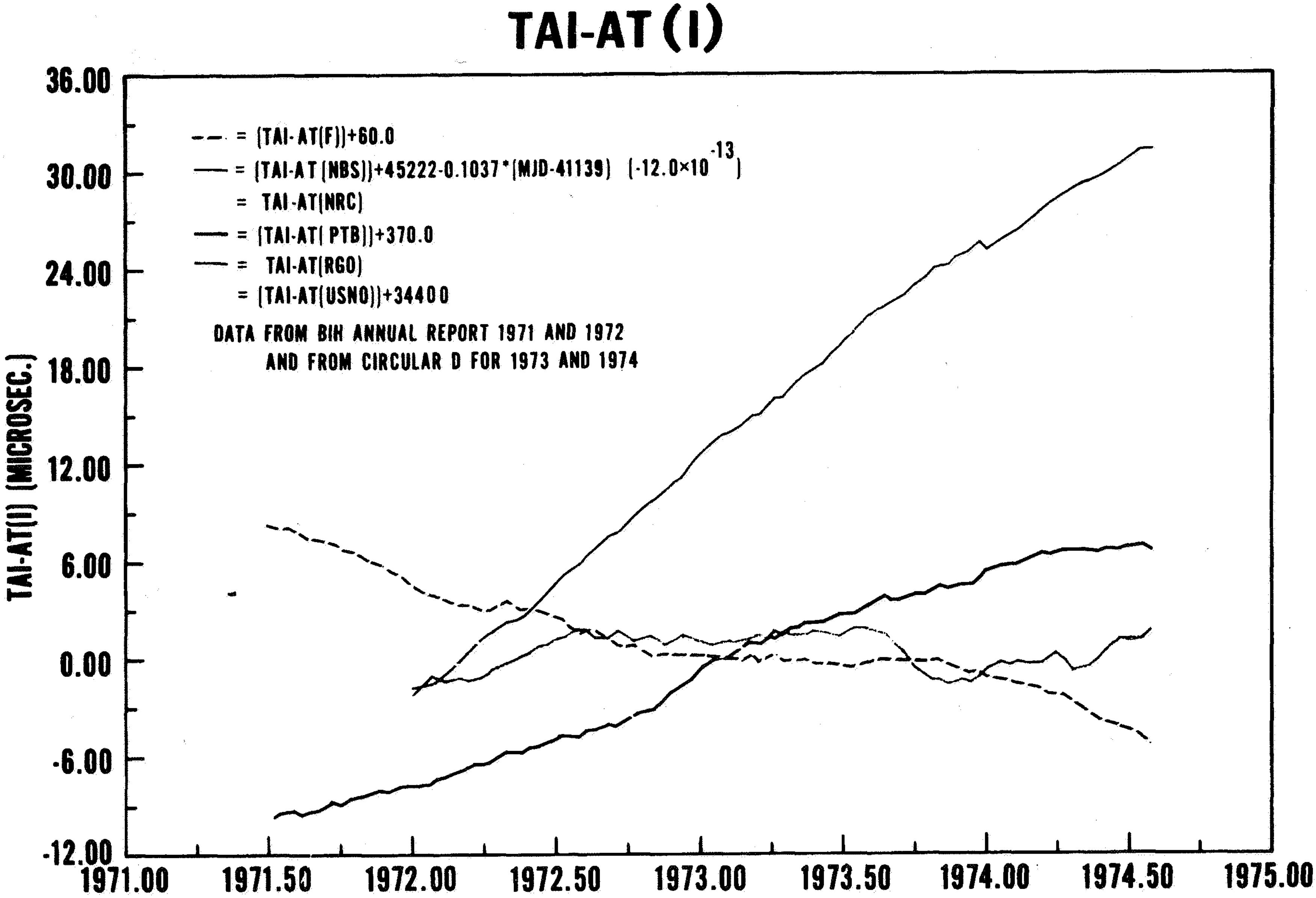
The international clock time scales IAT and UTC are based on a number of individual clocks, presently operated by the following contributors:

CONTRIBUTORS TO TAI (BIH)
(SOURCE BIH)

AGENCY	WEIGHT PER CLOCK	CLOCKS	TOTAL %	RANK
	%		%	
NPL	89	4	10	3
PTB	83	4	9	4
IEN	78	3	6.5	7
RGO	74	4	8.2	5
USNO	56	24	37	1
F	54	8	12	2
NBS	48	6	8.1	6
ON	44	4	5	8
NRC	37	3	3	9
ORB	26	1	0.7	10
TP	13	1	0.4	11
OMSF	3	2		
FOA	0	2		
PTCH	0	1		
VSL	0	1		

The table reflects the August 1974 situation. The Time Services in turn keep their coordinated scales for dissemination within about 10 μs of the BIH by making very small adjustments to their scales (10^{-13}). The clocks which contribute to the BIH are not adjusted.

The graph TAI - AT(i) depicts the performance of the internal scales of the major contributors as derived from BIH reports.


TAI-AT (I)
= (TAI-AT(F))+60.0
= (TAI-AT(NBS))+45222-0.1037*(MJD-41139) (-12.0×10^-13)
= TAI-AT(NRC)
= (TAI-AT(PTB))+370.0
= TAI-AT(RGO)
= (TAI-AT(USNO))+34400
DATA FROM BIH ANNUAL REPORT 1971 AND 1972
AND FROM CIRCULAR D FOR 1973 AND 1974
TAI-AT(I) (MICROSEC.)
36.00
30.00
24.00
18.00
12.00
6.00
0.00
-6.00
-12.00
1971.00
1971.50
1972.00
1972.50
1973.00
1973.50
1974.00
1974.50
1975.00

The results of the timing operations are published in bulletins which give actual clock differences. This is an example from Section 3 of the BIH Bulletin, Circular D92 dated 1974 July 4.

COORDINATED UNIVERSAL TIME

a. From Loran-C and Television pulses receptions

Date 1974		May 2	May 12	May 22
MJD		42 169	42 179	42 189
Laboratory i		UTC-UTC(i)	(unit : 1 μs)	
DHI	(Hamburg)	- 1.3	- 1.2	- 0.6
FOA	(Stockholm)	+ 38.5	+ 39.5	+ 40.1
IEN	(Torino)	- 10.5	- 11.0	- 10.9
NBS	(Boulder)	- 2.2	- 1.8	- 1.5
NPL	(Teddington)	- 36.4	- 36.8	- 37.1
NRC	(Ottawa)	- 0.6	- 0.5	- 0.1
OMSF	(San Fernando)	- 0.2	- 0.2	- 0.3
ON	(Neuchâtel)	+ 20.5	+ 20.3	+ 20.2
OP	(Paris)	+ 1.7	+ 1.9	+ 2.0
ORB	(Bruxelles)	- 33.5	- 32.3	- 31.8
PTB	(Braunschweig)	+ 0.3	+ 0.2	0.0
RGO	(Herstmonceux)	- 2.1	- 2.3	- 2.6
TP	(Praha)	- 25.4	- 25.6	- 26.5
USNO	(Washington) (USNO MC)	+ 0.3	+ 0.4	+ 0.5
VSL	(Den Haag)	+ 21.2	+ 23.1	+ 25.0

b. From clock transportations (unit : 1 μs)

From "Daily Phase Values", Series 4, No. 382, USNO

San Fernando Naval Observatory, San Fernando, Spain:
1974 May 16 (MJD = 42 183.3), UTC(USNO MC) - UTC(OMSF) =
- 1.2 ± 0.1

CONCLUSION

PTTI technology offers capabilities which are desirable and useful in many modern electronic systems. With the availability of high performance atomic clocks (cesium beam, rubidium-gas cell and hydrogen-masers), the system designer can allow remote stations to operate with a high degree of independence (e.g. the VLBI receivers need no link, only initial synchronization).

As always, such extra benefits extract a premium price of additional complexity and training of operators. A standard timing interface (1 pulse per second, etc), with the large number of systems which are coordinated with UTC, allows some additional benefits and/or redundancy. One can therefore expect an expansion of the PTTI activities in the future.

APPENDIX

U.S. NAVAL OBSERVATORY
Time Service Publications

Series 1. LIST OF WORLDWIDE VLF AND HF TRANSMISSIONS suitable for Precise Time Measurements. Includes: Call sign, geographic location, frequencies, radiated power, etc. **(Time Signal Transmissions)**

Series 2. SCHEDULE OF U.S. NAVY TIME SIGNAL TRANSMISSIONS in VLF and HF bands. Includes: Times of broadcast, frequencies, etc.

Series 3. SCHEDULE OF U.S. NAVY VLF TRANSMISSIONS, including OMEGA System. Includes: Location, frequencies, power radiated, maintenance periods, type of transmission, etc.

Series 4. DAILY RELATIVE PHASE VALUES (Issued weekly). Includes: Observed phase and time differences between VLF, LF, Omega, Television, Portable Clock measurements, and Loran-C stations and the UTC(USNO Master Clock). Propagation disturbances are also given.

Series 5. DAILY TELETYPE MESSAGES (sent every working day). Includes: Daily relative phase and time differences between UTC(USNO MC) and VLF, LF, Omega, Loran-C stations. Propagation distrubances and notices of immediate concern for precision timekeeping.

Series 6. USNO A.1 - UT1 DATA. Preliminary daily values distributed monthly with final data issued as available.

Series 7. PRELIMINARY TIMES AND COORDINATES OF THE POLE (issued weekly). Includes: General time scale information: UT1 -- UTC predicted 2 weeks in advance: time differences between A.1, UT1, UT2, UTC(BTH) and UTC(USNO); provisional coordinates of the pole; DUT1 value; and satellite information.

Series 8. TIME SERVICE ANNOUNCEMENTS pertaining to synchronization by television. Includes: times of coincidence (NULL) ephemeris tables.

Series 9. TIME SERVICE ANNOUNCEMENTS PERTAINING TO LORAN-C. Includes: Change in transmissions and repetition rates, times of coincidence (NULL) ephemeris tables, coordinates and emission delays, general information, etc.

Series 10. ASTRONOMICAL PROGRAMS (issued when available). Includes: Information pertaining to results, catalogs, papers, etc. of the Photographic Zenith Tube (PZT), Danjon Astrolabe, and Dual-Rate Moon Position Camera.

Series 11. TIME SERVICE BULLETINS. Includes: Time differences between coordinated stations and the UTC Time Scale; earth's seasonal and polar variations (as observed at Washington and Florida); Provisional coordinates of the pole; adopted UT2 -- A.1, etc.

Series 12. Time Service Internal Mailing.

Series 13. Time Service Internal Mailing.

Series 14. TIME SERVICE GENERAL ANNOUNCEMENTS: Includes: General information pertaining to time determination, measurement, and dissemination.

Should be of interest to all Time Service Addressees.

Series 15. BUREAU INTERNATIONAL de l'HEURE (B.I.H.) Circular D: Heure Définitive et Coordonnées du Pôle a O^h TU: Includes: Coordinates of the pole: UT2 – UTC, UT1 – UTC, and TA(AT) · UTC; UTC – Signal.

NOTE: USNO Time Service will distribute Circular D of the B.I.H. to U.S. addressees only.

Series 16. COMMUNICATION SATELLITE REPORTS: giving the differences UTC(USNO) -- SATCOM Clock for each of the available SATCOM stations.

Series 17. TRANSIT SATELLITE REPORTS: Includes Satellite Clock –UTC(USNO) and the frequency offset for each of the operational satellites.

QUESTION AND ANSWER PERIOD

DR. REDER:

What was the semi-disaster?

DR. WINKLER:

The semi-disaster refers to some questions concerning the link across the North Atlantic on which the contributions to the BIH from the National Research Council, the National Bureau of Standards, and the U.S. Naval Observatory depend. There were also some operational difficulties which in the meantime, I think, have been straightened out. Most, but not all, of the questions have been clarified.

I think there has been an increased noise contribution to the various rate measurements as they are available to the BIH. But we are talking about fractions of microseconds and not more.

DR. GUINOT:

I wish to make some comments on what Dr. Winkler said. We have the impression that the link through Loran-C is the link of the American clocks to the BIH. I want to make clear that the European clocks and the American clocks have a completely symmetrical role in the BIH. The fact that the BIH is located in Europe does not influence at all the weights which are given to the clocks.

The Loran-C disturbance recently prevented us from making the necessary computations.

MR. LIEBERMAN:

Ted Lieberman, NAVELEX.

On your slide where you talk about the frequency standard precision and about the complexity, that may be far beyond what you need. Once again, I would like to emphasize or try your opinion on the life-cycle course that the Admiral talked about versus the initial complexity. How much does it take to keep something that is marginal for your needs to meet the requirements such as crystals, rubidium, et cetera.

DR. WINKLER:

I don't quite understand the question. You talk about what total effect it has, not only at the original purchase point, but also in maintaining that standard and all through its complete lifetime?

MR. LIEBERMAN:

Right.

DR. WINKLER:

I think it will have, of course, an even greater effect. An item like a precision cesium standard which has five times as many components as a rubidium standard, (simplified bare bones rubidium standard) can be expected to present, I wouldn't say five times as much maintenance effort, would certainly require much greater maintenance effort.

What I am asking for, what I am recommending, is that before a decision is made for any particular standard, one should not only consider the purchase price, but consider everything which comes after which is again at least as much in dollars and cents as the budget, maybe more. I think it is completely hopeless to establish true and completely independent, self-consistent field maintenance capabilities for cesium standards.

Anyone who is going to attempt that will pay very, very dearly. He will pay so dearly because it takes a good technician about, I would say, a year to become familiar with it. The effort in training, the effort in stockpiling of spare parts, I think is simply not worth such a method.

You also should consider that these clocks, even the lesser performers here, all have mean time between failures which certainly ought to be greater than 10,000 hours.

So you are dealing with standards where only rarely something can be expected to go wrong. Now how much training effort do you want to spend in field locations where people may be reassigned after six months? It is simply not a practical concept. And all of these aspects have to be considered.

Incidentally, in the literature, there have been several points where attempts have been made to put the benefits into some kind of a payoff matrix. For instance, in the special issue of the IEEE Proceedings, May, 1972, I believe, there are at least two locations where such matrices are discussed. And I have some reprints here of my own paper on path delays.

This can be only understood as a first try. I think such engineering decisions ought to be made much more sophisticated that what they are. Up to now, to say it quite bluntly and frankly to you, I think most of these decisions are made on the basis of glamor.

MR. MITCHELL:

Don Mitchell, Kwajalein Missile Range.

We have two cesiums and we do at the present time have a qualified techniciam who is capable of working on these and has a complete complement of spares. How would we go about getting our cesiums into the Naval Electronics Repair System?

DR. WINKLER:

I wouldn't recommend it: you have a special situation. You have been lucky enough to keep personnel on the job for a sufficient time to familiarize themselves with problems.

The point I am making is that you must allow specialization to a great degree and assure that the people, these specialists, are kept on location or at least in the same field of applications for a long time and then you can do what you do quite successfully. I think an alternative is that you do not field-maintain these standards at all and simply operate on the basis of redundancy. Equip every station with two, or if you can, three standards. If any one fails, send it back to a central depot.

That is the idea of having established the Naval Engineering Command Maintenance System where there is a central location where these cesiums can be diagnosed, readjusted, repaired to a certain degree.

But I tell you, that system sometimes works out like the following. We received from a distant station a cesium, and all that was wrong is that the alarm light doesn't go out, and you have to adjust the trigger circuit. Many repairs are of this kind of sophisitication.

REVIEW OF TIME SCALES

DR. B. GUINOT
Bureau International de l'Heure
Paris, France

ABSTRACT

The basic time scales are presented: International Atomic Time, Universal Time, and Universal Time (Coordinated). These scales must be maintained in order to satisfy specific requirements. It is shown how they are obtained and made available at a very high level of precision.

INTRODUCTION

Until 1956, the unit of time, the second, was defined as a fraction of the mean solar day. However, the duration of the mean solar day was found to be variable, and a better definition, made possible by the progress of physics, was given in 1967, when the second was defined to be a certain number of periods corresponding to a transition of the cesium atom. The relative accuracy of the realization of the second was thus improved from 1×10^{-7} to 1×10^{-13} (1974). In the meantime, from 1956 to 1967, the second was defined to be a certain fraction of the year, more stable than the day; but this second was so difficult to implement, that its quasi-unique use was to calibrate the atomic second.

The situation of the unit of time is clear: only the last defined unit is used by the physicists. Nevertheless, none of the time scales associated with the three definitions of the unit could be abandoned, because they satisfy specific requirements. We thus have three basic time scales in simultaneous existence: Universal Time, UT1 (often called Greenwich Mean Time), based on the rotation of the Earth; the Ephemeris Time ET, based on the motion of the Earth around the Sun; and the International Atomic Time TAI (fig. 1). In the following, we will not discuss the problems of Ephemeris Time, because ET is in limited use and is being redefined; we will concentrate on UT1 and TAI.

The origin of TAI was arbitrarily chosen so that the TAI and UT1 readings on January 1st 1958 were the same. But they do not run at the same rate, and now, in December 1974, they differ by more than 13s; even less sophisticated users cannot ignore this difference. As we shall see, some users need UT1, others TAI. In order to avoid the risk of confusion which would arise from the dissemination of two time scales, it was agreed that the time signals will follow a unique compromise time scale, designated Universal Time (Coordinated), UTC. The definition of UTC is very simple: it differs from TAI by an integral number of seconds, this integral number being changed by one unit, when necessary, in order to maintain $|UT1-UTC| < 0.9$ s. The International Radio Consultative Committee gave precise rules for the implementation of UTC, and also defined a simple code used in time signal emissions which enables the field user to obtain UT1 immediately to ± 0.1 s (1).

The problems of the determination and of the dissemination of UTC are the same as for TAI and will be discussed together in what follows.

Figure 2 shows the relative behaviour of UT1, TAI and UTC.

INTERNATIONAL ATOMIC TIME AND UNIVERSAL TIME (COORDINATED)

Their formation

As soon as the frequency of crystal clocks could be calibrated in real time by a cesium frequency standard, at the National Physical Laboratory in 1955 (2) astronomers began to form a time reference suitable for the study of the rotation of the Earth. When other cesium standards appeared, data were combined in order to increase the stability. Several atomic time scales were thus developed in national and international institutions, differing slightly in rate and phase. As the use of atomic time extended to many other fields of activity, it was desirable to agree on a unique time reference. This was done in October 1971, by a decision of the 14th General Conference of Weights and Measures, which defined International Atomic Time TAI as the time reference maintained by the Bureau International de l'Heure (BIH) from the readings of atomic clocks.

TAI is presently based on the data of about 60 commercial cesium clocks, located in 15 laboratories and observatories of North America and Europe. These clocks are daily intercompared by the use of LORAN-C pulses, with an accuracy of a few 0.1 μs. Their data are combined by an algorithm which intends to 1) minimize the noise due to introductions and removals of clocks, 2) ensure the long term stability (over years) by an appropriate weighting procedure (3). The random noise in TAI for a sampling time τ over 2 months is a flicker frequency modulation (4) with σ (2, τ = 1 year) of the order of 0.5×10^{-13}. For smaller values of τ the main source of uncertainty is the LORAN-C link across the Atlantic Ocean, which introduces fluctuations extending over a few weeks, with an amplitude reaching 1 μs (5). Some small non-random errors of TAI were revealed by reference to the recently developed primary frequency standards; the frequency of TAI should be corrected by about $-1 \times 10^{-12} + 1 \times 10^{-13}$ (t - 1973), t in years, the amount of the frequency drift being very uncertain. In the near future, these non-random errors will be reduced and the long term stability will be improved by the use of the data of primary standards, after convenient filtering (6). Other improvements are expected from the elimination of some systematic errors in the LORAN-C time transfers and from the extension of the coverage of precisely synchronized chains. With the present coverage, sets of good clocks, especially in Japan and Australia, are not included.

TAI is the best measure of time for long term studies and therefore is to be used in dynamical studies of the motions of celestial bodies, both natural and artificial. It also acts as a frequency memory which enables one to compare the frequencies of oscillators separated in space and time, and it provides users with a means of referring frequencies to any of the primary frequency standards.

As previously said, TAI is not disseminated; the time signals and the master clocks of laboratories follow UTC, which is therefore the common worldwide reference by which all events must be dated. Of course, according to its definition, UTC is produced by the BIH simultaneously with TAI.

Dating of events in UTC

UTC (and TAI) is established in retrospect as the result of computations, and no real clock runs exactly on UTC.

The first step for dating an event in UTC is to find some real reference clocks giving access to UTC. For those laboratories of which the clocks enter into the determination of UTC and TAI, the outputs of the BIH algorithm are corrections to be added to the readings of these clocks to get UTC and TAI. Any such clock is therefore a local time reference, but for the purposes of simplification one per laboratory is generally selected which produces the local approximation to UTC, designated UTC(i) for laboratory (i). The tables published monthly by the BIH give the values of UTC-UTC(i) every 10 days, with uncertainties of a few 0.1 μs, but in arrears by 1 to 2 months (fig. 3). It is, however, possible in well equipped laboratories to extrapolate UTC-UTC(i) up to the present with errors less than ±1 μs and even, in some cases, to steer a clock so that it remains close to UTC. For instance, the USNO master clock did not deviate by more than 1 μs from UTC from 1 January 1973 to 21 July 1974. Within these limits of ±1 μs, UTC is therefore immediately available.

For the observer, the problem now is to find a time link with one of the standards UTC(i). It is beyond the scope of this paper to present the various techniques which are available. But it is worthwhile to note that for the larger part of the globe, microsecond accuracy can be reached by clock transportation only. When millisecond accuracy is sufficient, UTC is directly available by standard time signal emissions.

It must be emphasized that, at the present level of precision, international co-operation in matters of atomic time scale depends entirely on the LORAN-C time transfers with the help of occasional clock transportations. Long distance time intercomparisons are less amenable to future improvements than the clocks themselves. Any improvement of the LORAN-C time transfers or the development of more precise methods will have a direct impact on the quality of TAI and UTC and on their dissemination.

UNIVERSAL TIME

Under the general designation "Universal Time," there are several time scales, close to each other and related to the rotation of the Earth. Only the UT1 scale is important for the general user; it expresses a measure of the angular position of the Earth around its instantaneous axis of rotation.

Although it is questionable to a logical mind to consider UT1 as a time scale, it is practical and convenient to do so. Since the rotation of the Earth is not uniform, the difference of times assigned to the same event in the UT1 and TAI scales will vary with the calendar date. But as this difference, expressed by UT1-TAI, is slowly varying (by about 3 ms per day, presently), it is sufficient to have tables giving UT1-TAI and UT1-UTC. The reception of time signals in the UTC system and the use of these tables give easy access to UT1, but not in real time; and for UT1, no good extrapolation is possible.

There are two main reasons why UT1-TAI must be known as precisely as possible, simultaneously with the two coordinates of the terrestrial poles, which are moving on the Earth's surface: the geophysical applications, and the geometrical ones.

The geophysical processes which give rise to the irregularities of the Earth's rotation and therefore of UT1-TAI are not yet fully known. The motion of the atmosphere plays an important role, especially for short-term irregularities, but contributions are also due to tidal fiction, motions in the oceans and in the fluid core of the Earth. UT1-TAI cannot be predicted, and precise experimental measurements are needed for a better knowledge of the perturbing forces.

The geometrical applications are related to the tracking of celestial bodies. Most of the observations are made from the rotating Earth and are referred to a terrestrial frame of reference. It is therefore necessary to know all the parameters of the Earth's rotation in space. One of them is UT1. For instance, UT1 is needed for reducing meridian observations of stars and some radiointerferometric measurements. But the most striking application is to the navigation of interplanetary space probes. At a distance equal to that of the Sun from the Earth, 1 ms error in UT1 (which is the present level of uncertainty) corresponds to about a 10 km error in position, which is far from being negligible.

The only technique presently used for determining UT1 on a routine basis is the observation of star transits across a reference circle by about 60 astronomical instruments: photographic zenith tubes, astrolabes, and meridian transit instruments. The data of these instruments are combined by the BIH, which publishes monthly tables giving UT1-UTC and UT1-TAI every five days. The short term stability of these results is given by the square root of the Allan variance σ $(2, \tau = 5 \text{ days}) = 1.5\,\text{ms}$. But the errors are not white noise; besides periodic annual errors with a possible amplitude of 2 to 3 ms, the noise seems to lie between white and flicker phase modulation (fig. 4).

Improvements in the measure of UT1 can be expected from new astronomical instruments such as the large PZT of the U.S. Naval Observatory and the photoelectric astrolabe developed in France. However, classical methods are limited by the turbulence of the atmosphere. New techniques such as satellite observations and lunar laser ranging either alone or in association with classical astrometry are promising. Long baseline radiointerferometry could reduce the errors by a factor 10 or even more. But it must be kept in mind that the Earth's rotation must be monitored continuously. The classical methods, which are not so expensive as the new ones, will have to be used until it is proved that the new ones provide better results on a continuous basis.

Another improvement from an operational point of view would be to reduce the delay in providing UT1 to a given level of uncertainty.

In some cases UT1 should be available immediately, as, for instance, for the navigation of space probes. Presently, the delay of 1 to 2 months necessary to reach 1 ms accuracy is due to the need of having a two-sided smoothing for reducing the effect of accidental errors; the shortening of this delay also requires more precise observations.

CONCLUSION

In matters of time scales, international cooperation is important both for a better evaluation of the scales and for ensuring their worldwide acceptance. I will not enter into the political intricacies of the official organizations dealing with time. It is often difficult to say which organization is responsible for what. But the international arrangements work surprisingly well. The BIH, which is the executive body acting under the sponsorship of these organizations, does not receive contradictory instructions.

The BIH, formerly in charge of publishing the times of emission of signals in UT1, extended its activities to atomic time and to the coordination of clocks in the UTC system in recent years. Well automated data handling has enabled us to cope with an increase of work in spite of reductions in the number of our staff and in our grants.

However, nothing could have been accomplished without the constant support of all the laboratories and observatories which concur to produce the final data. Here is the appropriate place to thank the U.S. organizations which are especially helpful: the National Bureau of Standards, the U.S. Coast Guard, and the U.S. Naval Observatory.

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	Unit of time		Associated Time Scales
Definition	Validity of the definition	Relative Accuracy of the realized unit of time	
1/86 400 mean solar day	⟶ 1956	1×10^{-7}	Universal Time UT1
1/31 556 925.9747 tropical year (for 1900 Jan. 0)	1956-1967	5×10^{-9}	Ephemeris Time ET
9 192 631 770 periods correspon-ding to a transition of the cesium atom	1967 ⟶	1×10^{-13}	International Atomic Time TAI

Figure 1.

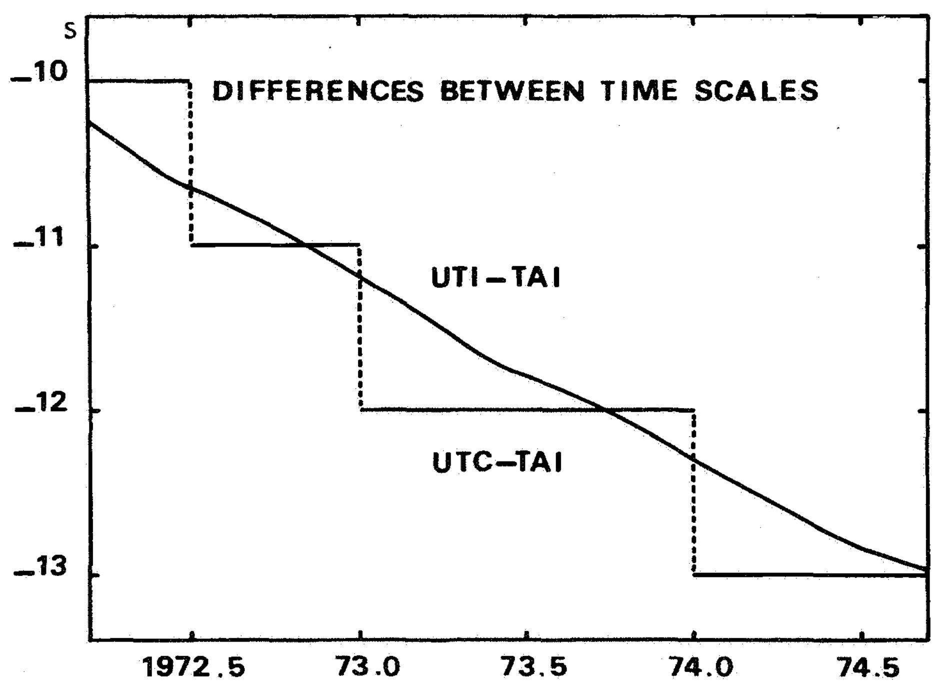


Figure 2.

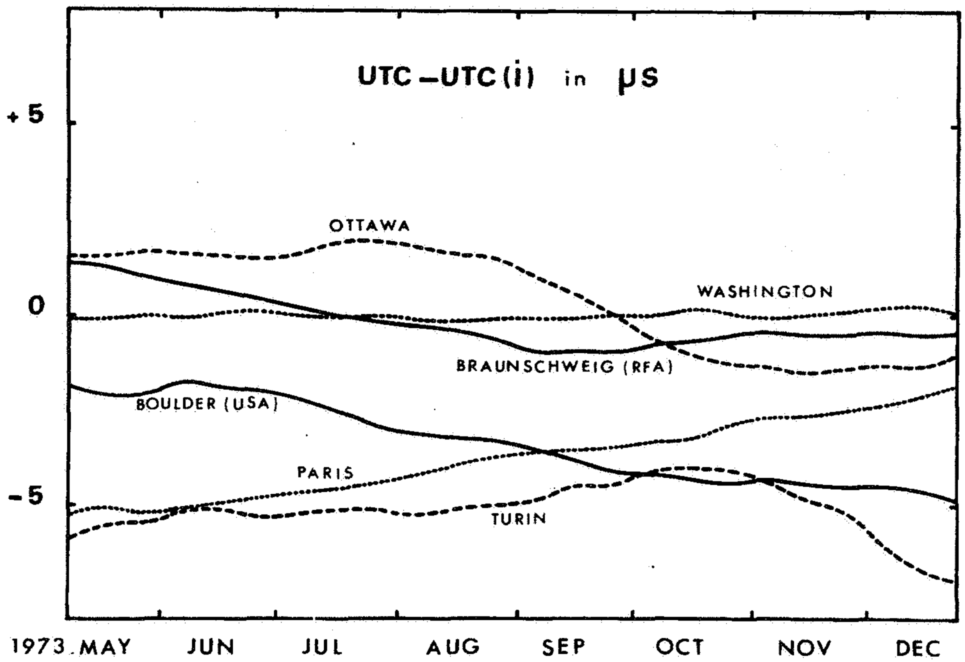
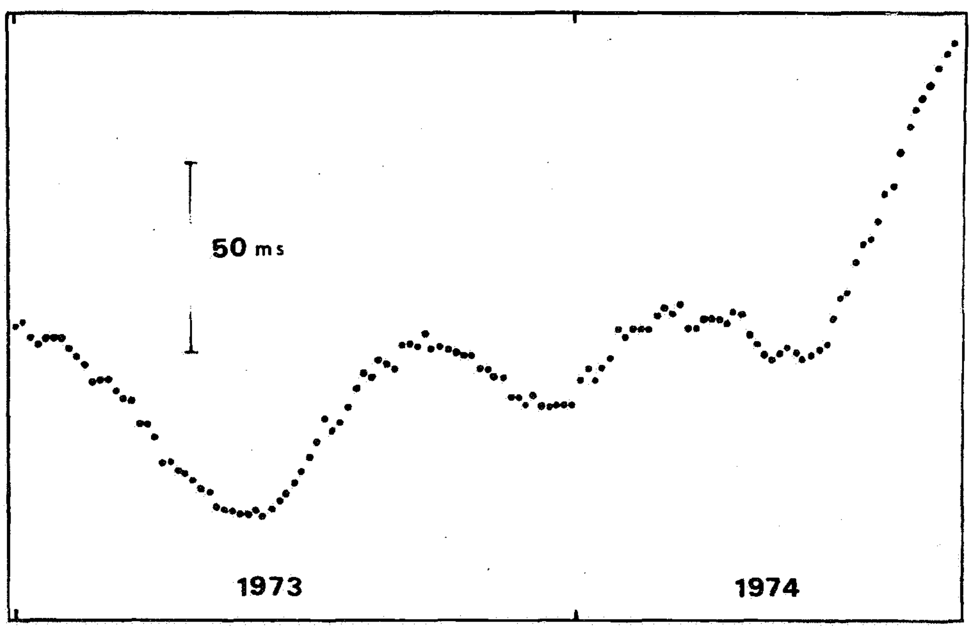


Figure 3.



UT1 — UNIFORM TIME

Figure 4.

QUESTION AND ANSWER PERIOD

DR. KLEPCZYNSKI:

Klepczynski, Naval Observatory.

Of the 60 cesiums which go into forming TAI, how many are the high performance standards?

DR. GUINOT:

The number of high performance standards must now be about ten. I remind you that for TAI, we are interested in the very long-term stability (over months). In this respect the high performance cesiums do not appear better than the standard ones. In several cases, we observed large frequency drifts.

MR. CHI:

My name is Andy Chi from Goddard Space Flight Center.

I would like to ask you a question on the weighting factor for the determination of the UTC. Based on an earlier talk by Dr. Winkler, there might be an impression that the membership of the weighting factor is determined by the past performance which might be several votes.

On the other hand, it sounds to me as if the performance is the criteria, it's probably more exclusive club membership. What happens if the new members are not known well enough? This makes the scale continuous in the true sense? Or is average of the membership voting process give the apparent continuity of the scale?

DR. GUINOT:

I think that there are several points to answer to your question. First of all, the weighting procedure which is used by the BIH is a mixed procedure. Of course, it looks at the past of the clock. There are really some bad clocks. And we know them; they are bad maybe because there is some poor environment, for instance. They can't be detected by the algorithm. We do not rely on this clock. That is the meaning of the weighting procedure.

But the more important point is that a weighting procedure eliminate the clock which suddenly deviates in frequency from its past frequency. That is an elimination procedure. Even the laboratories where no weighting procedure is applied, in fact, they do apply a procedure. When the clock stops, it receives the weight zero. And all the laboratories who do not apply weighting procedure remove what they call the bad contributors. And that is partly what we are doing at the BIH.

I am afraid that I missed the second part of your question.

MR. CHI:

By the introducing of the new clocks and removing the old clocks, the average is no longer the same kind of average. In other words, I was wondering whether you have a true reference with the ins and outs of different clocks.

The questions really is that do we have a true continuity of the time scale by introducing and removing clocks?

DR. GUINOT:

The answer is yes. When we introduce a new clock, we first determine its rate correction so that it agrees with the rate of TAI. So that the true continuity is preserved.

But we are aware that with such a procedure, we can deviate progressively from the true realization of the second. That is the reason why it is necessary to refer to the primary frequency of ceisum standards. It was not done before now because the primary cesium standards were not available to 60 percent accuracy. But now, several of them are available or will be available so that we will in the future steer the TAI so that it remain in accordance with the determination of the second made by this frequency standard.

This can be done without deteriorating the stability. The problem is to select the appropriate filter in order to introduce the absolute measurement of the second. When the appropriate filter is selected, we can observe that not only the accuracy of the time scale is preserved, but also the stability is improved, especially in the long term.

MR. CHI:

What are the true primary standards to which you are referring?

DR. GUINOT:

One is at the National Bureau of Standards; one is at the National Research Council; one is at the National Physical Laboratory; one is at the Physikalisch-Technische Bundesanstalt; another one is now in Japan. It is not operational now, but it will be soon.

N75 27176

REVIEW OF AVAILABLE SYNCHRONIZATION AND TIME DISTRIBUTION TECHNIQUES

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U. S. Naval Observatory

T. N. Lieberman
Naval Electronic Systems Command

R. R. Stone
Naval Research Laboratory

ABSTRACT

The methods of synchronizing precision clocks will be reviewed placing particular attention to the simpler techniques, their accuracies, and the approximate cost of equipment. The more exotic methods of synchronization will be discussed in lesser detail.

The synchronization techniques that will be covered will include satellite dissemination, communication and navigation transmissions via VLF, LF, HF, UHF and microwave as well as commercial and armed forces television. Portable clock trips will also be discussed.

Before we discuss methods of synchronization, we should briefly review who the users of Precise Time and Time Interval (PTTI) are, and why they need synchronization.

Celestial navigation has, probably, the most users of precise time: certainly more than 100,000. They have very modest requirements, time to about 100 milliseconds at best. However, they do put a requirement on the more precise users of time. That is, they force the DUT1 code on the time signal and force the leap seconds. Because most of these users are very unsophisticated as far as time is concerned, their time must be "on time" for their navigation requirements. Users of precise time must always be aware of leap seconds - which, at the present time, occur about once a year.

Geodesy has more precise requirements time to one millisecond or perhaps even 100 microseconds for position determinations on the Earth's surface.

There are two main users of synchronization. First are the communicators requiring synchronization to 25 microseconds or better due to the increasingly high data modulation rates, time division multiplexing,

pp. 27 + 28 blank

and the use of synchronized spread spectrum. Second are users of synchronization for positioning systems. We must remember that the speed of radio waves or of light is approximately 300 meters per microsecond or approximately 1000 feet per microsecond. For electronic navigation, particularly in the rho-rho navigation mode, distance from the transmitter must be known. To know position to 1000 feet, time must be known to better than one microsecond.

Time and frequency are also used for identification, as for example, in collision avoidance systems and Identification - Friend or Foe, etc.

Many of these systems do not necessarily require synchronization to time of day. However, in the interest of redundancy and economy, it is essential that all systems be externally synchronized to the same time scale. This allows backup in case of failures. For example, satellite systems can, in case of failure of their clocks, use a nearby Loran-C station to synchronize their clocks again. The time scale to which all systems should be synchronized in the Defense Department is that of the Naval Observatory. But since the Naval Observatory time scale is coordinated with that of the Bureau International de l'Heure, and the National Bureau of Standards, there are many sources of time that can be used for synchronization depending on the accuracy required. However, care must be taken as international synchronization or domestic synchronization is not absolute to one microsecond. Many of these sources, however, can be reduced to that accuracy after corrections are applied.

There are many methods to synchronize clocks. Which method to choose depends on several requirements. The first requirement is the precision of synchronization. One must be aware that if he wants one tenth of a microsecond precision he is not going to be able to do it by looking, for example, at a wall clock. The user has to know what precision of synchronization he wants before he can determine which of the many methods of synchronization to use. The second requirement is the frequency of access to synchronization. If the user can synchronize every five minutes, then he can obviously use a very poor oscillator. However, if he can only synchronize once a year, then he is very limited in terms of the number of oscillators he can use. A third requirement, related to the second, is the quality of the clocks used both in reliability and performance.

For economy of PTTI distribution, we impose PTTI on both navigation and communications stations. We use these transmissions because there is very little additional cost in order for them to be "on time". It simply means an interface with an external time system. For redundancy, we use many different systems. For obvious reasons, the organization of PTTI services is a hierarchy. The master clock or timing signal for DoD is located at the Naval Observatory. From the Naval Observatory we then use trunk line timing to the precise-time reference stations, many of which are at SATCOM terminals. From these we can monitor Loran-C transmissions. Thus Loran-C is the next step down. This process continues down to the user.

There are many methods of distributing PTTI information. High frequency radio time signals have an accuracy of approximately one millisecond. With an excellent operator this can be reduced somewhat. However, it is global in distribution if foreign radio time signals are also used. These signals are given in Series 1 of the Naval Observatory Time Service publications, in case such a list of stations is needed.

Portable clock trips accurate to about one-half microsecond, again global, are presently being conducted. In the Department of Defense, an Air Force request for portable clock trips can be made to the Newark Air Force Station, Newark, Ohio. Army or Navy requests for portable clock trips can be made to the Naval Electronic Systems Engineering Center, Washington, located on the Naval Observatory grounds. Stops at or for other agencies and international organizations can be arranged. The Naval Observatory still makes a limited number of clock trips.

VLF and OMEGA have from one to three microseconds accuracy in phase tracking. This is a relative measure. It does not give absolute time. Once a clock is "on time", these measures can be used to keep it "on time".

Other than portable clocks, Loran-C is still probably the best and most precise time-distribution system available at the present time. It, unfortunately, is not even available in all areas of the northern hemisphere. In the future, it will be available in the western part of the United States, which will then make Loran-C available to users throughout most of the northern hemisphere. The SATCOM or the defense communication satellite is used for trunk line timing with an accuracy of approximately one-tenth of a microsecond. Transit satellite, a Navy navigation satellite, can also be used for time and can provide about 10 microseconds accuracy, globally. The Navigational Technology satellites have an accuracy, or certainly will have, of approximately one-tenth of a microsecond on a global basis.

Television can be used both locally and at fairly long range (at least in the United States) with a local precision of approximately 20 nanoseconds, or even better. However, 20 nanosecond precision requires that the two synchronizing stations observe the same television station. For long range, the accuracy is perhaps one microsecond. Here, care must be taken that the same live network program be used. This is done between Boulder, Colorado, Newark, Ohio and Washington, D.C., and the results are published in Series 4 of the Naval Observatory Time Service publications.

Microwave can also be used to synchronize in line-of-sight. Optical devices can be used in line-of-sight, where the error of determination can, perhaps, be as little as one nanosecond. There are many others, such as very long baseline interferometry (VLBI), cables, power lines, pulsars, and moon bounce.

Before discussing these different systems, let us examine the general problem of synchronization (Figure 1). The transmitter is to be used as a marker, not necessarily "on time". At receiver A, clock A starts counter A and the marker stops it. Reading A is the time of clock A minus the time of the marker (which is unknown) plus the delays in the system. System delays include the delay in propagation from the transmitter to the receiver plus the delay in the receiver. Similarly at B, reading B is the time of clock B minus the time of the marker plus the delays from the marker to B. This is always true. It is always algebraically the start of the counter minus the stop of the counter. If it is done this way, one of the largest, most common errors made in synchronization may be avoided, namely, the sign of the difference in time of the two clocks. The difference of these two readings must be taken algebraically, thus the time of clock A minus the time of clock B is equal to the reading of counter A minus the reading of counter B minus the sum of TAU A minus TAU B, where TAU A and TAU B are the propagation delays from the transmitter to clock A and B respectively. It is easiest to determine TAU A and TAU B by means of a portable clock with which to calibrate the system. However, TAU A and TAU B can usually be determined with sufficient accuracy from theoretical calculations.

If the transmitter is "on time" or the correction to the transmitter is known, two stations are no longer required. It requires that the propagation time, TAU A, be calculated. The Naval Observatory will, upon request, calculate these progation delays for users if they do not have the capability. The request must include the location of the station and the transmitter that is being used. Once the propagation time and the receiver delays are known, then the reading at A is simply the time of clock A, which started counter A minus the time of the marker which stopped counter A plus the delays.

Let us go into more detail on PTTI signals from communication stations. High frequency time signals are useful signals, because very many of the very precise time signals have an ambiguity and require that the user be within a certain accuracy initially. The easiest and cheapest way to get to the required accuracy is to use a high frequency time signal. The Navy time signals have an accuracy of about one millisecond and receivers cost several hundred dollars. However, the time signals are broadcast only for five minutes at intervals of six hours. They can be heard anywhere in the world. The schedules are given in Series 1 of the Naval Observatory Time Service publications. The signal is on for 300 milliseconds, off for 700 milliseconds, and it transmits a code each minute indicating how many minutes are left before the hour. Probably, more useful signals to most everyone are the PTTI signals such as WWV, CHU, WWVH, etc. which are on continuously. They have an accuracy of a little better than one millisecond. The reason for this is that the propagation varies from time to time with this order of accuracy. HF timing receivers are very inexpensive.

On low frequency, there is WWVB at 60 kilohertz, which can be used for phase tracking in order to determine standard frequencies.

All Navy VLF stations will be on Frequency Shift Keying (FSK). The assigned frequency is the "mark". The "space" is the frequency that is 50 hertz away. The mark, while not continuous, sounds exactly like the high frequency signals. Receivers for VLF cost from $1000 to $5000. Time signals are on only five minutes before the hour on certain stations. The code stream from VLF stations is timed so that the time difference between the middle of the rise time of each pulse (frequency shift) and the middle of each decay time is exactly a multiple of 20 milliseconds. This can be used as a timing signal with an ambiguity of 20 milliseconds. VLF stations are used primarily for phase tracking. The frequency of the VLF stations is good to a few parts in 10^{12} per day, therefore with phase tracking and corrections published in Series 4 of the Naval Observatory Time Service publications, the user can maintain an oscillator relative to the Naval Observatory oscillator with an accuracy in time of one to five microseconds. There are several problems, however, in phase tracking VLF stations. There is a diurnal shift each day, so the user must be careful and only use the portion where daylight is continuous between the receiver and the transmitter. There are also sudden ionospheric disturbances (SID) that occur occasionally. Usually, these are quite apparent and after a little practice users learn to recognize that an SID is occurring and ignore that period. Times of SID's are given in the Series 4 or in the teletype Series 5 of the Naval Observatory Time Service publications. There are also polar cap absorptions which are a little more difficult to identify because they last longer, on the order of several days.

We use the Television Line 10, odd, horizontal sync pulses as a marker for time comparisons. A receiver can cost as little as $400 and can give time comparisons as accurate as 10 nanoseconds. In the Washington area, we have placed the transmitter of Channel 5 "on time" and corrections are given in Series 4 of the Naval Observatory Time Service publications. It can be used as a time signal. For long distance, a live program must be used. The delays change quite often.

PTTI information is also transmitted over electronic navigation systems. Navigation VLF stations that can be used for standard frequency are the OMEGA signals. For them also, the SID, polar cap absorptions, and diurnal shifts have to be taken into account. They can be used exactly as the communication stations; however, they have lower power and a commutator is necessary because they time share the navigation signals. They do have some unique frequencies such that time sharing is not necessary, and a commutator would not be necessary.

Loran-C and Loran-D are probably the most important synchronization signals at the present time. There are now eight chains in operation. All have cesium oscillators operating so they all have very good frequency. Time can be obtained at distances of 1500 miles from these stations to an precision of 1/10 of a microsecond with corrections from Series 4 of the Naval Observatory Time Service publications, and absolute time to better than several microseconds. The Western Pacific, North Atlantic, East Coast, Norwegian Sea and Mediterranean chain times are usually kept to better than 5 microseconds. In the future, additional chains will be added; 3 on the east coast, 2 in the Gulf of Mexico and 7 on the west coast of the United States. This should cover the coastal regions of North America. However, all of them may not be timed. Automatic receivers cost about $4000 to $5000. Very competent operators may obtain high precision using low cost receivers ($1500).

How do we keep these chains "on time"? The East Coast chain is measured directly at the Naval Observatory so that the quantities that are in Series 4 of the Naval Observatory Time Service publications are direct measures. The Norwegian Sea chain and the Mediterranean chain are tied to the U. S. Naval Observatory through the North Atlantic via the U. S. Coast Guard (daily messages) and a monitoring station in Northern Scotland. This allows us to have 2 measures across the North Atlantic. We can also measure the North Atlantic chain directly with respect to the East Coast chain at the Naval Observatory. The Northwestern Pacific chain is tied to the Naval Observatory via portable clock trips (approximately every 6 months), SATCOM terminals in Okinawa and Guam, and by the rate correlation method. There are approximately 14 cesium clocks monitoring Loran-C in the Western Pacific. The rate correlation method simply means that if one clock changes in frequency, it should be reflected in any difference measured with respect to that clock. If you take differences A minus B and A minus C and clock A changes by one part in 10^{13}, both of these differences should change by one part in 10^{13}, whereas, the difference between B and C should not change at all. It works very well in the Pacific and the last clock trip indicated about a half a microsecond deviation over the previous six months. The Central Pacific chain is tied to the Naval Observatory via the SATCOM in Hawaii and portable clock trips.

There are other navigational signals that can be used for synchronization. The TRANSIT satellite is good to about 10 microseconds (Laidet, L. M., Proc. IEEE, 60, p 630, 1972).

Timation navigational technology satellite, and the GPS can provide timing accuracy of approximately 1/10 of a microsecond.

A portable clock is still probably the most accurate method to transfer time over long distances. Portable clocks have an accuracy of half a microsecond. The costs are simply the costs of three airplane tickets plus per diem plus two strong backs.

Some stations are built primarily for PTTI information. These are the standard time and frequency stations throughout the world such as WWV, WWVH, CHU, JJY and a great number in Europe. In fact, the problem really is that there are too many of them and the user has difficulty knowing which one he is receiving unless he is well aware of the various characteristics of these stations. The list of these stations is given in Series 1 of the Naval Observatory Time Service publications. The National Bureau of Standards also has a satellite time service, the ATS satellite, which is good to approximately 50 microseconds. It is a stationary satellite useful in the United States.

There are many other methods of synchronization. One method is to use shielded cables. The user must remember that it does take the signal time to go through the cable and he does have to measure these delays if the cable is very long. Also, if the cable is very long, he has to worry about temperature effects. The changes in 10,000 feet of test cable at the Naval Observatory varied from 10 to 20 nanoseconds each day due to the diurnal changes in temperature. Microwave links can be used for synchronization to better than 10 nanoseconds. There are optical means to synchronize, such as optical fibers or a flashing light. One can use calculations to keep a clock in synchronization, such as the rate correlation method. This method requires at least 3 oscillators, and the more oscillators there are, the more accurate the method becomes. Not all the oscillators need to be in the users own laboratory. For example, if the user has a Loran-C receiver, the cesium oscillator at the Loran-C station can be used as one oscillator.

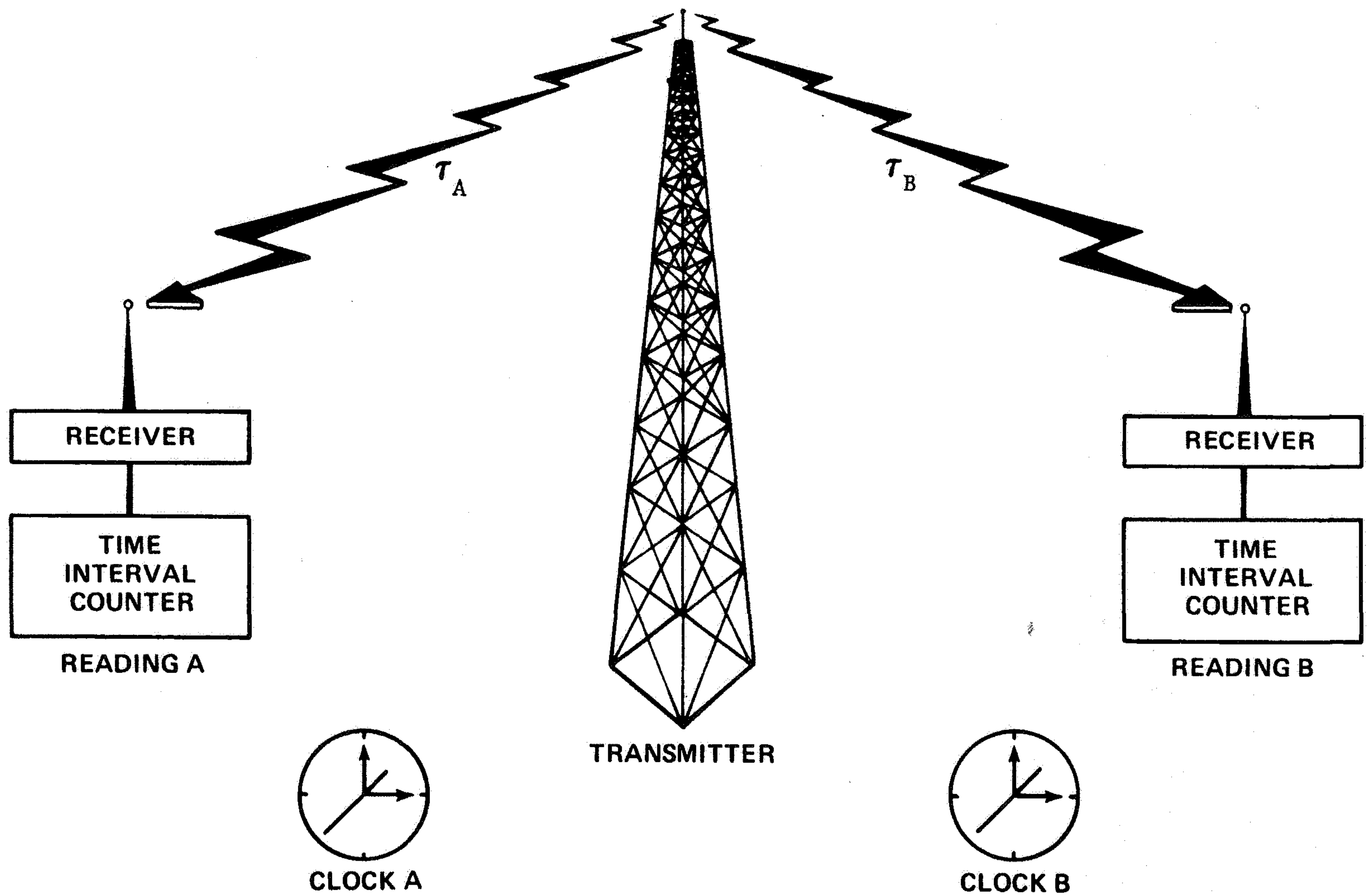
One must also remember that quite frequently one can get synchronization from a neighbor. Hopefully, this meeting will identify the stations with precise time. If the stations who have precise time would share with their neighbors, this would help a great deal.

There are several exotic methods of synchronization, such as VLBI and pulsars. It is very expensive, of course, to set up unless a receiver is already available. Also, there are pulsars, one of which now seems to be constant enough to be used as a marker for synchronization.

In this matter of synchronization, there is a very good chapter in the NBS Monograph 140, the NBS Time and Frequency book (edited by Byron Blair). It discusses a great number of these systems in detail. Another general review is in Volume 60 of the Proceedings of the IEEE of May 1972.

In the future, we can look forward to the Global Positioning System, which should give us very accurate time in the global sense.

"PASSIVE" SYSTEM FOR DIFFERENTIAL TIME TRANSFER



$$[\text{CLOCK A} - \text{CLOCK B}] = [\text{READING A} - \text{READING B}] - [\tau_A - \tau_B]$$

Figure 1.

QUESTION AND ANSWER PERIOD

MR. TEWKSBURY:

Dave Tewksbury, Smithsonian

Geodesy requirements in epoch (UTC) time for laser data reduction for the Smithsonian Astrophysical Observatory ask $\pm 25\ \mu s$ maximum. This precision is necessary to accurately determine intercontinental distances to $\pm 10 \rightarrow 40$ cm. To measure continental drift and/or plate movement will require even more precise epoch time.

DR. HALL:

I think your requirements come about because rotational time doesn't enter in the reduction. It is hopeless to get UT1 to an accuracy of 25 microseconds. If you are using UTC for synchronization or distance measures that is not really what I referred to as geodesy relative to the star system.

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N75 27177

APPLICATIONS OF PTTI TO NEW TECHNIQUES FOR DETERMINING CRUSTAL MOVEMENTS, POLAR MOTION, AND THE ROTATION OF THE EARTH

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ABSTRACT

New extra-terrestrial techniques for geodesy and geodynamics include laser range measurements to the moon or to artificial satellites, Doppler measurements with the Transit satellite system, and both independent-clock and linked-antenna microwave interferometry. The ways in which PTTI measurements are used in these techniques will be reviewed, and the accuracies expected during the latter half of the 1970's will be discussed. At least 3 of the techniques appear capable of giving accuracies of 5 cm or better in each coordinate for many points on the Earth's surface, and comparable accuracies for the Earth's rotation and polar motion. For fixed stations or for sites a few hundred km apart, baseline lengths accurate to 1 cm may be achieved. Ways in which the complementary aspects of the different techniques can be exploited will be discussed, as well as how they tie in with improved ground techniques for determining crustal movements. Some recent results from the extra-terrestrial methods will be mentioned.

INTRODUCTION

Since the mid-1950's a true revolution in our understanding of the Earth has taken place. From the mid-1960's the majority of earth scientists have come to regard the plate tectonics theory as a major unifying concept in describing the dynamical forces which have shaped the Earth as we know it today. I think that you are all aware of the general outline of this theory: tectonic plates roughly 100 km thick make up the surface, and they move about on a low-viscosity layer perhaps 200 km thick called the aethenosphere. The plates move away from the "ridges" or "rises", usually in the oceans, where new material coming up from the mantle is added onto the plates. Where two plates approach each other, one normally is pushed or pulled down and penetrates to depths of roughly 700 km in the mantle before evidence of its existance fades out. The geological and geophysical record of the

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past motions is written in the present materials and properties of the plates, the aesthenosphere, and the upper mantle.

We now know a great deal about the average motions in the past, but unfortunately this is like having watched cakes of ice floating on a swirling body of water, and trying to understand what is happening from the grindings, distortions, and relative motions of the semi-rigid cakes. If we are reduced to only knowing the long term average motions, the problem is even more difficult. Better measurement methods are just what is needed to determine the present motions and distortions of the plates, and these methods all involve Precise Time and Time Interval techniques.

The new extra-terrestrial techniques are Doppler measurements with the Transit satellite system, both linked-antenna and independent clock microwave interferometry, and laser distance measurements to the moon and to artificial satellites. However, it appears that these techniques will be very much complemented by new developments in ground measurement methods. These are the use of 2-wavelength microwave modulated laser devices for measuring point-to-point distances on the earth's surface and of portable high-precision gravimeters for measuring changes in gravity with time at a given point. The futures of both types of ground measurements look very bright. The first has an expected distance accuracy of better than 1×10^{-7} over distances of roughly 30 km, and the other enough expected accuracy to detect gravity changes due to 1 cm vertical motions.

MICROWAVE INTERFEROMETRY AND DOPPLER TECHNIQUES

One of the important developments in geodesy recently has been the use of Doppler frequency shift measurements with signals received from Transit satellites to determine the location of over 200 points on the Earth's surface. These points now can be used as a world-wide network of control points, which appear to have an accuracy of about 2 meters. The National Geodetic Survey now plans to make use of about 130 Doppler-determined points in North America as the basis for its work on readjustment of the North American Geodetic Network. The Doppler satellite method has been described in a number of places,[1-5] and will not be described further here. The main experimental limitations on accuracy come from inospheric effects, because of the relatively low transmitted frequencies which are used, and orbit determination problems due to the fairly low altitudes of the satellites. Future developments expected with the Global Positioning System are discussed later in this Meeting.

Microwave interferometry promises to be a major source of information on geodynamics. Basically, a comparison of the arrival times of radio signals from a very distant source at two antennas gives the component of the baseline vector between the two sites projected onto the direction toward the source. Extra-galactic microwave sources furnish the signals for most long-baseline work, with fluctuations in the emission in effect providing the events whose differences in arrival time are measured. Measurements with a number of sources in different directions give the vector baseline between the sites. If the two antennas are linked by cables or microwave transmission between them, then the time difference can be determined directly. If very long baselines are used, then ultra-stable independent clocks at the two sites are employed, with differences in the clock epochs and rates being solved for from the data.

A major point to be made is that atmospheric corrections to the microwave path lengths through the troposphere are likely to be the largest source of error in future geodynamics measurements. If this is so, extending the baseline lengths doesn't help very much over some range of distances because the errors in the corrections become less well correlated. However, when the separation is large enough so that little correlation is left anyway, or so that one can obtain accurate enough measurements of the atmospheric corrections at the sites independently, then the resulting limitation on fractional baseline accuracy goes down with increased baseline length. For this reason, although very useful results have been obtained with linked antennas, the independent clock variety are likely to be more important for geodynamics.

Independent clock microwave interferometry, or very long baseline interferometry (VLBI) as it is usually called, is discussed in depth later in the Meeting. I will only say a few words about its accuracy here. The most stable frequency standards available are needed for geodynamics work, as well as the use of two observing frequencies to remove ionospheric effects, careful antenna calibration procedures, and the use of extra-galactic sources which show as little structure as possible over long baselines. However, these considerations are really factors in the ease of making the observations, and hopefully will not affect the final accuracy.

The one accuracy limitation which is not shared with laser range measurement techniques is the sensitivity of the microwave propagation velocity to water vapor in the atmosphere. This appears to require the use of water vapor monitoring at each antenna by means of microwave radiometers looking along the line of sight.[6,7,8] With this approach, an accuracy of at least 1 to 2 cm in the water vapor correction at any time for vertical propagation through the atmosphere appears to be achievable, and some experimental data on this question is now available.[9] This limitation may be worse for propagation at lower elevation angles, but it should be recognized that substantial benefits from averaging can be obtained for many applications of the data. Water vapor tends to lie mostly below 3 km in the atmosphere and to be rather patchy in distribution, so that averaging is probably more effective than for the dry part of the atmosphere which affects optical observations. Also, to the extent that the water vapor distribution is horizontally stratified, it can be taken out at least partially from the observations themselves.

A major advantage of the VLBI approach compared with laser range techniques is the all-weather capability of the method, which means that observations can be made a considerably larger fraction of the time than with the laser techniques. A number of papers are now available which discuss geodynamics applications of VLBI.[10-18] In addition to accurate determinations of UT1, polar motion, and plate tectonics measurements with fixed stations, the desirability of using mobile VLBI stations to measure crustal movements at a large number of points on the Earth's surface has been emphasized.

LASER DISTANCE MEASUREMENTS TO ARTIFICIAL SATELLITES AND THE MOON

The beginnings of a new era in worldwide geodesy can be tied to the introduction of satellite geodesy and, within the U.S., to the start of the National Geodetic Satellite Program. This program, which is now completed,[19-24] succeeded in tying together many points throughout the world with an accuracy of roughly 5 meters. The results were based mainly on angular position measurements of artificial satellites against the stars, although some Doppler measurements and laser distance data were included also.

It can be shown that optical or electromagnetic distance measurements are much less affected by atmospheric refraction uncertainties than are angle measurements. For this reason, laser distance measurements to satellites offer great improvements in geodetic accuracy over photographic methods. However, in order to take advantage of the improved measurement accuracy for determining a worldwide network of fundamental reference points, it is necessary to increase the satellite altitude greatly. This is required in order to stringently decrease the perturbations on the orbit, so that observations from different ground sites at different times can be tied together via accurate dynamical calculations of the orbit. Even if nearly simultaneous observations from a number of ground stations are used in order to reduce dependence on the orbit computations, a high altitude still is necessary in order to permit mutual visability from widely separated sites.

The Laser Geodetic Satellite[25] (LAGEOS), which is scheduled for launch by NASA in 1976, is intended to fill the need for a stable, high altitude retroreflector satellite. The currently planned orbit is nearly circular, with an altitude of about 6000 km and an inclination of 70 degrees. The satellite is as dense as possible, subject to the launch vehicle weight limitations and the surface area needed for the desired number of retroreflectors. It is completely passive and highly symmetrical, and the retroreflector arrangement is such that the geometrical offset between the center of mass of the satellite and the average optical reflection point is accurately known.

Although a satellite like LAGEOS is needed in order to obtain very high accuracy geodynamics results, a large amount of work based on laser distance measurements to other artificial satellites already has been reported.[26-36] When LAGEOS is available, the main limitations on determining crustal movements and polar motion probably will be: 1) uncertainties in the orbit at the time of the measurements; 2) uncertainties in the atmospheric correction to the measured round-trip laser travel time; and 3) systematic and statistical errors in the travel time measurement. The second limitation has been considered by several authors,[37-39] and a correction procedure based on the assumption of hydrostatic equilibrium seems very powerful. The water vapor effect is about 100 times less than for microwave measurements, and horizontal gradients in the atmospheric conditions are likely to contribute less than 0.5 cm to the uncertainty. Deviations from hydrostatic equilibrium are small under almost all conditions when laser measurements are likely to be made, and the overall atmospheric correction error at elevation angles of down to 20 degrees thus is likely to be 1 cm or less. The third limitation-travel time measurement uncertainty - already is 10 cm or less even with laser pulse lengths of several nanosec. It seems likely to be improved to 0.1 nanosec (i.e. 1.5 cm) or better when sub-nanosec pulse length lasers are used. The timing accuracy referred to here is that of a "normal point" constructed from several minutes of data.

For the orbit uncertainty limitation, a simple numerical value is difficult to obtain. Simulations of geodetic measurements using LAGEOS are being carried out at the Smithsonian Astrophysical Observatory and the Goddard Space Flight Center. Once we have improved our knowledge concerning the lower harmonics of the Earth's gravitational field from studies of LAGEOS orbit perturbations or from other satellites to a sufficient extent, the main orbit perturbation which is likely to cause trouble is that due to inaccuracy in modeling variations in the Earth's albedo radiation pressure on the satellite. However, the extent of the build-up in orbit uncertainty depends on the distribution in location and time of range observations from all of the stations participating in the program. Also, the effect of a certain amount of orbit uncertainty will be less if the relative locations of several stations within a limited geographical area are being determined rather than station locations all over the Earth. In any case, with a sufficient number of well-distributed high-accuracy ground stations, the orbit uncertainty limitation is not expected to be substantially worse than the other two limitations.

For laser range measurements to optical retroreflectors on the moon,[40-43] the atmospheric and timing limitations are quite similar to those for ranging to artificial satellites. The orbit stability is much higher, which is certainly an advantage. The librations of the moon about its center of mass appear to be modelable down to below the usual systematic measurement error limits by fitting data from differential measurements to the different reflectors.

However, even if the lunar orbit and libration uncertainties are negligible, and even if the only object were to determine crustal movements, it would still be necessary to make frequent measurements from a number of fixed stations in order to monitor variations in the Earth's rotation and polar motion. Present information indicates that polar motion fluctuations are slower than those in rotation.[72] Thus how much less monitoring from fixed stations is needed for lunar ranging than for LAGEOS may depend on how large the power spectrum of fluctuations in the Earth's rotation is at short periods, compared with the fluctuations in the unmodelable orbit perturbations for LAGEOS.

The main disadvantage of lunar ranging for determining crustal motions, compared with the artificial satellite method or VLBI, is connected with the slow rate of declination change for the moon. Since the period for declination change is 27 days, a mobile lunar ranging station has to stay at one site for perhaps 3 weeks, allowing for weather, in order to make measurements over the whole range of declinations. Measurements at different declinations are necessary in order to determine all 3 components of the station location accurately. Assuming that the ultimate measurement accuracy of the other techniques is high enough so that the same site coordinate accuracy can be determined in a shorter time, lunar ranging would be at a disadvantage in terms of the number of sites covered per year per mobile station. On the other hand, if fewer fixed stations are needed than for satellite ranging, it is not clear how the trade-offs would work out. A related disadvantage of lunar ranging is that one cannot obtain all 3 coordinates of the site with good accuracy for station locations above 45 to 50 degrees in latitude. The range of declinations available with the moon at elevation angles of 20 degrees or higher becomes too limited, and the Z-axis coordinate accuracy is reduced.

GROUND MEASUREMENT TECHNIQUES

At present the main ground survey methods used in geodynamics studies are accurate point-to-point distance measurements with modulated laser beams (laser geodimeters) and classical leveling for vertical motions. The accuracy reported by the National Geodetic Survey for their high-precision traverses, which cross the U.S. both north-south and east-west at roughly 1000 km intervals to provide overall horizontal control, is 1×10^{-6}. These traverses have been carried out with laser geodimeters, and the main accuracy limitation is from uncertainty in the atmospheric correction to the measured distances. For a number of baselines ranging up to 35 km in length in the western U.S., J. C. Savage and W. H. Prescott of the U.S. Geological Survey have reported measurement precisions equal to the root-sum-square of 2×10^{-7} of the length and a 3 mm contribution independent of length.[44] This is achieved by flying aircraft along the line of sight to measure the atmospheric characteristics. However, Savage and Prescott state: "Even at this level of precision, determination of the strain accumulation at sites along the San Andreas fault system will require annual observation of many line lengths over a period of at least 5 years." The need for increased ground measurement accuracy is also stated strongly by the U.S. Geodynamics Committee.[45]

Attempts to achieve higher accuracy by using two laser wavelengths, one in the red and the other in the blue, have been made at several laboratories. Microwave modulation is used in order to achieve the highest possible accuracy in determining the red-blue path difference. A correction proportional to the measured path difference is then applied in order to remove the effect of the atmosphere. Work at NOAA with this type of device has been reported,[46-49] and more extensive measurements have been obtained with an improved instrument developed by Huggett and Slater at the Applied Physics Laboratory, University of Washington.[50,51,73] Work is also under way at the National Physical Laboratory in England. The measurements by Huggett and Slater currently are over fixed baselines of up to 10 km near Seattle, and a microwave distance system has been added in order to correct for water vapor. The present measurements use retroreflectors at the far end of the path, so that the light beams have to travel both ways over the path. If improved signal-to-noise ratios are needed in order to achieve the geodynamically desirable goal of 1×10^{-7} or better accuracy over paths of roughly 30 km length, an approach in which only one-way laser propagation is used may be needed. This would correspond to having the microwave modulator and demodulator at opposite ends of the path, with synchronization provided by a round-trip microwave link.[52]

It would be very desirable if gravity measurements could be used in place of leveling as a monitoring technique for vertical motions. This is because the cost per km of leveling is high. It now appears that relative gravity measurements with accuracies of 3 microgal or better are achievable with existing instrumentation.[53] This means that the sensitivity is sufficient to detect relative vertical motions of roughly a cm if other processes are not going on. Such vertical motions are expected in seismic zones from the theory of dilatency. In addition, in connection with the interiors of tectonic plates, the U.S. Geodynamics Committee refers to evidence for widespread vertical motions at rates as high as a cm per year, and states:[54] "The rates of vertical motion determined by leveling surveys are so high that such motions cannot continue for very long intervals of time. Perhaps oscillatory or episodic movements occur." Improved methods for looking at such motions, both locally and regionally, certainly are desirable.

The main limitation in interpreting gravity changes probably will come from complicating mass motions which can occur. Horizontal motions of material within the aesthenosphere can occur over long periods of time, while changes in the local water table can offset gravity on a short time scale. Thus, the interpretation is not unique. However, stable gravity measurements still give evidence against vertical motion, and leveling or other techniques then can concentrate on making measurements where gravity is changing.

There also is a need for portable absolute gravimeters with roughly 3 microgal accuracy. They are necessary both to detect regional gravity variations over large areas and to provide scale calibrations for relative gravimeters. A portable absolute gravimeter with roughly 50 microgal accuracy was developed by Hammond and Faller, and measurements were made with it at 8 sites in North America, Europe, and South America.[55,56] A fixed-station gravimeter of accuracy approaching one microgal has been described by Sakuma,[57,58] so that accurate checks on portable instruments can be made. Recently joint French-Italian efforts have resulted in a portable absolute gravimeter with 20 microgal accuracy.[59] Further improvements to achieve the desired accuracy of about 3 microgal appear to be feasible. In regions of long term elevation changes, it clearly is important to understand how gravity is changing also in order to determine what is going on.

GEODYNAMIC APPLICATIONS OF THE NEW TECHNIQUES

In high accuracy geodynamics studies, one of the problems will be how to separate polar motion and earth rotation variations from motions of the observing stations. The general question of coordinate systems for geodynamics was discussed at IAU Colloquium No. 26 in Torun, Poland. A general view expressed was that there is a strong need for a worldwide geophysical coordinate system which approximates the motion of the solid part of the Earth as well as possible.[60-64] The rotation and tipping of this frame against an external reference frame, such as the planetary-plus-lunar dynamical frame[65,66] or the extra-galactic frame,[65] would determine what we mean by UT1, polar motion, and nutation. General agreement seems to be developing that the geophysical system should be defined in terms of a large number of points throughout the world for which geocentric coordinates are assigned, as well as assigned linear drift rates for the points based on the best available geodynamic models. It has been suggested that updating of the models used would be needed at appropriate intervals of perhaps several years, as our understanding of crustal movements improves.[63]

With at least 3 of the new techniques, it appears feasible to determine the locations of points over most of the Earth's surface with an accuracy of 5 cm or better. Progress in this direction already is very impressive. For example, a satellite ranging experiment in 1971 using long laser pulse lengths gave agreement for two stations 25 m apart to about 4 cm in each coordinate. A 1972 experiment with similar apparatus on a 900 km baseline across the San Andreas fault in California gave a scatter of 30 cm in the baseline length measurements, with much of this presumably due to uncertainties in the satellite orbit. With sub-nanosecond pulse length lasers and much better knowledge of satellite orbits in the future, the same baseline is expected to be recoverable in different years with an accuracy of 1.5 cm.[36] Satellite laser ranging systems with 10 cm or better accuracy and 6 or 7 cm rms single-pulse jitter already are available, and the scatter obtained on a transcontinental baseline even with existing satellites seems encouraging.[67] For lunar ranging, studies indicate an expected accuracy of 3 cm or better in each coordinate for determining the location of a mobile station in most parts of the world.[42,68] However, baseline measurements must await the availability of data from a second station besides McDonald.

For VLBI, a one meter scatter in baseline length was observed over a 845 km baseline from Haystack to Greenbank with data from as early as 1969.[10] For a 16 km baseline in California, a 5 cm or less scatter in each coordinate was obtained for 3 runs made in 1972.[15] Measurements on the 3,900 km Haystack-Goldstone baseline gave an rms variation of less than 20 cm for the baseline length for 9 separate experiments carried out in 1972 and 1973.[13] For very short baselines, a recent comparison with survey results for a 300 m baseline between a portable 9 m antenna and a fixed antenna in California has given agreement in each coordinate to within the $\pm$ 3 cm measurement uncertainty.[18] An even more recent result for the 1.2 km Haystack-Westford baseline length gives an 0.6 cm rms scatter for 5 measurements made over a 3 month period, and an agreement with survey results to 0.5 cm.[69] It is impressive that all of these results have been obtained even without the use of dual frequency capability and of water vapor radiometers, which will be added to the existing systems soon.

The major contributor to polar motion determinations so far among the new techniques is the Doppler satellite network. Normal variations in the polar position are determined regularly every 2 days with an accuracy which is believed to be about 30 cm in each coordinate.[4] The results are now being incorporated along with data from the classical techniques in the BIH adjustments. Laser range measurements to satellites have been used to determine polar motion to roughly one meter accuracy,[27,31,34] while VLBI measurements have given comparable accuracy for polar motion and for UT1.[13]

Recently lunar ranging data has been used to obtain preliminary individual-day checks on the BIH values of UT0 (a combination of UT1 and one component of polar motion) for the McDonald Observatory on 153 days.[43] The median accuracy of 22 cm which was achieved is encouraging, but it should be remembered that the fraction of days on which sufficient data was available from the single station is fairly small. A network of 6 fixed lunar ranging stations is expected to be in operation by late 1976, and hopefully data from a similar VLBI network also will be available by then. Additional high-accuracy information on polar motion and on short period fluctuations in the Earth's rotation rate are expected from satellite range measurements soon after LAGEOS is launched. However, the continuation of classical observations for a decade longer is needed in order to complete a careful comparison of the methods.

With the achievement of 5 cm or better accuracy on a worldwide basis highly probable, it is clear that a new era in geodynamic/geodetic measurement accuracy is approaching. The initial goal will be to measure the positions of hundreds of control points throughout the world with as high accuracy as possible. From our present vantage point it is difficult to tell just how low the costs of using the extra-terrestrial methods can be made, but it seems clear that the separations between the fundamental geodynamic/geodetic control points should be 300 km or less in most areas. The frequency with which points should be redetermined will depend on the local conditions, but will be chosen so that the probability of deviations from linear motion between measurements by more than the measurement accuracy is small. Improved ground techniques also will be used to keep track of more local motions within geodynamically interesting areas such as seismic zones or regions of unusual vertical motions. When unexpected motions or gravity changes are detected in a particular area, both the extra-terrestrial methods and improved ground techniques can be used on a fast-response basis to find out what is going on.

It should be emphasized that a combination of the new techniques may be more efficient for rapid establishment of the desired worldwide geodynamic/geodetic control network than any one of the techniques alone.[70] For example, one can think of first using one technique to establish and maintain 3 to 6 fundamental reference points on each major plate, and then using another technique to establish the much larger additional number of reference points within a given plate which are needed. For the first part of the job, the most important factor would be accuracy and reliability over long distances. An independent check by using at least 2 of the methods would be desirable for this phase of the work. For the second phase, a regional approach in which most of the effort is concentrated on a particular continent or area for a certain period of time seems desirable. For example, putting perhaps 6 mobile satellite ranging stations in one area, with some of them at the pre-determined fundamental points, would give minimum dependence of the results on uncertainties in the satellite orbit. Although simultaneous 4-station measurements would not be required, the intensive tracking over a limited region would give excellent knowledge of the orbit in that region. In this way, the desirable features of two or more techniques could be utilized in a complementary way.

During the 1974 International Symposium on Recent Crustal Movements, the following resolution was sponsored jointly by the Inter-Union Commission on Geodynamics and the Commission on Recent Crustal Movements, and was adopted:[71] "Instrumented systems capable of precise geodetic measurements such as Geodetic Satellites, Lunar Ranging, and VLBI are of the greatest value to the study of recent crustal movements and geodynamics. The Commission on Recent Crustal Movements and the Inter-union Commission on Geodynamics together strongly recommend that earnest attention be given to the further development of these systems so that such basic questions as the instability of the earth and the causes of movements can be investigated. The Commission on Recent Crustal Movements and the Interunion Commission on Geodynamics particularly emphasize that not only is doing the measurements important, but it is also important that the measurements be made in the optimum places in the light of geodynamics." Essentially all of the new techniques make heavy use of Precise Time and Time Interval measurements to achieve their high accuracies. Whether the need is for the highest possible stability in frequency standards suitable for use in rapidly moving mobile VLBI stations, or for relatively cheap and reliable laser frequency standards with 1×10^{-9} accuracy for use in portable absolute gravimeters, the needs from geodynamics for continued improvements in PTTI techniques are likely to be strong.

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QUESTION AND ANSWER PERIOD

MR. KEATING:

Mr. Keating, Naval Observatory.

I heard a lot about accuracy here, one centimeter, five centimeters. Yet, I heard nothing about the systematic errors you might have. In particular, the velocity of light.

Recently, I ran across two radio astronomers. One was using a velocity of light which was recently obtained by the NBS, and the other one was using another one which was almost one kilometer different from the recent NBS value. I don't quite understand how one can speak of accuracy under such circumstances. Really, you mean differential precision, don't you?

DR. BENDER:

No, I don't. In talking about accuracy for distance measurements, one has to specify what the standard is for the meter, for the length. Actually, the International Astronomical Union a year ago recommended that in all astronomical measurements of very high precision, a particular new value that had been recommended for such use by the consultative committee on the definition of the meter be used so that there would be no problem whatsoever in the comparisons of results obtained by different investigators because of the uncertainty in the speed of light.

It is also recommended that when a new definition of the meter is adopted, which hopefully will be within a few years, this value of the speed of light will be retained exactly.

Now, what this amounts to is a refinement of the definition of the meter so that it agrees within the precision with which the krypton meter can be realized with the old definition. However, it is in effect an auxiliary way of realizing the unit to better accuracy than the roughly 4 in 10^9 that the krypton lamp is capable of giving.

So I think until recently, there may have been such problems, but I believe these new measurements of the speed of light and the recommendations by the CCDM and the IAU really will remove this problem. It really is not a basic problem anyway except one of confusion because it is really the changes in distance in which everyone is interested. The present measurements are good to 4 in 10^9 for the speed of light. I don't know of any measurement where one wants to use distance measurements with higher accuracy than that other than just in a relative sense.

So I think there are really two answers. One is there is now a better speed of light which is likely to survive. And the second is the measurements are basically relative anyway.

DR. REDER:

Reder, Fort Monmouth.

If the measurements are relative, I don't understand why you said when you showed the slide showing the Goldstone and Haystack results with the transmitter on the moon and you mentioned that some of the deviations may have been due to a modulation of the transmitter, why would that come in?

DR. BENDER:

I am sorry. Let me say I didn't mean that the geodetic measurements point to point on the earth's surface were relative. I only meant, for example, that if you are looking at the distance to the moon or to a satellite where the basic quantity is the length to the moon, it is really differences in that distance to the moon which come into determining the distances between stations on the earth's surface. The same is true for the satellite geodesy.

So that it is only relative in the sense that until we get the 4 in 10^9 for the accuracy of baseline determinations on the earth we wouldn't have to worry even if we didn't know what the speed of light was, even if we didn't have a better definition of the meter.

DR. REDER:

How does the modulation of the transmitter come in that?

DR. BENDER:

It is nothing fundamental at all; it is just a noise source that is present in the data that makes it look more noisy than it really is.

A REVIEW OF PRECISION OSCILLATORS

Helmut Hellwig
National Bureau of Standards

ABSTRACT

Precision oscillators used in PTTI applications include quartz crystal, rubidium gas cell, cesium beam, and hydrogen maser oscillators. A general characterization and comparison of these devices is given including accuracy, stability, environmental sensitivity, size, weight, power consumption, availability and cost. Areas of special concern in practical applications are identified and a projection of future performance specifications is given. An attempt is made to predict physical and performance characteristics of new designs potentially available in the near future.

INTRODUCTION

Very recently, the author published a survey of atomic frequency standards [1,2]. This survey covered in an exhaustive way the presently available atomic standards, the manufacturers of these standards, as well as laboratories which are active in this field. The survey also included all known and published principles which are leading or may lead to new or improved frequency standards in the future. The reader is encouraged to study this and other recent surveys [3-8]. This paper does not duplicate these published results but rather expands them to include precision oscillators other than atomic oscillators and quantitative data on operational parameters such as warmup, retrace and several environmental effects. Also, this paper attempts to predict the performance of some new concepts which have been developed and which appear to pose no technical difficulties in their realization as frequency standards available in the near future. For these concepts stability, operational, and environmental parameters are predicted.

In this paper we will refrain from any discussion of new concepts or principles which, though promising, cannot yet be envisioned as being available in the near future. The following illustrates this important constraint: Saturated absorption stabilized lasers are omitted because their use as frequency standards or clocks is not possible at the present time because of the unavailability of a practical frequency synthesis chain in the infrared* which would allow the generation of precise standard frequencies and time signals from these standards which otherwise have documented competitive stability, and an interesting accuracy potential [10-13].

AVAILABLE STANDARDS

Figure 1 is adapted from Ref. 1 and 2. It includes crystal and superconducting cavity oscillators and various types of laboratory and commercial atomic frequency standards. Figure 1 shows that for short sampling times quartz crystal oscillators and superconducting cavity oscillators or rubidium masers are the oscillators of choice. For medium-term stability, the hydrogen maser and superconducting cavity oscillator are superior to any other standard which is available today. For very long-term stability or clock performance, cesium standards are presently the devices of choice. Rubidium standards are not superior in any region of averaging times, however, as shown in Table 1, they excel in the combination of good performance, cost and size.

It should be noted that in Fig. 1 the best available stabilities are listed for each class of standards regardless of other characterization of the devices. In contrast, Table 1 (and the following tables) combine stability data with operational data and other device characteristics. For each listed device in Table 1 the data may be viewed as being compatible, i.e., realizable in the very same device. Frequently, one finds in publications or other reference material that best performances are combined to create a super-device which is not actually available.

* The present realization is still too complex and lacks precision [9]; however, this important problem is being studied at various laboratories, and significant technical breakthroughs may be expected in the future.

Table 1 and Fig. 1 illustrate that the choice of atomic frequency standards should be a matter of very careful consideration and weighing of the trade-offs and actual requirements. For any system application of precision oscillators, it is important to first determine the actually needed stability performance of the devices; secondly, to consider the environmental conditions under which the standard has to perform; and thirdly, the size, weight, cost and turn-on characteristics of the standard. Occasionally a system designer will find that a standard with all the characteristics needed does not exist yet on the market. In this case, the designer has two alternatives: either to adjust his system parameters to accommodate one of the available standards or to choose a combination of these standards to fulfill his need. The latter is an important aspect; for example, we assume that a system requires very good long-term stability and clock performance but at the same time high spectral purity, i.e., very good short-term stability. In addition, no cost, weight or size constraints are imposed. An optimum combination for this case could be a crystal oscillator paired with a cesium beam frequency standard. The systems concept as a solution to a design problem is a very powerful tool, and it can be realized technically at no sacrifice to the performance of the individual components of the system. The only actual restrictions may be physical size and cost. It should be noted here that many time scale generating systems are based on clock ensembles which feature not only several clocks of the same type but a combination of clocks of different design. For example, at the National Bureau of Standards we routinely use a combination of crystal oscillators and cesium standards when testing precision oscillators.

POTENTIALLY AVAILABLE STANDARDS

As was outlined in the Introduction, we list here only those devices and concepts which appear to be easily realizable within today's technology. A great many of highly promising and interesting concepts have been omitted at this time because they are too far removed from practical realizations or even practicality.

First, we assess existing standards (Table 1) and their future development capability (Table 2). In particular, we note that we expect stability improvements of about 1 order of magnitude in all four devices: crystal oscillators, hydrogen masers, cesium beam tubes, and rubidium standards.

In the case of crystals, this is due to better understanding and control of the noise behavior [14,15]. In the case of hydrogen, we expect an even better control of the cavity pulling effects which transduce temperature, pressure and vibrational effects into frequency fluctuations. A better understanding and control of the aging of rubidium cells due to improved control of the lamp intensity, as well as the gas composition in the cell appears possible. In cesium, an understanding of the flicker noise performance is expected as well as improved signal levels. Flicker noise effects may be due to cavity temperature gradients, microwave interrogation power fluctuations, magnetic field variations etc., all of which can be controlled to higher precision [1,2,16].

Table 3 lists five new concepts of devices. The cesium gas cell device is very much like the rubidium gas cell device except that cesium is used which necessitates a different lamp filter arrangement [17,18]. There is the potential that some aging effects may be better controllable with a cesium device because its different filter permits better control and higher symmetry of the optical spectrum. However, aside from this, the cesium gas cell device is expected to have characteristics similar to the projected performance of rubidium gas cell devices.

The dual-crystal concept is depicted in Fig. 2. The device consists of a crystal oscillator which is locked to a crystal resonator with a reasonably long time constant. The lock between the crystal oscillator and the passive crystal resonator can be envisioned as being rather simple using the dispersion lock technique studied in its basic feasibility with the hydrogen maser [19,20]. The advantage of a combination of a passive crystal with an active crystal oscillator lies in the realization of exceedingly high short-term stability in the oscillator, while the crystal resonator can be specifically designed for excellent long-term stability. In crystal oscillators short-term and long-term stability have been opposing goals, because high short-term stability typically requires rather high driving levels whereas excellent long-term stability requires low drive levels at the crystal resonator. A combination using two crystals could optimize on both in the same package.

The passive hydrogen device has been studied in detail and has demonstrated feasibility [19,20]. Its advantages rely to a high degree on the significant reduction of cavity pulling. As was mentioned already, cavity pulling serves as the transducer for temperature fluctuations, pressure fluctuations, mechanical stress fluctuations, etc., into frequency fluctuations. The passive device allows cavity Q's of 100 times or more below that of an oscillator and thus leads to a corresponding reduction in the cavity pulling effect. An increased environmental insensitivity coupled with a simplified design and excellent long-term stability without very high demands on the temperature stability can be realized. Figure 3 shows a block diagram of such a device. The hydrogen resonance is interrogated by a signal derived from a crystal oscillator. The signal is used to lock the crystal oscillator to the hydrogen resonance. In Fig. 3, dispersion locking is depicted which could simplify the overall system. A low cavity Q can be realized by using a lossy cavity but it appears advantageous to realize the low Q by using a very high cavity Q with a well defined mode, and lowering the Q electronically with negative feedback. This concept is shown in Fig. 3. In order to discriminate against long-term phase shifts in the electronics, an amplitude modulation of the hydrogen signal may be added. As shown in Fig. 3, this could be a hydrogen beam modulation.

Figure 4 shows the concept of a small and inexpensive atomic frequency standard. Traditionally, atomic frequency standards have been devised, designed, and built in order to achieve performances impossible to reach with crystal oscillators. In other words, the atomic resonance was used in the past to achieve excellence in performance. Thus, the selection of the atomic resonance as well as the whole design concept was directed towards achieving the utmost in stability and accuracy. A different design philosophy, however, appears possible. The weaknesses of a crystal oscillator are certainly not its size, weight, or power. They are the fact that crystals do not have a precise frequency without calibration,and that the crystal shows environmental sensitivity, in particular, with regard to temperature and acceleration (constant load, vibration, shock, etc.). If the atomic resonance is viewed only as a means to reduce or eliminate these negative performance characteristics of a crystal oscillator we are not necessarily constrained to resonances which lead to utmost stability and accuracy performance but others may be considered that lead to simpler designs. We therefore propose that a simple atomic standard could be built based on the well known inversion transition in ammonia*. Ammonia will not permit the design of a standard exceeding signicantly a 10^{-10} performance level in stability, accuracy, and environmental insensitivity, however, up to the 10^{-10} level a rather simple design concept should be realizable. Such an ammonia standard is depicted in Fig. 4 and its projected performance is depicted in Table 3. Again one could use the simple dispersion lock concept to control the frequency of the oscillator. The oscillator has not necessarily to be a crystal oscillator. If the standard is to operate under severe acceleration and vibration, the sensitivity of a crystal against these influences may cause loss of lock to the atomic resonance. Therefore, it may be advantageous to use other oscillator concepts such as a conventional LC or a Gunn effect oscillator. The device will have a performance which is in certain ways inferior to that of laboratory type crystal oscillators but it is projected that a combination of low cost, size and environmental insensitivity can be obtained which is not presently available with any other design solution.

Finally, in Fig. 5, we depict the superconducting cavity oscillator. This oscillator concept has been recently developed and studied, and it has demonstrated stability performance which exceeds that of any other known oscillator [23,24]. In fact, stabilities in the 10^{-16} region have been realized at averaging times of hundreds of seconds [25]. The superconducting cavity oscillator appears adaptable to commercial design and would be the best oscillator for medium-term stabilities (averaging times of 10 to 1000 s). It could therefore be of interest to users such as those engaged in very long baseline interferometry. It appears, however, unlikely that the superconducting cavity oscillator can become a very small and rugged device and it is equally unlikely that its environmental sensitivity can be reduced significantly from those values projected in Table 3.

* The ammonia molecule has served in the first "atomic clock" device [21] as well as in the ammonia maser [22] which opened up the modern field of quantum electronics. Ammonia was discarded for clock applications because 25 years ago it was technologically cumbersome to reach K-band and because ammonia is inferior with regard to the realization of superior accuracy and stabilities.

So far, we have only discussed stabilities for averaging times of 1 s or longer. Stabilities in the millisecond region correspond to very high spectral purity. This spectral purity is especially needed in the generation of frequencies in the infrared and visible radiation region from microwave sources. The two oscillators which play a crucial role in this regard are superconducting cavity oscillators and crystal oscillators. Studies of both of these devices have shown that significant improvement in the millisecond stability region should be possible which, in turn, should allow multiplication of these signals into the infrared region without the need for intermediate oscillators. Such oscillators (lasers) presently serve as spectral filters in the infrared synthesis work and speed of light measurements [9].

It has been projected that linewidths of less than about 100 Hz in the near infrared region should be possible without intermediate oscillators using either improved crystal oscillators or superconducting cavity oscillators, or using today's crystal oscillator paired with today's superconducting cavity as a filter at X-band [26]. Such linewidths would be totally adequate to do high precision metrology, since 100 Hz in the near infrared region represents parts in 10^{13}.

Thus the realization of a unified standard for length and time [27,28] and a control of frequencies in the infrared and visible region is crucially tied to the availability of new oscillators.

Acknowledgements

The author is indebted to the many individuals, laboratories and companies who provided information which made possible the compiling of data of Tables 1 and 2 and Fig. 1. D. W. Allan and F. L. Walls contributed important information in many discussions. S. R. Stein provided data on the superconducting cavity oscillator; Fig. 5 is adapted from his thesis [25].

Tables 1-3

The listed data are average values for the respective types of standards taken from publications, reports and manufacturers specifications. There may be significant deviations towards better or worse data for certain models under certain operating conditions. The listed data for one type have generally been realized in at least one existing device. Therefore, some stability data are not as good as those of Fig. 1 which refer to the best achieved values (regardless of operational, physical, or environmental characteristics). The following is an explanation of the terms used in the second half of the Tables (the terms in the first part of the Tables are self-explanatory): Warmup is the time required to reach a frequency within 10^{-9} of the "final" frequency (i.e., after several days). In atomic standards it is practically equivalent to the time required for reaching a locked condition. Retrace is the ability of the device to reproduce - after a complete turn-off (long enough to return to shelf storage temperature) - the frequency before the power interruption. Temperature and acceleration sensitivities are self-explanatory, however, it must be noted that crystals are inherently sensitive to these effects due to the fact that the crystal resonator itself changes frequency under these environmental loads, whereas atoms are inherently unaffected. However, the proper design of temperature control can reduce these effects significantly. Acceleration refers quantitatively to constant g-loads; however, the values indicate qualitatively the related sensitivities to vibration and shock. Barometric effects are transduced into frequency variations via design features, and thus are reducible by improved design. Magnetic effects are acting directly on the atoms changing their frequency, but - as in the case of temperature for crystals - this effect can be reduced almost arbitrarily by shielding (though affecting cost and size) for all atomic standards.

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AVAILABLE TODAY

	COST (K$)	SIZE (ℓ)	WEIGHT (lb)	POWER (W)	STABILITY 1s	FLOOR	DRIFT (per day)
X-tal	0.7 – 3	1	1	3	10^{-11}	10^{-11}	10^{-10}
Rb(gas cell)	3.5 – 8	1	2	15	10^{-11}	10^{-12}	10^{-12}
Cs (tube)	15	20	40	30	10^{-11}	10^{-13}	10^{-14}
H (maser)	100	100	90	20	10^{-12}	10^{-14}	10^{-14}

	WARM-UP TIME for 10^{-9}	RETRACE	ENVIRONMENT TEMP (per °C)	ACCL. (per g)	BAROM. (per mbar)	MAG. FIELD (per G)
X-tal	1h	10^{-10}	10^{-11}	10^{-9}	–	–
Rb (gas cell)	10 min.	10^{-11}	10^{-11}	10^{-12} (est.)	10^{-12}	10^{-12}
Cs (tube)	30 min.	10^{-12}	10^{-13}	10^{-13}	10^{-14}	10^{-12}
H (maser)	1 min.	10^{-12}	10^{-13}	10^{-12} (est.)	10^{-14}	10^{-12}

TABLE 1 Available devices

ORIGINAL PAGE IS OF POOR QUALITY

POTENTIALLY AVAILABLE

	COST (K$)	SIZE (ℓ)	WEIGHT (lb)	POWER (W)	STABILITY 1s	FLOOR	DRIFT (per day)
X-tal	0.7 – 3	0.5	0.5	2	10^{-11}	10^{-12}	10^{-10}
Rb (gas cell)	2	1	2	10	10^{-12}	10^{-13}	10^{-13}
Cs (tube)	10	10	20	20	10^{-12}	10^{-14}	10^{-15}
H (maser)	80	100	90	20	10^{-12}	10^{-15}	10^{-15}

	WARM-UP TIME (for 10^{-9})	RETRACE	ENVIRONMENT TEMP (per °C)	ACCL (per g)	BAROM (per mbar)	Mag Field (per G)
X-tal	1 hr.	10^{-10}	10^{-11}	10^{-9}	- -	- -
Rb (gas cell)	10 min	10^{-12}	10^{-12}	10^{-13}	10^{-13}	10^{-12}
Cs (tube)	15 min	10^{-12}	10^{-13}	10^{-13}	10^{-14}	10^{-12}
H (maser)	1 min	10^{-12}	10^{-13}	10^{-12}	10^{-14}	10^{-12}

TABLE 2 Potential of presently available devices for the near future.

POTENTIALLY AVAILABLE

	COST (K$)	SIZE (ℓ)	WEIGHT (lb)	POWER (W)	STABILITY 1s	FLOOR	DRIFT (per day)
Dual X-tal	1 - 3	1	1	2	10^{-13}	10^{-13}	10^{-11}
Cs (gas (cell)	4 - 8	2	3	10	10^{-12}	10^{-13}	10^{-13}
H (passive)	50	60	70	15	10^{-12}	10^{-15}	10^{-16}
Utility atomic standard	1 - 2	1	2	2	10^{-}[illegible]	10^{-11}	10^{-12}
SCC-Osc.	20	100	100	100	10^{-13}	10^{-16}	10^{-13}

TABLE 3a Potential of new design concepts judged realizable in the near future.

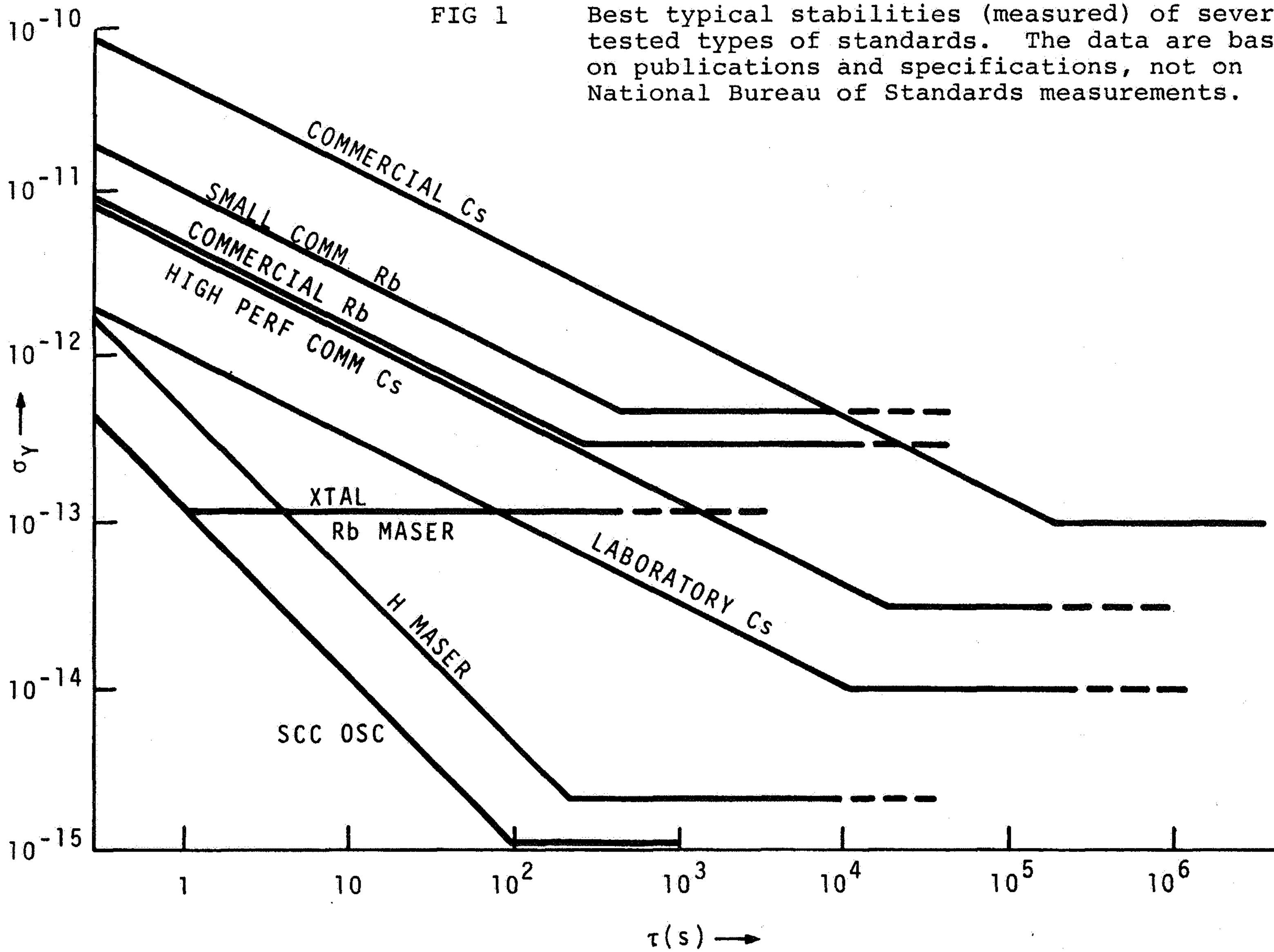
POTENTIALLY AVAILABLE

	WARM-UP		ENVIRONMENT			
	TIME (for 10^{-9})	RETRACE	TEMP (per °C)	ACCL. (per g)	BAROM. (per mbar)	MAG. FIELD (per G)
Dual X-tal	10 min	10^{-11}	10^{-11}	$10^{-[illegible]}$	- -	- -
Cs (gas cell)	10 min	10^{-12}	10^{-12}	10^{-13}	10^{-13}	10^{-12}
H (passive)	1 min	10^{-13}	10^{-15}	10^{-14}	10^{-15}	10^{-12}
Utility atomic standard	1s	$10^{-[illegible]}$	10^{-12}	10^{-14}	10^{-15}	10^{-13}
SCC-Osc	3h	$10^{-[illegible]}$ *	($10^{-[illegible]}$)	$10^{-[illegible]}$	(10^{-14})	- - - -

* assuming that the device stays at superconducting temperatures, otherwise 10^{-7}

TABLE 3b Potential of new design concepts judged realizable in the near future.

FIG 1 Best typical stabilities (measured) of several tested types of standards. The data are based on publications and specifications, not on National Bureau of Standards measurements.



C-4

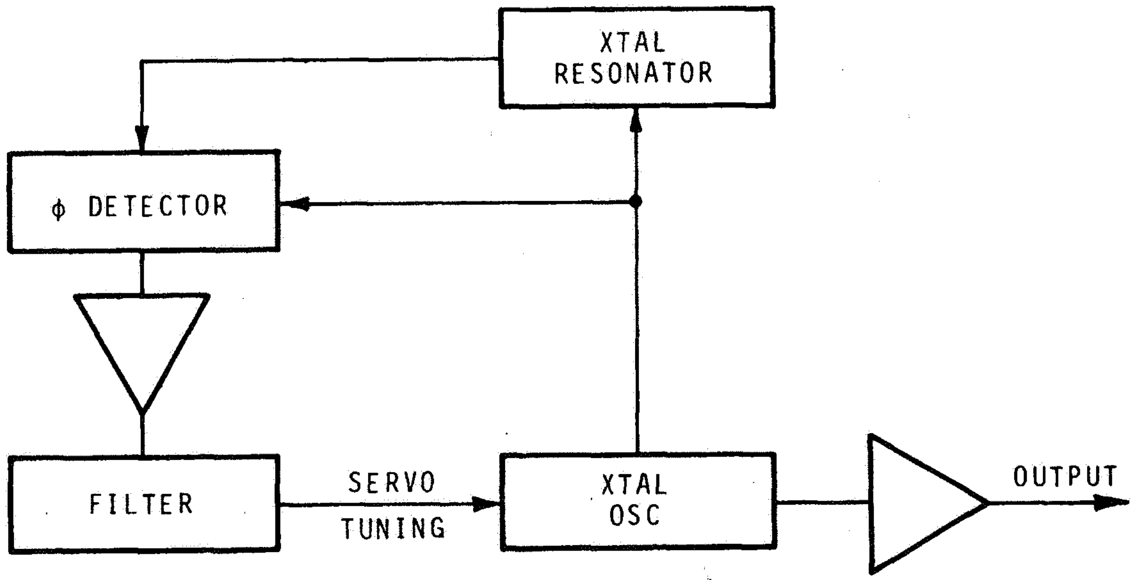


FIG. 2 Dual crystal concept. The crystal oscillator (high-level drive) is servoed to a passive crystal resonator (low drive level) using the phase sensitive dispersion lock technique.

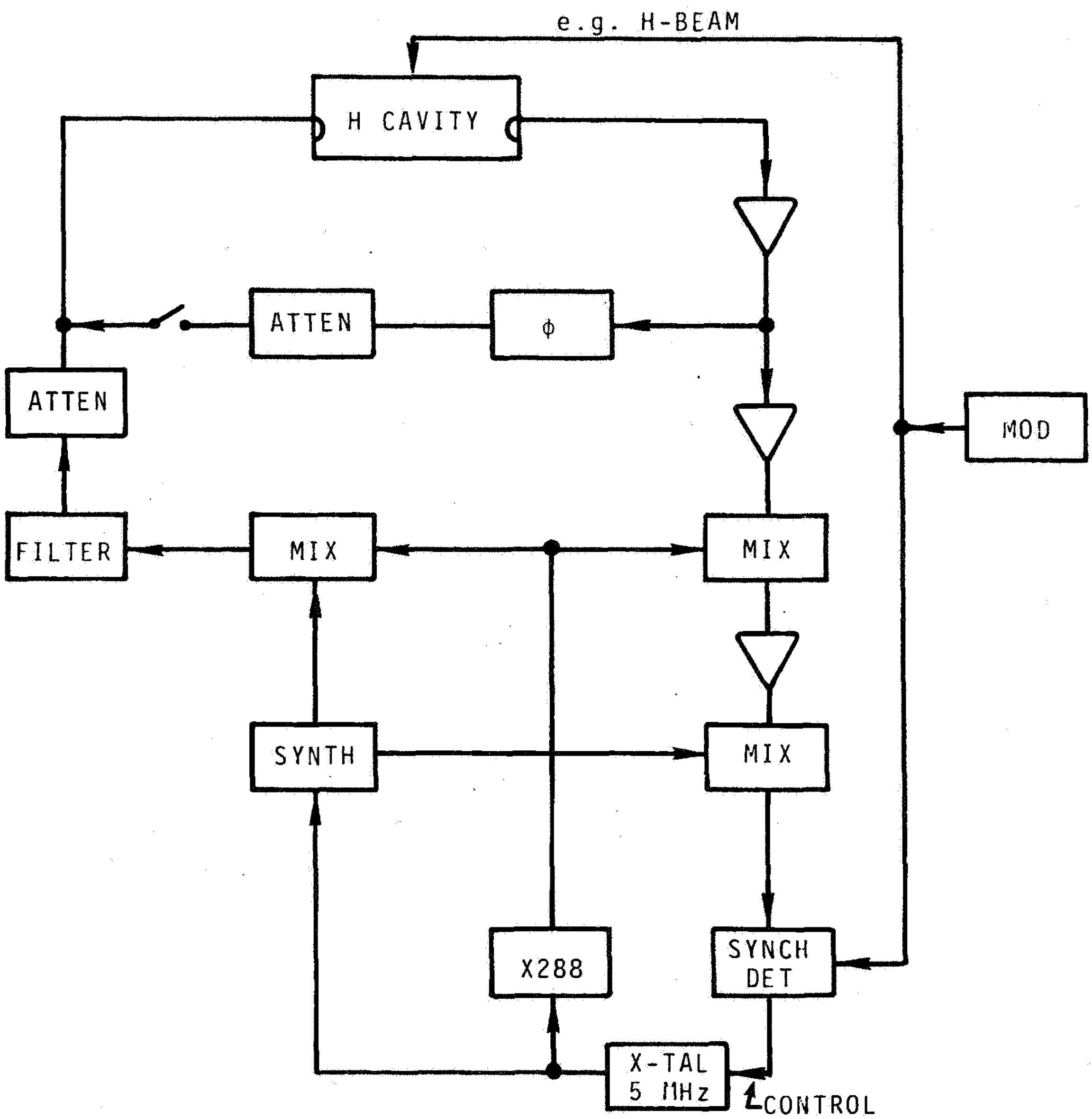


FIG. 3 Passive hydrogen concept. The crystal oscillator is locked to the hydrogen resonance using the phase sensitive dispersion lock technique. The cavity-Q is lowered using negative electronic feedback.

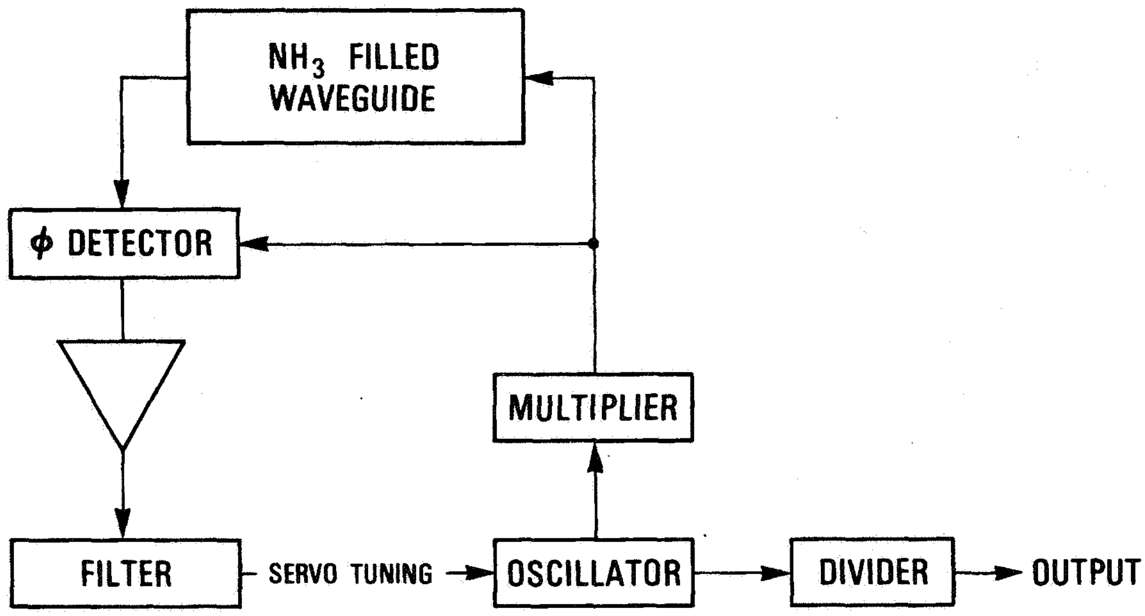


FIG. 4 Utility standard concept. The oscillator is locked to a resonance in ammonia (K-band) using the phase sensitive dispersion lock technique. The oscillator may not necessarily be a crystal oscillator but a Gunn effect oscillator or other conventional source.

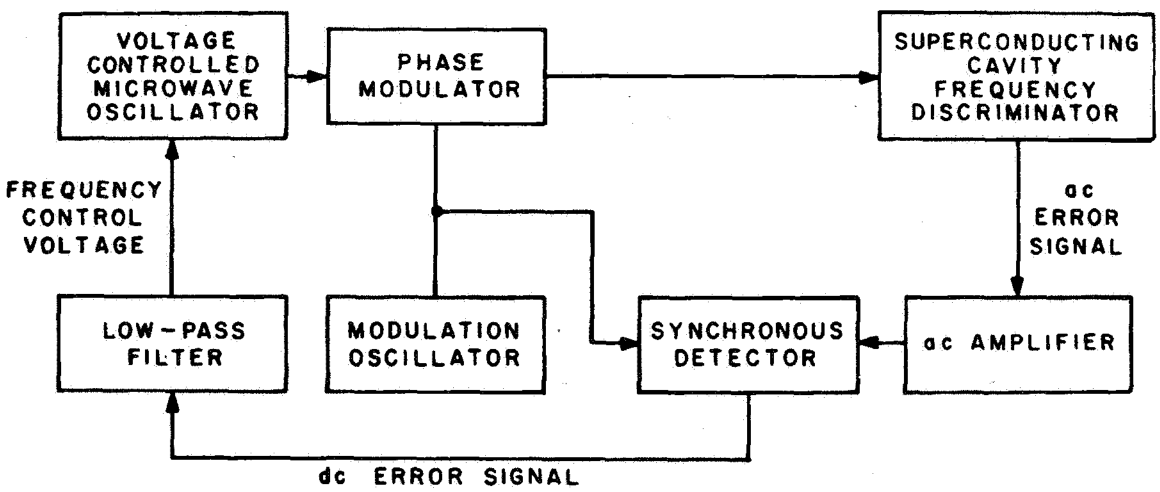


FIG. 5 Superconducting cavity oscillator. A Gunn effect oscillator is servoed to a superconducting cavity using conventional lock loop techniques [23,24].

QUESTION AND ANSWER PERIOD

DR. REDER:

I wonder why Dr. Winkler doesn't have a question on the inclusion of different standards in the general time scale.

DR. WINKLER:

I agree. I think that would be very desirable. But I have indeed a question or a comment regarding your slide No. 2.

There is a comment that region III really is not a drfit region, but a random walk frequency modulation. That is physically something completely different from a drift.

DR. HELLWIG:

If I remember what I said, I said that this is a deterioration of stability with increasing averaging times which may contain a drift or aging.

DR. WINKLER:

Yes. Well, the drift variations come with a true slope of plus one whereas you have indicated here a slope of plus one-half which would be a random walk frequency modulation, something quite reasonable to assume or even to see when you talk about atomic standards where you have some random variations. They occur presumably with a Poisson frequency, Poisson distribution. And for a lifetime, they will cause drifting away of frequency, but not necessarily in a continuous, monotonous way.

And I think it is important for us to realize that.

Another thing, of course, is I believe to understand what you have said concerning the combination of two standards or two frequency generators is really capable of widest generalization. That is, if you need very high, long-term stability. you must have a passive resonator. And if you must have very high or extreme short-term stability, you must have an active resonator, whatever it is. A passive one could be a crystal resonator, but also a cesium beam standard. And the active one could be a hydrogen maser or a crystal designed for very high short-term stability.

Indeed, I am quite certain that you are right that these approaches should be more pursued, particularly the combination of phase-locked filter to cesium standard, I think, which is closest to the practicability.

DR. HELLWIG:

Yes, I fully agree with all your comments. And just to defend myself once more, the fact that this slope is one-half indicates that I had the same opinion as you. But it makes it very difficult to give data for this region. And that is why I omitted them in my next slide.

DR. KARTASCHOFF:

Peter Kartaschoff, Swiss Post Office, Telecommunications Research Division.

For the user, data on

—Reliability

—Expected lifetime

of the various frequency standards would be very valuable and should be collected and made known.

DR. HELLWIG:

I fully agree; however, (a) not enough data are available readily to make general statements, and (b) the data on reliability would necessarily be tied to specific models of specific manufacturers. It does not behoove NBS to publicly state such data which would imply a relative quality rating of different commercial units. A general statement on lifetime can be made: The crystal or atomic resonators do not principally limit the design lifetime because better or different engineering can always lead to improvements. However, in the case of cesium and hydrogen devices, there is the basic mechanisim of exhaustion of the atom source and of the vacuum pump capacity.

LT. PARKIN:

Larry E. Parkin, U.S. Coast Guard.

If the quartz crystal within the cesium standard can be improved such that its output (stability) is 10^{-13} , will the long term stability of the cesium standard be significantly increased?

DR. HELLWIG:

No; the short-term stability may increase up to the crystal performance. However, a longer servo-attack-time is to be used which may affect the environmental sensitivity.

MR. LIEBERMAN:

Ted Lieberman, NAVELEX.

I was wondering about your warm-up times on your slides, first in the present-day cesium, rubidium and crystal. You talked about 30 minutes for cesium and 15 minutes for crystal. Isn't it essentially how long it takes to lock?

I think the cesium, rubidium come on much less time and in the future, will it be dependent on how soon you could lock or are you talking about different design?

DR. HELLWIG:

No. I think I did not project any change in cesium or rubidium for the future, any significant change, because, as you correctly said, this is the time required to produce your atomic resonance. You have to produce rubidium gas and cesium gas in a sense. And this first requires a time to warm up a device, an oven.

So there is fundamentally a problem in speeding that up. You could speed it up, of course, if you increase your initial power substantially.

MR. LIEBERMAN:

What we are talking about is five minutes or six minutes, not fifteen minutes or thirty minutes.

DR. HELLWIG:

What I quoted is the time to reach a certain performance. And some devices will reach lock within five—well, five is a little fast—7, 10 minutes. What I tried here again is not to describe particular devices, but sort of an average. And all the numbers I gave, stability of these numbers, give them the benefit of a good variance, really.

MR. TURLINGTON:

Tom Turlington, Westinghouse Electric.

Why do you think your proposed dual crystal oscillator will warm up about six times more rapidly than single crystal oscillator?

DR. HELLWIG:

Because a good long-term stability and low aging requires a careful oven design which makes a rapid warm-up difficult. In single crystal oscillators, usually the long-term performance is important. Thus rapid warm-up is usually not found in so-called precision oscillators. Good short-term stability requires only a rather simple temperature control; thus, rapid warm-up is possible. Therefore, in a dual crystal where the tasks of good short-term and good long-term performance are assigned to different crystals, rapid warm-up is possible without sacrifice in long-term stability, i.e., stability for one-day and longer.

TIME MEASUREMENT TECHNIQUES

J. F. Barnaba
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ABSTRACT

This paper will describe the common time measurements as used by the US Air Force Measurements and Standards Laboratory, Aerospace Guidance and Metrology Center (AGMC), Newark Air Force Station, Ohio.

The need for time measurements at several user levels will be discussed. These include comparisons between USNO and AGMC, time measurements in the lab at AGMC, comparisons between AGMC and Air Force precise time activities, and measurements at the activities themselves.

The emphasis will be on electronic counter time interval measurements since this is the most common time comparison measurement in use. The proper use and setting of controls will be covered along with helpful hints and common mistakes to be avoided.

Applications of time measurements will be described. Some of these are timekeeping via Loran-C, TV Line-10, and WWV. Frequency determination using periodic time readings will also be discussed.

This paper will be on a level that can be understood by individuals not previously involved in active day-to-day PTTI measurements. In fact, the purpose of this paper is to acquaint non-PTTI oriented individuals with the intricacies of precise time measurements and to stimulate discussion among others present whose methods may vary from those expressed by the author.

INTRODUCTION

As you may or may not be aware of, time can be measured more precisely than any other basic unit of measurement.

Many precise time measurements are used by the US Air Force Measurements and Standards Laboratory at the Aerospace Guidance and Metrology Center (AGMC), Newark Air Force Station, Ohio. Precise time measurements are also accomplished at various other Air Force activities. This paper describes the techniques normally used by Air Force Laboratories and activities to satisfy precise time measurement requirements.

TIME INTERVAL MEASUREMENTS

The most common precise time measurement is the time interval measurement. In many cases, this measurement is called a delay measurement. An oscilloscope is occasionally used to make time interval measurements but more frequently, a time interval counter is utilized. A time interval reading represents the amount of time that has elapsed between two chosen events. An example of a larger time interval would be the elapsed time between seeing a lightning flash and hearing the thunder. An example of a short time interval would be the time required for the electron beam in a TV picture tube to travel from the gun in the neck to the phosphors on the screen. Naturally, when using a time interval counter, or even an oscilloscope, these events must be defined electrically.

CLOCK COMPARISON

A frequent application of time interval measurement is the comparison or time synchronization of two clocks by determining the amount of time elapsed between the respective 1 pulse-per-second (1 pps) "tick" pulses of the individual clocks. This is accomplished by connecting one clock pulse to the start input and the other clock pulse to the stop input of the time interval counter. In the interest of valid measurements and especially for time interval counters with time base oscillators of questionable accuracy, the external reference frequency standard input can be utilized. The 1 MHz from one of the clocks being measured is most generally used for this purpose. Correct trigger level and slope conditions must be established and will also affect the accuracy of the measurement if not accomplished properly.

A "tick" pulse, or any other pulse, has, along with other shape characteristics, polarity, slope, rise time, pulse length (or duration), and fall time portions. Ideally, before making a time interval measurement, the two clock pulses involved should be observed with the aid of an oscilloscope and the following parameters determined: level (positive or negative), slope (positive or negative) and loading requirements. Next, the point on the pulse that is "on time" must be determined. The time interval counter start and stop trigger level and slope controls can now be set and a reading taken at the rate of once per second. If the time interval counter being used has a storage feature, it can be utilized to hold readings between samples. The algebraic sign given to the time interval reading should be considered next. If the reference clock 1 pulse per second (1 pps) is connected to the start input and the 1 pps of the clock to be measured is connected to the stop input and a reading of less than one-half second results, then the time interval reading is considered to be positive. If a time interval measurement is accomplished and a reading of more than one-half second results, the reading is subtracted from one second and is given a negative sign.

APPLICATIONS

Applications of time interval measurements used by AGMC and other Air Force activities will now be discussed. A time interval measurement is used when comparing the USAF master clocks to the USNO, the USAF master clocks to the AGMC traveling (portable) clocks, and the traveling clocks to the Precise Time Reference Stations (PTRS) at Vandenberg AFB, California, Elmendorf AFB, Alaska, and other Air Force activities who require precise time calibration.

The master clocks at AGMC are steered by daily Loran-C comparisons with USNO. Many other Air Force activities are using the Loran-C comparison method of timekeeping. The reference delay numbers utilized are determined by a time interval measurement. The time interval counter is started with the local clock 1 pps and stopped with the 1 pps from the Loran-C timing receiver.

Another timekeeping technique gaining popularity because of its low cost is the Line-10 TV method. In this instance, the time interval counter is started with the 1 pps from the local clock and stopped with the tenth line odd pulse which occurs once per picture from the Line-10 discriminator. The Air Force is currently using this technique at AGMC, Guam, Colorado, and New Hampshire.

If an activity is keeping time via Loran-C or TV Line-10 and the clock stops, time would have to be known to within a few milliseconds to reestablish precise time. This requirement is usually met by knowing the reference delay number for WWV. An oscilloscope is used for this purpose. It is started (triggered) by the local clock and stopped (position of tick noted on the display) by the detected signal from the HF receiver. So, in essence it is a time interval reading. The measurement represents the time elapsed from the transmission of the tick to the reception of the tick at the timekeeping location.

Another application of time interval measurement is known as "tick to phase" and checks a portion of a clock's digital divider chain. The time interval counter is started with the 1 pps tick pulse and stopped with the 100 kHz from the clock. The trigger level on the stop is adjusted around the zero level until switching the polarity selector from positive to negative yields a 5.0 microsecond difference. The positive polarity reading is then noted and checked from time to time, especially on a clock trip to see if the clock digital divider has jumped.

A characteristic of the 1 pulse per second output from a clock will be discussed next. Here we are concerned with the regularity or repeatability of the 1 pps. The measurement is called tick-to-tick jitter and consists of taking repeated time interval measurements, starting and stopping the time interval counter with successive 1 pps output pulses from the clock being evaluated. A time interval counter with nanosecond or sub-nanosecond resolution and accuracy is a requirement for this measurement. The start trigger is slightly later on the 1 pps pulse than the stop, so the time interval reading is less than one second.

Using successive time interval measurements for determining the frequency offset or frequency drift of a clock will now be described. Basically, this procedure consists of equating the number of microseconds gained or lost in a period of time and computing the offset. A simplified example of this is the timekeeping rule of thumb that approximately one part in ten to the eleventh (1×10^{-11}) frequency offset is the result of gaining or losing one microsecond in one day.

Computing frequency offset after measurement of time gained or lost over a period of days elapsed is routinely used by the Air Force Precise Time Synchronization Teams to determine the frequency offset of various activities site clocks. C-Field adjustment of Cesium clocks are determined using the results of these computations. Actually this is about the only method used at the Air Force Measurement and Standards Laboratory in determining frequency offsets. A variation of this method is sometimes used when time is short and only a few hours or days are available. In this case, a phase comparator/recorder is used. Normally, the 1 MHz signals from a reference and the standard to be measured are compared. This yields a 1 microsecond change each time the indicator travels full scale. Hundredths of microseconds can be read from these recorders and the frequency offset calculations can be accomplished in the normal manner. If greater resolution is desired, a vector voltmeter can be utilized and the degrees phase change measured between the two frequencies being compared is converted to microseconds. One may then use this data to compute frequency offset.

Two other measurements are used by AGMC as confidence checks. First, a good unchanging period count is required of the TV Line-10 pulses prior to obtaining the daily delay numbers. Secondly, although a precise time synchronization team may leave AGMC with sub-microsecond accuracy on their 1 pps of their portable time standard, a check is always made to see that the clock readout indicates the proper hour, minute and second. Credibility is sometimes in doubt when a team claims to be carrying time to better than one microsecond with a clock that indicates a several second or minute error.

SUMMARY

I have attempted to show the need for precise time measurements within the Air Force, how the various measurements are accomplished, and applications of each of the measurements.

QUESTION AND ANSWER PERIOD

MR. PICKETT:

I am Bob Pickett from SAMTEC.

Is it general policy when you find a timing offset to correct it or just log it? That is question No. 1.

Question No. 2, what are you going to do about using satellites for this rather than traveling clocks?

MR. BARNABA:

If we measure your clock, let's say, and its 75 microseconds off, generally before the team leaves, they will set the clock to nominal or to the portable. And they would do this unless they were told not to by the particular site. Some people just want to know where they are, but they don't want it moved.

MR. PICKETT:

Will they try to set the frequency offset?

MR. BARNABA:

Our general rule of thumb on that is if it is 3 parts in 10^{12} or better, we leave it alone. If it is worse than that, we adjust the C field generally.

On your second part about the satellites, I think just about everyone agrees that time will be transferred in the future through satellites. And we are watching the advances, and that's all I can say. We will try to implement them as soon as systems become available.

DR. WINKLER:

I would like to add to your comments. The first one, my urgent suggestion that whatever is being done, you should report two measurements. One before the clock has been reset, and one after it has been reset if a reset is made. Whether it is to be made or not will depend on local policy. I think you are very right to say this will require different decisions in various agencies.

But whatever is to be done, measurements have to be made before and after reset. Because if you do not make the measurement before the reset, all the previous measurements become worthless or may become worthless. Please do not forget if there is a reset made in a clock, make two measurements.

Number two, certainly I think we will hear more about satellites later on in the conference; it is a problem which I think is purely administrative, but it is close to a solution, I hope.

MR. BARNABA:

On your comment on the noting what the frequency was before and after and the time before and after, we have a data sheet that our teams take out. We have initial frequency, final frequency, and we make note of all the digital divider settings. So this is fully documented, I assure you.

N75 27180

USE OF PRECISION TIME AND TIME INTERVAL (PTTI)

J. D. Taylor, ADTC, Eglin AFB

INTRODUCTION

An introduction, or rather a reintroduction for many, to the practical utilization of time synchronization and time interval measurements on the various DoD test ranges is the topic for today. The presentation will review the overall capabilities of various missile ranges to determine precise time-of-day by synchronizing to available references and applying this time point to instrumentation for time interval measurements. Global and downrange test sites will not be addressed.

A backward look over the past 20 years indicates that the origin and evolution of the ranges has been directly proportional to the DoD development efforts in the aircraft, missile, and defense systems fields. Tremendous advances in range technology paralleled industrial efforts to improve weapons systems. Range timing applications have historically fitted into the scheme of testing weapons systems even in the earliest days of testing. Interestingly enough, the essential importance of instrumentation time interval measurements has not changed over the years. Only the methods used in the determination of precise time and the formulation of interval measurement codes have changed.

An important aspect of range operations must be remembered; PTTI on a test range is actually separated into two distinct disciplines, time synchronization to a known source and the development of synchronized codes for interval measurements. These integral tasks are accomplished routinely every day, but range people normally interpret TIME as being related to time interval measurement, i.e., time code application, rather than time synchronization.

SYNCHRONIZATION

A review of range time synchronization methods over the past years suggests a chronological outline for the technical development of the ranges. As a beginning, visualize that in the 1950s installations similar to Eglin Air Force Base were used to test relatively simple weapons. Instrumentation film cameras were common and

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tape recorders were coming into good use. In the latter 1950s the Armament Development & Test Center (ADTC), along with other potential missile test centers, began preparations for the missile era. Sophisticated range instrumentation was installed which required accurate time correlation of events such as tracking radar time space position information (TSPI). Computer analysis of data demanded time correlation between sites to machine process the data. During this period, the IRIG Standard Time Codes were published and the Naval Observatory began PTTI with Loran transmissions. ADTC was one of the ranges fortunate enough to be within easy range of the East Coast chain. Our synchronization problems were eliminated. Other ranges, particularly in the West, were not so fortunate. In fact, until 1973, the Western ranges did not have Loran transmissions for PTTI purposes. In the summer of 1973, the Loran-D site at Nellis AFB, NV, came into being. Until that time, the Hawaiian Loran chain, WWV, or portable atomic clocks had to be used. This Loran-D installation made available accurate Loran synch to all the Western ranges and for the first time, low-cost, accurate time-of-day synch to the Naval Observatory was available to all the continental ranges and sophisticated time correlation was easily available. Of course, even today all ranges are not synched to Loran as there is no need for all ranges to be so accurately synchronized. However, today's ranges are converting to Loran synchronization techniques because of the inherent accuracy and cost effectiveness, a giant step forward. A few years ago, 10 microsecond synchronization was a debatable subject for everyday range operation, today it is expected.

APPLICATIONS

The DoD test range mission support requirements and capabilities are intricate and ever changing. Instrumentation equipment and test schemes vary widely from coast to coast according to the requirements and type of testing conducted for each service, i.e., Army, Navy, Air Force. Considering the three services, it is easy to imagine that ground, air, and water testing will require different physical as well as instrumentation environments. Each service has specialty, such as Ft. Huachuca for the Army, AFWR for the Navy, and AFFTC for the Air Force. With such diversity, it is difficult to realize any commonality between installations, yet there is one data system mutual to all DoD test ranges. This is PTTI.

PTTI has two general classes of range applications, These two types of applications can be described as the WWV millisecond synch type and the WWV-Loran microsecond synch type. Within these two techniques, the former application can be applied more readily to ranges smaller in physical size and generally operate within the range boundaries. The second type application refers to larger installations which must operate timing equipment closely synchronized over large distances which prohibit synch distribution by practical methods. Also, this includes the larger national and space ranges which must operate together in real-time for tracking and data work. These large ranges have the more stringent synchronization accuracy requirements.

Typical examples of the above WWV synch type ranges which operate within their own boundaries are: NWL, Dahlgren, VA., Tonopah Test Range, NV., Dugway Proving Ground, UT., Ft. Huachuca, AZ, and Holloman AFB, NM. These ranges operate within smaller restricted physical sizes which allows time distribution from a central point. Synchronization is maintained at the central facility to the required accuracy and distribution of the time signals is by transmission over VHF or data line to the local users. The accuracy of time correlation between the closely positioned points is limited by the time delay of the distribution system and is usually in the order of milliseconds. This is not to say that some of the smaller ranges do not have precision PTTI requirements for data correlation. In fact, some of the most difficult and precise time interval measurements are required in the unusual environments of ballistics tunnels or other weapons ballistics tests.

The second type of PTTI application involves WWV-Loran type synch and ranges which use this type synch are: NATC, Patuxent River, MD., ADTC, EAFB, FL., WSME, NM., COR Ranges, NWC., and Yuma Proving Ground, AZ. These ranges employ two different concepts of approaching PTTI: (1) a central timing facility with associated distribution system and/or (2) independently synchronized installations.

A range which can be used as a prime example of the central timing facility concept is WSMR. WSMR has a central timing facility equipped with Loran synch receivers and three primary atomic standards for stable time base sources. After development of the proper timing signals, distribution is made from the timing central to a VHF transmission system and various combinations of microwave and data line drivers for utilization on theodolite stations, high-speed cameras, etc. One of the more important and interesting aspects of this distribution system is the resynchronization technique used for stabilizing distant radar or satellite installations with the timing central in lieu of individual site synchronization with Loran. This type system was developed in the Western part of the continent in the late 1950s and early 1960s for the simple reason that Loran was not available and WSMR had requirements for accurate intrarange synch at remote installations. The results were the problem was technically solved by measuring round trip transmission delays and correcting for these delays in the receiving unit. Until the Dana, Oh, Loran station came into existence, this was the only feasible method WSMR or any other Western range had of achieving PTTI. As an example, when WSMR had a requirement to operate a tracking site at Green River, UT, in 1965, the only method available to achieve the required accuracy at this site 600 miles from the timing central was to use portable atomic clocks. Of course, the Nellis Loran-D installation has made all these type PTTI problems history.

A second approach to achieving accurate PTTI is separately to synchronize each site or installation to a Loran transmission. This method is used at such installations as: ADTC, AFETR, SAMTEC, AFWR, and PMR for interrange and intrarange PTTI solutions. This method requires that each site to be used have a Loran synch system capable of independent determination of PTTI, and can either be composed of the newer automatic tracking receivers or a manual system be used. An advantage of the independent method is that each site can independently maintain a synchronization to the Naval Observatory and eliminate the problems associated with transmission systems reliability. Cost is not appreciably increased for these sites and if the cost of the transmission system were considered, the independent synch method would be the most cost effective method. Very good PTTI is available with this concept of range synchronization.

As previously stated, global and down-range sites will not be discussed. When the site is not within range of a Loran transmission, then some of the advanced techniques explained in the earlier papers must be employed.

Any discussion of DoD range PTTI would not be complete without a few words on the airborne data correlation situation. Correlation of airborne collected data with ground instrumentation had historically been a problem. In today's world of electro-optical weapons, airborne data correlation has become even more important. Ranges involved in this type testing have two alternatives for time tagging airborne data: (1) transmission of a time code or, (2) an onboard PTTI device. The former case of the transmitted time code is often inadequate as the data correlation is on the order of milliseconds. The latter case of an onboard clock poses the problem of synchronizing the clock accurately enough to satisfy the requirements over the time profile of the mission. Certainly, the clock frequency standard must be stable enough to maintain adequate synch after the initial setup. An interesting and obvious situation develops during preflight clock synch if the aircraft is not on aircraft internal power. During power switch, errors can be injected in the clock so caution must be exercised.

Within the past 12 months, ADTC has been required to support electro-optical type tests with very demanding time correlation. For instance, one particular laser decoy test required time correlation and resolution within 1 microsecond between airborne and ground instrumentation. As of this time, ADTC has not actually achieved a data correlation this accurate for this test.

CONCLUSION

This paper has attempted to present the status of the majority of DoD test ranges in regard to PTTI. The status of PTTI for these ranges is that time-of-day synchronization to the U. S. Naval Observatory via Loran methods has eliminated synch accuracy problems within the continental boundaries of the U. S. Time interval measurements are likewise being satisfied by a diversity of methods. This is not to imply that all PTTI problems are solved, as they are not. Fortunately, this country has the technical resources from organizations such as the Naval Observatory, Bureau of Standards, and AGMC to help solve existing and future PTTI problems. One thing is always certain in PTTI applications, accuracy requirements always seem to increase.

QUESTION AND ANSWER PERIOD

DR. REDER:

What is the particular transmission reliability problem in the South? Why is the South different from the West, from the East, from the North?

MR. TAYLOR:

One is lightning. For some reason, the communication lines in the South, if they are buried or above ground don't seem to last very long, especially on the Florida coast. We can't rely on landline transmission. If we have bad storms in a particular mission off another part of the range, microwave gets interfered with quite a bit, too.

DR. REDER:

Well, you also mentioned problems with air borne synchronization—synchronization of equipment on fighter planes. Has this been formulated properly, and has it been brought to the attention of all the research labs? You know, the research labs are dying to get something to do which is relevant.

MR. TAYLOR:

Generally when you get into a problem like this, it runs into something like we have a problem, and it shows up, how do you solve it, do you have money to solve it? You have got to consider we need something that operates in the outboard powerline of an F-4 and have a part 10^9 stability. And how do we run this clock and synchronize it?

It has just now become evident that we are going to have to develop something of this nature to solve these problems. Maybe the Navy or somebody will feedback into the labs so we can come up with a product.

DR. REDER:

Do they really know what the problem is? Has it been spelled out?

MR. TAYLOR:

It is becoming very evident right now because of the type missile, the EO devices, we are using now. They are becoming very sticky about testing those devices.

DR. REDER:

I hope you do spell it out soon and feed it to the research labs.

LCdr. KIES:

LCdr. Kies, East Coast Loran-C Chain.

One question. I understand the D chain is going back to Europe the first of the year. And I wonder what plans were out West.

MR. TAYLOR:

I think the status is — I am almost certain — that the master station at Nellis will be permanent, won't leave.

Does anybody from the Observatory know that now?

MR. LAVANCEAU:

Jean Lavanceau from the U.S. Naval Observatory.

The crew of the station of the Loran-D network are being deployed now to Germany. However, the master station located in Nellis Air Force Base will remain and operate the timing equipment for the Western part of the United States.

As far as I know, time transmission will still be available with the same high frequency, same precision, as you now have available from Nellis Air Force Base.

N75 27181

THE PRESENT DEVELOPMENT OF TIME SERVICE IN BRAZIL, WITH THE APPLICATION OF THE TV LINE-10 METHOD FOR COORDINATION AND SYNCHRONIZATION OF ATOMIC CLOCKS

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ABSTRACT

A short historical review will be followed by a description of the resources available at the Time Service of the National Observatory. Various methods presently used for the dissemination of time at several levels of precision will be described along with future projects in the field. Different aspects of time coordination will be reviewed and a list of future laboratories participating in a National Time Scale will be presented. A Brazilian Atomic Time Scale will be obtained from as many of these laboratories as possible. The problem of intercomparison between the Brazilian National Time Scale and the International one will be presented and probable solutions will be discussed. Needs related to the TV Line-10 method will be explained and comments will be made on the legal aspects of time dissemination throughout the country.

Following this there will be a description of measurements taken between two laboratories, ONRJ and INPE. A comparison will be made between these measurements and those obtained in 1969 and 1970 by the NAFS and USNO in the U.S.A. Finally, a comparison will be made between the Line-10 and the physical clock transportation methods. The comparisons show good promise for the effectiveness of the Line-10 method in Brazil.

I - SHORT HISTORICAL NOTE

The Time Service of the National Observatory of the Ministry of Education and Culture, active since 1847 is specifically dedicated to the countrywide dissemination and determination of Legal and Astronomical Time in Brazil.

In 1902 our Time Service obtained time by solar and certain star meridian passages and maintained time by pendulum and chronometers. Time transmission for public use was visible by the release of a balloon from a small tower on the terrace of the Observatory on a hill near the center of Rio de Janeiro.

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The law nº 2784 of June 18, 1913 that established legal time in Brazil and adopted the time zones, which was regulated by the Decree nº 10.546 of November 5, 1913 is still valid. It determined that the National Observatory of Rio de Janeiro, as well as future stations that may be designated, are responsible for the determination of time and its transmission for geographical and navigational purposes by telegraphic or "Time Ball" means, in agreement with the accepted and valid international agreements.

On June 1, 1918 the first radio-telegraph station of time signals was inaugurated. They were transmitted twice daily, from 13h 55m 55s to 14h 00m 00s, and from 23h 55m 55s to 00h 00m 00s, GMT.

The operation of the Observatory was regulated by Decree nº 6361 of October 1, 1940 which established that:

> Chapter III, Art. 7 - The Division of Meridian Services and attached Services, will determine and transmit legal time by radio-telegraphy in accordance with decisions of the International Time Committee, with the adequate precision not only for the purposes of navigation, but for engineers and the public and also, in cooperation with the Bureau International de l'Heure, for Universal Time determination:

With these fundamental objectives operating since the time of the Empire (before 1889) several techniques and varied instruments have been used by generations to cooperate with the Time Service, beginning with pendulums and arriving at the present status where everything depends on atomic clocks.

II - ACTUAL SYSTEM

We are now in a transition state in which we are trying to solve our problems of time dissemination for both scientific and non-scientific users. We are only beginning to adapt to our conditions, some techniques previously used by other countries.

Of course this adaptation implies, in all cases, an investigation of the methods of all possible theoretical and practical considerations. It is possible that we must develop new techniques more useful to our particular conditions in South America.

For this purpose we have had pendulum clocks, clocks with crystal oscillators and more recently commercial Cesium and Rubidium frequency standards.

To establish a time scale based on as many standards as possible, we began in December 1972 making comparisons between all available standards using one of our Rubidium standards as a portable clock.

We know of course, that the Rubidium standard is not the best choice for a portable clock, and we intend as soon as possible to get a Cesium for this purpose.

In July of last year, 1973, we started the comparisons between standards located in Rio and two places in Sao Paulo using the Line-10 method. Initially we studied the observed flucuations in the propagation delay in the path. The two locations now used are approximately 300 and 450 km from Rio. More experiments are being made at Brasilia, Belém, Natal and Manaus, which are far from Rio at straight distances of 900; 2470; 2170 and 2820 km respectively.

At present, we have in Brazil a "Working Group on Time" that, with the coordination of "National Observatory" and sponsored by our "National Research Council," has regular meetings. All the Brazilian institutes that have atomic clocks participate in the Brazilian time scale.

For the dissemination of time and frequency we are now using broadcast transmissions in HF (Short waves) and VHF. We know the limitations involved by these bands. For precision comparisons of time or frequency we normally go with our Rubidium to the users that require such precision, or they come to us, or we have a connection by telephone line, depending on the frequency.

We are now installing in our capital of Brasilia, a new time service station. We intend in the next year to begin transmissions of time signals and standard frequencies using the advantage that Brasilia is more or less a central point in Brazil. We have started experimental transmissions, using the help of a government broadcasting station, that is putting high power transmitters of 250 kw and 300 kw into operation.

Using the facilities of our Brazilian Telecommunication Company, EMBRATEL, that has a microwave link along the entire coast, we will retransmit by new coastal stations, (16) time signals, that are useful for the ships communicating with those stations.

Normally in some transmissions of Time signals, for users of low precision we transmit voice announcements of time every 10 seconds. These announcements are generated from automatic equipment which is synchronized with our Cesium standard.

We have daily reception of Time signals from other countries in VLF, HF and VHF, (two years ago, during the experimental transmission of the ATS-3 satellite).

In the near future, we intend to have regular comparisons between the Brazilian time scales and the International time scales using portable clocks and/or reception of signals transmitted from satellites.

III - LINE-10 METHOD IN BRAZIL

As there are now or soon will be, various laboratories with atomic frequency standards (commercial types only) in Brazil, it was decided by the GTH ("Working Group on Time," created by the National Research Council) that the National Observatory would initiate experiments to obtain a national standard time scale from the individual scales of the several laboratories.

Table 1 presents a list of these laboratories and Figure 1 presents the map of Brazil with their locations. Because of the dimensions of Brazil (more or less 3200 km in the N-S direction and 4200 km in the E-W direction) line-10 will be the most useful method available for comparisons.

TABLE I

POSSIBLE AND ACTUAL PLACES USING THE LINE-10 METHOD

City-State	Institution	Standard (Commercial)
Rio de Janeiro-GB	EMBRATEL	Cs (1) HP
	UFRJ	Cs (1) Ebauche
	ON	Cs (2) HP. Rb (2) HP and Tracor
S. José dos Campos-SP	INPE	Cs (1) HP
S. Paulo-SP	IAG	Cs (1) Ebaushe; Rb (1) Sulzer
Atibaia-SP	CRAAM	Cs (1) HP, Rb (2) Tracor

EMBRATEL - Brazilian Telecommunication Corporation
UFRJ - Federal University of Rio de Janeiro
INPE - Space Research Institute
IAG - Astronomical and Geophysical Institute of S. Paulo University
CRAAM - Radio Astronomy and Astrophysical Center of Mackenzie

The experiments were started with measurements between INPE (Space Research Institute) and ONRJ (National Observatory of Rio de Janeiro) which are approximately 300 km apart.

ONRJ versus INPE

The measurements are made twice per week for six minutes each day. As there is transmission in both directions, measurements are made during three minutes in each direction. This system allows determination of propagation delay between the two laboratories.

Only 30 measurements are used for the reduction of the measurements made during the 3 minutes.

The reduction actually is made by means of a small table calculator, and when more laboratories start to participate we will use a PDP8/E from Digital Equipment Corp. (DEC).

Figure 2 presents the results for ONRJ-INPE in comparison with the result of NAFS-USNO comparison, in terms of the Allan variance.

We can observe that our result is more or less ten times worse that the other. We think that this is because we are comparing only two single standards, whereas the NAFS-USNO is a comparison between two scales resulting from several standards each. Another difference between the two results is in the number of data points; our situation covers only one 100 day interval.

Another result is also presented.

Parallel to the Line-10 measurements, we make physical transportation of clocks for precise measurements of propagation delay. Figure 3 presents this comparison.

Following are observations on this figure.

a - the line-10 values are not as dispersed in the JUL-OCT interval as in the Nov-Mar interval. This may be due to the rain precipitation that is more pronounced in the latter period.

b - in the end of November there was a sudden change in the relative frequency because of a failure in one of the two clocks.

c - the variation, -1.5×10^{-12} and $+1.0 \times 10^{-12}$ is in agreement with the specification of the two standards, which is $\pm 5 \times 10^{-12}$.

d - propagation delay in this experiment is of no importance because its variations, over one year, is of the order of $\pm 0.3\ \mu s$.

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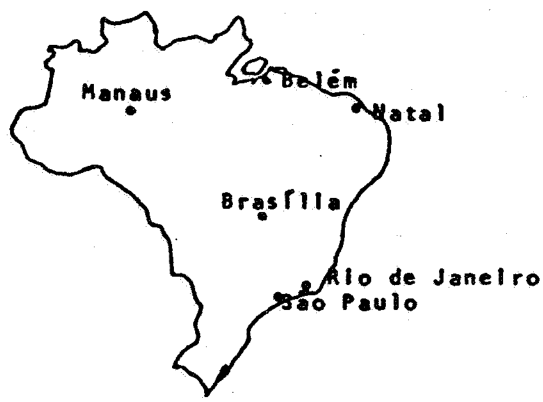

Figure 1.

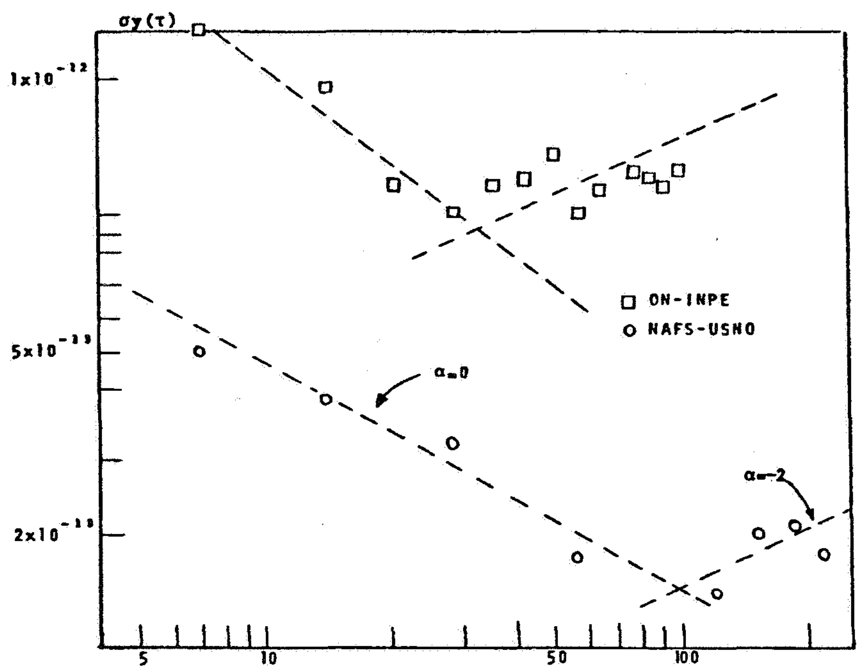

Figure 2. Sampling time (τ) in days

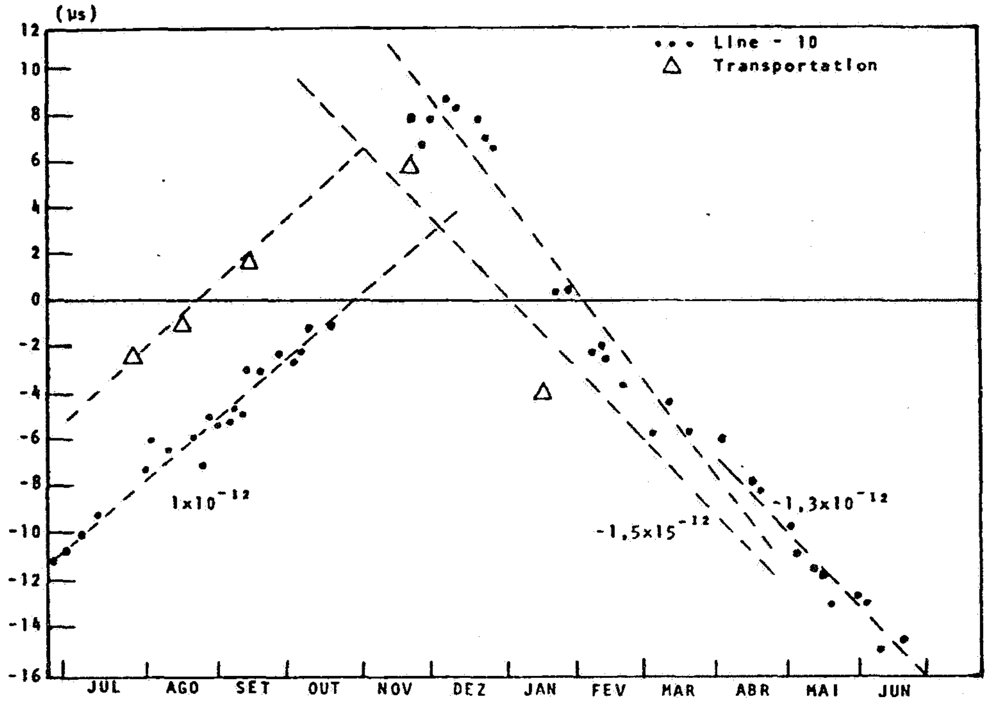

Figure 3. Comparison between the Line-10 and physical clock transportation

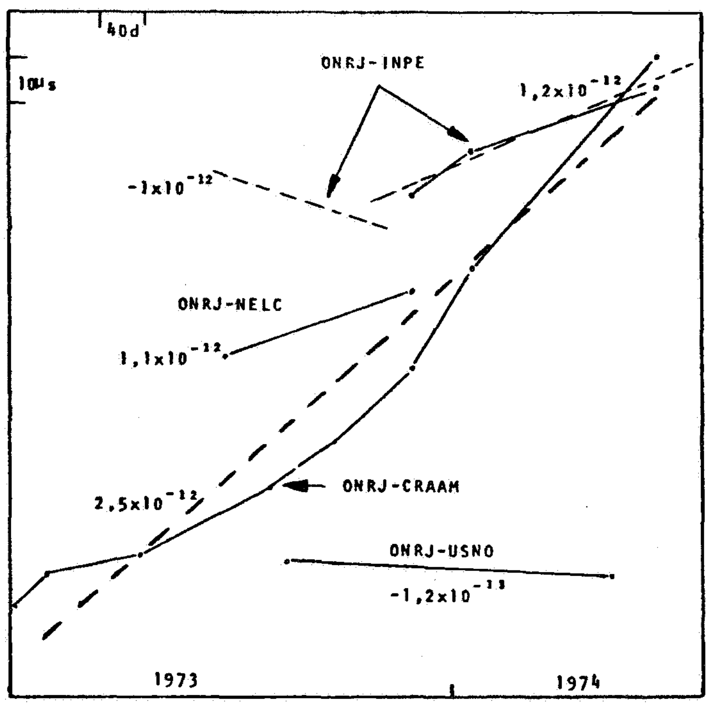

Figure 4. Global comparisons

THE MEASUREMENT OF FREQUENCY AND FREQUENCY STABILITY OF PRECISION OSCILLATORS

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ABSTRACT

The specification and performance of precision oscillators is a very important topic to the owners and users of these oscillators. This paper presents at the tutorial level some convenient methods of measuring the frequencies of precision oscillators -- giving advantages and disadvantages of these methods.

Conducting such measurements, of course, gives additional understanding into the performance of the given pair of oscillators involved. Further it is shown that by processing the data from the frequency measurements in certain ways, one may be able to state more general characteristics of the oscillators being measured. The goal in this regard is to allow the comparisons of different manufacturers' specifications and more importantly to help assess whether these oscillators will meet the standard of performance the user may have in a particular application.

The methods employed for measuring frequency are designed for state-of-the-art oscillators, and an effort has been made to allow for fairly simple, inexpensive, and/or commonly available componentry to be used in the measurement systems. The method for measuring frequency stability is basically that recommended by the IEEE subcommittee which wrote the paper "Characterization of Frequency Stability," IEEE Transactions on Instrumentation and Measurement, IM-20, No. 2, pp. 105-120, (May 1971).

INTRODUCTION

Precision oscillators play an important role, in high speed communications, navigation, space tracking, deep space probes and in numerous other important applications. In this paper I will review some precision methods to measure the frequency and frequency stability of precision oscillators. The paper will be tutorial in nature and will concentrate on fairly well established methods; however, it will present one apparently unexploited and useful method. I will first define some terms and some basic concepts that will be useful later on and then discuss four different ways of measuring frequency and frequency stability. Finally, I will discuss briefly some useful methods of analyzing the results--to more nearly maximize on the information that may be deduced from the data.

The typical precision oscillator, of course, has a very stable sinusoidal voltage output with a frequency ν and a period of oscillation τ , which is the reciprocal of the frequency, $\nu = 1/\tau$, as illustrated in Fig. 1. The goal is to measure the frequency and/or the frequency stability (instability is actually measured, but is often called, with little confusion, stability in the literature) of the fluctuations of the sinusoid. The voltage out of the oscillator may be modeled by equation 1:

$$V_1 = V_p \sin (2\pi\nu_1 t). \tag{1}$$

Of course, one sees that the period of this oscillation is the number of seconds per cycle or the inverse of the frequency in cycles per second. Naturally, fluctuations in frequency correspond to fluctuations in the period. Almost all frequency measurements, with very few exceptions, are measurements of phase or of the period fluctuations in an oscillator, not of frequency, even though the frequency may be the readout. As an example, most frequency counters sense the zero (or near zero) crossing of the sinusoidal voltage, which is the point at which the voltage is the most sensitive to phase fluctuations.

One must also realize that any frequency measurement always involves two oscillators. In some instances the oscillator is in the counter. One can never measure purely only one oscillator. In some instances one oscillator may be enough better than the other that the fluctuations measured may be considered essentially those of the latter. However, in general because frequency measurements are always dual, it is useful to define:

$$y(t) = \frac{\nu_1 - \nu_o}{\nu_o} \tag{2}$$

as the fractional frequency deviation of say oscillator one, ν_1, with respect to a reference oscillator ν_0 divided by the nominal frequency ν_0 . Now, $y(t)$ is a dimensionless quantity and useful in describing oscillator and clock performance; e.g. the time fluctuations, $x(t)$, of an oscillator over a period of time t are simply given by:

$$x(t) = \int_0^t y(t)\, dt \tag{3}$$

Since it is impossible to measure instantaneous frequency, any frequency or fractional frequency measurement always involves some sample time, τ --some time window through which the oscillators are observed; whether it's a picosecond, a second, or a day, there is always some sample time. So when determining a fractional frequency, $y(t)$, in fact what happens in the device is that the time fluctuation is being measured say starting at some time t and again at a later time, $t + \tau$. The difference in these two time fluctuations, divided by τ gives the average fractional frequency over that period τ :

$$y(t, \tau) = \frac{x(t + \tau) - x(t)}{\tau} . \tag{4}$$

Tau, τ, may be called the sample time or averaging time; e.g. it may be determined by the gate time of a counter.

What happens in many cases is that one samples a number of cycles of an oscillation during the preset gate time of a counter; after the gate time has elapsed the counter latches the value of the number of cycles so that it can be read out, printed or stored in some other way, and then there is a delay time for such processing of the data before the counter arms and starts again on the next cycle of the oscillation. During the delay time or process time information is lost. We have chosen to call it dead time and in some instances it becomes a problem. Unfortunately it seems that in typical oscillators the effects of dead time hurt the most where it is the hardest to avoid. In other words, for times that are short compared to a second, where it is very difficult to avoid dead time, that is usually where whether you do or do not have dead time makes a difference in the data. Typically for common oscillators, if the sample time is long compared to a second, the dead time makes little difference except in data analysis unless it is excessive [3].

SOME METHODS OF MEASUREMENT

In reality of course, the sinusoidal output of an oscillator is not pure; but it contains noise fluctuations as well. This section deals with the measurement of these fluctuations to determine the quality of a precision signal source.

I will describe four different methods of measuring the frequency fluctuations in precision oscillators.

A. The first is illustrated in Fig. 2. The signal from an oscillator under test is fed into one port of a mixer. The signal from a reference oscillator is fed into the other port of this mixer. The signals are in quadrature, that is, they are 90 degrees out of phase so that the average voltage out of the mixer is nominally zero, and the instantaneous voltage corresponds to phase fluctuation rather than to the amplitude fluctuations between the two signals. The mixer is a key element in the system. The advent of the Schottky barrier diode was a significant breakthrough in making low noise precision stability measurements and in all four measurement methods described below the double balanced Schottky barrier diode mixer is employed. The output of this mixer is fed through a low pass filter and then amplified in a feedback loop, causing the voltage controlled oscillator (reference) to be phase locked to the test oscillator. The time constant and gain are adjusted such that a very loose phase lock condition exists. Caution: the attack time is not the time constant of the RC network shown.

The attack time is the time it takes the servo system to make 70% of its ultimate correction after being slightly disturbed. The attack time is equal to the inverse of π times the servo bandwidth. If the attack of the loop is about a second then the voltage fluctuation will be proportional to the phase fluctuation for sample times shorter than the attack time or for Fourier frequencies greater than about 1 Hz. Depending on the quality of the oscillators involved, the amplification used may be from 40 to 80 dB via a good low noise amplifier, and in turn this signal can be fed to a spectrum analyzer, for example, to measure the Fourier components of the phase fluctuation. This system of frequency-domain analysis has been well documented in the literature [1,2,3] and has proven very useful at NBS; specifically, it is of use for sample times shorter than one second or for Fourier frequencies greater than 1 Hz in analyzing the characteristics of an oscillator. It is also specifically very useful if you have discrete side bands such as 60 Hz or detailed structure in the spectrum.

B. The second system (shown in Fig. 3) is essentially the same as in Fig. 2 except that in this case the loop is in a tight phase lock condition; i.e. the attack time of the loop should be of the order of a few milliseconds. In such a case, the phase fluctuations are being integrated so that the voltage output is proportional to the frequency fluctuations between the two oscillators and is no longer proportional to the phase fluctuations for sample times longer than the attack time of the loop. The bias box is used to simply adjust the voltage on the varicap so that you are at a tuning point that is fairly linear and of a reasonable value. Typically, the oscillators we have used at NBS are about 1 part in 10^9 per volt. The voltage fluctuations prior to the bias box (biased slightly away from zero) are fed to a voltage to frequency converter which in turn is fed to a frequency counter where one may read out the frequency fluctuations with great amplification of the instabilities between this pair of oscillators. The frequency counter data are logged with a printer or some other data logging device. The coefficient of the varicap and the coefficient of the voltage to frequency converter are used to determine the fractional frequency fluctuations, y_i, between the oscillators, where i denotes the i^{th} measurement as shown in Fig. 3. The sensitivity of the system that we have set up at NBS is about a part in 10^{14} per Hz resolution of the frequency counter, so one has excellent precision capabilities with this system.

The advantages and disadvantages of this type of tight phase lock system are as follows:

ADVANTAGES: The component cost is not too expensive unless one does not have a voltage controllable oscillator. Voltage to frequency converters can now be purchased for about $150.00. Most people involved with time and frequency measurements already have counters and oscillators and so I have not entered these as expenses. In addition, good bandwidth control is obtainable with this system and the precision is adequate to measure essentially any of the state-of-the-art oscillators. The sample time can be of the order of a second or longer; it is difficult to go shorter than one second or an interaction will occur with the attack time of the tight phase lock loop. The dead time can be small; in fact, if you have a very fast counter, that is a counter which can scan the data more quickly than the attack time of the loop, the dead time will be negligible.

DISADVANTAGES: An oscillator that is controllable is necessary. For the price of increased precision, one has increased complexity over simply measuring with a direct frequency counter. The varicap tuning curve is nonlinear and so that curve must be calibrated and doing so is sometimes a bit of a nuisance. For that reason and some other reasons it is not useful in measuring the absolute frequency difference between the pair of oscillators involved in the measurement. The system is basically conducive to measuring frequency stability.

C. Beat Frequency Method. The next system I would like to describe is what is called a hetrodyne frequency measuring method or beat frequency method. The signal from two independent oscillators are fed into the two ports of a double balanced mixer as illustrated in Fig. 4. The difference frequency or the beat frequency out, ν_b, is obtained as the output of a low pass filter which follows the mixer. This beat frequency is then amplified and fed to a frequency counter and printer or some recording device. The fractional frequency can simply be obtained by dividing ν_b, by the nominal carrier frequency ν_o.

ADVANTAGES: This system has excellent precision; one can measure essentially all state-of-the-art oscillators. The component cost is quite inexpensive.

DISADVANTAGES: The sample time must be equal to or greater than the beat period, and for good tunable quartz oscillators this will be of the order of a few seconds; i.e. typically, it is difficult to have a sample time shorter than a few seconds. The dead time can be a problem for this measurement system because it will be equal to or greater than the beat period unless, for example, one uses a second counter which starts when the first one stops. Observing the beat frequency only is insufficient information to tell whether one oscillator is high or low in frequency with respect to the other one--a significant disadvantage for making absolute frequency measurements. However, it is often not difficult to gain this additional information to determine the sign (+ or -) of the beat frequency. The frequencies of the two oscillators must be different.

D. Dual Mixer Time Difference System. The last system is one that has just recently been developed at NBS* that

*Dr. Costain informed me that Herman Daams has developed a similar system at NRC.

shows some significant promise. A block diagram is shown in Fig. 5. In preface it should be mentioned that if the time or the time fluctuations can be measured directly an advantage is obtained over just measuring the frequency. The reason being that you can calculate the frequency from the time without dead time as well as know the time behavior. The reason in the past that frequency has not been inferred from the time for sample times of the order of several seconds and shorter is that the time difference between a pair of oscillators operating as clocks could not be measured with sufficient precision (commercially the best that is available is 10^{-10} seconds). The system described in this section demonstrated a precision of 10^{-13} seconds with the potential of doing about 10^{-14} seconds. Such a precision opens the door to making time measurements as well as frequency and frequency stability measurements for sample times as short as a few milliseconds as well as for longer sample times and all without dead time. In Fig. 5, oscillator 1 could be considered under test and oscillator 2 could be considered the reference oscillator. These signals go to the ports of a pair of double balanced mixers. Another oscillator with separate symmetric buffered outputs is fed to the remaining other two ports of the pair of double balanced mixers. This common oscillator's frequency is offset by a desired amount from the other two oscillators. In which case two different beat frequencies come out of the two mixers as shown. These two beat frequencies will be out of phase by an amount proportional to the time difference between oscillator 1 and 2--excluding the differential phase shift that may be inserted; and will differ in frequency by an amount equal to the frequency difference between oscillators 1 and 2. Now this system is also very useful in the situation where you have oscillator 1 and oscillator 2 on the same frequency. The hetrodyne or beat frequency method, in contrast, cannot be used if both oscillators are on the same frequency. Quite often it is the case with Atomic standards (Cesium, Rubidium and Hydrogen frequency standards) that oscillator 1 and 2 will nominally be on the same frequency.

Illustrated at the bottom of Fig. 5 is what might be represented as the beat frequencies out of the two mixers. A phase shifter may be inserted as illustrated to adjust the phase so that the two beat rates are nominally in phase; this adjustment sets up the nice condition that the noise of the common oscillator tends to cancel when the time difference is determined in the next step--depending on the level and the type of noise as well as the sample time involved. After amplifying these beat signals, the start port of a time interval counter is triggered with the zero crossing of one beat and the stop port with the zero crossing of the other beat. If the phase fluctuations of the common oscillator are small during this interval as compared to the phase fluctuations between oscillators 1 and 2 over a full period of the beat frequency the noise of the common oscillator is insignificant in the measurement noise error budget, which means the noise of the common oscillator can in general be worse than that of either oscillator 1 or 2 and still not contribute significantly. By taking the time difference between the zero crossings of these beat frequencies, what effectively is being measured is the time difference between oscillator 1 and oscillator 2, but with a precision which has been amplified by the ratio of the carrier frequency to the beat frequency over that normally achievable with this same time interval counter. The time difference x(i), for the i^{th} measurement between oscillators 1 and 2 is given by equation 5:

$$x(i) = \frac{\Delta t(i)}{\tau\nu} - \frac{\phi}{2\pi\nu} + \frac{n}{\nu} \tag{5}$$

where $\Delta t(i)$ is the i^{th} time difference as read on the counter, τ is the beat period, ν is the nominal carrier frequency, ϕ is the phase delay in radians added to the signal of oscillator 1, and n is an integer to be determined in order to remove the cycle ambiguity. It is only important to know n if the absolute time difference is desired; for frequency and frequency stability measurements and for time fluctuation measurements, n may be assumed zero unless one goes through a cycle during a set of measurements. The fractional frequency can be derived in the normal way from the time fluctuations.

$$y_{1,2}(i,\tau) = \begin{cases} \dfrac{\nu_1(i,\tau) - \nu_2(i,\tau)}{\nu} \\[2ex] \dfrac{x(i+1) - x(i)}{\tau} \\[2ex] \dfrac{\Delta t(i+1) - \Delta t(i)}{\tau^2\,\nu} \end{cases} \tag{6}$$

In equations (5) and (6), the assumptions are made that the transfer or common oscillator is set at a lower frequency than oscillators 1 and 2, and that the beat $\nu_1 - \nu_2$ starts and $\nu_2 - \nu_o$ stops the time interval counter. The sample time by appropriate calculation can be any integer multiple of τ:

$$y_{1,2}(i,\ m\ \tau) = \frac{x(i + m) - x(i)}{m\tau}, \qquad (7)$$

where m is any positive integer. If needed, τ can be made to be very small by having very large beat frequencies. In the system set up at NBS the common or transfer oscillator was replaced with a low phase noise synthesizer, which derived its basic reference frequency from oscillator 2. In this set up the nominal beat frequencies are simply given by the amount the output frequency of the synthesizer is offset from ν_2. Sample times as short as a few milliseconds were easily obtained. Logging the data at such a rate can be a problem without special equipment, e.g. magnetic tape. In the NBS set up, a computing counter was used with a processing time of about 1.5 ms, and sample time stabilities were observed for 2 ms and longer (see appendix for some computing counter program possibilities).

ADVANTAGES: If the oscillators, including the transfer oscillator, and a time interval counter are available, the component cost is fairly inexpensive ($500, most of which is the cost of the phase shifter). The measurement system bandwidth is easily controlled (note, that this should be done in tandum with both low pass filters being symmetrical). The measurement precision is such that one can measure essentially all state-of-the-art oscillators. For example, if the oscillators are at 5 MHz, the beat frequencies are 0.5 Hz, and the time interval counter employed has a precision of 0.1 μs, then the potential measurement precision is 10^{-14}s (10 femto seconds) for τ = 2s; other things will limit the precision such as noise in the amplifiers. As has been stated above, there is no dead time which is quite convenient for very short sample times (of the order of milliseconds). Dead time problems are difficult to avoid in this region. One obtains as long a sample time as is desired. This is determined essentially by the beat period or multiple of the same. If one replaces the common oscillator by a synthesizer then the beat period may be selected very conveniently. The synthesizer should have fairly low phase noise to obtain the maximum precision from the system. The system measures time difference rather than frequency and hence has that advantage. One may calculate from the data both the magnitude and the sign of the frequency difference. This system, therefore, allows the measurement of time fluctuations as well as time difference, and the calculation of frequency fluctuations as well as absolute frequency differences between the two oscillators in question. The system may be calibrated and the system noise be measured by simply feeding a signal from one oscillator symmetrically split two ways to replace oscillators 1 and 2.

DISADVANTAGES: The system is somewhat more complex than the others. Because of the low frequency beats involved, precautions must be taken to avoid ground loop problems; there are some straight forward solutions; e.g. in the NBS system a saturated amplifier followed by a differentiator and isolation transformer worked very well in avoiding ground loops. Buffer amplifiers are needed because the mixers present a dynamic load to the oscillator--allowing the possibility of cross-talk. The time difference reading is modulo the beat period. For example, at 5 MHz there is a 200 nanosecond per cycle ambiguity that must be resolved if the absolute time difference is desired; this ambiguity is usually a minor problem to resolve for precision oscillators.

As an example of the system's use, Fig. 6 illustrates a plot of a strip chart recording of a digital to analog output of the significant digits from the time interval counter between a quartz oscillator and a high performance commercial cesium oscillator. In other words this is a plot of the time fluctuations between these two oscillators as a function of time. The high frequency fluctuations (over fractions of a second) would most probably be those between the quartz oscillator and the quartz oscillator in the cesium servo system. The low frequency fluctuations (over seconds) would most probably be those induced by the cesium servo in its effort to move the frequency of its quartz oscillator to the natural resonance of the cesium atom--causing a random walk of the time fluctuations for sample times longer than the servo attack time.

SOME METHODS OF DATA ANALYSIS

Given a set of data of the fractional frequency or time fluctuations between a pair of oscillators, it is useful to characterize these fluctuations with reasonable and tractable models of performance. In so doing for many kinds of oscillators it is useful to consider the fluctuations as those that are random (may only be predicted statistically) and those that are non-random (e.g. systematics--those that are environmentally induced or those that have a causal effect that can be determined and in many cases can be predicted).

A. Non-random Fluctuations

Non-random fluctuations are usually the main cause of departure from "true" time or "true" frequency.

If for example one has the values of the frequency over a period of time and a frequency offset from nominal is observed, one may calculate directly that the time fluctuations will depart as a ramp (see Fig. 7). If the frequency values show some linear drift then the time fluctuations will depart as a quadratic. I mention this because in almost all oscillators the systematics, as they are sometimes called, are the primary cause of time and/or frequency departure. A useful approach to determine the value of the frequency offset is to calculate the simple mean of the set, or for determining the value of the frequency drift by calculating a linear least squares fit to the frequency. A precaution is to not calculate a least squares quadratic fit to the phase or time departure--such is not as efficient an estimator of the frequency drift for most oscillators.

B. Random Fluctuations:

After calculating or estimating the systematic or non-random effects of a data set, these may be subtracted from the data leaving the residual random fluctuations. These can usually be best characterized statistically. It is often the case for precision oscillators that these random fluctuations may be well modeled with power law spectral densities, [4,5,6,7]:

$$S_y(f) = h_\alpha f^\alpha, \tag{8}$$

where $S_y(f)$ is the one-sided spectral density of the fractional frequency fluctuations, f is the Fourier frequency at which the density is taken, h_α is the intensity coefficient, and α is a number modeling the most appropriate power law for the data. It has been shown [3,4,5,8], that in the time domain one can nicely represent a power law spectral density process using a well defined time-domain stability measure, $\sigma_y(\tau)$, which I will explain later. For example, if you have a log $\sigma_y(\tau)$ versus log τ diagram and you observe a particular slope--call it μ --over certain regions of sample time, τ ; this slope has a correspondance to a power law spectral density or a set of the same with some amplitude coefficient h_α , i.e. $\mu = -\alpha-1$ for $-3< \alpha <1$ and $\mu \simeq -2$ for $1 \leq \alpha$. Further, a correspondance exists between h_α and the coefficient for $\sigma_y(\tau)$. These coefficients and relationships have been calculated and appear in the literature [2,3,4]. The transformation for some of the more common power law spectral densities has been tabulated, [2,3,4]--making it quite easy to transform the frequency stability as may have been modeled in the time-domain over to the frequency domain and vise-versa. Some examples of some processes modeled by power law spectra that have been simulated by computer are shown in Fig. 8. In descending order these have been named, white noise, flicker noise, random walk, and flicker walk (the ω in Fig. 8 is angular Fourier frequency, $\omega = 2\pi f$). In Fig. 9 are plotted the actual data of the Atomic Time Scale of the National Bureau of Standards versus International Atomic Time (TAI) over a four year period. A least squares fit to the frequency drift has been subtracted from these data. The plot then is just the time fluctuations of the AT(NBS) scale with respect to TAI. There is a peak-to-peak deviation of about 6 microseconds. Figure 10 shows a plot of the same thing for the United States Naval Observatory atomic time scale versus TAI over the same four year period, and again a least squares fit to the frequency drift has been subtracted from the data. The peak-to-peak fluctuations are again about 6 microseconds. Figure 11 is a plot of the residual time fluctuations between a high performance cesium standard and our primary frequency standard, NBS-5, over about one-half day. The peak-to-peak fluctuations in this case are less than a nanosecond. Just by visual comparison of Figures 9, 10 and 11 with the simulated noises shown in Figure 8 indicates that these random processes are not white noise--hence the need for better frequency stability characterization.

Suppose now that you are given the time or frequency fluctuations between a pair of precision oscillators measured, for example, by one of the techniques outlined above, and you wish to perform a stability analysis. Let this comparison be depicted by Fig. 12. The minimum sample time is determined by the measurement system. If the time difference or the time fluctuations are available then the frequency or the fractional frequency fluctuations may be calculated from one period of sampling to the next over the data length as indicated in Fig. 12. Suppose further there are M values of the fractional frequency, y_i. Now there are many ways to analyze these data. Historically, people have typically used the standard deviation equation shown in Fig. 12, $\sigma_{std.\ dev}(\tau)$, where $\bar{y}$ is the average fractional frequency over the data set and is subtracted from each value of y_i before squaring, summing and dividing by the number of values minus one, (M-1), and taking the square root to get the standard deviation. At NBS, we have studied what happens to the standard deviation when the data set may be characterized by power law spectra which are more dispersive than classical white noise frequency fluctuations. In other words, if you have flicker noise or any other non white noise frequency deviations, one may ask what happens to the standard deviation for that data set. In fact, one can show that the standard deviation is a function of the number of data points in the set, of the dead time, and of the measurement system bandwidth (5,9). For example, using as a model flicker noise frequency modulation, as the number of data points increase, the standard deviation monotonically increases without limit. Some statistical measures have been developed which do not depend upon the data length and which are readily usable for characterizing the random fluctuations in precision oscillators (2-5,9). An IEEE subcommittee on Frequency Stability has recommended a particular variance taken from the set of useful variances developed, and an experimental estimation of the square root of this particular variance is shown as the bottom right equation in Fig. 12. This equation is very easy to implement experimentally as you simply add up the squares of the differences between adjacent values of y_i, divide by the number of them and by two, take the square root and you then have the quantity which the IEEE subcommittee has recommended for specification of stability in the time domain.

One would like to know how $\sigma_y(\tau)$ varies with the sample time, τ. A simple trick that one can use, that is very useful if there is no dead time, is to average y_1 and y_2 and call that y_1 averaged over 2τ, then average y_3 and y_4 and call that y_2 as averaged over 2τ, etc., and finally apply the same equation as before to get $\sigma_y(2\tau)$. One can repeat this process for other desired integer multiples of τ and from the same data set be able to generate values for $\sigma_y(m\tau)$ as a function of $m\tau$ from which one may be able to infer a model for the process that is characteristic of this pair of oscillators. If you have dead time in the measurements you cannot average adjacent pairs in an unambiguous way to simply increase the sample time. You have to retake the data for each new sample time--often a very time consuming task. This is another instance where dead time can be a problem.

How the classical variance (standard deviation squared) depends on the number of samples is shown in Fig. 13. Plotted is the ratio of the standard deviation squared for N samples to the standard deviation squared for 2 samples ($\sigma^2(2, \tau)$ is the same as $\sigma_y^2(\tau)$). One can see the dependence of the standard deviation with the number of samples for various kinds of power law spectral densities commonly encountered as reasonable models for many important precision oscillators. Note, $\sigma^2_y(\tau)$ has the same value as the classical variance for the classical noise case (white noise FM). One main point of Fig. 13 is simply to show that with the increasing data length the standard deviation of the common classical variance is not well behaved for the kinds of noise processes that are very often encountered in most of the precision oscillators of interest.

Figure 14 is an actual $\sigma_y(\tau)$ versus τ plot for a rubidium standard that was analyzed at the Bureau. One observes apparent white noise FM with the slope of $\tau^{-1/2}$ and then flicker noise frequency modulation, τ^0; and some random walk FM for sample times of the order of a tenth of a day and longer. Having this time-domain analysis, one can use the equations and the tables mentioned before to transform to the frequency domain, $S_y(f)$ versus Fourier frequency f, and this transformation is plotted in Fig. 15. An equation which shows directly the mapping for a model that is often used for cesium decives for sample times longer than 1 second is given by the following pair of equations:

$$S_y(f) = h_o + h_{-1}f^{-1} \tag{9}$$

$$\sigma_y^2(\tau) = \frac{h_o}{2} + 2 \ln 2\, h_{-1} \tag{10}$$

The h_o term in each case is due to the white noise FM fundamentally induced by the shot noise in the cesium beam. The second term is flicker noise FM (flicker floor) that seems to always appear as a reasonable model for cesium as well as other standards. It does not have a well understood cause. As an example of equation (9) and (10), suppose from a $\sigma_y(\tau)$ versus τ plot we determined that

$\sqrt{h_{o/2}} = 2 \times 10^{-12}[s]^{1/2}$ and $\sqrt{2 \ln 2h_{-1}} = 1 \times 10^{-14}$ as

for one comparison made between the NBS primary frequency standards, NBS-4 and NBS-5, then $h_o = 4 \times 10^{-24}$ and $h_{-1} = 7.2 \times 10^{-29}$.

If the frequency drift is not subtracted from the data then the $\sigma_y(\tau)$ versus τ plot as shown in Fig. 15, takes on a τ^{+1} behavior. Often such is the case with quartz crystal oscillators. The equation relating $\sigma_y(\tau)$ and the drift, D, is as follows:

$$\sigma_y(\tau) = \frac{D\tau}{\sqrt{2}} \tag{11}$$

where D has the dimensions of fractional frequency per unit of τ , i.e. if τ is in days then D could be, for example, 10^{-10} per day. Suppose also that the data contain discrete side bands such as 60 Hz then the $\sigma_y(\tau)$ versus τ diagram may appear as shown in Fig. 17. The model for this figure, calculated by Sam Stein, was for the situation where the white phase noise power in a 1 KHz bandwidth was equal to the power in the 60 Hz side bands.

In Fig. 18 I have used the dual mixer time difference measuring system in order to observe the $\sigma_y(\tau)$ versus τ behavior for a high performance cesium standard versus a quartz crystal oscillator. The plot contains a lot of information. The measurement noise of the dual mixer system is indicated. One can see the short term stability performance of the quartz oscillator in the cesium versus the comparison quartz oscillator (Diana). One can see a little bit of 60 Hz present as indicated by the humps at 1/2 and 3/2 of τ = 1/60 Hz. One observes the attack time of the servo in the cesium electronics perturbing the short term stability of the quartz oscillator and degrading it to the level of the shot noise of the cesium resonance. The white noise frequency modulation characteristic then becomes the predominant power law causing $\sigma_y(\tau)$ to improve as $\tau^{-1/2}$ until the flicker floor of the quartz crystal oscillator (Diane), in this case 6 parts in 10^{13}, becomes the predominant noise source. Thus using this particular measurement system I was able to well characterize for sample times of a few milliseconds all the way out to 1000 seconds, the stability characteristics of this particular pair of oscillators. Longer sample times are of course easily achievable.

CONCLUSIONS

Some inexpensive (less than $1000) methods of precisely measuring the time difference, time fluctuations, frequency difference, and frequency fluctuations between a pair of state-of-the-art time and/or frequency standards have been reviewed or introduced. One novel method introduced demonstrated the capability of measuring all four of the above, plus being able to cover an impressive segment of sample times ($\tau \geq$ few milliseconds) with a time difference precision of better than 1 picosecond. Fraction frequency instabilities due to the noise in this novel measurement method were demonstrated to be less than one part in 10^{16} for $\sigma_y(\tau \geq 2 \times 10^4\ \mathrm{s})$.

Also reviewed were some efficient methods of data analysis--which allow one to gain insight into models that would characterize both the random and non-random deviation between a pair of frequency standards. A specific example was shown demonstrating the time domain fractional frequency stability, $\sigma_y(\tau)$, between two state-of-the-art commercial standards, i.e. a quartz oscillator and a high performance cesium standard for $2\ \mathrm{ms} \leq \tau \leq 10^3$ s.

ACKNOWLEDGEMENTS

Many stimulating discussions preceeded the writing and experimental results, as well as influenced the content of the material in the text. To all those so involved I express gratitude. In particular I wish to thank Dr. Fred L. Walls for his contributions. In addition I wish to thank Jorge Valega and Howard Machlan for instrumentation assistance and data processing, respectively.

APPENDIX:
COMPUTING COUNTER PROGRAM

A. The following program may be used in a computing counter, is useful in determining the fractional frequency stability, $\sigma_y(\tau)$, and is unique as compared with other similar types of programs to determine stability in that it does so with no dead time. The following program actually determines the root-mean-square second difference, $(\Delta^2(\Delta t))_{rms}$, of the time difference readings between a pair of clocks or oscillators, and therefore complements very nicely the dual mixer time difference measurement system described in the text. The fractional frequency stability may be calculated from computer program results as follows:

$$\sigma_y(\tau) = \frac{1}{\sqrt{2\tau^2\nu}} (\Delta^2(\Delta t))_{rms} \tag{A1}$$

If additional programing steps were available, of course one could program the computing counter to calculate an estimate of $\sigma_y(\tau)$ directly. Following is the program procedure to generate $(\Delta^2(\Delta t))_{rms}$:

1. clear x
2. $c \rightleftarrows x$
3. Plug-in
4. $a \rightleftarrows x$
5. Plug-in
6. $a \rightleftarrows x$
7. $\overrightarrow{a\ x\ y}$
8. -(subtract)
9. $b \rightleftarrows x$
10. Xfer Program
11. Plug-in
12. $a \rightleftarrows x$
13. $\overrightarrow{a\ x\ y}$
14. -(subtract)
15. $b \rightleftarrows x$
16. $\overrightarrow{b\ x\ y}$
17. - (subtract)
18. $\overrightarrow{xy}$
19. x (multiply)
20. $\overrightarrow{c\ x\ y}$
21. + (add)
22. $c \rightleftarrows x$
23. Repeat
24. Xfer Program
25. $c \rightleftarrows x$
26. $\overrightarrow{N\ x\ y}$
27. $\div$ (divide)
28. $\sqrt{x}$
29. Display x
30. Pause

The confidence of the estimate will improve approximately as the square root of the number of times (N) the sub loop is repeated as preset by the programmer [10].

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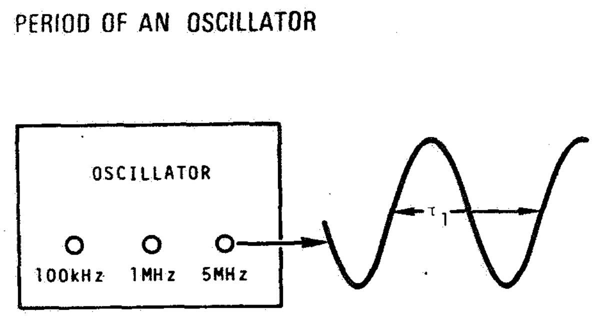


FIG. 1 Depiction of the sinusoidal voltage output from a precision oscillator, e.g. using quartz, rubidium, cesium or hydrogen as the frequency determining element. If the frequency out is ν_1, the the period of oscillation is $\tau_1 = 1/\nu_1$

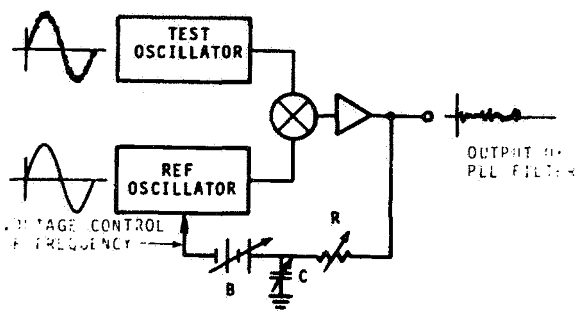


FIG. 2 A phase (or time) fluctuation measurement system. The reference oscillator is loosely phase-locked to the test oscillator--attack time is about 1 second. The reference and test oscillators are fed into the two ports of a Schottky barrier diode double balanced mixer whose output is fed through a low pass filter and low noise amplifier, hence to an RC network, a battery bias box and to the varicap of the reference oscillator. The instantaneous output voltage of the phase locked loop (PLL) following the low noise amplifier will be proportional to the phase or time fluctuations between the two oscillators.

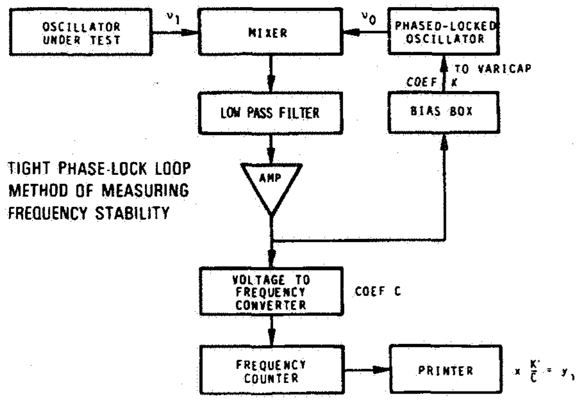


FIG. 3 A frequency fluctuation measurement system. The attack time of the phase lock loop in this case is much less than a second. The amplifier (AMP) output voltage fluctuations for sample times significantly larger than the servo loop attack time will be proportional to the frequency fluctuations between the oscillators.

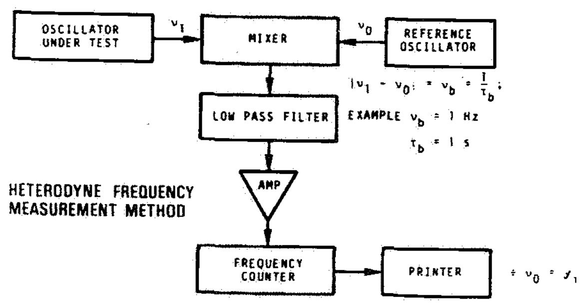


FIG. 4 A frequency and frequency fluctuation measurement system. The difference frequency, $|\nu_1 - \nu_0|$ is measured with a frequency counter. A counter measuring the period (or multiple period) of the beat (difference) frequency could equivalently be used.

DUAL MIXER TIME DIFFERENCE SYSTEM

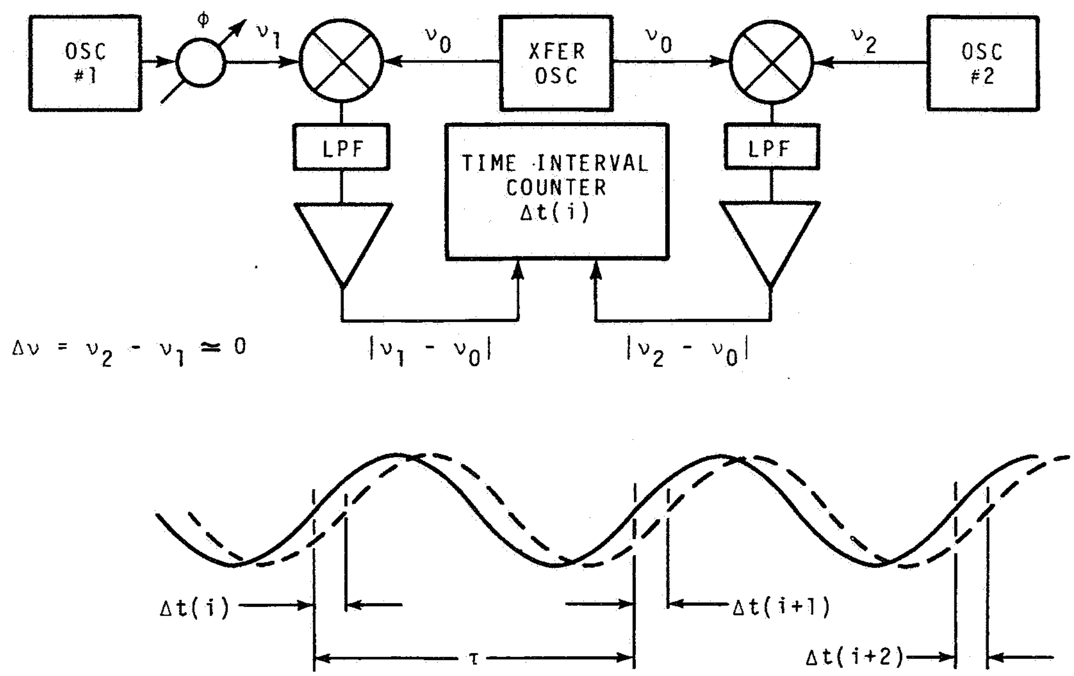


FIG. 5 A time difference and time fluctuation measurement system. The low pass filters (LPF) determine the measurement system bandwidth and must pass the difference frequencies which are depicted by the solid-line and dashed-line sinusoids at the bottom of the figure. The positive going zero volts crossing of these difference (beat) frequencies are used to start and stop a time interval counter after suitable low noise amplification. The i^{th} time difference between oscillator 1 and 2 is the $\Delta t(i)$ reading of the counter divided by $\tau\nu$ and plus any phase shift added, ϕ, where $\nu \simeq \nu_1 \simeq \nu_2$ is the nominal carrier frequency. The frequency difference is straight forwardly calculated from the time difference values.

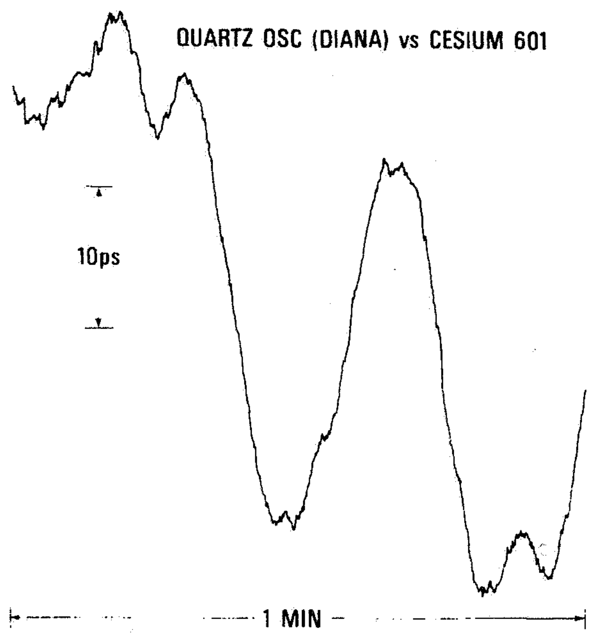


FIG. 6 A copy of a strip chart recording of the time fluctuations versus running time using the dual mixer time difference measurement system. The oscillators involved were a high performance commercial cesium standard and a high quality quartz crystal oscillator. The common oscillator employed was a low noise synthesizer. The measurement system noise was about 0.1 ps.

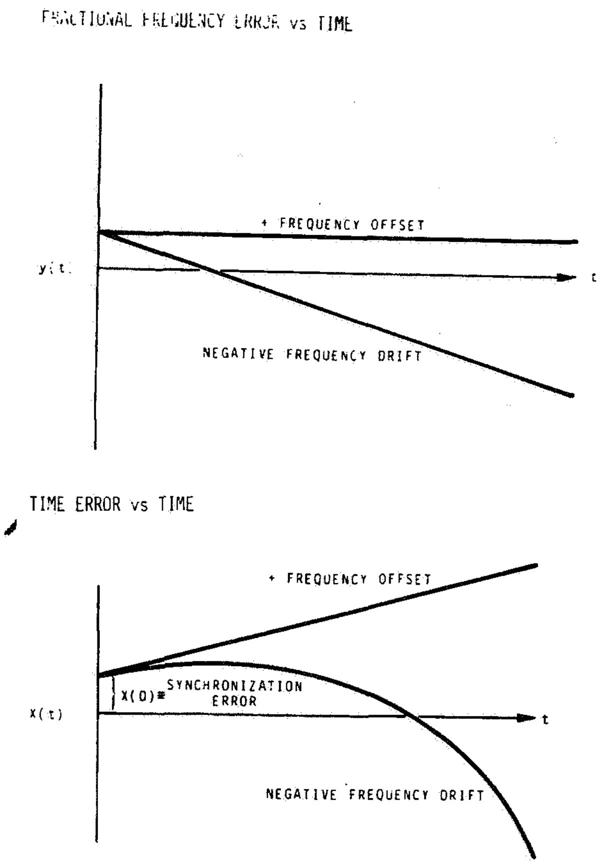


FIG. 7 Depiction of some commonly encountered non-random frequency and time deviations; i.e. a frequency offset error which maps into a linear time drift, and a linear frequency drift which maps into a quadratic time deviation.

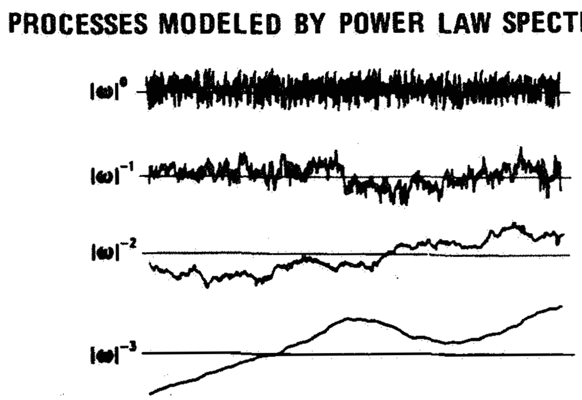


FIG. 8 Some sample plots of processes which may be modeled by power law spectral densities, $S(f) = h_\alpha f^\alpha$ ($\omega = 2\pi f$), as simulated with a computer. The white noise, $|\omega|^0$, is bandwidth limited. The subscript is left off of $S(f)$ as these plots may represent anything, e.g. frequency or time fluctuations.

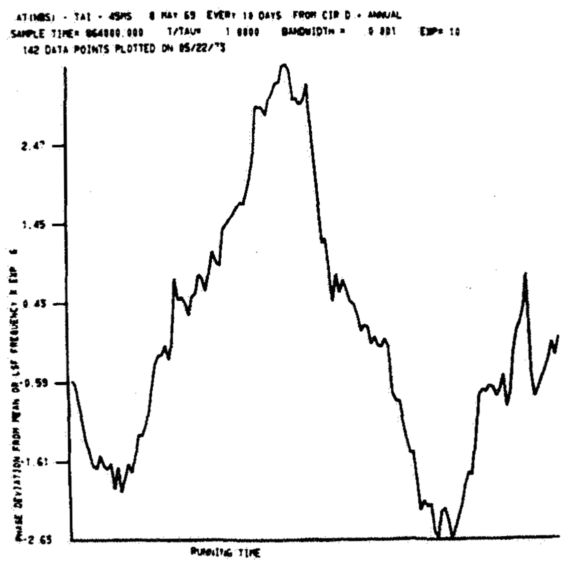


FIG. 9 The residual time fluctuations between the National Bureau of Standards Atomic Time Scale, AT(NBS), and the International Atomic Time Scale, TAI, after subtracting a least squares fit to the frequency. The vertical scale is in microseconds and the abscissa shows 1420 days following 8 May 1969. The peak-to-peak deviation is about 6μs.

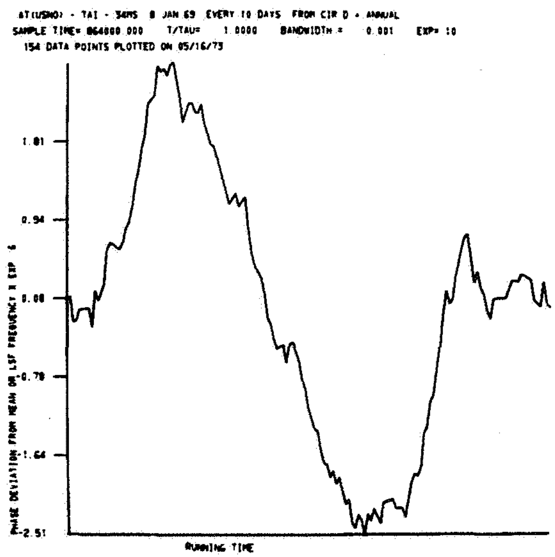


FIG 10 The residual time fluctuations between the United States Naval Observatory's Atomic Time Scale, AT (USNO), and the International Atomic Time Scale, TAI, after subtracting a least squares fit to the frequency. The vertical scale is in microseconds and the abscissa shows 1540 days following 8 Jan. 1969. The peak-to-peak deviation is less than 6μs.

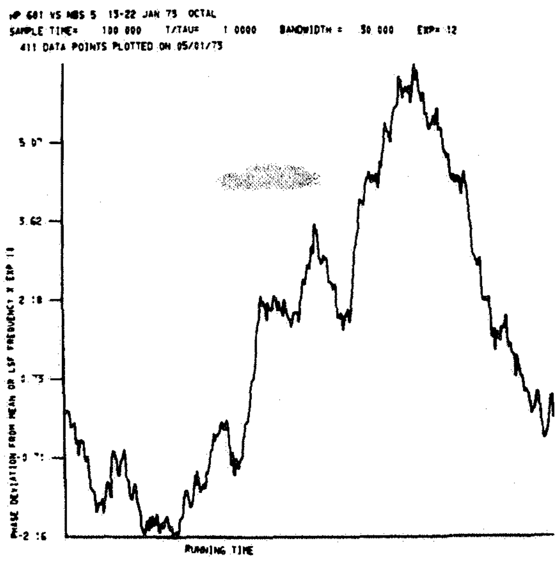
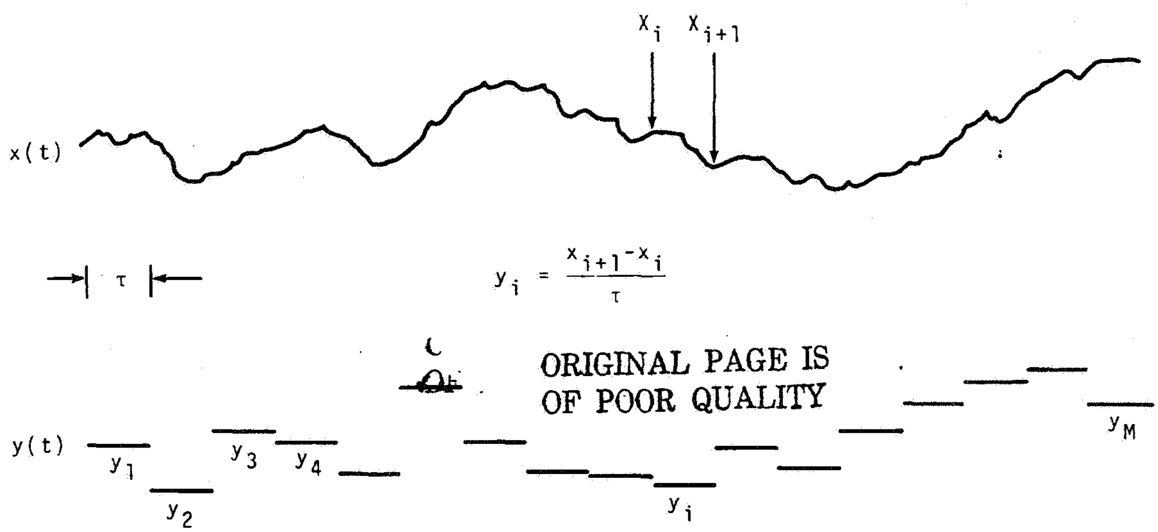


FIG 11 The residual time fluctuations between a high performance commercial cesium standard and one of the NBS primary frequency standards, NBS-5, after subtracting a mean frequency difference. The vertical scale is in units of 0.1 μs, and the abscissa shows 41100 s duration(~1/2 day). The peak-to-peak deviation is about 0.9 μs.



$$\sigma_{\text{STD DEV } y}(\tau) = \sqrt{\frac{1}{M-1} \sum_{i=1}^{M} (y_i - \bar{y})^2} \qquad \sigma_y(\tau) = \sqrt{\frac{1}{2(M-1)} \sum_{i=1}^{M-1} (y_{i+1} - y_i)^2}$$

FIG 12 A simulated plot of the time fluctuations, x(t) between a pair of oscillators and of the corresponding fractional frequencies calculated from the time fluctuations each averaged over a sample time τ . At the bottom are the equations for the standard deviation (left) and for the time-domain measure of frequency stability as recommended by the IEEE subcommittee on Frequency Stability (right).

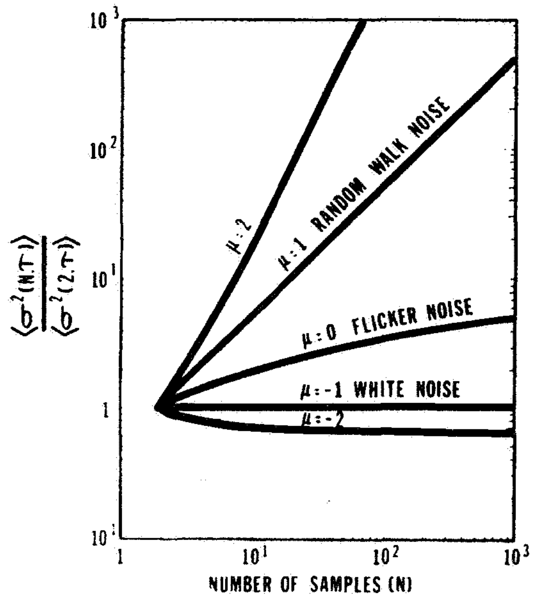


FIG 13 The ratio of the time average of the standard deviation squared for N samples over the time average of a two sample standard deviation squared as a function of the number of samples, N. The ratio is plotted for various power law spectral densities that commonly occur in precision oscillators. The figure illustrates one reason why the standard deviation is not a convenient measure of frequency stability; i.e. it may be very important to specify how many data points are in a data set if you use the standard deviation.

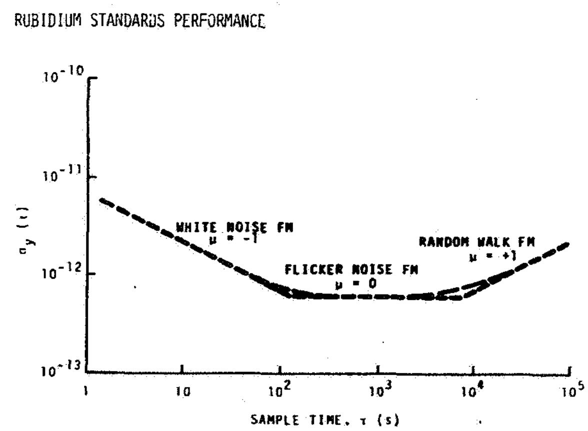


FIG 14 A $\sigma_y(\tau)$ versus τ plot modeling some actual data taken at NBS on some commercial rubidium standards. Notice that if $\sigma_y^2(\tau) \sim \tau^{\mu}$, then $\sigma_y(\tau) \sim \tau^{\mu/2}$ hence the $\tau^{-1/2}$ slope for $\mu = -1$. etc.

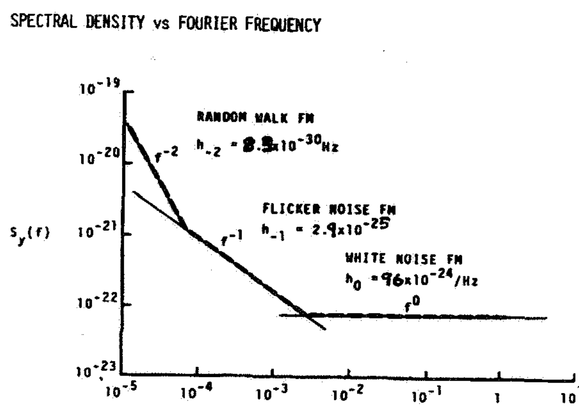


FIG 15 A plot of $S_y(f)$ versus f as transformed from the time-domain data plotted in Fig. 14.

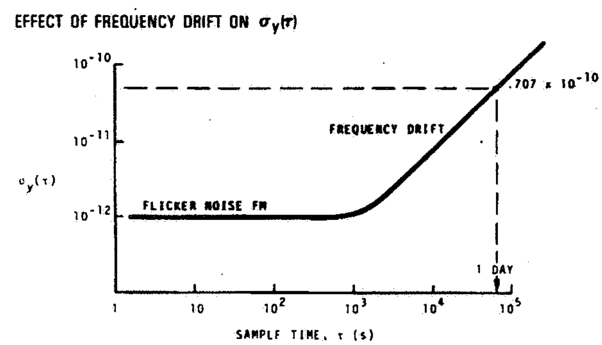


FIG 16 An example $\sigma_y(\tau)$ versus τ plot of an oscillator with both random fluctuations of flicker noise FM and a non-random linear fractional frequency drift of 10^{-10} per day. A plot appearing similar to this would be common for quartz crystal oscillators, for example.

$S_\phi(f) = 2.5 \times 10^{-15} [1+10^3 \delta(f-60 \text{ Hz})]$

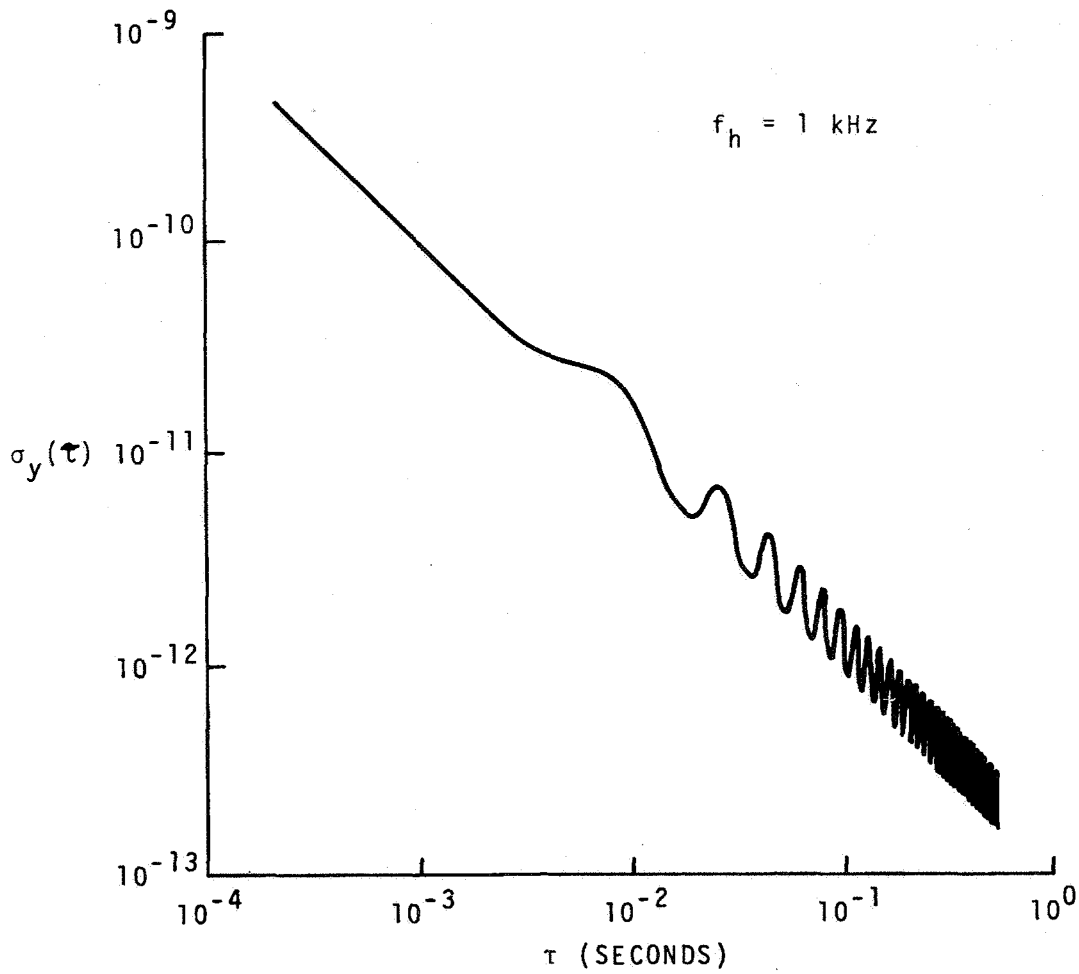


FIG 17 A calculated $\sigma_y(\tau)$ versus τ plot of white phase noise ($\alpha = +2$) with some 60 Hz FM superimposed. The power in the 60 Hz sidebands has been set equal to the power of the white phase noise in a 1 kHz bandwidth, f_h. Note: $S_\phi(f) = (\nu^2/f^2) S_y(f)$ and $\phi(t) = (2\pi)^2 \nu^2 \cdot x(t)$.

QUARTZ OSCILLATOR (DIANA) VS COMMERCIAL CESIUM (#601)

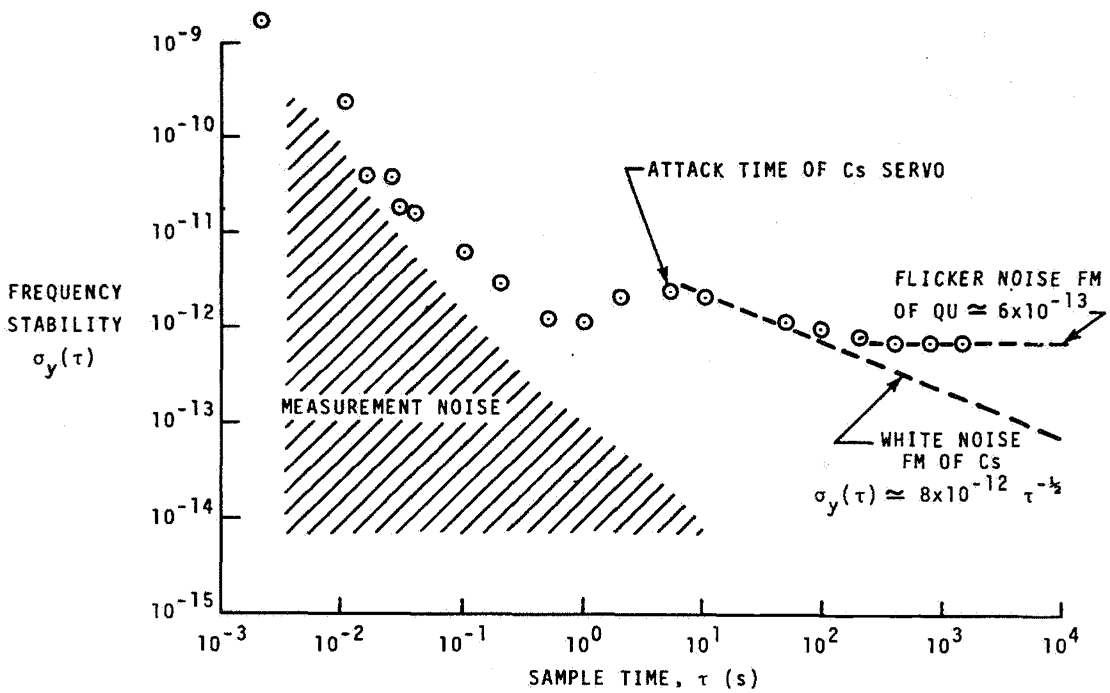


FIG.18 A $\sigma_y(\tau)$ versus τ plot of the fractional frequency fluctuations, y(t) between a high performance commercial cesium beam frequency standard and a commercial quartz crystal oscillator.

QUESTION AND ANSWER PERIOD

DR. COSTAIN:

National Research Council.

Herman Damms had been doing a very similar dual mixer system and it does give a fantastic advantage when you have the two oscillators on the same frequency. As a matter of fact you can only test the system by putting the same signals into the two channels.

MR. ALLAN:

That's a good point. It's very conducive to testing the measurement noise, whereas with other systems it's sometimes quite difficult. This one is very amenable to looking at the measurement noise.

N75 27183

MEASUREMENTS OF THE SHORT-TERM STABILITY OF QUARTZ CRYSTAL RESONATORS - A WINDOW ON FUTURE DEVELOPMENTS IN CRYSTAL OSCILLATORS

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TIME AND FREQUENCY DIVISION
NATIONAL BUREAU OF STANDARDS

ABSTRACT

Recent measurements of the inherent short-term stability of quartz crystal resonators will be presented. These measurements show that quartz resonators are much more stable for times less than 1s than the best available commercial quartz oscillators. A simple model appears to explain the noise mechanism in crystal controlled oscillators and points the way to design changes which should permit more than 2 orders of magnitude improvement in their short-term stability. Stabilities of order 1 part in 10^{12} at .001 s appear obtainable. The achievement of short-term stabilities of this level would in many cases greatly reduce the time necessary to achieve a given level of accuracy in frequency measurements. Calculations show that a reference signal at 1 THz, derived from frequency multiplying a 5 MHz source with the above measured crystal stability, should have an instantaneous or fast linewidth of order 1 Hz. These calculations explicitly include the noise contributuion of our present multiplier chains and will be briefly outlined.

INTRODUCTION

Quartz crystal controlled oscillators play a key roll in frequency metrology in that they are used in nearly all precision frequency measurement and generation devices. Indeed, the short-term frequency stability of virtually every precision frequency source is determined by a quartz crystal controlled oscillator. The short-term frequency stability sets a fundamental limit on the minimum amount of time necessary to reach a specified level of accuracy in frequency measurements, limits the spectral purity, and limits the highest frequency to which an oscillator can be multiplied and still be used as a precision source.

In the following we will show experimental results which indicate that the inherent short-term stability of some quartz crystal resonators is at least 100 times better than the best commercially available crystal controlled oscillators. Next we will briefly outline the reasons for the decrease in stability of the crystal controlled oscillators relative to the quartz crystals and indicate how the short-term stability is related to spectral purity and how these limit the maximum frequency to which the frequency of an oscillator may be multiplied and still be used as a precision source.

EXPERIMENTAL RESULTS

Figure 1 shows a schematic diagram of the phase bridge used to measure the inherent short-term stability of the quartz crystal resonators. Two crystal resonators which are as identical as possible are driven by the same low noise source. By careful adjustment of crystal tuning and the balancing of the relative Q's, the output from the double balanced mixer, which is used as a phase detector, is independent of both residual amplitude and frequency modulation in the source. This reduction of noise from the source is crucial to being able to measure small time varying frequency deviations of the crystals [1]. At balance the mixer output is directly proportional to the difference in the resonance frequency of the two crystal resonators. This voltage can now be processed to yield both the spectral density of fractional frequency fluctuations, $S_y(f)$, or the time domain stability, $\sigma_y(\tau)$, per the recommendation of the IEEE subcommittee on frequency stability [2].

Figure 2 shows a typical example of frequency domain data. $S_y(f)$ for a pair of 5 MHz crystal resonators is plotted versus Fourier frequency offset, f, assuming equal contribution from each crystal. Note the change from flicker of frequency to random walk frequency modulation at a Fourier frequency equal to one half of the crystal bandwidth. Crystal drive was approximately 200 microwatts. Figure 3 shows a similar plot for a pair of very high quality 5 MHz crystals. The change from flicker of frequency to random walk of frequency modulation should occur at a Fourier frequency of 1 Hz, which was the lower limit of our spectrum analyzer.

Figure 4 shows the time domain data for the same pair of 5 MHz quartz crystal resonators. The solid dots are the actual time domain measurements. The lower heavy solid lines show the frequency domain data translated to time domain [2], where h_{-1} and h_{-2} are the intensity coefficients for the assumed power law spectral densities f^{-1} and f^{-2} respectively. These data show that the inherent time domain stability of the quartz crystals improves as the sample time, τ, becomes short compared to the inverse half angular bandwidth γ, of the crystal. The functional dependence is $\sigma_y(\tau) = \kappa\tau^{\frac{1}{2}}$. As one goes to shorter and shorter times the stability becomes worse again due to noise in the isolation amplifier and the measurement system. This noise causes an uncertainty in the measurement of the position of the zero crossing. If the noise is white then the frequency fluctuations will have a white phase modulation character and $\sigma_y(\tau)$ will go as τ^{-1} for times larger than the inverse bandwidth of the measurement system, which in this case was $\sim 4 \times 10^{-6}$ seconds.

The line labelled "Johnson noise from amplifier" indicates the estimated contribution of our measurement system to $\sigma_y(\tau)$. Calculations of the Johnson noise in the series loss resistance of the crystal, R_S, show that this contribution to $\sigma_y(\tau)$ is very small compared to that of most active circuits [1].

For comparison, the stability of these same two crystals in a high performance crystal oscillator at 65° C is also indicated in Figure 4. Note the dramatic difference in stability for times less than 1s. This difference is just the noise contribution due to the electronics in the crystal controlled oscillators. The difference for measurement times greater than 1s is primarily due to the decrease in the stability of this crystal pair at 65° C.

The character of the oscillator stability for times less than 1s is very similar to that of the crystal measurements below 10ms, only the level is different. Our measurements show that the noise in the buffer amplifier fully explains the short-term stability of the oscillator.

The above confirms the widely held belief (see e.g.[3,4]), that Johnson noise sources in the amplifier and oscillator stages that are not filtered by the crystal are the cause of the observed noise in this and most low drive crystal oscillators. Short-term stability could be greatly improved merely by increasing crystal drive. A factor of 100 increase in crystal drive should produce a factor of 10 improvement in the short-term stability of the oscillator. Recent measurements [5] by J. Groslambert, G. Marianneau, M. Oliver and J. Uebersfeld on a crystal controlled oscillator with 50μW of crystal drive, yield a factor of 10 improvement in the short-term stability as compared to the oscillator of of Figure 4 which has approximately 1μW of drive. In both oscillators multiplicative phase modulation was reduced by local negative feedback as originally suggested by D. Halford [6]. Additional improvements in short-term stability can be obtained by using a high input impedance buffer amplifier and driving it with a series resonant circuit from a point in the oscillator where the noise is bandwidth limited by the crystal. This can increase the signal level to the buffer amplifier by a factor of 10 without changing the level of Johnson noise in the buffer amplifier. This should improve the short-term stability by a factor of 10. Moreover, most buffer amplifiers are designed for isolation and not low noise. With a little more care in the design of the buffer amplifier, the noise level could be reduced by approximately a factor of 4. The net result should be a crystal controlled oscillator with a short-term stability at least 100 times better than present state-of-the-art commercial 5 MHz crystal controlled oscillators. Stabilities approaching one part in 10^{12} at .001 seconds appear feasible. Even at this level the short-term stability will be limited by the electronics and not the crystal resonators, if the best available crystals are used.

The medium term stability of a crystal controlled oscillator is determined by the flicker of frequency level in the crystal. Measurements on a number of crystal pairs show that the flicker of frequency level or stability floor is approximately given by $\sigma_y(\tau) = \frac{10^{-6}}{2Q}$. This has been verified for crystals ranging in frequency from 5MHz to 125MHz and crystal Q's from 10^4 to 2×10^6. Individual crystals with identical Q's sometimes vary as much as a factor of 10 in their stability floor, indicating that fabrication techniques have a considerable influence on stability beyond just considerations of obtainable crystal Q's. The departure of solid line derived from h_{-1} from the experimental time domain data is probably due to the limited amount of frequency domain data that could be taken to cover this region.

Figure 5 illustrates the effect of white phase modulation or additive Johnson noise on the spectral purity of the signal and how this limits the maximum frequency to which an oscillator can be multiplied and still be used as a precision signal source.

Curve a shows the rf spectrum of a precision 5MHz crystal controlled oscillator after multiplication to 9 GHz (x-band). The broad base is called the noise pedestal while the central peak is called the carrier. The noise pedestal determines the short-term fractional frequency stability of the oscillator. In this case $\sigma_y(\tau) = (2 \times 10^{-13})/\tau$: The carrier width is determined by the flicker of frequency level of the oscillator. The width is approximately

$$\Delta\nu = 2\nu \left(\sigma_y(\tau)_{flicker}\right) = .006\text{Hz}$$

at 9.2GHz for the present oscillator. The narrow peaks of a and b have a width of 10 KHz which is the bandwidth of the spectrum analyzer. Curve b shows the rf spectrum at 9.2GHz when the additive noise level has been increased by a factor of 50 over its initial value. This corresponds to a short term stability of $\sigma_y(\tau) = 10^{-11}/\tau$. Note that the relative power in the carrier has dropped 8dB and that the height of the noise pedestal has risen 34dB. The power in the carrier is now -8dB or 16% of the total available power. Curve C shows the rf spectrum at 9.2 GHz when the additive noise has been increased by a factor of 150 over its initial value. This corresponds to a short term stability of $\sigma_y(\tau) = 3 \times 10^{-11}$. The carrier has now totally disappeared!

Although there still is power available, the line width has increased a factor of 10^8 from .006 Hz to 600 KHz. Clearly Curve c can no longer be used as a precision reference signal. These results are of significance for the design of both precision frequency oscillators and of the total system in which they are used. For, as Figure 5 illustrates, the addition of even relatively small amounts of noise can seriously degrade the short-term stability, the spectral purity, and the useful operating range of a precision frequency source.

These results can be generalized and summarized by the following. The relative power in the carrier, P_c, and the relative power in the pedestal, P_p, are given by[7]:

$$P_c(\nu) = e^{-\Phi_p(\nu)}, \text{ and}$$

$$P_p = 1 - P_c = 1 - e^{-\Phi_p(\nu)}$$

where $$\Phi_p(\nu) = \int_{\text{pedestal}} S_y(f) \left(\frac{\nu^2}{f^2}\right) df$$

Recall that $S_y(f)$ is the spectral density of fractional frequency fluctuations, ν is the carrier frequency, and f is the fourier frequency offset from the carrier. The short-term fractional frequency fluctuations for white phase noise or additive Johnson noise is given by:

$$\sigma_y(\tau) = \left(\frac{1}{\tau}\right)\left(\frac{1}{2\pi}\right)\sqrt{\left(3\, S_y(f) B_o\right)/f^2}$$

where B_o is the bandwidth of the noise.

CONCLUSIONS

It has been shown: (1) that the inherent short-term stability of the resonators is vastly superior to the best available commercial crystal controlled oscillators, (2) that the short-term stability of a crystal controlled oscillator is dominated by noise processes in the buffer amplifier, (3) that the adoption of several design changes should produce crystal controlled oscillators with short-term fractional frequency stabilities approaching $\sigma_y(\tau) = \dfrac{10^{-15}}{\tau}$ and (4) that the short-term stability or, alternately, the spectral purity limits the maximum frequency to which an oscillator can be used as a precision source.

ACKNOWLEDGEMENT

The authors are grateful to H. Hellwig, S. Jarvis Jr., D. W. Allan, and A. DeMarchi for many helpful discussions.

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[7] The contribution of the multiplier chains to the noise pedestal is absorbed in $S_y(f)$. Our present 5 MHz to 9.26 GHz multiplier chains increase $S_y(f)$ by less than .1 dB over the value of $S_y(f)$ for the 5 MHz crystal controlled oscillator by itself.

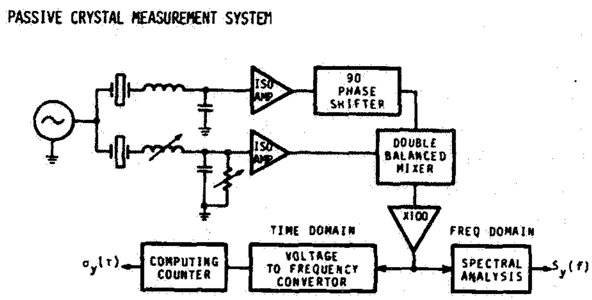

FIGURE 1 Passive system used to measure the inherent frequency stability of pairs of similar quartz crystal resonators.

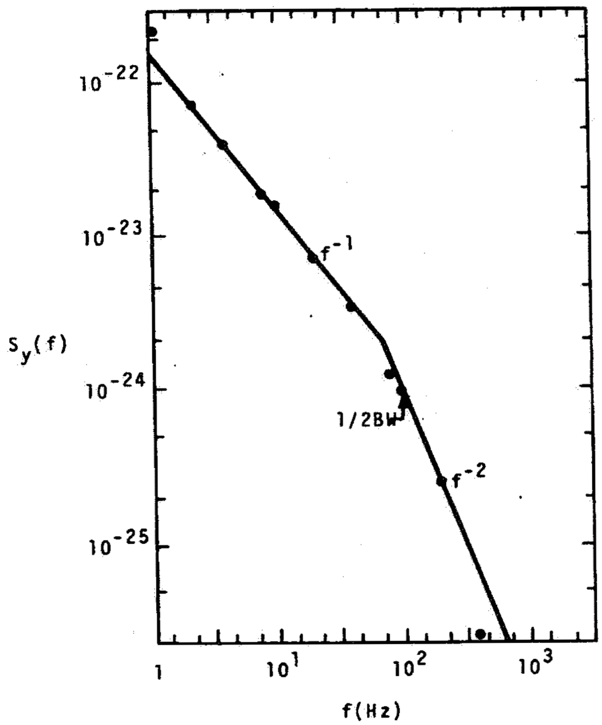

FIGURE 2 Frequency domain measurements on crystal pair 5A-200 at 28° C. These are 5 MHz crystals with a bandwidth of 200 Hz. $S_y(f)$ is shown for a single crystal.

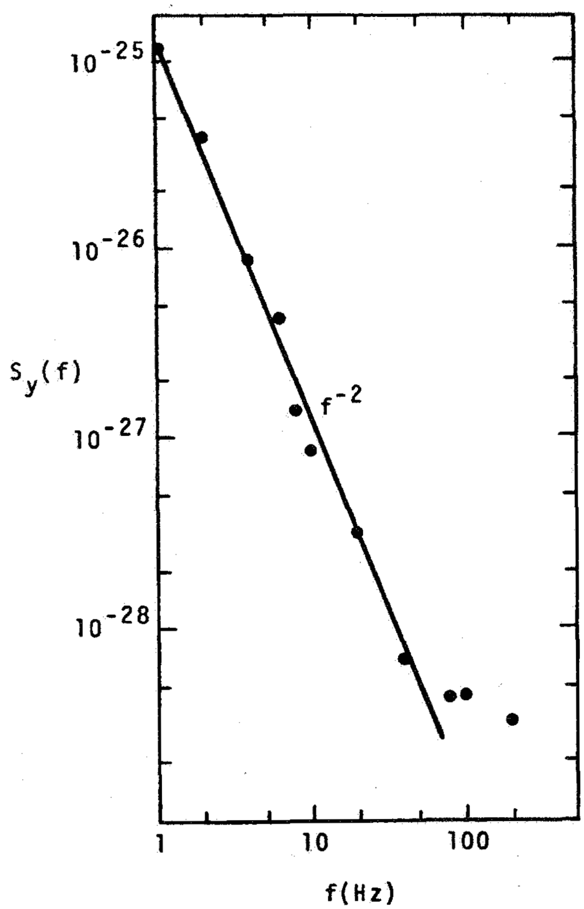

FIGURE 3 Frequency domain measurements on crystal pair 5B-2 at 28° C. These are 5 MHz crystals with a bandwidth of 2 Hz. $S_y(f)$ is shown for a single crystal.

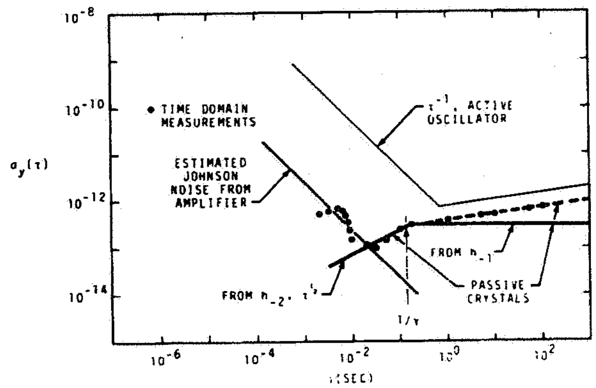

FIGURE 4 Time domain measurements as a function of sample time τ, for crystal pair 5B-2 at 28° C. Also shown are the frequency domain results of Figure 3 converted to time domain, and the stability of a high quality oscillator controlled by one 5B-2 crystal at + 65° C. $\gamma = \pi BW$; here the bandwidth is BW = 2 Hz

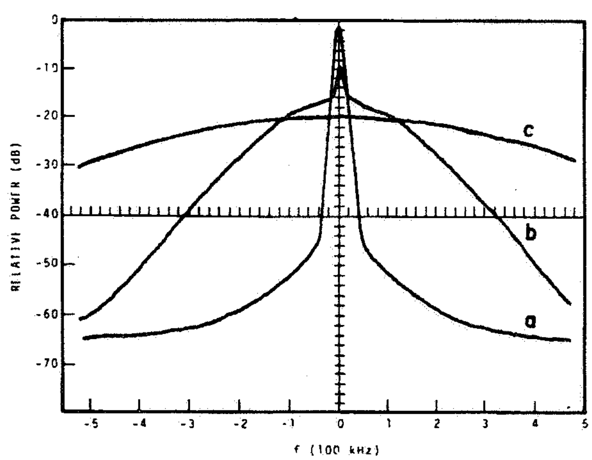

FIGURE 5 rf spectrum of 5 MHz crystal controlled oscillators after multiplication to 9.2 GHz for 3 different short-term stabilities. Curves a, b and c are for oscillators having a short-term fractional frequency stability of $\sigma_y(\tau) = \frac{2 \times 10^{-13}}{\tau}$, $\frac{10^{-11}}{\tau}$ and $\frac{3 \times 10^{-11}}{\tau}$ respectively.

QUESTION AND ANSWER PERIOD

DR. WINKLER:

Winkler, Naval Observatory.

You have mentioned the role of buffer amplifiers as contributors to noise. I think probably for practical applications the most important example of that is the buffer amplifiers in the cesium standards which we have.

The 5 megahertz crystal oscillators which provides the output at 5 megacycles has to be buffered very extensively in order to prevent reflective power and side bands getting back into the oscillator and into the multiplier which would shift the frequency of the cesium resonance.

But on the other hand, that severe buffering deteriorates somewhat the performance of that crystal for very short integration times. One second or shorter.

Now there are two possibilities. If people have a requirement, and I know of some such requirements, to use the output of that 5 megahertz source not only for time keeping but at the same time also for generation of microwave signals, where spectral purity is required there are two ways to go about that. One would be to take out part of the buffering in the output circuits, to increase it directly which is dangerous.

The other one would be to phase lock a second crystal oscillator which could be designed according to your recipe and so to provide that spectral purity from a secondary oscillator.

Now, would you like to comment on these two possibilities, particularly what is your estimate on the required quality of that second oscillator? If you really do not need any stability, any inherent stability, beyond one second integration time, which would be provided by the phase-lock loop on the cesium, what would be the requirement for such a second crystal?

DR. WALLS:

I'm not sure I understand exactly where you want the requirements—on the crystal or on the crystal oscillator?

DR. WINKLER:

On the crystal and the crystal oscillator. It is clear that you need still a high Q crystal for that.

DR. WALLS:

Yes. You would want to have as high a Q crystal as you could which is about 2-1/2 million at 5 megahertz and you would want to drive it rather hard, you're not interested in stability at 10 seconds or 100 seconds, for example. And you would want very few stages of buffering, not 10 or 15 stages.

DR. WINKLER:

But am I correct in assuming that actually that design could be extremely simple? You wouldn't even need temperature control, maybe.

DR. WALLS:

That's true.

DR. WINKLER:

So it's not an expensive substance.

DR. WALLS:

It shouldn't be.

DR. WINKLER:

It would not cost $15,000 per unit?

DR. WALLS:

No. I agree. It could be a much simplified design.

DR. HELLWIG:

I'd also like to comment on your question. If one substitutes higher performance crystal oscillators in existing cesium standards, but still goes through the buffer amplifiers of the existing cesium amplifiers, you will not realize the better short-term stability. So be careful in doing that. That is my advice.

The other comment is, as I said yesterday, you have to get away from the one second time constant of the cesium if you replace the internal oscillator.

DR. WINKLER:

What you just said is one should not go about replacing the internal workings but put a makeshift externally to that oscillator.

DR. WALLS:

I would prefer that.

DR. WINKLER:

Yes. It's much cheaper and much more direct and much more reliable.

DR. WALLS:

Yes, one should really think in terms of systems, right? And you can, if you use two components, sometimes have the best of both worlds rather than having one device be everything to all people.

MR. PHILLIPS:

The Naval Research Lab has taken some of these items into account and developed a system called a disciplined time and frequency oscillator.

That wasn't the system we developed. And we have noticed very large improvements when multiplied to X band so that these are very real effects and this is a very powerful approach for the person who needs the long-terms stability of a cesium and then must require the short-term stability so that he can have a pure signal at microwave frequency. So this is a very real thing and we have been addressing it. I wondered if you have, in commercial oscillators, looked at this particular system?

DR. WALLS:

Well, we have commercial 5 megahertz oscillators that we have multiplied to X band and the measurements you saw there were on some commercial 5 megahertz oscillators. They weren't laboratory designed oscillators. We have not tried to change the internal power or the buffer amplifiers yet. That is something that we hope to do.

DR. KARTASCHOFF:

In this context of crystal oscillators, I just remembered that about 15 years ago the Marconi Company in England developed a crystal oscillator system where they had a high Q crystal in the bridge and they servoed the frequency of a half driven second crystal oscillator to that bridge. Of course that was done with tube technology about 15 years ago, but it might be that this scheme, in view of the results of the measurements of Dr. Walls, might be well worth looking at again.

DR. HELLWIG:

I think it is a concept worth pursuing. I claim the concept, which I call the dual crystal concept, would be superior if that second crystal is not used in an oscillator but passively.

I think that is even superior. Replacing tubes by transistors will help too.

N75 27184

THE MAGNETIC MATRIX TIME INTERVAL METER*

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ABSTRACT

A time interval meter is being developed which allows the recording of a number of event times with high resolution over a relatively long period of time.

INTRODUCTION

In a number of experimental areas, a means for accurately recording relative times of occurrence of a series of events is needed. A technique which easily lends itself to such recording was investigated during the development of a high-speed single-transient recording device, the Magnetic Matrix Recorder.[1-4] The application of this technique to a time-interval meter results in a system that has capabilities for measurement of large timing intervals with high resolution, multiple channels timed directly from the same reference source, non-volatile radiation-hard data storage, computer-compatible data retrieval, and small physical size.

DISCUSSION

The basis of the system is a matrix of thin-film magnetic recording elements, located at the intersections of two orthogonal sets of control traces (Figure 1). With no current flowing in the lines, the magnetization of an element points either direction along an "easy" axis built into the matrix during fabrication. The application of a sufficient current to a word line will pull the magnetization into the hard axis. A current in the bit line pulls the magnetization toward the easy axis, the direction depending on the polarity of the current. When the word-line current is removed, the magnetization will fall back to the easy-axis direction it is being pulled toward, recording the state of the bit-line current at that instant.

In the application of this technique to a Time Interval Meter (TIM), the bit lines are driven with bipolar signals developed by time-code generating digital logic. The word-line currents are controlled by the events of interest, with the state of the clock recorded at the time each word-line is triggered.

*This work being supported by the U.S. Atomic Energy Commission, Nevada Operations Office, under Contract AT(29-1)-1183.

An initial bread-boarded prototype of such a TIM was constructed, and verified the feasibility of the concept. The unit presently under construction is an engineering prototype designed to allow a full investigation of the capabilities of this technique (Figure 2).

The time code in this unit is synchronized by a 100-MHz crystal-controlled oscillator feeding two separate generators. The first generator produces an 8-bit binary Gray code, a minimum-transition timing code, which gives 2.5-nanosecond resolution over a period of 0.64 microseconds. The second generator contains a set of delay lines, giving eight separate phase-delayed signals at the main oscillator frequency. Combined with the Gray code, this allows 0.5-nanosecond resolution, for somewhat greater than 10 bits of overall resolution.

In this design, the word-lines are controlled through buffer logic by differential ECL-compatible input signals. A record enable signal, externally supplied by the system user, serves to gate the channels only during the time of interest. A calibrate mode is also provided, in which an external calibrate signal will strobe all 16 channels at the same instant, allowing channel-to-channel calibration of the unit at any time.

Since the timing code generators are free-running, the data recorded gives the relative time of occurrence for each event. If an absolute time measurement is desired, one channel would be strobed by a reference-time signal to relate the data to an absolute standard. Also, since the code is cyclic, the units can be cascaded to increase the system time range covered. For example, adding another unit with 16 bits of Gray code to the above would allow timing over .04 seconds with 0.5-nanosecond resolution.

Although tests have not yet been performed on the engineering prototype, an idea of the overall system performance can be gathered from the bread-boarded prototype. Since the system is digital, its timing accuracy is affected primarily by variations in logic behavior caused by changes in temperature or supply voltages. With the unit calibrated, the overall accuracy is expected to be within ±1 least-significant-bit (±0.5 ns in this case). The other source of error is in the oscillator driving the code generators, which has a specified accuracy of 0.0001% for the present unit. However, any external oscillator capable of being adapted to ECL levels can be used to obtain higher stability and accuracy.

To read out data from the matrix, the word line for a selected channel is strobed by the internal readout logic, and the outputs of the bit-line sense amplifiers are transferred to buffer registers. In the manual readout mode, the channel is selected with front-panel switches and the data appear on a light-emitting diode display. Under the remote mode, readout takes place through computer control via a CAMAC Dataway at rates up to the CAMAC maximum of 1 megaword/second.

The digital circuitry is primarily ECL logic, with the high-speed portions using Motorola's MECL III circuits. For both speed and size benefits, the circuits surrounding the matrix card are fabricated using hybrid circuit techniques. Both thin and thick film approaches have been used. A plug-in module arrangement allows ease of fabrication and maintenance as well as a multilayer circuit capability in the hybrid portion. The engineering prototype unit will be housed in a 1 3/4" x 19" rack chassis, with further packaging emphasis directed toward a CAMAC Instrumentation Module.

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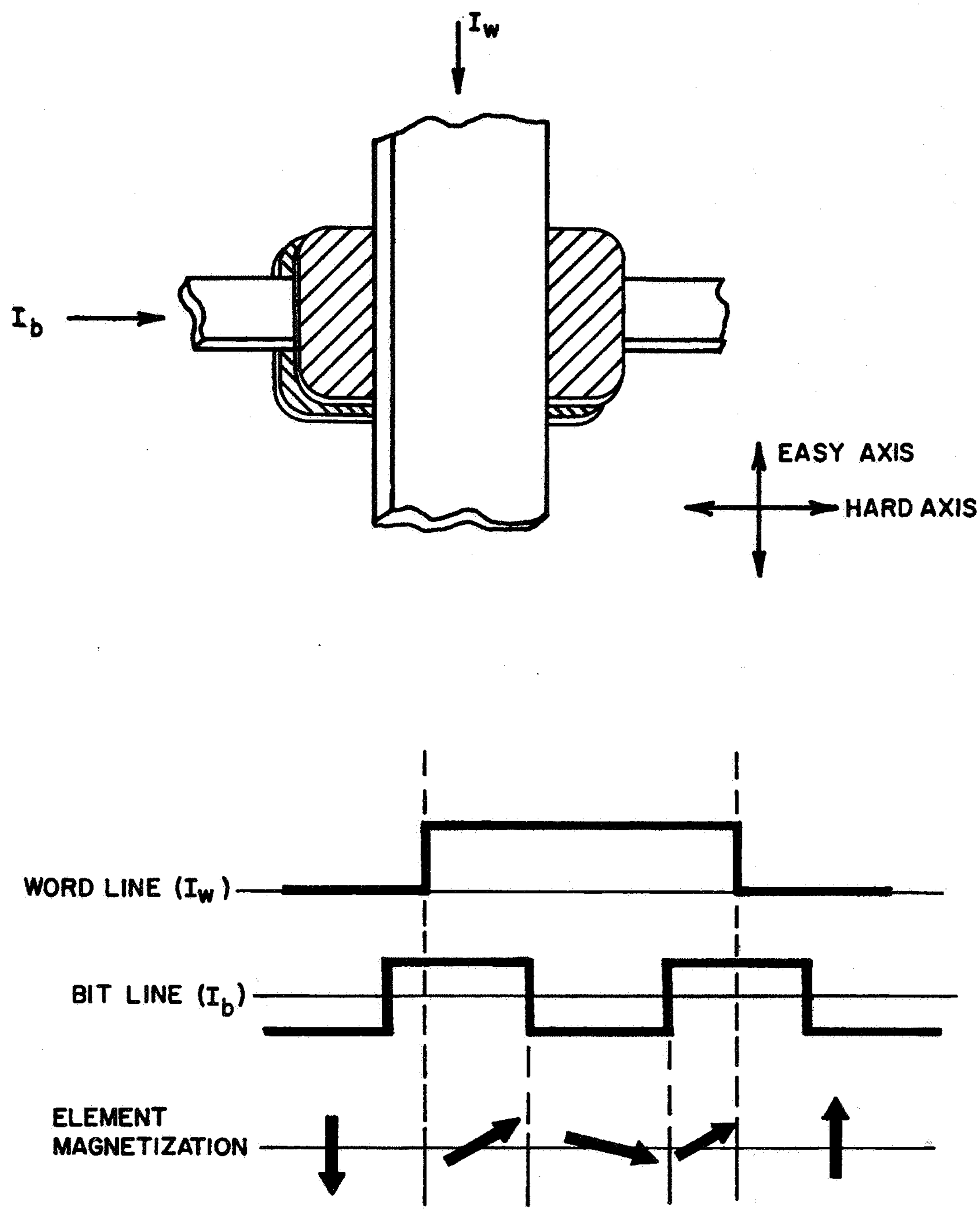

Figure 1. Magnetic matrix element.

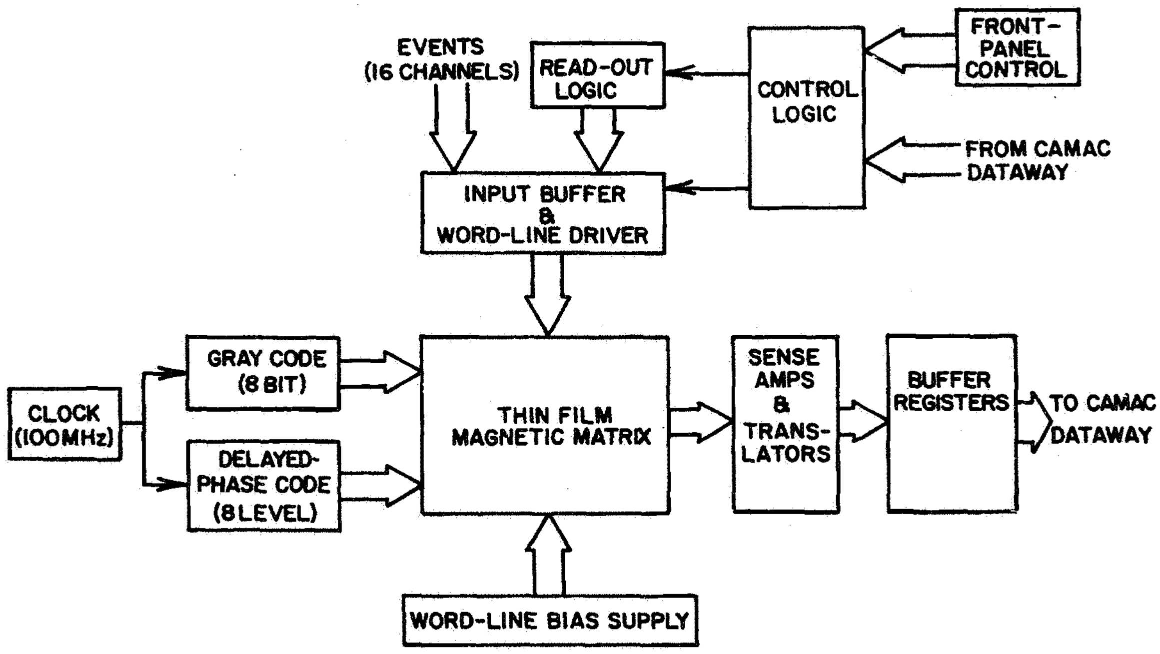

Figure 2. Magnetic matrix time interval meter.

N75 27185

OMEGA NAVIGATION SYSTEM STATUS AND FUTURE PLANS

CDR Thomas P. Nolan
Mr. David C. Scull
USCG OMEGA Navigation System Operations Detail

INTRODUCTION

OMEGA is a very low frequency (VLF) radio navigational system operating in the internationally allocated navigation band in the electromagnetic spectrum between 10 and 14 kilohertz. Full system implementation with worldwide coverage from eight transmitting stations is planned for the latter 1970's. Experimental stations have operated since 1966 in support of system evaluation and test. These stations provided coverage over most of the North Atlantic, North American Continent, and eastern portions of the North Pacific. This coverage provided the fundamental basis for further development of the system and has been essential to the demonstrated feasibility of the one to two nautical mile root-mean-square system accuracy. OMEGA is available to users in all nations, both on ships and in aircraft.

HISTORICAL

OMEGA uses very low radio frequencies and phase-difference measurement techniques to provide radio navigation information. These principles were proposed to the Navy in 1947 by Professor J. A. Pierce of Cruft Laboratory, Harvard University.

As a result of his proposals and his experiments in measuring phase delay at VLF and establishing the phase stability of signals at VLF, the Navy developed an experimental system operating in the vicinity of 50 kHz with a sine wave modulation of 200 Hz. The system was designed by Naval Electronics Laboratory Center (NELC), San Diego, and was called Radux. Radux had an accuracy of three to five miles and a range of about 2,000 miles. While this system showed the wisdom of using phase-difference measurement techniques, the attained accuracy and desire to obtain even greater range resulted in another system which combined a separate VLF transmission near 10 kHz with the low frequency (LF) signal. This system was called Radux-OMEGA. To further increase the range of the system, the LF signals were discontinued. The single frequency VLF system was called OMEGA and, later, expanded to a multi-frequency OMEGA system. Thus, OMEGA can trace its development back over a twenty-year period.

Early transmissions from the shore-based stations were derived from a conventional primary-secondary configuration. Modern transmission of OMEGA signals is derived from a cesium frequency standard at each station and each station is controlled as a source of standard signals. This arrangement is most efficient and practical for a global system because the navigator can pair stations in any convenient way to obtain useful hyperbolic geometry and signals.

SYSTEM CONFIGURATION

TRANSMITTING ANTENNA SITES -

The OMEGA navigation system is a shore-based electronic aid to navigation that uses measured signal phase-differences from sets of stations for fix reduction. Eight stations geographically dispersed are required to provide worldwide coverage. Two of the eight stations are located on U. S. sovereign soil. The remaining six are being sited in cooperation with partner countries.

Experimental stations, operating since 1966, were located at Forestport, New York; Bratland, Norway; Trinidad, West Indies; and Haiku, Hawaii. These stations employed either existing facilities or temporary electronic equipments which proved adequate for the evaluation phase. The stations provided about one kilowatt of radiated power. Two of these four stations were selected as sites for permanent stations: Bratland, Norway; and Haiku, Hawaii.

The first high power OMEGA station of the projected configuration of eight stations is located in La Moure, North Dakota. This station has been operational since late 1972. The second station to be built on U. S. sovereign soil is located at Haiku, Hawaii. This site is the location of one of the original experimental stations. This station, like all others, will broadcast a signal of ten kilowatts.

The Bratland, Norway, site originally used during the operational evaluation phase provided signal coverage from temporary electronics housed in vans. In cooperation with the Government of Norway, this site was selected as one of the eight permanent stations. This station has since been completed with a permanent new facility housing a full set of new OMEGA electronics. It is currently broadcasting with an effective radiated power of six to seven kilowatts but once antenna problems are resolved, the station should radiate ten kilowatts.

As was the case with Norway, rather than negotiating for permission to build and operate U. S. transmitting stations on foreign soil, the Navy sought out foreign partners to join the U. S. in completing the OMEGA system. This policy emerged from the consideration that OMEGA is not peculiarly a military system, nor even a U. S. system, but an international navigation system that can be and undoubtedly will be used by all seafaring and airline operating nations of the world.

The Governments of Japan, Argentina, and Liberia have concluded diplomatic agreements with the U. S. for stations on their soil. The final agreement with France for a station on their soil is near final approval. Construction work is currently in progress on these stations. The sites are located on the Island of Tsushima in the Sea of Japan, on the Island of La Reunion in the Indian Ocean, Golfo Nuevo, Argentina, and near Monrovia, Liberia, respectively.

Diplomatic negotiations are currently in progress with the Government of Australia for siting of the final transmitting station. Figure 1 depicts the existing stations along with stations under construction and a probable location for the Australian station.

SYSTEM DESIGN

SIGNAL FORMAT -

The system design calls for a network of eight stations each transmitting a continuous wave (CW) signal which is periodically interrupted to allow it and other OMEGA signals to enter a time sharing or multiplex pattern. The various OMEGA stations always transmit in the same order with the length of the transmission varying between 0.9, 1.0, 1.1, and 1.2 seconds from station to station. Each transmitting station broadcasts three basic navigational frequencies 10.2, 11-1/3, and 13.6 kHz and is also capable of broadcasting what has been termed two unique frequencies. The original purpose of these frequencies, unique to each station, was for use in the synchronization process through interstation communication. The high stability of atomic frequency standards (cesium beam) now used in the system has made this requirement obsolete and other uses have been proposed. A final use for these frequencies has not been determined, however, and is still under study.

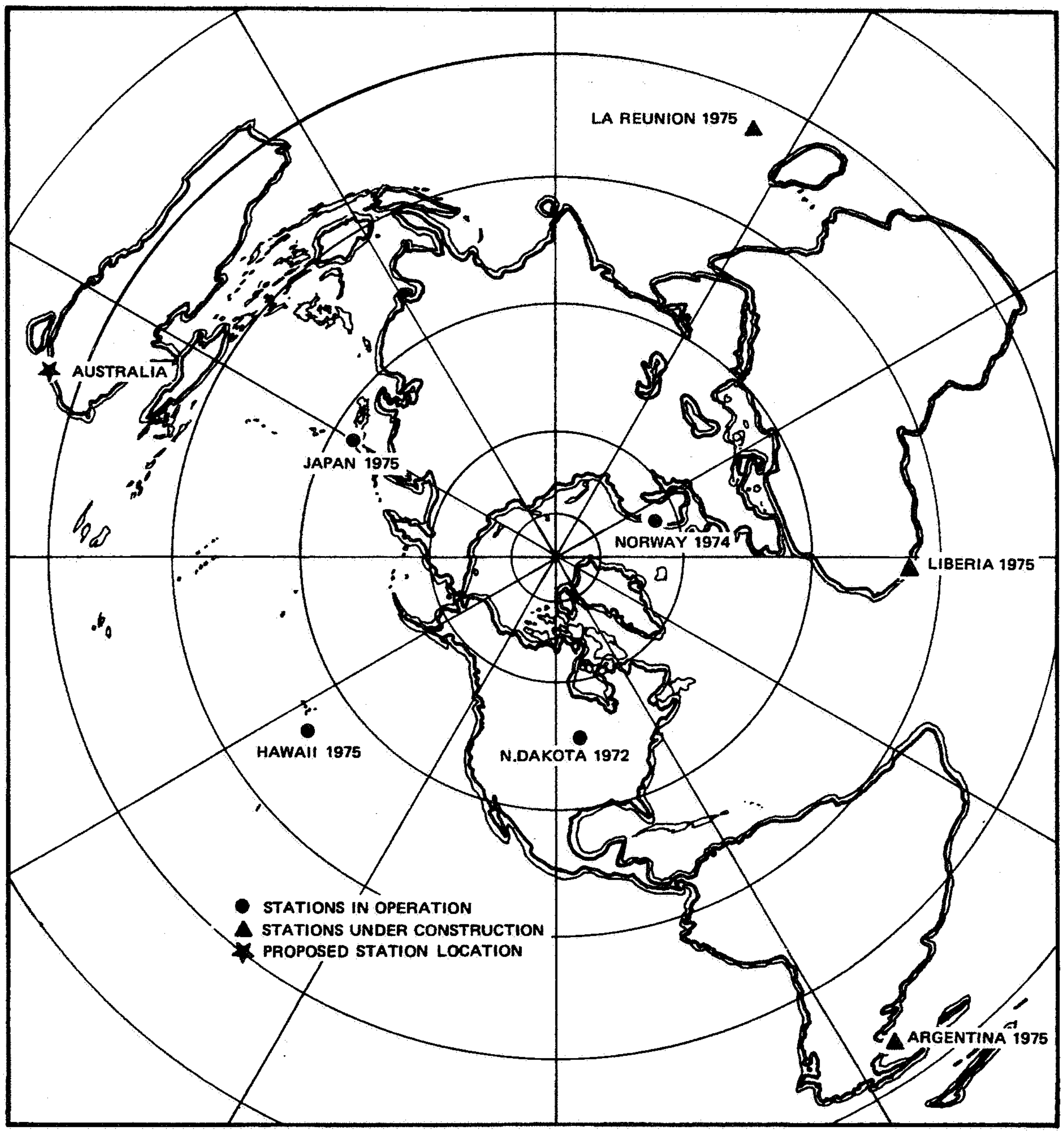

Fig. 1--OMEGA Navigation System

The complete, as originally envisioned pattern or transmission for all stations is shown in Figure 2. It should be noted that the various pulses are length-coded to provide one of several ways in which emissions of the various stations can be identified. Each of the shared carrier frequencies (that is, every frequency except the unique ones) passes through a particular phase at the end of each 30 seconds. Thus, at each half-minute of time, all carrier frequency currents in all transmitting stations pass through zero with a positive slope. Thus, all stations are synchronized to a given point in time and can be considered independent. It is important to note the OMEGA epoch does not correspond with universal coordinated time (UTC).

R-15394

STATION \ SEGMENT	A	B	C	D	E	F	G	H
NORWAY (A)	10.2	13.6	11 1/3	12.1	12.1/12.35	12.1/12.35	12.1/12.35	12.35
LIBERIA (B)*	12.25	10.2	13.6	11 1/3	12.0	12.0/12.25	12.0/12.25	12.0/12.25
HAWAII (C)	11.8/11.55	11.55	10.2	13.6	11 1/3	11.8	11.8/11.55	11.8/11.55
N. DAKOTA (D)	13.1/12.85	13.1/12.85	12.85	10.2	13.6	11 1/3	13.1	13.1/12.85
LA REUNION (E)*	12.3/12.05	12.3/12.05	12.3/12.05	12.05	10.2	13.6	11 1/3	12.3
ARGENTINA (F)*	12.9	12.9/13.15	12.9/13.15	12.9/13.15	13.15	10.2	13.6	11 1/3
AUSTRALIA (G)*	11 1/3	13.0	13.0/12.75	13.0/12.75	13.0/12.75	12.75	10.2	13.6
JAPAN (H)	13.6	11 1/3						10.2
Duration	0.9	1.0	1.1	1.2	1.1	0.9	1.2	1.0

TIME (SEC): 0.0, 1.1, 2.3, 3.6, 5.0, 6.3, 7.4, 8.8, 10.0

*HELIX NOT YET TAPPED

Fig. 2--OMEGA Signal Transmission Format

PROPAGATION -

The OMEGA navigational system is a skywave dominant system that is inherently dependent on the ability to predict propagational factors associated with such skywaves in order to arrive at a useful navigational system. Thus, the accuracy of navigation is dependent on ability to derive a useful set of corrections, such that the navigator at a given time and location can reduce the phase-difference measurements to a geographic position.

The field strength and velocity of propagation at VLF form too complex a subject for detailed discussion in this short paper. A simple summary can be given best in terms of the mode and wave guide theory. We would like to have a single mode of propagation greatly exceeding all others at all necessary distances. This condition is most nearly met near 10 kHz. At higher frequencies such as 20 kHz, the excitation of the first-order transverse magnetic wave is inferior to the excitation of the second-order wave, especially at night, while the attenuation rate of the first-order is considerably less than that of the second.

There is, at VLF, a considerable asymmetry in transmission normal to the horizontal component of the earth's magnetic field. At the geomagnetic equator, at 10.2 kHz, the day-time attenuation rate for transmission toward the West is more than twice the value for transmission toward the East. This results in large differences in useful range of a signal in various directions. Transmission toward the West (at the geomagnetic equator) cannot be used for more than 4,500 nm. Toward the East, however, transmission is satisfactory for about 10,000 nm, except that there is a region probably a few hundred miles in radius, at the antipode of the transmitter, where the large field strength is provided by rays coming from many directions and the prediction of resultant phase is difficult.

The velocity of propagation is relatively less affected by direction than is the field strength. Of major importance is the change in velocity between day and night. The velocity is reduced by transmission over land, but the effect is not major unless the land is of unusually poor conductivity, as in the arctic and antarctic regions.

From the practical standpoint, these phenomena result in resonant modes, each with a different velocity and attenuation, being developed within the spherical shell wave guide between the earth and ionosphere. At frequencies near 10

C-3

kHz, the first mode is generally dominant over others at ranges greater than 600 miles. At the same time, diurnal changes in ionospheric height are responsible for expansion or compression of the wave guide along the propagation path, with the result that there is a corresponding variation in the propagated phase.

Propagation of the VLF signal must be corrected to coincide with charted phase contours prior to navigator utilization to attain OMEGA's phase-of-the-signal fundamental measurement. Propagation corrections accomplish this melding operation.

These corrections are easily predicted because the basic parameters concerned with propagation of the first mode are known and ionospheric heights can be calculated along day/night paths. This is not to oversimplify the task of calculation, since effects of the geomagnetic field on east-west propagation paths and the secondary phase retardation factors attributed to ground conductivity must also be considered.

Previously, all published propagation correction tables were based on a global theory of OMEGA propagation incorporating theoretical and empirical principles where the relative contributions of the various effects are determined by regression analysis on millions of hours of data. The physical model has undergone continual refinement for ten years. Currently, skywave corrections for limited areas are also receiving the benefit of a "Force-Fit" wherein local prediction errors are determined by monitoring and then removed over whatever spatial extent may be justified by the statistics. Regardless of the method of derivation, the purpose of the propagation correction is to remove undesirable variations so that the observations can be corrected to charted LOP's with the best practical accuracy. A sample propagation correction table is shown as Figure 3.

10.2 KHZ OMEGA PROPAGATION CORRECTIONS IN UNITS OF CECS   LOCATION 36.0 N 76.0 W
STATION A NORWAY

DATE	GMT 00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1-15 JAN	-56	-61	-62	-60	-60	-61	-62	-63	-63	-58	-49	-38	-3	-11	-27	-29	-28	-29	-31	-33	-38	-42	-51	-50	-56
16-31 JAN	-58	-63	-63	-63	-65	-64	-63	-63	-59	-56	-44	-30	-2	-12	-24	-24	-24	-25	-26	-28	-32	-38	-49	-54	-58
1-14 FEB	-60	-62	-62	-62	-62	-62	-62	-60	-56	-46	-40	-22	-2	-14	-19	-18	-17	-19	-21	-23	-26	-35	-46	-55	-60
15-29 FEB	-57	-60	-62	-61	-61	-61	-61	-54	-48	-40	-31	-12	-4	-13	-12	-11	-11	-13	-17	-19	-24	-32	-43	-52	-57
1-15 MAR	-55	-58	-59	-60	-60	-61	-57	-48	-42	-35	-26	-4	-4	-9	-6	-6	-8	-9	-14	-18	-24	-29	-38	-50	-55
16-31 MAR	-57	-61	-61	-63	-63	-58	-51	-44	-42	-35	-23	-8	-11	-10	-9	-10	-9	-11	-16	-21	-26	-29	-38	-50	-57
1-15 APR	-52	-56	-59	-58	-54	-48	-42	-42	-36	-27	-15	-12	-16	-9	-4	-5	-6	-8	-12	-16	-18	-23	-32	-44	-57
16-30 APR	-47	-53	-55	-53	-41	-42	-37	-36	-29	-24	-11	-14	-14	-5	-5	-5	-5	-7	-8	-12	-15	-21	-26	-36	-47
1-15 MAY	-44	-50	-54	-55	-55	-47	-42	-35	-29	-20	-8	-11	-16	-9	-3	-1	-3	-4	-6	-10	-13	-16	-22	-33	-44
16-31 MAY	-39	-45	-50	-52	-53	-51	-45	-35	-27	-17	-8	-11	-14	-5	1	2	3	0	-1	-4	-9	-14	-20	-28	-39
1-15 JUN	-39	-46	-49	-53	-54	-52	-48	-38	-29	-18	-14	-17	-23	-12	0	5	4	0	-3	-7	-10	-16	-21	-28	-39
16-30 JUN	-33	-41	-45	-49	-50	-48	-44	-34	-25	-14	$\boxed{-7}$	-11	-15	-7	2	7	5	2	-1	-4	-7	-10	-16	-22	-33
1-15 JUL	-32	-41	-44	-49	-49	-48	-44	-33	-29	-15	-10	-13	-9	-2	6	5	1	2	-1	-5	-7	-8	-13	-22	-32
16-31 JUL	-40	-46	-50	-53	-54	-53	-46	-36	-31	-20	-13	-16	-9	-2	1	1	2	1	-1	-8	-13	-16	-18	-27	-40
1-15 AUG	-40	-45	-50	-52	-53	-49	-40	-33	-25	-13	-9	-10	-13	-2	-3	-2	-3	-2	-4	-8	-13	-16	-22	-30	-40
16-31 AUG	-46	-56	-62	-56	-49	-44	-45	-36	-30	-20	-11	-6	-8	-4	-2	-4	-1	-1	0	-4	-10	-15	-22	-30	-46
1-15 SEP	-50	-55	-57	-58	-53	-50	-42	-37	-31	-22	-7	-1	-1	0	0	-1	-2	-2	-1	-5	-9	-15	-25	-36	-50
16-30 SEP	-49	-59	-59	-60	-62	-56	-45	-41	-35	-27	-14	-2	-7	-7	-6	-7	-7	-8	-11	-15	-15	-21	-33	-40	-49
1-15 OCT	-45	-53	-54	-53	-52	-51	-47	-46	-41	-35	-21	-4	-11	-13	-11	-13	-15	-18	-22	-23	-24	-29	-35	-41	-45
16-31 OCT	-42	-49	-52	-52	-52	-54	-52	-49	-45	-39	-27	-4	-12	-18	-15	-14	-17	-20	-22	-26	-27	-33	-40	-43	-42
1-15 NOV	-42	-46	-53	-53	-54	-55	-55	-55	-51	-45	-34	-10	-11	-23	-23	-22	-23	-26	-28	-31	-35	-40	-44	-43	-42
16-30 NOV	-44	-46	-55	-55	-56	-57	-57	-62	-57	-53	-41	-24	-6	-23	-30	-28	-30	-31	-33	-37	-42	-45	-50	-46	-44
1-15 DEC	-48	-51	-56	-56	-55	-56	-57	-61	-62	-58	-49	-35	-3	-17	-32	-33	-32	-34	-36	-39	-43	-47	-50	-48	-48
16-31 DEC	-45	-52	-58	-58	-58	-58	-59	-62	-64	-61	-52	-39	-3	-12	-29	-32	-32	-31	-33	-36	-40	-45	-47	-46	-45

Fig. 3--Sample Propagation Correction Table

The two principal sources of error are propagational variation and ability to predict propagation corrections. The distinction is significant. Propagation corrections are computed for intervals well in advance of use. Thus, they cannot be expected to reflect particular propagation conditions on any single day, but only the anticipated average phase-difference observations for the location and time considered. Error with perfect propagation corrections would still exist, since, in general, phase difference measurements on a particular day would not exactly match the anticipated normal measurements. The distinction is largely academic to the practical navigator since he is constrained to use published propagation corrections. To the system designer, however, the distinction is real, since propagation correction errors can be reduced as experience is gained and prediction techniques are refined.

Figure 4 shows a typical phase variation curve. The predicted values indicated are derived from calculations and are available in the form depicted in Figure 3. The difference in predicted and actual values includes both errors noted above. This sample is typical and would produce about one-half mile for the navigational fix.

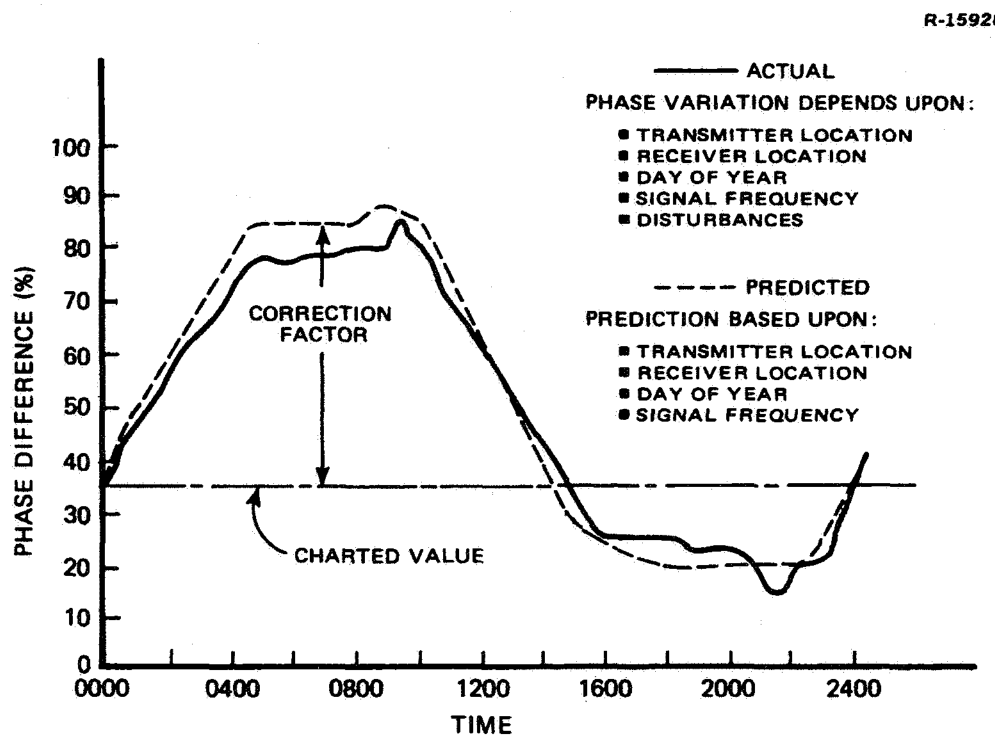

Fig. 4--Typical Phase Variation Curve

LANE IDENTIFICATION -

If positional measurements are made in terms of carrier phase at only a single frequency, it is clear that the phase observations will be identical at a large number of points in a nearly rectangular grid. At 10.2 kHz the separations of these ambiguous points would be about 8 miles, or 1/2 wavelength. This problem of ambiguity would never arise if the navigator should start from a known place and carry his positions forward by making observations (or having them continuously recorded) at intervals smaller than the time within which his errors of dead reckoning could reach 4 miles. On shipboard, this is the chosen solution. In an aircraft, however, a 4 mile uncertainty can accumulate in a few minutes, and the navigator might not care to place his entire reliance upon the continuity of operation of his equipment and of the signal reception.

For these and other reasons, the system has been designed to provide lane identification, in such a way that it may be used (or not) at the operator's convenience. In OMEGA, complete identification must be done in several stages.

If one made a second measurement of a line of position at a frequency of 3400 Hz (1/3 of 10.2 kHz), it is clear that it would coincide with one of each three possible 10.2 kHz positions, if the error of the measurement at the lower frequency were safely less than 1/2 of the period of the higher frequency. Since 3.4 kHz cannot be radiated successfully from the OMEGA antenna, this comparison is made by measuring the phase of the beat between 10.2 kHz and 13.6 kHz. These two frequencies cannot be radiated simultaneously, but in effect the 10.2 kHz phase is stored for the carrier-frequency measurement and this stored phase can be compared with the 13.6 kHz phase when it appears.

Continuing the process, a period of 3400 Hz signal can be identified by a measurement at a frequency three times lower, or at 1133-1/3 Hz. This frequency is the difference between the 10.2 kHz carrier and the 11-1/3 kHz carrier.

These multiple frequencies are employed as noted to create lanes which are larger than the basic 8 nm half-cycle wavelength. Use of the 3400 Hz frequency generates a 24 nm lane and 1133-1/3 Hz generates a lane width of 72 nm. Use of these frequencies reduces the problem of lane ambiguity commensurately. Very few receivers should need to resolve ambiguities of 72 nm unless an intermittent operation is expected. Figure 5 shows the relationship of these lanes.

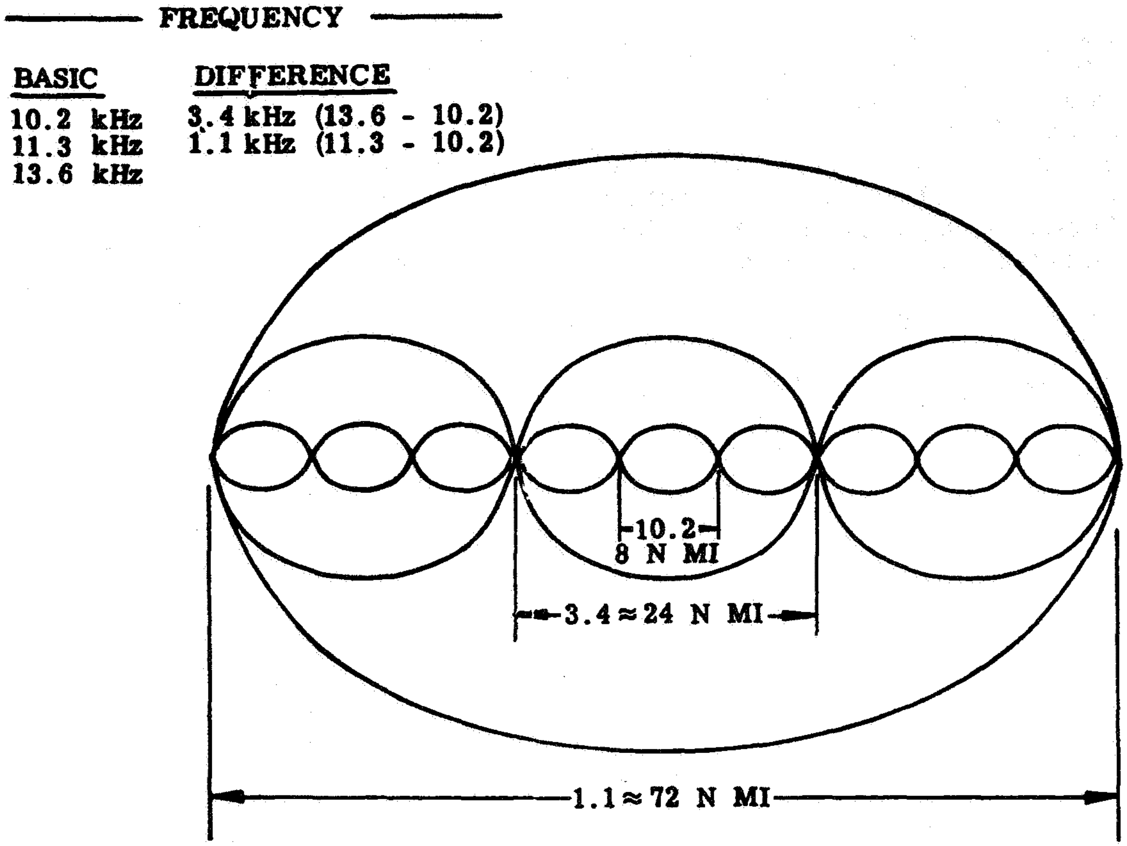

Fig. 5--Lane Resolution Relationships

SYNCHRONIZATION -

As noted previously, the definition of synchronization in OMEGA is that all antenna currents shall be in absolute phase whatever the locations of the antenna. This definition obviously neglects the fact that the various stations actually radiate their common frequencies at different epochs. The sources of frequency are, however, continuous and in phase. This condition is achieved and maintained as follows.

Each station is controlled by the mean of the frequencies of four standards, each locked to an atomic resonance but adjustable over at least a few parts in 10^{11}. All needed frequencies are derived from this combined source, and are internally checked and maintained to achieve very high reliability of phase. The precision of frequency is such that each phase can be trusted to 1 micro-second per day.

This frequency source is used to provide all radiated signals and also to drive a clock. At each station, this clock is used to record the time of arrival of every signal from every other station. Once each day these observed times of arrival are reduced to a single number for each station. By appropriate calculations, these numbers are intercompared to each other and to standard time, such as from the Naval Observatory, to compensate for any offset that may occur between the atomic clocks of the various stations.

TRANSMITTING STATION IMPLEMENTATION

The OMEGA system, when completed, will consist of eight stations as discussed earlier. For ease in identification, these stations have been assigned letter designations of A through H. Table I identifies the station by letter designation, location, and antenna type.

TABLE I

STATION	LOCATION	ANTENNA TYPE
A	Bratland, Norway	Valley Span
B	Trinidad/Liberia	Valley Span/Grounded Tower
C	Haiku, Hawaii	Valley Span
D	La Moure, North Dakota	Insulated Tower
E	La Reunion Island, Indian Ocean	Grounded Tower
F	Golfo Nuevo, Argentina	Insulated Tower
G	South East Australia	Ground-Tower (Proposed)
H	Tsushima Island, Japan	Insulated Tower

Except for the commutation pattern depicted in Figure 2, the electronics characteristics of the station are alike. The principal difference is associated with the antenna type which has some effect on the bandwidth, and thus on the rise and decay times of the waveform. These minor differences have no practical impact on the navigator. The selection of the antenna type was based on site characteristics and cost associated trade-offs.

The Norwegian Station construction was completed in December 1973 by the Norwegian Telecommunications Administration. This station is currently broadcasting the OMEGA signals at an effective radiated power of six to seven kilowatts.

The Trinidad OMEGA station, in existence as an operational evaluation station since 1966, will be replaced by a new station in Liberia. Relocation of this mid-equatorial Atlantic station to the African Coast will improve the OMEGA coverage available to the major shipping and trade routes from Europe around Cape of Good Hope. Liberia, in cooperation with the United States, has made final the site selection and survey. Construction is in progress with a scheduled completion date of September 1975.

The Haiku, Hawaii, OMEGA station renovation and upgrading has been completed. A new valley span antenna complex and ground system has been installed. Interior building renovation to accommodate a new electronic suite is included. Construction has been completed.

The La Moure, North Dakota, OMEGA station was the first permanent OMEGA station. This station has been providing operational signals since October 1972.

The La Reunion Island OMEGA station is under construction by the French Navy on a site near Port des Galets. This site is located in the Indian Ocean cyclone area which has significant impact on construction schedules, in particular the schedule for erection of the 1,400' tower. Tower fabrication and erection schedules currently support an on-air date of no earlier than December 1975.

The Argentine OMEGA station at Golfo Nuevo, located in the coastal area of central Argentina, is approximately 600 miles south of Buenos Aires. This region of the country is comparable to the southwestern United States, and its flat terrain provides an excellent platform for a tower antenna system. The tower for OMEGA Argentina is on site with construction in progress under supervision of the Argentine Navy. Scheduled on-air date is July 1975.

The Government of Australia is currently reviewing a proposal from the Government of the United States that Australia construct and operate an OMEGA navigation station on their sovereign soil. It is anticipated this station might be located in southeastern Australia. In all likelihood, it will use a tower antenna system. Until diplomatic procedures have been completed, no estimate of an on-air date can be made, but past experience has indicated about thirty-six months is required from final site selection to on-air.

Japan has undertaken to construct an OMEGA station on Tsushima Island in the Sea of Japan. This venture represents the first major OMEGA construction program to be totally directed by a partner nation. Design has been completed and construction is in progress. This station will feature a 1,500' cylindrical tower antenna structure. It is now broadcasting and it is expected that the station will be operational by April 1975. It will provide the first expansion to system coverage since 1966.

SYSTEM MANAGEMENT

Overall system implementation is continuing under the direction of the U. S. Navy OMEGA Project Manager[1]. Agencies of the other participating nations are coordinating their programs with the United States. The U. S. Coast Guard operates the U. S. stations.

The Coast Guard OMEGA Navigation System Operations Detail[2] was established in July 1971. This organization has recently assumed operational responsibility for the OMEGA system. It is intended that the Coast Guard Operations Detail operate the system for the Navy pending total implementation or when mutual agreement is reached for the Coast Guard to assume full U. S. responsibility for the OMEGA system.

OMEGA stations on foreign soil will be operated by host nation agencies who will be responsible for maintaining the OMEGA signal without interruption and in phase with the worldwide OMEGA navigation system. These agencies are listed in Table II.

TABLE II

STATION	AGENCY
A. Norway	The Norwegian Telecommunications Administration
B. Liberia	Department of Commerce, Industry, and Transportation
C. Hawaii	U. S. Coast Guard
D. North Dakota	U. S. Coast Guard
E. La Reunion	French Navy
F. Argentina	Argentine Navy
G. Australia	Department of Transport Coastal Services Division
H. Japan	Japanese Maritime Safety Agency

[1] Commander Neal F. Herbert, USCG
OMEGA Project Office (PME-119)
Naval Electronic Systems Command
Washington, D. C., 20360
(202) 692-8777

[2] Commander Thomas P. Nolan, USCG
Commanding Officer
USCG OMEGA Navigation Operations Detail
U. S. Coast Guard Headquarters (G-ONSOD/43)
Washington, D. C., 20590
(202) 245-0837

MR. STETINA:

Fran Stetina from Goddard.

How long will the Trinidad station be operational?

MR. SCULL:

Until the Liberian station becomes operational which we estimate now as being December of '75.

MR. STETINA:

Is the North Dakota station going to be torn down for maintenance?

MR. SCULL:

I hate to use the word, "torn down." I don't know all the details. I'm not in the engineering aspect of the system, but evidently there is some problem with some of the insulators on the radials. They may be able to do some of this work while the station is transmitting. But there is some indication that they will stay off for a day or two.

DR. WINKLER:

The case of the unique frequency falls under three different considerations.

Number 1—communications. I think you have shown on your third slide that the OMEGA system was not to be used for communications. That would imply that we should not use the system to communicate time-of-day as has been proposed by several users. That communication was to have been done by switching on and off some of these remaining five segments on two frequencies.

Point number 2—unique frequencies are capable of being received by receivers without switching—without segment switching, and if all the power which is available on 5 segments, is concentrated on just one unique frequency which can proceed without switching, I think one has additional navigational capability. Particularly important for fast moving crafts—aircraft where duty cycle is of major importance and signal-to-noise is of major importance.

Such a use also would be in the interest of a very large community spread throughout the Department of Defense and other agencies where people phase track with the simplest possible equipment to provide for local standards for frequency measurements. The Army, I believe, has some 900 of these stations on the air.

That point will be even more important in the future if, and when, the Navy high power communication stations would switch to the MSK instead of FSK. The unique frequencies at that time may be the only source for simple phase tracking VLF frequency standards.

The third point is a question of cycle identification. It has been proposed, and has been tested very successfully by the NASA group under A. Chi, that two unique frequencies spaced closely together, 250 hertz, can be used in a very simple straight-forward way to identify a particular cycle. The point, however, is, that that can be also done with one unique frequency and some switched segments, 13.6 combination to unique or the 10.2 to unique. This provides a similar capability.

I do not yet understand, and I hope that the next paper on the GRAN system will explain, why the lane identification problem is not really the same as the cycle identification problem. So if I consider all of these problems and the complication, my conclusion is that it may be the wisest to transmit just on one unique frequency and to attempt the cycle identification in conjunction with the OMEGA navigational frequencies which are switched, and not to use the segments for communicating time-of-day for which probably better methods are available.

MR. SCULL:

I think in the original implemetation plan for OMEGA unique frequencies were to be used for interstations communications. At some point they decided this was probably not the best way to go. This is from the standpoint that the time you need to communicate between stations is generally when you lose a station in the area due to a power failure or some other means.

So really the use of unique frequencies for that purpose was sort of lost somewhere along the line. Your description of various uses of unique frequencies, I think, are very appropriate and in discussions we've had with you and Andy Chi, I feel quite confident that we can almost accommodate all of the requirements by getting together and actually comparing these.

The only thing is time is getting short and we must go with a unified position in this area.

DR. OSBORN:

Is there any recent body of data since Beuker's data was taken that relates to phase stability of the signal on land? There's been a considerable controversy, as I'm sure you know, as to what the phase stability is.

MR. SCULL:

I've seen some but I think you're possibly trying to describe, or are describing, the modal propagation problems that we've had. In the near field around our megatransmitter we do get multimode propagation effects which do appear to interfere with the stability of the signal. These also occur at distance from the transmitter in certain regions, particularly in the transequatorial regions.

Yes, we do have data on these. Most of the data is based on ionospheric models. Primarily because there isn't a receiver built that will detect modal interference when it occurs. It's only through an analysis of long-term data that this can be shown and through comparison with the theoretical models such as integrated prediction problems, a program developed by NELC that we can see this type of thing.

I think the data concerning the stability of the standards which are used to synchronize the system, generally within a few microseconds on the present four stations network, isn't published any place but I'm sure we can make this available to interested parties.

DR. OSBORN:

So you're essentially saying then that you're content with Beuker's data, is that correct?

MR. SCULL:

No, —I read one of Beuker's reports where he indicated it was modal interference on certain paths and I certainly agree that this occurred. I'm not too sure where it happens in all regions of the earth's globe. If this is enough to limit the use of the system I'd say no. I think it's been well recognized that on certain paths we will have modal interference problems and the way around that is the built-in redundancy of the OMEGA signals.

This is where things become very acid between say, the Coast Guard which is calibrating the system and agencies like the Defense Mapping Agency which produce charts for this system. We have to know what stations will be virtually interfered with at a particular time on a given path; so we can guide the navigator, publish the proper LOP's on a chart.

Again, it's just a physical phenomena that occurs, I think we're not able to define it very well at this point and not until we improve our data base.

DR. KLEPCZYNSKI:

In November there was a meeting on OMEGA here in Washington and I believe there was a paper which did something like Beuker just did and which should be published in their proceedings. Do you recall that paper?

MR. SCULL:

Yes, I think it's part of the work done by NASA at Langley, Virginia and they noticed modal interference on the North Dakota path, which is an overland path. Modal interference can happen in the ocean regions as well, and generally some of the studies that we have done on modal interference support their contention that certain hours of the day we get modal interference. In fact on the Trinidad signal when we receive in a Y, an east-west path, we have severe modal interference. I was there a couple of weeks ago looking at it during the day and it exists.

But the way around that is to choose other stations in the system, but, of course, we do have to know which ones to choose and that's a very important point. We have to develop the data base and the data bank is aimed toward that goal.

MR. KEATING:

Mr. Keating, Naval Observatory.

I would like to return to the distinction between lane identification and cycle identification. Is there is a distinction and if so, what is it?

MR. SCULL:

Lane identification is a word I think used by the navigator where maybe cycle identification is a word used by the propagation physicist or the PTTI scientists.

Essentially there is no difference, except you get into a complication: hyperbolic systems lane is half a wave length and the cycle identification system is a full wave length. But generally they are interchangeable words. Please correct me if I'm wrong somebody. I think that's a safe assumption.

MR. CHI:

I'd like to make an observation on Dr. Winkler's excellent summary of the potential applications of OMEGA for navigation by using additional frequencies.

It is certainly an excellent way to use as many frequencies as possible, in particular, as strong a signal strength as possible. However, there are some problems which should probably be considered.

One is lane identification or cycle I.D. Specifically, it's on the phase stability. The theory, if one uses the present model for propagation delay prediction, is not quite as good as we would like to have, especially if you want to expand to global coverage. For certain areas it is good.

On the other hand, the use of the unique frequencies which permit all the timing people to enter in the measurement of the time transmission, improves the propagation delay measurement by simply using clocks to measure the propagation delay. The result could be overwhelming in the refinement of the model of the prediction.

Additionally, I feel that the phase stability obtained by using two closely spaced frequencies would help in the reception of the signals, although one can certainly use present OMEGA navigation frequencies for timing. There is no difference between using two or even three frequencies. Of course, the minimum is two. The problem involved is that if there are sudden phase pertubations, if the frequencies of the pair on diffusion are too far apart, the difference in phase will not be quite as close as it would be if the frequencies were closely spaced.

Certainly there is room for discussion in the design and transmission of the frequencies. On the other hand, I believe the objective in the application of the OMEGA system, is the same as in the Loran-C system. It is to serve as many users as possible.

The question is what is really needed.

MR. BEEHLER:

At the risk of disagreeing a bit with Dr. Winkler on his home ground, I think we shouldn't be too hasty about writing off the utility of a time-of-day code on OMEGA. At NBS we have been studying this question as long ago as five years, and after throughly exhaustive studies, of the user community, we have come to a couple of conclusions. One of them is that there is a real need, particularly for wide scale or wide spread systems, for data monitoring networks which can benefit appreciably from providing, or making generally available, time-of-day information to which the user has access on a 24 hour a day continuous basis and at a fairly nominal cost.

Now, our studies indicate the number of users are fairly significant. For example, there are many hundreds of data monitoring stations involving geophysical data, and they do need to have, for example, a time code that can be put right onto their chart recorders for a time index and this sort of thing. I think, contrary to what Dr. Winkler indicated, that while there are other alternatives, they are not nearly as good, at least in short-term. Perhaps satellites will eventually turn out to be better. But I think this is a good short to medium term solution to good time of day information.

NBS has made proposals for doing this in a fairly simple way. Furthermore we feel that it can be done compatibly with some of the other proposed uses for the unique frequencies.

So I would like at this point simply to kind of reaffirm the NBS interest in the time code on OMEGA and state that we do have funding available for further experimentation that is committed if that is agreeable at some point with the OMEGA people. Finally, I would like to conclude with kind of a quick question or ask for clarification. I tended to interpret your comment about not using OMEGA for communications as referring to the original, more internal use of the system or internal communications within the system, rather than the more general interpretation of communicating any kind of information such as time-of-day to the outside. I wonder if you could elaborate at all on that?

MR. SCULL:

Well, just briefly. I base everything on the SOR, the Statement of Operational requirements that's put forth by the Navy in the system and developed in the system. They do not address in that document any requirement for the unique frequencies.

The primary objective is to use it as a navigational system.

MR. TAYLOR:

You remarked that the positional accuracy of the system was one or two miles. I'd like to know whether this is a conservative estimate on your part. Do you think you can get better, or is it going to be hard to attain this? The second question is, is this accuracy based on equipping a ship with a cesium beam standard for running the OMEGA instrument or whether it's including the oscillator that's presently installed by some of the companies in the equipment?

MR. SCULL:

That's a two-part question. The figure I used is one to two nautical miles. I believe it is a conservative figure, if you use the qualification, after the system is calibrated.

We have demonstrated that accuracy in certain parts of the North Atlantic area.

Further accuracy is achievable through the use of differential OMEGA which requires the establishment of a local monitor; asuming that local propagation conditions are the same, we can use a differential technique and there have been various studies, range of accuracies runs from a quarter of a mile or even down to a tenth of a mile, over distances of 150 to—well, I think the most accurate figure I saw is a quarter mile up to 50 miles in range. After that it falls off to something like three-quarters of a mile in 150 miles.

But there have been numerous reports and I think a lot of them have been hardware limited. We haven't had the receivers until quite recently to be able to demonstrate this.

Yes, greater accuracy is achievable. Another point, however, is that in the continental United States it has been established that Loran-C will serve as the system for the coastal component zone navigation, and we have no plans at least within the Coast Guard to implement differential OMEGA in the continental United States.

N75 27186

RECENT FIELD TEST RESULTS USING OMEGA TRANSMISSIONS FOR CLOCK SYNCHRONIZATION

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ABSTRACT

This paper presents the results of clock synchronization experiments using OMEGA transmissions from North Dakota on 13.10 kHz and 12.85 kHz. The OMEGA transmissions were monitored during April 1974 from NASA tracking sites located at Madrid, Spain; Canary Island; and Winkfield, England. The sites are located at distances between 6600 kilometers (22,100 μs) to 7300 kilometers (24,400 μs) from North Dakota.

The data shows that cycle identification of the received signals was accomplished. There are, however, discrepancies between the measured and calculated propagation delay values which have not been explained, but seem to increase with distance between the receiver and the transmitter. The data also indicates that three strategically located OMEGA transmitting stations may be adequate to provide worldwide coverage for clock synchronization to within ± two (2) microseconds.

INTRODUCTION

The field tests were conducted from April 1 through April 22, 1974. The objectives of these tests were to determine the adequacy of unique OMEGA transmissions for time determination at distances greater than 6000 km from the transmitter and to collect experimental data that would indicate the minimum number of sites, appropriately located, required for worldwide clock synchronization to within ±2 μs.

Receiving transmissions from the OMEGA North Dakota (N. D.) station, data were collected at Madrid, Spain (7185 km); Canary Island (7298 km); and Winkfield, England (6626 km). Previous test results conducted at Greenbelt, Md. (1934 km); Washington, D.C. (1922 km) and Rosman, N.C. (1794 km) were reported at the 1973 PTTI Meeting.(1) Further tests will be conducted during September-October 1975 at Hawaii and Australia.(2) Transmissions from OMEGA stations N.D. and Hawaii will be used. Transmissions from OMEGA N.D. will be monitored at Kauai, Hawaii (5926 km) and from both N.D. and Hawaii will be monitored at Orroral, Australia (14,408 km and 8443 km respectively from the transmitters).

The use of the OMEGA system for time transmission not only will augment existing systems such as Loran-C by providing an additional capability in the northern hemisphere, but would also provide coverage in the southern hemisphere where Loran-C transmitters do not exist and time synchronization is limited to within ±25 μs.

PROPAGATION DELAY MEASUREMENT

If the phase velocities for two VLF signals (f_1 and f_2) are v_1 and v_2 respectively, then the propagation delays for a path length D are:

$$t_{p_1} = \frac{D}{v_1} \tag{1}$$

and

$$t_{p_2} = \frac{D}{v_2} \tag{2}$$

Since the two signals were emitted in phase at time t_{xm} at the transmitter, the signals as received at a station at time t_{rv} relative to the station clock must satisfy the following conditions(3):

$$t_{xm} - t_{rv_1} = t_{p_1}^m = n\tau_a + (n_1 + \Delta n_1)\tau_1 \tag{3}$$

$$t_{xm} - t_{rv_2} = t_{p_2}^m = n\tau_a + (n_2 + \Delta n_2)\tau_2 \tag{4}$$

where t_{rv_1} and t_{rv_2} are the time of signal reception of f_1 and f_2 relative to the receiving station clock, and $t_{p_1}^m$ and $t_{p_2}^m$ are measured propagation delay values. The received cycle of each carrier, n_1 and n_2 is determined from the phase measurements Δn_1 and Δn_2.

The ambiguity identification of n for τ_a (20 milliseconds) is considered a priori knowledge or determined from the theoretical predicted propagation delay (see table 1) which is in error by much less than 4 milliseconds. The receiver design actually requires the ambiguity resolution to 4 milliseconds (see cycle identification p. 193 and reference 2).

Equations (3) and (4) can be used to calculate the measured propagation delay if the receiving station clock time is known relative to the transmitter clock. Having measured the propagation delays via portable clock, the received VLF signals can be used to synchronize a receiving station clock.

Table 1

Ambiguity Identification of n from Predicted Propagation Delays

NASA Tracking Sites	Predicted Delay (μs)		Ambiguity Determination	
	t_{p_1} (13.10 kHz)	t_{p_2} (12.85 kHz)	n	$n\tau_a$ (μs)
Madrid	23,974.8	23,972.1	1	20,000
Canary Island	24,346.3	24,343.5	1	20,000
Winkfield	22,113.0	22,110.5	1	20,000

EXPERIMENTAL DATA AND PROCESSING

VLF phase data at each station visited were recorded in both analog and digital form as shown in Figure 1. The analog data was replotted for the 13.1 and 12.85 kHz signals to demonstrate the diurnal phase signature for each station as shown in Figures 2, 3, and 4 (solid line). The predicted phase data furnished by C. P. Kugel of the Naval Electronics Laboratory Center (NELC) is the dotted curve. It can be seen from these figures that the agreement between the observed and predicted phase is rather good.

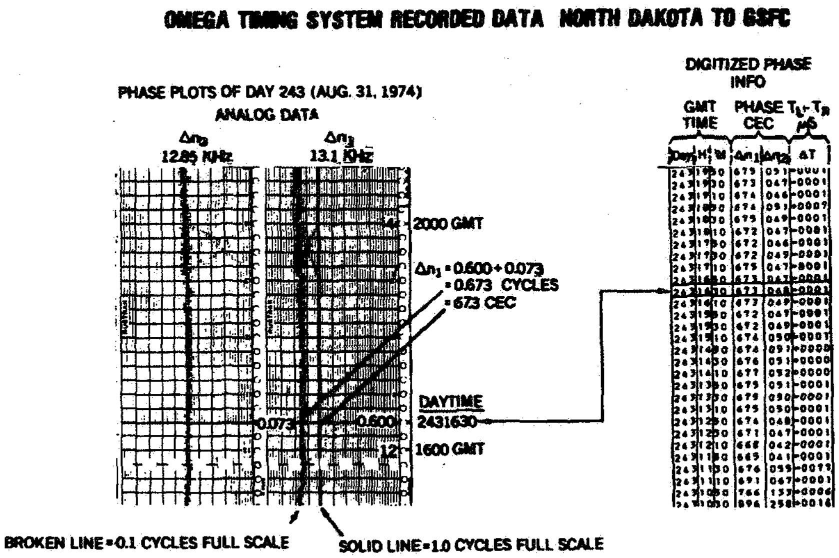
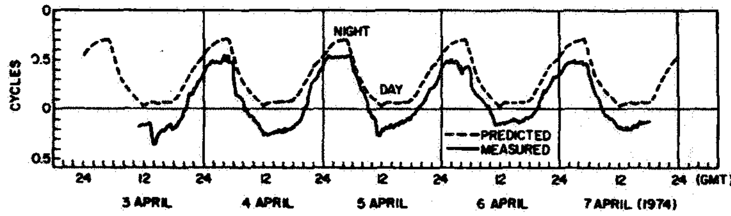
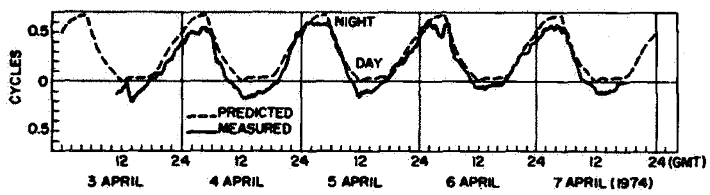


Figure 1. VLF signal phase data as recorded by the OMEGA Timing Receiver in analog (left) and digital (right) form.

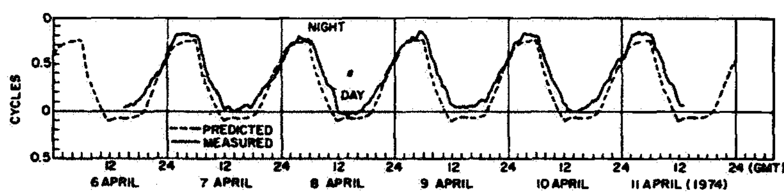


MEASURED AND PREDICTED DIURNAL PHASE OF
13.1 KHz OMEGA N. DAKOTA TO MADRID, SPAIN

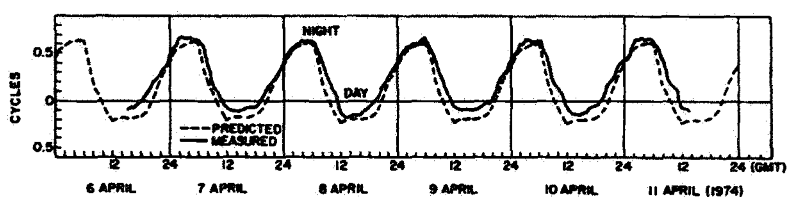


MEASURED AND PREDICTED DIURNAL PHASE OF
12.85KHz OMEGA N.DAKOTA TO MADRID, SPAIN

Figure 2. Diurnal phase records of OMEGA North Dakota transmitted signals as received at Madrid, Spain on April 3 to 7, 1974.

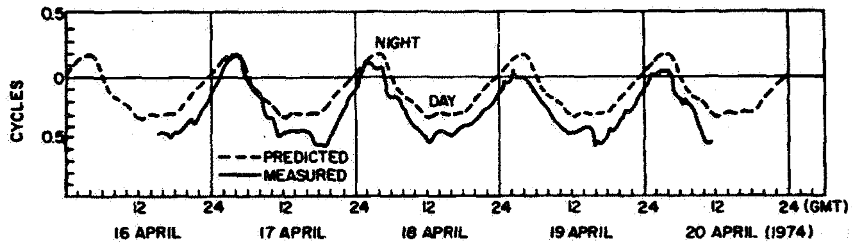


MEASURED AND PREDICTED DIURNAL PHASE OF
13.1 KHz OMEGA N.DAKOTA TO CANARY ISLAND, SPAIN

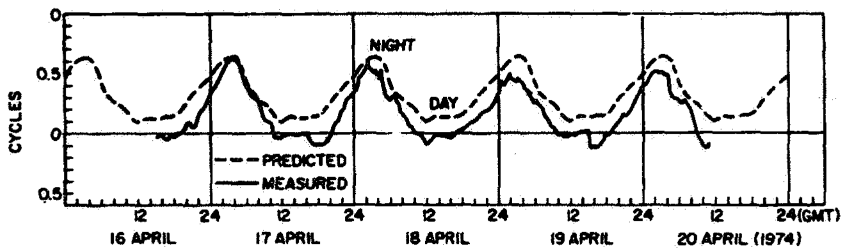


MEASURED AND PREDICTED DIURNAL PHASE OF
12.85 KHz OMEGA N. DAKOTA TO CANARY ISLAND, SPAIN

Figure 3. Diurnal phase records of OMEGA North Dakota transmitted signals as received at Canary Island, Spain on April 6 to 11, 1974.



MEASURED AND PREDICTED DIURNAL PHASE OF
13.1 KHz OMEGA N. DAKOTA TO WINKFIELD, ENGLAND



MEASURED AND PREDICTED DIURNAL PHASE OF
12.85 KHz OMEGA N. DAKOTA TO WINKFIELD, ENGLAND

Figure 4. Diurnal phase records of OMEGA North Dakota transmitted signals as received at Winkfield, England on April 16 to 20, 1974.

The digital data were grouped in time periods according to the diurnal phase record. This was done by taking the average of the data points obtained over 15 or 20 minute intervals during the periods of sunrise, daytime, sunset, and nighttime (see table 2). Due to local interference problem in Madrid, only phase record during the daytime transmission period were collected.

With reference to the results given in table 3, Δn_1 is the phase difference of the received signal (13.10 kHz) relative to the station clock and similarly for Δn_2 (12.85 kHz). The difference of the two received signal phases is given as Δn_{12} which is $\Delta n_1 - \Delta n_2$.

CYCLE DETERMINATION

Combining equations (3) and (4):

$$\Delta t_p \equiv \Delta t_p^m = t_{p_1}^m - t_{p_2}^m = (n_1 + \Delta n_1)\tau_1 - (n_2 + \Delta n_2)\tau_2 . \tag{5}$$

Let:

$$m = n_1 - n_2$$

$$\Delta\tau = \tau_1 - \tau_2$$

Table 2

Time of Day (GMT) When Data Were Collected

Time of Day	Madrid*	Canary Island**	Winkfield**
Sunrise	—	0630 - 1050	0510 - 1150
Day	1100 - 1800	1110 - 1810	1210 - 1650
Sunset	—	1830 - 0250	1710 - 2350
Night	—	0310 - 0610	0010 - 0450

*Data was collected at 15 minute intervals.
**Data was collected at 20 minute intervals.

Table 3

Average of Measured VLF Signal Phase in April 1974

Averaging Period	Madrid (April 4-7)		Canary Island (April 6-11)		Winkfield (April 16-19)	
	Δn_1	Δn_{12}	Δn_1	Δn_{12}	Δn_1	Δn_{12}
Sunrise	—	—	—	.140	—	.557
Day	.825	.899	.063	.141	.508	.556
Sunset	—	—	—	.136	—	.554
Night	—	—	.808	.164	.999	.556

$$\tau_b = \frac{\tau_1 \tau_2}{\tau_2 - \tau_1} = -\frac{\tau_1 \tau_2}{\Delta\tau}$$

and

$$\Delta n_{12} = \Delta n_1 - \Delta n_2$$

then equation (5) becomes:

$$\Delta t_p^m = (n_1 + \Delta n_1)(\tau_2 + \Delta\tau) - (n_2 + \Delta n_2)\tau_2$$

$$= (n_1 - n_2 + \Delta n_1 - \Delta n_2)\tau_2 + (n_1 + \Delta n_1)\Delta\tau$$

$$\therefore \Delta t_p^m = (m + \Delta n_{12})\tau_2 + (n_1 + \Delta n_1)\Delta\tau \qquad (6)$$

Rewriting equation (6):

$$n_1 + \Delta n_1 = -(m + \Delta n_{12})\frac{\tau_2}{\Delta\tau} + \frac{\Delta t_p^m}{\Delta\tau}$$

$$= (m + \Delta n_{12})\frac{\tau_b}{\tau_1} - \frac{\Delta t_p^m}{\tau_2 - \tau_1} \qquad (7)$$

Similarly:

$$n_2 + \Delta n_2 = (m + \Delta n_{12})\frac{\tau_b}{\tau_2} - \frac{\Delta t_p^m}{\tau_2 - \tau_1} \qquad (8)$$

Either equation (7) or (8) can be used to determine the received carrier cycle of either f_1 or f_2 respectively. This is so because Δn_1, Δn_2 and Δn_{12} are measured quantities; m is the highest integer multiple of the beat frequency period within the propagation delay value between the transmitter and the receiving station. Values of (n) and (m) are therefore known. The values of (n) and (m) used for the stations visited in 1973 and 1974 are given in table 4.

The particular cycle of a carrier signal received at a station as calculated from equation (7) or (8) is found by assuming a parametric value for Δt_p^m, i.e., $\Delta t_p^m = 0$, 1, 2, 3, 4, etc. μs. After $n_1 + \Delta n_1$ has been calculated, the value is rounded to an integer by the following rule:

(a) Round $n_1 + \Delta n_1$ downward to n_1, if

$\Delta n_1 \leq 0.44546 \rightarrow 0.4455 \rightarrow 0.446 \rightarrow 0.45 \rightarrow 0.4 \rightarrow 0$

(b) Round $n_1 + \Delta n_1$ upward to $n_1 + 1$, if

$\Delta n_1 \geq 0.54546 \rightarrow 0.5455 \rightarrow 0.546 \rightarrow 0.55 \rightarrow 0.6 \rightarrow 1$

The 0.1 cycle difference, between the upper bound of one cycle, n_1, (0.44546) and lower bound of another cycle, $n_1 + 1$, (0.54646), is the wall thickness of the cycle well. This is the same as saying that 90% of the data is grouped correctly into a particular cycle and 10% of the data is grouped into either one cycle high or one cycle low.

Table 4

(n) and (m) Values Used for Cycle Determination
for OMEGA North Dakota and NASA Tracking Stations

Station	Predicted Propagation Delay (μs)	Ambiguity Reduction		
		n	m	Predicted Propagation Delay (μs)
Rosman, N.C.	5994	0	1	1994
USNO, Wash., D.C.	6421	0	1	2421
GSFC, Md.	5458	0	1	1458
NELC, Ca.	7388	0	1	3388
Winkfield	22113	1	0	2113
Madrid	23974	1	0	3974
Canary Island	24346	1	1	346

PROPAGATION DELAY ANOMALY, Δt_p^m

The knowledge of the propagation delay anomaly in the frequency range of 11.05 kHz and 13.15kHz is not accurate. This is because there is a lack of adequate phase velocity data in this frequency range. A more accurate method to determine the propagation delay anomaly is perhaps by the use of the time measurement. Table 5 gives a comparison of predicted and measured propagation delay values.

One area in which more research needs to be done is the determination or analysis of propagation anomalies in the OMEGA frequency range where propagation predictions are not known to sufficient accuracy for microsecond clock synchronization. The propagation delays must be measured with a clock which is known relative to the clock at the transmitter. An alternate approach is to obtain an average of the measured phase differences for f_1 and f_2 for day and night time transmissions. From these average values one can calculate the propagation delay, such as shown by Table 6. Table 6 gives the sample calculation of cycle determination for data obtained from Winkfield.

Table 5

Comparison of Predicted and Measured Propagation Delay Values in Microseconds for Indicated Values of tp's

Station	Predicted				Measured		Received Carrier (f_1) Cycle Determination	
	t_{p_1}	Δt_p	n	m	Δt_p	t_{p_1}	Predicted	Measured
Winkfield	22,113.0	2.5	1	0	0 3	22,253.7 22,099.5	— 27	— 27
Madrid	23,974.8	2.7	1	0	0 3	23,644.8 23,498.1	— 52	— 45
Canary Island	24,346.3	2.8	1	1	0 3 4 5	24,585.7 24,508.6 24,432.3 24,355.9	— 57 — —	— 59 58 57
Greenbelt	6,458	—	0	1	2	6,463.8	84	84

RESULTS

The propagation delays for each station visited were measured. The results are given in Table 5. It is to be noted that for $\Delta t_p = 3\ \mu s$, the measured propagation delays for Winkfield and Madrid are lower than the predicted values; Canary Island is higher.

A sample calculation of cycle determination of n_1 for $\Delta t_p = 0, 1, 2, 3, 4\ \mu s$ is given in Table 6. The average of the measured propagation delays are 2097.5 and 2137.3 μs respectively for day- and night-time transmission paths.

It is noted that the propagation anomaly for a particular receiving station is determined only when the station clock is known relative to the transmitter clock. This information can be obtained by the use of a portable clock. During these field tests the OMEGA North Dakota station was measured relative to the U.S. Naval Observatory (USNO) Master Clock (MC) via a portable clock. It was determined by the USNO that OMEGA North Dakota was slow relative to USNO-MC by 7.4 microseconds. Also, during the tests a portable clock referenced to the USNO-MC was used. All known biases such as clock differences must be taken into account in the calculation of the propagation delay values. Once these values are established, microsecond time can be obtained since the only limitation is the phase stability of the received VLF signals.

Table 6

Sample Calculation of Cycle Determination for data Obtained from Winkfield, England.

Date		Data No	$\overline{\Delta n_1}$ Cycle	$\overline{\Delta n_{12}}$ Cycle	n_1 For Δt_p =					t_{p1}^m (μs) =
					0	1	2	3	4	$(27 + \overline{\Delta n_1})\, \tau_1$
1974 Apr	16	9	0.487	0.562	29	29	28	27	27	2099.2
1310 - 1750	17	13	0.510	0.548	29	28	27	27	26	2100.0
(Day Time Path)	18	15	0.508	0.556	29	28	28	27	26	2099.8
	19	15	0.498	0.560	29	29	28	27	27	2099.1
1974 Apr	16	15	1.088	0.556	29	28	28	27	26	2144.1
0110 - 0530	17	15	1.003	0.554	29	28	28	27	26	2137.6
(Night Time Path)	18	15	0.955	0.566	30	29	28	28	27	2133.9
	19	15	0.950	0.547	29	28	27	27	26	2133.6

$$t_{p1}^m \text{ (Day)} = \overline{(27 + \Delta n_1)\, \tau_1} = 2097.5\ \mu s$$

$$t_{p1}^m \text{ (Night)} = \overline{(27 + \Delta n_1)\, \tau_1} = 2137.3\ \mu s$$

CONCLUSIONS

Results based on the phase data collected during the field tests show that cycle determination of a received carrier signal can be determined and that the accuracy of time measurement using two VLF signals is within ±2 microseconds.

For a worldwide time transmission system the field test results indicate that a minimum of three transmission stations are needed. These stations which transmit the present dual frequency format must be selected from the OMEGA Navigation System appropriately in order to provide the coverage.

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N75 27187

FREQUENCY CALIBRATION TECHNIQUES

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ABSTRACT

The techniques and standards used by the U. S. Army Metrology and Calibration Center for frequency calibration are discussed.

I. INTRODUCTION

This paper on frequency calibration techniques is intended as a tutorial discussion of the frequency calibration techniques used by the U. S. Army Metrology and Calibration Center (USAMCC). Hopefully, a discussion of the equipment and techniques used by USAMCC will assist persons faced with the task of performing similar measurements.

Background

The most stringent workload for frequency calibration by USAMCC is presently frequency counter time base oscillators. Requirements for time exist in the Army, however, these requirements are presently being met by NBS and the U. S. Naval Observatory. Pending final studies of the long-term requirements for time in the Army, USAMCC may be required to provide frequency and time calibration support. In the meantime, the Army must support crystal oscillators of virtually every type now commercially available.

Until about 1968, frequency calibration of crystal oscillators used the 5, 10, and 15 megahertz signals from WWV. As accuracy measurements exceeded the capabilities of WWV reception, USAMCC engaged in a program to improve frequency calibrations.

The first attempt to replace VHF signals visualized no dependence on radio signals. A prototype calibration system, constructed for USAMCC by a contractor, used a rubidium frequency standard for frequency calibration. Analysis by USAMCC of the rubidium system and other techniques showed that VLF signals could meet Army requirements in the most cost effective manner.

II. THE ARMY FREQUENCY CALIBRATION EQUIPMENT

The equipment now used for frequency calibration (refer to Fig. 1) includes a VLF tracking receiver, a quartz oscillator, a frequency difference meter, and an Omega gating unit. This system is used in a small number of fixed locations, but is principally used in mobile Army Calibration Teams which are referred to as "ACT's." An ACT may move as often as twice a week or may remain for 90 days in one location.

A. VLF Receiver. The VLF Tracking Receiver, Tracor Model 599J, is the key element of the system. The VLF Tracking Receiver (Tracor Model 599J) compares the phase of the received signal to the phase of a local 1 MHz frequency source and produces an error signal which is displayed by a strip chart recorder. It is used to monitor the frequency of the quartz oscillator which is then corrected as shown by the VLF receiver's phase plot.

B. Quartz Oscillator. The Quartz Oscillator, Vectron Model FS-323, MIS-10223, has a basic stability specification of ± 5 parts in 10^{10} per day. Output frequencies are 100 kHz, 1 MHz, and 5 MHz. No battery is used with the oscillator. Consequently, every time the ACT truck is moved, the quartz oscillator must be restabilized and adjusted as shown by the VLF receiver.

C. Frequency Difference Meter. The Frequency Difference Meter (FDM), Hickok Model FDM 2100, is used to compare stable 100 kHz, 1 MHz, and 5.0 MHz sources to the ACT's quartz oscillator or other local standard. The FDM compares an unknown frequency standard with a reference frequency standard and indicates the difference. The FDM indication is a relative reading; therefore, the accuracy and stability of the reference must be considered in using the FDM. The comparison capability of the FDM is from 0 to ± 10 parts in 10^7 through 0 to ± 10 parts in 10^{11} (direct reading).

D. Omega Gating Unit. The Omega Gating Unit, Tracor Model 543, enables the VLF receiver to operate with the Omega navigation signals or with the standard VLF transmissions. Since Omega stations broadcast in 1-second bursts while time sharing the same frequency with the Omega stations, it is necessary to gate the VLF receiver ON only during the desired 1-second burst.

III. GENERAL TECHNIQUES

After arriving at a new location the calibration team will energize the frequency calibration system and align the antenna for maximum signal strength. After the desired VLF signal is located, the VLF receiver is used to monitor the warmup of the quartz oscillator. Fig. 2 shows an actual warmup of the Vectron Quartz

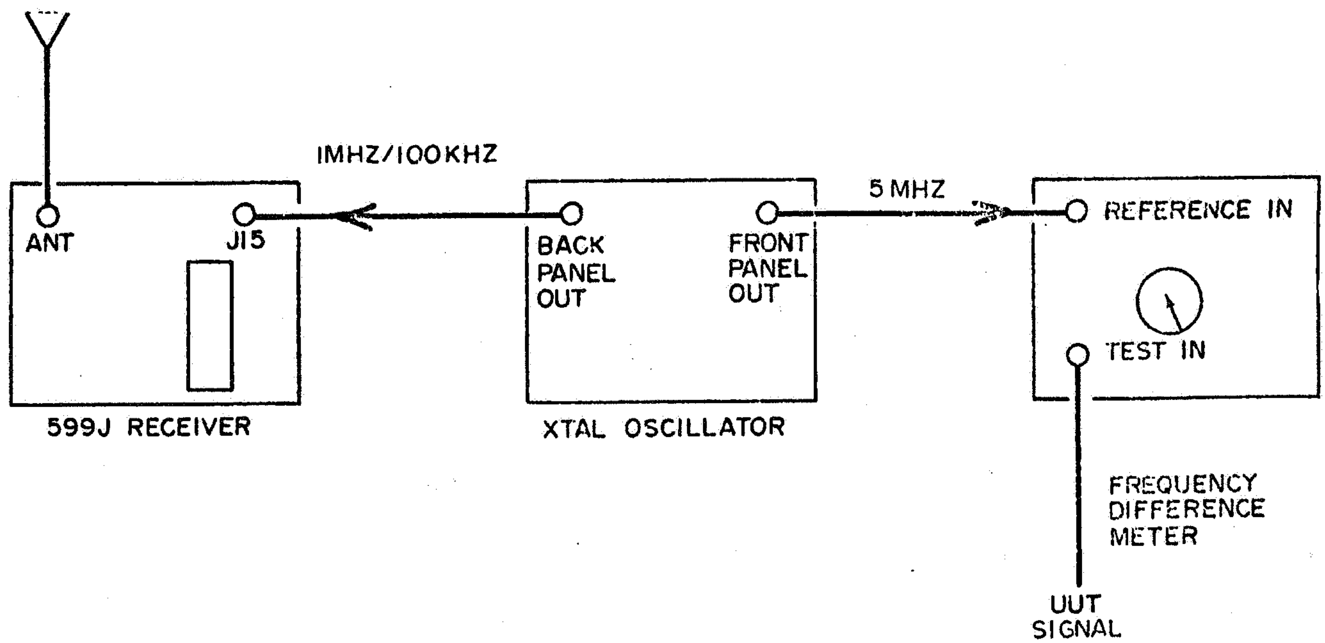


Fig. 1—Frequency calibration techniques

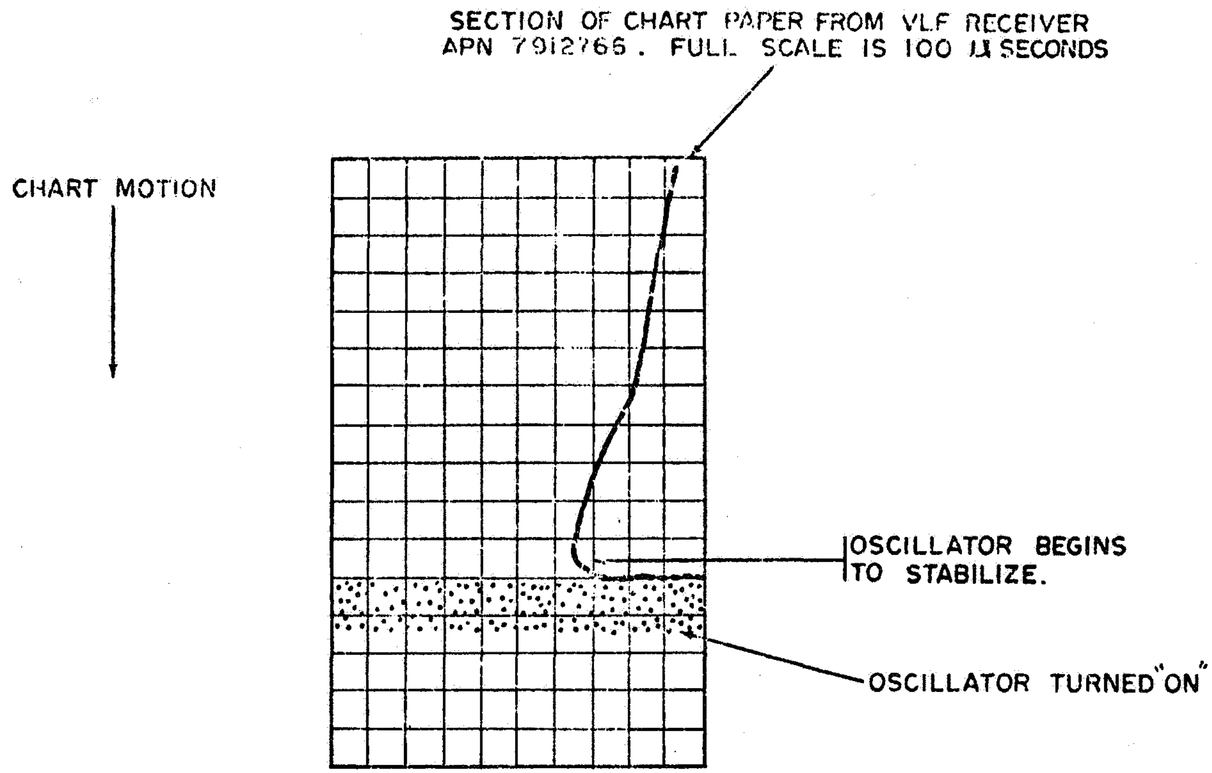


Fig. 2—Typical warmup drift of Quartz Oscillator, MIS-10223

Oscillator following a 24-hour OFF period. Fig. 2 has been redrawn from the original strip chart. Note that each vertical segment represents 15 minutes.

Fig. 3 shows another warmup for the same oscillator also after 24 hours OFF, however, this time the frequency error is corrected. Thereafter, the operator monitors the VLF receiver and makes corrections as needed. The procedure, as shown, uses all daylight paths from the transmitter to the receiver site. In remote locations, obtaining a good DoD signal can be a problem if rapid set up of the quartz oscillator is desired.

After set up of the equipment, calibration is performed according to a Technical Bulletin step-by-step procedure for each test item. Typically a Technical Bulletin of 1968 vintage required adjustment of the time base oscillator to a minimum frequency difference with a standard oscillator by observing the drift rate on a CRT display. Having adjusted for a minimum frequency difference, calibration of the oscillator was considered complete. USAMCC has attempted to improve the calibration procedure for quartz oscillators while still keeping costs down to a reasonable level. Current procedure is outlined as follows:

A. Warm up all oscillators to manufacturer's specifications.

B. Set the time base oscillator to a minimum frequency difference with the standard oscillator. (As a rule of thumb we say adjust to a minimum frequency difference which is less than the daily stability specification.)

C. After setting to a minimum frequency difference, monitor the oscillator's stability. To date, we have only implemented this change for 24-hour stability specifications.

USAMCC's present procedure is to observe those oscillators with 24-hour stability specifications of approximately $\pm$ 5.0 parts in 10^{10} per 24 hours for 24 hours and oscillators with specifications of approximately 3 parts in 10^{9} per 24 hours, for 8 hours. A 24-hour stability is extrapolated from the 8-hour measurement. Stability specifications for weekly or monthly rates extend over too long an interval to allow ACT's to monitor a significant period. Extrapolation of 24-hour data in these cases is not recommended.

Short-term stabilities - for example, over a period of 1 second - are presently not being calibrated by USAMCC. Discussions with several manufacturers have shown little benefit to be expected from such a calibration at this time. Comments on the validity of not performing regular measurement of the short-term stability of quartz oscillators are of interest to USAMCC.

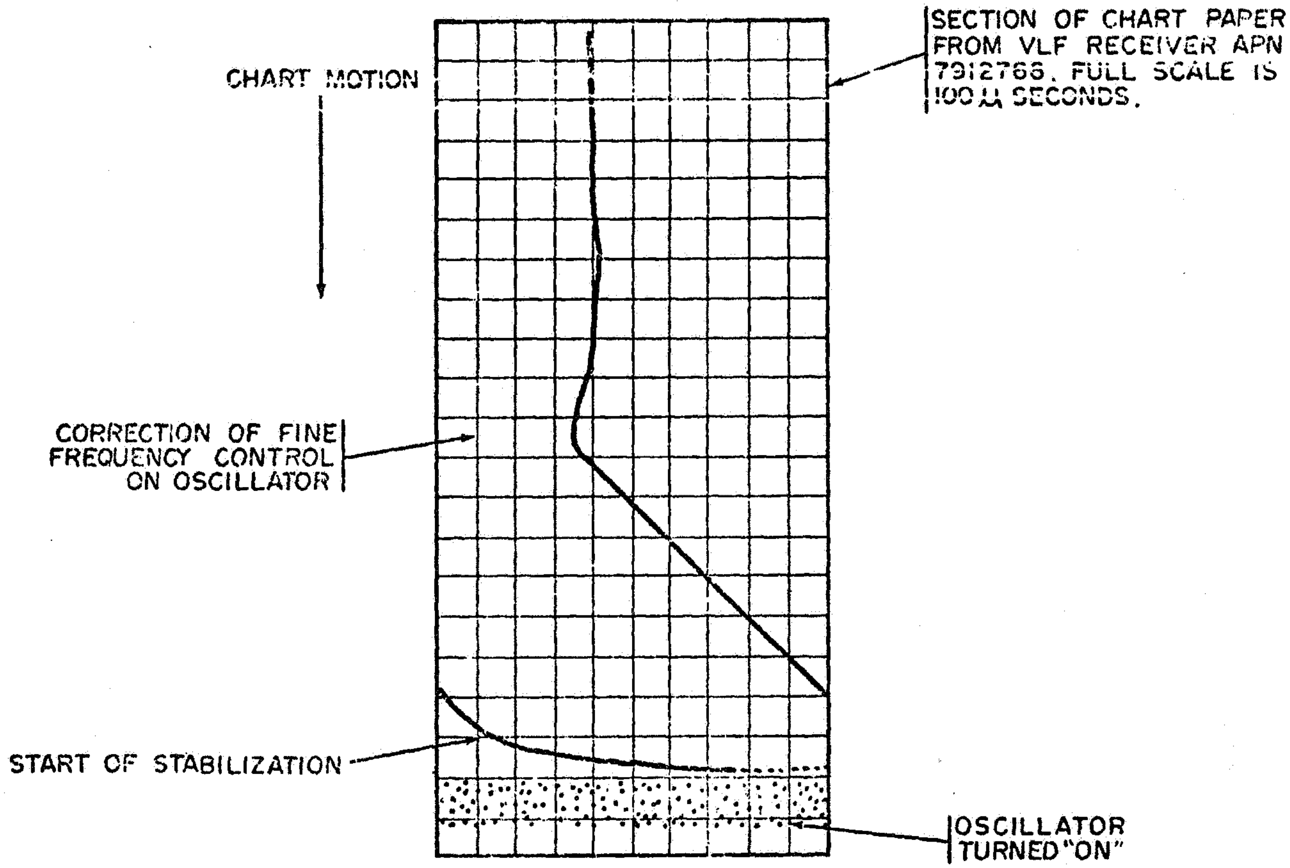


Fig. 3—Typical warmup drift of Quartz Oscillator, MIS-10223, showing correction of frequency difference

At present, the Army Calibration System has made no significant changes to the calibration of air bath crystal oscillators. Tests have shown that frequency changes due to temperature variations under normal operating conditions exceed daily crystal long-term aging specifications. Discussions with one manufacturer showed that calibration of an air bath crystal temperature characteristics might be much more useful than any attempt to determine the long-term aging rate from observations over a relatively short time period at a fixed temperature. However, such a calibration of temperature characteristics would be expensive and probably achieve little real benefit in increased accuracy of the product.

The problem of characterizing the actual accuracy of quartz oscillators over an extended period requires historical data. As automation enables data keeping and analysis to reach affordable levels, we plan to keep records on the stability of instruments. At present each calibration is a separate entity with no data carried forward to the next calibration. Data keeping would particularly aid the customer to determine the expected accuracy of his equipment under field conditions and would give solid data on which to base calibration intervals.

Due to manpower and power restrictions, we have been asked to look into shortening the warmup time for oscillators prior to calibration. We plan to conduct testing during the next year on some high density frequency counters to determine if this shortened warmup can be used without undesirable effects on the required accuracy of the equipment the counters support.

IV. PROBLEMS

A. VLF Receiver. The VLF receiver has been generally reliable, both in terms of maintenance and operation. Some locations have had difficulty obtaining good quality DoD signals for a sufficient length of time. In Europe, for example, a full 8-hour workday is not available from a DoD signal which has an all daylight path - except for Omega. Due to these problems and other complaints, the Omega gating unit was added to the VLF receiver.

B. Omega Gating Unit. The Omega gating unit's main difficulty lies with synchronization. No VHF time signals are available, or any other source of time, except in those few cases where a calibration team is operated near an organization with access to a time signal such as a communications unit. Instead of time signals, the Omega gating unit is synchronized by ear. The advance or retard controls are manipulated as necessary to match the blinking light for the required time segment with the tone from the selected Omega station. It has been often necessary to utilize headphones and careful adjustment of the blanking on the receiver to find the Omega signal. The synchronization is performed with the VLF receiver ON all the time - not gated. After the Omega signal and the required time segment are aligned, then the receiver is switched to the gated position and the phase track observed to determine if the receiver has locked on to the Omega signal. Reception of Omega is made more difficult by the noisiness of the reception. In fact, if one attempts to adjust the gating in the gated mode, the 1-second burst of noise is filtered by the receiver and sounds very similar to an Omega signal. Consequently, it is necessary to get an accurate identification of the Omega tone and not confuse it with noise.

C. Quartz Oscillator. The quartz crystal oscillator has performed well with one exception, that exception being an unexpectedly high failure rate due to crystal fracture. At one point over 5% of the 150 units fielded had suffered crystal fracture. No exact reason has been determined but part of the problem may lie with the physical shocks the oscillator unit absorbs in a mobile environment.

D. Antennas. The VLF receiver was originally supplied with a loop antenna which was effective - if somewhat cumbersome. The difficulties of antenna erection and storage, combined with new requirements which necessitated monitoring by the VLF receiver at locations outside the truck, made a more convenient antenna necessary. A ferrite core antenna was procured which utilizes a low noise amplifier to achieve the required sensitivity. The ferrite antenna has proven to be a very satisfactory unit with no significant failures. The unit is easily field mounted and in many good signal areas in the United States functions well setting on top of the receiver in unshielded locations.

E. Frequency Difference Meter.

The frequency difference meter has had excellent reliability. The zero center meter display of frequency difference has proven to be particularly well suited to adjusting one oscillator to match the frequency of another. The CRT display has proven to be of little benefit and requires periodic replacement due to burning of the phospher.

An additional output of 25 kHz was obtained with the frequency difference meter produced for the Army Calibration System which is derived from the 5 MHz output of the local frequency standard. By attenuating the 25 kHz signal to a level approximating that of a typical RF signal (which would be present at the input to the VLF receiver) a system checkout can be easily performed which will give the user added confidence in his equipment (refer to Fig. 4). Since the VLF receiver is a phase tracking device, feeding a 25 kHz signal in the antenna connector and a 1 MHz signal in the reference oscillator input will yield a vertical track on the recorder chart when the signals are derived from the same oscillator.

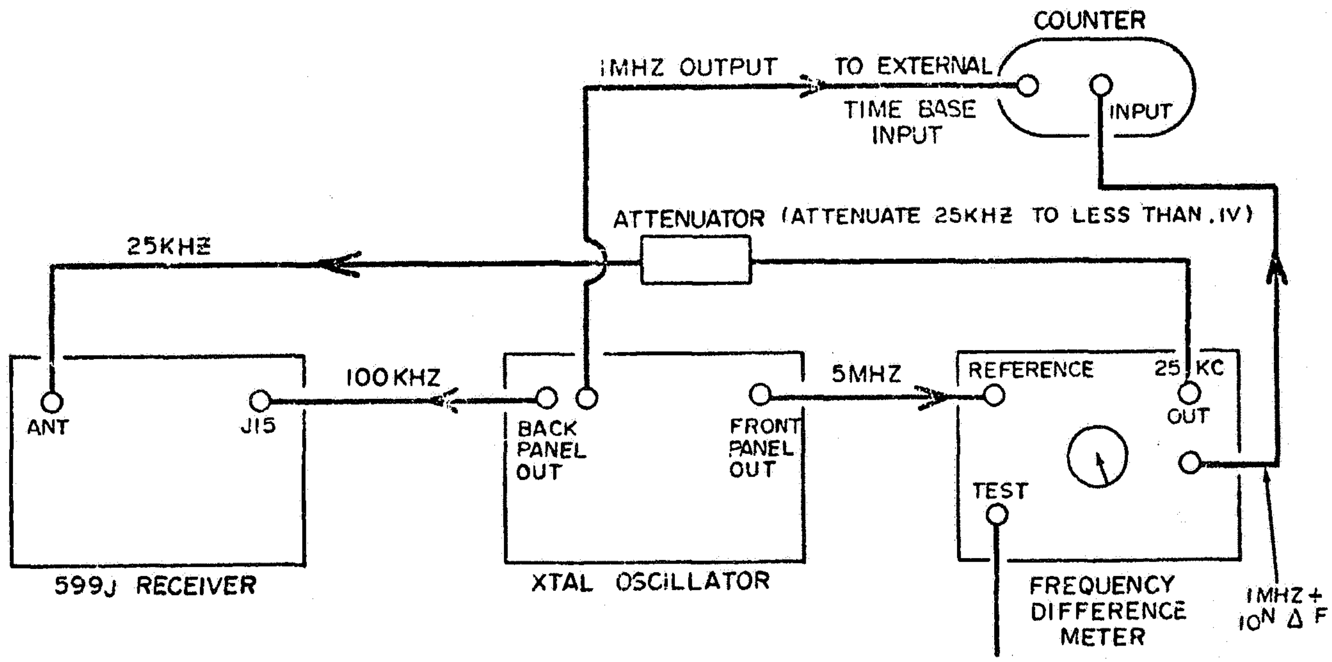


Fig. 4—System checkout for frequency calibration

If the ideal frequency difference meter were purchased now, it would have both a zero center meter for setting oscillators to a minimum frequency difference and a digital display for monitoring the stability of the oscillator under test.

V. SUMMARY

The system used by USAMCC has generally performed well and has thus far justified its selection over alternate techniques and systems. Reliance on VLF does require labor,setting up and operating the VLF receiver, making judgments on the displayed phase plot, and adjusting the quartz oscillator.

N75 27188

"THE GLOBAL RESCUE ALARM NET (GRAN): CONCEPT AND APPROACHES"

Clara L. Calise and CDR William R. Crawford,
Naval Air Test Center

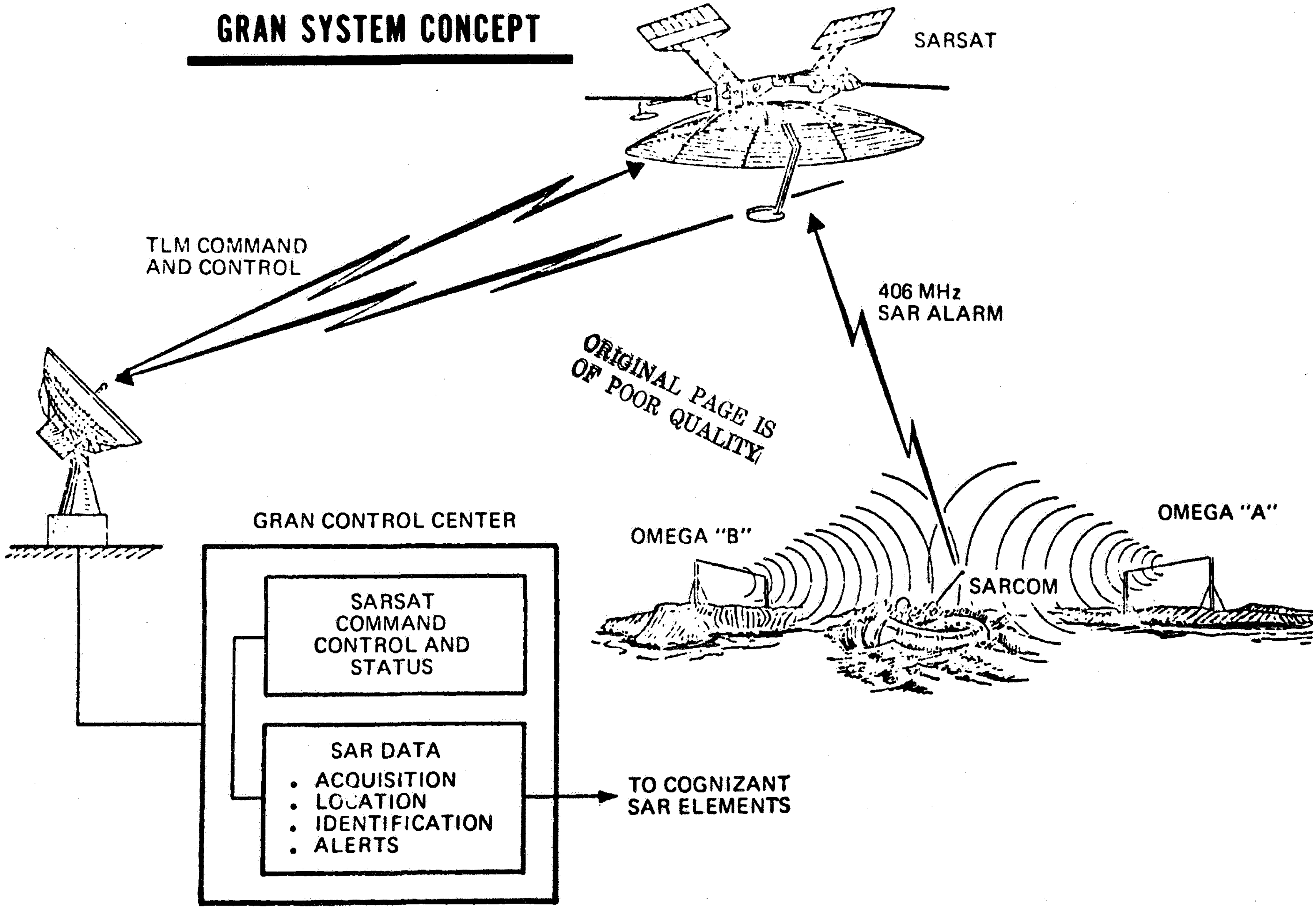
ABSTRACT

The GRAN Experiment is designed to prove a world-wide search and rescue (SAR) system utilizing Omega navigation system signals and geo-synchronous satellites. In order to develop a SAR system, the original NASA Omega Position Locating Equipment (OPLE) experiments have been expanded by the Naval Air Test Center, Patuxent River. Specifically, a fourth frequency (10.880 KHz) has been added experimentally to two Omega transmitters. This will increase line of position (LOP) ambiguities from 72 nautical miles to 360 nmi apart. Algorithms have been developed to resolve the 360 nmi ambiguities. During September and October 1974, two series of tests were conducted with Lincoln Experimental Satellite 6 (LES-6) to demonstrate the position locating potential of the four-frequency Omega concept. This paper presents the experiment design, results, and conclusions as they apply to the GRAN system.

INTRODUCTION

The Global Rescue Alarm Net (GRAN) was conceived as a worldwide search and rescue (SAR) system designed to provide real time distress alerting, identification and position location. The Omega Navigation System, presently under construction, will provide the information from which the distress site will be computed. The GRAN concept basically consists of portable battery powered search and rescue communicators (SARCOMs), appropriate frequency translators aboard earth synchronous satellites (SARSATs) , and a network of three or more ground receiving stations (SARCENs) (figure 1). The GRAN concept has been under development for five years. It evolved as an application of the OMEGA Position Location Experiment (OPLE) performed in 1967 by the NASA Goddard Space Flight Center. In this experiment, raw OMEGA navigation signals were received at a remote test site, upconverted in frequency to VHF, and retransmitted to a synchronous satellite (ATS-1 and 3) for relay to a ground processing center where a geographic position was computed. This experiment demonstrated that OMEGA data could be relayed without distortion. (reference 1).

In 1969, the U. S. Naval Air Test Center at Patuxent River, Maryland, performed an OPLE test using a low power (less than 5W EIRP) UHF uplink. This series of experiments demonstrated


GRAN SYSTEM CONCEPT
SARSAT
TLM COMMAND
AND CONTROL
406 MHz
SAR ALARM
ORIGINAL PAGE IS
OF POOR QUALITY
OMEGA "B"
OMEGA "A"
SARCOM
GRAN CONTROL CENTER
SARSAT
COMMAND
CONTROL AND
STATUS
SAR DATA
• ACQUISITION
• LOCATION
• IDENTIFICATION
• ALERTS
TO COGNIZANT
SAR ELEMENTS

the feasibility of low power SARCOMs for retransmission of raw OMEGA data to earth-synchronous satellites (reference 8).

The OPLE experiments required a foreknowledge of the re-transmission site to within 72 miles which is the ambiguous "lane" structure of the basic three frequency OMEGA system. For the GRAN application to search and rescue such foreknowledge cannot be assumed. Thus, it became necessary to devise a method for obtaining unambiguous position location from Omega in the absence of any foreknowledge of position.

Originally, OMEGA was proposed as a five frequency system with ambiguities arising approximately every 3600 miles. However, the U. S. Navy found little demand for the five frequency format. Instead, maritime users seemed willing to accept a three frequency system with its 72 mile ambiguities. This appeared to pose no special problems for ships which could "initialize" their Omega receivers at known geographic positions upon embarkation, and keep count of lanes as they slowly traversed the seas to their destinations. The U. S. Navy was satisfied to construct the less costly three frequency Omega system with its concommitant savings in individual receiver-processor units for shipboard use. It is probable that that decision underestimated the potential user population for OMEGA, particularly air traffic. As of this writing at least one U. S. carrier is testing Omega receivers as a potential replacement for some on board inertial platforms which have demonstrated very high cost of acquisition and maintenance. For instance, many Boeing 747 passenger jets carry three inertial platforms. These remarks are offered to justify the GRAN efforts to expand the present three frequency Omega system to a four frequency system. These efforts are well within the scope of the original Omega concept, and the applications for an expanded Omega satisfy an unforeseen demand for a worldwide, reliable, inexpensive area navigation system.

The GRAN concept utilizes a four frequency OMEGA format with an additional signal at 10.880 KHz. The additional frequency was selected by Dr. J. A. Pierce of Harvard University, and has been added to two Omega transmitters for test purposes. The addition of the fourth frequency increases the lane width from 72 nmi to approximately 360 nmi, and permits use of the maximum likelihood estimator technique for resolution of position within the larger lane.

The location of the SARCOM in distress is accomplished in three steps:

1. Reception from one of three geo-synchronous satellites determines which 1/3 of the earth's surface contains the distress site.

2. A coarse lane estimate is then determined by one of two methods:

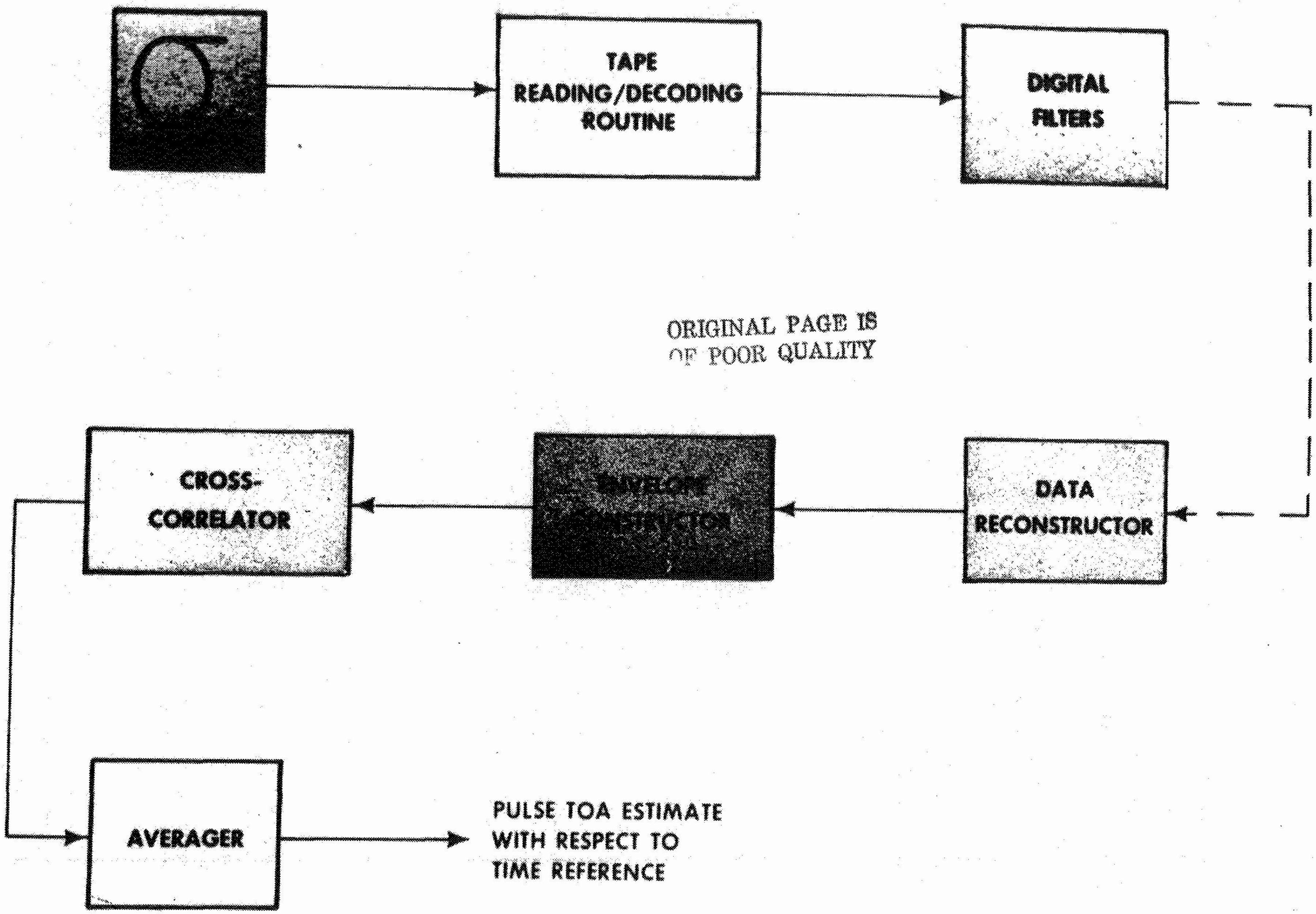
a. Signal-to-signal comparison of the relayed Omega can be used to reduce the area of interest to approximately 1000-2000 nmi.

b. Difference in time of arrival (TOA) of the Omega pulse envelope to determine a 360 nmi lane.

3. A maximum likelihood estimator, or walkup algorithm, refines this estimate to a correct 8 nmi lane and then further to a 1-2 nmi area.

The signal-to-signal comparison is based on the fact that the amplitude of very low frequency (VLF) signals decrease in strength approximately inversely with distance from the transmitter. A comparison of signals from Omega receivers potentially could be used as a coarse ranging function. Preliminary computations indicated an accuracy of ± 500 nmi at the baseline (between two Omega stations) and ± 750 nmi at the farthest location away from the baseline. Initial experiments to prove this concept were conducted by the Naval Air Test Center and Texas Instruments, Dallas, Texas, and are reported in reference (2). These experiments indicate that when the Omega transmitters are at full power (10 KW at 10.2 KHz) the signal-to-signal ratios may provide a coarse ranging function, but this function will not satisfy the GRAN requirements for a ± 180 nmi estimate to the increased lane width from the additional Omega frequency. The method of time of arrival (TOA) is more applicable to the GRAN needs than the signal-to-signal comparison.

The solution to determine the TOA of the pulse envelope can be approached in a number of ways. One approach that has been considered is outlined in figure 2. Four frequency Omega data from a recent test period has been stored on magnetic tape. This data would be digitally filtered to obtain the four individual Omega frequencies from each station. Reconstruction of the signal would then be accomplished using a third order hold technique. The reconstructed signal would then be sampled in quadrature and a technique developed by Mr. Eric Swanson of the Naval Electronics Laboratory Center (NELC), San Diego, (reference 3) would be used to construct a pulse envelope. The envelope for each frequency would then be cross correlated with a model of pulse rise and pulse decay to establish a relative time of arrival. The resulting pulse time of arrival estimate would then be averaged. The final result would be a TOA estimate with respect to the time reference, recorded on the data tapes, for each Omega station frequency. This approach will work only if amplitude information is available to determine the start of the signal. Since this amplitude



TIME OF ARRIVAL TECHNIQUE

information is not available in our present system configuration, another approach also is being considered.

Instead of detecting pulse TOA via amplitude, a means for frequency detection is being explored. This can be accomplished by:

1. Fast Fourier Transform

The application of this technique depends on the rise time of the pulse. If the signal is distorted enough in the rise time region by the automatic gain control (AGC) in the ground station, then the frequency may not be detected until the level period of the pulse, thus, diminishing the possible use of a fast fourier transform.

2. Coherent Detector

This detector provides a translation of the carrier frequency to direct current. It does not destroy phase information nor does it destroy amplitude information. The coherent detection is efficient especially when signal-to-noise ratios are low. It has the disadvantage that pulse rise times may be distorted.

3. Zero-Crossings Detector

Information contained in the zero-crossings of the waveform can be used to detect the presence of signal in noise. Of particular interest is the distance between the crossings of the waveform along the zero voltage axis. The variations in distance depend on whether signal plus noise is present, or noise alone. One possible form of this detection is a phase filter which is dependent on the frequency of the input signal and not its amplitude.

These are just a few of the possible avenues for solution of TOA estimation. Each is being evaluated to determine its adaptability to the needs of the GRAN system.

The final step in determining position location utilizes the maximum likelihood estimator derived by LCDR C. J. Waylan of the Naval Postgraduate School, Monterey, California (reference 6). His work was supported by the GRAN project and has been incorporated in the GRAN processing technique. This maximum likelihood estimator assumes that the correct major (360 nmi) lane has been identified. The estimation is then performed within this unambiguous lane by fixing the sum of the great circle distances from each of the Omega stations to the center of the lane of interest, and then varying one great circle distance over a range of values necessary to traverse all candidate lines of position (LOP) in the given lane.

This variation would be $\pm$ 180 nmi on the baseline between the two stations (figure 3). The likelihood function varies with great circle distance (figure 4), and the number of local maxima in the unambiguous lane is determined by the values of the function and the number of Omega frequencies. The cyclic nature of the function shows the necessity for lane ambiguity resolution and yields LOP estimates which fall into three categories:

1. Estimates within 1-2 nmi or less of the correct LOP.

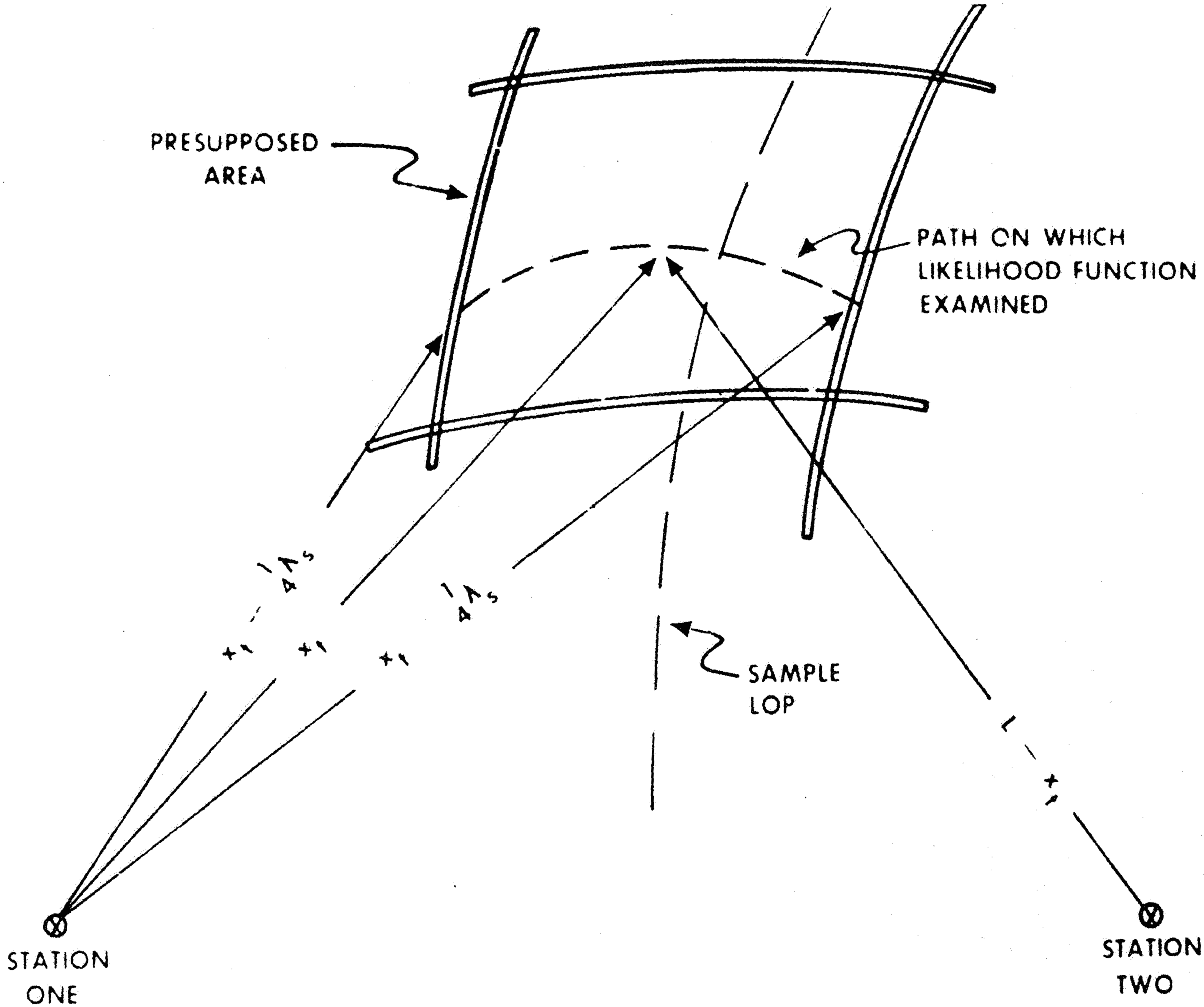
2. Estimates one half wavelength of the four Omega frequencies form the correct LOP (minor lane error).

3. Estimates farther from the correct LOP than the previous two (major lane error).

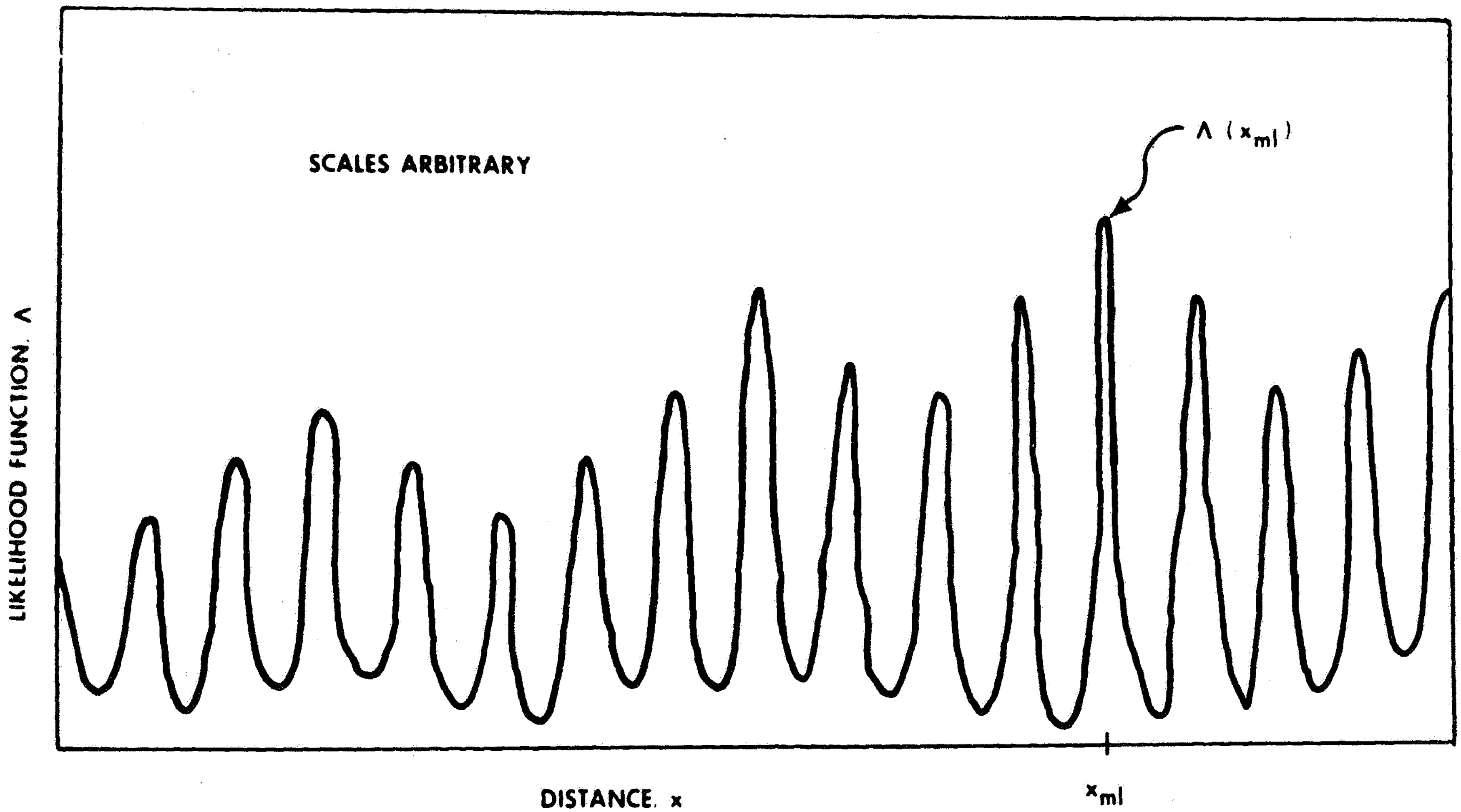
In the GRAN application at least three stations (two station pairs) would be used to obtain two LOP's. The intersection of these LOPs would yield a better position estimate of the SARCOM than the use of one LOP. The use of four stations (three station pairs) would pinpoint the 1-2 nmi distress area.

Data retransmission tests are presently being conducted at remote sites using LES-6 as the SARSAT link and two experimental four frequency Omega stations (Forestport and Trinidad). The data collected from each of the seven remote sites will be processed using both the maximum likelihood estimator and the walk-up technique developed by Professor Pierce (reference 4). Processing using the walk-up method, is being done at Texas Instruments, Inc., Dallas, Texas. These results will be compared with those of the maximum likelihood estimator as part of the analysis to help determine the adapatability of the estimator in the present configuration. Further analysis of the data will be done to determine the effect of using skywave correction factors in the calculations.

From the detailed analysis of the collected data it will be possible to determine the best position estimate, using the maximum likelihood estimator, based on a foreknowledge of the correct 360 nmi. Also, the best technique for arriving at a TOA estimate of this 360 mile lane in order to fit the GRAN system, will evolve from this collected data. Each of these pieces when added together, will equal a global search and rescue system with a position location ability of 1-2 nmi.



GEOMETRY FOR THE ESTIMATION PROBLEM



A TYPICAL LIKELIHOOD FUNCTION

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4. Texas Instruments, Inc., Four Frequency Omega Experiment Final Report, Vol. I, prepared for Naval Air Station, Patuxent River, Maryland, under contract # N00421-73-C-7617.

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QUESTION AND ANSWER PERIOD

MR. CHI:

In the global rescue system, what is the philosophy in the first large determination of the location of the person to be rescued? How far do you have to know—distance wise? How do you locate it? Do you have several stations in the globe?

MS. CALISE:

There will be several SAR centers or, search and rescue centers, located in different parts of the world.

MR. CHI:

So what is the ambiguity resolution then you need?

MS. CALISE:

We need a 360 mile lane, which will be accomplished with the fourth frequency. The data that we've selected has shown that if we're using a 360 mile lane we can come within, say, one to two nautical miles, in determining the position—actually in this case, a line of position.

MR. CHI:

If there are numerous users with this equipment, then I believe you will need perhaps a system to reduce the distance in order to make quick rescue,

MS. CALISE:

The techniques that we'd use would take the 360 mile lane. And resolve it down to a position, if I understand you right.

MR. CHI:

How do you know which 360 mile lane?

CDR. CRAWFORD:

The philosophy is, at this point, to make some kind of trade-off between not having any knowledge of where you are and zeroing in within one or two miles.

First of all, you know which satellite so that puts you in an area—we're talking about a global system and we're also talking about getting a snapshot of OMEGA data. And this is really where the trade-off comes in, how long a snapshot do you really need.

So when Clara talked about having a computation time of three minutes, we're looking at still maintaining the three minute Opal retransmission time of the data. Of course, the longer you collect OMEGA data the better you're going to get a feeling for the phase.

So this puts some demands on the amount of power that you're going to carry in the battery in the SARCOM. Some studies by Eric Swanson at NELC, and he took the worse case conditions, indicated that with three frequencies his integration time, in order to get within the 72 mile lane, or really half of 72 mile lane, was something like between 30 and 45 minutes.

If you have four frequencies you have more data but with the fourth frequency you have the wider lane. In this case, on the base line you have 360 miles. Start looking at that integration time under worse case conditions and the integration time then goes down toward between 3 and 6 minutes.

This is also almost within the present window of Opal transmission time of 3 minutes of relaying of data. So, it's a tradeoff between lane width and integration time to be able to pick the correct length.

MR. CHI:

The reason I raised the question is that I believe the system is very good if the time of arrival of rescue is short. In any event, the philosophy of reducing to the positional location of the person in need of help, is the lapse of time which really is under consideration. Whether you go from 8,000 miles to 360 miles and go down to 72, but I obviously have to go to the direct point before you can help the person.

Now, what is the overall time regardless of how you would do it, and what is the philosophy of approaching it which would, actually should, allow one to reduce time to a minimum to yet the location of the person?

I can see there are difficult tradeoffs that you can use. The question is, how long do we have?

CDR. CRAWFORD:

I'm going to take a tangent here for a minute. Let's look at the OMEGA format problem which I'm certain is behind some of your comments here. One of the things we proposed, and Miss Calise made reference to it, is that a fourth frequency, a fourth navigational frequency, be transmitted, and of course the 1088 does give you with two frequencies differences 226 hertz lanes.

Another set of frequencies, let's say some timing frequencies, spaced by 250 hertz certainly is a solution to doing the lane identification, you know, the 72 mile lane identification in this philosophy of stepping down. Although, then there is a tradeoff, there's another tradeoff that we've looked at as far as the bandwidth of the system goes.

This means that we're looking at trying to fit say, 40 channels into the 100 kilohertz bandwidth which has already been assigned as a search and rescue frequency at 406.0 to 406.1 megahertz. We're looking at a 2-1/2 kilohertz bandwidth for each one of the retransmissions so this allows us to accommodate a large number of users.

So you can use a frequency in time diversity, let's say, because you won't have somebody coming on calling for and sending in an alarm at the same frequency at the same time. Now as far as time to get to a person, this is going to be primarily determined by the distance from the accident site and the nearest search and rescue force.

Now, we're looking at the total amount of processing time, the retransmission between the three minutes, let's say for the SARCOM, and a two minute processing time, total computer time, before you get an identification of who it is and where he is. So that this should take approximately five minutes.

Then you have to relay the information to the appropriate Coast Guard site or Air Force recovery site and then it's up to them to get there.

Does that answer your question as far as time goes? What we're really looking at is—can a small snapshot of OMEGA data, say three minutes long, collected from anywhere in the world, give us a unique location or, with some confidence, let's say a number of locations, but certainly not a complete coverage area that's maybe 300 miles square?

DR. WINKLER:

You have proposed a fourth OMEGA frequency which presumably will also be time shared. Could that be accomplished with a unique frequency at each station with just one which also should give you the same lane resolution, albeit at a small penalty?

The answer's yes?

CDR. CRAWFORD:

How many unique frequencies would you have on those? Are you talking about eight?

DR. WINKLER:

Yes. But of course these would not be audible in all segments which you have serviced. It was said in one from North Dakota for instance, cannot be received anywhere in the Indian Ocean, I think. So there would be no likelihood for the frequency to appear at that time.

On the other hand when you hear a certain one loud and strong you would know you have your fellow somewhere on North America. It would make identification much simpler, I think.

N75 27189

A GENERAL DESCRIPTION OF LORAN-C: PRESENT AND POTENTIAL APPLICATIONS

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U. S. Department of Commerce
Office of Telecommunications
Institute for Telecommunication Sciences

ABSTRACT

Loran-C is a low frequency (100 kHz) pulse navigation system. The pulse format and phase stability of the system are of paramount importance for both navigation and time synchronization using this system.

The need for a low frequency loran system was born out of the shortcomings of the standard loran system used during World War II. Many early tests of low frequency loran culminated in the testing of Cytac by the U. S. Air Force in the early and mid 1950's. This was a tactical bombing system, and was a direct predecessor to Loran-C.

Present Loran-C installations operated by the U. S. Coast Guard cover much of the northern hemisphere. A recent government-wide decision has declared that Loran-C will be the U. S. Coastal confluence navigation system for the immediate future. Therefore, Loran-C stations are presently being installed or planned to cover the entire U. S. coastline.

In addition to standard navigation and timing applications of Loran-C, auxiliary navigation and timing applications are presently being considered or are potentially available. These include differential or relative Loran-C for high precision positioning, urban vehicle or residence location by the AEC, the FBI and the Census Bureau, off shore oil drilling, and collision avoidance by ships or aircraft.

Finally, the unique nature of the Loran-C pulse transmission allows one to separate ground wave and sky-wave transmission. Also, the pulse provides a transient capable of validating transient propagation theory. Therefore, the Loran-C transmissions have proven to be very effective diagnostic tools for validating propagation theories. Continued efforts in this direction will undoubtedly lead to improved prediction and calibration procedures for use with all Loran-C systems.

INTRODUCTION

Loran-C is a hyperbolic radio navigation system utilizing 3 or more transmitters in a simple chain configuration (see figure 1). The transmitters radiate fast rising pulses so that a phase and envelope measurement can be made on the early part of the pulse (ground wave), before the arrival of the first hop sky wave (the first signal to arrive after reflecting once from the ionosphere D-region--see figure 2). By tagging a point in time on the ground wave portion of the radio wave pulse, stabilities of about one order of magnitude more accurate than the combined ground wave and sky wave phase measurement on the propagated pulse are observed (i.e. to propagation time measurement error less than one microsecond). The above description explains the method for deriving time information from Loran-C within the ground wave range of any transmitter.

For navigation purposes, the user must also be within ground wave range of two or more slaves. A similar propagation time measurement is made on the slave and the master and the difference between these measurements is shown as a TD (time difference). A single TD measurement will define an LOP (line of position) relative to the master and slave. Two LOP's relative to a master and two slaves will then define a position fix as indicated in figure 1.

To insure that the master and subsequent slave signals will not overlap in time within the service area, coding delays are introduced into the slave transmissions in a sequential order. Each station radiates groups of 8 pulses, and the master station radiates a ninth pulse for identification purposes. All stations transmit the phase of the pulse in a 0 or 180° coded format. This phase code aids in automatic receiver identification and automatic phase synchronization of the receiver with the master and slave signals. The phase coding also gives protection against synchronous CW interference.

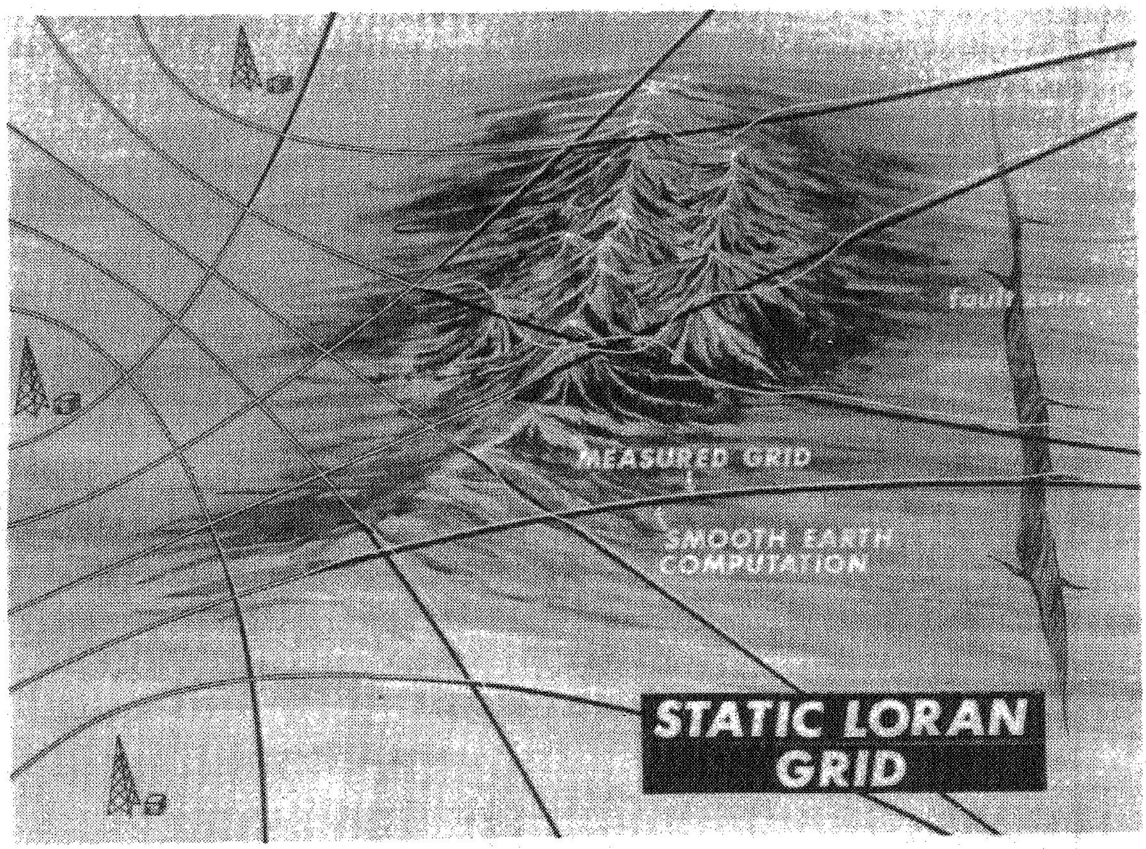

Figure 1. Loran-C static grid depicting the effect of terrain anomalies in a three station chain.

This 100 kHz pulse type loran radio navigation system was first developed in the early and mid 1950's by the U. S. Air Force as a tactical system under the name Cytac. The objective of the development was a ground based bombing system for use in aircraft [1] targeting. In the early tests on this system it was recognized that radio signal propagation time was influenced by the electrical properties of the ground over which the signals propagated. These electrical properties can be represented compactly as a ground impedance. Thus, the impedance of the ground was considered to be primarily determined by such ground electrical constants as the conductivity, the dielectric constant, and the permeability. At 100 kHz the effect of conductivity is dominant and theoretical calculations [2] used impedance calculators [3] which converted conductivity into impedance and then calculated a secondary phase correction, or the phase correction due to the fact that the signals travels slower than the speed of light in microseconds. Early attempts to evaluate the effect of ground conductivity and indeed to predict and update predictions by using measured data have been reported [1].

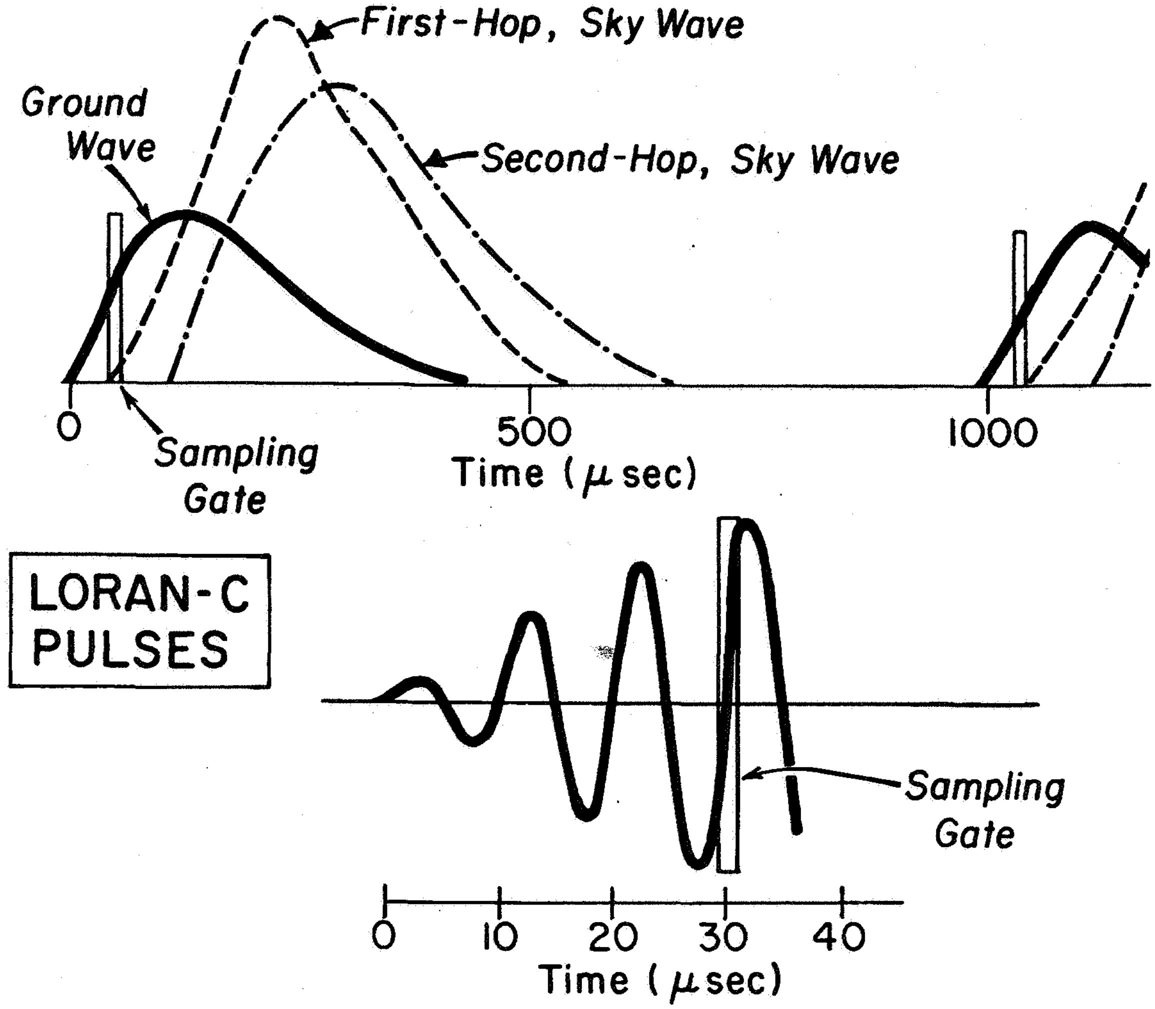

Figure 2. Loran-C pulse as transmitted along with the effect of ground wave and sky wave signals received. This figure also demonstrates the ground wave sampling prior to the sky wave arrival time.

The early measuring equipment was quite complex and required considerable size and power to operate as demonstrated in figure 3.

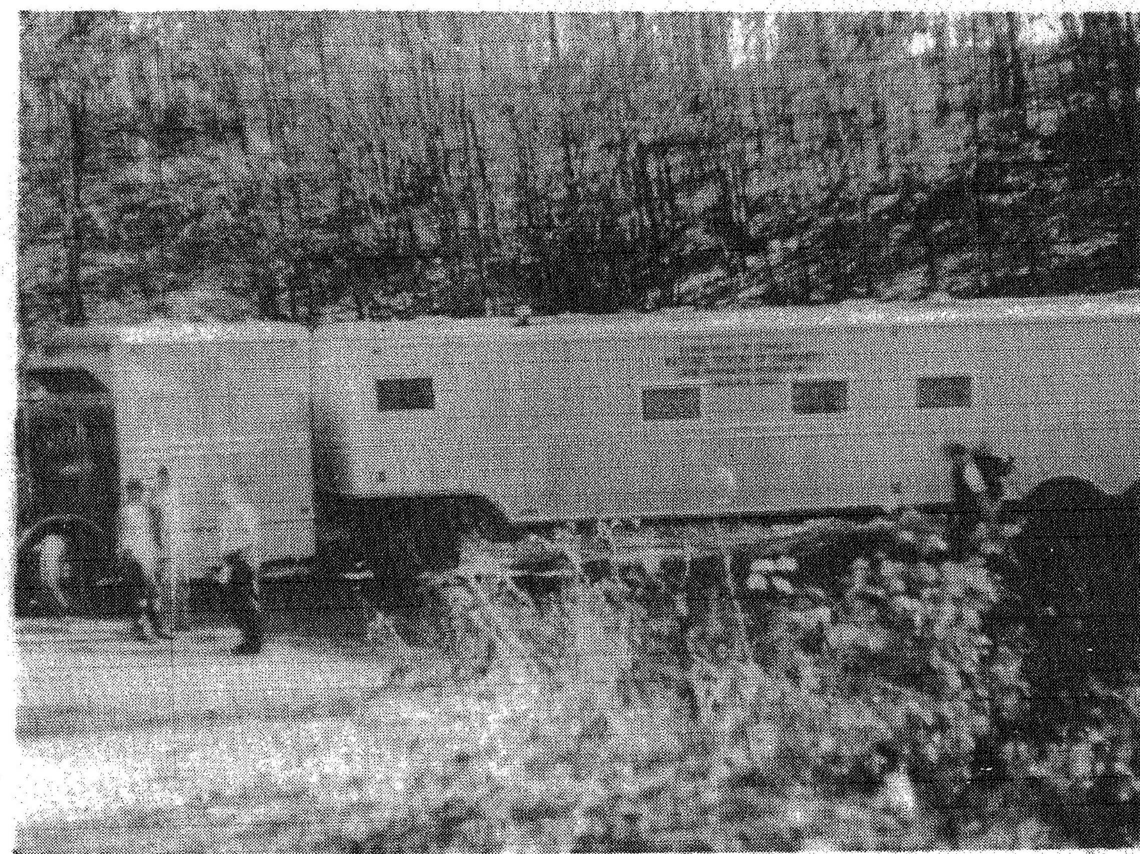

Figure 3. Vehicle housing Cytac (predecessor to Loran-C) receiving equipment in 1954.

Attempts to measure effects in rough terrain, such as those depicted in figure 1, were very difficult as shown in figure 4. Recent advances in electronic miniaturization have allowed back pack receivers shown in figure 5 to replace two 15 kw diesel generators and seven relay racks of equipment that were housed in the tractor trailer during the Cytac tests. Today, rough terrain spatial variation may be more readily investigated. Complete resolution of a propagation change on an individual path requires the direct phase measurement of propagation time from a particular station. To make these measurements today, the equipment shown in figures 6 and 7 is employed.

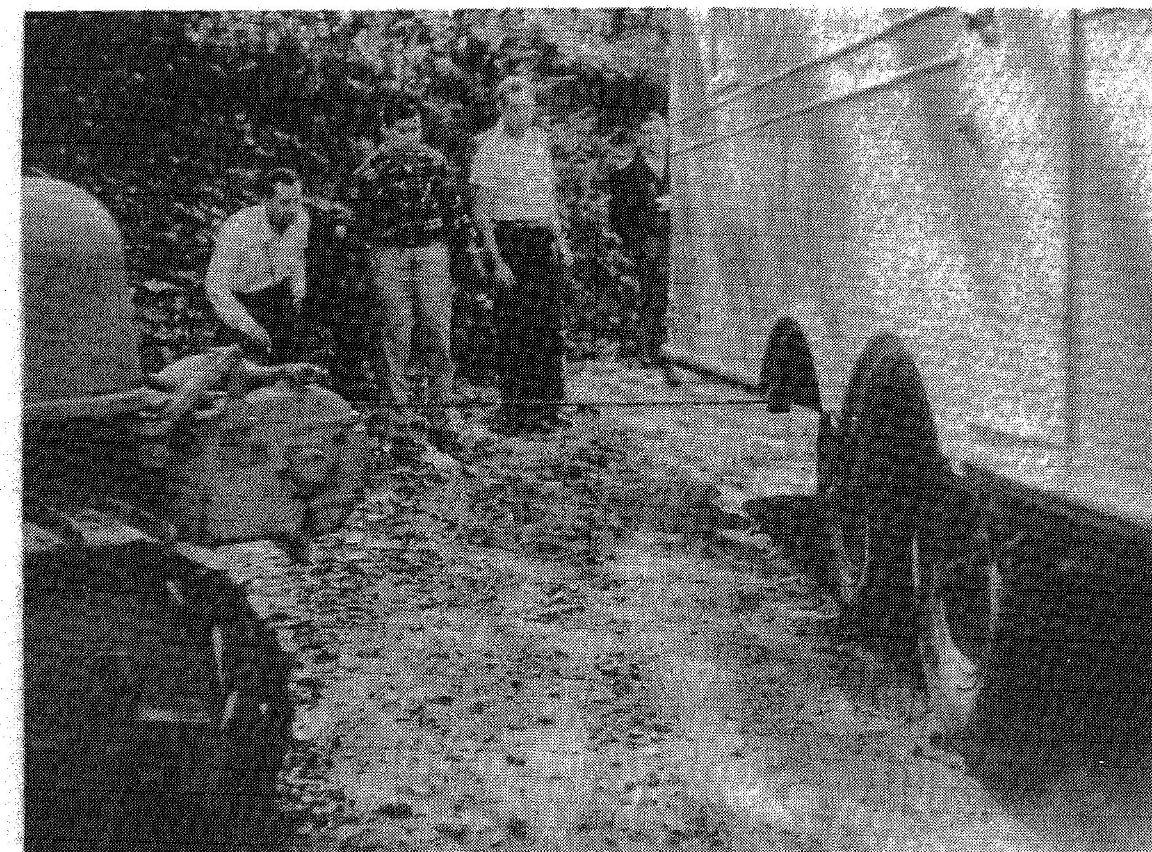

Figure 4. Difficulty with 1954 vehicle in attempting to make measurements particularly in irregular terrain.

Following the U. S. Air Force development of this loran system, the U. S. Coast Guard adopted the system for navigation on the high seas. The system was named Loran-C by the U. S. Coast Guard, and a number of loran chains (comprising a master station and two or more slaves) for over the ocean coverage were subsequently installed [4]. The impedance of sea water has a value, $\Delta = 0.001055 \exp(i\ 0.7854)$ relative to free space or 377 ohms. This corresponds to a conductivity of 5 mhos per meter and a dielectric constant of $\epsilon_2 = 80$ where the permeability of a propagation medium, $\epsilon = \epsilon_2 \epsilon_0$ and ϵ_0 is a universal constant of nature, $\epsilon_0 = 8.8542(10^{-12})$F/m. It can also be noted that sea water is an excellent conductor at 100 kHz and a good approximation for sea water would be: $\Delta = 0$ and the conductivity, $\sigma = \infty$.

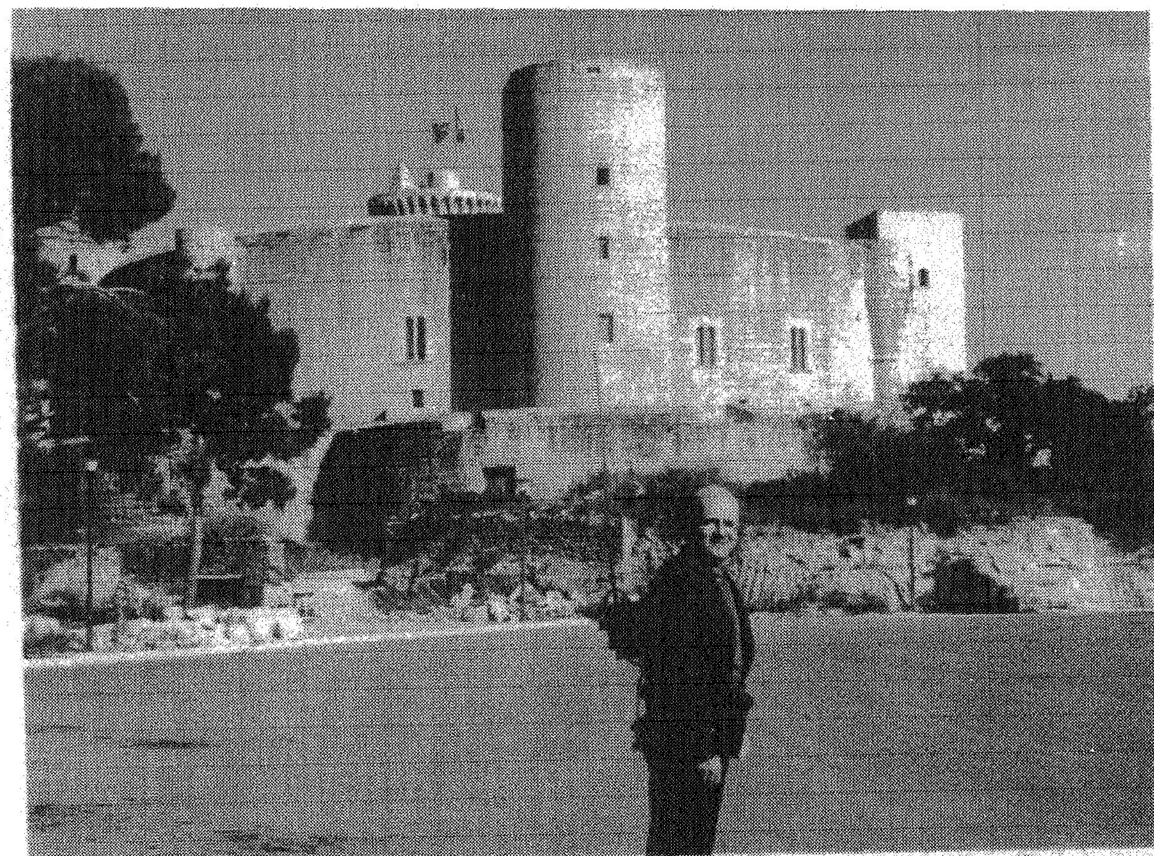

Figure 5. Back pack Loran-C receiver used in measurement program in 1973.

The salt water model for secondary phase correction was relatively simple and using the salt water curve in reference [1], algorithms for this model were programmed into several receivers. Although the secondary phase correction is directly related to physical parameters of the path of propagation, the salt water model has sometimes been accepted as a standard, and corrections over and above the salt water corrections are termed "additional secondary phase" (ASP) corrections. These "additional secondary phase" corrections have no physical significance, because it is the total secondary phase correction that is significant. The "additional secondary phase" correction cannot be derived directly from theory, but can only be deduced by differencing two separate theoretical calculations. The physical cause of the secondary phase correction is (1) the ground impedance discussed above and (2) the earth curvature. In exceedingly irregular terrain as indicated in figure 1, the earth curvature factor may become a significant contributor to the secondary phase corrections as pointed out by Johler [3].

Figure 6. Vehicle housing modern Loran-C equipment capable of measuring both direct propagation time (U) and time difference (y) for calibration purposes.

Two points relative to this secondary phase factor in irregular terrain are quite significant: (1) The spatial variations are essentially static, that is, the measurements are repeatable with time; (2) The spatial variations can be uniquely predicted using Maxwell's equations and existing propagation theory, if one is sufficiently thorough in defining the propagation path from the transmitter to the receiver. Therefore spatial variations in the Loran-C system can be calibrated or predicted.

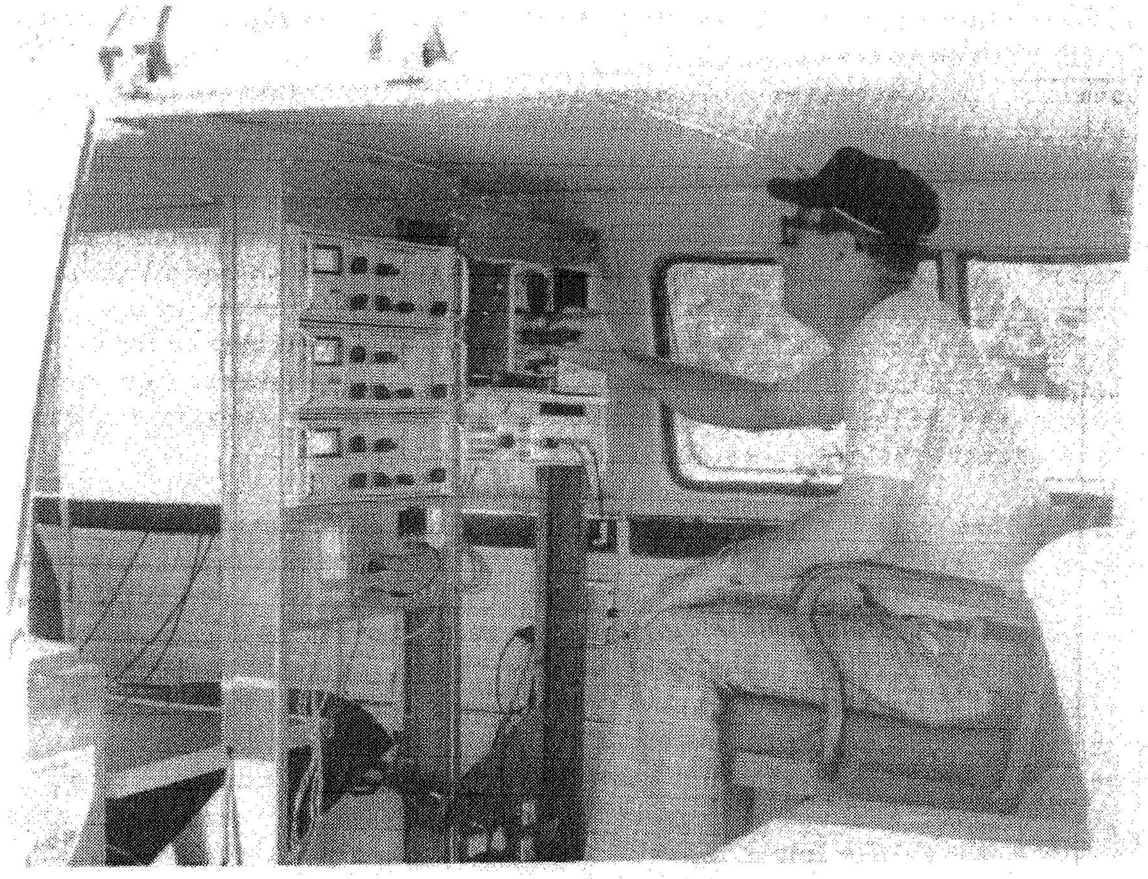

Figure 7. Close up of equipment housed in vehicle shown in figure 6.

Loran-C Applications Present and Potential

Loran-C Ground Wave Applications

Loran-C is and always has been a navigation or position fixing system, and this context always dictates its area deployment and the specific transmitter locations. These dictates, however, do not necessarily limit the use of the system for other reasons, such as timing or diagnostic propagation studies. Conversely the lack of stations, for example in western U.S. have often limited the auxiliary usage of the system. The recent U.S. decision to make Loran-C the coastal confluence navigation system should help this problem. The present and future deployment of Loran-C chains is adequately covered in a subsequent paper in this proceedings by LCDR J. F. Roeber.

The decision to employ Loran-C as the coastal confluence navigation system does not require mid continental deployment of the Loran-C system. A number of governmental and civilian agencies are potentially interested in using Loran-C in the continental U.S. There is a specific interest in using Loran-C to located non-urban or rural residences in the 1980 census; there is interest in vehicle tracking and locating by both the F.B.I. and the A.E.C.; and there is considerable interest in using Loran-C for locating off shore oil drilling platforms. There has also been considerable interest in using Loran-C or the mini loran version of Loran-C for urban vehicle tracking. This last application is most difficult because large steel structures and power and telephone lines can act as reradiators and thus destort the received signal.

In addition to the long range navigation system, Loran-C, some shorter range systems variously known as Loran-D, mini loran, augmented loran, etc. have entered the picture. All of these systems have been developed to meet specific needs in areas where Loran-C coverage is not available. The only notable change between these short range systems and the Loran-C long range system is the use of 16 rather than 8 pulses in the Loran-D system and the changing of the ground wave sampling point from 30 to 50 microseconds (3^{rd} to 5^{th} cycle). Both of these changes are possible because it is a short range system where one hop sky wave time delays are greater, and multi hop sky wave interference is less severe.

Loran-C low frequency ground wave propagation, as mentioned previously, differs from the speed of light propagation by the small correction, denoted as the secondary phase correction. For example, figure 8 shows predicted and observed variations of approximately 2 microseconds over a small change in path distance on a path where the total propagation time is approximately 1000 microseconds. The solid cruve represents predictions along a path that crosses Death Valley California. The Xs represent measurements at points that lie essentially on this path including point D that was directly below the precipitous drop into Death Valley. The ⊡ marked 1 through 9 represent measurements made along the highway that decended gradually into Death Valley. A much more complete description of the experiment is given in reference [5]. This is considered to be a severe or maximum deviation case in the navigation or timing predictability of the system. Although this variation represents only 1 part in 250 to 300 of the predicted propagation time, such a variation could develop an error of several thousand feet in a navigational fix.

This size of error, if not corrected, is unacceptable in many applications. Fortunately, the prediction ability exists, but it is not simple.

The spatial variations described above are essentially time invariant i.e. you would always return to the same place with the same measurement. As one probes further and further into the measurement capability of this system, one finds that the system is capable of measuring temporal phase changes in the ground waves [6]. These changes have been correlated with weather variations such as temperature changes, as well as the passage of frontal systems. The degree of correlation of these signals with weather phenomena suggest that measurements of the signal might be used as an adjunct to weather predictions. The temporal variations can approach one or two microseconds in the most severe case. This case is a long propagation path over land subjected to sub freezing conditions. Over shorter propagating paths, in temperate climatic regions and propagation paths over sea water temporal variations seldom exceed 0.1 or 0.2 microseconds.

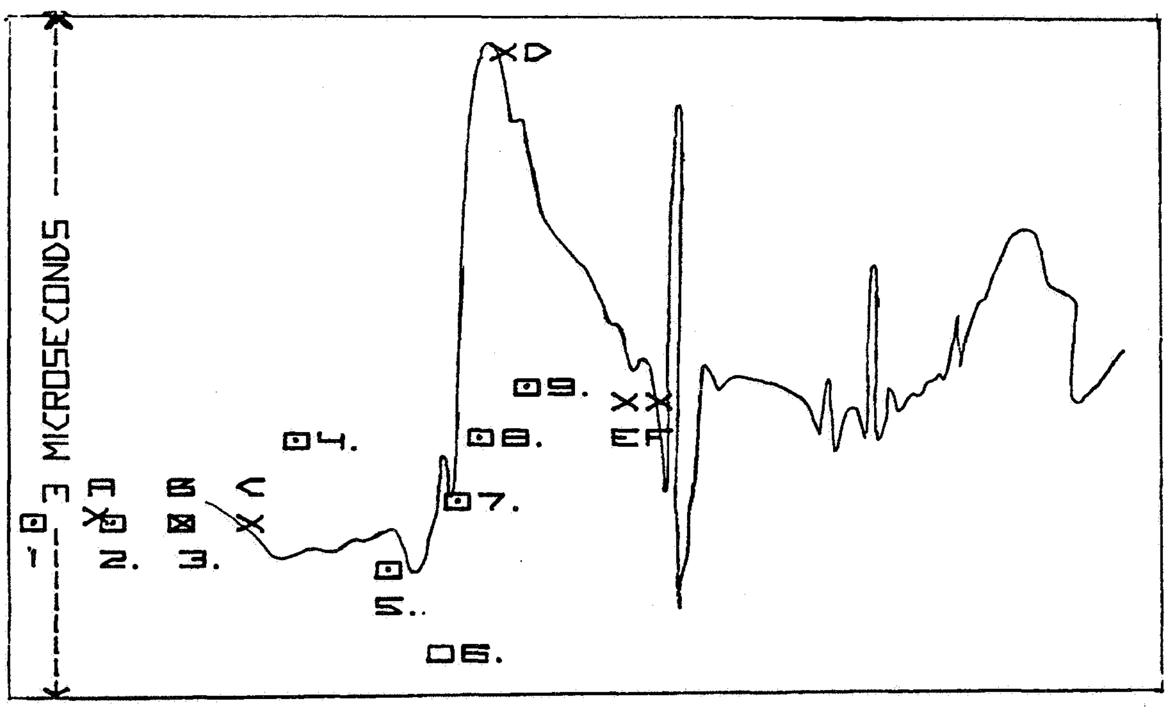

Figure 8. Predicted and observed direct propagation time (U) for a Loran-D signal in rough terrain.

One obvious method for eliminating the error caused by temporal variations over long paths is by using "differential" or relative Loran-C. In this mode of operation a station at a known control location will observe and broadcast corrections to users within the vicinity of the control station. Figure 9 and reference [7] show some initial comparisons between differential loran and differential Omega. The upper solid curve designated A shows a differential Loran-C measurement over a 10 day period where the distance between the two receivers was 300 km. The lower solid curve designated B shows measurements over the same 10 day period for receiver separation of 700 km. The standard deviations for these measurements were $\sigma_A = .08$ and $\sigma_B = .11$ microseconds. For comparison the bars representing 1.62 microseconds and 2.63 microseconds were given by Nard [8] for differential Omega. Also peak deviations for differential Omega give by Beukers [9] exceeded the scale of the graph. These measurements are explained in greater detail in reference [7]. A subsequent study [10] has shown that a U. S. Coast Guard harbor and estuary requirement for 50 feet positional accuracies could be met using a relative loran concept. Continuing studies of the same data used in the "differential" or relative Loran-C study [10] has shown that major temporal variations during summer months are due to chain variations. New data will be collected during the winter months in early 1975 for direct comparison with the summer data previously reported.

The use of loran in a relative or "differential" mode can improve position fixing capability and potentially could be used for aircraft or ocean vessel collision avoidance through retransmission of the measured TDs to other craft in the immediate vicinity. Accuracies of this order of magnitude are also potentially competitive with the extensive DME-VOR system used by commercial aircraft.

It was recognized prior to 1960 [11] that Loran-C would be capable of time synchronization of remotely separated clocks. Furthermore, if time synchronization can be established periodically, time interval measurement capability also exists. In the 1961 publication, it was suggested that synchronization capability of 1 microsecond or better could be achieved operationally using ground wave propagation. The paper also stated that operational capabilities of 10 microseconds could be achieved using sky waves. A subsequent publication [12] in 1972 reported ground wave synchronization capability with $\sigma = 0.28$ microseconds, and that initial tests by NASA suggested sky wave synchronization capabilities on the order of several microseconds were possible.

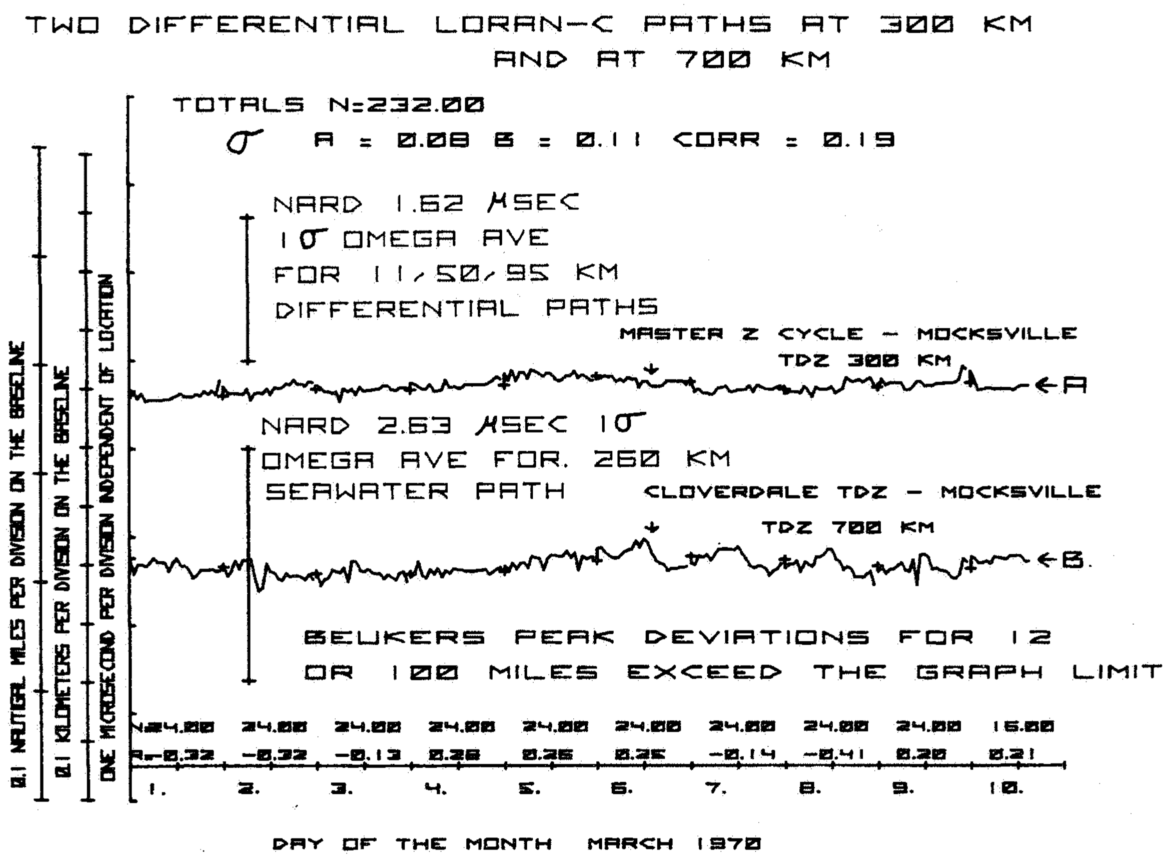

Figure 9. Differential Loran-C compared to differential Omega.

Loran-C has been used extensively for synchronizing clocks at widely separated locations where there was a need to measure a common event. Specifically, this timing capability was very important in the early space program, and in measuring the arrival time of pulses from nuclear detonations. It should be recognized that the prediction capabilities discussed earlier will be of paramount importance in a time synchronization application if the ultimate timing potential of the system is desired.

Loran-C Sky Wave Applications

Sky wave signals will always be delayed relative to ground wave signals, because they travel further in reflecting from the ionospheric

D-region as shown in figure 10. By sampling the received Loran-C pulse at a later time, it is possible to monitor a signal primarily related to a single reflection from the ionosphere. This is particularly true at ranges where the ground wave signal is weak relative to the sky wave signal. Many sky wave measurements have been made at existing Loran-C transmitting locations through the courtesy of the U. S. Coast Guard. To date these measurements have been used primarily for diagnostic purposes to validate propagation theory and for ionospheric studies.

There has been interest in using sky wave signals for both navigation and timing purposes. The limitation for sky wave use of the system has been the inability to resolve the proper cycle of the sky wave pulse. Resolving the proper cycle on the leading edge of the uncontaminated ground wave signal is possible by making a separate envelope measurement. In the sky wave case, the ground wave and sky wave mix as shown in figure 11 [13].

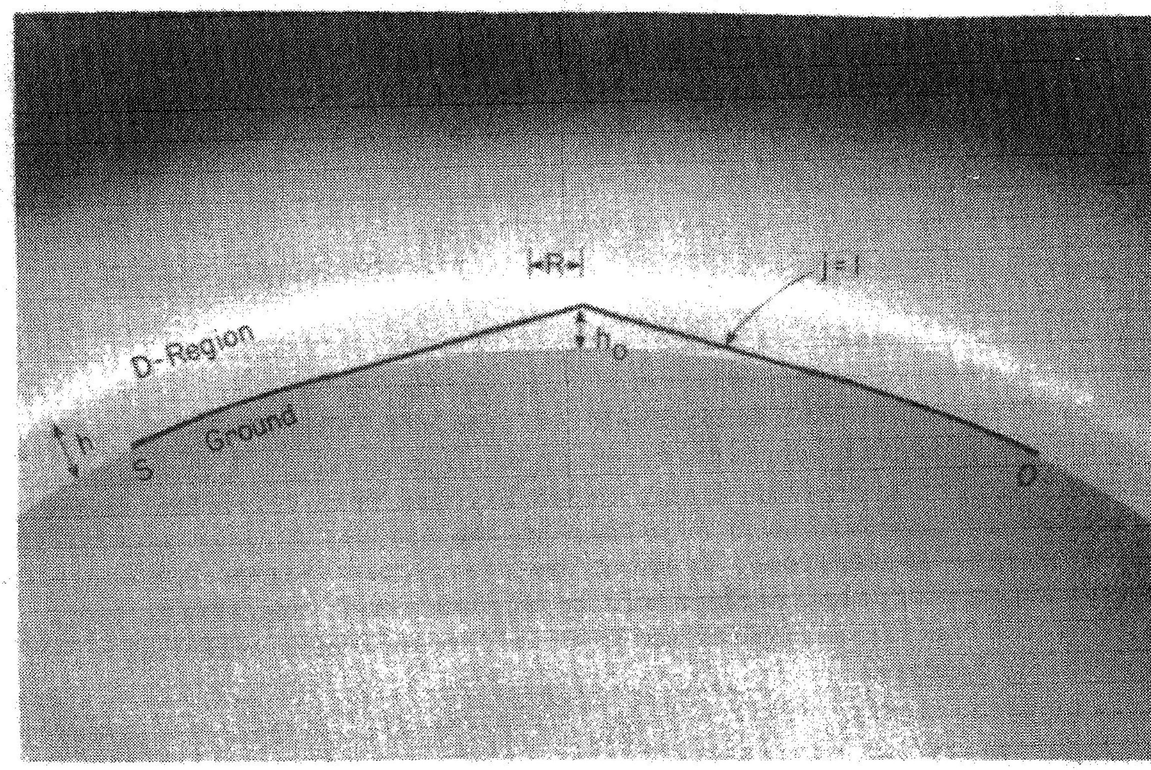

Figure 10. Pictorial display of surface wave path and D-region ionospheric propagation path.

The theoretically predicted signal in figure 11 looks quite similar to the measured signal in figure 12. An example of the diagnostic use of these sky wave signals was the interpretation of the solar eclipse measurements in figures 12 and 13 in terms of oxygen and ozone changes in the ionospheric D-region during an eclipse [14,15,16]. In references [15] and [16] many other observed phenomena on the Loran-C sky wave signals are noted and explained. Also, observations of nighttime sky waves yielded identification of particle precipitation events in the D-region at lower latitudes than had been previously suspected [17]. Continuous observations of these signals have indicated that changes in the D-region occur seasonally as well as diurnal changes shown in figure 14. Variations with geomagnetic latitude have also been noted [15].

Problems and Limitations of Loran-C

The propagation limitations on the Loran-C ground wave systems have been previously noted. By way of review, spatial variations of 1 to 3 microseconds will produce positioning errors 1,000 to 2,000 feet if not properly removed. Removal of these large errors is possible by calibration or prediction using physiographic features of the surface. Temporal variations of tenths of microseconds will produce positioning errors in the hundreds of feet if not properly removed. Temporal variations over sea water and temperate land paths will be much smaller. Removal of temporal variations can best be achieved by using differential or relative loran. It may be possible after further studies to predict temporal variations similar to the way spatial variations can be predicted now.

System or chain variations of approximately tenths of microseconds or hundreds of feet presently occur in the Loran-C chain operation. These variations could probably be reduced or removed by different chain operating procedures or by installation of new equipment. This type of variation is also removed by using differential or relative Loran-C techniques.

A Loran-C problem that will increase with increasing density of Loran-C installations is the cross rate interference problem. As can be seen from figure 14, any interference problem Loran-C has with itself will be worse at night. The cross rate interference (one Loran-C chain interfering with another) can be minimized by proper selection

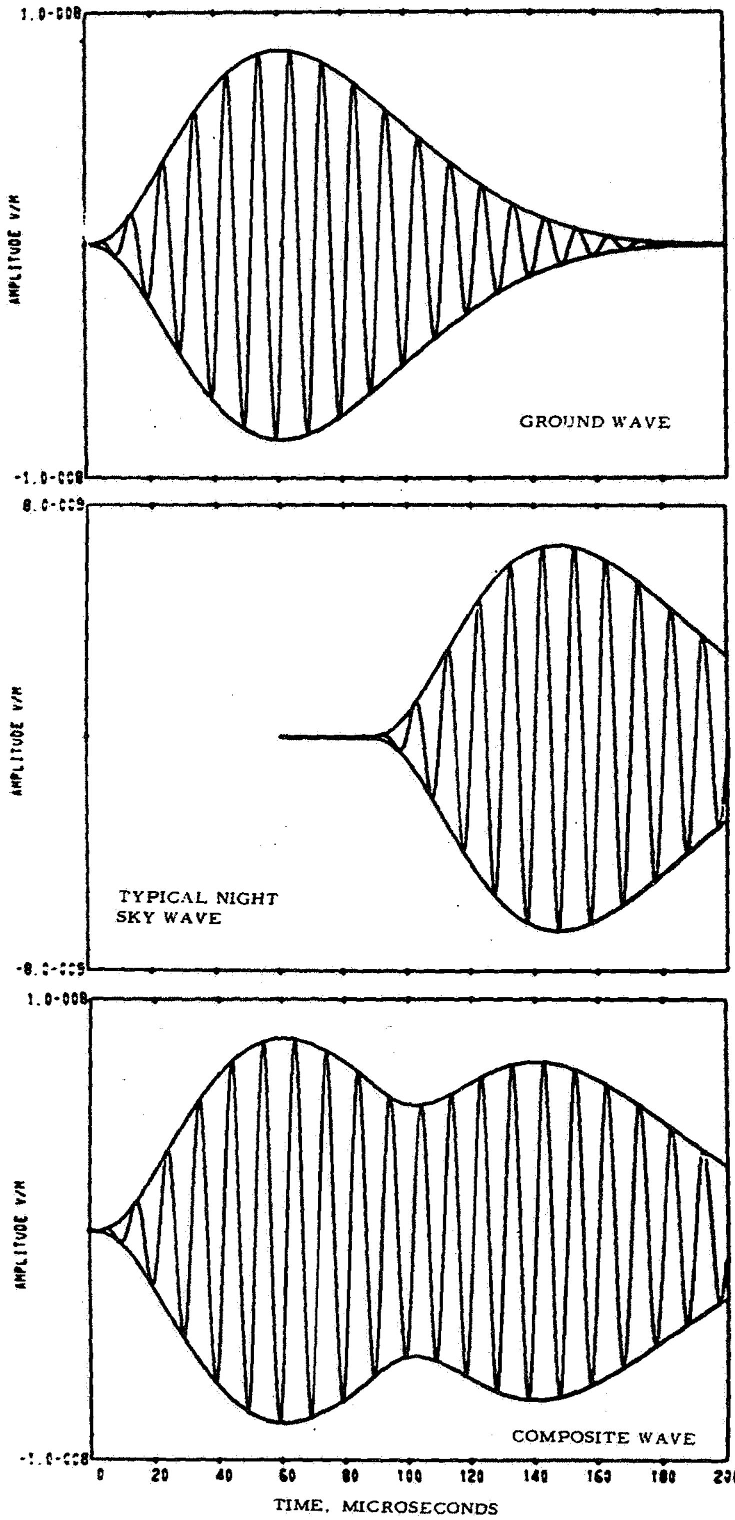

Figure 11. Theoretically predicted ground wave and sky wave pulse arrival times.

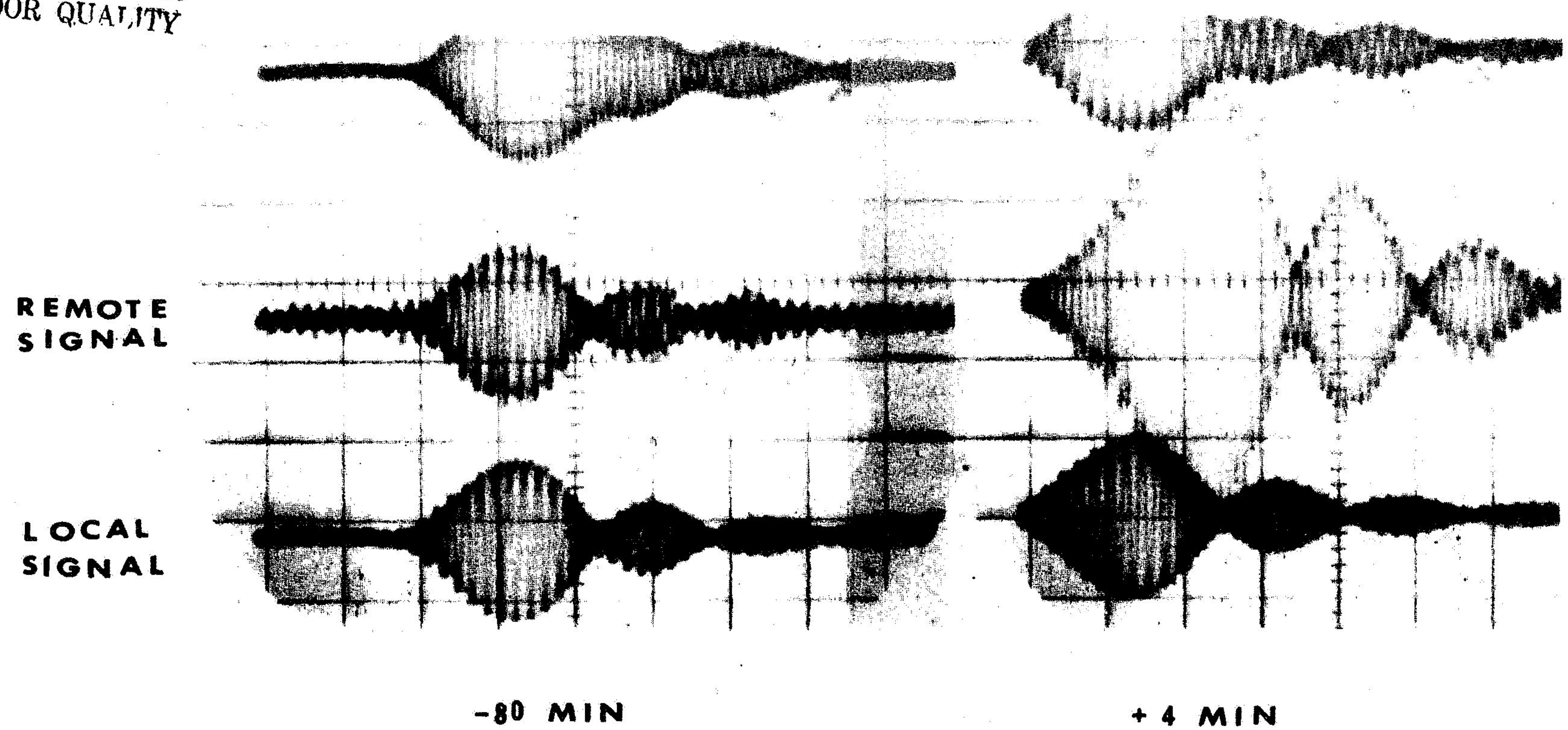

Figure 12. Observed ground wave and sky wave propagated signals during a solar eclipse.

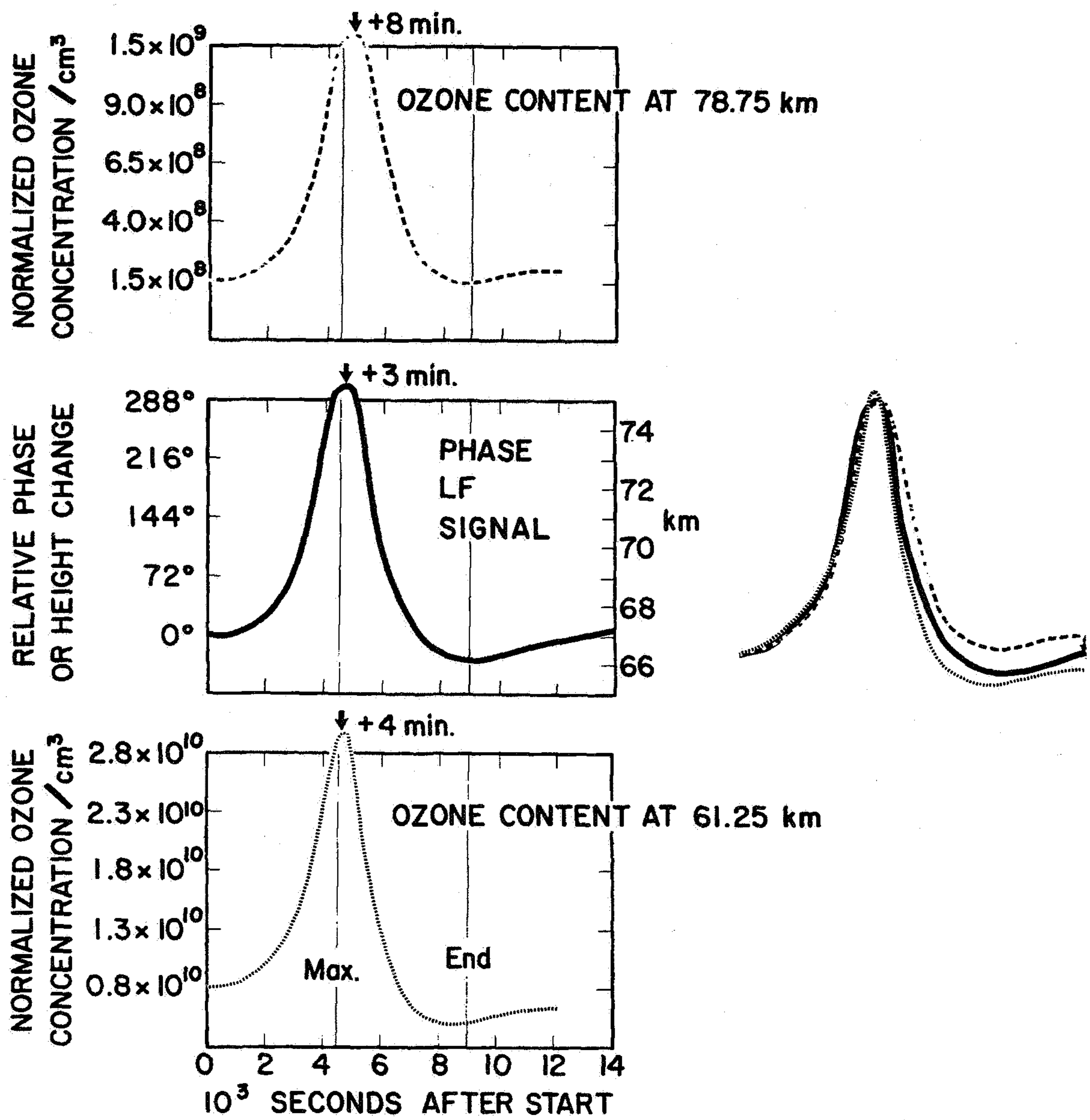

Figure 13. Relative phase measurements of a Loran-C sky wave signal compared to computed ozone changes for a solar eclipse occurring in July 1963.

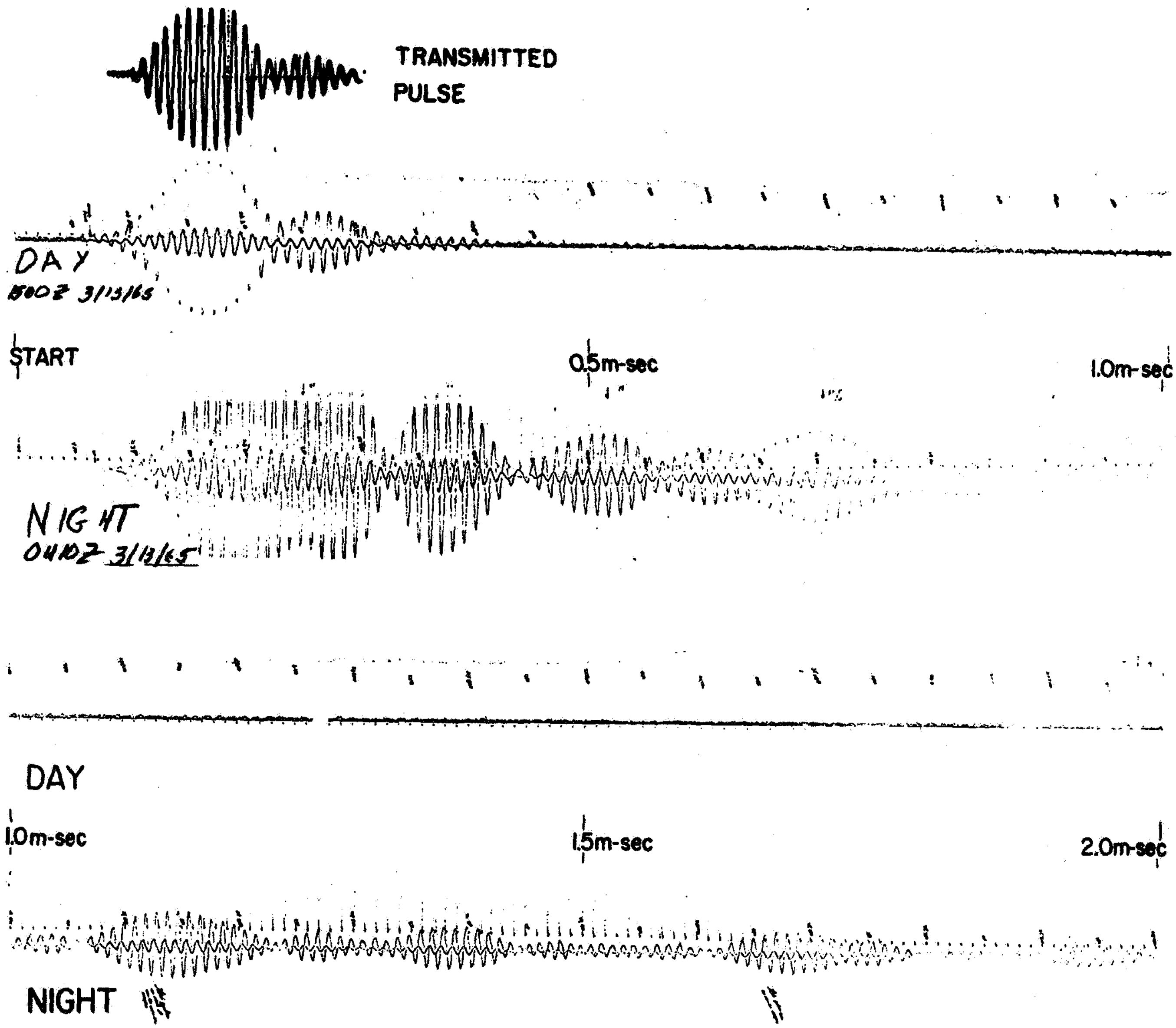

Figure 14. Multiple hop Loran-C sky waves observed at night compared to one hop sky wave observed during the day on a path from east coast to Boulder, Colorado.

of pulse repetition rates. The problem cannot be eliminated entirely by repetition rate selection, and as more chains are added more signals will be radiated, and the problem will become more severe.

Proper cycle identification is a Loran-C problem because loss of proper cycle identification is nearly always the limiting factor in establishing the usable range of the system. This problem is more a function of different receiving equipment rather than propagation conditions. Fundamentally all Loran-C receivers measure an envelope arrival time and phase or cycle arrival time. The envelope arrival time determines the coarse time and the phase or cycle arrival time gives the ultimate accuracy in units, tenths, and hundreths of microseconds. The difference between the envelope and cycle reading is denoted as the envelope to cycle "difference" or discrepancy (ECD). From this description, it can be seen that an ECD occurs for each signal and two ECDs are involved in a time difference (TD) measurement. The propagation theory predicts ECD as a function of distance from the transmitter. To the author's knowledge, no receiver manufacturer has attempted to program this ECD correction into their receivers. The theory also predicts large ECD variations in the vicinity of irregular terrain [16]. The ECD variations associated with irregular terrain are unique to each particular terrain path.

Finally, one of the most serious problems with Loran-C is the "jargon" used by the Loran-C community. It is difficult to communicate with people outside the Loran-C community when those within understand a complete set of acronyms and speak in terms of them. As a result of these problems in communications between the loran community and the non loran community, a new set of nomenclature is proposed here. This nomenclature uses subscripts freely, and letters previously unassociated with Loran-C measurements. For example, y is used to denote a time difference measurement rather than TD; u is used to denote a direct measurement of the propagation time of a Loran-C signal from a single transmitter. The propagation of Universal time through the system, which includes the baseline propagation time and the coding delay for the slaves, is designated by U. Formerly this measurement was called TOA to stand for time of arrival. For the ECD (envelope to cycle difference) described above, the Greek symbol Γ was selected. The envelope propagation time correction is designated by T_c and the cycle or phase propagation time secondary phase correction by t_c, such that $\Gamma = T_c - t_c$. The secondary phase correction is denoted t_c and time delays associated with receivers are denoted R. A subscripting system $y_{i,j}$, $U_{i,j}$, $\Gamma_{i,j}$ etc is used to refer to locations i and j, such that φ_i, λ_i, or φ_j, λ_j are the latitude and longitude of these locations. In all cases, the i refers to a transmitter location, $i = 0$ is used for the master transmitter, $i = 1$ for the slave with the lowest coding delay (formerly called slave A, slave X, or slave W), $i = 2$ for the slave with the second lowest coding delay, etc. In all cases the j stands for the receiver location φ_j, λ_j. If the j subscript for a particular measurement is 4 or less, then the receiver is located at a transmitting site. The j subscript may become as large as necessary to describe a given set of Loran-C measurements. Since the time difference measurements always involve the slave arrival time minus the master arrival time, there will be no y values with an i subscript of 0.

The East Coast Loran-C chain will be used as an example to demonstrate how this system works. For the master at Carolina Beach, $i = 0$,; for the Z slave (4th slave in the East Coast chain) at Dana, Indiana, $i = 4$. For an arbitrary location where $j = 7$, the arrival time of the master signal will be $U_{0,7} = \eta / c(d_{0,7}) + t_c(d_{0,7}) + R_7$, and the arrival time of the Dana slave signal will be $U_{4,7} = \eta / c(d_{4,7}) + t_c(d_{4,7}) + R_7 + \beta_4$, where d stands for distance, η for the surface index of refraction, c for the speed of light in a vacuum, and β_4 for the coding delay associated with the no 4 slave, Dana, plus the propagation time from the Master to the Dana slave. Following this, the time difference will be simply $y_{4,7} = U_{4,7} - U_{0,7}$. At the master station the direct phase measurement of the Dana slave signal would be $U_{4,0}$, and the time difference would be $y_{4,0}$. At the Dana slave the direct phase measurement of the master would be $U_{0,4}$ and the time difference would be $y_{4,4}$. The Γ's at these sites would have the same subscripting as the U's and they would relate to the envelope measurement or prediction minus the phase measurement or prediction [16]. This same nomenclature has been expanded to include the differential Loran-C measurements and their associated time constants.

CONCLUSIONS

It would appear, in view of the great user interest and recent government wide decisions, that Loran-C will remain a viable and useful system for the forseeable future. At the present time it would appear that Loran-C is one of the better long range timing and time interval standards available for general use. Loran-C still has a considerable unexploited potential in differential usage, such as collision avoidance and high precision position fixing. Loran-C has been very useful for validating low frequency propagation theory for both ground wave and sky waves. It has also been useful as a diagnostic tool for probing the ionospheric D-region to better evaluate its characteristics. This particular usage of the Loran-C system could be exploited and extended much further.

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QUESTION AND ANSWER PERIOD

DR. REDER:

If you are in a mountainous region and you have a Loran-C receiver, how accurately can it determine your position?

MR. DOHERTY:

If you are in a mountainous location with a loran receiver and you're interested in being about to return to that position, then we feel that the accuracy is of the order of 50 feet. If you're interested in knowing precisely where that position is, then the answer is how much money are you willing to spend to predict where that position is theoretically. Because we again feel that we can approach the 50 foot accuracy if we have the information necessary to predict it, but this means the terrain and impedance, information all the way back to the transmitting station.

Now, we're rapidly approaching the ability to do this entirely digitally on computers. So, well you say it's trivial. It's not trivial. It takes big computers and lots of tapes and things like that, but we are getting to the point where we can do this.

MR. KEATING:

Mr. Keating, Naval Observatory.

One of the problems with this approach is that it requires, I believe, a fairly detailed knowledge of the terrain, the conductivities, the area over which you're going to integrate. You're quite right about this numerical integration being very complex, but how do you go about getting this data? Some of this mapping of the terrain can be horrendous or is your method much simpler?

MR. DOHERTY:

No, it's not much simpler. Well, maybe it is in one way. The terrain mapping information exists in the form of digitized tapes at DMA for many locations. It boils down to a single tape for the entire United States, from which you can go from path A to path B.

We have done that much and we believe that the detail is sufficient for the analysis that we have done here. We don't have the impedance information on magnetic tape I might indicate at the present time. We're proposing that it should be done.

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DESIGN AND OPERATION OF A LORAN-C TIME REFERENCE STATION

Kenneth Putkovich
U.S. Naval Observatory

ABSTRACT

The purpose of this paper is to explore some of the practical questions that arise when one decides to use Loran-C in a time reference system. Since the subject of Loran-C PTTI has been covered extensively in the literature (see bibliography), a minimum of time is devoted to the concept and implementation of precise time on Loran-C. An extensive effort is made to provide basic, practical information on establishing and operating a reference station. This paper covers four important areas in this regard.

1. The design, configuration and operational concepts which should be considered prior to establishing and operating a reference station using Loran-C.

2. The options and tradeoffs available regarding capabilities, cost, size, versatility, ease of operation, etc., that are available to the designer.

3. What measurements are made, how they are made and what they mean.

4. The experience the U.S. Naval Observatory Time Service Division has had in the design and operation of such stations.

In general, an attempt is made to answer basic questions which arise when Loran-C is being considered for use in a time reference system.

INTRODUCTION

The purpose of this paper is to explore some of the practical problems that arise in using Loran-C in a precise-time reference system (PTRS). The use of Loran-C for timing has been covered extensively in the publications listed in the bibliography. For the purpose of this paper it is assumed that the intended user has satisfied himself that his timing requirements can be met using Loran-C and that his location is such that reception of Loran-C is possible. In general, this is relatively easy to determine; in a few cases it may require some on-site field testing. In any case, a sound design philosophy of determining specific requirements and examining and analyzing systems available to meet these requirements is an absolute necessity.

DESIGN, CONFIGURATION AND OPERATIONAL CONCEPTS

The design, configuration, and operational concepts are formed with the objective of creating a system which will produce consistently useful data. As design parameters vary according to system requirements in each individual case, a universal design is virtually impossible. The aspects common to all the systems dictate some design uniformity; however provisions must be made to allow for system modification where individual variations may become necessary. The design philosophy should be one of flexibility, allowing for a variety of contingencies.

Configuration or hardware concepts must also be extremely flexible to allow for unforeseen operating problems, variations in space available for equipment installation, or additional capabilities which may be needed. Operational concepts are the most important and least appreciated factor in putting a system into operation. The successful implementation of operational concepts is an absolutely necessary complement to the design and configuration concepts. Operational concepts deal with the people involved and thus are the factors which may well spell the difference between success or failure.

In developing these concepts, there are a number of questions which must be answered definitively if the design and operation of the station is to have a chance at being successful.

A. What types of data are required?

1. Is it necessary to know time-of-day, phase, or both?

2. Will measurements be relative or absolute?

3. To what accuracy do the quantities measured have to be known?

4. To what precision do the measurements have to be made?

The types of data required will dictate the type and complexity of equipment needed. The realization of absolute time-of-day to 5 microseconds with a precision of ± 0.1 microsecond requires more sophisticated techniques and equipment, for example, than that needed to determine relative phase to an accuracy of 10 microseconds with a precision of ± 1 microsecond. Obviously, any measurement requiring greater accuracy and precision requires more sophisticated techniques and equipment.

What is not obvious is the great difference in the degree of difficulty in making an absolute time-of-day measurement and making a relative phase measurement. This is true not only due to the inherent difficulties in making absolute measurements of any type but also due to the limitations which presently exist in the Loran-C time dissemination and monitoring scheme.

B. How current must data be, how often must they be reported and what means are available for reporting?

1. Are data needed in real-time, hourly, daily or after-the-fact?

2. Is a special reporting system necessary?

3. What facilities are available for data communication?

The intended use of the data dictates when, how and if they are to be sent to a central collection point. If data are for use solely in-house at the site, there is no need for reporting. However, if the site is part of a network requiring real-time response capability for system synchronization, consideration must be given to designing a reporting system. This involves developing a meaningful recording format with uniform and consistent notation as to units, sign, etc., developing a standard message format with built-in data error checks and having a communication network available which is compatible with system needs.

C. Where is the station going to be located?

1. Is the location within groundwave or skywave range of a Loran-C transmitter?

2. What are the local signal reception conditions?

3. What local primary power is available for operating the station?

4. How much and what kind of space is available for equipment?

The location is a vital factor in the design and operation of a time-reference station using Loran-C. Groundwave reception versus skywave reception means the difference between units and tens of microseconds in system capability. Severe interference problems may require additional equipment and impose additional demands on operating personnel if consistent data are to be obtained. Poor regulation and frequent, extended outages of primary power are conducive to equipment breakdowns and data discontinuities. Limitations in installation space and operating enviornment may impose restrictions on the reference station design.

D. How will the station be initially synchronized and periodically checked for proper operation?

1. Can portable clock visits be made?

2. Is there an operational PTTI satellite system available?

3. Are there other timekeeping activities in that locale?

If a station is to be part of a coordinated reference system, some means of performing an initial synchronization and periodic checks must be available for verification of output data. If there are other timekeeping activities in the area or if access to a PTTI satellite system is available, the problem is minimal. If that is not the case, and the location is not on a routinely traveled portable clock route, clock synchronization can be a vexing and costly problem.

E. Who will be operating the station and taking data?

1. Will a highly qualified and interested scientist, engineer, or technician be in charge?

2. Will the station be operated by civilian or military personnel?

The success or failure of any field operation is dependent upon field personnel. This is particularly true in the case where timekeeping is a secondary objective only loosely related to the station's primary responsibilities. The qualifications, attitudes, and interest of those immediately involved in the system, coupled with the command or management structure, can be the factor that spells success in situations where the technical aspects are marginal or the factor that assures failure in situations that should otherwise be successful.

F. How will logistical support be handled?

1. Is local logistical support available?

2. Will all logistics be handled from headquarters?

If the station is located in an area where supplies and services are available, no problems usually exist. Location in areas where no local suppliers exist or transportation facilities are meager may require extensive preplanning if the logistical problems are to be overcome.

G. How will equipment maintenance and repair be handled?

1. Will maintenance be on a repair or replacement basis?

2. Will it be local or by a central depot?

3. Will it be on a component, card, module or equipment basis?

All equipment included in the system must be chosen on the basis of favorable, established performance and mean-time-before-failure characteristics. However, most equipment needs periodic maintenance and some equipment will eventually fail. How these problems are to be solved is dependent on several factors such as station location, logistical support available and the capabilities of local personnel. At one extreme, one might have highly qualified personnel in a location where expert help and adequate logistical support is available. In this case, local repair at the component level would be indicated. At the other extreme, one might have inept, disinterested personnel at a remote site with no support available. In this case, replacement of the equipment and repair at some central depot would be necessary. The decision on what approach is to be used must be made early in the design stage as the speed with which a system failure can be corrected is an important factor in deciding how redundant the system must be made.

H. How will training of site personnel be accomplished?

1. Will training be on site, on-the-job at each site or centralized?

2. Are operating personnel permanent or subject to reassignment on a regular basis?

The probability of success in designing and operating any system is directly proportional to the capabilities, interest and enthusiasm of the operating personnel. Good data can be obtained by skilled, interested personnel using a relatively poor system, while unskilled, disinterested personnel can turn the finest system into a shambles. Training can consist of anything from a formal, structured classroom and laboratory course to informal, on-the-job, self-instruction from an instruction manual. Whatever the means of instruction, motivation and interest are two factors which must be stressed. In cases where personnel are frequently reassigned, the problem is compounded by this repeated turnover and provisions must be made for periodic retraining.

DESIGN OPTIONS AND TRADE OFFS

The options and trade offs regarding cost, size, versatility, ease of operation, etc., available to the system designer are illustrated in Figure 1 and Table 1. Table 1 summarizes the most important characteristics of typical general equipment configurations. Figure 1 provides a breakdown of the equipment and costs for each configuration. Numer-

SUBSYSTEM	EQUIPMENT	BASIC	AUTOMATIC	AUTO/REDUNDANT
CLOCK	Clock	5-23K	5-23K	10-45K
	Microstepper			3,000
	Distribution Amp		1,500	3,000
RECEIVER	TRF Receiver	750		
	Auto Receiver		6,800	13,600
	Multifilter		650	1,300
	GRP Generator	850		
DISPLAY	Oscilloscope	2,000	2,000	2,000
	Counter		1,800	1,800
	Recorder		2,000	4,000
POWER	DC Standby		1,500	3,000
	Uninterruptible			2,600
MISC	Racks, etc.	200	800	2,500
TOTAL (EXCLUSIVE OF CLOCKS)		3,800	17,050	36,800

Figure 1. Loran-C Reference Station Equipment Costs

	Basic Manual	Basic Automatic	Automatic Redundant
Cost (without clock)	\$3-4K	\$15-20K	\$30-40K
Size (inches of rack)	20-30	40-50	90-100
Versatility	Least	Better	Best
Ease of Operation	Difficult	Moderate	Moderate
Continuity of Data	Least	Better	Best
Skill Required	High	Moderate	Moderate
System Precision (microseconds)	±1-5	±0.1-1.0	±0.1-1.0

Table 1. Comparison of Typical Systems

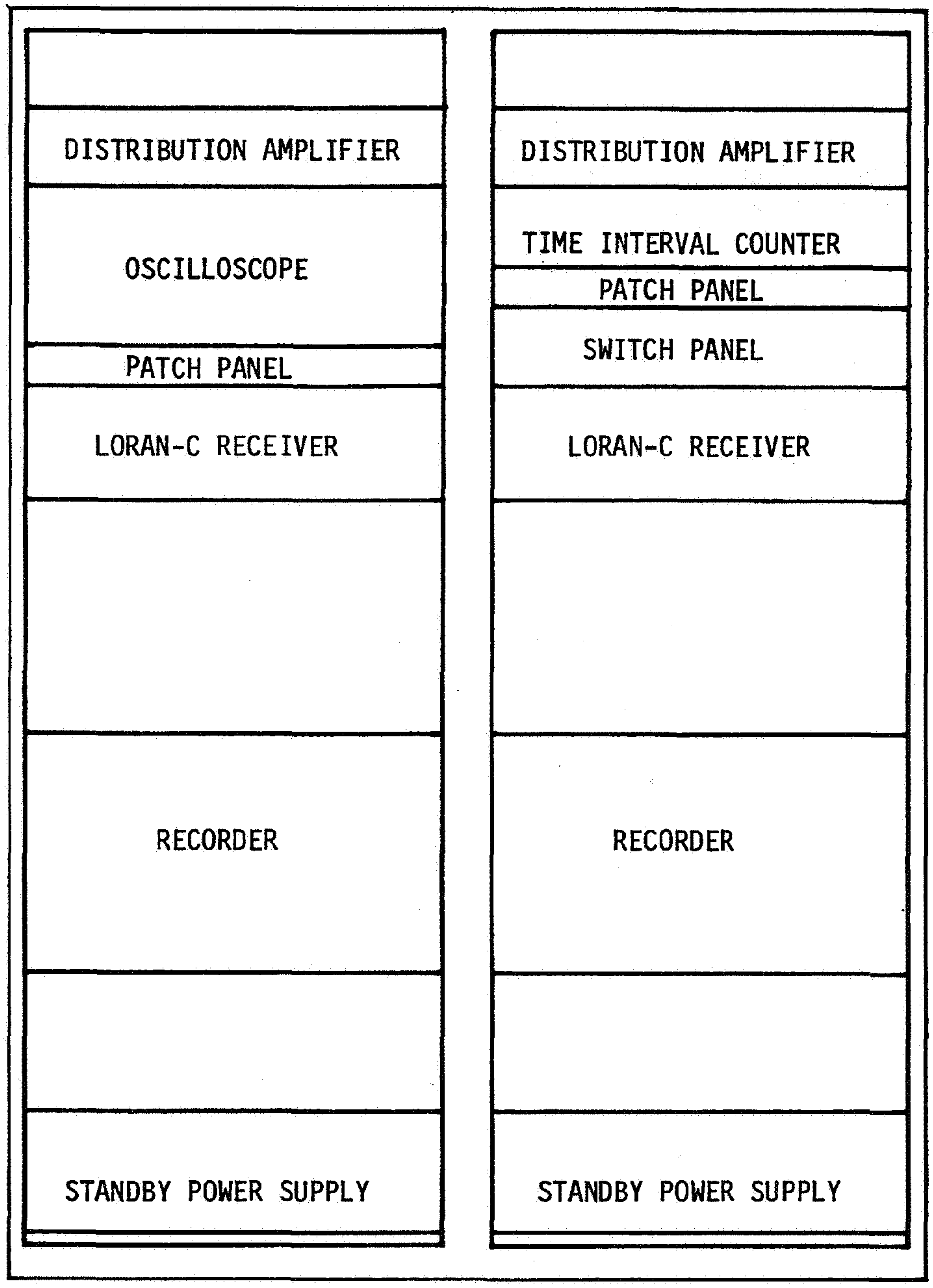

Figure 2. U.S. NAVAL OBSERVATORY PRECISE TIME REFERENCE STATION

ous other configurations are possible. A typical Naval Observatory PTRS is shown in Figure 2. As is generally true with most systems, improved operational capability means increased size and cost.

MEASUREMENTS

Typical measurements made in a Loran-C time reference system are simple. The required output data are time interval between the local clock and the Loran-C clock. Using corrections available from the Naval Observatory, (TSA Series 4), time relative to the master clock can be determined. Present state-of-the-art equipment is available for making time interval measurements with a precision of 0.1 nanosecond. This is several orders of magnitude greater than the usable limits of Loran-C transmissions; hence no measurement problems exist which are due to hardware limitations.

There are, however, problems of initially interpreting the meaning of the measurements. System delays (propagation times, antenna and receiver delays, tracking point locations, etc.) must be defined, measured and removed from the time-interval measurement to arrive at clock differences. The definition and measurement of these quantities are difficult and require special skills, techniques and equipment. Total uncertainties of several microseconds can exist in the measurements and calculations made to determine delays. Improper definition of tracking point and antenna characteristics can lead to half-cycle and full-cycle errors of five or ten microseconds. Final resolution of discrepancies usually involves field testing with a well calibrated system and portable atomic clocks.

USNO EXPERIENCE

The Time Service Division of the U.S. Naval Observatory has been responsible for the design, construction, and operation of a number of precise-time reference stations in the past seven years. Results have been mixed, with success or failure of any station being directly related to the organization and personnel operating the station. As one would expect, laboratories, whether government or private, directly involved in time-keeping are most adept at successfully employing Loran-C in time reference centers. Conversely, at locations where PTTI is a secondary effort, where highly qualified and interested personnel are unavailable, where personnel changes are frequent and where operational responsibility is spread over several organizations, attempts at consistent operation of the stations have met with numerous problems severely limiting their value and adversely affecting their data output. Even though much more effort is expended in putting those stations together and training station personnel, they experience significantly more discontinuities in data, more equipment failures and more operational problems than expected. Attempts to lessen the impact of these problems by building redundancy into the instrumentation have met with only limited success. More equipment in unfavorable circumstances seems to engender more equipment failures. With the exception of correcting obvious technical faults, improved operations at these locations depends entirely on what solutions can be found to the problems involving operating personnel idiosyncracies. It has become obvious that these problems are common to all organizations which seek to establish remote monitoring capabilities and are particularly acute in areas such as precise timekeeping where continuity and traceability are of primary importance.

CONCLUSION

An attempt has been made to highlight some of the problems encountered in using Loran-C in a precise-time system. Equipment exists to take full advantage of the timing capability inherent in synchronized Loran-C transmissions. Success at employing this equipment is dependent on operating personnel, organizational structure and system design philosophy. The concept of remote time-reference stations employing Loran-C has been proven workable; however, implementation is extremely difficult if proper conditions are not available.

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QUESTION AND ANSWER PERIOD

DR. WINKLER:

I think Ken is absolutely correct, but there is another way of looking at it. My way of looking at it is that you're going to run into problems at any rate, whatever you do. Our example is the SATCOM stations, the planning for the precise time reference stations is a good one, I think. Whatever you do, you will run into problems. If time is short, as it usually is, you may combine the learning period by throwing everything together and make the people learn how to do it while the system accumulates experience. That is a very unorthodox philosophy of management, but if it is coupled with a great degree of redundancy which also you must have at any rate, because even the best clock will stop, even at the best station, the best operators will goof, if you combine these, you end up, still despite all the trouble, with an operating system, and I think today, despite all the problems, there are many stations which produce with very little initial effort very useful data. And that is the other side of the coin. I think they both have to be looked at, but, of course, I think then the problems are increasing, the ones which Ken has mentioned, particularly I think our transportation problems. There is no question about they are on the increasing side.

We have had no shipment recently without a damaged part and I'm increasingly becoming concerned. Maybe in a timing field where we do operate with greater requirements for attention and training, we may be the first ones to notice something. But I have a feeling that it will be more difficult to translate basic capabilities as mentioned by Bob Doherty before into actual operational ones, which was what Ken Putkovich has been talking about. And where there is a factor of a thousand between the two.

MR. MITCHELL:

First off, we must have the transportation system that they use in Guam because we have that problem also. Being in the same area as Guam, I'm sure it is the same transport.

We have just recently started collecting data from SS1. Now SS1 is a low power transmitter for Loran-C and due to the distance we're way down in the mud on the signal and it's fairly hard to distinguish when we are on the signal and if it is the right signal.

The multifilter that you mentioned, would this help us in determining the signal and does it have any drawbacks?

MR. PUTKOVICH:

Yes, it will help you if your noise is essentially discrete—in discrete frequencies I should say. You can, with the currently available filters, probably notch out, I think, 6 or 8 discrete frequencies that are bothering you. If you have a really bad noise problem where your noise is across the full spectrum, I don't know whether that will help you. There are drawbacks in using the multifilter in that you introduce additional delays and additional uncertainties in your system.

MR. MITCHELL:

One other question. Is there anybody that publishes some kind of data on new equipment that's available for the Loran-C? I know we're kind of out of the country there and it's kind of hard for us to get information. We would like to make improvements to the system if we could.

Is there a source of information for this?

MR. PUTKOVICH:

Well, there's a problem in that area in that you have a very limited number of people producing Loran-C equipment and it was specifically requested that we don't advertise for any particular companies. It turns out however, that if you want a cesium oscillator, you don't have very many places to go and the same thing is true if you want Loran-C equipment. There is only one company that produces an automatic timing receiver now, possibly two; and if you get in touch with that company, you get the information on what's available.

MR. STRUCKER:

Pete Strucker with the Navy Metrology Engineering Center California.

I'd just like to comment on that noise condition and say that you can get a synchronous filter that will take care of broad band noise and it will pull the signal right out of the noise for you.

MR. PUTKOVICH:

It's produced by the same company, incidentally.

DR. WINKLER:

There is one more point maybe which we should also mention in this context and that is even for precisions of a tenth of a microsecond, temperature control in the Loran-C receiver environment is an absolute must. Some of these filters have temperature coefficients which are inordinately high and I think they could be improved.

We have 5 receivers on hand which are interrogated every hour by the computer. After you subtract from the readings, the individual receiver system delays (they operate on two antennas) you should end up with identical measurements every hour for these 5 receivers. They all operate in a reasonably well temperature-stabilized environment.

Now what is the standard deviation for an individual reading? It is in the order of 50 nanoseconds and peak-to-peak variations can occur of several tenths of a microsecond, and we have no explanation for that except the temperature sensitivity of the receiver, number one. And number two, I think also not to be forgotten is coherent interference. It's not only crossrate interference as mentioned before, but in most areas of civiliation, unfortunately civilization also produces coherent carriers, highly coherent carriers.

In Europe transmissions at 75 and 60 and 50 kilohertz, in the United States 60 kilohertz and 88 kilohertz are very dangerous and when that carrier comes on at 88 kilohertz it's being sampled coherently and unless you are careful to eliminate that interference, you will have unavoidably a step of several tenths of a microsecond, in your received signal due to that source.

Coherent interference and temperature instability are two things which one must remember.

DR. REDER:

Training of personnel seems to be a crucial thing. Now, you could say all right, let's try the handbook, you know how to do it, a cookbook. The trouble with a cookbook by the time it's finished, the system's obsolete. Now, you do publish a lot of tables—daily phase values and so on. Why not every time you run into a specific problem and since you are the ones who have apparently most the receivers in the United States, so you should also have a lot of problems, so every time you run into such a problem write a very short thing in a single page and distribute it to users?

DR. WINKLER:

It is not a joke, but we now have an automatically produced teletype, which is sent to each station and every day inadvertently sent messages to the wrong address identifier and they don't look it up.

It's a real problem. Any kind of a sophisticated system which depends upon people looking even into instruction manual will be doomed, I believe.

MR. PUTKOVICH:

That's exactly true. We go to many of the stations to find out why we're not getting good data from them, and you can't find the instruction manuals. You can't even find TOC tables that they're supposed to be using to set their receivers.

DR. WINKLER:

You must have redundancy.

MR. STRUCKER:

One of the ways that we tried to overcome this training problem, since we do have a lot of time Loran-C calibration systems on board ship where the personnel are rotated, was to produce a series of videotapes starting from the history of time and time dissemination and Loran-C and the operation of the system—how you use the system to calibrate the device that you have to calibrate, maintenance of the receiver, and we even included some of the HP tapes on replacing the beam tube and on and on and on.

We found the personnel are more apt to sit down and watch a TV program since everybody is already tuned in to television, rather than sit down and read a lengthy manual, and in most cases, we found it worked quite well.

I'd like to add one other thing though, we did have a problem with the series of videotapes, we also had to supply a video cassette player and a TV set, and we did run into some problem with installing TV sets in the calibration labs aboard ships.

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PERFORMANCE OF LORAN-C CHAINS RELATIVE TO UTC

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ABSTRACT

With the advent of space science and applications the requirements for precise and accurate time and time interval have approached to the order of microseconds and below. To meet these needs users must examine the various techniques to maintain the time scale and assess their long-term performance.

Loran-C navigation system has been widely used in the last few years as a precise time reference signal for international comparison of the primary clocks in the northern hemisphere. This paper presents the long-term performance of the eight Loran-C chains in terms of the Coordinated Universal Time (UTC) of the U.S. Naval Observatory (USNO) and the use of the Loran-C navigation system to maintain the user's clock to a UTC scale.

The atomic time (AT) scale and the UTC of several national laboratories and observatories relative to the international atomic time (TAI) are presented. In addition, typical performance of several NASA tracking station clocks, relative to the USNO master clock, is also presented.

Recent revision of the Coordinated Universal Time (UTC) by the International Radio Consultative Committee (CCIR) in its 13th Plenary Assembly is given in an appendix.

PERFORMANCE OF LORAN-C CHAINS RELATIVE TO UTC

INTRODUCTION

National time keeping and maintenance agencies for each country have primary responsibilities in the maintenance and dissemination of accurate time to the users. These primary clocks which provide the accurate time are maintained on a long term basis and are traceable to the origin of an epoch. The time signals[1] are disseminated through radio frequency emissions or other techniques to users, including other national time keeping agencies. The international comparisons of time signals among the national time keeping agencies comprise the data base for the adoption of uniform time scales such as the Coordinated Universal Time (UTC) and the International Atomic Time (TAI). It is the time as a scale rather than the time as an epoch that is in increasing demand by modern users.

With the advent of space science and applications in the last decade the requirements for precise and accurate time and time interval have approached the capabilities of national time keeping and maintenance agencies. To satisfy the sophisticated users, the national time keeping agencies issue time corrections periodically in the form of bulletins or announcements. These corrections are given relative to a primary time standard or master clock. For example, the Bureau International de l'Huere (BIH) issues a monthly circular, circular D, which gives the time comparison between the various national time standards relative to UTC and TAI. The use of these bulletins, announcements, and circulars and the long term stability of the primary time standards relative to the internationally adopted time scales is presented in this report. Users who need precise and accurate time and time interval on the order of microseconds or better undoubtedly recognize the need to use these corrections. The proper interpretation of the user's requirements in terms of time or time interval, the difference between accuracy and precision of measurement, and the accuracy of maintaining a clock relative to a time scale is generally the responsibility of the users who must communicate effectively to those experts who generate and maintain the time standards and/or who provide the techniques for clock synchronization.

CLOCK COMPARISON TECHNIQUE AND DATA

Clock comparison techniques are numerous and vary in accuracy and precision. In general, radio frequency transmissions in VLF, LF, and HF bands have been used as the work-horse and provided continuous, reliable and real-time time transfer references for clock comparisons. Portable clocks, satellites (both natural and artificial), and coherent radiations from quasars are in increasing use to meet specific needs. As the accuracy in timing requirements is increased, not only must the accuracy of transmission and the precision of measurement be increased, but also the stability of the oscillators (fly wheel) which generate the time must be increased.

The most often used time transfer reference signal for clock comparison among primary clocks in national laboratories is the 100 kHz transmissions of the Loran-C navigation system. At present, Loran-C consists of eight chains which provide coverage for the northern hemisphere. The resolution of time comparison of an identified cycle of the received signal is about 1/100th of a cycle or 0.1 microseconds. The long term stability of the propagation delay, even for groundwave, is probably not much better than ±0.5 microsecond. The long term stability of the time transmission of a Loran-C chain at present is about one order of magnitude lower. The requirement imposed by users to the U.S. Coast Guard who operates the Loran-C chains for controlling the emitted time relative to the master clock of the U.S. Naval Observatory is much larger. This requirement has been stated between 15 and 25 microseconds. The performance of the Loran-C chains varies from chain to chain but is better than the stated requirement.

The data collected by each national laboratory or observatory is published and is available to the users. For example, in the United States the Naval Observatory issues to general users a series of time bulletins and announcements on a weekly basis, and sends corrections by telegrams on a daily basis to special users. The National Bureau of Standards issues a special publication, NBS Special Publication 236, on a monthly basis. In other countries, for example in the United Kingdom. the Royal Greenwich Observatory publishes a monthly Time Service Circular. Also, the National Research Council of Canada publishes their Loran-C measurements in letter form once every ten days and Time and Frequency Bulletins monthly. The Institute Electrotecnico Nazionale of Italy publishes a monthly circular and the Bureau International de l'Heure publishes monthly circulars and annual reports. The contents, as well as the frequency of publications vary as do the needs. In general, the information is readily available and the publications can be had upon request. Typical time service notices, bulletins, announcements, and circulars are given in Appendix A.

HISTORICAL BACKGROUND OF ATOMIC TIME

Present primary time standards, as maintained by national laboratories, are based on cesium atomic oscillators which are made either in the laboratories or by a commercial firm. The time maintained by these oscillators is referred to as atomic time. Historically, A.1 was the weighted average of nine cesium atomic standards which were located in nine laboratories in four countries.[2] This average was maintained by the U.S. Naval Observatory (USNO). A.1 is presently the average of an ensemble of 15 to 30 commercial cesium atomic standards maintained at the USNO.[3] Each individual national laboratory also maintained an atomic time scale identified with a laboratory such as the U.S. Atomic Time (USAT) of the National Bureau of Standards which is now known as AT (NBS). Other examples are the Greenwich atomic time (GA) and now the GA2 of the Royal Greenwich Observatory, and the A3 of the BIH.

As the various atomic time scales went through the process of evolution it became obvious to many that an international standard must be adopted.[4,5] Thus, the XIIIth General Conference of Weights and Measures (CGPM) adopted in 1967, the definition of the second as "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium atom 133." The CGPM also defined International Atomic Time (TAI) as "the time coordinate established by the BIH on the basis of the readings of atomic clocks operating in various establishments conforming to the definition of the second, the unit of time of the International System (SI) of Units."

The XIIth Plenary Assembly of the International Radio Consultative Committee (CCIR) of the International Telecommunication Union, adopted in 1970 the improved UTC system. The improved UTC system was revised by the XIIIth Plenary Assembly of the CCIR in 1974 as given in Appendix C. This system eliminated the changing frequency offset between UTC and TAI and increased the step-time adjustments from 0.1 to 1 second which is now called a leap second.[6] Thus the UTC and TAI have the same rate.

CLOCK COMPARISONS

Based on the published clock correction data of BIH, the atomic time scales, as maintained by several national laboratories and observatories, are plotted for 900 days as shown in Figures 1 and 2. In these figures the ordinate is plotted as the clock difference, Δt, in microseconds between TAI and the AT of a laboratory shown in parenthesis. The three abscissas shown are the elapsed time in days, the Modified Julian Day (MJD), and the year, month, and day (YR, MO, DY). The clock off-sets of the several laboratories were not removed, for historical reasons or by choice, so as to maintain a continuous time scale for the particular laboratory.

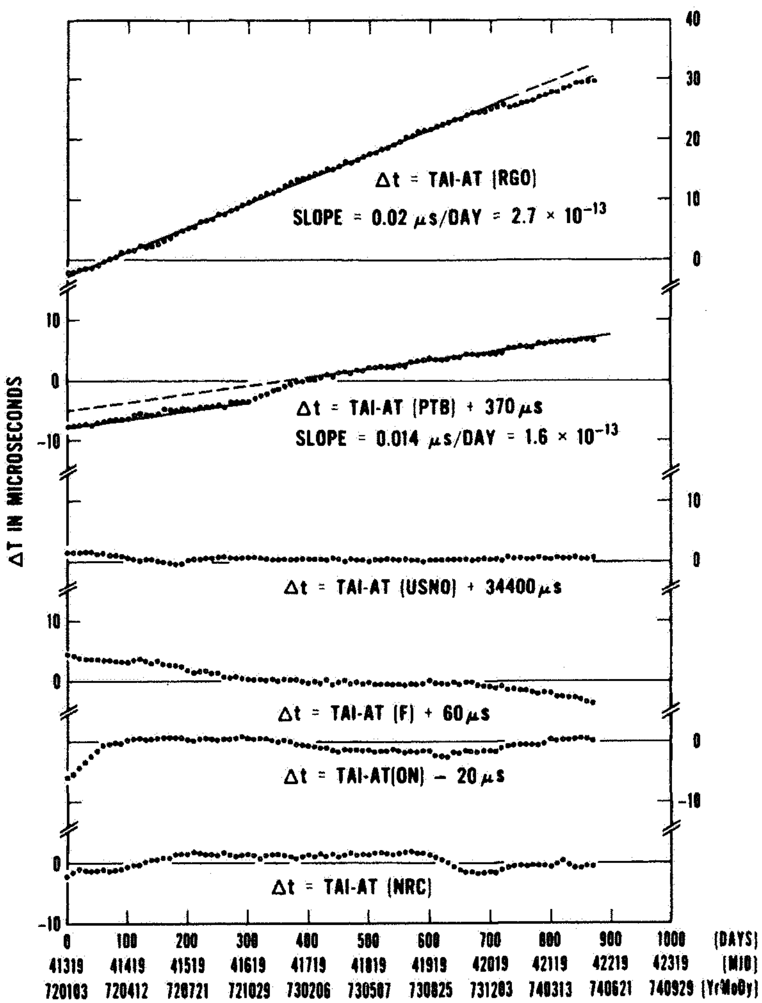

Fig. 1—Independent Local Atomic Time Scales, AT (Laboratory-i), Relative to TAI (International Atomic Time). (Data Source -- Circular D Bureau International de l'Heure)

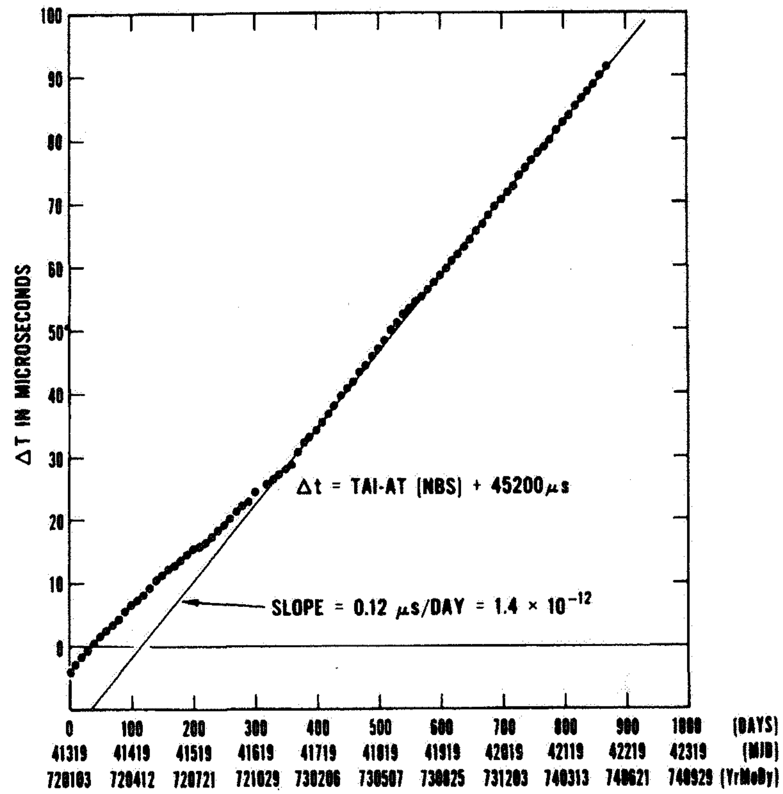

Fig. 2—Independent Local Atomic Time Scale, AT (NBS), Relative to TAI (Continued From Figure 1)

In Figures 1 and 2 these clock offsets were arbitrarily chosen so that the origins of the curves are near zero. The larger slope or clock rate difference between TAI and AT (NBS) shown in Figure 2 is attributed to the frequency difference between laboratory and commercially made cesium atomic standards.[7] Although the Physikalisch-Techische Bundesanstalt (PTB) of Federal Republic of Germany and the National Research Council (NRC) of Canada also have laboratory made cesium atomic standards, it is not known if these standards are used to steer their working standards, which are commercially made cesium atomic standards. Atomic time scales are maintained by national laboratories; their relation to the International Atomic Time Scale is of interest. Only through this known relation can the time variant data collected by experimenters in different countries be correlated and compared.

Those measurements which are dependent on the earth's position are made relative to the Coordinated Universal Time (UTC). The UTC of each laboratory relative to the UTC of BIH is also plotted for 900 days as shown in Figures 3 and 4. The difference between UTC (BIH) and TAI is -10 seconds as of January

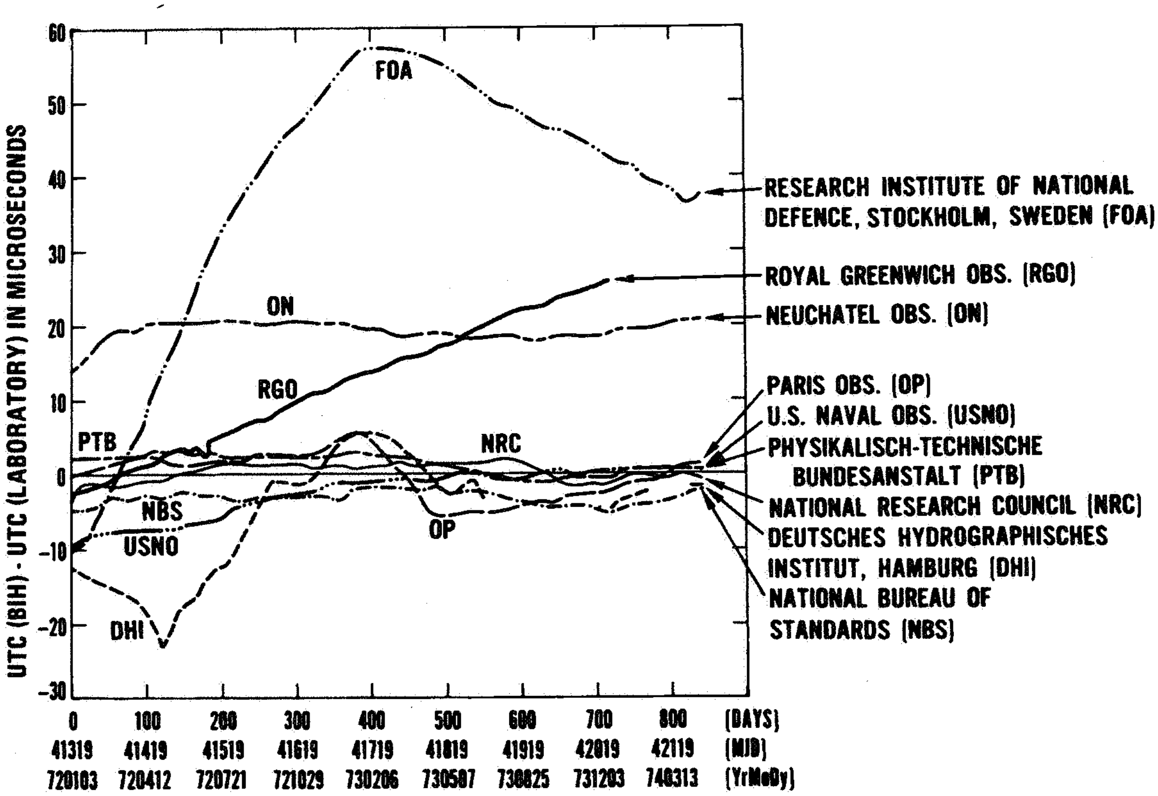

Fig. 3—Coordinated Universal Time (UTC) Scales of Independent Laboratories Relative to UTC (BIH) (Data Source -- Circular D, Bureau International de l'Heure)

1, 1972 (with the negative sign indicating UTC late), -11 seconds on July 1, 1972, -12 seconds on January 1, 1973, -13 seconds on January 1, 1974, and -14 seconds on January 1, 1975.

Figure 5 shows the UTC time comparison of three national laboratories for 550 days using the East Coast chain of the Loran-C navigation system as the time transfer reference signal. The East Coast chain consists of five stations with the master station being located at Cape Fear, North Carolina and four slave stations located at: Jupiter Inlet, Florida; Cape Race, Newfoundland; Nantucket, Massachusetts; and Dana, Indiana. Also shown at the bottom of the figure is the time difference between UTC (USNO) and UTC as transmitted by the Mediterranean Sea chain. Thus, these data permit the time comparison between the East Coast and the Mediterranean Sea chains using UTC (USNO) as the time transfer reference. The obvious single break in the East Coast chain data, which occurred on MJD 41994 (Nov. 8, 1973) are due to step time corrections made at the master stations as are the two breaks in the Mediterranean Sea data which occurred on MJD 41840 (June 7, 1973) and on MJD 42090 (Feb. 12, 1974). The smaller step time corrections and frequency changes of the oscillators made from time to time at the master station will become obvious when the detailed data is examined. It should be pointed out here that the time transmitted by Loran-C chains is required to be within only ±25 microseconds of the master clock of the U.S. Naval Observatory (USNO MC). This requirement (as can be seen in Figure 8) is met with a safety factor of one to three.

Figure 6 shows the relative time differences of the Mediterranean Sea chain and the Norwegian Sea chain with respect to UTC of the Istituto Elettrotecnico Nazionale (IEN) of Turin, Italy and UTC of the USNO. From this figure one can calculate the UTC time difference between IEN and the USNO and between the two Loran-C chains as shown in Figure 7. It should be pointed out that these calculations were made on the assumption that the propagation delays are constant for the time of observation between the monitoring stations and the Loran-C transmitters and between the slave stations and their master stations. This assumption is reasonable for a short period of time (days), and is under question for a longer period of time (months or longer).

LONG-TERM TIME STABILITY OF LORAN-C CHAINS

Figure 8 shows the time differences of six of the eight Loran-C chains relative to the master clock of the U.S. Naval Observatory (USNO MC) as a function of time for about 900 days. Figures 9, 10, and 11 show the time difference of nine individual Loran-chains relative to the USNO MC. Figure 9 shows the present behavior of time controlled Loran-C chains. Figures 10 and 11 show the progress of implementing the time control of a Loran-C chain. In Figure 11, the performance of the West Coast Loran-D chain, which was recently implemented, is also given.

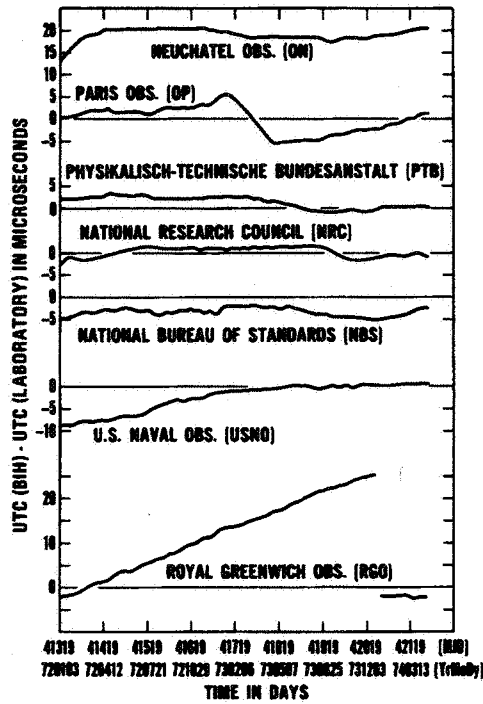

Fig. 4—Coordinated Universal Time (UTC) Scale of Individual Laboratory Relative to UTC (BIH)

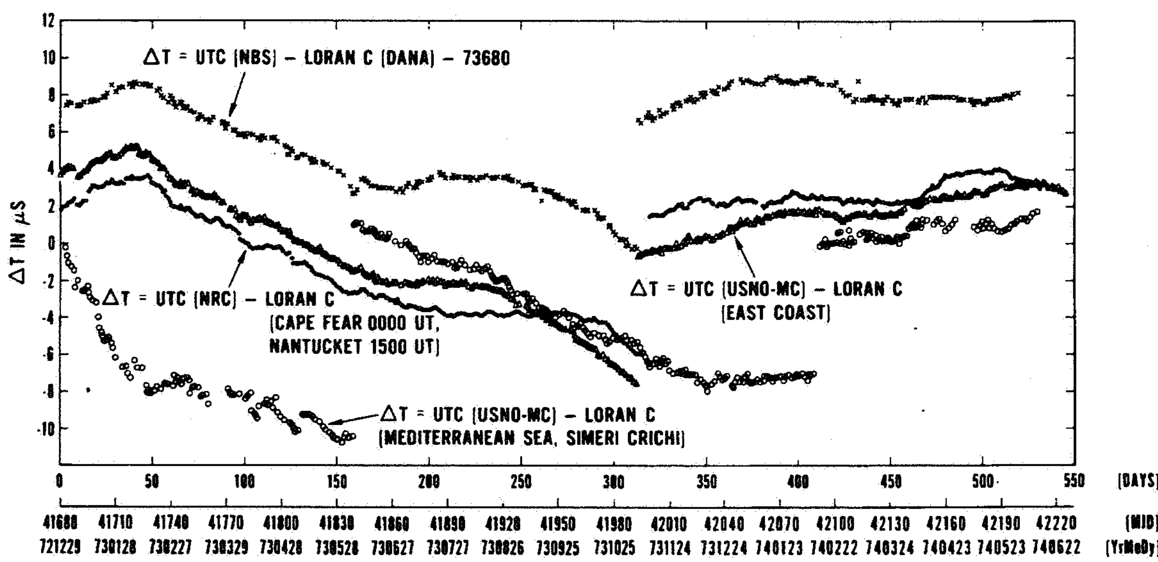

Fig. 5—Comparison of Coordinated Universal Time Scales Via Loran-C East Coast Chain (Data Source -- National Bureau of Standards' Special Publication 236, U.S. Naval Observatory's Daily Phase Values and Time Differences Series 4, and Canadian National Research Council's Loran-C Measurements)

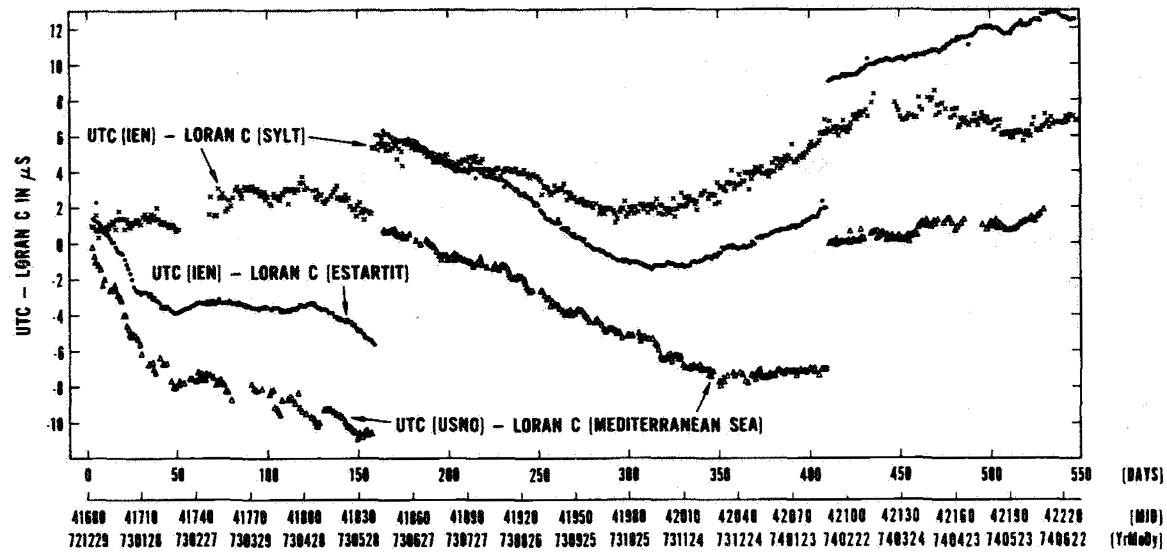

Fig. 6—Comparison of Coordinated Universal Time Scales Via Loran-C Mediterranean Sea and Norwegian Sea Chains (Data Source -- Circulars of Istituto Elettrotecnico Nazionale -- Tourin, Italy and U.S. Naval Observatory's Daily Phase Values and Time Differences Series 4)

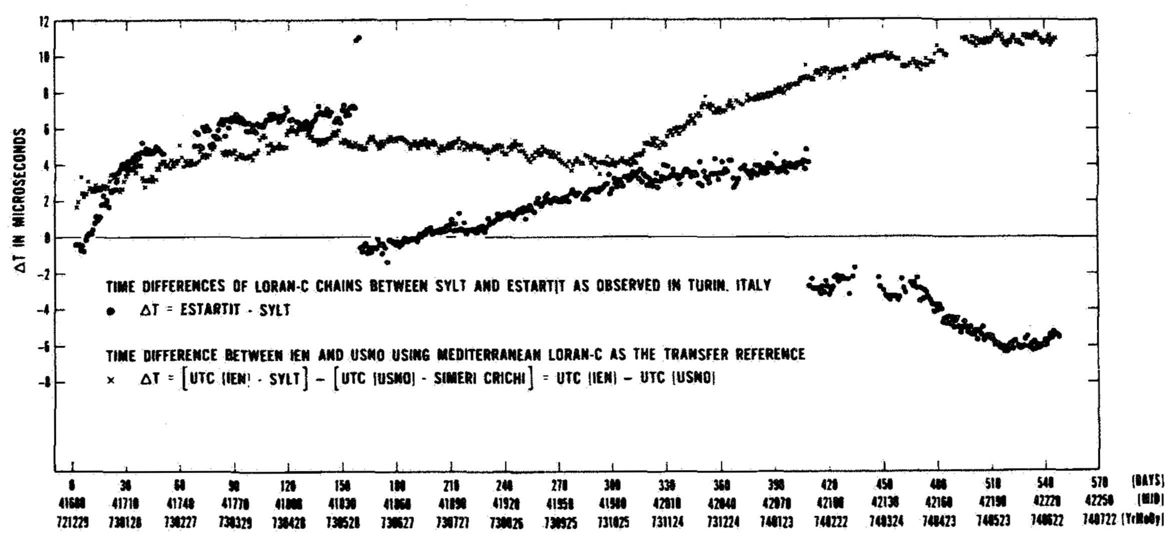

Fig. 7—Comparison of Time Transmissions of Loran-C Chains Via an Independent Monitoring Laboratory (IEN) and of Coordinated Universal Time Scales of Two Independent Laboratories Via Multiples of Loran-C Chains

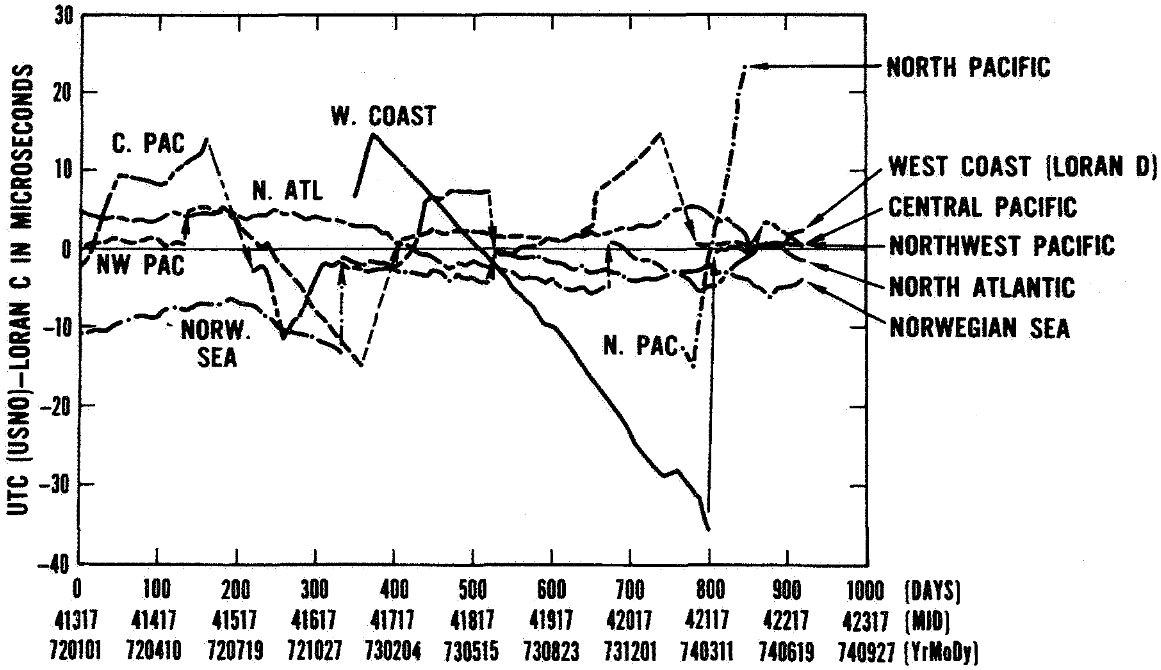

Fig. 8—Performance of Loran-C Transmissions as a Precise Time Reference Signal (Data Source -- U.S. Naval Observatory Daily Phase Values and Time Differences Series 4)

For convenience some reference information on Loran-C and Loran-D is given in Appendix B of this report. Table B-1 gives the stations of the nine Loran-chains, and their repetition rates. Users of Loran-C are advised that the repetition rate for each chain has been changed from time to time since 1970. This is done to avoid cross chain interference of the Loran-C tranmissions and to identify the chains. Table B-2 gives the basic group repetition rates. Table B-3 gives the Loran-C group period in microseconds for basic and specific rates. Table B-4 gives the phase reversal coding sequence of the eight pulses within each group for the master and slave stations.

USE OF UTC AND LORAN-C

Based on the excellent performance of the clocks maintained by the national laboratories and observatories it is obvious that special facilities and supporting personnel are required to maintain a constant time scale in addition to an ensemble of highly accurate clocks. This is particularly true if the time scale is to be compared to another such as UTC (BIH) or TAI (BIH). Users who have requirements for clock time accurate to a few microseconds or better relative to a national time standard such as UTC (USNO MC) or UTC (NBS) must use

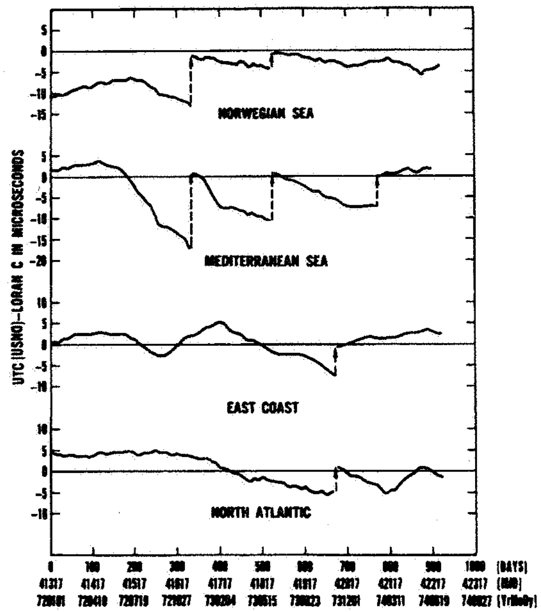

Fig. 9—Performance of Individual Loran-C Chains Relative to U.S. Naval Observatory Master Clock

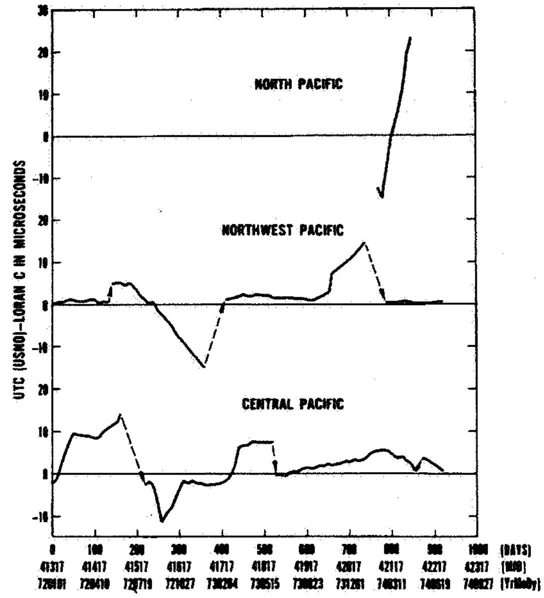

Fig. 10—Performance of Individual Loran-C Chains Relative to U.S. Naval Observatory Master Clock -- Continued from Figure 9

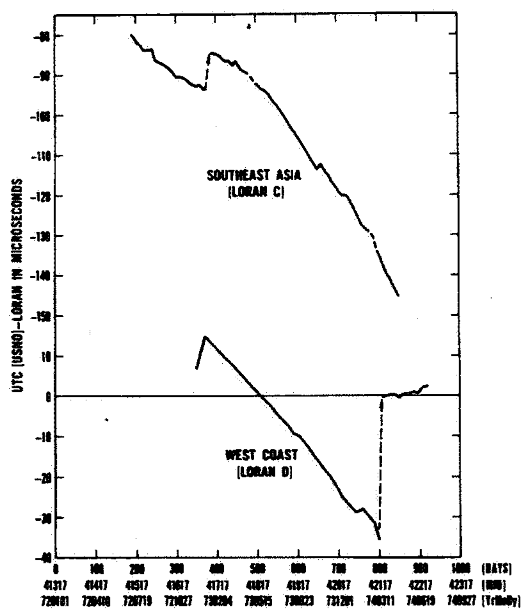

Fig. 11—Performance of Individual Loran-C Chains Relative to U.S. Naval Observatory Master Clock -- Continued from Figure 10

the corrections provided by the national time keeping agencies. This is true even for precise time interval users who may correlate periodicities or compare independent observations which were made over a long span of time.

The daily time corrections made to the Loran-C transmission are determined by real time measurements made by monitoring stations. In addition, portable clocks or satellite time transfer techniques are used to measure the clock differences between the monitoring stations and the USNO. From these clock measurements post corrections are occasionally generated to correct the Loran-C corrections. New users of precise time must pay special attention to the proper use of the circulars, bulletins, or announcements issued by the national laboratories.

TYPICAL NASA TRACKING STATION CLOCK PERFORMANCE

NASA Spaceflight Tracking Data Network (STDN) is equipped with cesium atomic frequency standards, VLF receivers, Loran-C receivers and WWV receivers. Each station has at least one cesium beam tube standard with automatic backup to a rubidium gas cell standard and a crystal oscillator standard[8] in the event of a failure. Some sites have two cesium standards -- one prime and one backup. Eventually, by late 1975, all sites will have two cesium standards. Each station also has either a dual redundant or a triple redundant majority logic time code generating system. The timing systems have many and varied frequency, pulse, and time code outputs to meet station frequency and time requirements.

The station clock is rated with respect to the USNO MC via a naval communications VLF transmission such as the VLF station NAA at Cutler, Maine. When it has been determined that the frequency of the station clock deviates by more than $\pm 1 \times 10^{-12}$, for three months or longer, the station timing engineer is directed by the network operation engineer in charge of timing to change the clock frequency by an amount to minimize the deviation. A typical performance record is shown in Figure 12 which shows the phase difference between the Canary Island station clock relative to the USNO MC (labeled as time advance) as a function of time for fiscal year 1974. The phase difference measurement is actually made by using the NAA VLF station as the transfer frequency reference. When the VLF phase suffered a phased jump, as indicated by the crosses which are not in coincidence with the circles, the phase is corrected. If the VLF phase record is discontinuous, e.g., due to propagation anomalies, the phase jump can often be measured and corrected as shown by the circles. If the discontinuity is due to equipment failure, the phase jump can only be estimated. Since a phase jump can be several cycles, the actual measured VLF phase differences often fall outside the range of the scale ±100 microseconds. The fact that the phase of a VLF signal is not continuous is a major shortcoming for time transmissions. The use of dual VLF for time transmission is an approach to remove or to reduce the phase jumps.

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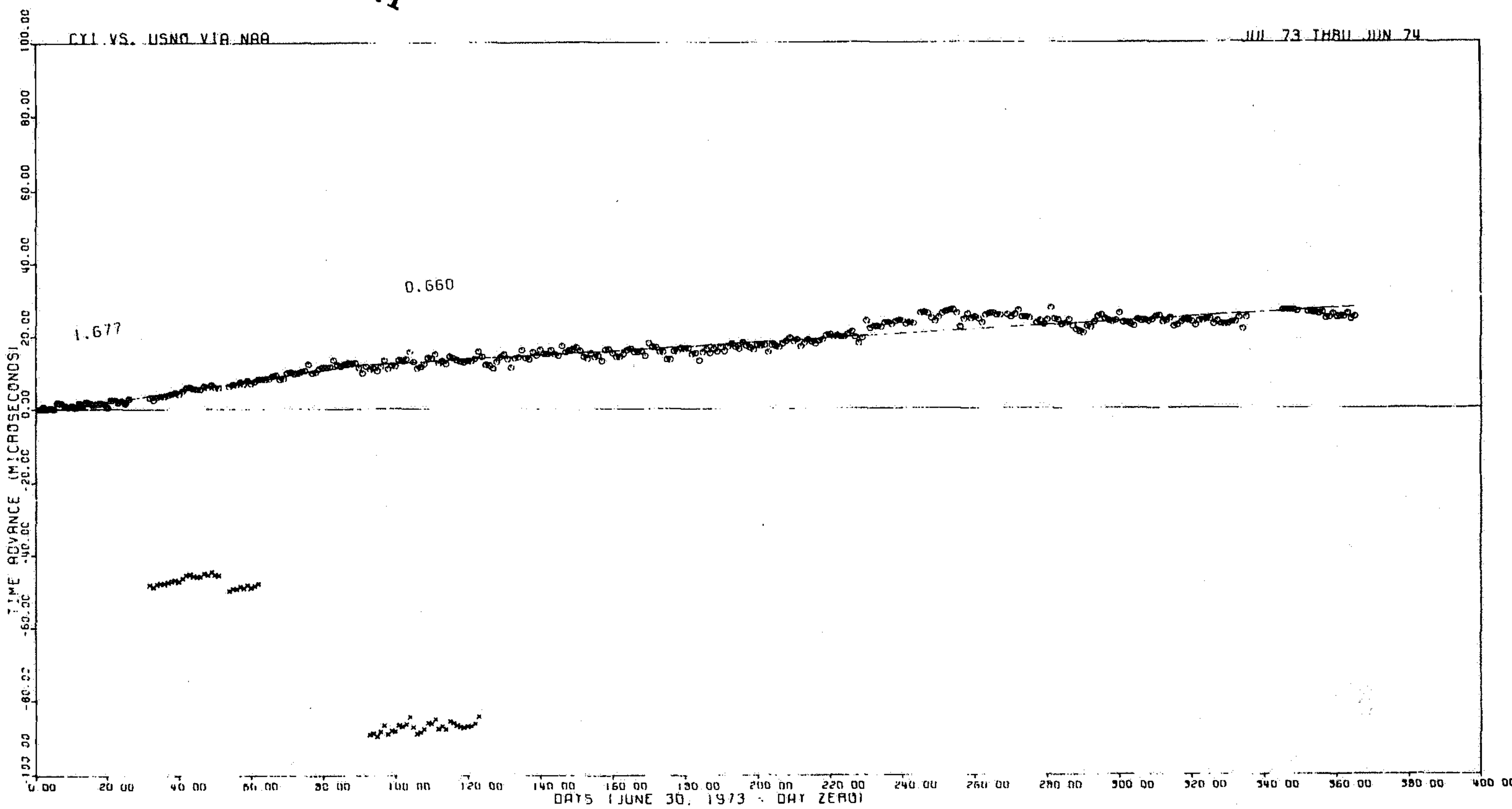

Fig. 12—Frequency Comparison and Rating of NASA Tracking Station Clock at Canary Island (CYI) Relative to U.S. Naval Observatory Master Clock Via Naval Communication VLF Station NAA, Cutler, Maine

The station clock is synchronized via a standard time signal emission, such as WWV, for coarse time. The fine time is obtained via a Loran-C signal. Those stations which are within the range of the groundwave propagated signals at 100 kHz, can usually maintain their clocks to ±20 microseconds or better depending on the operation procedure and geographical location relative to a Loran-C chain. The curves in figures 12 through 15 represent the time difference and the circles, the phase difference. The least square fit of the phase difference of a segment of data is the frequency difference between the station cesium frequency standard and the USNO MC. Figure 13 shows the Canary Island (CYI) station clock relative to USNO via Estartit, a slave station of the Mediterranean Sea chain. It is interesting to compare these frequency differences as measured via NAA (Figure 12) and Loran-C Mediterranean Sea chain (Figure 13). The agreement is within 0.5×10^{-12}.

The best performance of a NASA station clock maintained to the USNO MC is that of the station at Merritt Island, Florida (MIL) as shown in Figure 14. For the data shown it actually surpasses the performance of the Loran-C East Coast chain. While the East Coast chain was used as the transfer time reference, the fact that the frequency of the station clock was not adjusted probably accounts for its superior performance.

When a NASA station is located outside the range of the groundwave propagated signal of a Loran-C chain such as Carnarvon in northwest Australia, the skywave propagated signal was used. For convenience in calculation it was assumed that the same mode of propagation took place for the path between the station and the transmitter. Figure 15 shows the station clock performance at Carnarvon relative to USNO MC via the 5th hop propagated from Iwo Jima of the Northwest Pacific Loran-C chain. It can be seen from this figure that the Carnarvon station clock was maintained to within 75 microseconds of USNO MC for the year shown.

Although extensive analysis of the performance of the NASA's station clocks cannot be presented in this paper, enough evidence has been presented to the users for the need of the corrections to frequency or time transfer reference signals if they are to be used to maintain the user's clocks. Some evidence was also presented to support the body of opinion that the best performance of a clock is achieved by fewer corrections or perturbations.

The author wishes to express his appreciation to Mr. John K. Jones, GSFC Network Operation Engineer in charge of timing for implementing the computer data reduction and analysis of the NASA station clocks relative to USNO master clock and for providing the graphs to the author for publication. He also wishes to acknowledge the assistance of Leslie Lobel who plotted Figures 1 through 11 during the summer of 1974.

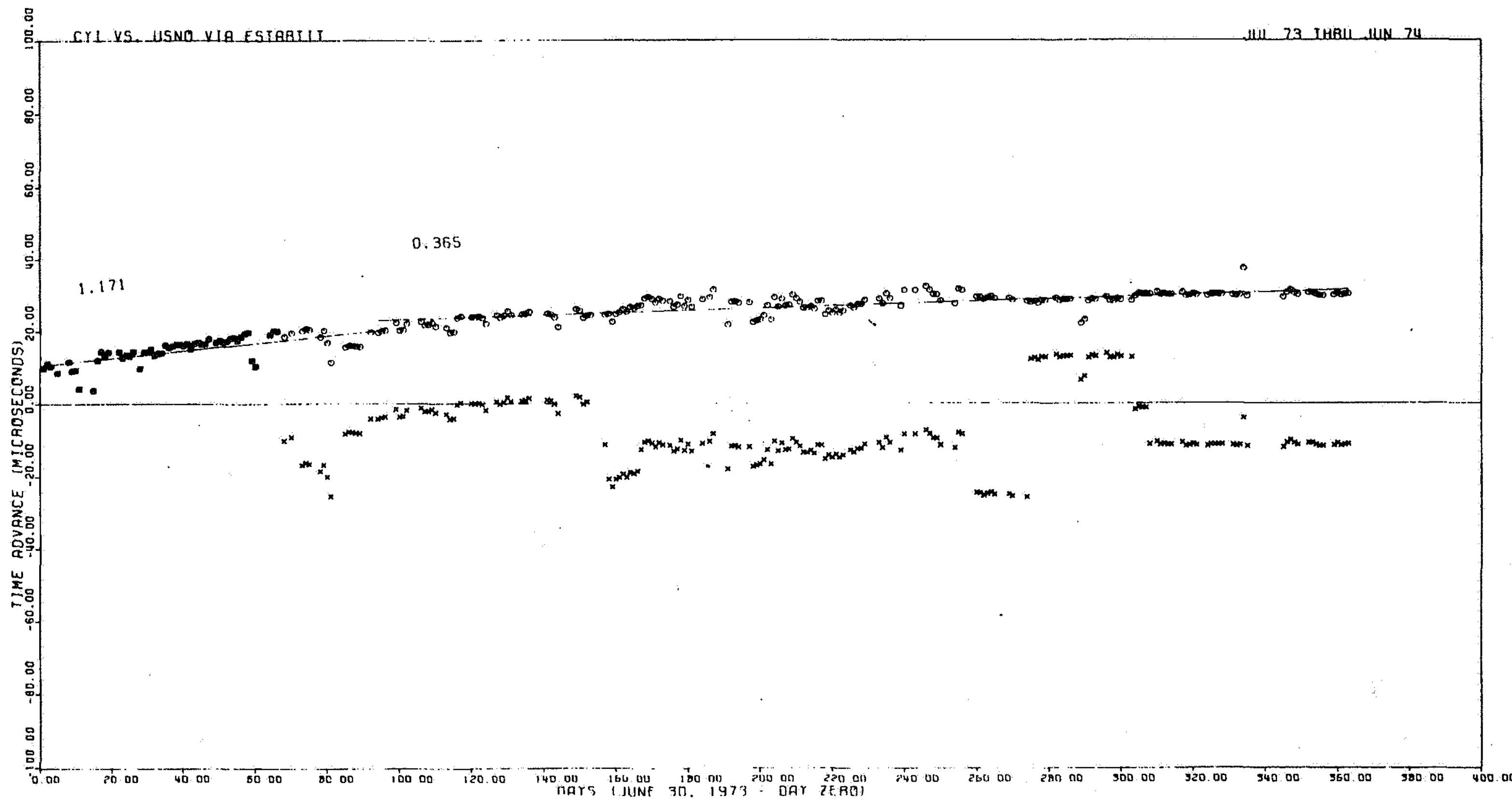

Fig. 13—Time Comparison and Control of NASA Tracking Station Clock at Canary Island (CYI) Relative to U.S. Naval Observatory Master Clock Via Loran-C Mediterranean Sea Chain

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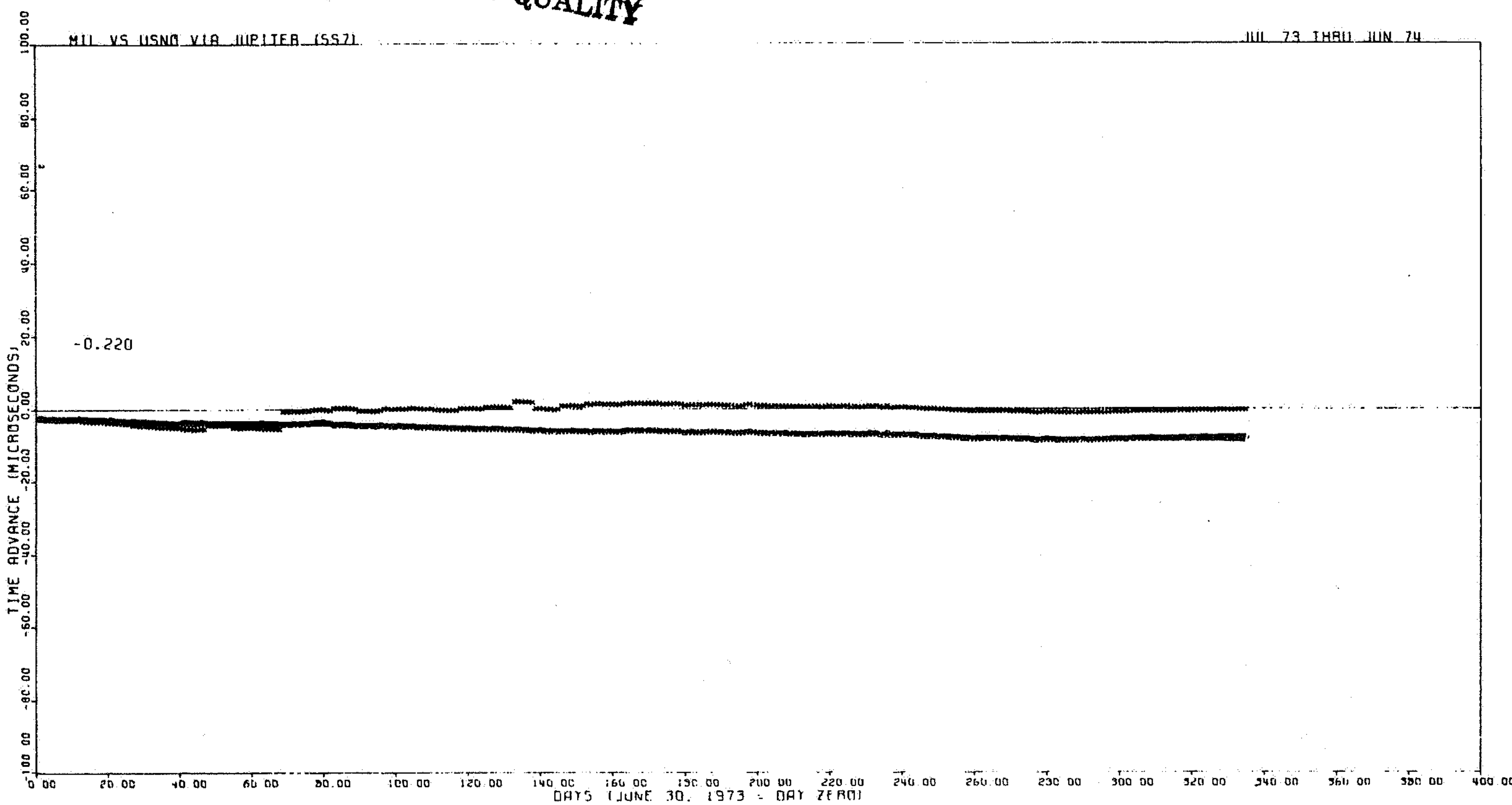

Fig. 14—Performance of NASA Tracking Station Clock at Merritt Island, Florida (MIL) Relative to U.S. Naval Observatory Master Clock Via Loran-C East Coast Chain (This is the Best Performance of a NASA Tracking Station Clock Among Twenty)

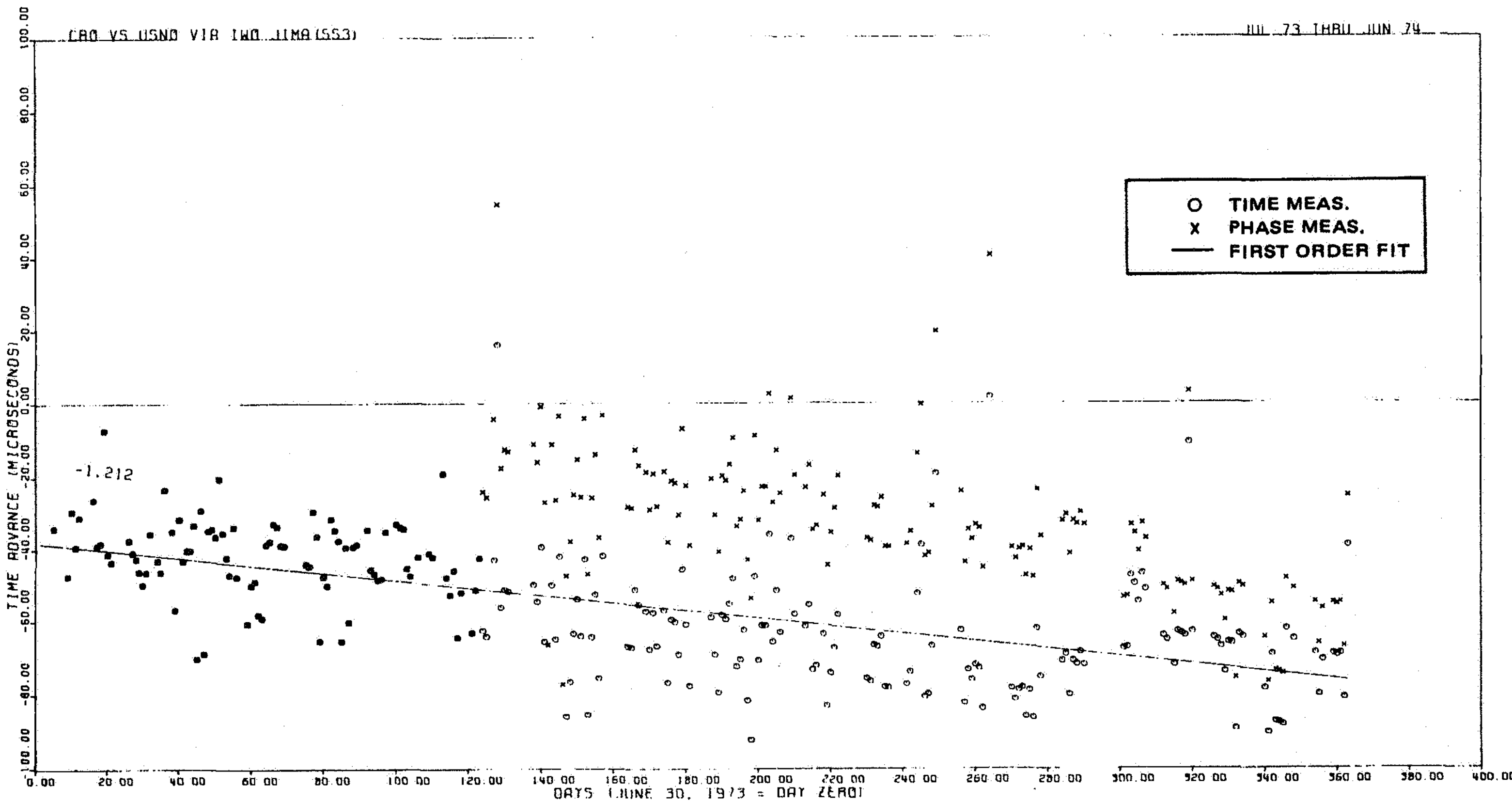

Fig. 15—Time Comparison and Control of NASA Tracking Station Clock at Carnarvon, Australia (CRO) Relative to U.S. Naval Observatory Master Clock Via a Skywave Propagated Signal From Loran-C Northwest Pacific Chain

REFERENCES

1. In a broad sense any radio frequency transmission which broadcasts time information may be considered as a time signal emission. In a strict sense only those stations which conform with the recommendations of the International Radio and Consultative Committee (CCIR) are considered as the standard frequency and time signal emissions.

2. A. R. Chi, "A Survey Paper on Atomic Frequency Standards Used in the United States," NATO Conference of Experts on Electronics, Paris, France, Sept. 1962; also W. E. Fizell, On The Determination of Universal Time and The Use of U. S. Naval Observatory Time Service Bulletins, Notices, and Announcements, GSFC X-Document, X-521-70-108.

3. G. M. R. Winkler, R. G. Hall, D. B. Percival, "The U. S. Naval Observatory Clock Time Reference and The Performance of a Sample of Atomic Clocks," Metrologia, 6, 4 p.p. 126-134, October 1970.

4. H. M. Smith, "International Time and Frequency Coordination" Proc. IEEE 60, 5, p.p. 479-487, May 1972.

5. J. T. Henderson, "The Foundation of Time and Frequency in Various Countries," Proc. IEEE, 60, 5, p.p. 487-493, May 1972.

6. A. R. Chi and H. S. Fosque, "A Step in Time Changes in Standard-Frequency and Time-Signal Broadcasts -- January, 1972" IEEE Spectrum 9, 1, p.p. 82-86, January 1972. Also NASA Technical Note, NASA TN D-7065, January 1973.

7. Private communication with J. A. Barnes of NBS.

8. Cesium beam standards are Hewlett-Packard's models 5060, 5061A, and 5061A with option 004 high performance cesium beam tube. Rubidium gas cell standards are Varian Associates' Model R-20 and Tracor Model 304D. Crystal oscillators are Hewlett-Packard's Model 106 and Sulzer's Model A5.

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APPENDIX A

U. S. NAVAL OBSERVATORY
WASHINGTON, D.C. 20390

28 AUGUST 1974

DAILY PHASE VALUES AND TIME DIFFERENCES SERIES 4 — NO. 395

REFERENCES: (A) TIME SERVICE INFORMATION LETTER OF 15 AUGUST 1973
(B) TIME SERVICE ANNOUNCEMENT, SERIES 9, NO. 36 (LORAN-C)
(C) DAILY PHASE VALUES AND TIME DIFFERENCES, SERIES 4, NO. 389 (LORAN-D)
(D) DAILY PHASE VALUES AND TIME DIFFERENCES, SERIES 4, NO. 195 (TV)

THE TABLE GIVES: UTC(USNO MC) - TRANSMITTING STATION — UNIT = ONE MICROSECOND

*MEASURED BY USNO TIME REFERENCE STATIONS WITHIN GROUND WAVE RANGE BUT CORRECTED TO REFER TO USNO MASTER CLOCK.
**COMPUTED FROM DIFFERENTIAL PHASE DATA PROVIDED BY THE U.S. COAST GUARD STATIONS OPERATING ON THE NORTH ATLANTIC REPETITION RATE AND FROM USNO MEASUREMENTS.

FREQUENCY KHZ (UTC)	MJD	LORAN-C* SS3 NORTHWEST PACIFIC 100	LORAN-C* S1 CENTRAL PACIFIC 100	LORAN-C SS7 EAST COAST U.S.A. 100	LORAN-C** SL3 NORWEGIAN SEA 100	LORAN-C** SL1 MEDITERRANEAN SEA 100	LORAN-C** SL7 NORTH ATLANTIC 100
AUG. 14	42273	-3.5	-	0.6	-3.8	1.2	-5.1
15	42274	-3.5	-	0.5	-3.7	1.4	-5.1
16	42275	-3.6	-	0.4	-3.8	1.1	-5.3
17	42276	-3.5	-	0.4	-3.7	1.3	-5.4
18	42277	-3.5	-	0.3	-3.6	1.3	-5.5
19	42278	-3.6	-	0.3	-3.5	1.4	-5.3
20	42279	-3.6	-	0.2	-3.9	1.2	-5.7
21	42280	-3.6	-	0.2	-3.7	1.2	-5.6
22	42281	-3.7	-	0.1	-3.7	1.1	-5.6
23	42282	-3.8	-	0.0	-3.4	-	-5.4
24	42283	-3.7	-	-0.2	-3.7	-	-5.8
25	42284	-3.7	-	-0.2	-3.8	-	-5.9
26	42285	-3.7	-	-0.2	-3.9	-	-6.0
27	42286	-3.8	-	-0.3	-3.6	-	-6.0
28	42287	-3.6	-	-0.3	-3.5	-	-5.9

FREQUENCY KHZ (UTC)	MJD	LORAN-C** SH3 SOUTHEAST ASIA 100	LORAN-C* SH7 NORTH PACIFIC 100	LORAN-D S7 WEST COAST U.S.A. 100	6 OMEGA ND 10.2 6,000+	7 OMEGA ND 13.1 6,000+	5 OMEGA ND 13.6 6,000+
AUG. 14	42273	-162.3	-	4.4	427	428	428
15	42274	-162.4	-	4.3	428	429	429
16	42275	-162.1	-	4.4	428	429	429
17	42276	-162.5	-	-	428	430	431
18	42277	-162.9	-	-	428	430	431
19	42278	-	-	4.5	428	429	430
20	42279	-	-	4.6	-	-	-
21	42280	-	-	4.8	-	-	-
22	42281	-	-	4.7	425	426	427
23	42282	-	-	4.7	426	426	427
24	42283	-	-	-	425	426	427
25	42284	-	-	-	425	426	427
26	42285	-	-	5.0	426	427	428
27	42286	-	-	5.1	426	427	428
28	42287	-	-	5.1	425	425	428

FREQUENCY KHZ (UTC)	MJD	1 OMEGA T 13.6 11,000+	4 GBR 16.0 19,000+	2 NAA 17.8 3,000+	3 NLK 18.6 12,000+	8 NBA 24.0 11,000+	WASHINGTON, DC WTTG CHANNEL 5 EMITTED
AUG. 22	42281	627	518	224	589	-	3.9
23	42282	627	517	223	589	-	3.9
24	42283	627	517	223	589	073	3.9
25	42284	628	517	223	588	073	-
26	42285	628	518	224	589	072	3.8
27	42286	628	516	222	589	071	3.8
28	42287	627	518	223	589	070	-

DAILY PHASE VALUES AND TIME DIFFERENCES SERIES 4, NO. 395 (CONTINUED)

NATIONAL TELEVISION NETWORKS

			NBC	NBC	CBS	CBS	ABC	ABC
			19:25:00 UT	19:31:00 UT	19:26:00 UT	19:32:00 UT	19:27:00 UT	19:33:00 UT
		MJD						
AUG.	22	42281	27,271.2	20,248.6	6,831.2	33,175.2	9,238.8	2,216.3
	23	42282	7,292.7	3,215.1	23,088.8	16,066.1	25,532.4	18,509.9
	24	42283	10,514.9	3,492.3	29,832.3	22,792.5	26,978.6	19,820.0
	25	42284	2,452.0	28,659.2	22,240.1	15,219.4	10,652.7	3,493.6
	26	42285	20,856.2	1,126.1	5,131.0	-	6,154.5	-
	27	42286	24,450.0	17,426.6	21,388.1	14,363.4	22,448.5	15,426.0
	28	42287	11,008.6	406.2	4,277.1	30,621.0	5,375.3	31,719.5

NOTES:

(1) PROPAGATION DISTURBANCES WERE OBSERVED NEAR THE FOLLOWING TIMES:
23 AUG. 1135/3
24 AUG. 1430/3
27 AUG. 1855/3
28 AUG. 1655/4.

(2) NAVY STATION OFF-AIR TIMES:
NBA 25 AUG. 1127 TO 1128 UT
1433 TO 1434 UT
1910 TO 1912 UT

(3) (SH3) SOUTHEAST ASIA LORAN-C
12 AUG. -161.5
13 AUG. -160.5

(4) (SL3-W) NORWEGIAN SEA LORAN-C SLAVE SYLT, GERMANY WAS OFF THE AIR 0950 TO 1947 UT 27 AUG.

(5) (S1-X) CENTRAL PACIFIC LORAN-C SLAVE UPOLU POINT, HAWAII IS SCHEDULED TO BE OFF THE AIR 1730 TO 0430 UT DAILY COMMENCING 1730 UT 27 AUG. AND ENDING 0430 UT 1 SEP. AND FIVE-MINUTE PERIODS DAILY AT 1730, 2200, 2300, 0200, AND 0430 UT COMMENCING 1730 UT 1 SEP. AND ENDING 0435 UT 15 SEP.

(6) (SS3-M) NORTHWEST PACIFIC LORAN-C MASTER IWO JIMA IS SCHEDULED TO BE OFF THE AIR 0130 TO 0430 UT 29 AUG.

(7) (SS7) EAST COAST LORAN-C CHAIN IS SCHEDULED TO BE DECREASED IN FREQUENCY BY APPROXIMATELY 8.0 PARTS IN TEN TO THE THIRTEENTH AT 1600 UT 6 SEP.

(8) (SL7) NORTH ATLANTIC LORAN-C CHAIN IS SCHEDULED TO BE DECREASED IN FREQUENCY BY APPROXIMATELY 1.0 PART IN TEN TO THE TWELFTH AT 1600 UT 6 SEP.

(9) OMEGA STATIONS OFF-AIR TIMES:

NORTH DAKOTA	24 AUG.	0502 TO 0504 UT
		0526 TO 0535 UT
		0641 TO 0643 UT
		2217 TO 2220 UT
	25 AUG.	0435 TO 0437 UT
		0452 TO 0454 UT
		0513 TO 0515 UT
		0842 TO 0844 UT
		0921 TO 0923 UT
		0929 TO 0931 UT
		0948 TO 0950 UT
		1048 TO 1050 UT
		1257 TO 1259 UT
		1418 TO 1420 UT
		1710 TO 1712 UT
		1817 TO 1819 UT
		1918 TO 1919 UT
TRINIDAD	28 AUG.	ABOUT 1005 TO 1015 UT

BUREAU INTERNATIONAL DE L'HEURE
(B.I.H.)
61, Avenue de l'Observatoire
75014 - PARIS

Circular D84
Paris, 1973 November 5

1 - UNIVERSAL TIME AND COORDINATES OF THE POLE

Date (0h UT) 1973	MJD	smoothed values x 0".001	y 0".001	UT2-UTC 0.0001s	UT1-UTC 0.0001s	raw values x 0".001	y 0".001	UT1-UTC 0.0001s	UT1-TAI s
Sept. 4	41 929	+ 8	+340	+ 414	+ 645	- 5	+349	+ 597	-11.9355
9	934	+ 16	+341	+ 254	+ 505	+ 6	+334	+ 521	9495
14	939	+ 25	+342	+ 94	+ 360	+ 26	+334	+ 359	9640
19	944	+ 33	+344	- 65	+ 213	+ 53	+337	+ 206	9787
24	949	+ 41	+346	- 223	+ 63	+ 35	+342	+ 86	9937
29	954	+ 48	+347	- 379	- 89	+ 59	+352	- 102	-12.0089
Oct. 4	959	+ 55	+348	- 533	- 243	+ 62	+342	- 245	0243

TAI-UTC is exactly 12s since 1973 Jan. 1st, 0h UTC.

2 - EMISSION TIME OF TIME SIGNALS, for Sept. 1973.

a - Time signals emitted in the UTC time scale, within ± 0.0002 s

CHU, DAM, DAN, DAO, DCF77, DGI, DIZ*, FFH, FTA91, FTH42, FTK77, FTN87, GBR, HBG, IAM, IBF, JJY, LOL, MSF, NSS(hf), OMA, PPE*, RWM, (and other signals from USSR), VNG, WWV, WWVB, WWVH, ZUO.
* DIZ : irregularities on 1973 Sept. 25.
* PPE : corrigendum : |UTC-PPE| < 0.0002s since, at least, January 1973.

b - Other time signals (unit : 0.0001s) : UTC-OLB5 = + 8.

3 - COORDINATED UNIVERSAL TIME

a - From LORAN-C and Television pulses receptions

Date 1973 / MJD	Sept. 4 / 41 929	Sept. 14 / 41 939	Sept. 24 / 41 949
Laboratory i	UTC-UTC(i) (unit : 1 µs)		
PTB (Braunschweig)	- 1.0	- 0.9	- 0.9
USNO (Washington) (USNO MC)	- 0.1	+ 0.1	+ 0.1
OP (Paris)	- 3.7	- 3.6	- 3.5
NBS (Boulder)	- 3.6	- 3.8	- 4.1
RGO (Herstmonceux)	+ 22.1	+ 22.3	+ 22.7
NRC (Ottawa)	+ 1.0	+ 0.6	- 0.1
FOA (Stockholm)	+ 47.9	+ 47.4	+ 46.9
ON (Neuchâtel)	+ 17.9	+ 17.8	+ 17.8
IEN (Torino)	- 4.9	- 4.5	- 4.5
NPL (Teddington)	- 30.4	- 30.7	- 30.9
OMSF (San Fernando)	+ 30.6	+ 34.1	+ 37.4
TP (Praha)	- 15.7	- 15.7	- 15.8

P. T. O.

b - From clock transportations (unit : 1 µs)

From "Daily Phase Values", Series 4, N° 349, USNO

National Physical Laboratory, Teddington, Middlesex, England :
1973 Sept. 17 (MJD = 41942.3), UTC(USNO MC)-UTC(NPL) = - 32.7 ± 0.2

Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, England :
1973 Sept. 17 (MJD = 41942.6), UTC(USNO MC)-UTC(RGO) = + 19.2 ± 0.2

Paris Observatory, Paris, France :
1973 Sept. 26 (MJD = 41951.7), UTC(USNO MC)-UTC(OP) = - 6.7 ± 0.2

Note : A discrepancy of about 3 µs appears between the data of the clock transportations and those obtained by LORAN-C, between America and Europe. Investigations are in progress.

4 - INDEPENDENT LOCAL ATOMIC TIME SCALES AT(i)

The value of TAI-AT(i) are given for the laboratories contributing in the formation of TAI. They are obtained from LORAN-C pulses receptions.

Date 1973 / MJD	Sept. 4 / 41 929	Sept. 14 / 41 939	Sept. 24 / 41 949
Laboratory i	TAI-AT(i) (unit : 1 µs)		
PTB (Braunschweig)	- 366.4	- 366.3	- 366.2
USNO (Washington) (1)	- 34 399.7	- 34 399.6	- 34 399.6
F (Paris) (2)	- 60.2	- 60.2	- 60.2
NBS (Boulder)	- 45 140.3	- 45 139.2	- 45 138.1
RGO (Herstmonceux) (3)	+ 22.1	+ 22.3	+ 22.7
NRC (Ottawa)	+ 1.0	+ 0.6	- 0.1
ON (Neuchâtel)	+ 17.9	+ 17.8	+ 17.8

(1) AT(USNO) is designated by A1(Mean) by USNO
(2) F denotes Commission Nationale de l'Heure, Paris
(3) AT(RGO) is designated by GA2 by RGO

5 - INFORMATIONS

a - Introduction of a positive leap second in UTC

A positive leap second will occur at the end of December 1973. The sequence of dates of the UTC second markers will be, as recommended by Annex I of the CCIR Report 517 :

31 Dec. 1973 , $23^h 59^m 59^s$
31 Dec. 1973 , $23^h 59^m 60^s$
1 Jan. 1974 , $0^h 0^m 0^s$.

TAI-UTC will be +13s after the introduction of the leap second.

Circular n. 26

IEN - Istituto Elettrotecnico Nazionale - Turin (Italy)

VLF, LF AND LORAN C SIGNALS RECEIVED AT IEN

REFERENCE: HP 5061 A Cesium Standard
UTC(IEN) - SIGNAL
microseconds

DATE MARCH 1974	M.J.D.	kHz UT	NAA 17.8 1400 9,000+	GBR 16.0 1400 9,000+	MSF 60.0 1400 1,000+	ESTARTIT 100.0 1400	SYLT 100.0 1400	IAM 5,000 0800 x10^3
1	42107		891.0	994.5	671.5	+9.4	+7.0	-
2	8		891.0	994.0	689.0	+9.5	+7.2	-
3	9		887.0	992.5	673.0	+9.6	-	-
4	10		885.0	992.0	675.0	+9.6	+7.2	-
5	11		886.0	992.0	655.0	+9.8	+7.4	-
6	12		885.5	992.0	625.0	+10.2	+7.0	-
7	13		-	-	-	+9.9	-	-
8	14		888.0	994.0	624.5	+9.9	+7.7	-
9	15		891.0	994.0	593.0	+9.9	+8.2	-
10	16		888.0	993.5	609.0	+9.9	-	-
11	17		888.0	994.0	609.0	+10.0	-	-
12	18		887.5	995.5	592.0	+10.0	-	-
13	19		888.0	996.0	579.0	+10.1	-	1.8
14	20		889.0	996.0	579.0	+10.1	-	-
15	21		889.0	996.0	579.0	+10.1	-	1.9
16	22		890.0	995.5	581.0	+10.2	-	-
17	23		889.0	996.0	545.0	+10.2	-	-
18	24		890.0	996.0	528.0	+10.1	-	-
19	25		895.0	996.0	513.0	+10.1	-	-
20	26		893.0	996.5	482.0	+10.1	-	-
21	27		893.0	996.5	447.0	+10.1	+7.8	-
22	28		892.0	997.0	430.0	+10.2	+7.5	-
23	29		891.0	998.0	448.0	+10.2	+7.2	-
24	30		891.0	997.5	449.5	+10.2	+6.9	-
25	31		893.0	997.0	450.0	+10.3	+6.9	1.4
26	32		890.0	997.0	418.0	+10.2	+6.7	-
27	33		890.0	997.0	400.0	+10.1	+6.8	-
28	34		890.0	997.0	385.0	+10.2	+6.9	-
29	35		891.0	997.0	369.0	+10.3	+7.0	-
30	36		890.0	997.0	385.0	+10.3	+7.0	-
31	37		891.5	997.5	369.0	-	-	-

NATIONAL RESEARCH COUNCIL, OTTAWA, CANADA

LORAN C MEASUREMENTS

DATE	MJD	UTC(NRC)-LORAN C MICROSECONDS
740724	42252	1.40
740725	42253	1.33
740726	42254	1.28
740727	42255	1.25
740728	42256	1.29
740729	42257	1.32
740730	42258	1.27
740731	42259	1.09
740801	42260	0.99
740802	42261	0.94

THE ABOVE VALUES OF UTC(NRC)-LORAN C REFER TO EMISSION TIMES FROM THE MASTER STATION AT CAPE FEAR AT 00:00 UT. THE SIGNAL FROM THE NANTUCKET STATION IS MEASURED AT 15:00 UT ON WEEKDAYS ONLY, AND THE ABOVE VALUES ARE ALL LINEAR INTERPOLATIONS BETWEEN ADJACENT MEASUREMENTS.

PROPAGATION AND RECEIVER DELAY CORRECTIONS ARE BASED ON A PORTABLE CLOCK COMPARISON MADE ON MAY 21, 1974. THIS CORRECTION IS ASSUMED CONSTANT.

THE TIME SCALE UTC(NRC) IS BASED ON TWICE-WEEKLY CALIBRATIONS OF AN HP CLOCK ENSEMBLE IN TERMS OF CS III, THE 2.1 METRE NRC PRIMARY CESIUM BEAM FREQUENCY STANDARD.

APPENDIX B

Table B-1

LORAN-C DATA SHEETS

GENERAL SPECIFICATIONS AND NOTES

The latitude, longitude, and baseline lengths listed herein were furnished by the Defense Mapping Agency, Hydrographic Center and are based upon Mercury Datum 1960 - Center of Mass (CM). Appropriate geodetic satellite shifts have been added to relate these coordinates to the center of the earth.

The following parameters were used in the computations.

a. Signal propagation: Use the velocity of light in free space as 2.997942×10^8 meters/sec. and an index of refraction of 1.000338 at the surface for standard atmosphere.

b. Phase of the groundwave: As described in NBS Circular 573.

c. Conductivity: Sigma = 5.0 mhos/meter (seawater). Baseline electrical distance computations were made assuming a smooth, all seawater transmission path between stations.

d. Permittivity of the earth, esu: $e_2 = 80$ for seawater

e. Altitude in meters: $h_2 = 0$

f. Parameter associated with the vertical lapse of the permittivity of the atmosphere: $a = 0.75$.

g. Frequency = 100 kHz

h. Fischer Spheroid (1960):

equatorial radius (a) = 6,378,166.000 meters

polar radius (b) = 6,356,784.283 meters

flattening (f) = $(a-b)/a = 1/298.3$

Inquiries pertaining to the LORAN-C system should be addressed to:

Commandant (GWAN-3)
U.S. Coast Guard
400 Seventh Street, S.W.
Washington, D.C., 20590

NOTE 1. Monitor station and/or antenna physically relocated. Positions given on old Data Sheets no longer valid. System control established using correlated numbers.

LORAN-C Data Sheet

Table B-1a

U. S. East Coast Chain - Rate SS7 (99,300 μsec.)

26 March 1973

Station	Coordinates	Station Function	Coding Delay & Baseline Length	Major Equipment			Radiated Peak Power	Remarks
	Latitude & Longitude			Frequency Standards	LORAN-C Equipment	Xmiting Antenna		
Carolina Beach N. C.	34-03-46.50N 77-54-47.29W	Master		Cesium/ URQ-11	FPN-41 (Tmr) FPN-42 (Xmtr)	TIP	1.0 MW	Transmissions synchronized to UTC. Exercises operational control of chain. Control for W.
Jupiter, Florida	27-01-58.85N 80-06-53.59W	W Secondary	11,000 μs 2695.51 μs	Cesium/ URQ-11	FPN-41 (Tmr) FPN-42 (Xmtr)	625 ft Tower	400 KW	
Cape Race, Newfoundland	46-46-31.88N 53-10-29.16W	X Secondary	28.000 μs 8389.57 μs	Cesium/ URQ-14	FPN-46 (Tmr) FPN-45 (Xmtr)	1350 ft Tower	2.0 MW	Host nation manned. Double-rated to NORLANT chain (SL7-Z).
Nantucket, Massachusetts	41-15-12.29N 69-58-39.10W	Y Secondary	49,000 μs 3541.33 μs	Cesium/ URQ-11	FPN-41 (Tmr) FPN-42 (Xmtr)	625 ft Tower	400 KW	
Dana, Indiana	39-51-08.30N 87-29-12.75W	Z Secondary	65,000 μs 3560.73 μs	Cesium/ URQ-14	FPN-46 (Tmr) FPN-44 (Xmtr)	625 ft Tower	400 KW	
Electronics Engineering Center, Wildwood, N. J.	38-56-58.59N 74-52-01.94W	T Secondary	82,000 μs 2026.19 μs	Cesium/ URQ-11	FPN-41, FPN-46 FPN-54 (Tmrs) FPN-42, FPN-44 (Xmtrs)	625 ft Tower	200 to 400 KW	Experimental station Not normally on air.
Bermuda U. K.	32-15-53.18N 64-52-34.27W	System Monitor		URQ-14	FPN-43 (Tmr)			Control for X & Y.
Eglin AFB, Florida	Note 1.	System Monitor		5C/5P	SPN-30 (Rcvr)			Control for Z.

LORAN-C Data Sheet

Table B-1b

North Atlantic Chain - Rate SL7 (79,300 μsec.)

26 March 1973

Station	Coordinates	Station Function	Coding Delay & Baseline Length	Major Equipment			Radiated Peak Power	Remarks
	Latitude & Longitude			Frequency Standards	LORAN-C Equipment	Xmiting Antenna		
Angissoq, Greenland	59-59-17.19N 45-10-27.47W	Master		Cesium/ URQ-11	FPN-46 (Tmr) FPN-45 (Xmtr)	625 ft Tower	500 KW	Host nation manned. Synchronized to UTC.
Sandur, Iceland	64-54-26.07N 23-55-20.41W	W Secondary	11,000μs 4068.07μs	Cesium/ URQ-11	FPN-46 (Tmr) FPN-45 (Xmtr)	1350 ft Tower	1.5 MW	Host nation manned. Double-rated to Norwegian Sea Chain (SL3Y).
Ejde, Faroe Islands	62-17-59.64N 07-04-26.55W	X Secondary	21,000μs 6803.77μs	Cesium/ URQ-11	FPN-46 (Tmr) FPN-44 (Xmtr)	625 ft Tower	400 KW	Host nation manned. Double-rated to Norwegian Sea Chain (SL3M).
Cape Race, Newfoundland	46-46-31.88N 53-10-29.16W	Z Secondary	43,000μs 5212.24μs	Cesium/ URQ-14	FPN-46 (Tmr) FPN-45 (Xmtr)	1350 ft Tower	2.0 MW	Host nation manned. Double-rated to U.S. East Coast Chain (SS7X).
Keflavik, Iceland	Note 1	System Monitor		URQ-14	SPN-30 (Rcvr)			Control for W & X. Exercises operational control of NORLANT chain.
St. Anthony, Newfoundland	Note 1	System Monitor			SPN-29 (Rcvr)			Host nation manned. Control for Z.

LORAN-C Data Sheet

Table B-1c

Norwegian Sea Chain - Rate SL3 (79,700 μsec.)

26 March 1973

Station	Coordinates	Station Function	Coding Delay & Baseline Length	Major Equipment			Radiated Peak Power	Remarks
	Latitude & Longitude			Frequency Standards	LORAN-C Equipment	Xmiting Antenna		
Ejde, Faroe Islands	62-17-59.64N 07-04-26.55W	Master		Cesium/ URQ-11	FPN-46 (Tmr) FPN-44 (Xmtr)	625 ft Tower	400 KW	Host nation manned. Transmissions synchronized to UTC. Double-rated to NORLANT.
Bo, Norway	68-38-06.55N 14-27-48.46E	X Secondary	11,000 μs 4048.16 μs	Cesium/ URQ-14	FPN-38 & FPN-54 (Tmrs) FPN-39 (Xmtr)	625 ft Tower	250 KW	Host nation manned.
Sylt, Germany	54-48-29.24N 08-17-36.82E	W Secondary	26,000 μs 4065.69 μs	Cesium/ URQ-11	FPN-41 (Tmr) FPN-42 (Xmtr)	625 ft Tower	400 KW	
Sandur, Iceland	64-54-26.07N 23-55-20.41W	Y Secondary	46,000 μs 2944.47 μs	Cesium/ URQ-11	FPN-46 (Tmr) FPN-45 (Xmtr)	1350 ft Tower	1.5 MW	Host nation manned. Double-rated to NORLANT (SL7W).
Jan Mayen, Norway	70-54-51.63N 08-43-56.57W	Z Secondary	60,000 μs 3216.20 μs	Cesium/ URQ-14	FPN-38 & FPN-54 (Tmrs) FPN-39 (Xmtr)	625 ft Tower	250 KW	Host nation manned. Control for X.
Shetland Is., U.K.	(1) 60-26-25.27N 01-18-05.22W (2) 60-26-17.49N 01-18-19.08W	System Monitor		URQ-14	FPN-46 (Tmr)			Exercises operational control of chain. Control for W, Y, Z.
	(1) North antenna (2) South antenna							

LORAN-C Data Sheet

Table B-1d

Mediterranean Sea Chain - Rate SL1 (79,900 μsec)

26 March 1973

Station	Coordinates	Station Function	Coding Delay & Baseline Length	Major Equipment			Radiated Peak Power	Remarks
	Latitude & Longitude			Frequency Standards	LORAN-C Equipment	Xmiting Antenna		
Simeri Crichi, Italy	38-52-20.23N 16-43-06.39E	Master		Cesium/ URQ-14	FPN-38 & FPN-54 (Tmrs) FPN-39 (Xmtr)	625 ft Tower	250 KW	Temporarily synchronized to UTC.
Lampedusa, Italy	35-31-20.80N 12-31-29.96E	X Secondary	11,000 μs 1755.98 μs	Cesium/ URQ-14	FPN-46 (Tmr) FPN-44 (Xmtr)	625 ft Tower	400 KW	ATLS Station.
Targabarun, Turkey	40-58-20.22N 27-52-01.07E	Y Secondary	29,000 μs 3273.23 μs	Cesium/ URQ-14	FPN-38 & FPN-54 (Tmrs) FPN-39 (Xmtr)	625 ft Tower	250 KW	
Estartit, Spain	42-03-36.15N 03-12-15.46E	Z Secondary	47,000 μs 3999.76 μs	Cesium/ URQ-14	FPN-38 & FPN-54 (Tmrs) FPN-39 (Xmtr)	652 ft Tower	250 KW	
Rhodes, Greece	36-25-20.66N 28-09-31.92E	System Monitor		URQ-14	SPN-30 (Rcvr)			Control for X & Y.
Sardinia, Italy	39-10-51.26N 09-09-35.02E	System Monitor			SPN-29 (Rcvr)			Control for Z.

LORAN-C Data Sheet

Table B-1e

North Pacific Chain - Rate SH7 (59,300 μsec.)

26 March 1973

Station	Coordinates	Station Function	Coding Delay & Baseline Length	Major Equipment			Radiated Peak Power	Remarks
	Latitude & Longitude			Frequency Standards	LORAN-C Equipment	Xmiting Antenna		
St. Paul, Pribiloff Is., Alaska	57-09-12.10N 170-15-07.44W	Master		Cesium/ URQ-11	FPN-41 (Tmr) FPN-42 (Xmtr)	625 ft Tower	400 KW	Controls X, Y, Z.
Attu, Alaska	52-49-44.40N 173-10-49.40E	X Secondary	11,000 μs 3875.17 μs	Cesium/ URQ-11	FPN-41 (Tmr) FPN-42 (Xmtr)	625 ft Tower	400 KW	
Port Clarence, Alaska	65-14-40.35N 166-53-12.95W	Y Secondary	28,000 μs 3068.97 μs	Cesium/ URQ-11	FPN-41 (Tmr) FPN-42 (Xmtr)	1350 ft Tower	1.8 MW	
Sitkinak, Alaska	56-32-19.71N 154-07-46.32W	Z Secondary	42,000 μs 3284.83 μs	Cesium/ URQ-11	FPN-41 (Tmr) FPN-42 (Xmtr)	625 ft Tower	400 KW	

LORAN-C Data Sheet

Table B-1f

Northwest Pacific Chain - Rate SS3 (99, 700 μsec.)

26 March 1973

Station	Coordinates	Station Function	Coding Delay & Baseline Length	Major Equipment			Radiated Peak Power	Remarks
	Latitude & Longitude			Frequency Standards	LORAN-C Equipment	Xmiting Antenna		
Iwo Jima, Bonin Is.	24-48-04.22N 141-19-29.44E	Master		Cesium/ URQ-11	FPN-46 (Tmr) FPN-45 (Xmtr)	1350 ft Tower	3.0 MW	Transmissions synchronized to UTC.
Marcus Is.	24-17-07.79N 153-58-53.72E	W Secondary	11,000 μs 4284.11 μs	Cesium/ URQ-11	FPN-46 (Tmr) FPN-45 (Xmtr)	1350 ft Tower	3.0 MW	
Hokkaido, Japan	42-44-37.08N 143-43-10.50E	X Secondary	30,000 μs 6685.12 μs	Cesium/ URQ-11	FPN-46 (Tmr) FPN-44 (Xmtr)	625 ft Tower	400 KW	
Gesashi, Okinawa, Japan	26-36-24.79N 128-08-55.99E	Y Secondary	55,000 μs 4463.24 μs	Cesium/ URQ-11	FPN-46 (Tmr) FPN-44 (Xmtr)	625 ft Tower	400 KW	
Yap, Caroline Is.	09-32-45.84N 138-09-55.05E	Z Secondary	75,000 μs 5746.79 μs	Cesium/ URQ-14	FPN-46 (Tmr) FPN-45 (Xmtr)	1000 ft Tower	3.0 MW	
Saipan, Mariana Is.	15-07-47.07N 145-41-37.62E	System Monitor			SPN-30 (Rcvr)			Controls W & Z.
Fuchu, Japan	Note 1	System Monitor		Cesium	SPN-30 (Rcvr)			Controls X & Y. Time Service Monitor.

LORAN-C Data Sheet

Table B-1g

Central Pacific Chain - Rate S1 (49,900 μsec.)

26 March 1973

Station	Coordinates	Station Function	Coding Delay & Baseline Length	Major Equipment			Radiated Peak Power	Remarks
	Latitude & Longitude			Frequency Standards	LORAN-C Equipment	Xmiting Antenna		
Johnston Is.	16-44-43.85N 169-30-31.63W	Master		Cesium/ URQ-11	FPN-41 (Tmr) FPN-42 (Xmtr)	625 ft Tower	300 KW	Transmissions synchronized to UTC.
Upolo Pt. Hawaii	20-14-50.24N 155-53-08.78W	X Secondary	11,000 μs 4972.38 μs	Cesium/ URQ-14	FPN-41 (Tmr) FPN-42 (Xmtr)	625 ft Tower	300 KW	
Kure, Midway Is.	28-23-41.11N 178-17-29.83W	Y Secondary	29,000 μs 5253.08 μs	Cesium/ URQ-11	FPN-41 (Tmr) FPN-42 (Xmtr)	625 ft Tower	300 KW	
French Frigate Shoals	23-52-05.23N 166-17-19.60W	System Monitor		5C/5P	SPN-29 (Rcvr)			Controls X & Y.

LORAN-C Data Sheet

Table B-1h

Southeast Asia Chain - Rate SH3 (59700 μsec.)

26 March 1973

Station	Coordinates	Station Function	Coding Delay & Baseline Length	Major Equipment			Radiated Peak Power	Remarks
	Latitude & Longitude			Frequency Standards	LORAN-C Equipment	Xmiting Antenna		
Sattahip, Thailand	12-37-06.91N 100-57-36.58E	Master		Cesium/ Rubidium	FPN-46 (Tmr) FPN-44 (Xmtr)	625 ft Tower	400 KW	
Campang, Thailand	18-19-34.19N 99-22-44.31E	X Secondary	11,000 μs 2183.11 μs	Cesium/ Rubidium	FPN-46 (Tmr) FPN-44 (Xmtr)	625 ft Tower	400 KW	
Con Son, RVN	08-43-20.18N 106-37-57.39E	Y Secondary	27,000 μs 2522.07 μs	Cesium/ Rubidium	FPN-46 (Tmr) FPN-44 (Xmtr)	625 ft Tower	400 KW	
Tan My, RVN	16-32-43.13N 107-38-35.39E	Z Secondary	41,000 μs 2807.28 μs	Cesium/ URQ-14	FPN-46 (Tmr) FPN-44 (Xmtr)	625 ft Tower	400 KW	ATLS Station.
Udorn, Thailand	17-22-44.20N 102-47-12.40E	System Monitor		URQ-14	FPN-46 (Tmr)			Controls X, Y, Z.

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U. S. Naval Observatory
Washington, D. C. 20390

Table B-1i

Daily Phase Values Series 4 — 17 October 1973

LORAN-D Transmissions — No. 350

Experimental transmissions of precise time are available in the western part of the United States via the LORAN-D system. These transmissions are compatible with LORAN-C timing receivers. TOC tables and computed propagation time delays between user monitoring stations and any of the transmitting stations can be obtained from USNO.

The chain operates with a repetition rate of 49,300 microseconds. Coordinates and total emission delays are:

Glendale, Nevada (M)	36° 41' 17."6 N,	114° 38' 39."3 W	ON TOC
Palmdale, California (SA)	34° 32' 40."5 N,	117° 51' 17."2 W	12,255.0 Microsec.
Middlegate, Nevada (SB)	39° 17' 08."2 N,	118° 00' 53."9 W	24,380.0 Microsec.
Little Mountain, Utah (SC)	41° 14' 46."9 N,	112° 13' 25."4 W	36,830.0 Microsec.

Effective 23 Oct. 1973 the transmission schedule of the master station (M) will be 1800 to 0200 UT seven days a week and of the slave stations (SA, SB, SC) will be 2000 to 2400 UT seven days a week. Any changes in transmission schedule will be announced in Series 4.

U. S. Naval Observatory
Washington, D. C. 20390

17 July 1974

No. 389

Daily Phase Values and Time Differences Series 4

The coordinates and total emission delays of the west coast U. S. A. LORAN-D stations are as follows:

Master Lake Meade Aux, Nellis AFB, Nv	36° 14' 57."296N	114° 58' 57."459W	ON TOC
A Slave Pearblossom, Ca	34° 32' 40."453N	117° 51' 17."220W	12,077.30 μs
B Slave Fallon, Nv	39° 31' 00."402N	118° 54' 48."054W	24,675.14 μs
C Slave Little Mountain, Ut	41° 14' 46."924N	112° 13' 25."413W	37,019.61 μs
Monitor China Lake NWC, Ca	35° 41' 14."393N	117° 45' 16."168W	

The chain is maintained on time to the UTC time scale every day between the hours of 1900 and 2300 UT.

For more details see time service announcement Series 9, No. 86, of 19 Jul. 1974.

Table B-2

LORAN-C Basic Group Repetition Rates and Periods

Basic Designator	Rate (pps)	Corresponding Period for Specific Rate 0 (μsec)
SS	10	100,000
SL	12-1/2	80,000
SH	16-2/3	60,000
S	20	50,000
L	25	40,000
H	33-1/3	30.000

Table B-3

LORAN-C Group Repetition Periods for Specific Rates

Specific Rate	Basic Repetition Rate (μsec)					
	SS	SL	SH	S	L	H
0	100,000	80,000	60,000	50,000	40,000	30,000
1	99,900	79,900	59,900	49.900	39,900	29,900
2	99,800	79,800	59,800	49,800	39,800	29,800
3	99,700	79,700	59,700	49,700	39,700	29,700
4	99,600	79,600	59,600	49,600	39,600	29,600
5	99,500	79,500	59,500	49,500	39,500	29,500
6	99,400	79,400	59,400	49,400	39,400	29,400
7	99,300	79,300	59,300	49,300	39,300	29,300

Table B-4

LORAN-C Pulse Coding for Master and Slave Stations

Code Group	Pulse Phase in Degrees							
	1	2	3	4	5	6	7	8
M-1	0	0	180	180	0	180	0	180
M-2	0	180	180	0	0	0	0	0
S-1	0	0	0	0	0	180	180	0
S-2	0	180	0	180	0	0	180	180

APPENDIX C

REVISION OF UTC

As Adopted by The 13th Plenary Assembly of
The International Radio Consultative Committee (CCIR) in 1974
(Excerpted from CCIR Recommendation 460-1—effective date January 1, 1975)

ANNEX I

TIME SCALES

A. Universal Time (UT)

In applications in which an imprecision of a few hundredths of a second cannot be tolerated, it is necessary to specify the form of UT which should be used:

UTO is the mean solar time of the prime meridian obtained from direct astronomical observation;

UT1 is UTO corrected for the effects of small movements of the Earth relative to the axis of rotation (polar variation);

UT2 is UT1 corrected for the effects of a small seasonal fluctuation in the rate of rotation of the Earth;

UT1 is used in this document, since it corresponds directly with the angular position of the Earth around its axis of diurnal rotation. GMT may be regarded as the general equivalent of UT.

B. International Atomic Time (TAI)

The international reference scale of atomic time (TAI), based on the second (SI), as realized at sea level, is formed by the Bureau International de l'Heure (BIH) on the basis of clock data supplied by cooperating establishments. It is in the form of a continuous scale, e.g., in days, hours, minutes and seconds from the origin 1 January 1958 (adopted by the C.G.P.M. 1971).

C. Coordinated Universal Time (UTC)

UTC is the time-scale maintained by the BIH which forms the basis of a coordinated dissemination of standard frequencies and time signals. It corresponds exactly in rate with (TAI) but differs from it by an integral number of seconds.

The UTC scale is adjusted by the insertion or deletion of seconds (positive or negative leap-seconds) to ensure approximate agreement with UT1.

D. DUT1

The value of the predicted difference UT1-UTC, as disseminated with the time signals is denoted DUT1; thus DUT1 $\approx$ UT1 - UTC. DUT1 may be regarded as a correction to be added to UTC to obtain a better approximation to UT1.

The values of DUT1 are given by the BIH in integral multiples of 0.1 s.

The following operational rules apply:

1. Tolerances

1.1 The magnitude of DUT1 should not exceed 0.8 s.

1.2 The departure of UTC from UT1 should not exceed ±0.9 s.*

1.3 The deviation of (UTC plus DUT1) from UT1 should not exceed ±0.1 s.

2. Leap seconds

2.1 A positive or negative leap second should be the last second of a UTC month, but first preference should be given to the end of December and June, and second preference to the end of March and September.

2.2 A positive leap second begins at $23^h\ 59^m 60^s$ and ends at $0^h\ 0^m\ 0^s$ of the first day of the following month. In the case of a negative leap second, $23^h\ 59^m\ 58^s$ will be followed one second later by $0^h\ 0^m\ 0^s$ of the first day of the following month. (See Annex III.)

2.3 The BIH should decide upon and announce the introduction of a leap second, such an announcement to be made at least eight weeks in advance.

*The difference between the maximum value of DUT1 and the maximum departure of UTC from UT1 represents the allowable deviation of (UTC + DUT1) from UT1 and is a safeguard for the BIH against unpredictable changes in the rate rotation of the Earth.

3. Value of DUT1

3.1 The BIH is requested to decide upon the value of DUT1 and its date of introduction and to circulate this information one month in advance.*

3.2 Administrations and organizations should use the BIH value of DUT1 for standard-frequency and time-signal emissions, and are requested to circulate the information as widely as possible in periodicals, bulletins, etc.

3.3 Where DUT1 is disseminated by code, the code should be in accordance with the following principles (except § 3.5 below):

—the magnitude of DUT1 is specified by the number of emphasized second markers and the sign of DUT1 is specified by the position of the emphasized second markers with respect to the minute marker. The absence of emphasized markers indicates DUT1 = 0;

—the coded information should be emitted after each identified minute.

Full details of the code are given in Annex II.

3.4 Alternatively, DUT1 may be given by voice or in Morse Code.

3.5 DUT1 information primarily designed for, and used with, automatic decoding equipment may follow a different code but should be emitted after each identified minute.

3.6 In addition, UT1-UTC may be given to the same or higher precision by other means, for example, in Morse Code or voice, by messages associated with maritime bulletins, weather forecasts, etc.; announcements of forthcoming leap-seconds may also be made by these methods.

3.7 The BIH is requested to continue to publish, in arrears, definitive values of the differences UT1-UTC, UT2-UTC.

*In exceptional cases of sudden change in the rate of rotation of the Earth, the BIH may issue a correction not later than two weeks in advance of the date of its introduction.

ANNEX II

CODE FOR THE TRANSMISSION OF DUT1

A positive value of DUT1 will be indicated by emphasizing a number (n) of consecutive second markers following the minute marker from second markers one to second marker (n) inclusive; (n) being an integer from 1 to 8 inclusive.

$$DUT1 = (n \times 0.1)s$$

A negative value of DUT1 will be indicated by emphasizing a number (m) of consecutive second markers following the minute marker from second marker nine to second marker (8 + m) inclusive; (m) being an integer from 1 to 8 inclusive.

$$DUT1 = -(m \times 0.1)s$$

A zero value of DUT1 will be indicated by the absence of emphasized second markers.

The appropriate second markers may be emphasized, for example, by lengthening, doubling, splitting, or tone modulation of the normal second markers.

QUESTION AND ANSWER PERIOD

MR. DOHERTY:

I wanted to ask, on that first series of slides, what was the reference? Was it the average of all of the various standards? How various standards deviate. What was the base?

MR. CHI:

The base is BIH minus the different laboratories.

MR. DOHERTY:

I wanted to mention one other thing I forgot in connection with the history of Loran and that was that the first timing measurements were made on the Atlantic Missile range about 1960. When I went through the history of it, I forgot to mention it. They were made by taking two receivers down to the Atlantic Missile Range and showing that one locked, say, on Jupiter and one on the master could compare with one another within about a microsecond at that time down as far as the Ascension Island.

MR. ALLAN:

On that last slide I wonder if we might have that reshown. This is data received in Australia, correct?

MR. CHI:

Right.

MR. ALLAN:

On the slide, it seemed evident that there was some granulation in the data—you could see some lines parallel to the lines that you had drawn, (I wasn't sure what the vertical scale was). If the scale was about right it could be cycle ambiguity and that is one of the real problems with cycle identification because you could see some definite granulation lines that could perhaps seep into that.

MR. CHI:

Agreed.

MR. ALLAN:

Is that an explanation, I'm not sure.

MR. CHI:

You've got to remember this is long-term data processed through the computer as they are received. The intent is to show that if you do not do anything, you should be able to achieve about 75 microseconds.

MR. ALLAN:

You can see some lines.

MR. CHI:

The circles are time measurements, the crosses are frequency measurements. Now, I did not take the pains to point it out, I only mentioned that using the Loran-C you could measure both frequency and time. But if you do measure frequency from the phase measurement, sometimes in order for us to do it properly, we've really had to do some pushing around; that is, move the points.

MR. ALLAN:

All those points are not time measurements then.

MR. CHI:

That's correct.

MR. ALLAN:

That's hard to interpret.

MR. CHI:

I agree. I apologize.

DR. WINKLER:

Would it be possible to have your second, third and fourth slides again, quickly?

I think they're interesting and warrant further discussion because a question can be raised whether the procedures as used by the U.S. Coast Guard and the Naval Observatory in cooperation, are the best procedures.

If you look at the U.S. Naval Observatory over these 1,000 days or 900 days interval, there was one adjustment in this whole thing, one deliberate adjustment and it was on 1 May 1973. That's at the point when the slope reached zero.

The slope was left deliberately at zero in order to bring the time scale into agreement with the BIH which was not the case when the first adjustment was made at the transition point from old UTC to new UTC. At this point, as many of you remember, they made an adjustment of, what was it, some large number and the answer was I believe 760 microseconds and many more microseconds; 106,760—something like that.

A residual was left and our policy, in general, is to make as few deliberate changes of frequency as possible—to maintain as uniform an operation as possible.

In a system going through several levels of inter-comparison, such changes generates waves. If you intercompare two distant clocks which supposedly have to be kept in synchronization but which get their synchronization information through different branches, these waves can produce sizeable errors. Therefore, our fundamental policy is to make as few changes as possible.

We see our mission in producing as uniform a reference scale as humanly possible. That's the reason why we have some 24 clocks in our own system and use any information we can get, in addition, to check the performance. So in all of this period there has been only one adjustment, and now the question comes up what is going to happen next? We have two conflicting goals to follow. One is to stay as close to the BIH as is possible: the other one is not to make any deliberate frequency changes if we can avoid it. I foresee that we will go through a period of hesitation because of some of the recent events which I alluded to yesterday, have caused some uncertainty in our links across the Atlantic and between the various Loran-C chains, and some more portable clock visits will be necessary and we want to wait for the resumption of satellite timing and similar things like that. So there is going to be a period of uncertainty.

The next slide please. Well, there's nothing much to be said about it other than you see an obvious attempt by all of the National time and service systems, and laboratories to cluster around zero—to be as close to the BIH as is possible which is certainly a very convenient thing to be. Some don't think it is necessary to do much better than maybe 20 microseconds; 5 microseconds or 10 microseconds may be a practical limit to which one may allow an offset in any national reference clock.

Next slide, please. I must take this opportunity to commend the Coast Guard for doing an absolutely outstanding job in keeping these chains on frequency.

What you see here must be interpreted properly. You are looking at three years of data and these variations which you seem to see in reality are very long pieces of very uniform performance of each of these chains.

The question is, how often do you want to agree with the Coast Guard and us to make a deliberate frequency change which is announced in advance in Series 4 and how often do you want to introduce a step. Also one should add that an improvement in operation is done by equipping the master station with microphase steppers which allow a very accurate and reproduceable frequency change which may obviate the need for time steps altogether in the future.

But I wanted to say that what you've seen here, may in reality be the worst way of looking at an otherwise wonderful performance. Also, the West Coast Loran is quite another subject. Here considerable uncertainly existed for a while and it was our policy, as long as it was not an operational chain, to let it run freely and only make an adjustment after all the information was in. That's the reason for the relatively long delay before making the adjustment. But to sum it all up, I think that since the Loran chains operate for very extensive periods, this very reliable frequency, extremely reliable frequency, indeed better than almost every other monitoring station which we know. It is not necessary to introduce deliberate frequency changes, only at the frequency of once every three or four months, and they always are announced in advance.

LORAN-C EXPANSION: IMPACT ON PRECISE TIME/TIME INTERVAL

John F. Roeber, Jr., USCG Headquarters

ABSTRACT

On 16 May 1974, the Secretary of Transportation and Commandant of the Coast Guard announced that Loran-C had been chosen as the navigation system to serve the U. S. Coastal Confluence Zone. At the present time, reliable CONUS Loran-C groundwave timing coverage extends westward only about as far as Boulder, CO. This paper illustrates the groundwave hyperbolic and timing coverage which will result from the planned CONUS expansion. Time frames are provided.

While not directly related to the subject of the paper, a status report on the planned reduction in Loran-C PTTI tolerances is presented.

INTRODUCTION

After several years of theoretical and practical evaluations of several navigation systems (Loran-A, Loran-C, Decca, and Differential Omega), the U. S. Coast Guard recommended to the Department of Transportation (DOT) that a single navigation system, Loran-C, could best serve the disparate navigation/positioning needs in the U. S. Coastal Confluence Zone (CCZ). The Secretary of Transportation subsequently approved the recommendation and, with the support of the Office of Telecommunication Policy and General Accounting Office, announced the choice on 16 May 1974. Follow-on announcements have described the expansion necessary to cover all of the CCZ.

LORAN-C EXPANSION

Figure 1 illustrates the existing Loran-C hyperbolic coverage in the CCZ. Notice that in Figure 1 the range limits are established for a receiver that requires a signal-to-noise ratio (SNR) of at least -10dB in order to acquire the Loran-C signals. While this is a limiting factor with the new, low-cost, civil-use receivers, it is not for a timing receiver. In timing receiver applications, of course, it is also not necessary to receive more than one station. Figure 2 is a projection of the groundwave timing coverage currently available in the U. S. In this case the range limits are based on my personal experience. I assume that signal acquisition is accomplished by identifying the Loran-C

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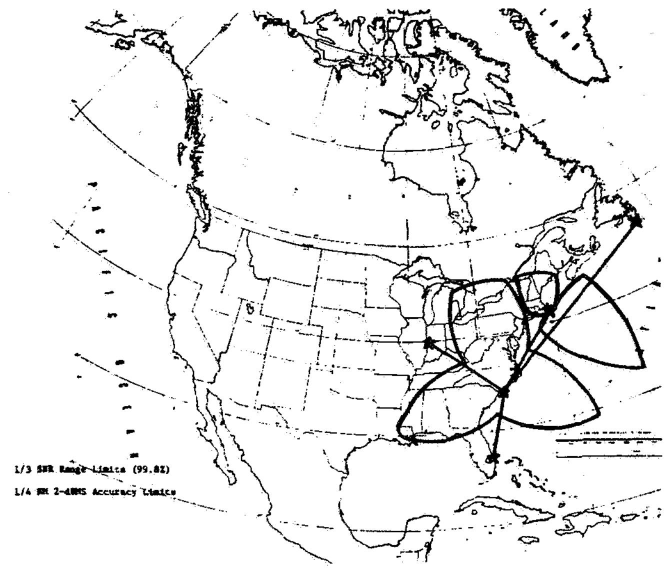

Figure 1. Existing U.S. CCZ Loran-C Hyperbolic Coverage

pulses visually on an oscilloscope. Third-cycle identification is assumed to be accomplished through the use of the Signal Strobe of an Austron 2000-C receiver to draw out the pulse. These assumptions, in short, give conservative range limits when compared with ranges available through the use of a synchronous filter, or knowledge of time and various delays to better than 5 microseconds so that signal acquisition and cycle identification can take place without "seeing" the signal. Figure 3 illustrates the approximate locations of the CONUS Loran-C stations after the expansion is completed. The stations are arranged in seven chains (including the existing North Pacific Chain). Again, the coverage shown is hyperbolic coverage for a civil-use receiver. Figure 4 is a schedule for the implementation. The first stage of the implementation, the U. S. West Coast Chain, was funded this fiscal year (FY). The next two chains to the North, the Northwest U. S. and Gulf of Alaska chains were originally scheduled for completion in late 1977, but due to the programmed completion of the Trans-Alaska Pipeline, the on-air date for all three of these chains was set as 1 January 1977 (assuming orderly approval of funds for the other two chains).

One of the new chains, the Cape Race/Caribou/Nantucket chain, shown on Figure 3, is not necessarily part of the expansion program. Since no additional funds are required to implement this chain other than the additional operating and maintenance expenses, and since it provides excellent coverage in a prime fishing area, such an operational chain may be established.

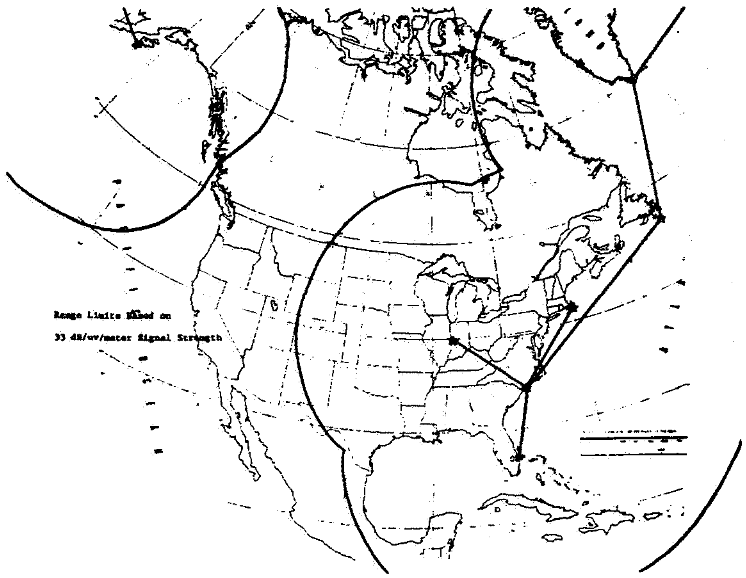

Figure 2. Existing U.S. Loran-C Groundwave Timing Coverage

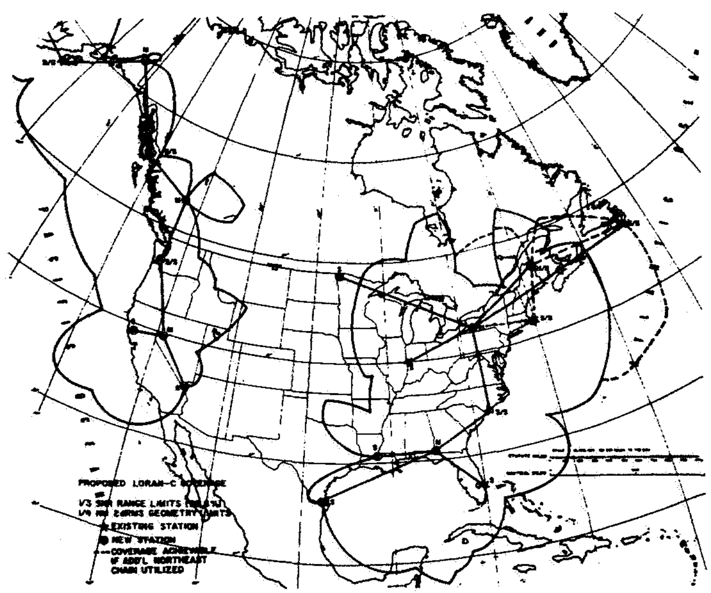

Figure 3. Proposed U.S. CCZ Loran-C Hyperbolic Coverage

CONUS TIMING COVERAGE EXPANDED

Figure 5 illustrates the timing coverage to be expected upon completion of the Loran-C CONUS expansion. There are at present no specific requirements to time any of the new chains. As a result, Figure 5, and the plans outlined in the following discussion are not final.

AREA	DATE
WEST COAST	1 JANUARY 1977
GULF OF ALASKA	1 JANUARY 1977
EAST COAST RECONFIGURATION	1 JULY 1978
GULF OF MEXICO	1 JULY 1978
GREAT LAKES	1 FEBRUARY 1980

Figure 4. Implementation Schedule For CONUS Loran-C Expansion

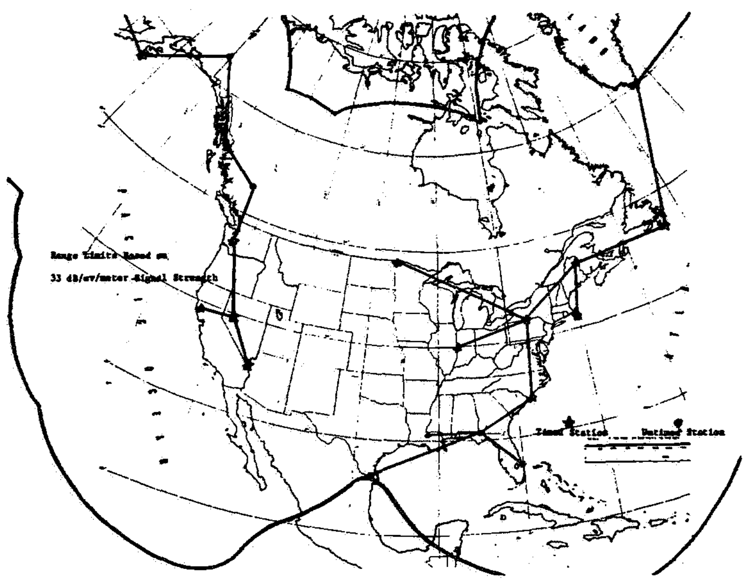

Figure 5. Proposed U.S. Loran-C Groundwave Timing Coverage

The basis for the timing coverage is that all points in CONUS must be within groundwave range of at least one station of a timed chain. The Coast Guard definition of a timed chain is a chain that has a specified time tolerance with respect to UTC(USNO). As can be seen from Figure 5, this basic timing criterion is met if only three of the CONUS chains are timed (East Coast, West Coast, and North Pacific). This would allow the use of a frequency offset in the other chains with attendant advantages in minimizing cross rate interference. These untimed chains could still be used to transfer time between two points that are both within the coverage area of any one chain. In addition, they could be used in the absolute sense if a suitable Null Ephemeris Table were developed.

LORAN REPLACEMENT EQUIPMENT

While the expansion of Loran-C under the National Implementation Plan (NIP) is the Loran-C program receiving the most publicity, there is another program with less dramatic, but still real impact on PTTI. This program is the Loran Improvement Program (LIP).

The first major step in modernizing the Loran-C ground station equipment was the development of the AN/FPN-54 (COLAC) timer at the U. S. Coast Guard Electronics Engineering Center (EECEN) in 1969-1970. An improvement in the operational performance of COLAC-equipped stations was demonstrated in the period 1971-1972. This improvement was directly attributed to the COLAC's solid-state circuitry, modular maintenance philosophy, and operator oriented design. After noting the success of COLAC and realizing the extent and possible consequences of the remaining Loran-C problems, an ambitious ground station equipment improvement program was initiated at EECEN during early 1973. The general goal of this program was to improve the Loran-C chain operational performance while simultaneously reducing the personnel manning levels and equipment costs. Basically this program consisted of the development of a solid-state Loran Replacement Equipment (LRE) package which would replace the older generation timers and low signal-level pulse generating equipment and, in addition, modify the existing Loran-C transmitters.

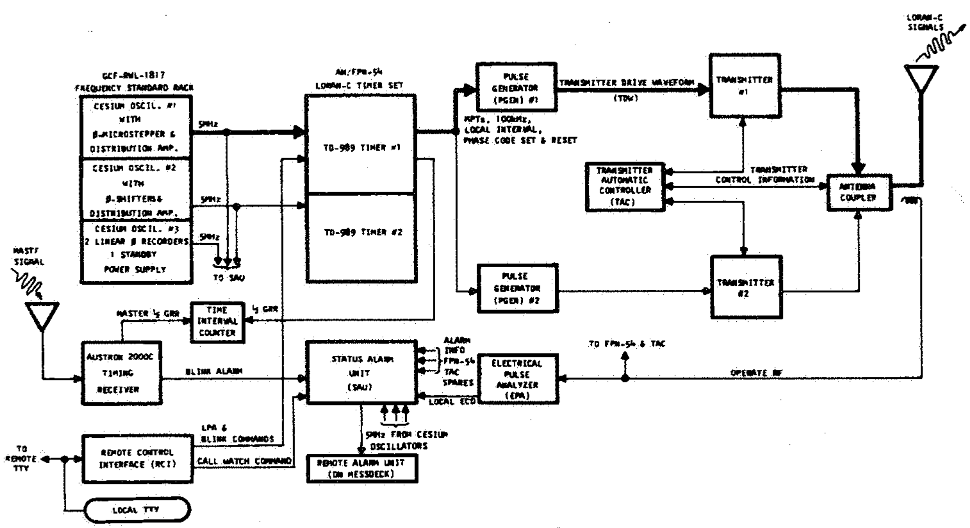

Figure 6. Loran Replacement Equipment

The LRE performs the basic Loran-C signal generation in a more precise, stable, reliable, and controllable manner than was possible with the older generation equipment. Figure 6 is a block diagram of a typical LRE configuration. A description of the major units which comprise the LRE package is presented herein.

Frequency Standard System. (Figure 7) This unit provides the 5 MHz and 1 MHz time base frequencies to the remaining LRE. The phase microstepper and phase shifters allow for precise correction of the cesium 5-MHz outputs. Two linear phase recorders provide continuous monitoring of the three cesium outputs.

AN/FPN-54 Loran-C Timer. The COLAC replaces the timing functions of the AN/FPN-38, 41, and 46 timers. The COLAC is a solid-state time generator whose basic function is to provide the signals necessary to drive the transmitters. More specifically, the COLAC provides the accurate and reliable timing waveforms which control the time of emission of the radiated Loran-C pulses.

Transmitter Control Set (TCS). The TCS replaces existing Transmitter Control Groups. The functions performed by the TCS are aiding in generation of a standard Loran-C pulse shape, monitoring the pulse amplitude, and automatically switching transmitters in the event of a transmitter failure. The TCS equipment units and their primary functions are:

(a) Pulse Generator (PGEN): Develops a transmitter driving waveform (TDW) from the timing signals received from the COLAC. The TDW is shaped within the PGEN to insure that the transmitter radiates a standard pulse shape with proper phase code and droop characteristics.

(b) Transmitter Automatic Controller (TAC): Automatically switches transmitters in the event of a failure of the operate transmitter. The TAC performs this function by monitoring the on-air Loran-C signal and the availability of the transmitter drive waveform. It also allows for manual switch of transmitters.

(c) Electrical Pulse Analyzer (EPA): Provides a capability for precise and unambiguous measurements of Loran-C pulse shape and amplitude. By appropriate programming, via front panel switches, the following measurements may be made: amplitide of pulse peak for any pulse, amplitude of half-cycle peaks (1 - 19) within the first pulse, and envelope-to-cycle difference (ECD) of the first pulse. All measurements are displayed on a front panel digital meter and provided at a rear panel connector in either analog or BCD form. In addition, the EPA generates a reference envelope waveform which is used in conjunction with an osciloscope and the operate PGEN to permit pulse analysis to be accomplished.

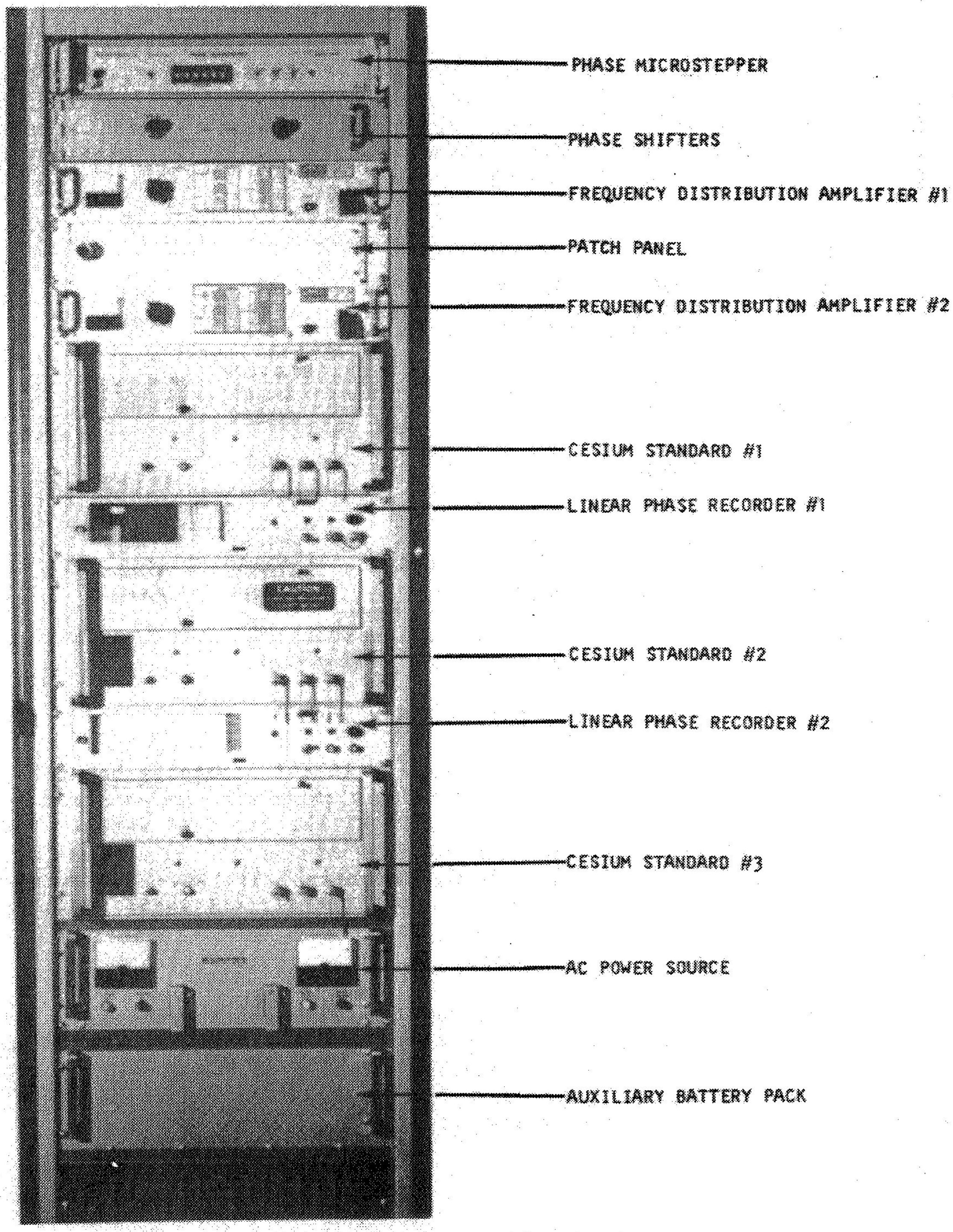

Figure 7. Frequency Standard System

Auxiliary Rack. The Auxiliary Rack contains units which perform the following functions:

(a) Status Alarm Unit (SAU): Provides a centralized alarm node and display position for all LRE alarm indications. In addition, the SAU monitors alarms for other important parameters (failure of 5 MHz, excessive ECD fluctuations, etc.) which affect the ability of the station to stay on-air in tolerance (Figure 8).

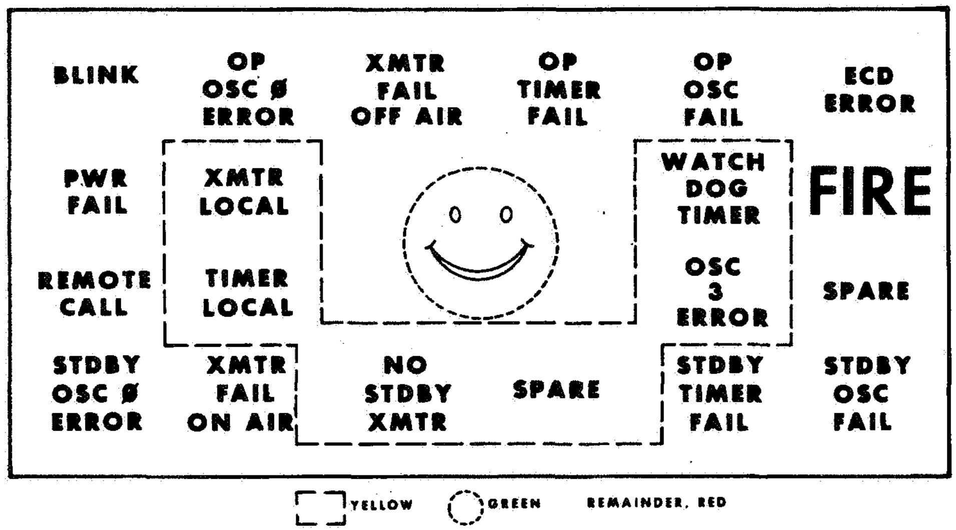

Figure 8. Status Alarm Unit

(b) Remote Control Interface (RCI): The RCI presently being installed with the LRE permits the following commands to be entered: local phase adjustments (LPA), start and stop blink, and call watch. The CALL WATCH command activates the audio alarms of the SAU to awaken the station watchstander in the event of an emergency. The RCI-2, presently under development, will expand the RCI capabilities, and permit a remote computer to control the LRE and perform all of the control and logkeeping functions for a Loran-C chain.

(c) Austron 2000-C Timing Receiver: Replaces the monitoring function of the older generation timers at secondary stations. A station "control number" is generated by comparing the receiver sampling strobe, tracking the master station, to the 1/2 Group Repetition Rate (1/2 GRR) generated in the COLAC at the secondary station.

RELIABILITY AND MAINTAINABILITY

One LRE design goal was to improve the reliability of the Loran-C ground station equipment, and hence the system operational performance. Improved equipment reliability was achieved through careful design of the LRE units and overall system.

Reliability. The LRE was designed using high quality solid-state components. The printed circuit modules were conservatively designed, insuring that all components functioned at far below maximum ratings during normal operation. These efforts contribute to a very high Mean Time Between Failure (MTBF) for the LRE units, and thus to the high reliability of the Loran-C system. For example, under normal circumstances, there is no need to switch from the operate to the standby timers. This is in contrast to the operation of the older generation timers with weekly switches to perform preventative maintenance.

The complete LRE package is presently installed at LORSTA's Nantucket, Dana, Jupiter, and Estartit. Daily message reports on the performance of the U. S. East Coast Chain stations so equipped were evaluated at Coast Guard Headquarters. The overall performance of these stations for the period July 1973 through September 1974 is illustrated in Table I.

TABLE I UNUSABLE TIME BEFORE LRE VS AFTER LRE

	BEFORE LRE INSTALLATION (minutes)				AFTER LRE INSTALLATION (minutes)	PERCENT REDUCTION IN
LORSTA	1971	1972	1973	AVERAGE	1974	UNUSABLE TIME
JUPITER	889	506	623	673	317	52.9
NANTUCKET	530	479	991	667	231	65.4
DANA	858	367	716	647	336	48.1
TOTAL	2,277	1,352	2,330	1,986	884	55.5

Table I. Station Reliability Before and After LRE Installation

Maintainability. Use of the complete LRE package has significantly reduced the required maintenance. Table II illustrates the Loran-C equipment maintenance (excluding that for transmitters) required at LORSTA's Dana and Nantucket for periods before and after LRE installation.

LORSTA	BEFORE LRE AVERAGE 1971,1972, AND 1973 (hours) (Note 1)	AFTER LRE 1974 (hours) (Note 1)	PERCENT REDUCTION IN MAINTENANCE EFFORT
NANTUCKET	717	81	89.8%
DANA	877	35	96.6%
TOTAL			93.7%

NOTE 1. INFORMATION TAKEN FROM LORSTA'S REPORT OF LORAN STATION OPERATION AND ELECTRONICS ENGINEERING (CG-2899), MARCH THRU OCTOBER FOR YEARS INDICATED.

NOTE 2. TRANSMITTER MAINTENANCE NOT INCLUDED IN THIS TABULATION.

Table II. Station Maintenance-man-hours Before and After LRE

ALL CHAIN LORAN-C TIME SYNCHRONIZATION

A report on this program was presented at the 1973 PTTI Planning Meeting by LCDR Sherman. No significant changes have occurred in the program since that time save for an unfortunate delay of almost a year. This delay was caused by personnel shortages (witness the absence of LCDR Sherman at this year's meeting) and procurement delays. All of the required equipment is now in the procurement process, and in fact, most of the equipment has been delivered to our laboratory. The project to assemble the equipment in a rack, print suitable technical manuals, and ship the equipment to the stations has been initiated. We expect the first equipment to be in the field in the Spring of 1975. In the meantime, the Coast Guard, with the cooperation of the U. S. Naval Observatory, is attempting to maintain the values for (UTC(USNO)-Loran-C) within 5 microseconds for the timed chains. This will of course be much easier to accomplish when the equipment is in the field to make the published values independent of clock trips.

ACKNOWLEDGEMENTS

My thanks to LCDR G. R. Goodman and LT R. P. Oswitt for the information on the LRE.

QUESTION AND ANSWER PERIOD

MR. DOHERTY:

I wanted to correct any misimpression that I gave on ground wave signal at Boulder. First of all, we get strong ground waves from Dana. Also in that slide I was referring to the Carolina Beach master station and my comments were that the visible signal that you saw on the slide was sky wave, it was not ground wave. However, we do measure ground waves from Carolina Beach too.

LCDR. ROEBER:

I have been trying to keep my range on it very conservative.

MR. DOHERTY:

Yes, I'm sure your ranges are very conservative.

LCDR. ROEBER:

Where a signal would be visible, where it could be acquired from looking at the oscilloscope.

MR. DOHERTY:

Right. We do not have a visible ground wave there but we definitely have measurable ground wave at Boulder.

MR. OSBORN:

I have a continuing question on what is the position on installing precision timers throughout both the East and the West Coast chains? It is my understanding that up until rather recently you had not had cesium beam frequency standards in this.

LCDR. ROEBER:

That's not true. We always planned on cesium beam frequency standards in the West Coast.

MR. OSBORN:

And you have them on the East Coast, too?

LCDR. ROEBER:

The question is whether it has been timed or not, and there are various definitions of time. To my own personal definition and because of my temporary position, I guess the Coast Guard position on what a timed chain is, is one that has a tolerance with respect to UTC (USNO) and at the moment there is no requirement to maintain any such tolerance on any of the new chains.

MR. COSTAIN:

I would say I have no feeling of nationality in seeing these stations encroaching on Canadian territory. I'm very, very pleased to see it. I hope that they will be timed. In fact, they've relieved one of my worries in short how we could meet what I can see as a potential requirement for microsecond timing at the major airports.

LCDR. ROEBER:

Well, one thing to note. I showed those stations as untimed. Keep in mind that's untimed by my definition, meaning there is no tolerance with respect to the Naval Observatory. These chains could still be used for relative transfers between two points that are within range of the same chain. They could be used in an absolute sense if somebody wanted to develop a Null ephemeres that took intentional frequency offset into account.

MR. LIEBERMAN:

Ted Lieberman, NAVELEX.

I was wondering which of your chains had improved timing in the last year or so?

LCDR. ROEBER:

I meant to cover that. Here's OMEGA's chance to get back at us again. A paper was given last year at this conference by Lieutenant Commander Sherman, covering our plans for improving the timing capability or the monitoring capability, more than anything else, at the Loran-C transmitting station. I believe he probably gave a prognosis of the time that would take place. It hasn't.

One of the major reasons is personnel problems—personnel shortage. Witness the absence of Lieutenant Commander Sherman this year. Another problem is procurement cycles. Basically none of them have the equipment which will allow us to monitor the transmitting stations better and hence, to my mind even though some of the graphs shown in Andy Chi's paper showed that the tolerance is 25 microseconds, recently, at least for the most part, we have been keeping the chains within 5 microseconds.

I don't think we can guarantee this until we have the approved monitoring capability and one of the major contributions to this would be, first of all, finishing the project which is at the radio station—our laboratory at the radio station right now here in Washington. To get the equipment into the field and secondly, satellite time transfer.

One of the biggest problems right now in reducing the tolerance and maintaining the tolerance of 5 microseconds is the necessity for clock trips and the inevitability that one week after the clock trip, the operating standard at the station concerned changes frequency.

Then your extrapolation is off for another three months till your next clock trip. I think satellite time transfers plus getting the equipment into the field are necessary. I would estimate the first equipment, intended to go to Okinawa, will be in the spring of next year, but that really won't improve things until such time that we have satellite time transfers and can do away with, or at least lessen, the number of required clock trips.

DR. WINKLER:

You mentioned the problem of cross chain interference and the possibility of reducing it by deliberately offsetting frequency. Is there any information available to the merits of this procedure as compared to exact timing relationship? I should say exact without offset, where the timing relationship can be used to gate out the interfering signals, which is easier if you do not offset your own chain.

LCDR. ROEBER:

Well, we have not examined that. It is certainly true that if you have an exact time relationship development of a cross rate blanker is easier. Unfortunately anything, including making a new rate structure, that has cost or complexity, adds complexity to a user's receiver and is looked upon with jaundice eye by the user.

However, simple development of a cross rate blanker under those circumstances would add cost to the user and we must first look at potential solutions that will not add costs to the user's black box. We don't really even have hard data on the improvement in cross rate interference. If we do put in a frequency offset, we have the reverse situation. We have what happened to the cross rate interference problem when we stopped phase tracking or phase locking our secondary stations and started using cesium stations.

In addition to the cross rate interference problem, we also got into greater synchronous interference problems after the first of January, '72 when the UTC offset was eliminated. In effect we do have some data on what happens when we institute an intentional frequency offset but not on what happens in the case you described, sir.

DR. WINKLER:

There is, of course, the additonal problem that by destroying the easy or, let's say, the simple phase relationship between different rates, you also will prevent the utilization of stations from different chains which is now possible in the rho-rho mode.

LCDR. ROEBER:

You don't destroy that capability; you make it more complex.

MR. PICKETT:

Bob Pickett, Vandenburg Air Force Base, California.

What's the chance that you can be presumed upon to bring these stations up as they're built rather than waiting for the whole chain? Particularly, could you be so kind as to bring the three California stations up before 1977?

LCDR. ROEBER:

I sort of mentioned it. Perhaps there is some scepticism on my part of our ability to meet this schedule—never mind bringing the stations up before January 1, 1977.

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GROUND EFFECTS ON LORAN-C SIGNALS

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U. S. Army Electronics Command

ABSTRACT

In conjunction with the test and evaluation of the position fixing capabilities of the Army Manpack Loran Receiver AN/PSN-6, an extensive series of time difference and signal amplitude measurements were made within a 100 km map grid square encompassing Fort Monmouth, New Jersey. The test location is within the coverage area of the East Coast Loran-C Chain. The data were used to develop a simple "smooth-earth" model for the test area as well as to estimate the magnitude and distributions of deviations from this model. Local propagation processes associated with topographic features and the grid of overhead wires in the test area are shown to contribute to the deviations from the model.

INTRODUCTION

As part of a broad program to develop a capability for navigation and position fixing, the Army is in the process of developing a manpack loran receiver. The position fixing function of the receiver is to provide a real time display of either the loran time difference coordinates or the geodetic coordinates of the receiver position. This conversion between the time difference and geodetic coordinate systems is accomplished by a small computer within the receiver. The research described here was designed to provide a data base for development of simple conversion algorithms as well as to provide an error budget for the resulting conversion. Since a fundamental variable of a loran system is the propagation time of the 100 kHz signal and since the manpack loran receiver is designed to operate on the ground, the present research was planned to provide information on ground wave propagation at the surface of the earth. These propagation results are the subject of this paper.

BACKGROUND

The fundamental equation describing the functional relationship between a loran time difference and the loran chain parameters is

$$TD(P) = [(D_s - D_m)/C] + ED, \tag{1}$$

where TD(P) is the loran time difference at a field point P, D_s is the great circle distance from the slave transmitter to the point P, D_m is the great circle distance from the master transmitter to the point P, C is the propagation velocity of the loran signal, and ED is the emission delay, that is the sum of the propagation time from the master to the slave transmitter and the coding delay introduced at the slave station. [See Footnote (a).]

The non-constant propagation velocity, which varies with the density and amplitude of terrain features and the electrical properties of the overland path, severely limits the utility of Eq. (1) for time difference estimation. On the other hand, the ground wave propagation velocity over sea water is a well-known quantity, so Eq. (1) is very useful for this application. A complete knowledge of the propagation velocity for all propagation paths is necessary for rigorous use of Eq. (1). This procedure requires an extremely large volume of data and clearly is not practical for a manpack loran receiver. This fact furnished the impetus for the development of simplified coordinate conversion algorithms. In essence, the approach was to develop a simple local conversion model based on calibration and to investigate the accuracy characteristics of that model. The reader is referred to the work of Johler [1] and to the references cited therein for details on the complete treatment of overland loran propagation.

EXPERIMENTAL PROCEDURE

The test area in New Jersey is the 100 km square, 18T WV of the Universal Transverse Mercator Map System. A specially equipped four-wheel drive mobile unit was used during data acquisition. Present instrumentation includes 2 military loran receivers, a timing receiver system with rubidium standard, and ancillary items including printers, oscilloscopes, and power supplies. The military receivers used roof-mounted whip antennas whereas the timing receiver used a rotatable roof-mounted loop antenna.

The calibration procedure is relatively simple, namely to obtain time difference readings at sites of known geodetic control. To obtain estimates of loran receiver performance, approximately 100 time difference measurements were made with each receiver at each site. These measured values were then averaged to provide a time difference for each site. To eliminate separate site surveys, easily identifiable topographic locations, such as road intersections, were used for geodetic control. Coordinates of all sites were determined from 7.5 minute USGS topographic maps. Criteria for site selection were positive identification, freedom from strong electromagnetic scatterers, and accessibility with the mobile unit. In general, the absence of power lines was the most difficult criterion to meet. Several of the sites were at geodetic bench marks which provided a higher order geodetic control.

The distribution of calibration sites is shown in Fig. 1. The numbers shown in this figure are primarily for site identification purposes, but are also related to the time of calibration. Data at sites identified with numbers less than 1000 were obtained in December 1972, whereas those with identifiers greater than 1000 were obtained in July 1973. This latter study was designed to give an increased calibration density within a 60 km square located in the SE corner of the primary test area. In addition, the absence of nearby power lines was of extreme importance. It is estimated that for these locations, there were no wires within one kilometer of the site. For the December 1972 measurements there were no wires within 300 meters of a site. This consideration of the proximity of overhead wires led to the classification of first and second order TD data, as indicated in Fig. 1.

In October 1973, the timing receiver was used to obtain field strength information at the sites with identifiers less than 1000. Time difference measurements were also obtained to check the repeatability of earlier measurements.

A study of the absolute phase variations of the Loran-C transmissions was initiated in October 1974. The sites for a ray path to the SS7-Y, Nantucket transmitter are designated as phase track points in Fig. 1. All measurements were made relative to the reference point 1480 in Fig. 1. This point is approximately 1 km from the coast. The other sites are at approximately 10 km intervals along the ray path. The experimental procedure was to initialize at the reference point, make phase measurements at other sites, and then close the traverse at the reference site. Each

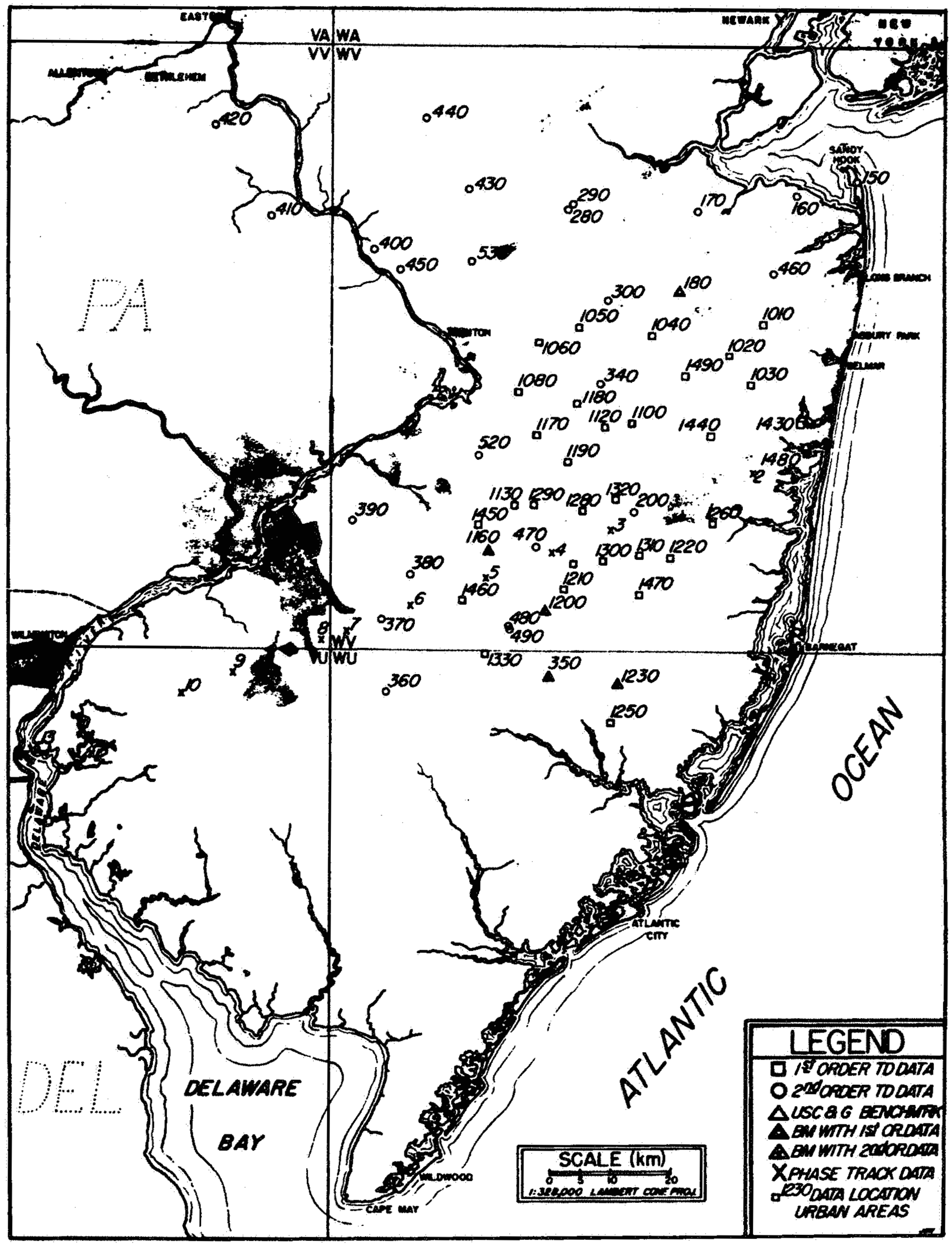

Fig. 1. Map of New Jersey Showing Locations of Loran-C Time Difference and Phase Data Measurements.

series of measurements required from 6 to 8 hours. Closing the traverse at the reference site provided an estimate of the frequency offset of the rubidium standard.

The test area is a segment of the coastal plain which is essentially devoid of pronounced terrain features and conductivity discontinuities. Thus no significant perturbations of the loran signals were expected from these sources.

ANALYTICAL PROCEDURE

The model adopted for data analysis is a modification of Eq. (1). The underlying assumption for this model is that for modest coverage areas, a constant overland propagation velocity will provide a useful approximation. The equation is:

$$TD(P) = (ED + \alpha) + \beta(D_s - D_m) + \varepsilon(\theta_s, \theta_m). \qquad (2)$$

In this expression, α and β are arbitrary parameters to be determined by least squares analysis of the measured data. The correction function, $\varepsilon(\theta_s,\theta_m)$, is to account for sea water paths at a bearing angle θ from the slave and master transmitters to the field point. This function is included to account for the significant difference between ground wave propagation velocity over land and over sea water. The parameter α can be interpreted as an average time difference offset characteristic of the test area. The parameter β can be interpreted as the reciprocal of the local propagation velocity. However, in view of the simplicity of the model and the statistical method of analysis, strict physical interpretation of these parameters should be approached with caution. [See Footnote (b).]

For data processing, the variables D_s and D_m were calculated using the method of Sodano and Robinson [2] for the Clarke 1866 spheroid [3].

The correction $\varepsilon(\theta_s,\theta_m)$ was constructed from tabulated functions of the sea water path length as a function of bearing angle from the Nantucket and Carolina Beach transmitters. The sea water path functions were prepared from maps in increments of 5° in the bearing angle. The path length for intermediate bearing angles was determined by linear interpolation. The sea water path length functions are shown in Figs. 2 and 3 for the Carolina Beach and

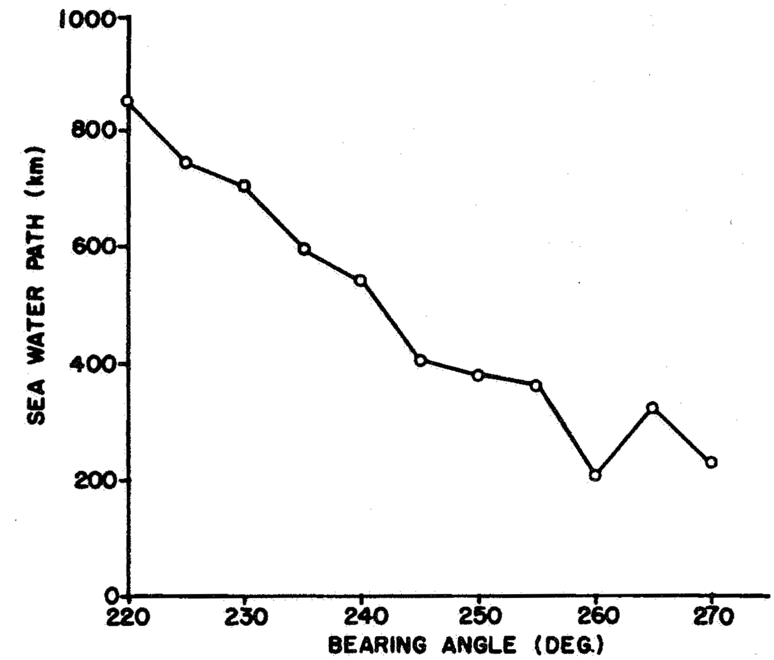

Fig. 2. SS7-Y (Nantucket) Sea Water Path vs. Bearing Angle.

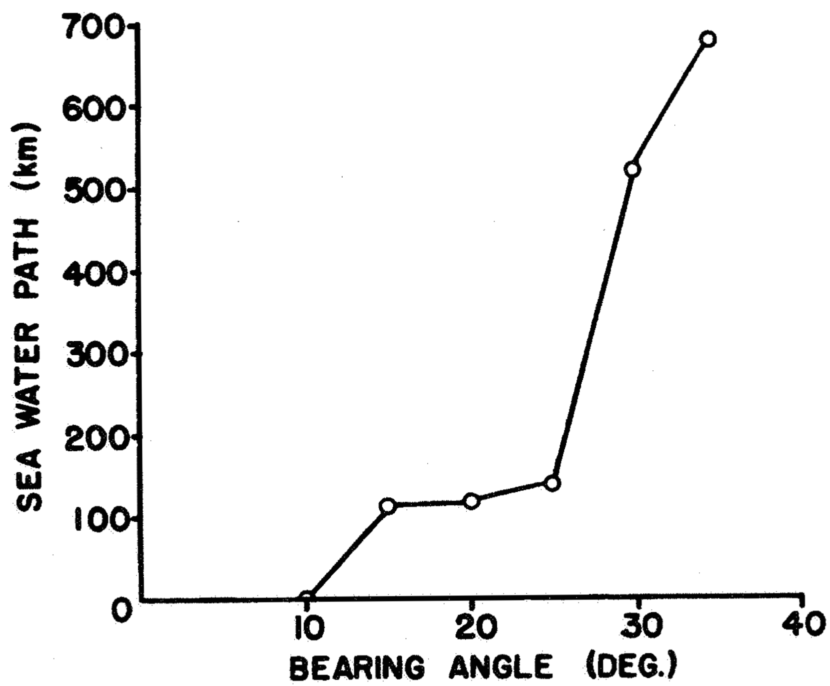

Fig. 3. Master (Carolina Beach) Sea Water Path vs. Bearing Angle.

Nantucket transmissions. In view of the simple interpolation procedure, the error associated with path length determination will be greatest for bearing angles greater than 25° for the Carolina Beach transmission. For this reason, all points with Carolina Beach bearing angles greater than 25° were not considered in the data analysis. This selection process left 61 calibration sites within the 100 km square.

The correction function is

$$\varepsilon(\theta_s,\theta_m) = k[L_s(\theta_s) - L_m(\theta_m)] \ . \tag{3}$$

In this expression, $L_s(\theta_s)$ is the sea water path length at a bearing angle θ_s from the slave transmitter and $L_m(\theta_m)$ is the sea water path length at a bearing angle θ_m from the master transmitter, $k = [(1/C_\ell) - (1/C_s)]$ where C_ℓ is the ground wave propagation velocity over land and C_s is the ground wave propagation velocity over sea water. The values used for these constants are: $(1/C_\ell) = 3.3416$ μs/km and $(1/C_s) = 3.3384$ μs/km. Thus the constant k has the value 0.0032 μs/km. The value of C_s was obtained from the tables of Johler and Berry [4]. The value of C_ℓ was estimated from calibration of a geologically similar area in North Carolina where no sea water correction was required.

ANALYTICAL RESULTS

As discussed previously, the data processing was designed to give the parameters α and β for the Nantucket and Dana slave configurations by the method of least squares. To evaluate the effect of coverage area size, the data were treated in two sets. One set included the total of 61 points. The second set included the points within a 60 km square in the SE corner of the 100 km square.

The analytical results are shown in Tables I and II. Also shown are the RMS deviations of the least squares fit for each data set.

TABLE I. STATISTICAL PARAMETERS FOR 100 km SQUARE (61 Data Points)

Transmission Pair	α (μs)	β (μs/km)	RMS Deviation for Set
SS7-Y	0.85	3.346	0.33
SS7-Z	-0.19	3.339	0.33

TABLE II. STATISTICAL PARAMETERS FOR 60 km SQUARE (30 Data Points)

Transmission Pair	α (μs)	β (μs/km)	RMS Deviation for Set
SS7-Y	0.74	3.346	0.22
SS7-Z	-4.11	3.349	0.25

An estimate of the experimental uncertainties was obtained by statistical analysis of the data acquired at each site. This procedure yielded an average value of 0.15 μs attributable to instrumental jitter. In addition, it has been estimated that the use of topographic maps introduces a location uncertainty of the order of 20 meters. For the test area, this corresponds to a time difference error of about 0.1 μs. Therefore, experimental processes are estimated to contribute an uncertainty of the order of 0.18 μs.

The distribution of the magnitude of the time difference deviations is shown in Figs. 4 and 5 for the Nantucket-Carolina Beach (SS7-Y) and the Dana-Carolina Beach (SS7-Z) configurations, respectively. The solid curves are the normal distributions corresponding to the standard deviations calculated for each slave configuration. The areal distribution of the time difference deviations for each slave configuration is shown in Figs. 6 and 7.

The results of the field strength study of October 1973 are shown in the contour plots of Figs. 8 and 9 for the Nantucket and Dana transmissions, respectively. The contour

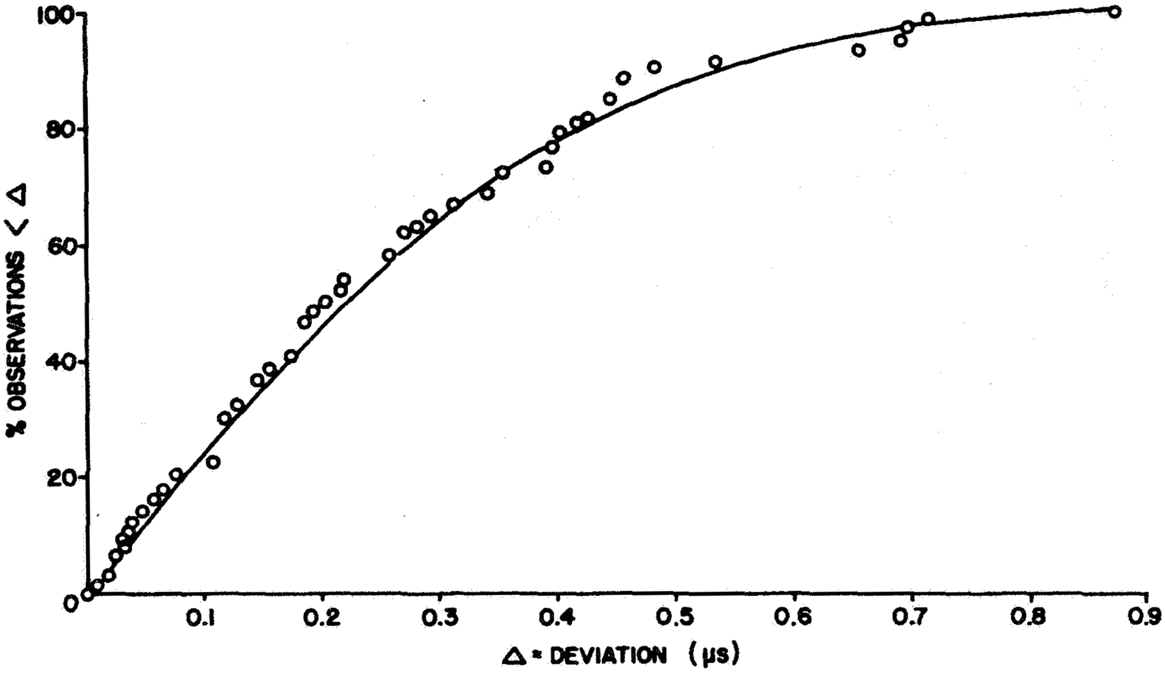

Fig. 4. SS7-Y Time Difference Deviation Magnitude Distribution.

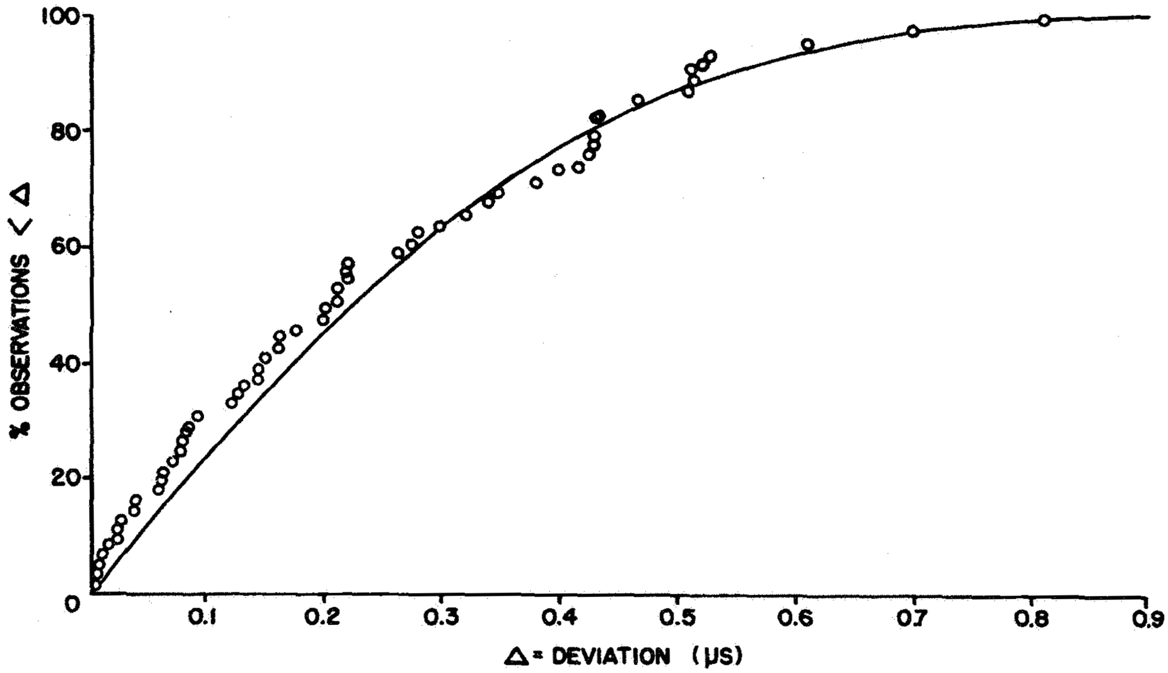

Fig. 5. SS7-Z Time Difference Deviation Magnitude Distribution.

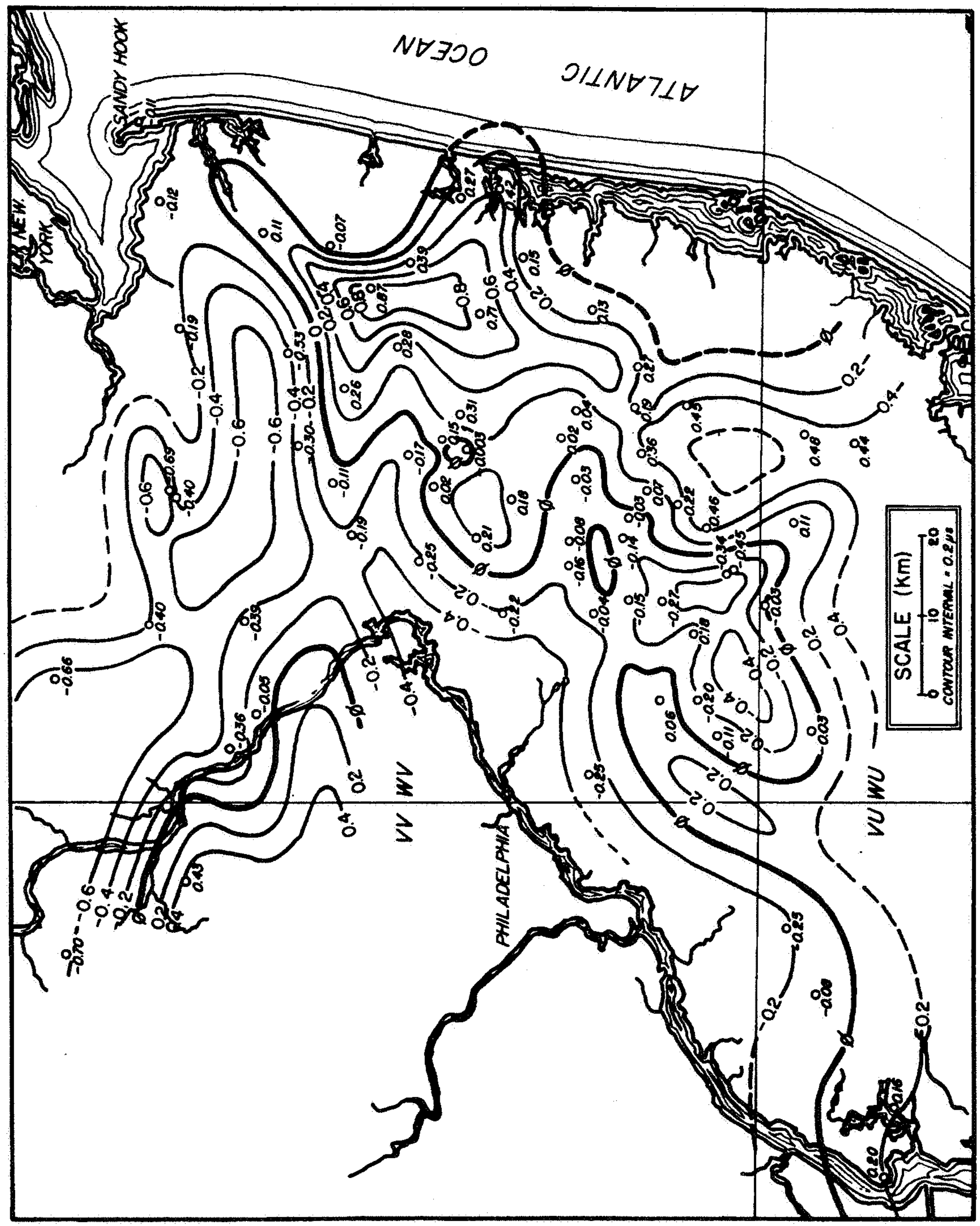

Fig. 6. Map Showing SS7-Y Time Difference Deviations from Theoretical Model.

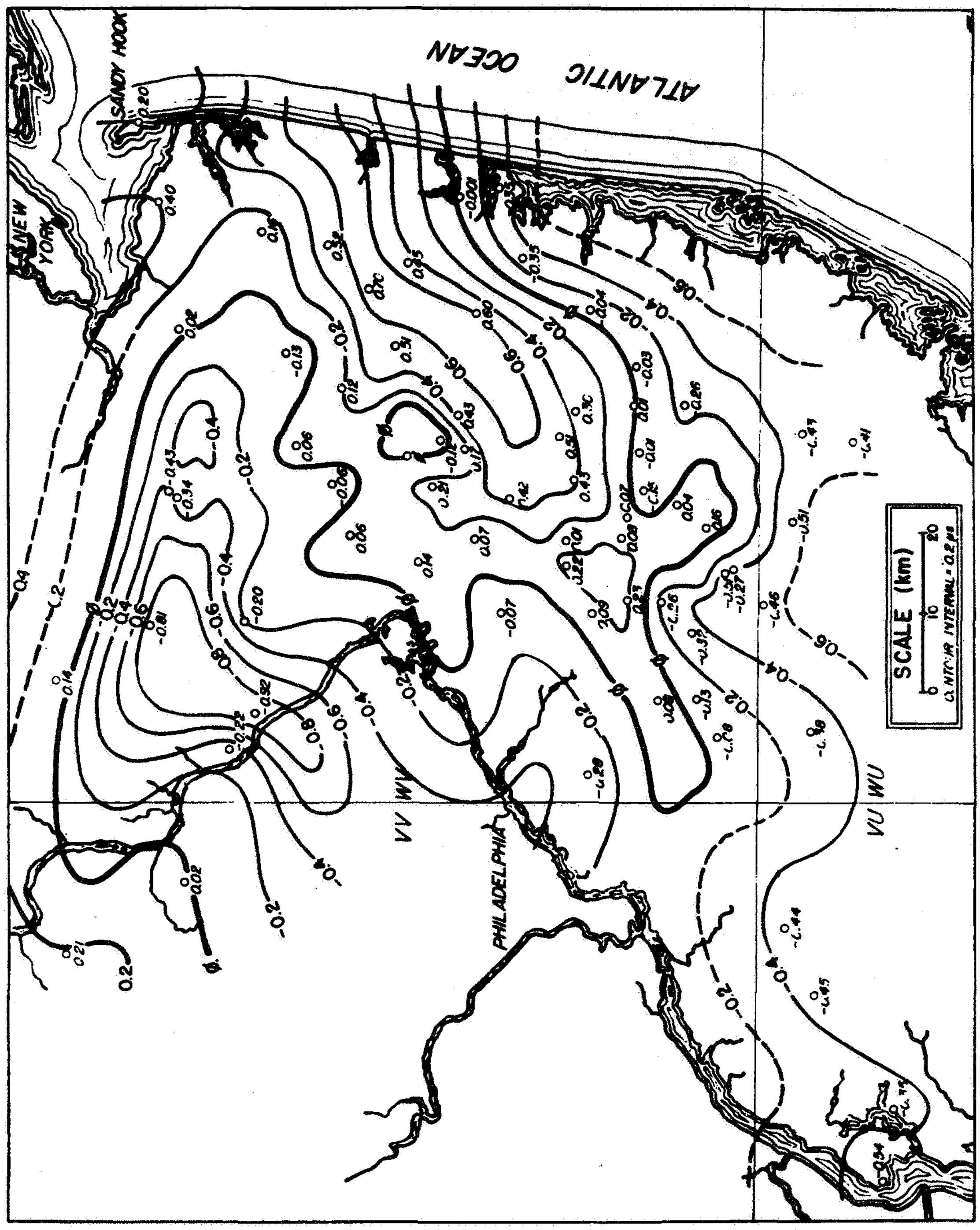

Fig. 7. Map Showing SS7-Z Time Difference Deviations from Theoretical Model.

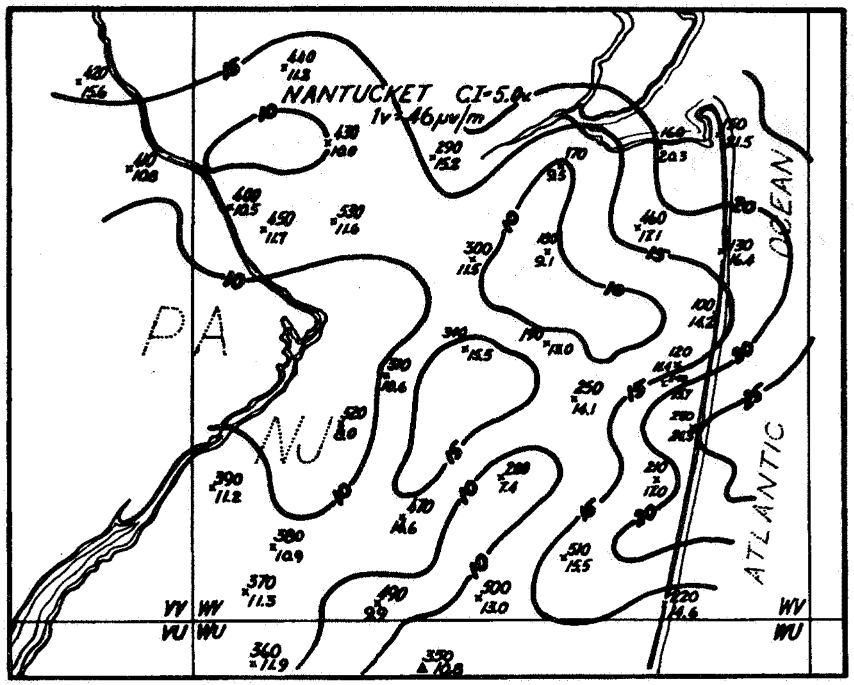

Fig. 8. Map Showing SS7-Y Field Strength Distribution.

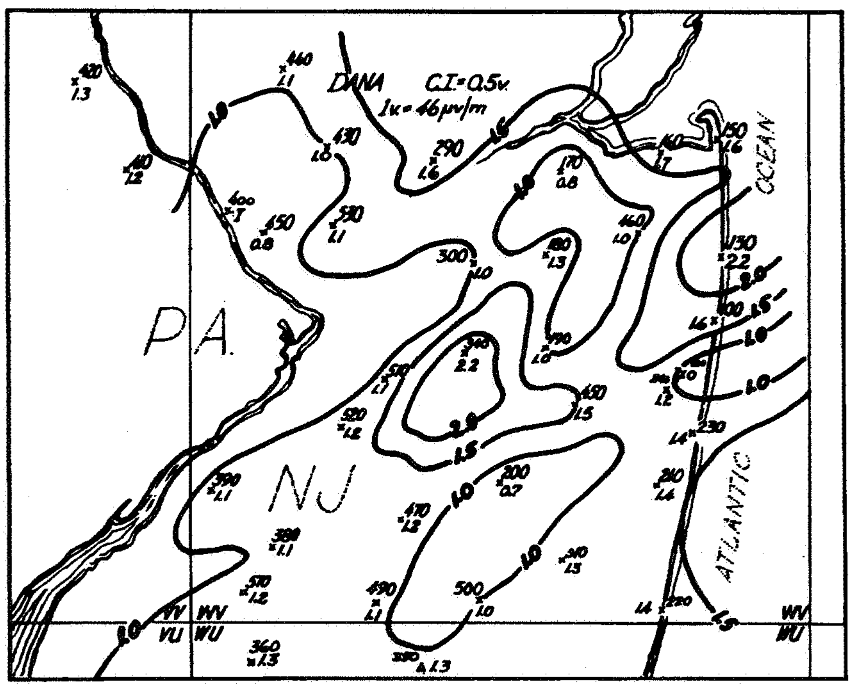

Fig. 9. Map Showing SS7-Z Field Strength Distribution.

values are the output voltage of the amplitude strobe of the timing receiver when tracking the third cycle crossover with an input attenuation of 40 dB. The indicated conversion constant of 46 μv/m/volt was estimated from the antenna characteristics to provide a corresponding approximate value of the field strength.

The phase of the Nantucket transmission relative to the reference point as a function of the distance from the transmitter is shown in Fig. 10. The plotted points are an average of measurements on six different days. The deviations of these measurements from a least squares fitted straight line are shown in Fig. 11. The experimental results have been corrected for loran chain variations from data furnished by the United States Coast Guard. The error bars in Fig. 11 represent typical uncertainty estimates arising from rubidium standard frequency offset.

DISCUSSION AND CONCLUSIONS

The simplified mathematical model presented provides a reasonably accurate description for a small segment of the coverage area, namely the 100 km square area. The observed magnitude of the deviations from the model are randomly distributed. Specific parameters of the model are sensitive to the size of the coverage area. In view of the simplicity of the model, strict interpretation of the parameters in terms of propagation properties is not possible. For example, the value of the parameter β for the SS7-Z slave shown in Table I (3.339 μs/km) is essentially the value expected for an all sea water path. [See Footnote (c).]

The time difference deviations and field strengths exhibit a pronounced areal variation. Furthermore, the contours of both variables exhibit a preferred orientation in a NE-SW direction. Figure 12 shows salient topographic and geological features of the test area. These features also exhibit a preferred orientation in a NE-SW direction. Consequently, there appears to be some correlation between contour orientation and the topographic and geological features.

The standard deviations of the time difference data are 0.33 and 0.22 μs for the 100 km square and the 60 km square, respectively. These values exceed the 0.18 μs estimated to arise from experimental sources. Clearly the results for the smaller test area are in better agreement with the theoretical model than are the results for the larger test area. The criterion for proximity of nearby overhead wires

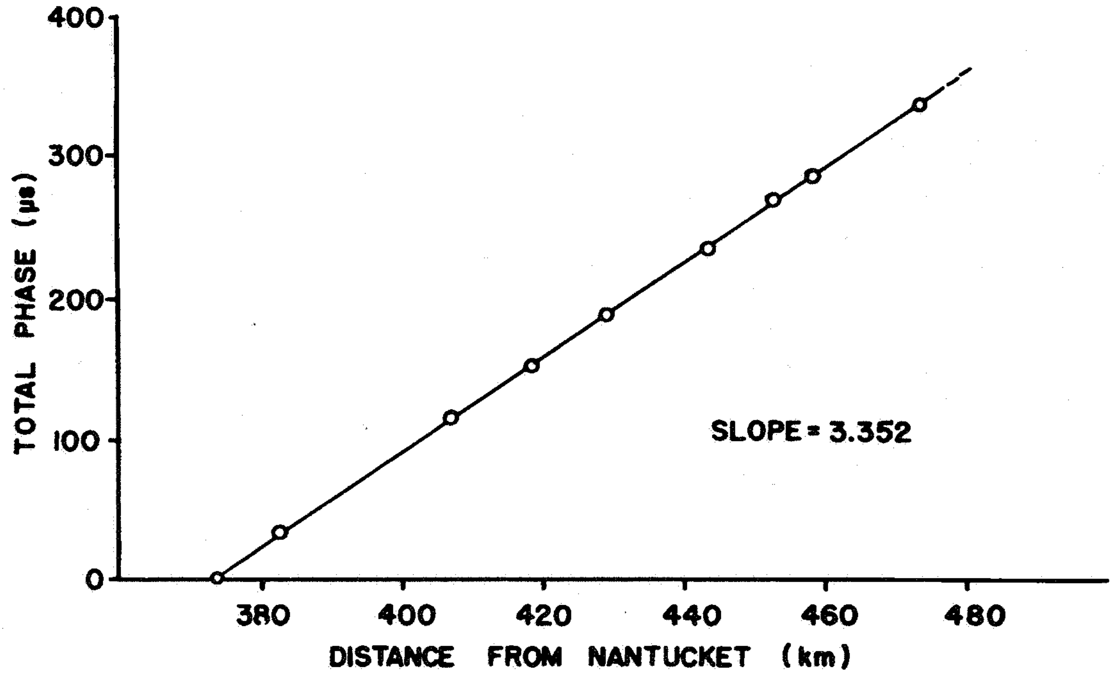

Fig. 10. SS7-Y Phase Variation vs. Distance.

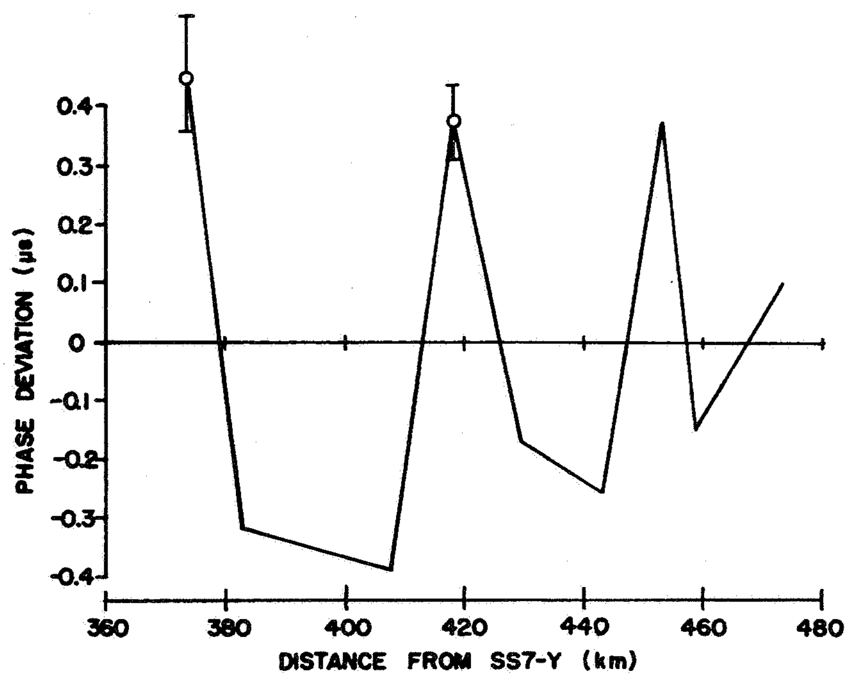

Fig. 11. SS7-Y Phase Deviation vs. Distance.

also influences the deviations from the theoretical model. Although the time difference data does not allow a definitive separation of the contributions of area size and proximity of overhead wires, both factors, as well as previously discussed topographic effects, appear to contribute to the deviations from the idealized model.

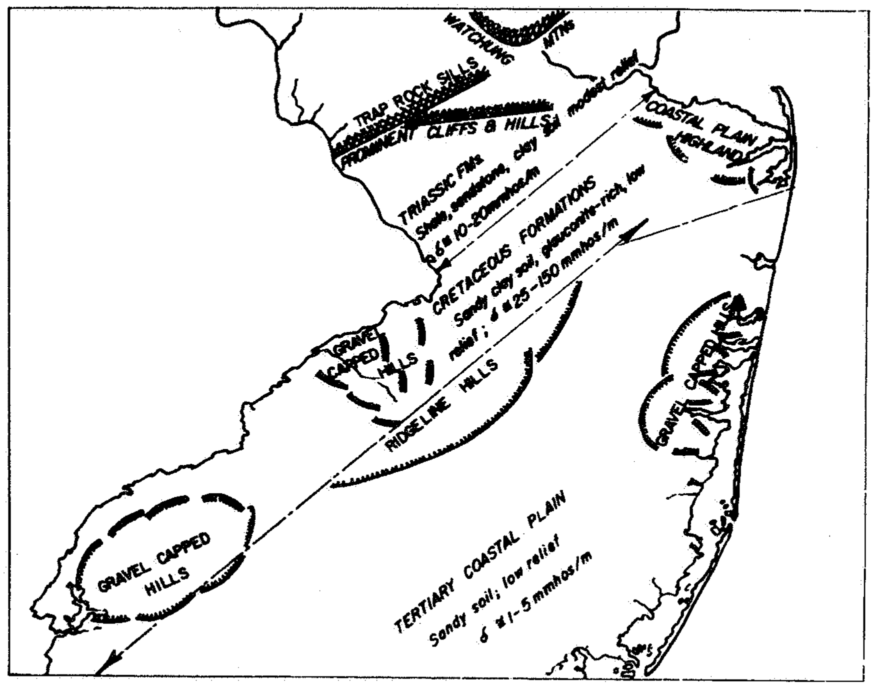

Fig. 12. Map of New Jersey Showing Salient Topographic and Geologic Features.

Preliminary measurements of absolute phase along a ray path from the Nantucket transmitter across the 100 km test area, yielded a linear variation of phase with distance from the transmitter. The least squares slope is 3.352 μs/km, with a standard deviation of 0.3 μs. These observations are considered to be consistent with the time difference measurements for the 100 km square. Since this particular ray path is located in a region of nearly constant conductivity and is devoid of terrain irregularities, it is assumed that the major contribution to the observed deviations arises from scattering associated with overhead wires.

These results are of importance to the position fixing accuracy of ground-deployed loran receivers. Randomly distributed time difference deviations of the order of 0.3 μs from an idealized model have been observed. This study suggests that scattering associated with topographic features as well as from man-made sources such as overhead wires contribute to the deviations. The results yield a realistic standard deviation of position location accuracy of the order of 60 meters.

ACKNOWLEDGMENTS

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Additional Background Information

(a) The assumption of identical propagation velocities over the paths D_s and D_m is implicit in Eq. (1).

(b) The interpretation of β as the reciprocal of a local propagation velocity is valid only to the extent that the propagation velocities over the paths D_s and D_m are identical.

(c) Furthermore, a change in the parameter α of 4 μs for two fits of the same area is devoid of physical significance. This behavior is related to the fact that D_s and D_m are large quantities so that in the least squares process, small variations in the parameter β are compensated for, by large variations in the parameter α. Additional physical constraints as discussed by Doherty [5] are necessary for a realistic physical interpretation of a statistical model.

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[5] Doherty, R. H., (1972), A Loran-C grid calibration and prediction method, OT/TRER 25 (Supt. of Documents, U. S. Government Printing Office, Washington, D. C. 20402).

LCDR. POTTS:

What period of the day were these measurements made? Were they all about the same time during the day? Different days?

DR. PEARCE:

Not really. It's the question of utilizing a full day to make a full set of measurements. We get one stage and keep going, and keep going, and then as soon as we get back, by dark. There was a night day.

LCDR. POTTS:

Well, my question's related to the fact that in past studies we've observed strong temporal correlation, as Bob Doherty well knows, and I wonder whether this had an influence on your readings?

DR. PEARCE:

No, as I say, these are very preliminary. I haven't checked it, but it seems to me that it was done at a very short period of time. I can't remember any essentially serious changes in the general condition, like weather fronts for instance, or things like this that might enter into it.

LCDR. POTTS:

Have you removed any adjustments that the station made, during the period you were making these observations?

DR. PEARCE:

No, no. This is essentially the data averaged. We visited each maybe four times. A criteria like this may be on four different days, but not that far apart in time and in the course of the experiment I don't recall anybody making any comments about it. There was nothing obvious as far as adjustments and so forth were concerned.

LCDR. POTTS:

Well, the point is you wouldn't be notified of the small adjustments which are necessary to retain synchronization?

DR. PEARCE:

No, that's right.

VOICE:

These are on the order of multiples of 20 nanoseconds but it can be large as 100 nanoseconds at one time.

DR. PEARCE:

Right. This has all got to be checked out. As I said this is just preliminary. The thing that disturbed us is actually the magnitude of it.

MR. DOHERTY:

The magnitude of it is surprising. That is 9 points and you say that is more than one single reading at each point.

DR. PEARCE:

Oh, yes. We've been doing it and doing it again. So there is repeatability there, right. The error bars essentially are that you do a certain station right near the beginning or the end. We tried to do it so we do a little bit to take care of the offset in case it isn't quite what we think it is.

MR. DOHERTY:

You only have error bars on two of the nine.

DR. PEARCE:

That's right. I've only worked out two.

MR. DOHERTY:

But you think they're typical.

DR. PEARCE:

That is correct. These numbers are consistent with the specifications that we have for this particular unit, too, as far as fractions of microseconds per hours. It meets the specifications and it's been tuned up against the cesium.

MR. DOHERTY:

This would be a very nice path to do a prediction on.

DR. MUELLER:

One question, I guess, is related to the fact that according to Mr. Putkovich's chart definition or classification, there are microsecond people and millisecond people and so forth. I consider myself a meter person.

Therefore I have some difficulty converting microseconds and especially microvolts per meters into some metric quantity. So my question is a simple one. Let's assume that you take your model for computing the ground wave effect and we take the given equipment and we set it up on one of the Coast and Geodetic benchmarks. How close can you get in position in meters, or in feet if you wish?

DR. PEARCE:

Well, for this area 60 meters standard deviation.

DR. MUELLER:

Sixty meters standard deviation, a sixty meter difference?

DR. PEARCE:

No, that's from a data set, averaged over. Because some of those points were geodetic benchmarks.

DR. MUELLER:

And my second question is, taking not just the receiver but the whole system that you need for real time positioning, what is your estimate of the cost of such a system?

DR. PEARCE:

You're addressing a problem that is much more important than the technical features of this at the present time. At the present time it looks like it's running around $15,000 for the complete package: receiver, readout, time difference, geodetic coordinates, and we'll even throw a battery in for that. But one of the problems is it's too much. That is a nontechnical feature of this program.

QUESTION AND ANSWER PERIOD

MR. DOHERTY:

I wanted to make a little addition. Dr. Winkler started pressing me on this nanosecond system and how can you do it. So I wanted to mention a little bit more.

In the first place, we are doing an analysis on the differential loran experiment that was carried out on the East Coast summer of '73. The analysis there suggests that ten to 20 nanoseconds capability exists between two stations. When we started looking much more closely at, why isn't it there continuously, we discovered the primary reason was that the 10 to 20 nanoseconds capability is not there at all times. This is because there are variations that occur at the transmitting stations in excess of this.

In the summertime, we were not able to find any propagation effects that were anywhere near as large as the variations that occurred within the chain. This suggests that an improvement in the chain could give you the type of nanosecond type timing or naviation. I should say navigation. With timing, you get into another problem, that is you've got to know your system. There should be an R in there, which is the receiver constant which then gets into the people problem.

Now the people problem I very much appreciate. I wanted to mention that we are presently doing a calibration of the Fort Hood chain down in Texas. It's a new Loran-C type chain and it's been recently installed down at Fort Hood, Texas and installed with a new concept. And that is that the transmitting stations are completely unmanned.

They are put in. They are turned on and they are left on—they're unmanned. As far as we've been able to determine to date, we seem to be getting our nanosecond type resolutions from this chain. Now, it's too early to say that this is definitely the case and it's too early to say you can get by with an unmanned chain continuously and it's far too early to say you can use Loran-C type powers with that concept. I want to give due credit to the Coast Guard in that I know that they paid for the work that developed the chain down at Fort Hood. It was sold to Megaparts but the Coast Guard hired—paid Megaparts to develop the transmitters that are actually being used at Fort Hood. But it looks as though this may be a very valid concept and I think it's one well worth considering.

The Fort Hood chain can be controlled by telephone data link. So from the monitoring station you can put in corrections but our experience has been that if maybe you can put in a slight shift once a day that it tracks within the order of a nanosecond through a day. Now we can't say over the time period that these people were talking about on their slides here today, because we've only got a few weeks worth of operation.

DR. MUELLER:

I'd just like to make one comment, I guess, on the question which came up several times this afternoon in different contexts. One was the comment of Dr. Winkler on Mr. Chi's slide which showed the differences between UTC (USNO) and the BIH and later the differences between the Loran-C transmissions and the UTC (USNO). And I guess the question also has some implications on the timing requirements that could be imposed on the Loran-C network.

The problem from the user's point of view, and I'm a user for those of you who don't know, is merely a question of being able to use the time signal as it comes or whether you have to apply some corrections to it. An analogy can be shown here of what happens, for example, in the use of UTC transmissions just lately. In the past, the difference between transmitted UTC and UT1, (UT1 is the time the user is interested in) was kept within, something like 50 milliseconds or so and if the Earth's rotation changed in such a way that the deviation from UTC was more than say, 50 milliseconds, a one-tenth of a second step adjustment was recommended by the BIH, together with some phase adjustment which changed the slope.

At that time, most geologists were satisfied with the time signal as it came. We didn't have to apply corrections to it. At some time a decision was made that the slope, the phase adjustment, should be eliminated and the step adjustment should be made in one second steps. Now the maximum deviation between UT1 and UTC may be as much as 0.8 of a second and this is, of course, unacceptable.

The geologist has to go to various tables published by the Naval Observatory and/or by the BIH to apply corrections to get UT1, which is fine. Of course, we think geologists are well educated and can make simple corrections like that, especially if somebody makes these corrections available. But the point is once you have made corrections, it doesn't make any difference how many of these numbers you have to add together. So as far as we are concerned, there is no advantage really for us in that Dr. Winkler made only a single adjustment in his UTC over that three year period, because if you would have made ten adjustments, that simply whould have meant that we have another number to add to our corrections to get back to some kind of reference.

But that's not the point. The point really is that the important requirement here is the realization and the continuation of very high accuracy monitoring systems.

So that the difference between the different systems could be made available to the users who then can correct their observations to the proper reference.

So, for example, if the Loran-C, if in the Loran-C network, the oscillators would not be phase adjusted and step adjusted as frequently as they are now or if in the future networks make no requirement whatsoever would be imposed on these stations to be set up, but the Naval Observatory still could let us know how big these differences are.

All right. We could live with that, that's really the only real requirement, besides monitoring and the continuous frequent distribution of the corrections. The rest is convenient—not a requirement.

DR. REDER:

I have a question on the advisability of making clock adjustments of people who are participating in the BIH time scale. Why did you do it? Are you pulling your own shoestrings? No?

DR. WINKLER:

This is an extremely crucial point.

The input into the BIH comes from individual clocks. No adjustments. Theoretically, yes. The Naval Observatory master clock is one which is steered to coincide with a coordinated time scale and there is an essential difference between these. Now I repeat what I said. The individual clocks which provide input to the BIH, and there are at the moment I believe some 60 individual clocks, are supposed to be, I underline that five times, without adjustments.

It is known, I know, that it is not true in all cases, but you must consider this really as a problem which is beyond discussion here.

DR. REDER:

Your individual clocks which are used in the BIH case, are not adjusted.

DR. WINKLER:

They're not adjusted. The measurements given to the BIH every ten days are clock readings against a Loran reading and of course by the chain of Loran and so eventually the BIH uses these individual clocks.

DR. REDER:

Now how do you adjust your master clock? Is that only on paper?

DR. WINKLER:

No. We, of course, want to provide a time scale which is better than any individual clock. In order to do that, we must adjust an arbitrary clock. In fact, it's not an adjustment of that clock; it's a phase adjustment of a clock's output, and we have in fact three clocks driven from one and the same frequency standard, and there are several such systems available.

So that is a clock where the individual variations of the driving frequency standard are taken out. You must look at that adjustment as a compensation for the long-term variations of the driving frequency standard.

DR. REDER:

So your master clock is not the average of those individual clocks which participate in the BIH?

DR. WINKLER:

Not necessarily. In fact, the two systems have only loose connections, but it is our attempt to provide a time reference tick, a one pulse per second, which is both as uniform as possible and in the long run does not deviate very much from BIH because there are additional consideration to what Prof. Mueller just said.

In fact we have a written requirement from the U.S. Coast Guard to minimize these changes in frequencies. The requirement was sent to us from your office two or three years ago. To minimize the number of even these intentional long-term changes to plus or minus one part in 10^{13}. That's the level of the coordination offset. Anyone who is concerned about that kind of precision of plus or minus one or two parts in 10^{13}, ought to receive our Series 7 regular bulletins which are concerned with the time scales and astronomical observations.

DR. GUINOT:

Of course the clocks which participate in the BIH computation should be independent.

If some are adjusted, people are requested to give the amount of the adjustments so that it may be taken into account by the BIH. Generally this does not happen, and the clocks are completely independent.

DR. KLEPCZYNSKI:

On Series 7 we distinguish several different types of time, USNO (MEAN) and UTC (USNO) and they are not necessarily the same thing.

DR. WINKLER:

Now that of course requires a third generation of people. That's the nanosecond people.

VERY LONG BASELINE INTERFEROMETRY (VLBI)

by

M. H. Cohen

California Institute of Technology

ABSTRACT

This is a tutorial paper which emphasizes the basic concepts of VLBI: simple block diagrams, coherence, and synchronization requirements. Typical large VLBI experiments have simultaneous objectives in positional astronomy, in astrophysics, in geodesy, in time and frequency synchronization, and even in geophysics! A brief review of the major experimental programs going on around the world will be given.

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QUESTION AND ANSWER PERIOD

DR. REDER:

I have a question on the transfer of the local oscillators by satellite. Do you mean time ticks or do you mean actual oscillations?

DR. COHEN:

My understanding of it is that the data transmit a local oscillator signal, not the time ticks but something similar to a time wave.

DR. REDER:

What do you gain over a hydrogen maser? It will not work because of atmospheric effects.

DR. COHEN:

I presume they'll go both ways. It's equivalent of having a microwave link and you can make round trips and compare, essentially the echo. This procedure is already used.

MR. GROVE:

It would be sent up and back and compared at the source. This is the way I understand it.

DR. REDER:

How could it be better than a hydrogen maser?

MR. GROVE:

It would be hard. It would be the high frequency, I guess that would be the thing that picks it out. It would be left subject to the atmospheric.

DR. WINKLER:

There is a third party who would like to make a comment. Dr. Johnston?

DR. JOHNSON:

I may be mistaken but I thought the purpose of the experiment of connecting the two antennas via satellite was just to give immediate data reduction. There isn't, in my mind, any attempt going to be made to maintain local oscillator coherence for the original experiment. I think the reason for that is the satellite motion is very bouncy. The position of the satellite can't be known to, say, centimeter accuracy that you may need for coherence, so they're not going to try to do anything like that.

DR. WINKLER:

Of course, one could again use the satellite only to provide long-term stability and for short-term rely on local standards. I would like to insert two comments here myself. One is, many of you will ask those who are not radio astronomers what has this got to do with what we are discussing in applications of time/frequency. So I encourage you to listen to these talks and to translate everything that you hear in the following way.

You have essentially an electronic navigation system where you determine your position by measuring the times of arrivals of an incoming electromagnetic wave. You get in fact your position so you get a baseline accuracy. You observe a not pseudorandom but a truly random modulated phase and for that reason you need to have your clocks initially within a certain acquisition window which we have heard from Dr. Cohen to be usually 5 microseconds or something like that.

These are all features which we also see in practically every electronic navigation system. The only advantage is that here we have relatively extremely fixed sources, despite your comments. I look at it from exactly the other side and you have a tremendous amount of data because you integrate over a considerable period of time.

Transit is being observed for quite a while with very wide band widths, 2 megacycles or something more. You have possibly the ability to utilize the very best clocks, and apparently you require frequency stability in an area where the hydrogen maser is at its best. It may even be that another oscillator, the super conductive cavity oscillator for that was mentioned by Dr. Hellwig two days ago, may also become useful for the application.

So all of these are thoughts which may be useful to keep in mind because we can learn from the experience here in a very sophisticated way to utilize frequency standards.

APPLICATION OF VERY-LONG-BASELINE INTERFEROMETRY TO ASTROMETRY AND GEODESY: EFFECTS OF FREQUENCY-STANDARD INSTABILITY ON ACCURACY

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ABSTRACT

The accuracy of geodetic and astrometric information obtained from very-long-baseline interferometry (VLBI) observations is dependent upon the stability of the frequency standard, or clock, used at each site of a VLBI array. The sensitivities of two hydrogen-maser frequency standards of different design to pressure, temperature, and magnetic field variations were measured and, for one of the standards, found to be severe enough to degrade the information content of VLBI measurements. However, the effect on the geometric and astrometric information of such clock instabilities, with time scales of hours or greater, can be sharply reduced through the use of differencing techniques.

INTRODUCTION

Very-long-baseline interferometry (VLBI) was made possible by the development in the 1950's and 1960's of high-stability frequency standards. A stability of about 1 part in 10^{12} was needed, for example, to detect many extragalactic sources when VLBI observations were made at a radio frequency of 10 GHz using the so-called Mark I recording system. The higher stability, up to about 1 part in 10^{14} for time scales from about 1000 seconds to a day, of hydrogen-maser standards was useful for combining the results from a set of pairs of these three-minute Mark I recordings (each an "observation") to determine source positions, baseline vectors, polar motion, and variations in the rate of rotation of the earth (see the review article by P. Bender in these Proceedings for references). If hydrogen-maser standards are used that do not meet such a performance criterion, then the effects on the astrometric and geodetic results of long-term instabilities can be minimized by the use in the data analysis of the differences of the results of observations, made in rapid succession, of sources in widely separated parts of the sky. With the use of such a technique in situations in which signal-to-noise ratios are not a limiting factor, the contributions of the frequency-standard instabilities to the uncertainties in the astrometric and geodetic quantities are, in good approximation, proportional to

$$[\sigma_1^2(T) + \sigma_2^2(T)]^{1/2}\, T$$

where $\sigma_i^2(T)$ is the so-called Allan variance[1] for the frequency standard at Site i, and T, assumed constant, is the time interval between adjacent observations.

In the remainder of this paper we describe the results of a study to evaluate directly the performance of two hydrogen-maser frequency standards, of different design, that have been used in VLBI experiments. The main emphasis was on the sensitivity of these standards to changes in environmental conditions such as temperature, pressure, and magnetic field.

EVALUATION OF FREQUENCY STANDARDS

Two hydrogen-maser frequency standards -- a VLG-10-P2 built by the Smithsonian Astrophysical Observatory and an NP-3 built by the Goddard Space Flight Center -- were operated in separate environments. One of the masers was placed in the standards' room of the Haystack Observatory and the other in a special room at the Westford communications antenna, about 1.2 km distant. The environment at Haystack is well controlled in temperature (to within 0.2°C), but unshielded from variations in magnetic field and atmospheric pressure. The environment at Westford is similar to that at Haystack except the pressure, temperature, and magnetic field can be changed and controlled within certain limits.

The signals from the masers were intercompared at Westford with a phase comparator and the results recorded digitally. Variations in the electrical path of the cable carrying the signal from the standard at Haystack to Westford were nullified by the use of the reflected signal to servo-control a mechanical "line stretcher". Figure 1 shows the curves for the square root of the Allan variance for various averaging times both for the maser comparison and for the measurement system itself, the comparator and associated cables. (Also shown are intercomparisons carried out earlier between the VLG-10 and both a Model HP-5065A rubidium standard and an old Model H10-1 hydrogen maser in rather poor condition.) During periods when the atmospheric pressure remained nearly constant, a relative stability of 5 parts in 10^{15} was observed. Figure 2 shows the comparison between the time kept by the two standards during such a period of exceptional stability. Tests made by changing the temperature, pressure, and magnetic field show that the hydrogen-maser standards exhibit appreciable sensitivity to their environment as indicated by the entries in Table 1. For VLBI, the most detrimental of these is the large sensitivity of the frequency of the signal from the VLG-10 maser to variations in atmospheric pressure. A pressure coefficient of $-3.5 \pm 0.2 \times 10^{-13}$ per inch of mercury (" Hg) was found for the VLG-10 maser from an analysis of the data obtained by modulation of the pressure by 0.15" Hg at the Westford site. (In particular, the pressure coefficient was obtained by cross correlation of the measured frequency changes with the measured pressure changes.) The base plate of the bell jar in the VLG-10 maser is apparently not sufficiently decoupled from the cavity to prevent pressure variations from affecting the cavity resonant frequency and shifting the frequency of the signal from the maser. Tests made in a barometric chamber[2] yielded a coefficient of -4.3×10^{-13}/"Hg. Figure 3 shows the frequency variations produced by variations in the atmospheric pressure during the passage of a weather "front". The pressure coefficient derived by cross correlation from these atmospheric changes is -6×10^{-13}/"Hg and is considerably larger than that obtained from modulation of the pressure at Westford. This comparison suggests that the NP-3 maser might have a positive pressure coefficient; however, separate tests conducted with the maser locations interchanged have shown that the NP-3 maser has a pressure coefficient less than 4×10^{-14}/"Hg. The differences between the coefficients obtained for the VLG-10 maser may be explained by the presence of mechanical hysteresis or by some non-linear behavior. Other evidence for such behavior comes from the observation that the frequency of the signal from the VLG-10 maser does not follow the pressure modulation smoothly and often jumps in frequency when the atmospheric pressure change reverses in sign, as can be seen in Figure 3.

CONCLUSION

The appreciable environmental sensitivity of some hydrogen-maser frequency standards used in VLBI experiments can severely limit the interpretation of VLBI measurements unless a suitable differencing technique can be employed. Although frequency stability of a few parts in 10^{15} can sometimes be attained with hydrogen-maser standards, their performances are often degraded by more than an order of magnitude by changes in the environment. If these standards can not be made insensitive to the environment, it may be necessary to control carefully the temperature, pressure, and magnetic field in their vicinity in order to use them most effectively in VLBI experiments.

ACKNOWLEDGEMENT

We thank Drs. D. Kaufmann and H. Peters of the Goddard Space Flight Center for their aid in obtaining the NP-3 hydrogen-maser standard for use at the Haystack Observatory.

REFERENCES

1. D. W. Allan, Proc. IEEE, 54, 221 (1966).

2. R. F. C. Vessot, private communication.

Table 1

Environmental Sensitivities of Hydrogen-Maser Frequency Standards

Frequency Standard	Pressure	Temperature	Magnetic Field (vertical component)
VLG-10-P2 (SAO)	-3.5×10^{-13}/"Hg to -6×10^{-13}/"Hg	1×10^{-13}/°C	1×10^{-12}/Gauss
NP-3 (NASA/GSFC)	4×10^{-14}/"Hg	2×10^{-14}/°C	5×10^{-12}/Gauss

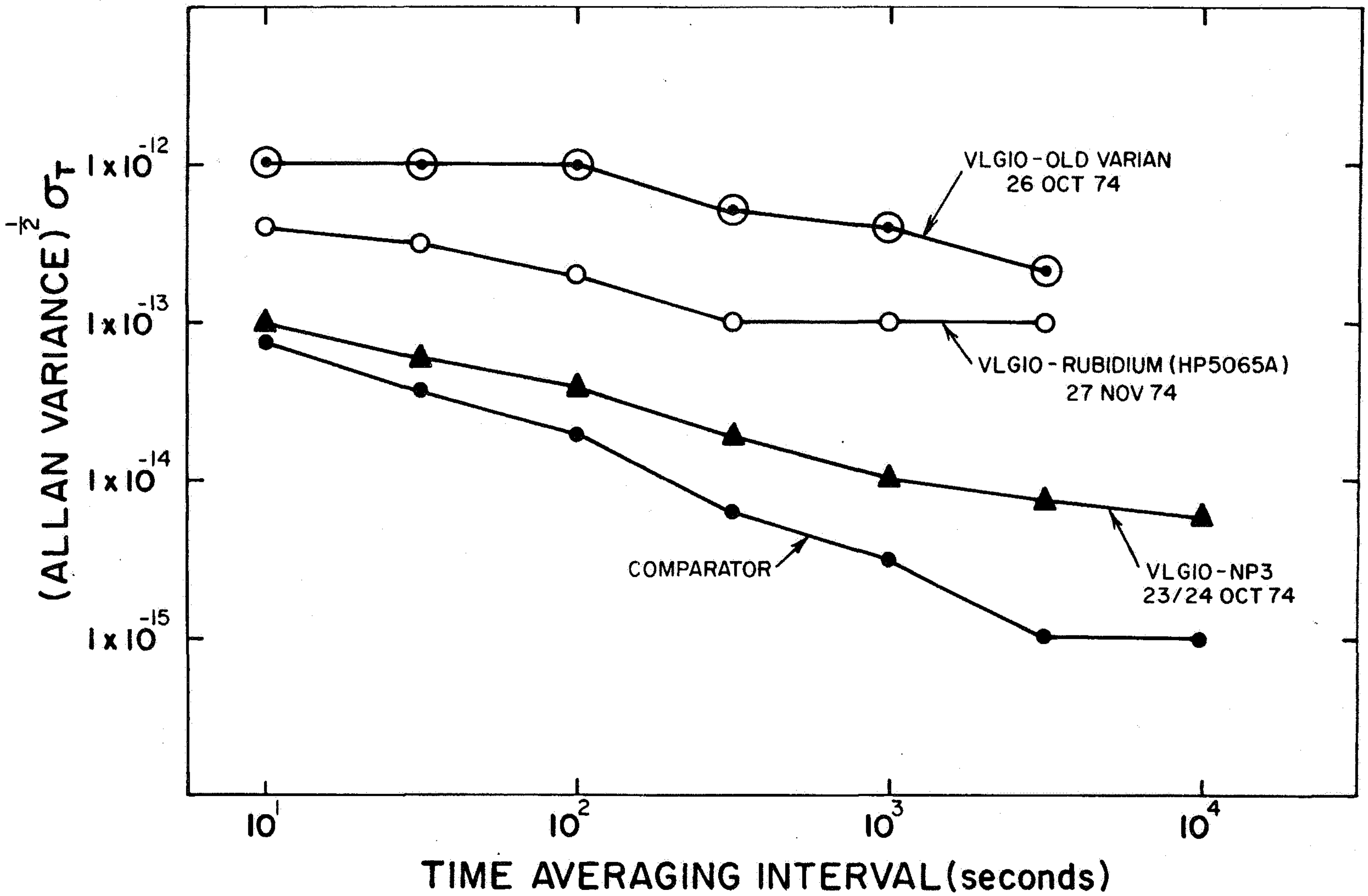

Figure 1. Relative stability of different frequency standards observed during periods of near-constant atmospheric conditions.

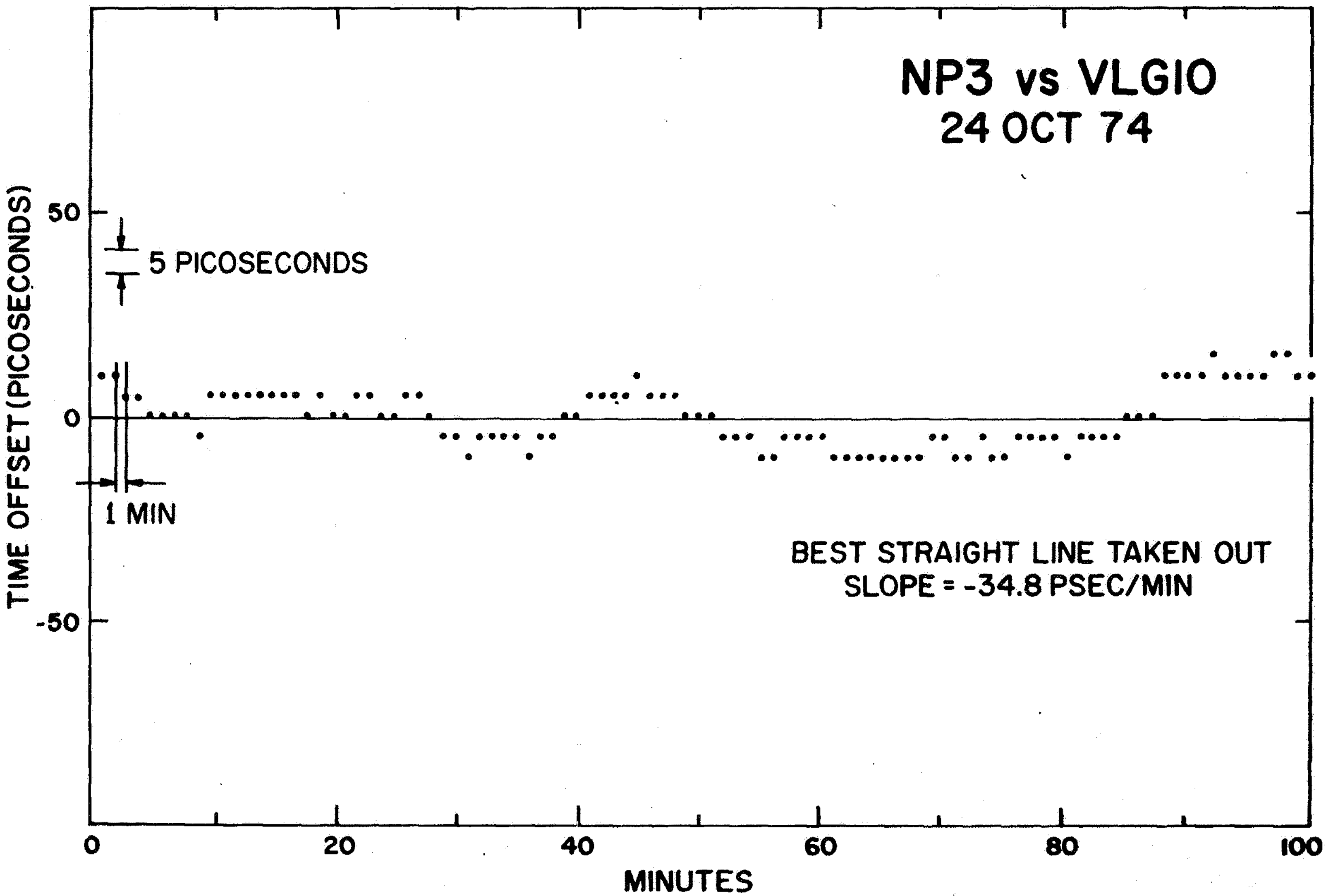

Figure 2. Selected period showing exceptional stability between two hydrogen-maser frequency standards. The 5-picosecond quantization is introduced by the computer program used to generate the graph.

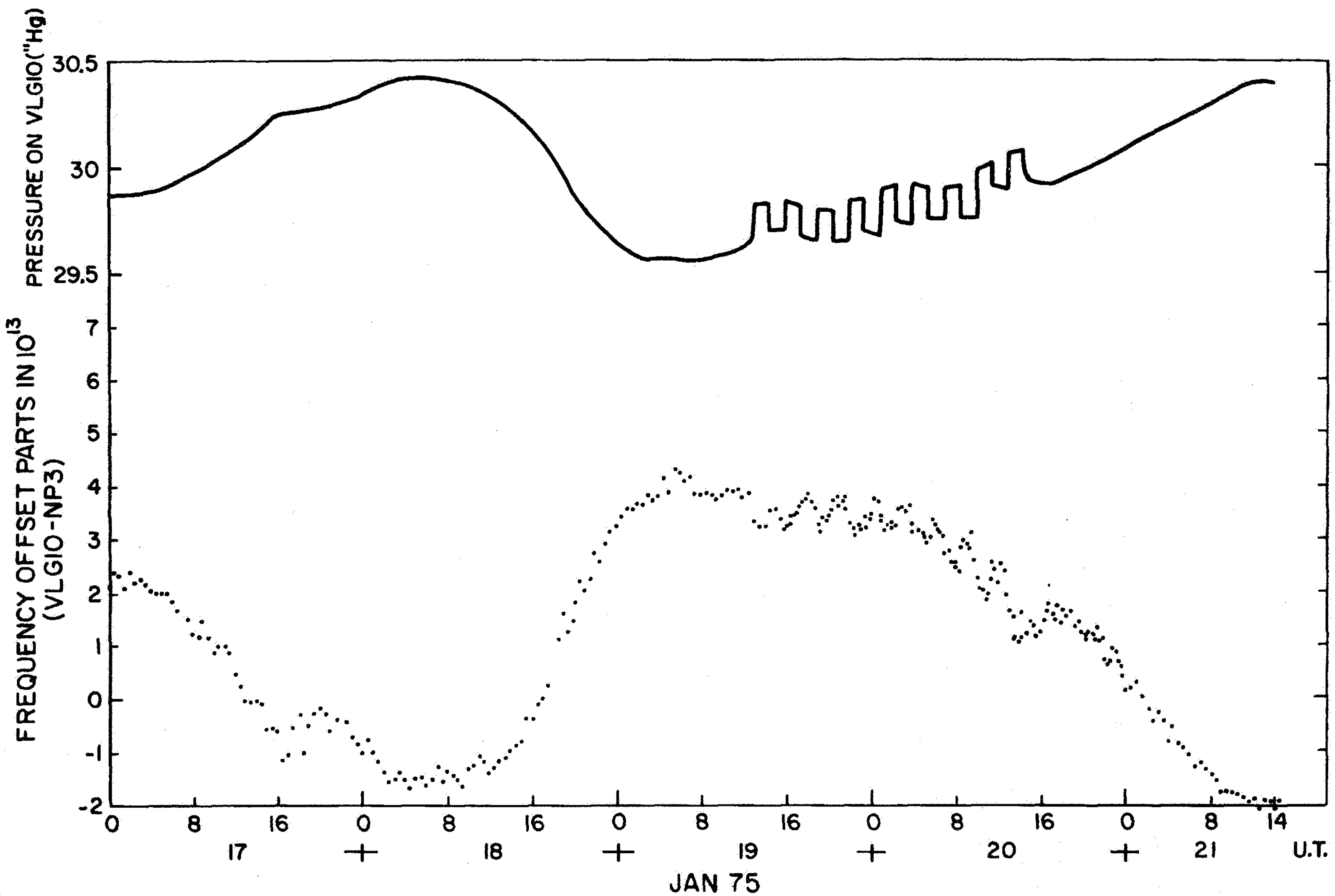

Figure 3. The effect of atmospheric pressure changes on the frequency offset between two hydrogen-maser standards with different sensitivities to pressure variations (see text).

QUESTION AND ANSWER PERIOD

MR. TEWKSBURY:

On your frequency offset through the atmospheric change, you have both masers in the atmospheric pressure or was one held at a constant pressure in a test chamber?

DR. WHITNEY:

One of the masers was held in an atmospheric pressure at about two-tenths of an inch of mercury above the other. That is, the one in the pressure radome had about two-tenths of an inch of mercury offset, which is the pressure required to keep the radome inflated.

MR. TEWKSBURY:

Well then, effectively both units experienced the variation in atmospheric pressure simultaneously?

DR. WHITNEY:

Yes, that's correct.

DR. HELLWIG:

If you don't design the maser correctly, you will have pressure effects; if you do it correctly, you will not have pressure effects. So I want to take out the notion that it is a fundamental effect associated with hydrogen devices.

DR. WHITNEY:

Yes, I should have made that point. In fact, we like to joke that we have the most expensive barometer of anybody around.

DR. WINKLER:

There is another comment that even better barometers are Rubidium standards, and I wondered whether you have kept that in mind?

DR. WHITNEY:

Well, we're aware of that, but investigation has not proceeded to that point yet.

DR. REINHARDT:

I just want to add to Dr. Hellwig's statement. In all fairness to Bob Vessot, who is not here, he has detected that problem and has removed it in his latest model maser.

DR. WINKLER:

But I think that one can generalize that it is extremely dangerous to draw far reaching conclusions from the investigation of just a few individual frequency standards. When I saw the first plot, the old V-10, my first inclination was to say, "Well, well, hydrogen masers are not that bad." Sometimes an individual frequency standard, cesium or rubidium standards, simply will have a problem, and I think all of these applications which we hear this morning are trying to extract the very best performance. So let's be very careful not to generalize too much. I think that's a problem which also can be shown extensively by the 8 frequency plots of super cesium around the corner here, which indicate that these are to be taken as individuals, and a generalized performance statement as required by systems designers ought to insert the factor of caution of at least 10 or maybe a hundred.

DR. ALLEY:

The implication of Dr. Reinhardt's remark is that it was probably in the Smithsonian maser rather than the NP3.

DR. WINKLER:

I should answer that, really.

It was known to Dr. Vessot that due to a peculiar design accident that particular model had a very high pressure sensitivity, but that is by no means to be understood as intrinsic to the hydrogen maser.

MR. ALLEY:

In fact I want to draw attention to the proper design of the NP3 in this respect.

DR. WHITNEY:

I think Harry Peters could probably answer that better. From what I know about the NP3 design it has been isolated from the belljar and probably it would be much less of an effect in NP3.

MR. ALLEY:

That is what I wish to bring out.

DR. WHITNEY:

I would like to make a comment that I did not make any judgment as to which, if either, of the masers might be mis-performing. We know and are well aware of some of the problems that Bob Vessot had encountered but, on the other hand, we have to do some more experimentation. In particular, we have to do the differential pressure measurements between the two masers and then swap them around and put the other one in the pressurized randome and keep the other one outside and do more experiments before we can say that one of them is free of the effect totally and that the other is fully to blame. We're not prepared to make a judgment on that this morning.

MR. STEIN:

In VLBI you're operating in two different pressure areas unless you isolate your pressure. Are you planning experiments in that type of thing where one is in Australia and another one is in Goldstone, for example?

DR. WHITNEY:

Well that type of experiment certainly is anticipated. I think that, as has been indicated, masers can be designed so that they are insensitive or nearly insensitive to ambient pressure changes. In any case, pressure changes are generally slow and smooth and can be characterized or solved for in a parameterized way in the solution which ultimately has to be done to get baseline and source positions.

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WORLDWIDE TIME AND FREQUENCY SYNCHRONIZATION BY PLANNED VLBI NETWORKS

Dr. Robert J. Coates
Dr. Thomas A. Clark

Goddard Space Flight Center

The general concept of Very Long Baseline Interferometry (VLBI) is shown in Figure 1. Two widely separated radio antennas receive radiation emitted from the same distant quasar. The receivers at each station use a hydrogen maser frequency standard clock for generating local oscillator signals for translating the received quasar energy down to baseband for recording. The frequency standard is necessary to assure that the two receiving systems are operating on very close to the same frequency. The output of each receiver is digitized and recorded on a magnetic tape. The magnetic tapes are then brought together and processed in a correlator. Since the received quasar signals are wideband noise, a sharp correlation peak occurs when the two signals are in time phase. In the example illustrated in Figure 1, the signal received in the left hand antenna is delayed by an amount τ from the signal received in the right hand antenna. Thus, by inserting a delay of τ in one arm of the correlation processor, the two signals will be brought into coincidence and a peak correlation occurs. The amount of delay necessary to produce correlation is dependent upon the position of the quasar relative to the two antennas and upon the length of the baseline between the two antennas. In actual observations, the two antennas are mounted on the earth which is rotating. Thus, the frequencies are doppler shifted and the delay required for correlation is continuously changing with time. Thus, in the processor, one determines both the differential delay and the delay rate of the signals propagating from the source to each site. Measurements of several different quasar sources with the same baseline can provide a sufficient number of independent observations to enable one to solve for the clock offset and clock drift rate in addition to the baseline vector and other parameters such as UT.1 and polar motion. With hydrogen maser frequency standards, the offset and drift terms are sufficient to describe the frequency during the 24-hour observing period.

At the 1974 PTTI meeting, T. Clark presented the very accurate baseline determinations and clock synchronization results obtained from the Quasar Patrol observations at X-band with the Goldstone-Haystack baseline, shown in Figure 2. The primary objective of the Quasar Patrol is to measure quasar structure. Thus, three or four stations usually are operated simultaneously as a VLBI array, as indicated by the dotted lines in Figure 2. In addition to Goldstone and Haystack, stations at Fairbanks, Alaska; Greenbank, West Virginia; and Onsala, Sweden were used. This full array of stations is being shown because it is a fairly widespread network that spans a large part of the globe.

All of these VLBI stations had hydrogen maser frequency standards. The solutions for the relative clock epochs between stations in the Quasar Patrol had an RMS residual of about 0.3 nanosecond. However, we estimate that the accuracy of the clock epoch determination was about one nanosecond, due to several small systematic factors. An example of the systematic factor is the environmentally dependent change in the electrical length of the cable carrying the standard frequency signal from the hydrogen maser to the receiver input at the feed of the antenna. Recent measurements at NRAO indicated a change of about 4 cm in electrical length of the standard frequency cable during a VLBI observing session of 24 hours.

The accuracy demonstrated for baseline length determinations was of the order of 16 cm. Studies conducted by the Goddard/Haystack/MIT group indicate that improved calibration and monitoring techniques will reduce the systematic factors by an order of magnitude; use of a much wider band recorder will improve the signal-to-noise ratio, and simultaneous monitoring of tropospheric and ionospheric propagation characteristics will reduce propagation uncertainties by an order of magnitude. This indicates that it should be feasible to make baseline length determinations with VLBI to an accuracy of a few centimeters.

Because of this potential, NASA has started a VLBI Project, called the Pacific Plate Motion Experiment (PPME). The primary objective of PPME is to measure directly the movement of the central part of the Pacific Plate relative to the North American Plate as indicated by the motion of the island of Kauai, Hawaii. The very long term movement of the Pacific Plate is estimated from current tectonic plate motion models to be about 8 cm/year toward the northwest from the East Pacific Rise (large arrow in Figure 3). However, there has been no direct measurement of this movement except for local geodetic surveys along bounding faults, such as the San Andreas; in addition, it is not known how this motion varies over relatively short (3 year) periods of time. Such variation is important not only scientifically but because short-term variations in plate motion of the center of the plate with respect to its edge are an indication of strain buildup along bounding shear faults that lead to earthquakes.

The PPME will use VLBI systems to measure very accurately (5 cm) the baselines between a station in Kauai, Hawaii, on the Pacific Plate, and stations on the North American Plate at Fairbanks, Alaska; Goldstone, California; and Haystack Observatory, Massachusetts, as shown (by solid lines) in Figure 3. Possible minor local movements of Kauai will be allowed for by geodetic surveys in the Hawaiian Islands. Because the western boundary of the North American Plate is a broad one, intraplate movements of the Alaskan and Californian stations will be measured by VLBI measurements of baselines to the Haystack Observatory (and possibly a station at Ft. Davis, Texas as shown by the dotted lines in Figure 3), well within the North American Plate.

Another objective is to determine by direct VLBI measurement the motion of a station at Kashima, Japan relative to the three stations on the North American Plate and relative to Kauai, Hawaii. Japan is in the boundary zone between the Pacific and Eurasian Plates where the Pacific Plate is believed to be consumed by subduction under the Japanese Islands, giving rise to frequent and often catastrophic earthquakes.

In order to achieve the 5-cm baseline determination accuracy, the instrumental and propagation errors will be reduced by augmenting the present type of VLBI systems with the following new capability: improved instrument calibration, microwave water vapor radiometers for tropospheric path length determination, and simultaneous dual frequency (8400 and 2300 MHz) reception for ionospheric path length determination.

All of the early VLBI experiments utilize large, high gain antennas which give sufficient signal-to-noise ratios for high accuracy VLBI. The PPME objectives require comparable signal-to-noise ratios when using the 9-m antenna in Kauai and the 26-m antenna in Fairbanks. This will be achieved by using a much wider bandwidth data system, called the Mark III system. In addition to the wideband data capability, the Mark III system will contain the VLBI sequence program and control for automated operation of the total VLBI system.

Hydrogen maser frequency standards will be used at all of the stations. A new calibration system will be used to accurately monitor the internal system delays at the picosecond level.

You can recognize that this particular network will automatically, as a fallout, establish time synchronization for all of these stations to the fractional nanosecond level.

We plan to be operational with this system in late '77 or early '78, and to conduct observations roughly every three months in order to track the motions of the Island of Kauai.

Another NASA program that is being implemented by the Jet Propulsion Laboratory is shown in Figure 4. This shows the baselines from the 210-foot antenna at the Goldstone Station in California to the DSN 210-foot antennas in Madrid and Australia. JPL is implementing VLBI in those stations to form a network of three stations for the precise determination of polar motion and UT.1. They also will use the dual S/X frequencies. As a matter of fact, the Goldstone station that will be used for the PPME is the DSN network station. It is the first station equipped with the dual S/X frequency capability. DSN will use water vapor radiometers, wide bandwidth synthesis, hydrogen masers and electronics calibrations very similar to the PPME. In fact, we are working to make these stations compatible with the PPME stations and vice versa.

This DSN VLBI capability is expected to be operational in 1977 for determining polar motion for deep space navigation. The operation that is envisioned is that on a normal basis the measurements of polar motion and UT will be made once a week. During critical mission phases, like planetary encounter, the measurements will be made on a daily basis.

In addition, of course, this VLBI will be used to synchronize the DSN clocks. The capability will be there for subnanosecond type synchronization.

Figure 5 is a world map showing the VLBI networks for PPME (solid lines), DSN (dashed lines) and Quasar Patrol (dotted lines). Common stations, such as Goldstone, form the tie between the networks. The Haystack Observatory station is involved in astronomical VLBI with many other radio astronomy stations such as Greenbank, W. Virginia; Owens Valley, California; Fort Davis, Texas; San Paulo, Brazil; Crimea, U.S.S.R.; and Algonquin Park, Canada. The Max-Planck-Institut fur Radioastronomie, Bonn, Germany, has indicated their desire to use their 100-m antenna for a VLBI link with Haystack. The NASA stations at Santiagc, Chile and S. Africa are potential VLBI terminals in the future. All of these site locations are marked on Figure 5 with small circles.

All of the stations joined by lines in Figure 5 will have hydrogen masers and comparable VLBI capability in the late '70's. In addition, many of the radioastronomy observatories that are active in VLBI have expressed an interest in obtaining hydrogen masers and the more advanced VLBI systems that NASA is planning to implement.

Looking at this, you see a rather extensive worldwide network of stations, probably all of them with hydrogen masers. This network in the VLBI mode will be synchronized to the subnanosecond level and will be periodically resynchronized, some on a weekly basis and some on a monthly basis. This forms a rather elaborate, far-reaching network with precise time and frequency synchronization.

So I would like to ask this audience what the time and frequency field would recommend for utilization of such a network for precise time and frequency applications. NASA strongly feels that there will be a significant capability here and there is probably an interest outside of NASA to make use of such a capability. I would like to hear from any of you who wishes to join in with us and work with the time and frequency aspects of the problem.

With a VLBI network, there are several things that would have to be done to make it an operational time and frequency network. For example, there is no time/frequency input or output to the present VLBI networks. The VLBI data is recorded, shipped to a central processing facility, and analyzed at a later date for clock offset and other parameters. It is usually several months after the data is taken that the analysis is completed. This delay reduces the usefulness of the output for many time and frequency applications. I envision that there would have to be direct input/output ties with the user organizations and with other ensembles of frequency standards in order to utilize the VLBI networks for precise time and frequency applications.

I would like to receive comments from any of you that are interested in working in a cooperative manner in this area.

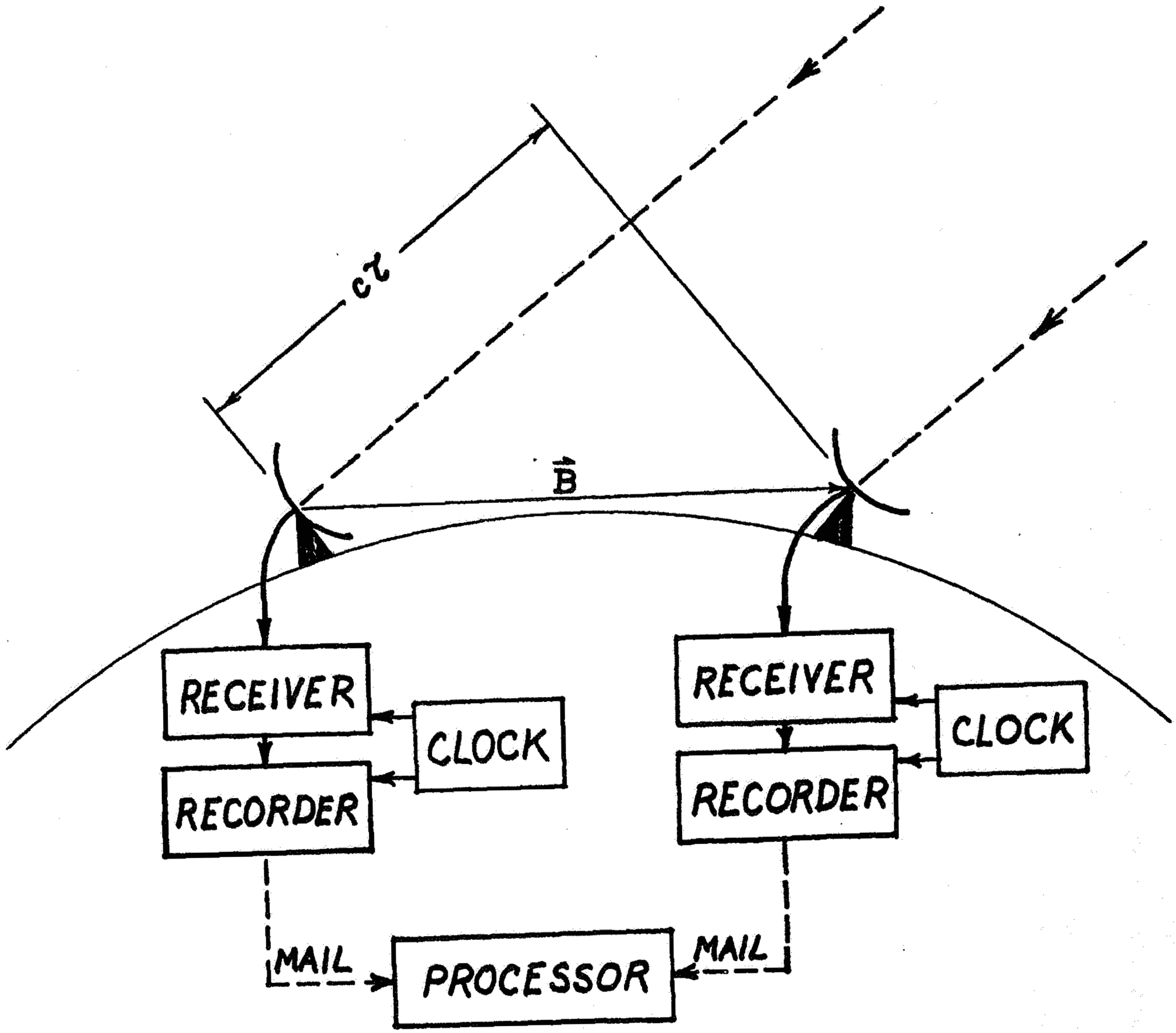

Figure 1. Very-Long-Baseline Interferometer Diagram

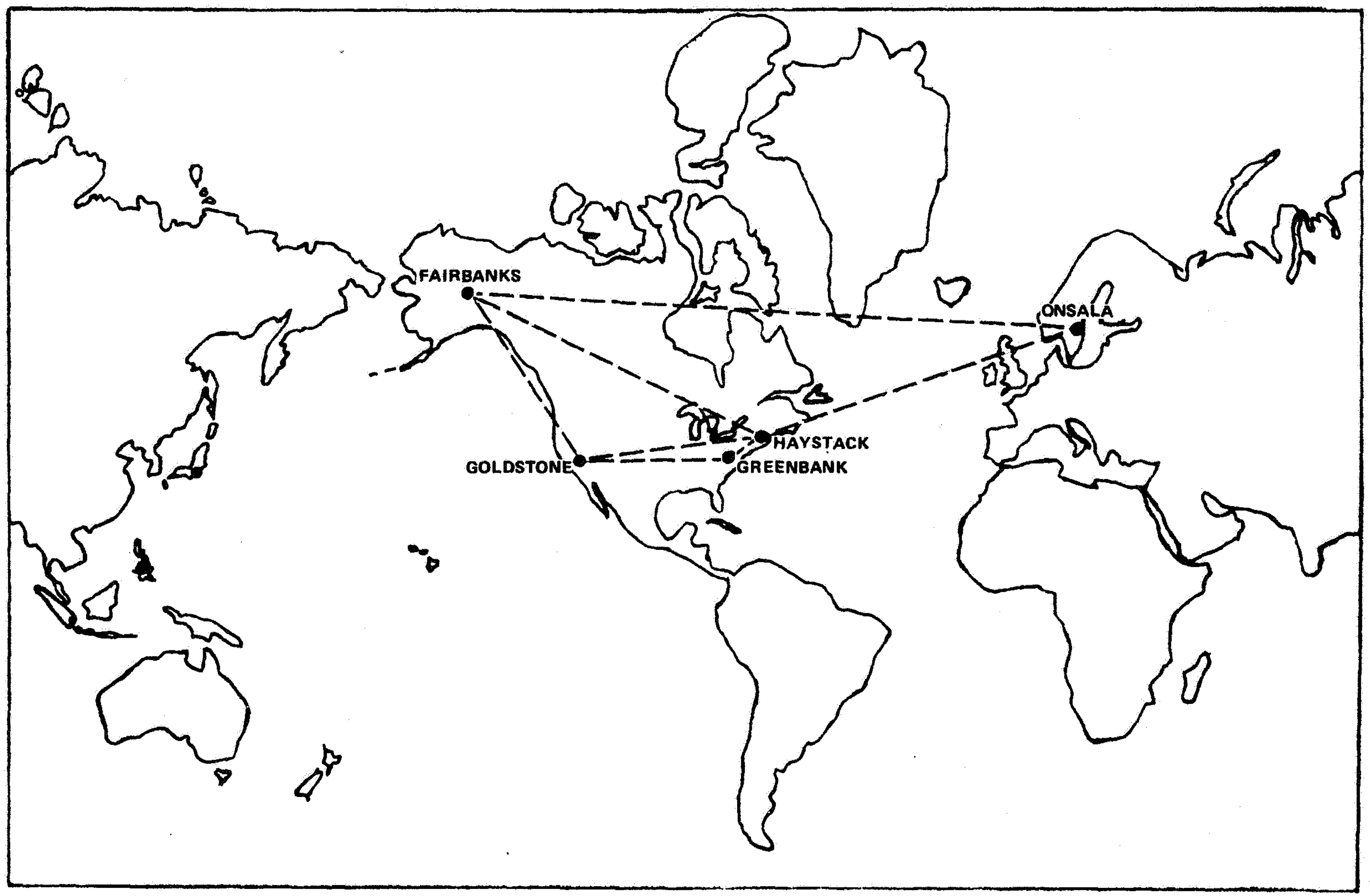

Figure 2. Stations for Quasar Patrol

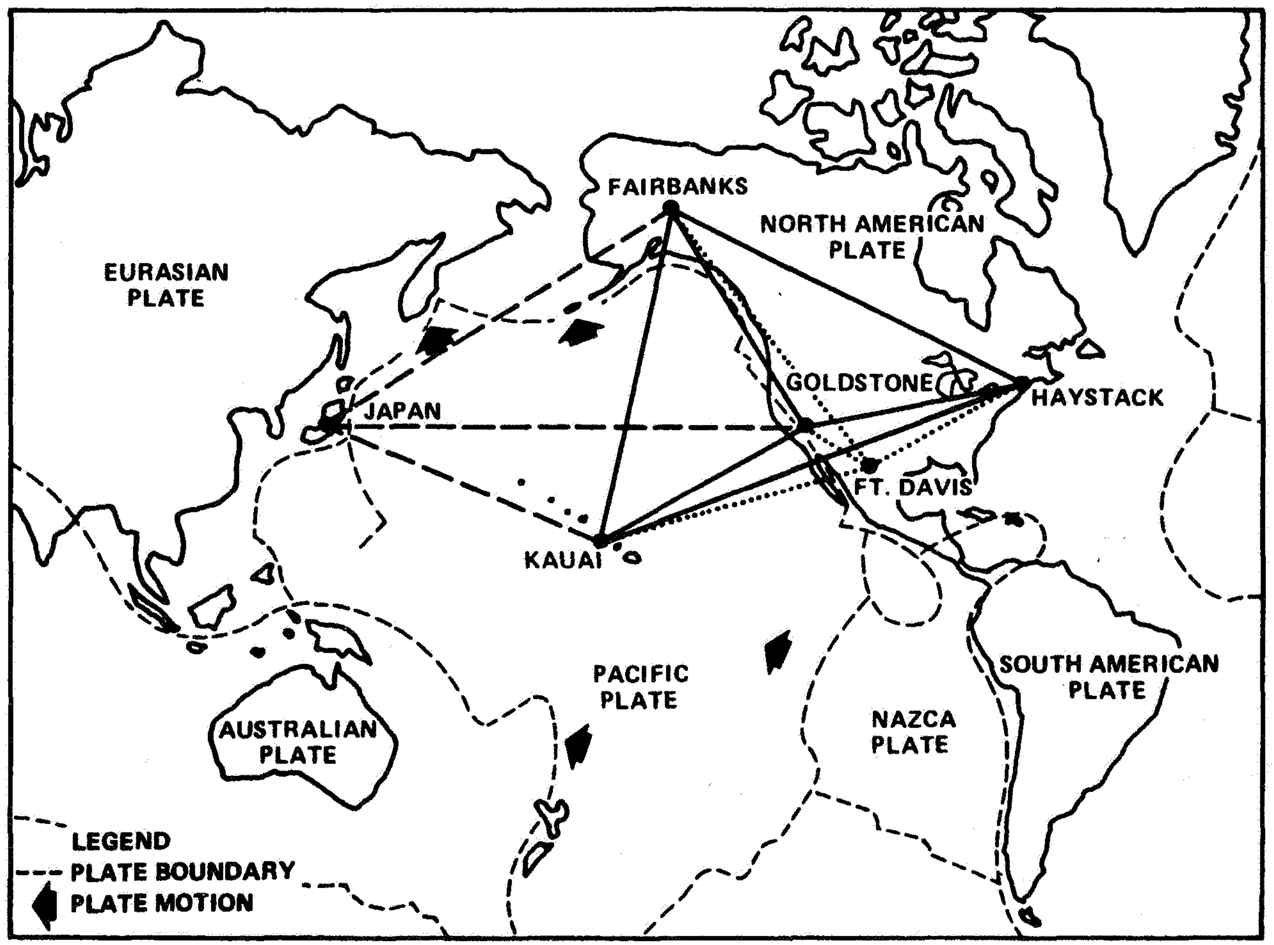

Figure 3. Antenna Configuration for Pacific Plate-Motion Experiment

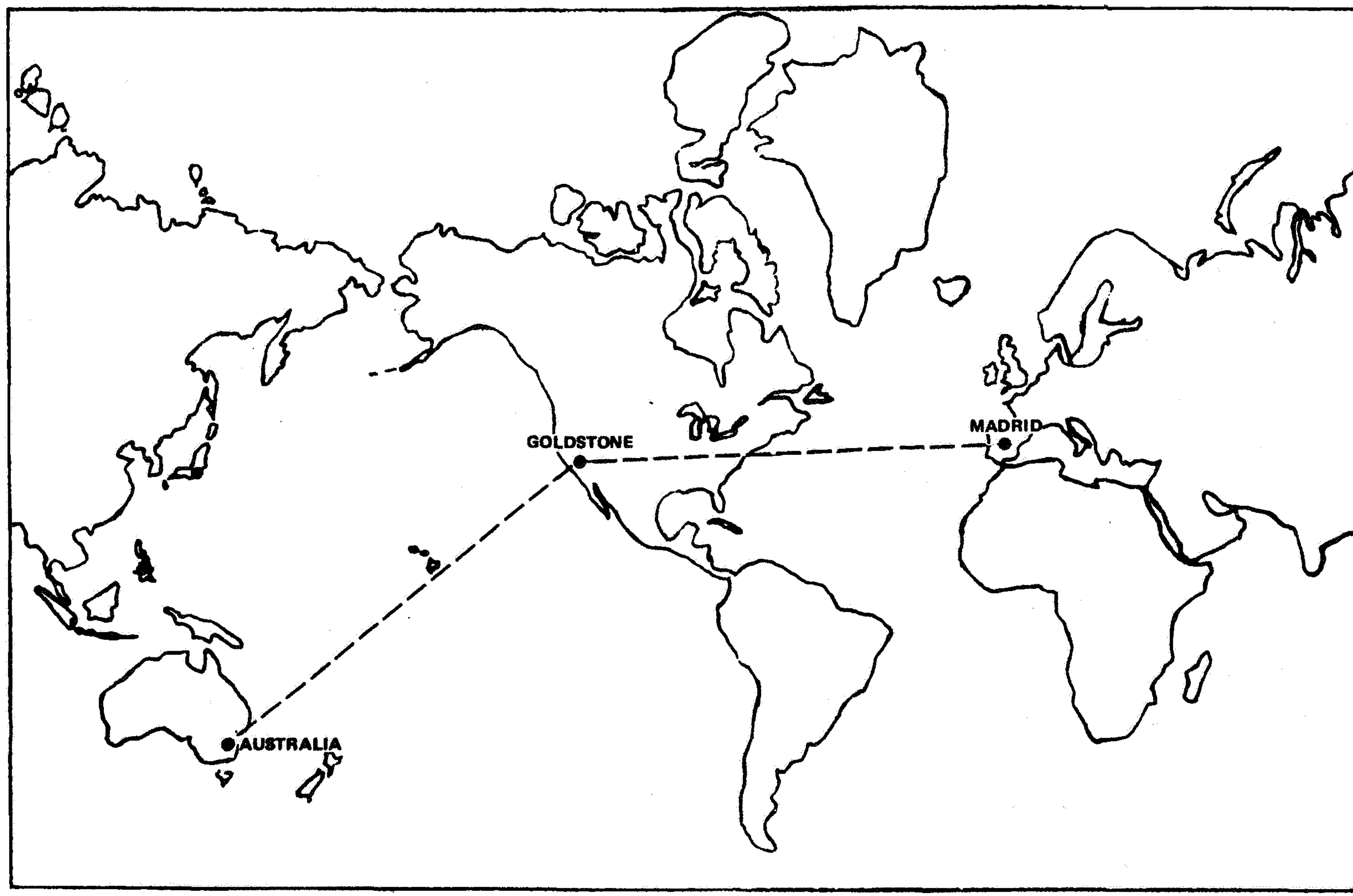

Figure 4. DSN VLBI Network

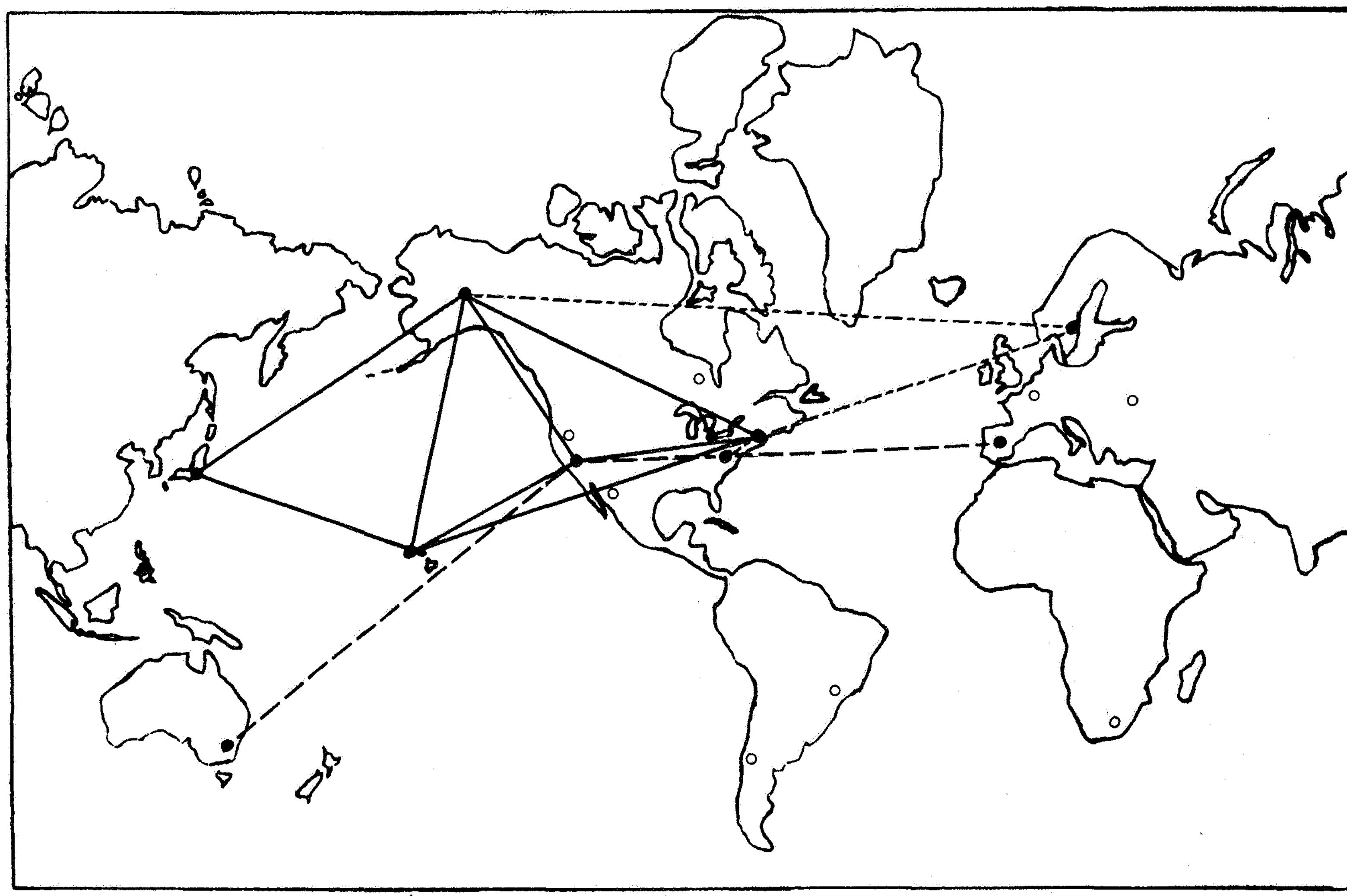

Figure 5. World Wide VLBI Networks

QUESTION AND ANSWER PERIOD

DR. WINKLER:

I would like to give you a very preliminary reply. What you have said has been in fact the concern of a part of the timing community. In the last CCDS meeting, the Committee for Definition of the Second, last July, a resolution has been passed, encouraging that, if and when such experiments become a matter of routine, that input should be provided to the timing community because it can be pretty useful.

In the simplest terms, that input can be provided by equipping every one of your stations with an interface to the existing local service. That could be a Loran-C receiver since most of your stations are in the area of a Loran chain. Every single measurement which is communicated to a time service or to the BIH, which is of course the central time service, will help strengthen our day-to-day operations. Television measurements might be considered in the European area. Television measurements in Australia, will connect the observatory in Australia to the Australian Time Service and thereby, help to provide a linkage.

So I see it only as a question of two aspects. One, there must be an interface provided by making regular reports to the time services that we have now in existence on other stations—loran stations, television receivers and so on.

That interface is very easy and very inexpensive to establish. And number two, these additional services can become of greatest benefit only when there is some assurance of their continuity and regularity.

I don't think there will be much benefit by having these things done on an experimental basis, and after one year the scientists hurry on to other things. This is what I'm afraid is going to happen. Interface is so inexpensive and can be established on such short notice. I would encourage everyone of the radio astronomers to start. Why don't you report every time comparison even if you have the data 5 months after the fact? It will be useful. Report your time of arrival of a loran signal against the same clock which has been used in the time difference measurements. That's all which is necessary.

MR. PICKETT:

Regarding your comment on using the 30 foot dish at Coquay, what kind of sources are you going to use that you can use that size dish and get this 5-10 centimeters accuracy you were talking about?

DR. COATES:

We'll be using quasars for the sources. Flux levels in the neighborhood of 1, 2, 3, flux units are sufficient using the wide band recording system to get the sufficient signal to noise ratio.

RADIO ASTROMETRY

Dr. Kenneth J. Johnston
E. O. Hulburt Center for Space Research
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ABSTRACT

Conventional and VLBI interferometer techniques show promise for accurate determination of UT1, polar motion, and radio source position catalogs.

INTRODUCTION

Radio interferometer measurements of celestial radio sources are being employed to determine variations in the Earth's rotation, polar motion, and a catalogue of radio source positions. Both conventional interferometry and the very long baseline interferometer (VLBI) technique have shown promise in previous experimental tests; the VLBI technique has been demonstrated to determine UT1 to an accuracy of 3 ms, polar motion to submeter accuracy and 0".1 in source catalogue position (Clark and Shapiro 1973; Shapiro et al. 1974), and the conventional technique has been used to determine UT1 to an accuracy of 4.3 ms (Elsmore 1973) and source catalogue position accuracy to 0".1 (Ryle and Elsmore 1973). Further tests are being conducted to evaluate experimental accuracies and atmospheric limitations for different baselines and measurement techniques.

RADIO INTERFEROMETRY

A signal is simultaneously received from a celestial source at two antennas which can be separated by distances of from hundreds of meters to thousands of kilometers. This signal is first mixed to an intermediate frequency. The signal at one of the antennas is delayed by τ_g, the geometric delay or the difference in the doppler shift to the source as seen from the two sites. Finally the signals are cross-correlated. The cross-correlated signal has an amplitude and phase. When the source size is small compared with the interferometer fringe spacing, the normalized correlation amplitude is unity. The phase of the cross-correlated signal yields information on where the source is located in the fringe pattern of the interferometer. One can visualize a pattern of lines or fringes projected onto the sky. As the earth rotates the source passes through this pattern. The phase of the cross-correlated signal changes by 2π radians from fringe to fringe. The separation of the fringes on the sky is simply

$$\Delta\theta = \frac{\lambda}{D \sin\theta} \text{ radians,}$$

where λ is the wavelength of the signal, D is the separation of the antennas and θ is the angle between the celestial source and the baseline. See figure 1.

The phase can be determined accurately to a fraction of a fringe in conventional interferometry and precise positions can be determined with a short baseline. For example a 5 km baseline operating at a frequency of 5 GHz, has a fringe spacing of $2''.5$. A determination of the phase of a celestial source to $5°$ results in a position accuracy of 0.035 arc seconds or 2 milliseconds.

The difference between VLBI and conventional interferometry is in the phase stability of the interferometer. Conventional interferometers offer phase stabilities of a few degrees for periods of days. The principal limitations to phase stability at frequencies above 5 GHz are short period variations in atmospheric refractivity and instrumental phase variations. VLBI on the other hand depends on independent local oscillators controlled by atomic frequency standards at the two locations, and has phase instabilities of several radians in a period of an hour. The principal limitation to phase stability is the frequency stability of the standards at each site used to generate the local oscillator chains. These L.O. chains are used to mix the signal down to an intermediate low frequency that can be recorded on magnetic tape.

Since VLBI has poor phase stability, the phase of the signal is not analyzed directly but rather its derivatives, delay which is the rate of change of phase with frequency, and fringe rate which is the rate of change of phase with respect to time. Thus for the same baseline, conventional interferometry will be orders of magnitude more accurate than VLBI. The very long baselines possible with VLBI, however, compensate for this difference in precision.

The major limitations to conventional interferometry are:

1) Short term changes in atmospheric phase path, i.e. the signal from the celestial source does not pass through identical atmospheric paths to the antennas. Small scale variations in atmospheric refractivity due mainly to water vapor cause the atmospheric phase path to vary in a random

manner on the order of minutes. Present data on the rms variation in atmospheric path length is very incomplete, but the trend is displayed versus baseline length in figure 2. The single point at 35 km is preliminary information from Wade (1974) of the National Radio Astronomy Observatory where the antennas were connected by a radio link. There is a marked difference between the phase path deviations on a summer day versus a winter day. The summer nights and winter nights resemble the winter day. Therefore observations obtained during a summer day would be expected to have one half the accuracy of those made at night or on a winter day.

2) Instrumental noise--If the antennas are connected by a radio link, noise over this link may contribute significantly to the data. There may also be significant noise contribution by noise generated in the local oscillator system. Temperature effects on the cables connecting the individual antennas and the delay lines also contribute to the system phase noise.

COMPARISON OF TECHNIQUES

The accuracy of conventional interferometry and VLBI in determining UT1 has been estimated. From figure 2, an estimate may be made of the contribution of short term changes in atmospheric refractivity to phase noise. Assuming this to be the major contributor to phase noise, the accuracy in the determination of UT1 may be predicted, and is displayed in figure 3 versus equatorial baseline.

In work done in collaboration with C. M. Wade and R. M. Hjellming of the National Radio Astronomy Observatory (NRAO) preliminary observations have been obtained over a baseline of 35 kilometers. The operating frequency was 2695 MHz (11.1 cm). The baseline is located on an azimuth angle of about -45°. Observations were obtained of 16 radio sources over a five day period in January 1974. From the observed phases, corrections to the equatorial and polar baselines, and source coordinates were calculated by least squares. This solution resulted in an rms phase noise of 16°. This is equivalent to a position accuracy of $0\overset{''}{.}029$ or 2 ms. For individual source coordinates, the accuracy depends on the baseline geometry and source declination. For a given baseline, there is a definite correlation versus source declination. The solution for right ascension and declination are not correlated for sources near the zenith. Therefore, observations of a source that transits through the zenith will yield the most accurate measurement of UT1.

This is attested to by the fact that the solution of this set of data for the right ascension of 3C84 ($\delta = 40°$) resulted in an internal accuracy of 2 ms.

The accuracies of the VLBI technique in fringe rate and time delay are calculated assuming an accuracy of 1×10^{-13} parts in fringe rate residuals (Moran et al. 1973; Cohen 1971) and an accuracy of 10^{-9} seconds in delay. The data by Shapiro (1974) agree well with this. Therefore at the present time conventional interferometry and VLBI offer similar accuracies in determining UT1.

Some of the advantages of the conventional interferometry technique over VLBI are:

1) Variations in atmospheric refractivity--the conventional technique is less influenced by variations in atmospheric refractivity since the antennas are located closer together and see more nearly the same atmospheric path conditions.

2) Solid Body Earth Tides--the relative effect of solid body Earth tides between the antennas of a conventional interferometer is negligible whereas for VLBI it is not.

3) Frequency Standards--there is no need for highly stable and precise frequency standards in a conventional interferometer, whereas VLBI requires hydrogen maser frequency standards and clock synchronization to a microsecond.

4) Data Reduction--the data may be reduced in real time. After a day's observation, UT and polar motion may be calculated immediately. There is no need to correlate magnetic tapes from widely separated locations to obtain correlation functions.

5) Station Management--it is much easier to manage stations that are 10-100 km apart than thousands of km apart.

PLANS

Conventional interferometry will be investigated initially through evaluation of observations obtained with the NRAO interferometer and VLBI techniques will be further evaluated. These data will define basic accuracy limitations and guide the design of optimum techniques for radio astrometry.

The author thanks C. H. Mayer for helpful discussions.

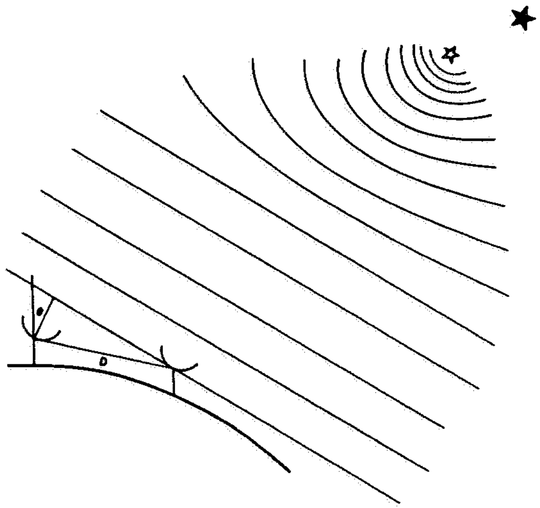

Fig. 1-Celestial Source and Antenna Configuration

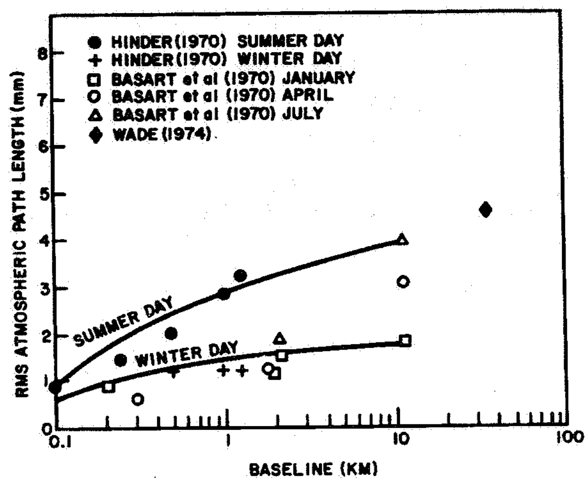

Fig. 2-Variation of RMS Path-length With Baseline

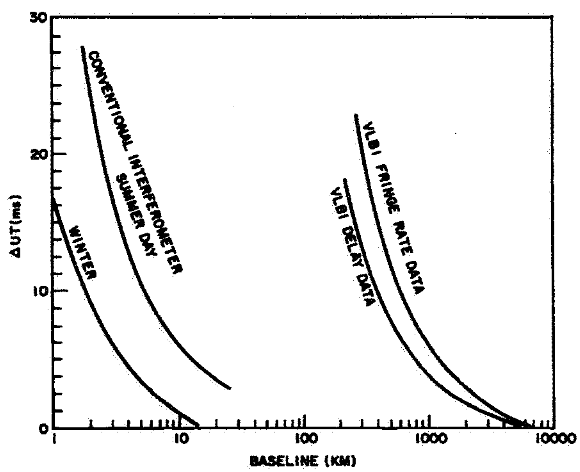

Fig. 3-Accuracy in UT1 Determination Versus Equatorial Baseline

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QUESTION AND ANSWER PERIOD

DR. COHEN:

Let me say that I agree that the short normal interferometry does indeed have many advantages over long-baseline interferometry for timing purposes and for source position work. In fact there's been a race for the last 5 or 8 years over who could more accurately do the work, and I think it has come out even so far. Long-baseline interferometry has the potential for doing very much better but that's still many years away, and so far has not been able to jump ahead of the short baseline business.

Let me also remark about the VLA. I should think that the VLA will automatically have to be calibrated against point sources in the sky at rather frequent intervals, and every time it does that it will automatically generate a UT number, so it will in any event do the timing. I'm almost sure it will.

DR. JOHNSTON:

That's right. I asked Barry Clark at NRAO just how accurate they were going to keep the timing for the VLA, and he said they were only going to maintain the position accuracy to a tenth of an arcsecond which is the smallest beam width that they plan to use. It doesn't quite meet the needs of the accurate timing, unfortunately.

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N75 27197

FREQUENCY STANDARDS REQUIREMENTS OF THE NASA DEEP SPACE NETWORK TO SUPPORT OUTER PLANET MISSIONS

by

Henry F. Fliegel
and
C. C. Chao

Jet Propulsion Laboratory
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ABSTRACT

Navigation of Mariner spacecraft to Jupiter and beyond will require greater accuracy of positional determination than heretofore obtained if the full experimental capabilities of this type of spacecraft are to be utilized. Advanced navigational techniques which will be available by 1977 include Very Long Baseline Interferometry (VLBI), three-way Doppler tracking (sometimes called quasi-VLBI), and two-way Doppler tracking. It is shown that VLBI and quasi-VLBI methods depend on the same basic concept, and that they impose nearly the same requirements on the stability of frequency standards at the tracking stations. It is also shown how a realistic modelling of spacecraft navigational errors prevents overspecifying the requirements to frequency stability.

****

Several papers delivered at this conference deal with Very Long Baseline Interferometry (VLBI), by which the difference between the times of arrival of a signal at two widely separated stations from a distant radio source is determined by cross-correlation of data tapes. The Jet Propulsion Laboratory is supplementing its VLBI program with a simpler technique, similar in principle but requiring far less data processing, which is informally called Quasi-VLBI (QVLBI). Although developed primarily to solve problems in spacecraft navigation, QVLBI can be used to compare the frequencies and time rates of change of frequency of widely separated oscillators.

By the methods which are now conventional at JPL, only two kinds of data are available for the radio navigation from the Earth of a distant spacecraft. The range may be determined by measuring the time required for a radio signal to travel to the spacecraft and back; and the range rate can be obtained from the doppler shift of the returned signal. Of course, these two data types determine only one mathematical function, since the second is merely the time derivative of the first. The fundamental problem of spacecraft navigation is that, of the three coordinates which an astronomer would use to locate an object in space -- radial distance, right ascension, and declination -- only the first is measurable using a single antenna, and the angular position must be deduced. At best, this deduction is difficult.

Several kinds of information are contained in the measurements of range rate, and only by combining them can the deduction of spacecraft position and velocity be made reliably. In Figure 1, bottom, the sinusoidal curve shows the effect of the rotation of the Earth on the frequency of the returned signal by the doppler effect. Where the spacecraft is below the horizon of the tracking station (that is, from spacecraft set to spacecraft rise), the plotted curve is dashed; the solid portion of the curve represents observable data. Since the phase of the curve depends on spacecraft right ascension and the Earth's rotational angle (UT1), the right ascension can be determined if UT1 is known; similarly, spacecraft declination can be determined from the amplitude of the curve. The uncertainty in our ability to target the spacecraft is represented by an elliptical area in a plane constructed perpendicular to the vector of spacecraft motion, within which the spacecraft is located to a certain confidence level, as illustrated at the top of Figure 1. As the spacecraft approaches the target planet, the gravitational pull causes a rapid change in the measured range rate (bottom of Figure 1). Not shown in Figure 1 is the small but measurable change in the gravitational acceleration of the spacecraft toward the Sun, which is a function of position of the spacecraft in its orbit, and which can therefore be used to infer that position. All these kinds of information have been used via the Double-Precision Orbit Determination Program (DPODP) at JPL to ascertain and then to correct the trajectory parameters of the Mariner and Pioneer spacecraft during the successful missions of the past twelve years. Until now, range and range rate information obtained by one tracking station at any given time (single station tracking) has been adequate to meet all mission requirements.

However, as requirements become more stringent, the sources of error in single station tracking become quite serious. Consider the case illustrated in Figure 2, in which a spacecraft is traversing a long path (say to Jupiter), and in which data is being accumulated for many days to render the gravitational bending of the vehicle toward the Sun most noticeable (the long arc method). This acceleration toward the Sun varies from only 6mm/sec^2 to 0.2 mm/sec^2 over the entire distance from Earth to Jupiter, and, over the last 100 million kilometers of distance travelled, changes by only 33%. Large uncertainties can be produced by small effects -- by non-gravitational forces such as gas leaks, by changes made to the spacecraft trajectory (maneuvers) if they cannot be perfectly modelled, and by unforeseen events (meteor impact, sudden venting of gas, and the like). The effect of the rotation of the Earth in controlling the spacecraft position determination through the diurnal doppler signature can be corrupted by the ionosphere and by the uncertainty in station longitude. And the effect of the gravitational pull of the target planet usually appears too late to be helpful for use in guidance. The basic difficulty is that spacecraft position is very difficult to determine by range (or range rate) information from a single tracking station.

Figure 3 illustrates what can be measured when two antennas track the spacecraft simultaneously, and the logic is very similar to that of VLBI. In going from single station to two station tracking, we have passed from so-called two-way ranging to three-way ranging. Single station tracking is called two-way ranging because there is an uplink (station transmitting to spacecraft transponder) plus a downlink (transponder replying to station). If a second station listens, but does not transmit, there is a third link (called the "three-way downlink"). The physically significant quantity in the situation is the difference, τ, in the time of arrival of spacecraft signal between the two stations; and if $\vec{B}$ is the baseline vector between the two stations, $\vec{s}_1$ is the unit vector indicating spacecraft direction, and c is the speed of light, then

$$(1) \qquad \tau = \frac{\vec{B} \cdot \vec{s}_1}{c} ,$$

which is the fundamental equation of VLIB. If the fractional frequencies of received signal at the two stations are differenced, this difference (called "two-way minus three-way doppler") is the dimensionless quantity $\dot{\tau}$, the time rate of change of τ. These new data types, τ or $\dot{\tau}$, as reduced from two-way and three-way range and doppler data, are called Quasi-VLBI (QVLBI).

The advantage of QVLBI for spacecraft navigation over single-station tracking is that the angular position of the spacecraft can be directly measured, and not merely inferred by the orbit determination program. But QVLBI also offers the possibility of measuring the frequency offset between the widely separated station oscillators. If these oscillators were perfectly synchronized, then one would measure

$$(2) \qquad \left(\frac{\Delta f}{f}\right)_{\text{observed}} = \dot{\tau} = A \cos \omega t \text{ (from the Earth's rotation)}$$
$$+ \text{ atmospheric effects}$$
$$+ \text{ equipment delay effects}$$

The atmospheric effects are caused especially by the difference in charged particle content in the ionosphere over the two stations, and by the difference in water vapor content in the troposphere, which is difficult to model. The equipment delays (for example, cable delays) will produce no effect if they are constant, but any variation (for example, temperature effects at sunrise) will map directly into the observed frequency offset. If the station frequency standards operate at different frequencies, then the last equation becomes

$$(3) \quad \left(\frac{\Delta f}{f}\right)_{observed} = A \cos \omega t + \left(\frac{\Delta f}{f}\right)_{standard} + . \ . \ .$$

where (. . .) represents the atmospheric and equipment effects. Notice that, given sufficient data (i.e., a sufficient number of observational equations of the form of Equation (3) one can solve for A and $\Delta f_{standard}$ separately; furthermore, by expanding $\Delta f_{standard}$ in a Taylor series, one could in principle solve for any number of coefficients in the polynomial expansion of Δf. In practice, the atmospheric sources of error make it impractical to solve for terms higher than frequency and frequency rate; Equation (3) becomes

$$(4) \quad \left(\frac{\Delta f}{f}\right)_{observed} = A \cos \omega t + \left(\frac{\Delta f}{f}\right)_{standard} + t \cdot \left(\dot{\overline{\frac{\Delta f}{f}}}\right) + . \ . \ .$$

These simplified QVLBI equations illustrate the basic principles. In practice, solutions from real data have been made using the Double Precision Orbit Determination Program (DPODP), which estimates frequency standard and spacecraft trajectory parameters simultaneously.

In 1971, the Mariner 9 spacecraft was simultaneously tracked by the Echo Deep Space Station (DSS 12) at Goldstone, California, and DSS 41 at Woomera, Australia, (no longer operational) during the month and a half prior to Mars encounter. It was the first time that the QVLBI technique was demonstrated with real tracking data. The results, though promising, were not as conclusive as might be hoped due to the limited amount of data and inadequate knowledge about the behavior of the frequency and time system employed. Later in 1973, a series of short baseline (≈15 km) two station doppler demonstrations with the Pioneer 10/11 spacecrafts was initiated to understand better the nature of variations of the frequency and timing system. Results indicate that the frequency offsets between stations vary slowly and linearly with a long-term ($\approx 10^6$ sec) stability on the order of 2 parts in 10^{12} ($\Delta f/f$). A successful QVBLI demonstration with real tracking data was made in December 1973 during the Jupiter Encounter of Pioneer 10 spacecraft. On the basis of this experience, a real-time demonstration of the QVLBI technique was planned and carried out during the Mariner 10 mission to Venus and Mercury (MVM).

MVM was the first interplanetary mission using one spacecraft to fly by two planets (Venus and Mercury) with the assistance of the gravitational attraction of one of the two planets. The official mission was successfully completed with the Mercury encounter of 29 March 1974, and was extended to have a second flyby of the planet Mercury on 21 September. The trajectory of Mariner 10, which is shown in Figure 4, consisted of many segments, each segment terminated by either planetary encounter or a trajectory correction maneuver (TCM). Therefore our demonstration was divided into five portions according to the following time spans:

1. TCM-1 to TCM-2 (from November 13, 1973 to January 21, 1974)
   Orbital determination solutions from this segment were used for TCM-2 in order to bring the space probe to the desired aiming point at Venus encounter.

2. TCM-2 to Venus encounter (from January 21 to February 5, 1974)
   This segment covered the closest approach to Venus, so that the position of the probe was accurately determined and provided a reference to compare solutions from the differenced doppler technique with conventional data.

3. Venus encounter to TCM-3 (from February 5 to March 16)
   This segment was to determine the trajectory to provide the parameters for TCM-3.

4. TCM-3 to Mercury encounter (from March 16 to March 29)
   This provided another opportunity to demonstrate the short arc ($10 \sim 12$ days) orbital determination capabilities using differenced doppler data.

5. TCM-4 to TCM-5 (from May 10 to June 24)
   This segment was in the extended mission phase (after Mercury flyby) and covered the superior conjunction, which offered an excellent opportunity to demonstrate how well the effects of noise from the solar corona could be removed.

The demonstration was successful in providing estimates of spacecraft velocity and position free of corrupting influences. It is especially interesting to consider the estimates which the data provided of the offsets between frequency standards.

Figure 5 illustrates two different types of estimate of frequency offsets between oscillators at the participating stations. All results are with respect to the DSS 14 (Mars) antenna frequency standard at Goldstone, California; other participating stations were DSS 12 (Echo) 16 km south of Mars antenna at Goldstone; DSS 42 and 43 in Australia, which shared a single frequency standard; and DSS 62 and 63 in Spain, each with its own standard. All stations used Hewlett-Packard 5065A rubidium standards for MVM navigation.

The first type of estimate is shown by the heavy black diamonds in Figure 5, each of which gives the solution from a single day's tracking data for Δf in millihertz between Mars and Echo oscillators (12 minus 14) at Goldstone. Since the tracking frequency is S-band (2.3 gigahertz), 7 millihertz corresponds to $\Delta f/f = 3$ parts to 10^{12}, the size of largest residual from the mean which occurred. Since these stations are so close (16 km.), both looked through virtually the same atmosphere, and the relative longitudes are known to within 6 cm., so that the results are nearly the best attainable by the present technique. We believe that these results display the real offsets between the station oscillators, though the tendency of the data to return to the mean value from the highest residuals, rather than to execute a random walk, is perhaps suspicious. Every user of VLBI or related techniques for clock or frequency standard comparison must observe that what is measured is the offset of an entire system -- antenna, cables, circuitry, and oscillator, under the local atmosphere -- rather than of the oscillator alone. In this case, we have no reason to suppose that effects other than frequency standard offset and drift are present, but the possibility cannot be ruled out completely.

The second type of estimate is displayed by the open circles, squares, and triangles in Figure 5. For each station, and for each of the time periods defined above, all tracking data were combined by the Orbit Determination Program, and estimates were formed of (1) frequency offset (2) standard deviation of the estimated frequency offset (3) rate of change of offset, when the estimate for rate was believed to be statistically significant. The estimates thus formed for DSS 12 and 14 agree fairly well with the black diamonds. The estimates for rate correspond fairly well with the differences between offsets estimated on different dates. The error bars were estimated by the Orbit Determination Program using *a priori* values of station longitude uncertainty of 5 meters; this estimate probably errs on the pessimistic side for stations of the Deep Space Net (DSN), but gives a fair idea of the uncertainties to be expected when conditions are not optimal. The extremely large errors bars on the right represent the data when the spacecraft was near the Sun as seen from Earth.

These data indicate that frequency offsets can be measured to a precision of 1 part in 10^{12} under fair conditions (error bars, Figure 5) to about 1 part in 10^{13} under the best conditions (scatter of black diamonds.)

The experiments reported here have been very useful in studies of what precision of frequency standard is needed for navigation in the DSN. They indicate that the behavior of the frequency standards can be modelled using solve-for parameters, along with spacecraft state, and so prevent us from overspecifying DSN standards. It has been shown at JPL that the existing rubidium standards were adequate to the needs of the MVM mission, but that requirements for outer planet missions will require the use of H-masers.

ORBIT DETERMINATION INFORMATION FROM PERTURBATION OF SPACECRAFT BY PLANET

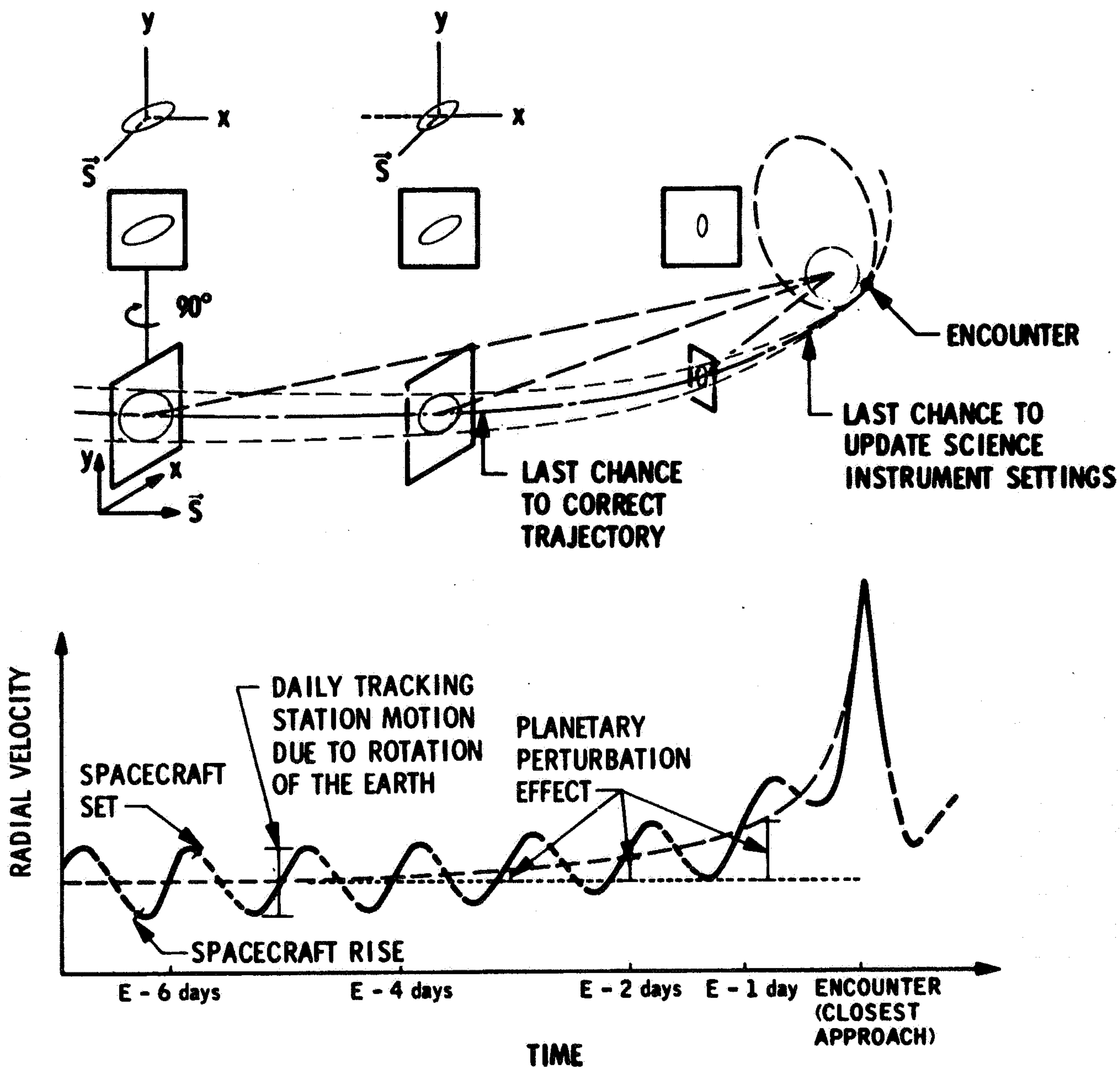


FIGURE 1

LONG ARC METHOD OF SPACECRAFT NAVIGATION

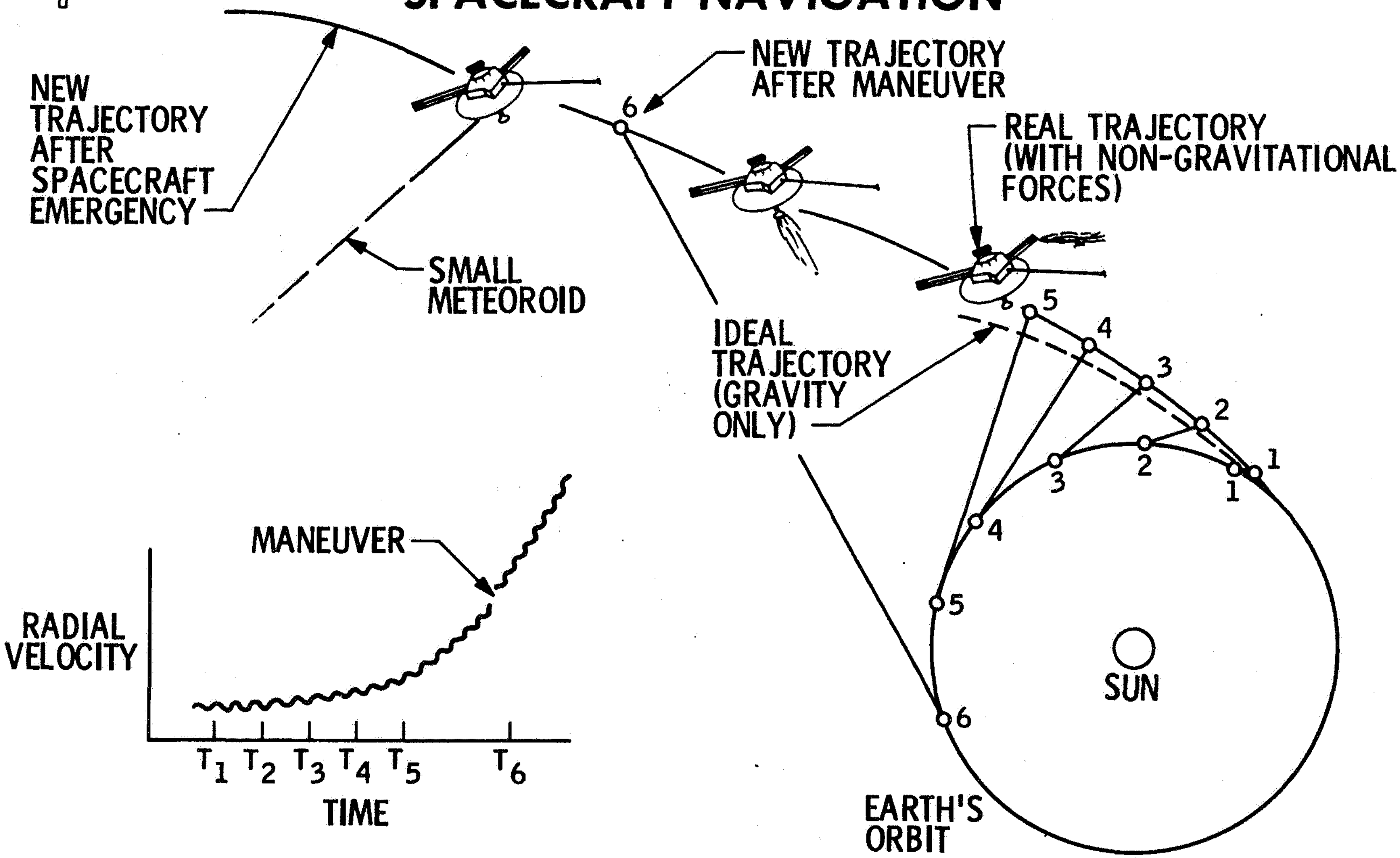


FIGURE 2

GEOMETRY OF QUASI-VLBI
(TWO AND THREE WAY TRACKING)

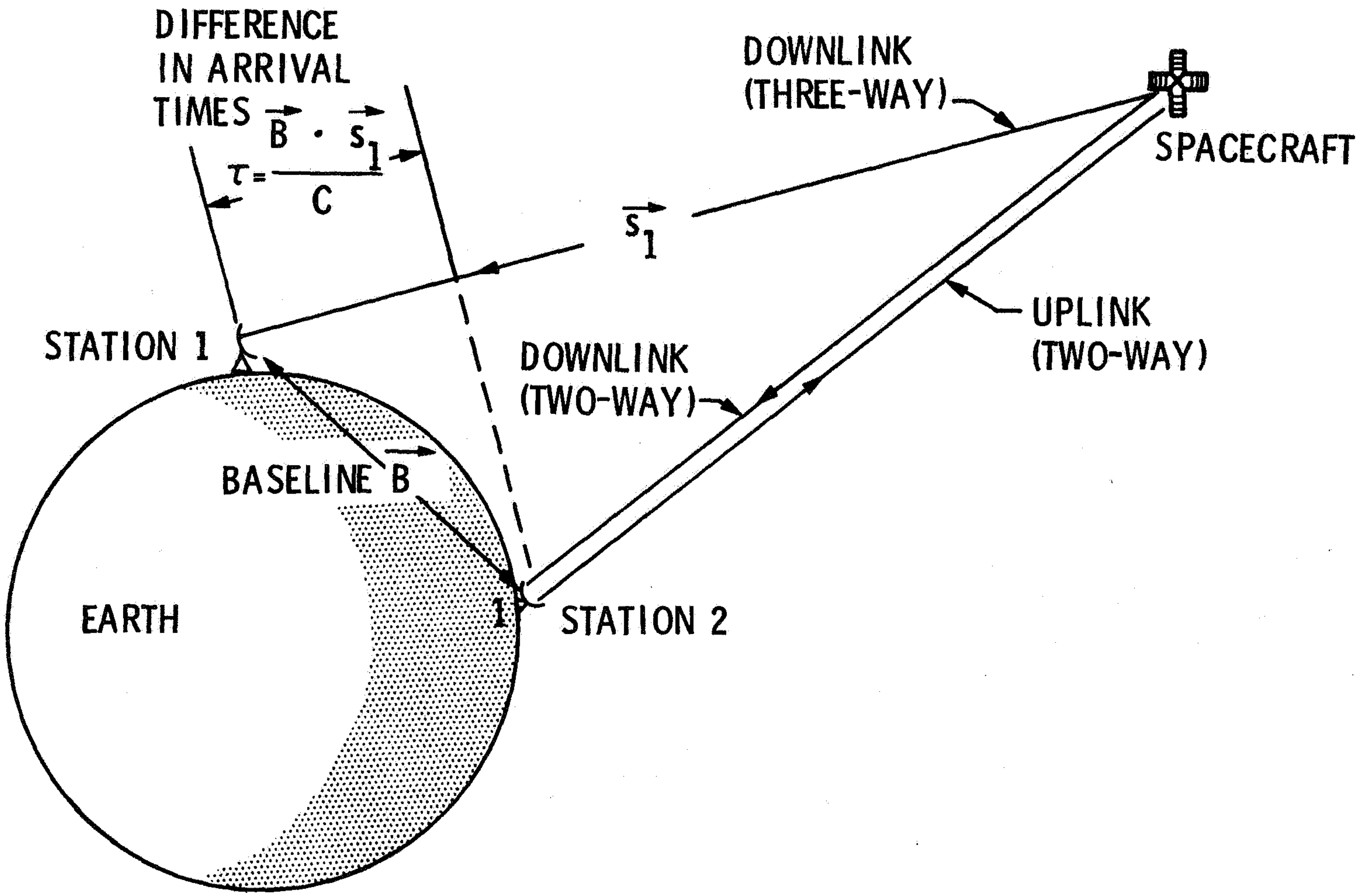
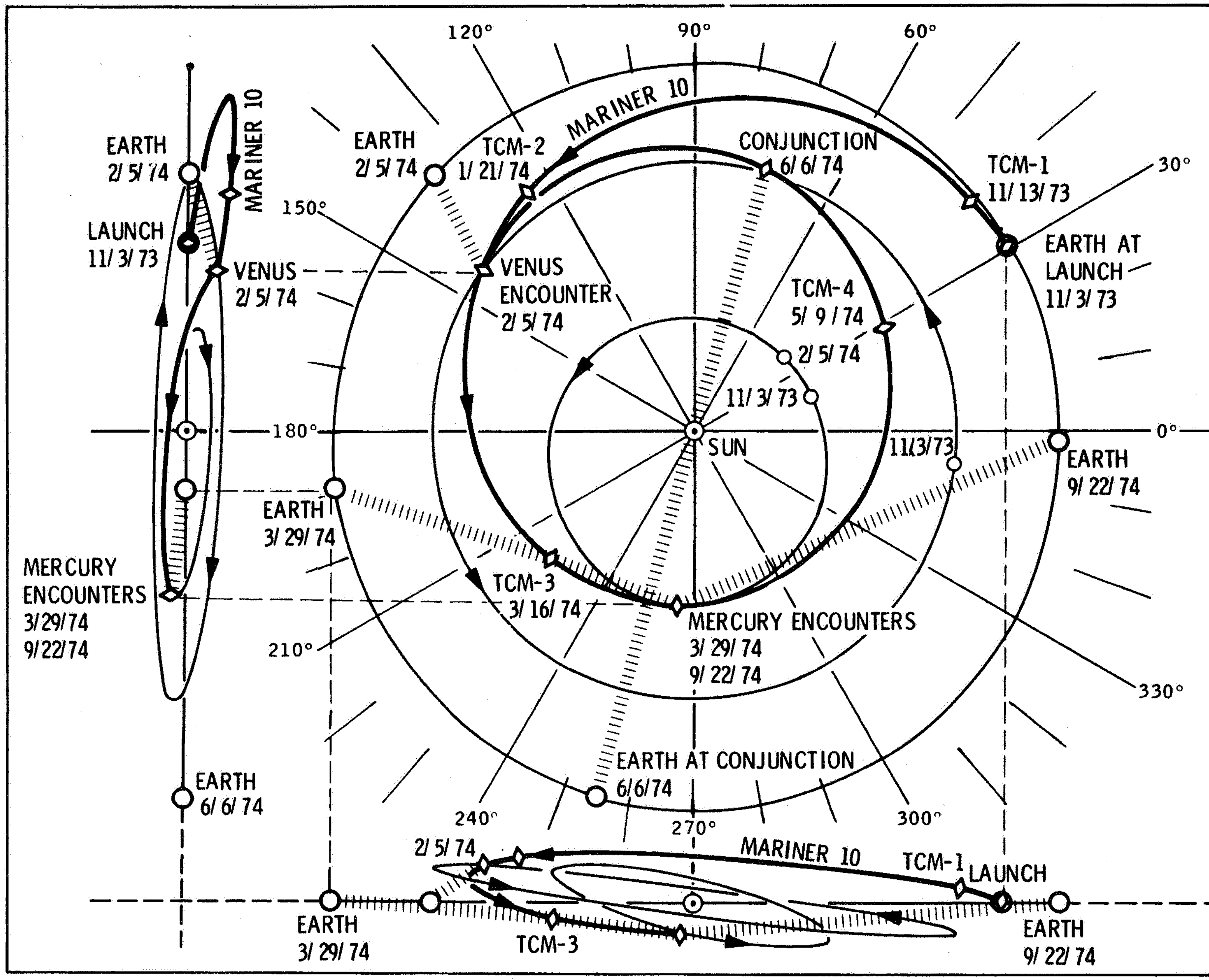


FIGURE 3



MARINER 10
EARTH
2/ 5/ 74
LAUNCH
11/ 3/ 73
VENUS
2/ 5/ 74
MERCURY
ENCOUNTERS
3/29/74
9/22/74
EARTH
6/ 6/ 74
120°
90°
60°
30°
150°
180°
0°
210°
240°
270°
300°
330°
EARTH
2/ 5/ 74
TCM-2
1/ 21/ 74
MARINER 10
CONJUNCTION
6/ 6/ 74
TCM-1
11/ 13/ 73
EARTH AT
LAUNCH
11/ 3/ 73
VENUS
ENCOUNTER
2/ 5/ 74
TCM-4
5/ 9 / 74
2/ 5/ 74
11/ 3/ 73
SUN
11/3/73
EARTH
9/ 22/ 74
EARTH
3/ 29/ 74
TCM-3
3/ 16/ 74
MERCURY ENCOUNTERS
3/ 29/ 74
9/ 22/ 74
EARTH AT CONJUNCTION
6/6/74
2/ 5/ 74
MARINER 10
TCM-1
LAUNCH
EARTH
3/ 29/ 74
TCM-3
EARTH
9/ 22/ 74

FIGURE 4

VALUES OF ESTIMATED FREQUENCY OFFSET RELATIVE TO DSS14

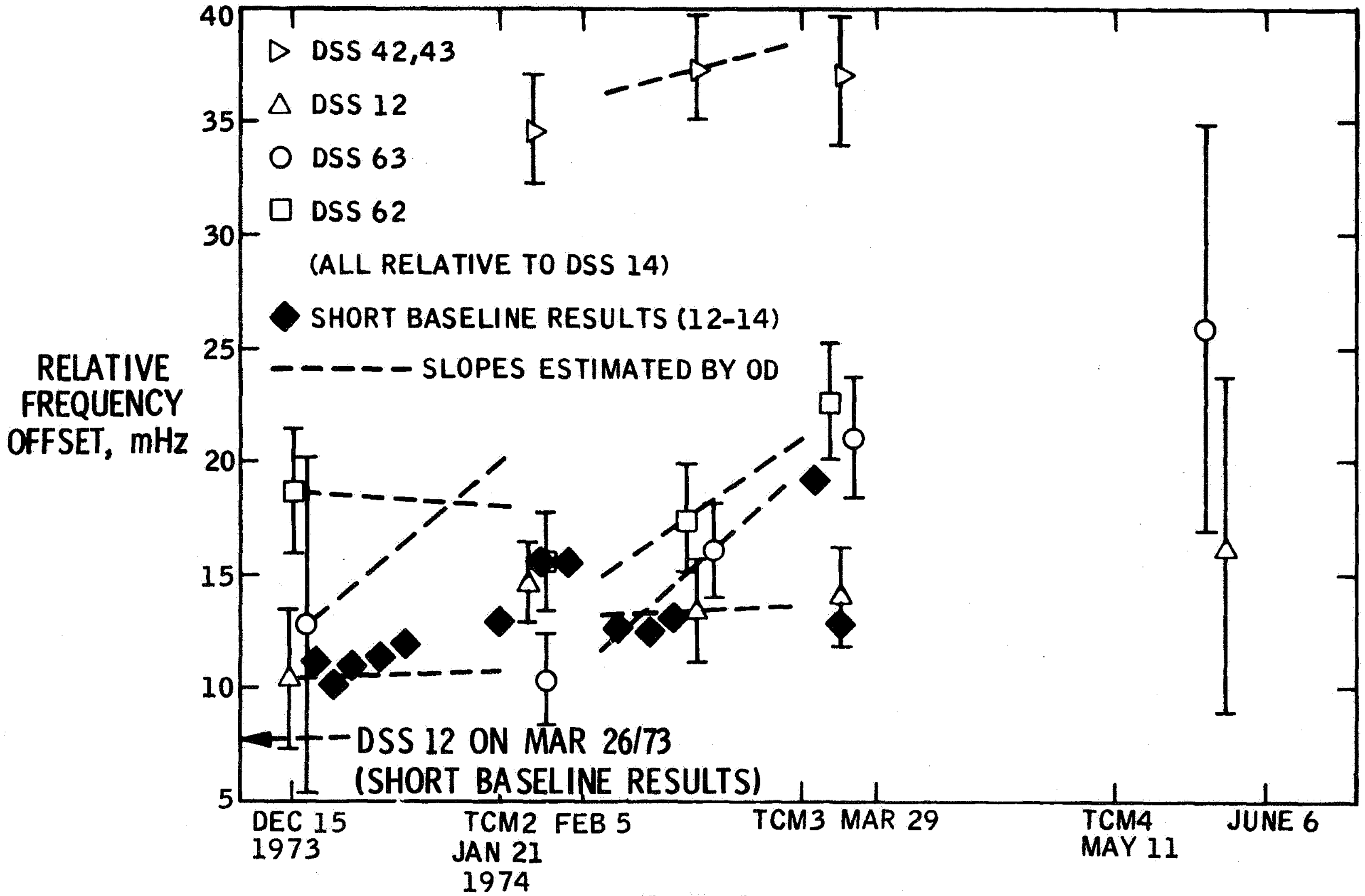


FIGURE 5

QUESTION AND ANSWER PERIOD

DR. WINKLER:

I think I would agree with your judgment that it is possible for the rubidium standards to behave like that.

DR. FLIEGEL:

Good.

DR. WINKLER:

Even so the extrapolations to 40 days, I think, would require that your temperature stability and your pressure sensitivity was extremely good.

But we have seen large frequency variations which returned to where the standard had been a week before or two weeks before.

N75 27198

RELATIVISTIC EFFECTS OF THE ROTATION OF THE EARTH ON REMOTE CLOCK SYNCHRONIZATION

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Abstract

A treatment is given of relativistic clock synchronization effects due to the rotation of the Earth. Unlike other approaches, the point of view of an Earth fixed coordinate system is used which offers insight to many problems. An attempt is made to give the reader an intuitive grasp of the subject as well as to provide formulae for his use. Specific applications to global timekeeping, navigation, VLBI, relativistic clock experiments, and satellite clock synchronization are discussed. The question of whether atomic clocks are ideal clocks is also treated.

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RELATIVISTIC EFFECTS OF THE ROTATION OF THE EARTH ON REMOTE CLOCK SYNCHRONIZATION

INTRODUCTION

The precision of global timekeeping is approaching the level where one should consider the relativistic effects of the rotation of the Earth on remote clock synchronization. This paper will treat such effects, both mathematically and heuristically, to provide the precise time user with both rigorously derived formulae and, hopefully, an intuitive grasp of the causes underlying these formulae. This paper will also attempt to cover the subject as completely as possible in order to provide a unified reference which will allay the user's qualms about the relevance of some effects as well as allow him to correct for others.

HOW IDEAL ARE ATOMIC CLOCKS?

In analyzing the effects of the Earth's rotation on clock synchronization, we will assume all clocks are ideal clocks. We should, therefore, consider first whether the most accurate clocks available to the precise time user, atomic clocks, deviate significantly from ideal behavior.

Velocity Effects

In atomic clocks, a moving atom is interrogated by in phase electromagnetic fields at two or more points.[6] For various reasons, depending on the device, the first order doppler shift due to atomic motion in the device is cancelled out; only the second order doppler shift due to atomic motion effects the frequency of the clock.[6] This shift is given by:[2]

$$f_c = \sqrt{1 - \frac{v_a^2}{c^2}}\, f_a \tag{1}$$

where f_a is the atomic transition frequency in the atom's rest frame, f_c is the clock's frequency in its rest frame, and v_a is the relative velocity of the atom with respect to the clock. If (1) is true when the clock is in motion as well as at rest, one can ignore the effect of the moving atom, and treat the clock as ideal. (1) has been shown to be invariant with respect to motion of the clock,[2] and so in this respect an atomic clock is indeed an ideal clock. For completeness, the derivation showing (1) is invariant is reproduced in Appendix I.

Acceleration Effects

Only acceleration effects common to all atomic clocks will be considered here. For acceleration effects due to individual clock designs, the reader is referred to the manufacturers' literature.[1] Since the Earth rotates with angular frequency ω, an atomic clock fixed on the Earth will observe its atomic transition frequency from this same rotating frame. In this non-inertial, rotating frame, the atomic transition frequency may appear altered. This would cause the clock to deviate from ideal behavior. The question of ideal behavior, therefore, reduces to the question of whether rotational acceleration will cause the atomic transition frequency to alter.

To determine the rotational effects on an atomic transition frequency, we must determine the effects of rotation on the energy levels of an atomic system. This is accomplished by examining the Hamiltonian of an atomic system in a rotating frame. In a rotating frame, a system's Hamiltonian is given by:[4]

$$H = H_0 - \vec{\omega} \cdot \vec{F}$$

where H_0 is the non-rotating Hamiltonian, $\vec{\omega}$ is the angular frequency vector, and $\vec{F}$ is the total angular momentum. Atomic clocks operate in low magnetic fields where $\vec{F}$ is a good quantum number.[5] Therefore, if $\vec{\omega}$ is parallel to the magnetic field, the energy levels of the atomic system are shifted by:

$$\Delta E_{FM} = - \hbar \omega M$$

where the quantum states are given by the quantum numbers F and M. One can also show that, if $\vec{\omega}$ is perpendicular to $\vec{F}$ (see Appendix II):

$$\Delta E_{FM} = \frac{\hbar \omega^2 M}{2\omega_z}$$

where ω_z is the angular Zeeman frequency. Since atomic frequency standards run on transitions in which M for the initial and final states is zero,[6] there will be no frequency shift in these transitions caused by the rotation of the clock, and thus again an atomic clock behaves like an ideal clock.

EFFECTS OF UNIFORM MOTION ON REMOTE CLOCK SYNCHRONIZATION

Einstein Light Signal Synchronization

Before discussing the more complicated effects of the rotation of the Earth on clock synchronization, it is instructive to consider the effects of uniform motion. The basis for our discussion will be the Lorentz transformations:[2,9]

$$x' = \frac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$t' = \frac{t - \frac{xv}{c^2}}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{2}$$

$$Y' = Y \qquad Z' = Z$$

where the primed system is moving with velocity v parallel to the x coordinate. These transformations are derived from the principal of the constancy of the velocity of light, and from a definition of clock synchronization (Einstein synchronization) based on a light source emitting pulses an equal distance from the two remote clocks[2] (see Figure 1). From (2), one can see that, to an observer moving with velocity v in the x direction, two remote clocks synchronized by Einstein synchronization will be out of sync by:

$$\Delta t = -\frac{vx}{c^2\sqrt{1 - \frac{v^2}{c^2}}} \tag{3}$$

where x is the x component of the separation between the clocks.

The significance of (3) is that it is path independent. If one were to set up a "global" network in a flat, special relativistic space with Einstein synchronization, even though, to a moving observer, this network will appear out of sync, it will be out of sync in a self-consistent manner independent of the paths used

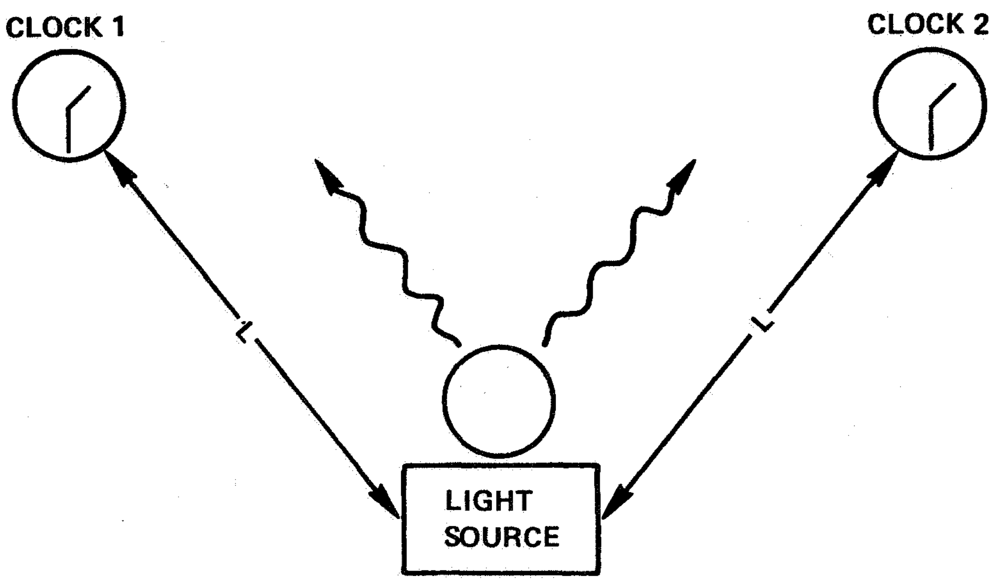

Figure 1. EINSTEIN SYNCHRONIZATION: IF CLOCKS 1 AND 2 RECEIVE LIGHT PULSES AT THE SAME TIME THEY ARE SYNCHRONIZED

for synchronization allowing one to ignore the effect; all the moving observer need do to restore synchronization is to apply (3).

Synchronization by Slowly Moving Clocks

Now let us consider remote clock synchronization by another, often used, method, by slowly moving a clock between the two remote clocks (see Figure 2). In this method, the moving clock, C_M, is synchronized to clock C_1, slowly moved with velocity ϵ along some arbitrary path, P, to clock C_2, and then used to synchronize C_2. Of course while C_M is moving, it will be doppler shifted as given by (1). To first order, its frequency compared with the frequency of C_1 will be given by:

$$\frac{f_M}{f_1} \simeq 1 - \frac{\epsilon^2}{2c^2}$$

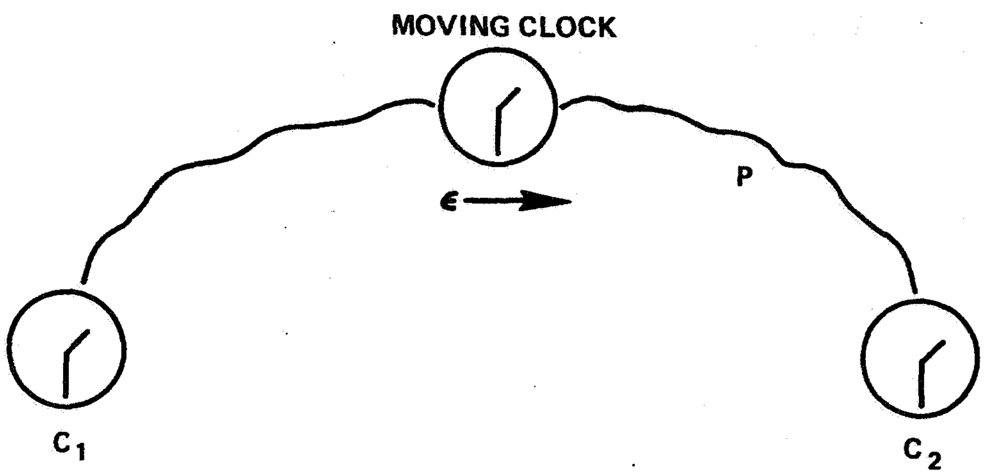

Figure 2. SYNCHRONIZATION BY SLOWLY MOVING CLOCK

which will cause C_M, when it reaches C_2, to differ from C_1 by:

$$\Delta t = -\int_P \frac{\epsilon^2}{2c^2}\, dt_1$$

Since the line element along P is given by:

$$dl = \frac{dt_1}{\epsilon},$$

this becomes:

$$\Delta t = -\int_P \frac{\epsilon}{2C^2}\, dl.$$

which goes to zero as ϵ goes to zero. Thus, in the rest frame of C_1 and C_2, the clocks C_1 and C_2 will be synchronized.

Now let us consider this slow clock synchronization from the point of view of a moving observer (see Figure 3). Let C_2 and C_2 be moving with velocity $\vec{v}$ with respect to this observer whose clock, C_0, reads time t. For simplicity let C_1, C_M, and C_0 be synchronized to zero when C_M leaves C_1.

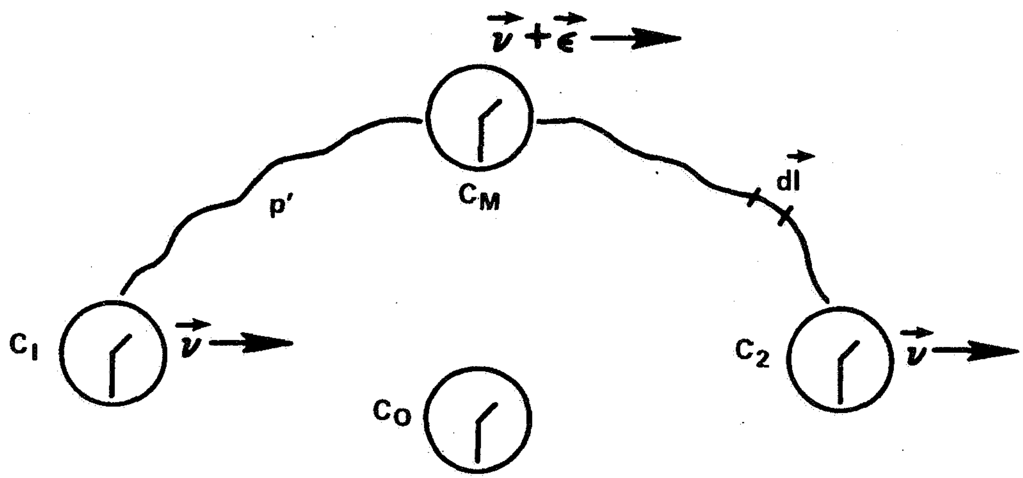

Figure 3. SYNCHRONIZATION IN MOVING FRAME

The frequency of C_M is given in terms of C_0's frequency by (1) (v^2 replaced by $(\vec{v}+\vec{\epsilon})^2$) which to lowest order in ϵ will yield:

$$\frac{f_m}{f_0} = \frac{1 - \vec{\epsilon}\cdot\vec{v}/c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

This means that now Δt is given by:

$$\Delta t = - \int_{P'} \frac{\vec{\epsilon} \cdot \vec{v}}{\sqrt{1 - \frac{v^2}{c^2}}} dt$$

But along P', to lowest order in ϵ:

$$d\vec{l} = \vec{\epsilon} dt,$$

so to lowest order in ϵ:

$$\Delta t = - \int_{P'} \frac{\vec{v} \cdot d\vec{l}}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Again letting ϵ go to zero, we obtain:

$$\Delta t = - \frac{1}{c^2 \sqrt{1 - \frac{v^2}{c^2}}} \int_{P'} \vec{v} \cdot d\vec{l}$$

Since $\vec{v}$ is independent of position, if v is in the x direction, we again obtain (3):

$$\Delta t = - \frac{vx}{c^2 \sqrt{1 - \frac{v^2}{c^2}}} . \tag{3}$$

so synchronization by slowly moving clocks is equivalent to Einstein light synchronizations in flat, special relativistic space.

CLOCK SYNCHRONIZATION ON THE ROTATING EARTH

For the proper treatment of clock synchronization on the rotating Earth, both the presence of gravitational fields and the non-uniformity of the motion necessitate the use of general relativity. Both the behavior of clocks and the propagation of light signals, in general relativity, is completely defined by the proper time line element metrically decomposed in terms of a suitable coordinate system.[9,10,11] Thus to describe clock synchronization on the rotating Earth, all we need derive is the proper time line element given in terms of Earth fixed coordinates.

For our starting point in deriving the proper time line element, we shall use the Schwarzchild line element for a point gravitational source in non-rotating spherical coordinates (r, θ, ϕ'):

$$d\tau^2 = \left(1 + \frac{2U}{c^2}\right) dt^2 - \frac{1}{c^2} r^2 d\theta^2$$

$$- \frac{1}{c^2} r^2 \sin^2 \theta d\phi'^2 - (c^2 + 2U)^{-1} dr^2 \qquad (4)$$

where:

$$U = -\frac{GM_{Earth}}{r}$$

This, to accuracy sufficient for our purposes, will properly describe the effects of the Earth's gravitation. To go to Earth fixed coordinates, we use the transformation:

$$\phi = \phi' - \omega t$$

to obtain the desired form of the proper time line element:

$$d\tau^2 = \left(1 + \frac{2U_T}{c^2}\right) dt^2 - \frac{1}{c^2} r^2 d\theta^2$$

$$- \frac{r^2 \sin^2 \theta}{c^2} (d\phi^2 + 2\omega d\phi dt) - (c^2 + 2U)^{-1} dr^2 \qquad (5)$$

where, U_T, the total gravitational potential in the rotating frame, is:

$$U_T = U - \frac{1}{2} r^2 \omega^2 \sin^2 \theta$$

(Note that U_T contains the centrifugal potential).

Synchronization by Slowly Moving Clocks

Consider, now, the consequences of (5) for synchronization by slowly moving clocks. For a clock moving along a differential path (dt, dr, $d\theta$, $d\phi$), in the limit where

$$\left(\frac{dr}{dt}, \frac{d\theta}{dt}, \frac{d\phi}{dt}\right)$$

goes to zero, to lowest order, (5) yields:

$$d\tau = \left(1 + \frac{u_T}{c^2}\right) dt - \frac{1}{c^2} r^2 \omega \sin^2 \theta d\phi \tag{6}$$

For a finite path, P, this becomes:

$$\Delta\tau = \int_P \frac{U_T}{c^2} dt - \frac{\omega}{c^2} \int_P r^2 \sin^2 \theta d\phi \tag{7}$$

where $\Delta\tau$ is the difference between the slowly moving clock and a coordinate clock.

Equation (7) has two terms both of which are path dependent. The first term is the usual gravitational red shift term which has been described elsewhere[12, 13] except that, in this case, the centrifugal potential is included as part of the gravitational potential. The second term is analogous to (3) in the uniform motion case except that, now, the time difference accrued by the slowly moving clock is path dependent. To see this more clearly, consider the following heuristic derivation.

Let us set up a non-rotating system of clocks to view our Earth clocks as shown in figure 4. These non-rotating clocks are all placed at the same

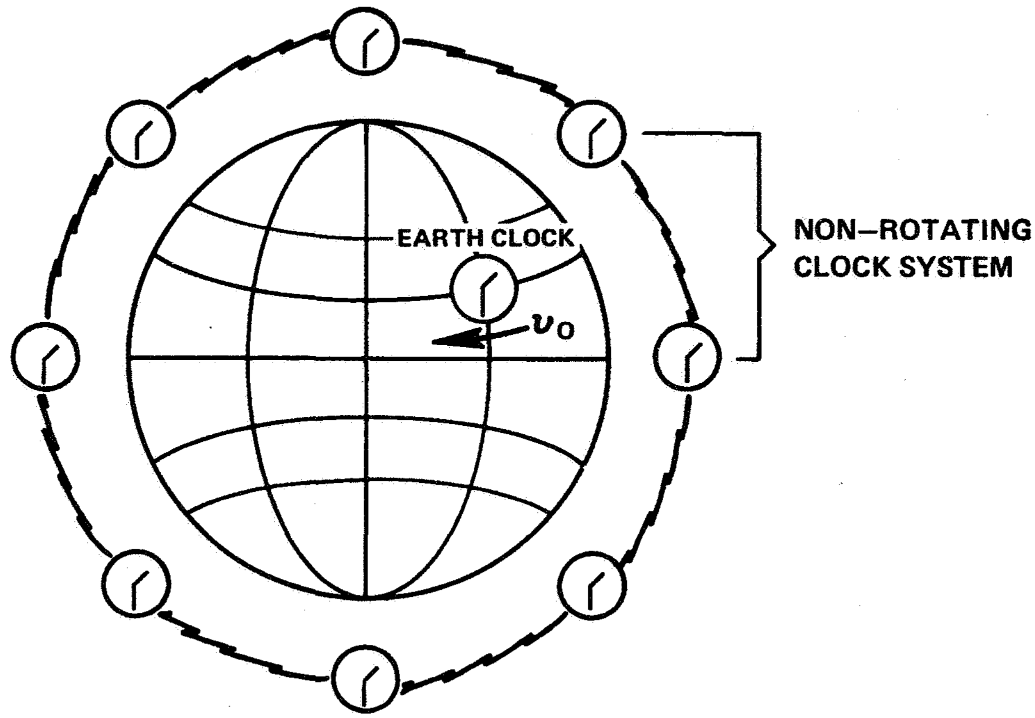

Figure 4. SYSTEM TO MEASURE ROTATIONAL EFFECT

gravitational potential, so they all run at the same rate, and can be synchronized to a clock at the north pole. If our clock system is placed at the same gravitational potential as a slowly moving clock on Earth, one of our system clocks can locally view the slowly moving clock, so special relativity can be used.[11] The local system clock sees the Earth clock doppler shifted by:

$$\frac{\Delta f}{f} \simeq -\frac{v_0^2}{2c^2} = -\frac{r^2\omega^2 \sin^2\theta}{2c^2},$$

and also sees the synchronization error given by (3) for a slowly moving clock:

$$d\tau_M \simeq -\frac{\vec{v}_0 \cdot d\vec{l}}{c^2} = -\frac{r^2\omega \sin^2\theta}{c^2}\, d\phi$$

Using this and the fact that our system of clocks will be red shifted from a coordinate clock by:

$$\frac{\Delta f}{f} = \frac{U}{c^2},$$

we obtain for the slowly moving clock on Earth:

$$d\tau_M \simeq \left(1 + \frac{U - \frac{1}{2} r^2 \omega^2 \sin^2 \theta}{c^2}\right) dt$$

$$- \frac{r^2 \omega \sin^2 \theta d\phi}{c^2}$$

where dt is the coordinate time interval. This equation is precisely that given by (6).

Light Synchronization

For the general relativistic case, the dependence of proper lengths on the coordinates complicates the definition of Einstein light synchronization. To simplify analysis, therefore, let us redefine light synchronization as shown in Figure 5. In this new definition, clock C_1 sends a light pulse to C_2, and records the time he sends it. When C_2 receives the light pulse, he immediately returns another pulse over the same path, P, and records the time of arrival of the first pulse. C_1 now receives the second pulse, and measures the time difference between the transmission of the first pulse and the reception of the second pulse, Δt. From this time, C_1 determines the propagation time, $\Delta t/2$, which C_2 can transmit to C_2 along with the time C_1 sent the first pulse. This enables C_2 to synchronize to C_1.

In order to analyze the relativistic effects of rotation on this form of synchronization, all we need use is the line element (5) and the fact that for light propagation (in vacuo):

$$d\tau = 0$$

These together with a path, P, parametrically described by $(r(\lambda), \theta(\lambda), \phi(\lambda))$ defines light propagation in terms of the quadratic equation:

$$A dt^2 + B \left(\frac{d\phi}{d\lambda}\right) dt d\lambda + C \left(\frac{dr}{d\lambda}, \frac{d\theta}{d\lambda}, \frac{d\phi}{d\lambda}\right) d\lambda^2 = 0$$

Solving for dt, one obtains:

$$dt = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} d\lambda$$

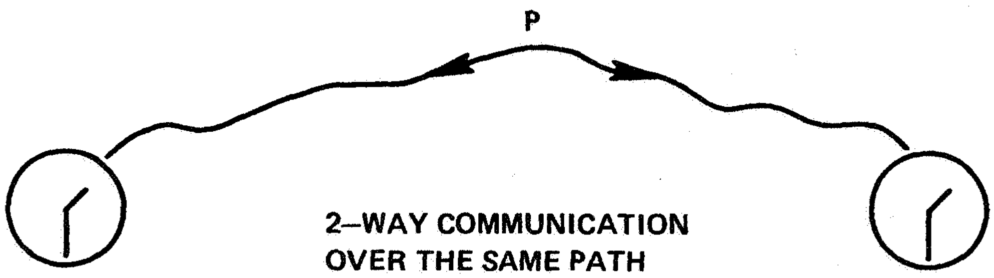

Figure 5. NEW LIGHT SYNCHRONIZATION DEFINITION

which for a finite path becomes:

$$t = \int_{\lambda_1}^{\lambda_2} \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}\, d\lambda \tag{8}$$

Notice that there is an ambiguity of sign in (8). This occurs because, along P, light can propagate in two directions, from $P(\lambda_1)$ to $P(\lambda_2)$, and vice versa. The presence of the B term causes the propagation time for light traveling in opposite directions to differ by:

$$\Delta t_p = 2 \int_{\lambda_1}^{\lambda_2} \frac{-B}{2A}\, d\lambda$$

or

$$\Delta t_p = -2\omega \int_p \frac{r^2 \sin^2\theta}{c^2 + 2U_T}\, d\phi$$

But from our light synchronization definition, this will introduce a synchronization error of:

$$\Delta t = \frac{\Delta t_p}{2}$$

or:

$$\Delta t = -\omega \int_p \frac{r^2 \sin^2 \theta}{c^2 + 2U_T} d\phi \tag{9}$$

where Δt is defined in terms of a coordinate clock. To lowest order, (9) reduces to:

$$\Delta t = -\frac{\omega}{c^2} \int_p r^2 \sin^2 \theta d\phi \tag{10}$$

which is the same as the second term in (7).

In order to obtain some insight into the reasons for the time difference given by (10), consider the following heuristic derivation from the point of view of a non-rotating frame as shown in Figure 6. In Figure 6, two clocks, C_1 and C_2, rotating with the Earth and separated by a small distance L, light synchronize along a straight line. In the time, t, it takes for the light to travel from C_1 to C_2, C_2 will move:

$$\Delta\vec{L} = \vec{v}_0 t = \hat{\phi} \frac{\omega r L}{c} \sin \theta$$

where $L = ct$ has been used. This will introduce a change in path given approximately by:

$$\Delta L \simeq \frac{\vec{L} \cdot \Delta\vec{L}}{L}$$

or:

$$\Delta L = -\frac{\omega r^2}{c} \sin^2 \theta \Delta\phi$$

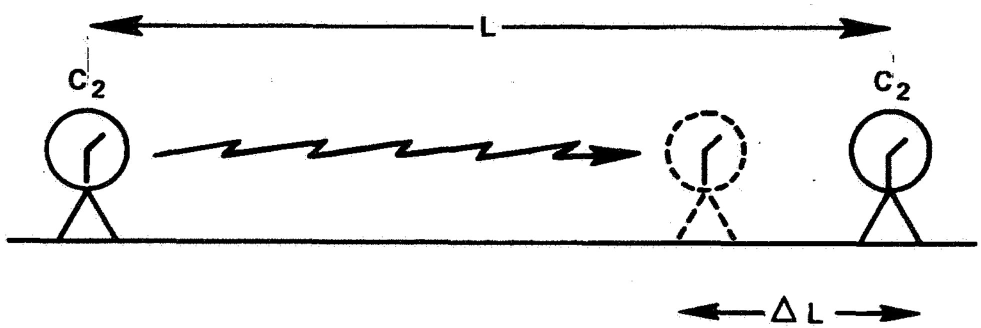

Figure 6. ROTATIONAL ERROR FOR LIGHT SYNCHRONIZATION

which corresponds to a change propagation time:

$$\Delta t = -\frac{\omega r^2}{c^2} \sin^2 \theta \Delta \phi \tag{11}$$

For a light signal going from C_2 to C_1, we would, similarly, obtain a change in propagation time as described by (11), but with the opposite sign. As viewed by a coordinate clock, therefore, C_1 and C_2 would be out of synchronization as given by (11). For a general light path, P, we can break the path down into N infinitesimal straight line segments, and repeatedly use (11) to obtain:

$$\Delta t = -\frac{\omega}{c^2} \int_P r^2 \sin^2 \theta d\phi$$

which is the same as (10).

Rotational Frequency Effects

Equation 9 shows that a clock on Earth has its frequency shifted from a coordinate clock by:

$$\frac{\Delta f}{f} = \frac{U_T}{c^2}$$

where:

$$U_T = U - \frac{1}{2} r^2 \omega^2 \sin^2 \theta$$

This is different from other formulations[15,12] in the inclusion of the centrifugal potential as part of the gravitational frequency shift term. This centrifugal effect has even been ignored entirely by some authors.[12] Inclusion of the centrifugal term in one form or another is important to obtain the proper operating frequency since the centrifugal term contributes a fractional frequency difference of 1.2×10^{-12} between a clock at a pole and one at the equator.

Because of this centrifugal term, however, on the surface of the Earth, one can ignore variations in clocks caused by the gravitational shift. If the Earth's surface was a rigidly rotating fluid, the surface of the Earth would be defined by:

$$U_T = \text{constant}$$

since a static fluid cannot maintain shear stresses. But sea level by definition is the surface of a static fluid; therefore, all clocks at sea level run at the same frequency. This means that, so far as the gravitational red shift is concerned, to obtain a consistent system of clocks, all one need do is to correct the frequency of a clock for deviations from sea level (at the fractional rate of 1.09×10^{-13} per km near sea level).

The fact that clocks at sea level all run at the same rate, however, is of little comfort if the user has a rigidly mounted clock, and sea level changes as a function of time. Tidal forces due to the Sun and the Moon cause such a time dependent change of sea level. As shown in Appendix III, these forces lead to frequency shifts given by:

$$\left.\frac{\Delta f}{f}\right|_{\text{Sun}} = -2.69 \times 10^{-17} \cos^2(\omega t)$$

$$\left.\frac{\Delta f}{f}\right|_{Moon} = -5.85\times 10^{-17} \cos^2(\omega t)$$

APPLICATIONS

Global Timing Networks

We have shown that for remote synchronization on the Earth, there is a path dependent synchronization error given by (7) for slow clock synchronization and (9) for light synchronization. This path dependent effect can cause discrepancies of as much as 0.2 μsec for differing synchronization paths. (The maximum effect occurs in synchronizing two clocks on opposite sides of the Earth on the Equator along paths going in opposite directions around the equator.) To set up a self-consistent timing network, one must either set up the synchronization network as shown in figure 7 or make corrections for (7) or (9) in all remote synchronization. For future reference, let us call this form of synchronization coordinate synchronization, and call synchronization in which (7) or (9) are not corrected for link synchronization.

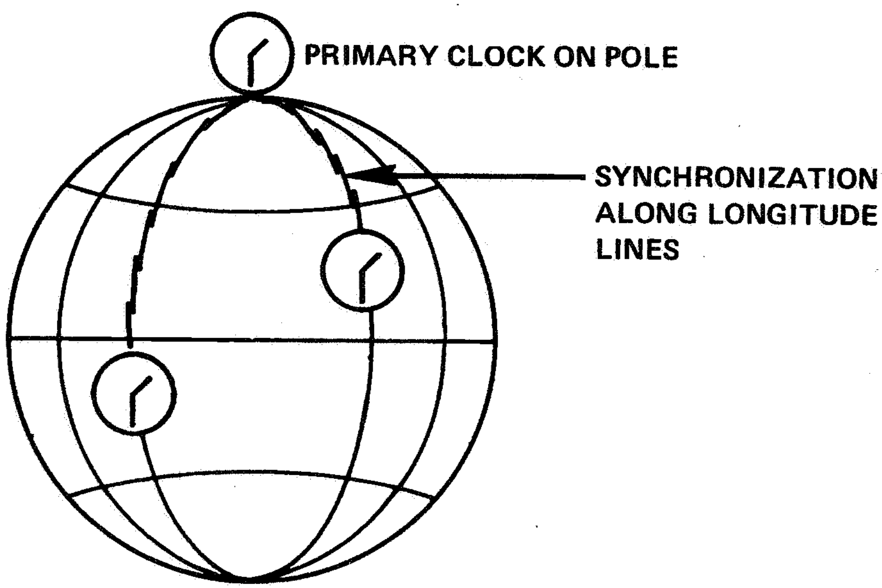

Figure 7. COORDINATE SYNCHRONIZATION NETWORK

Since we have also shown that clocks at sea level all run at the same rate, to obtain coordinate time from a sea-level, coordinate synchronized global timing network, all we need do is offset the network's frequency by:

$$\frac{\Delta f}{f} = -\frac{U_P}{c^2}$$

where U_P is the Newtonian gravitational potential at the pole.

Relativistic Timing Experiments

There are two basic groups of relativistic timing experiments involving moving clocks, those that involve only two clocks, and those that involve monitoring the moving clock with remotely synchronized clocks. The first type of experiment is detailed in Figure 8. In this type of experiment, a moving clock, C_M, is compared with a clock on the Earth, C_0, before and after C_M makes a trip around a closed path, P. One can see from (7) that, even for a slowly moving clock always in the same gravitational potential, there will be different results depending on the path.

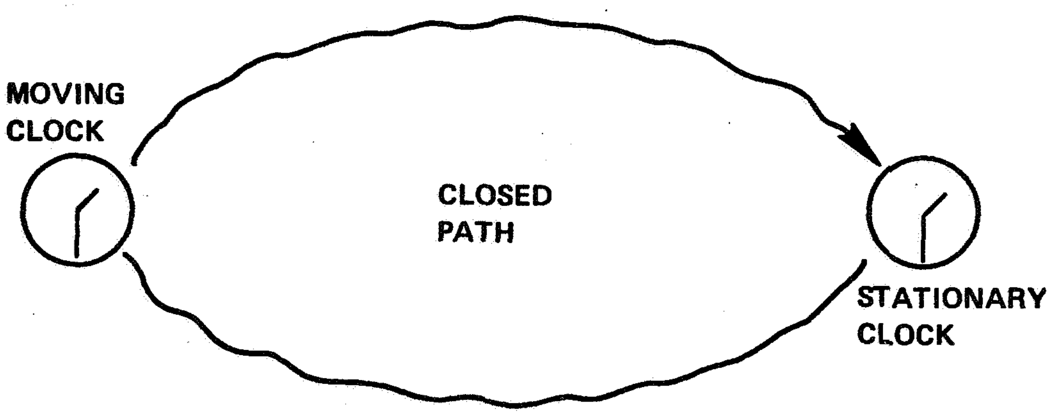

Figure 8. TWO CLOCK EXPERIMENT

The Hafele-Keating experiment[15] is a classic example of this type of experiment. In this experiment, sets of clocks which traveled around the world equatorially in opposite directions were compared with the U.S.N.O. Master Clock before and after each trip. Different results were obtained for the westerly versus easterly moving clocks. Qualitatively, this can be seen as a result of the part of (7) given by:

$$\Delta t = -\frac{\omega}{c^2} \int_P r^2 \sin^2 \theta d\phi$$

which for the same P will give Δt's of opposite sign depending on the sign of $d\phi$.

The second type of experiment involves remotely synchronized clocks as shown in Figure 9. In this type of experiment, a clock, C_M, is moved along a path, P, between two remotely synchronized clocks, C_1 and C_2, and compared with them. Here the results depend on which type of synchronization is used. For example, if we let the synchronization path, C_M's path, C_1, and C_2 all be along the same latitude, we let v_M, C_M's ground velocity, be constant, and we keep C_M at ground level, for coordinate synchronization, we obtain:

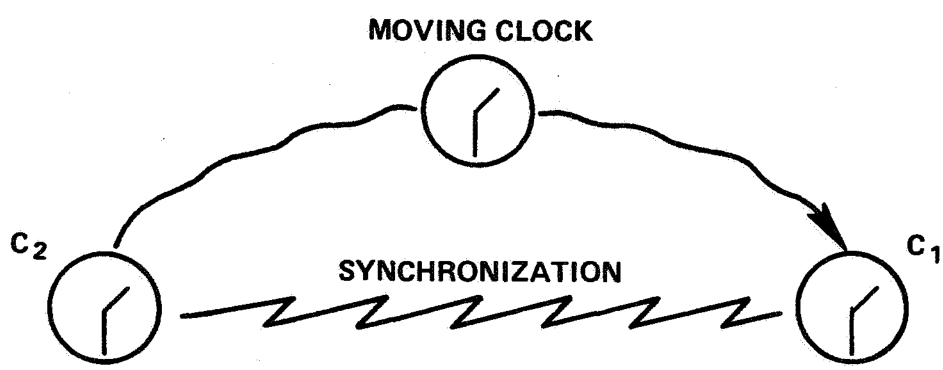

Figure 9. EXPERIMENT INVOLVING REMOTE SYNCHRONIZATION

$$\frac{\tau_M - \tau_2}{\tau_1} = -\frac{1}{2c^2}\ [v_e^2 + v_M^2 + 2\vec{v}_e \cdot \vec{v}_M] \tag{13}$$

where $\vec{v}_e$ is the rotational velocity of the Earth at the latitude chosen. Notice this result depends on the direction of $\vec{v}_M$ with respect to $\vec{v}_e$ just as the Hafele-Keating experiment does. If we use link synchronization for the same experiment, we obtain:

$$\frac{\tau_M - \tau_2}{\tau_1} = -\frac{1}{2c^2}\ [v_e^2 + v_M^2] \tag{14}$$

which is independent of the direction of $\vec{v}_M$ and $\vec{v}_e$. This is because the synchronization error between C_1 and C_2:

$$\Delta t \simeq \frac{\vec{v}_e \cdot \vec{x}}{c^2} = \frac{\vec{v}_e \cdot \vec{v}_M}{c^2}\tau_1, \tag{15}$$

just cancels the cross terms in (13).

For the two examples just given, the link synchronization case is the only one which has a special relativistic analogue; there are no cross terms just as would be true in special relativity. However if one tries to extend this analogue to the Hafele-Keating experiment, one gets into trouble. Treating the Hafele-Keating experiment special relativistically, leads one to the absurd consequence that the stationary clock is out of synchronization with itself. This occurs because a special relativistic treatment implies a flat space in which it would be impossible to return to the same clock by continuously moving in the same direction; the Hafele-Keating experiment, as well as all experiments of the first type, have no special relativistic analogue!

Global Radio Navigation

Radio navigation systems such as Loran-C and Omega utilize precise timing to determine the user's position.[14,16] By measuring the propagation delay for timing signals broadcast from fixed system transmitters with a portable clock, the user can determine his distance to the system transmitters, and thus determine his position. Rotational synchronization errors can introduce errors in the navigation system through two sources. First, if the fixed transmitters use link synchronization, timing errors can be introduced. These errors can be removed by using coordinate synchronization. Second, since the user is generally moving around, his clock will develop a cumulative synchronization error given by (7). This error can only be removed by a continuous path dependent correction of the users clock. This error, however, would be typically less than $0.1\,\mu$ s if the user coordinately resynchronized his clock every time he traveled half way around the Earth, and so would lead to a navigation error of less than 100 ft.

For ultra precise navigation, the user could use the following method which does not rely on a precise onboard clock. In this method, the user monitors three fixed stations simultaneously. From the measured propagation delays he could then solve for three unknowns, his coordinates θ, and ϕ, and his clock error, Δt.

Very Long Baseline Interferometry

Very long baseline interferometry has been suggested for both purposes of remote time synchronization,[14] and navigation.[17] The basic technique is outlined in Figure 10. Two remote stations on Earth, A and B, monitor a stellar radio source, record the results with timing marks from their local clocks, and later cross-correlate their results to determine Δt. For the purposes of remote time synchronization, θ and s are known, and Δt is used to synchronize clocks A and B. Since a non-rotating radio source is used, clocks A and B will be coordinately synchronized. For navigation, clocks A and B are synchronized, and Δt is used, together with a knowledge of θ, to determine s. If A and B are link synchronized, there will be a timing error $\Delta t'$ given by (7) or (12) which will produce an error in s:

$$\delta_s = \frac{c\Delta t'}{\sin\theta}$$

With Δt typically less than $0.1\,\mu$s, typically:

$$\delta s < \frac{30\text{m}}{\sin\theta}$$

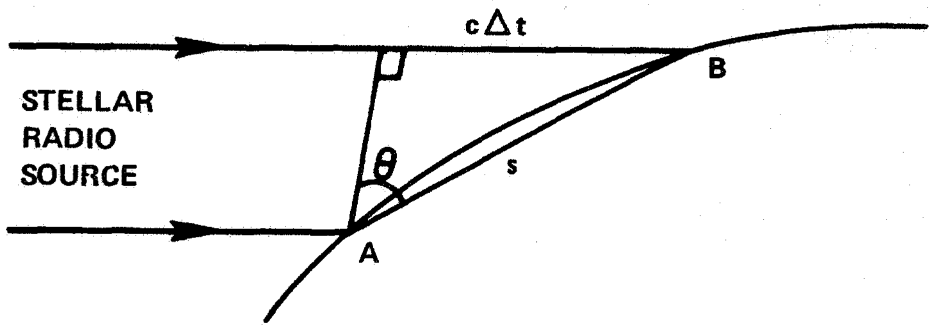

Figure 10. V L B I

Satellite Clock Synchronization

The most accurate form of remote synchronization by satellites is in the two way timing mode[14] as shown in Figure 11. In this mode radio signals are bounced or transponded off the satellite in both directions. Time synchronization is determined by the light synchronization method outlined in the previous section, so there is a synchronization error with this method given by (9). If uncorrected, this would lead to synchronization errors typically on the order of 0.1 μs or less.

For satellites carrying an onboard clock, (7) seems to indicate that there would be a frequency shift given by:

$$\frac{\Delta f}{f} = -\frac{\omega}{c^2} r^2 \sin^2 \theta \frac{d\phi}{dt} \tag{12}$$

This is not true because the satellite's finite velocity introduces other terms from (5) which cancel (12). To see this, consider the satellite from a non-rotating frame as viewed by a clock at the north pole where there are no

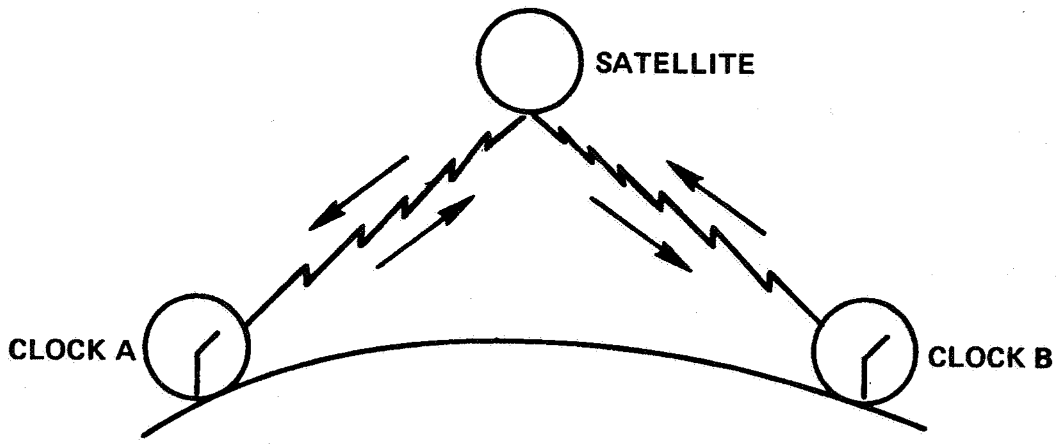

Figure II. SATELLITE TWO–WAY TIMING

rotational effects. The frequency difference between the pole clock and the satellite clock is given by:

$$\frac{\Delta f}{f} = \frac{U_s - U_P}{c^2} - \frac{v_T^2}{2c^2}$$

where U_s and U_P are the gravitational potentials at the satellite and at the pole respectively, and $\vec{v}_T$ is the satellite's velocity relative to the non-rotating frame. For a circular orbit, v_T is a constant, and so $\Delta f/f$ would just be a constant. Since for coordinate synchronization, all Earth clocks would be synchronized to the pole clock, $\Delta f/f$ would be a constant with respect to them also, precluding the possibility of any terms of the form of (12).

The difference between a moving satellite carrying a clock, and a moving ship or airplane carrying a clock is that the motion of the ship or airplane is simple (nearly uniform) with respect to the Earth, but the motion of the satellite is simple with respect to a non-rotating frame; as viewed from a non-rotating frame, the ship or airplane's motion is directly affected by the rotation of the Earth; whereas the satellite's motion, one of free fall, is not influenced by the rotation of the Earth. Formally both a rotating frame and a non-rotating frame are equally correct for analyzing relativistic problems; the choice between them is a subjective matter governed by simplifications or clarifications one frame or the other will bring to the solution of the particular problem of interest.

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APPENDIX I

An idealized picture of a moving atomic clock is shown in Figure I-1. In a moving observer's frame, the atom whose transition is being monitored is moving with velocity v_T. As the atom passes two clocks, C_1 and C_2, which are synchronized in their rest frame, and which are moving with velocity v_C, the atom's clock, C_a, is interrogated by C_1 and C_2. When the clock is at rest, C_1 and C_2 see C_a doppler shifted by (1). We must prove that this is also true to our moving observer.

Let C_1, C_a, and the observer's clock, C_0, all be synchronized to zero when C_a passes C_1. Using the Lorentz transformations given by (2), when C_a passes C_a, in terms of observers time, t_0, C_a and C_2 will read:

$$t_a = \frac{t_0 - v_T x_0}{\sqrt{1 - \frac{v_T^2}{c^2}}}$$

$$t_2 = \frac{t_0 - v_c x_0}{\sqrt{1 - \frac{v_C^2}{c^2}}} \tag{I-1}$$

where x_0 is the position of C_2 when C_a passes C_2(C_1 at $x = 0$ when C_a passes C_1). Using the fact that:

$$x_0 = v_T t_0$$

and (I-1), we obtain:

$$\frac{t_a}{t_2} = \frac{(1 - v_c v_T)}{\sqrt{1 - \frac{v_c^2}{c^2}}} \; \frac{\sqrt{1 - \frac{v_T^2}{c^2}}}{(1 - v_T^2)} \tag{I-2}$$

But in terms of v_a and v_c, where v_a is the velocity of C_a with respect to C_1 and C_2, v_T is:[2]

$$v_T = \frac{v_a + v_c}{1 + \frac{v_a v_c}{c^2}}$$

Using this and (I-2), after some algebraic manipulation, we obtain:

$$\frac{t_a}{t_2} = \frac{f_c}{f_a} = \sqrt{1 - \frac{v_a^2}{c^2}}$$

which is the same as (1).

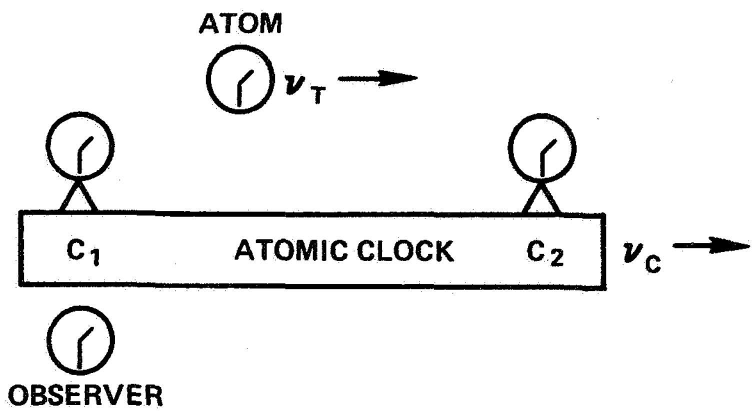

Figure I—I. IDEALIZED ATOMIC CLOCK

APPENDIX II

If $\vec{\omega}$ is perpendicular to $\vec{F}$, the Hamiltonian becomes:[7]

$$H = H_0 + \Delta H$$

where:

$$\Delta H = -\frac{\hbar\omega}{2}(F_+ + F_-)$$

and:

$$F_\pm = F_x \pm iFy$$

Since:[7]

$$\langle FM \,|(F_+ + F_-)|\, FM \pm 1\rangle = \sqrt{F(F+1) - M(M \pm 1)} \qquad \text{(II-1)}$$

and all other matrix elements are zero, there is no first order perturbation contribution to the energy levels.[8] The next highest perturbation contribution to the energy levels is the second order term:[8]

$$\Delta E_{FM} = \sum_{M' \neq M} \frac{\langle FM \,|\Delta H|\, FM'\rangle \langle FM' \,|\Delta H|\, FM\rangle}{E^{(0)}_{FM} - E^{(0)}_{FM'}}$$

using this and (I-1), one obtains:

$$\Delta E_{FM} = \frac{\hbar\omega^2}{2\omega z} M$$

where ω_z is the angular Zeeman frequency:

$$h\omega_z = E^{(0)}_{FM+1} - E^{(0)}_{FM}$$

APPENDIX III

To determine the effects of the tidal forces due to the Sun and the Moon on the frequency of a clock, consider the following derivation outlined in Figure III-1. At a point on the Earth, two sets of potentials caused by the Sun or Moon are at work, the gravitational potential:

$$-\frac{GM}{R}$$

where M, and R are the mass and the distance respectively to the Sun or the Moon, and the accelerational potential caused by the Earth's motion around the center of mass of the Earth-Sun or Earth-Moon system:

$$-\frac{1}{2}R'^2\omega_0^2$$

where R' is the distance to the center of mass, and ω_0 is the angular velocity of the Earth revolving around the Sun or Moon. The total potential from these effects, then, is:

$$U_T = -\frac{1}{2}R'^2\omega_0^2 - \frac{GM}{R}$$

Expanding in a power series about the center of the Earth (center of mass), and noting that, at the center of the Earth, the gravitational and accelerational forces must cancel, one obtains, to lowest order, a varying term given by:

$$\delta U_T = -\frac{3}{2}\ \frac{GM}{R^3}\ r^2 \cos^2 \omega t$$

where R_0 is the distance of the center of the Earth to the Sun or Moon, and r is the radius of the Earth. This yields a frequency shift:

$$\frac{\Delta f}{f} = -\frac{3GMr^2}{2c^2R_0^3}\cos^2 \omega t$$

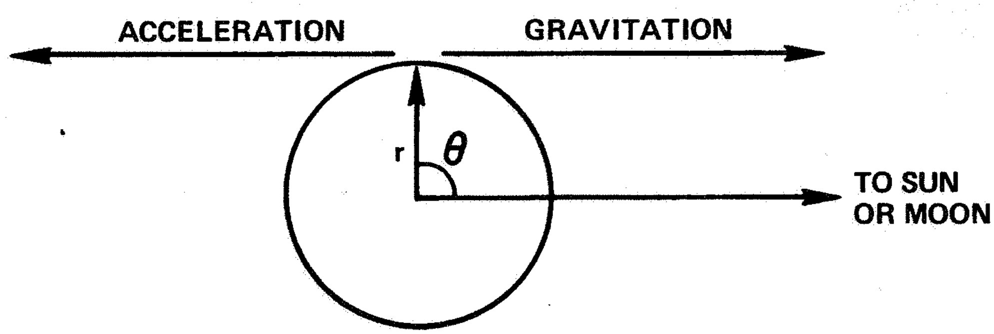

Figure III–I. EFFECT OF TIDAL FORCES

Substituting the relevant quantities for the Sun and the Moon, one obtains:

$$\left.\frac{\Delta f}{f}\right|_{sun} = -\ 2.69 \times 10^{-17} \cos^2(\omega t)$$

$$\left.\frac{\Delta f}{f}\right|_{moon} = -\ 5.85 \times 10^{-17} \cos^2(\omega t)$$

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A RELATIVISTIC ANALYSIS OF CLOCK SYNCHRONIZATION

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ABSTRACT

The relativistic conversion between coordinate time and atomic time is reformulated to allow simpler time calculations relating analysis in solar-system barycentric coordinates (using coordinate time) with Earth-fixed observations (measuring "earth-bound" proper time or atomic time.) After an interpretation of terms, this simplified formulation, which has a rate accuracy of about 10^{-15}, is used to explain the conventions required in the synchronization of a world-wide clock network and to analyze two synchronization techniques--portable clocks and radio interferometry. Finally, pertinent experiment tests of relativity are briefly discussed in terms of the reformulated time conversion.

INTRODUCTION

In the relativistic analysis of very long baseline radio interferometry (VLBI) data as well as spacecraft and planetary radiometric data, primary calculations are often most conveniently made in terms of non-rotating coordinates that have the solar system barycenter as an origin. However, measurements in these applications are usually made by Earth-fixed observers. Consequently, such analyses usually involve a relativistic time conversion (e.g. Moyer 1971) relating solar-system barycentric calculations (using coordinate time) with Earth-fixed observations (measuring atomic time). In this article, this time conversion, including all relevant speed and potential effects, is reformulated in order to facilitate both interpretation and analysis in these applications. After an interpretation of terms, the reformulated equation, which has a rate accuracy of about 10^{-15}, is used to consider the synchronization conventions associated with a world-wide clock network.

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Since clock stabilities have begun to routinely enter a relativistically significant range (10^{-12} to 10^{-13}), a discussion of such conventions is presently more than an academic exercise. Two synchronization techniques, portable clocks and VLBI, are analyzed in terms of the simplified time equation. Finally, pertinent experimental tests of relativity are briefly discussed.

II. REFORMULATION OF THE TIME CONVERSION

In this section, the time conversion between atomic time and coordinate time is reformulated by means of several approximations in order to cast it in a form that is more convenient for most applications. We will assume that, with appropriate rate and epoch specifications, the time reading of an atomic clock will, within the known stability limitations of the clock, be equal to proper time as calculated on the basis of the spacetime metric. Calculations will be made in terms of spacetime coordinates that are non-rotating and have the solar system barycenter as an origin. We will assume that the worldlines of the clocks in terms of these coordinates are known with sufficient accuracy. Coordinate time will be denoted by t and the proper time of the j^{th} earth-bound clock by τ_j.

In this analysis, approximations will be guided by the following considerations. Current, relatively well-developed oscillator technology (H-maser standards) can, at best, provide clocks with a long-term stability no better than $\Delta t/f \approx 10^{-15}$. Because of this instrumental limitation on time measurement, theoretical rate corrections ($d\tau/dt$) of the order of 10^{-15} or less will not be retained in the following analysis.

If one retains the most significant terms (i.e., the terms that lead to clock rate corrections greater than 10^{-15}) in the n-body metric tensor (e.g., Misner, Thorne and Wheeler 1973), then the resulting weak-field approximation to the differential equation relating coordinate time with proper time along the clock's worldline is given by the well-known expression (e.g. Moyer 1971):

$$\frac{d\tau_j}{dt} = 1 - \frac{\dot{\vec{y}}_j \cdot \dot{\vec{y}}_j}{2c^2} + \frac{\phi(\vec{y}_j)}{c^2} \tag{1}$$

where $\vec{y}_j$ and $\dot{\vec{y}}_j$ are the earth-bound clock position and velocity* given as a function of coordinate time and where $\phi(\vec{y}_j)$ is the total Newtonian gravitational potential at point $\vec{y}_j$. In this expression,

*A dot will denote differentiation with respect to coordinate time.

the $\vec{y}_j \cdot \vec{y}_j$ term corresponds to special relativistic time dilation due to clock speed and the ϕ/c^2 term corresponds to the general relativistic gravitational redshift. Note that, in this expression and in the following anaylsis, we treat the spacelike coordinates as vectors, which is an approximation of adequate accuracy under the weak-field assumptions.

The position vector $\vec{y}_j$ can be represented as a sum of a vector $\vec{x}_e$ from the solar system barycenter to the Earth's center of mass and a vector $\vec{x}_j$ from the Earth's center of mass to the clock so that

$$\vec{y}_j = \vec{x}_e + \vec{x}_j \tag{2}$$

In addition, the potential ϕ can be represented as a sum of two terms:

$$\phi(\vec{y}_j) = \phi_e(\vec{x}_j) + \phi_r(\vec{x}_e + \vec{x}_j) \tag{3}$$

where ϕ_e is the potential due to the Earth's mass and where ϕ_r is due to the mass of all other solar system bodies. The geopotential ϕ_e is very nearly constant for an Earth-fixed clock while the potential ϕ_r varies as the clock moves about due to both Earth spin and Earth orbital motion. Substituting these last two expressions in Eq. (1), we obtain

$$\frac{d\tau_j}{dt} = 1 - \frac{v_e^2 + 2\vec{v}_e \cdot \vec{v}_j + \vec{v}_j^{\,2}}{2c^2} + \frac{\phi_e}{c^2} + \frac{\phi_r}{c^2} \tag{4}$$

where $\vec{v}_e$ is the Earth's orbital velocity $(\dot{\vec{x}}_e)$ and v_j is the clock's geocentric velocity $(\dot{\vec{x}}_j)$. The order of magnitude of the various terms in Eq. (4) is as follows:

$\frac{v_e}{c} \approx 10^{-4}$	for Earth orbital speed
$\frac{v_j}{c} \approx 10^{-6}$	for clock geocentric speed
$\frac{\phi_r}{c^2} \approx 10^{-8}$	for gravitational potential at the Earth's orbit

$$\frac{\phi_e}{c^2} \approx 10^{-9} \qquad \text{for geopotential at the Earth's surface}$$

Two terms, $\vec{v}_e \cdot \vec{v}_j$ and ϕ_r, will now be manipulated* into more useful forms. As shown below, these manipulations lead to a time conversion for Earth-fixed clocks that does not involve an integral over $\vec{x}_j(t)$, the clock's time-varying position relative to the Earth's center of mass.

In order to separate Earth spin and Earth orbital motion, expand ϕ_r as follows:

$$\phi_r(\vec{x}_e + \vec{x}_j) \approx \phi_r(\vec{x}_e) + \nabla\phi_r(\vec{x}_e) \cdot \vec{x}_j. \tag{5}$$

It is readily shown that neglected quadratic terms due to the sun and moon are of the order of 10^{-17} at one earth radius. If one neglects relativistic terms of the order 10^{-15}, the gradient-$\nabla\phi_r$ is the acceleration $(\vec{a}_e)$ of the Earth's center of mass so that

$$\phi_r(\vec{x}_e + \vec{x}_j) \approx \phi_r(\vec{x}_e) - \vec{a}_e \cdot \vec{x}_j . \tag{6}$$

The time equation can be further modified by means of the identity:

$$\vec{v}_e \cdot \vec{v}_j = \frac{d}{dt}\left[\vec{v}_e \cdot \vec{x}_j\right] - \vec{a}_e \cdot \vec{x}_j \tag{7}$$

After substituting Eqs. (6) and (7) in Eq. (4), and integrating over coordinate time from t_c to t, we obtain the expression:

$$\tau_j(t) = \tau_c + t - t_c + \Delta t_s + \Delta t_j \tag{8}$$

where the two relativistic "correction" terms are defined by:

$$\Delta t_s \equiv \frac{1}{2c^2} \int_{t_c}^{t} \left[2\phi_r(\vec{x}_e) - v_e^2\right] dt \tag{9}$$

*A similar but unpublished analysis has been independently carried out by D. S. Robertson and R. D. Reasenberg at the Department of Earth and Planetary Science at MIT.

$$\Delta t_j \equiv \frac{1}{2c^2} \int_{t_c}^{t} \left[2\phi_e(\vec{x}_j) - v_j^2\right] dt \quad - \frac{\vec{v}_e(t) \cdot \vec{x}_j(t)}{c^2} \tag{10}$$

and where τ_c is the constant of integration. (It can be easily shown that, in order for all clocks to be synchronized according to the earthbound techniques of Section IV, this constant of integration must be the same for all clocks.) In this expression, we have divided the relativistic terms into two categories: the common terms (Δt_s) which are the same for all clocks, and the clock-specific terms (Δt_j) which might be different for each clock. Note that the two acceleration terms produced by the speed and potential terms have canceled. This cancelation in a different formulation has been noted by Hoffman (1961) and described as a manifestation of the equivalence principle for freely-falling geocentric coordinates. In this final form, the orbital and spin motions have been separated, except for the $\vec{v}_e \cdot \vec{x}_j$ term.

For a clock fixed with respect to Earth, the speed v_j and potential $\phi_e(\vec{x}_j)$ vary by no more than about one part in 10^6 (due, for example, to polar motion, earth tides, crustal motions). Therefore, to adequate approximation, the clock-specific correction for an <u>Earth-fixed clock</u> becomes:

$$\Delta t_j = \frac{2\phi_e(\vec{x}_j) - v_j^2}{2c^2} (t - t_c) \quad - \frac{\vec{v}_e(t) \cdot \vec{x}_j(t)}{c^2} \tag{11}$$

These expressions for the time conversion simplify the analysis in the following section which includes a discussion of terms and synchronization conventions.

III. INTERPRETATION OF TERMS AND CLOCK SYNCHRONIZATION ANALYSIS

World-wide timekeeping is now accomplished by a network of atomic clocks placed at various locations over the Earth. In this network member clocks are periodically synchronized with a master clock, which is carefully maintained at a fixed location. ("Master clock" in practice is the average time reading of a set of reference atomic clocks. Specific techniques for synchronization will be discussed in Section V on the basis of the relativistic time conversion.) Most synchronization work, based on the principles of classical physics, presently assumes that clocks, once synchronized in time and rate, will continue to indicate the same time, within instrumental accuracy, wherever they are moved on the Earth's surface. However, relativistic analysis, such as Eq. (8), indicates that classical assumptions may not be adequate if clock accuracies surpass the μs level in time and the 10^{-12} level in rate. That is, sufficiently accurate clocks can lose synchronization due to relativistic effects if they are separated on the Earth's surface. Consequently, an accurate clock network based on relativity theory must take these effects into account.

A relativistic understanding of the synchronization problem is facilitated by the formulation in Eq. (8) which connects coordinate time with the proper time of a given Earth-fixed clock. Even though this equation is not a direct comparison of Earth-fixed clocks, it contains all the information needed to study the synchronization problem, provided the various terms are properly interpreted. The following discussion attempts such an interpretation with emphasis on the establishment of synchronization conventions. Even though some aspects of this discussion are relatively well-known, they have been briefly included, sometimes without reference, for the sake of completeness.

The common correction term Δt_s in Eq. (9) contains the factors that cause the same rate offset for all clocks: the speed of the Earth center-of-mass and the "clock-invariant part" of the potential which is located at the Earth center-of-mass. Since this term is common to all clocks in the network, it will not cause a loss of synchronization. That is, this term is not significant in "earth-bound" comparisons of the clocks but is significant when converting between coordinate time and atomic time. In practice, the common term must be modified to account for any conventions affecting overall clock rates. For example, it is convenient to define the second so that, in principle, all clocks run at the same average rate as coordinate time (e.g. Moyer 1971). This rate definition is represented* formally in Δt_s by subtracting the time-average rate from the total rate in Eq. (9) as follows:

$$\widetilde{\Delta t}_s \equiv \Delta t_s - \overline{\Delta t}_s \equiv \frac{1}{2c^2}\int_{t_c}^{t} \left[2\Delta\phi_r - \Delta v_e^2\right] dt \tag{12}$$

where

$$\Delta v_e^2 \equiv v_e^2 - \overline{v_e^2}$$

$$\Delta\phi_r \equiv \phi_r - \overline{\phi}_r.$$

This rate adjustment, which is the order of 10^{-8}, leaves only the non-linear, principally periodic effects in Δt_s. (A detailed analysis to

*In the remaining analysis, a tilde over a term will denote that the term has been adjusted according to the synchronization conventions defined in this section.

establish the most appropriate definition for this time average and to model the most important time-varying residual terms is beyond the scope of this paper.) Even though these residual time-varying effects do not cause loss of synchronization between Earth-fixed clocks, they must still be included in conversions between proper time and coordinate time. For example, the predominant effect, orbital eccentricity, has an integrated amplitude of approximately 2 ms and an annual period (e.g. Moyer 1971).

The clock-specific correction Δt_j in Eq. (11) can lead to a synchronization loss between Earth-fixed clocks. This correction can be subdivided into two categories of time dependence for Earth-fixed clocks: linear and periodic.

In the first category, the linear term, $\left[\phi_e - v_j^2/2\right]$ $(t - t_c)$, is a rate correction based on clock geopotential and speed relative to the Earth's center-of-mass. This term corresponds to the conventional redshift due to geopotential since its coefficient is essentially the effective geopotential at point $\vec{x}_j$ as classically observed at the Earth-fixed clock (Cocke 1966). That is, the gradient of $v_j^2/2 - \phi_e$ gives the sum $(\vec{g})$ of the earth-spin "centrifugal force" and the earth's gravitational attraction at that point. Since mean sea level represents, to good approximation, a surface of constant effective geopotential, all Earth-fixed clocks at mean sea level should run at approximately the same rate without relativistic corrections. For two arbitrary Earth-fixed clocks, the differential rate correction can be approximately calculated on the basis of differential altitude by the formula $g\Delta h$, which predicts that the rate correction changes by approximately 1.1×10^{-13} per kilometer of differential altitude. (For airborne or orbiting clocks, it is readily shown that time-varying differential rate corrections of the order of 10^{-9} - 10^{-12} are possible.)

In the second category, the periodic term $\vec{v}_e(t)\cdot\vec{x}_j(t)$ is never greater than 2 μs and is essentially diurnal since $\vec{v}_e$ changes very little over one day. This term corresponds to the special relativity clock synchronization correction that accounts for the fact that simultaneous events in one frame (a "solar system frame") are not necessarily simultaneous in a frame (a "geocentric frame") passing by with velocity $\vec{v}_e$. Consequently, it is of significance in conversions between Earth-fixed time and coordinate time but is not present in "Earth-bound" comparisons between Earth-bound clocks. This assertion is supported analytically by the fact that the periodic term "changes" to match another clock if the two clocks are brought together on Earth.

The following conventions regarding synchronization are designed to accommodate these clock-specific terms. Since the linear terms can lead to gross disagreements between clocks over long time periods, they will be removed, either explicitly or implicitly, by making appropriate location-dependent definitions of clock rate. For such rate adjustments to be significant, the stability of the clocks in the network must, of course, be significantly better than a typical rate correction of roughly 10^{-13}. In principle, these corrections could be applied by means of explicit on-site rate adjustments based on a fundamental physical process. For example, at each location a second could be set equal to a particular altitude-dependent number of cycles (to more than 13 decimal places) on a cesium beam frequency standard where the cycle-count differential between altitudes would be based on the differential in effective potential. Since these rate adjustments are of the order of 10^{-13}, the oscillators would necessarily have to be capable of independent (absolute) calibration at a few parts in 10^{-14} or better (in addition to the similar stability requirement). Unfortunately, routine calibrations at this level are not feasible at present. In practice, this rate adjustment will be implicitly applied in a differential sense whenever a world-wide clock network is kept in time synchronization. For example, as in the present system, a "master clock" would be utilized, at a given location, to define the second and maintain a reference time. Other clocks over the world would then be forced into synchronization by means of "earth-bound" synchronization techniques (see Section V). Since the synchronization process prevents clock divergence, the appropriate differential rate correction will be implicitly applied without recourse to relativistic calculations.

Since the periodic term $\vec{v}_e(t).\vec{x}_j(t)$ does not affect the synchronization of Earth-bound clocks, it is not of consequence in the establishment of a synchronization convention.

By modifying Eq. (8) according to the definitions and conventions described above, one obtains a standardized conversion for Earth-fixed clock j:

$$\tilde{\tau}_j(t) = \tau_c + t - t_c + \frac{1}{2c^2}\int_{t_c}^{t} \left[2\Delta\phi_r(\vec{x}_e) - \Delta v_e^2\right] dt \qquad (13)$$

$$- \frac{\vec{v}_e(t) \cdot \vec{x}_j(t)}{c^2}$$

Note that the time equation no longer involves an integral over clock coordinates but only over coordinates for the Earth's center-of-mass. Therefore, relative to the original formulation, time calculations are much simpler.

In summary, with the conventions outlined above, the network clocks would be given selected initial times (at coordinate time t_c) and the same average rate (i.e. $\overline{d\tau/dt} = 1$). With these conventions, the clock network could be kept in synchronization according to Earth-bound observers by means of two synchronization methods now in use. These two techniques, portable clocks and VLBI, will be discussed in Section V in terms of these synchronization conventions.

IV. VLBI TIME DELAY

Radio interferometry holds great promise as a technique for the accurate synchronization of a world-wide clock network as well as for the accurate measurement of a variety of geophysical and astronomical phenomena [Shapiro and Knight 1970]. In this section, the primary component of the interferometric delay observable, the geometric delay, is calculated through the use of the reformulated time equation of the last section. The purpose of this derivation is to clarify the origin of the various terms in the geometric delay in preparation for a discussion of clock synchronization in Section V and experimental tests in Section VI.

The VLBI geometric delay is readily calculated using Eq. (13) as follows. Suppose that radio waves emitted by a distant source are observed by two Earth-fixed antennas. Let a given wavefront reach antenna 1 at coordinate time t and antenna 2 at t'. According to the two antenna teams, the wavefront arrives at $\tilde{\tau}_1(t)$ at antenna 1 and time $\tilde{\tau}_2(t')$ at antenna 2. When the two antenna teams compare arrival times, they will measure the "geometric" delay:

$$\tau_g(t) \equiv \tilde{\tau}_2(t') - \tilde{\tau}_1(t) . \tag{14}$$

We have assumed that instrumental and transmission media delays have been removed. In addition, we have assumed that the antenna clocks have been synchronized according to the conventions leading to Eq. (13). (A loss of synchronization would, of course, appear as an additive term in the measured delay.)

Since $|t' - t|$ is less than 30 ms for Earth-fixed antennas, the terms containing t' can be expanded about t to yield:

$$\tau_g(t) = \tilde{\tau}_2(t) - \tilde{\tau}_1(t) + \dot{\tilde{\tau}}_2(t)\ (t' - t) \tag{15}$$

$$= t' - t + \frac{1}{c^2}\left[\Delta\phi_r(\vec{x}_e) - \Delta v_e^2/2 - \vec{v}_e \cdot \vec{v}_2\right](t' - t) - \frac{\vec{v}_e(t) \cdot \vec{b}(t)}{c^2} , \tag{16}$$

where the baseline $\vec{b}$ equals $\vec{x}_2 - \vec{x}_1$. In this expression, we have neglected an $\vec{a}_e \cdot \vec{x}$ term and terms of order higher than the first in $t' - t$ with negligible loss of accuracy. Note that the geometric delay is equal to the "coordinate time delay", $t' - t$, plus time conversion corrections of two types. The first type is a "time dilation" correction, consisting of three terms proportional to $t' - t$. It is easily demonstrated that these terms are less than 20 psec (0.6cm) in magnitude. Consequently, these corrections are of marginal importance for even the most ambitious VLBI applications.

The second correction category, which corresponds to the clock synchronization correction (or aberration correction) found in a special relativity treatment, can be estimated as follows:

$$\frac{\vec{v}_e \cdot \vec{b}}{c^2} < 10^{-4} \cdot \frac{12000}{c} = \frac{1.2 \text{ km}}{c} = 4 \ \mu\text{sec} \tag{17}$$

Since $\vec{v}_e$ changes very little over a day, this term exhibits essentially diurnal time variations. In time delay calculations, this large correction must be treated very precisely.

Upon to this point, the coordinate time delay $t' - t$ has been treated in a general fashion and could denote any two events occurring near the earth. Since this section is primarily concerned with the relativistic conversion of a given coordinate time delay to proper time observations, a general discussion of delay calculations, including all factors, will not be attempted. However, as an example, the time delay for a very distant, fixed source (specifically, a compact extragalactic radio source) will be approximately derived in preparation for Section V and VI.

The geometric delay for an extragalactic source can be derived by first calculating the coordinate time delay and then transforming to antenna observers. We will give the signal a plane-wave representation that ignores transmission media and general relativity effects. The coordinate time delay for a plane wave is then easily shown to be given by

$$t' - t = - \frac{\hat{s} . \vec{b}}{c \left[1 + s \cdot (\vec{v}_e + \vec{v}_2)/c\right]} , \tag{18}$$

where $\hat{s}$ is a unit vector in the direction of the radio source relative to the solar system barycenter. The observed time delay is then obtained by inserting this expression into the time conversion, Eq. (16). All quantities in this expression are evaluated at coordinate time t, the time the wave front reaches antenna 1.

As an alternate but instructive approach, the geometric delay can be approximately derived to order v/c relative to a geocentric frame (e.g. Thomas 1972). In that derivation, the $\vec{v}_e \cdot \vec{b}$ term enters the delay as a result of the aberration correction to the source direction. As indicated by the two derivations, this large term can be viewed in two ways. For Earth-bound observers, it is a geometric correction applied to the position of the source. In contrast, relative to solar-system barycentric coordinates, it can be viewed as a time correction corresponding to a loss of synchronization between Earth-fixed clocks in the special relativity limit.

V. CLOCK SYNCHRONIZATION TECHNIQUES

This section will show how two synchronization techniques, portable clocks and VLBI, can be used to synchronize a world-wide clock network according to the synchronization conventions defined in Section III. The portable clock technique will be discussed first.

In the present world-wide timekeeping network, member clocks at various locations around the world are periodically resynchronized with the "master clock" by comparing them with a portable clock that is carried to each location. Before and after each trip, the portable clock is synchronized on-site with the "master clock". In this manner, a world-wide network of clocks can be placed in synchronization at the level (presently 1-10 μsec for routine applications) allowed by the instrumental and transportation stability of clocks involved.

Let a portable clock be synchronized with the master clock at coordinate time, $t = t_0$. Then let the portable clock follow path[1] $\vec{x}_p(t)$ over the Earth to some member of the clock network. (Note that $\vec{x}_p(t)$ and $\vec{v}_p(t)$ contain Earth-spin as well as clock transportation effects.) After the portable clock has reached the member clock j at time t', the clock-specific correction for the portable clock [see Eq. (10) but subtract the constant master-clock rate] will be

$$\Delta t_p = \frac{1}{2c^2}\int_{t_o}^{t} \left[2\phi_e(\vec{x}_p) - v_p^2 - 2\phi_e(x_m) + v_m^2\right] dt - \frac{\vec{v}_e(t') \cdot \vec{x}_j(t')}{c^2} , \qquad (19)$$

[1]Relative to the Earth center-of-mass.

where the subscripts p and m denote portable and master clocks respectively. (We have not included the other terms in Eq. (8) in this discussion since they are common to all clocks and do not affect synchronization.) The integral term in this expression accounts for the fact that the master clock rate adjustment (passed on to the portable clock during synchronization with the master clock) will not suppress the $2\phi_e - v_p^2$ integral for the portable clock once it starts its journey and changes its geocentric position and speed. Furthermore, the term $\vec{v}_e(t') \cdot \vec{x}_j(t')$ represents the value for the correction term $\vec{v}_e \cdot \vec{x}_p$ <u>after</u> the portable clock reaches the member clock $(\vec{x}_p \rightarrow \vec{x}_j)$.

According to the synchronization conventions established in Section III, the portable clock-member clock comparison must be handled as follows. The desired value for the clock-specific term for the member clock is given by

$$\widetilde{\Delta t}_j = - \frac{v_e(t') \cdot x_j(t')}{c^2} \quad . \tag{20}$$

Thus, comparing Eq. (19) and Eq. (20), we see that the portable clock must be corrected to account for the speed-potential integral that has accumulated in transit:

$$\Delta\tau_p = \widetilde{\Delta t}_p - \widetilde{\Delta t}_j \tag{21}$$

$$= \frac{1}{2c^2} \int_{t_o}^{t'} \left[2\phi_e(\vec{x}_p) - v_p^2 - 2\phi_e(\vec{x}_m) + v_m^2 \right] dt \tag{22}$$

For one day transit times, this correction can be of the order of $10^{-12} \times 10^5$ s = 100 ns. Further, the portable clock rate will differ from the conventional rate for site j by

$$\frac{2\phi_e(\vec{x}_j) - v_j^2 - 2\phi_e(\vec{x}_m) + v_m^2}{2c^2} \approx \frac{g\Delta h}{c^2} \quad , \tag{23}$$

so that the clock <u>rate</u> comparisons must include this correction factor. Thus, we see that, during transit, the periodic term $\vec{v}_e \cdot \vec{x}_p$ changes into the appropriate value while the "rate term" loses its adjustment and must be corrected.

It is interesting to note that the integral contained in Eq. (22) is essentially the theoretical time gain predicted by Hafele and Keating for their Earth-circumnavigation experiment (Hafele and Keating 1972), in which they measured the synchronization loss (relative to a stationary master clock) of atomic clocks flown around the world. In that paper, theoretical calculations only considered geocentric speed and geopotential effects. With a more general approach, the present formulation indicates that this integral is the total time gain, provided one can neglect rate terms less than about 10^{-15}. Thus, the warning by Hafele and Keating that effects of the sun and moon might perhaps not be entirely negligible appears to be unwarranted for clock stabilities worse than about 10^{-15}.

Clock synchronization by means of VLBI is conceptually, if not operationally, straightforward. For a given natural source, the time delay is measured between two antennas and appropriately corrected for transmission media and instrumental delays. The resulting delay should be equal to the geometric delay calculated according to Eq. (16). (We assume here that geophysical and astrometric quantities are known with sufficient accuracy.) Any difference between the measured delay and the calculated delay represents the synchronization loss between antenna clocks. In this manner, a world-wide system of clocks could be synchronized at interferometer accuracies, which are expected to reach about 0.1 nsec for future well-developed VLBI systems (Shapiro and Knight 1970).

VI. DISCUSSION OF PERTINENT RELATIVITY EXPERIMENTS

In a treatment of this nature, it is of interest to discuss pertinent tests of relativity in terms of the reformulated time conversion. As indicated in Section III, only the "geocentric" term, the integral in Eq. (8), will be evident in "earth-bound" comparisons of Earth-bound clocks. Contingent on instrumental feasibility, two basic types of Earth-bound clock experiments can be used to test the presence of this effect: moving clocks and Earth-fixed clocks. It is interesting to note that, while a moving clock experiment generally involves an integrated synchronization loss due to time-varying speed and potential, the relativistic effect for Earth-fixed clocks would, to first approximation, only consist of a constant rate offset due to a constant differential in geopotential. Consequently, an Earth-fixed experiment would essentially produce, to first order, a measurement of the conventional gravitational redshift, as first measured by Pound and Rebka (1960) and later but more accurately by Pound and Snider (1964). In those experiments, precise nuclear resonance measurements based on the Mössbauer effect determined the apparent frequency shift of γ-rays from the 14.4 kev transition in Fe^{57} where the local geopotential difference was established with a 22.5 m altitude differential.

In order for an Earth-fixed clock experiment to equal the 1% accuracy of the Pound-Snider experiment, a typical rate differential of roughly 10^{-13} (for a 1 km altitude differential) would have to be measured with an accuracy of 10^{-15}, which would, of course, require clock stability and accuracy at 10^{-15}. Except perhaps at standards laboratories, this clock rate calibration requirement would probably be the most difficult aspect of such an Earth-fixed clock experiment. One of the possible methods for measuring the synchronization loss in such an experiment would be the VLBI technique, which would have the advantageous option, for portable antennas, of making very precise synchronization measurements between standard clocks while they are carefully maintained in the existing ideal environments of two possibly widely separated standards laboratories. For example, with a VLBI clock synchronization accuracy of 0.1 nsec, a rate - differential sensitivity of roughly 10^{-15} would be obtained with about 24 hours of data. Unfortunately, even though the γ-ray resonance and clock techniques are significantly different, the current, established level in clock technology will not allow an Earth-fixed-clock measurement of the geopotential redshift that is significantly more accurate than the Pound-Snider experiment.

In general, the relativistic rate effect can be larger for moving clocks than for Earth-fixed clocks, potentially by as much as three orders of magnitude. One moving-clock experiment, involving airborne clocks (Hafele and Keating 1972), has already been carried out with positive results. In that experiment, the synchronization losses (273 nsec in the maximum case) relative to an Earth-fixed standard clock were observed to be in agreement with theoretical estimates, with an overall uncertainty of about 20 nsec. Another moving-clock experiment, presently in preparation (Kleppner et al, 1970; Vessot and Levine, 1971), would attempt to measure the time-varying relativistic rate differential between an Earth-orbiting clock and an Earth-fixed clock. Measurements of rate variations as large as 6×10^{-10} with an overall accuracy of 1 part in 10^5 are predicted for that experiment.

VII. SUMMARY

In the preceding sections, a reformulation of the relativistic time equation has simplified interpretation of the various effects entering the conversion between coordinate time and Earth-bound proper time (atomic time). Based on this analysis, the conventions and techniques involved in the synchronization of a world-wide clock network have been investigated. In addition, the new formulation has simplified a relativistic analysis of the "geometric delay" measured in VLBI applications. Finally, a brief discussion has been devoted to "Earth-bound" relativity experiments that are relevant to the reformulation.

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PLASMASPHERIC EFFECTS ON ONE-WAY SATELLITE TIMING SIGNALS

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ABSTRACT

At the 1973 PTTI Planning Meeting, the effects of the ionospheric retardation of satellite-emitted timing signals was presented. The retardation at the navigation frequencies, which is proportional to the total ionospheric electron content (TEC), was determined by Faraday polarization measurements of VHF emissions of a geostationary satellite. The polarization data yielded TEC up to ∿1200 km only, since the measurement technique is based on the Faraday effect which is weighted by the terrestrial magnetic field.

The radio beacon experiment aboard the recently launched geostationary ATS-6 offers the unique opportunity to determine TEC, or equivalently, the signal propagation delay, to geostationary altitudes. The beacon package provides the opportunity to conduct two relevant experiments. The first utilizes the Faraday rotation technique for determination of TEC. The second utilizes the dispersive group delay technique which is independent of the magnetic field and determines TEC to geostationary altitudes. The difference between the values of the integrated electron content obtained by the two techniques yields the content from ∿1200 km to geostationary altitudes, i.e., the plasmaspheric electron content.

Faraday rotation and dispersive group delay observations have been conducted at Fort Monmouth since the launch of ATS-6 in late May, 1974. The plasmaspheric content exhibited diurnal as well as day-to-day variations. Its absolute magnitude varied from 1 to ∿8 TEC units (10^{16} e/m^2). At night the plasmaspheric content was nearly always above 50% of the ionospheric content and on occasion exceeded 100%. During the day, this ratio averaged ∿35%.

INTRODUCTION

At the 1973 Precise Time and Time Interval (PTTI) Symposium, the effects of the ionospheric total electron content on the accuracy of transionospheric satellite navigation systems were discussed [1]. It was shown that in traversing the ionosphere, a propagating navigation signal is slowed by an amount which is directly proportional to the total electron content (TEC) along its path. This gives an apparent range that is larger than the equivalent free-space range. If the TEC is known, or is measured, a correction to the ranging may be applied. The TEC may be measured in real time, provided the user has dual-frequency capabilities. However, substantial reduction in the cost of user equipment could be realized if the navigation system used only one frequency. In such a case, the ionospheric time-delay will have to be determined through empirical modeling techniques based on existing and future global electron content data, and will be transmitted to the user for correction via the navigating signal.

Most TEC data to date has been obtained by the Faraday polarization rotation technique. The Faraday rotation is a terrestrial-magnetic-field-dependent phenomenon, and its magnitude is heavily weighted near the earth. It is therefore considered to provide electron content values at altitudes below $\sim$1200 km. The navigation system will utilize satellites at considerably higher altitudes. The navigating signal will be slowed by free electrons in the ionosphere as well as in the plasmasphere (i.e., at altitudes $>$ 1200 km). The corrections for TEC supplied by a model based on the Faraday technique will not adequately compensate for the total signal delay since the free electrons in the plasmasphere will not be accounted for. The radio beacon experiment (RBE) aboard the geostationary Applied Technology Satellite (ATS-6 launched in May 1974) permits the accumulation of TEC data which includes the plasmaspheric content. The technique utilized is the dispersive-group-delay technique which is independent of the terrestrial-magnetic-field and hence yields the integrated electron content from observer to satellite.

THE FARADAY AND DISPERSIVE-GROUP DELAY METHODS

The Faraday polarization rotation technique has long been used in measurement of TEC. In the high-frequency and quasi-longitudinal approximations, the two magneto-ionic modes are nearly circularly polarized in opposite senses; thus a plane polarized wave traversing the ionosphere may be regarded as the vector sum of the ordinary and extraordinary components. Since these two components travel at different phase velocities, the plane of polarization rotates continually along the signal's path. The total rotation from the signal source to the observer is related to the total electron content by the expression:

$$a = \frac{k}{f^2}\int_0^S B\cos\theta N ds = \frac{k}{f^2}\int_0^S (B\cos\theta\sec\chi)N dh, \qquad (1)$$

where $k = 2.36 \times 10^{-5}$, B is the local magnetic field flux density in gammas, θ is the angle between the radio wave normal and the magnetic field direction, and χ is the angle between the wave normal and the vertical. Since B decreases inversely with the cube of the geocentric distance, and since the electron density decreases exponentially with altitude above F_2 max (~ 300 km), the integral is heavily weighted near the earth and is considered to provide electron content values at altitudes below ~ 1200 km.

The term $M = B\cos\theta\sec\chi$ in Eq. (1) may be taken out of the integral sign and replaced by its value at a "mean" ionospheric altitude (420 km). Equation (1) then becomes:

$$a = \frac{k}{f^2}\,\overline{M}\cdot\int_{\text{Ionosphere}} N dh = \frac{k}{f^2}\,\overline{M}\,N_I, \qquad (2)$$

where N_I is the ionospheric total electron content measured by the Faraday rotation technique. At Fort Monmouth, where the numerical value for $\overline{M}$ is 56292 γ, for $N_I = 10^{16}$ e/m^2 defined as 1 TEC unit, we calculate a = 38.83° (for f = 140 MHz).

Using the dispersive-group-delay technique, the phase of the modulation envelope between a carrier and its sideband is compared at two frequencies (nominally f = 140 and 360 MHz with sideband displacements of $\Delta f = +1$ MHz). Since the phase is insensitive to the earth's magnetic-field, this technique yields the number of electrons along the entire path from satellite to observer (N_T).

The time delay of a signal propagated through a medium containing free electrons with a group velocity v_g is:

$$t = \int_0^S \frac{ds}{v_g} = \frac{1}{c}\int_0^S \mu_g \, ds = \frac{1}{c}\int_0^S \left(1 + \frac{kN}{f^2}\right) ds, \tag{3}$$

where μ_g is the group refractive index and c is the velocity of light in vacuum. For two signals at frequencies f_1 and f_2, the differential time delay is:

$$\Delta t = \frac{40.3}{c} \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \int_0^S N ds. \tag{4}$$

If the two signals are modulated by a sideband separated by an equal Δf, then the modulation time delay Δt_m is equal to the differential group time delay, i.e.,

$$\Delta t = \Delta t_m = \frac{\Delta\phi}{360} \frac{1}{\Delta f} = \frac{40.3}{c} \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \int_0^S N ds, \tag{5}$$

where $\Delta\phi$ is the differential modulation phase shift in degrees. It follows that

$$\int_{Total} N dh = N_T = \frac{\Delta\phi}{360} \frac{1}{\Delta f} \frac{c(\sec\chi)^{-1}}{40.3} \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)^{-1}. \tag{6}$$

At Fort Monmouth for $N_T = 10^{16}$, a phase difference of 30.55° is measured.

THE DATA

The variation of the total electron contents measured by the Faraday and group delay techniques is shown in Fig. 1 at 15-minute intervals for the time period 1600 EDT on 3 July to 0800 EDT on 8 July. The temporal variations of N_I and N_T were nearly parallel with most density variations observed on both curves.

Prominent during the time period covered were the large increases of total electron content in response to two large solar flares (see Fig. 1). Between 0945 EDT and 1000 EDT on 4 July, N_I increased by $\sim 1.5 \times 10^{16}$ e/m^2, while N_T increased by $\sim 2 \times 10^{16}$ e/m^2. Since the content values in Fig. 1 are given for every 15 minutes, the full increase of N_I and N_T is not indicated there. Starting at $\sim$0953 EDT, N_I increased by $\sim 3.3 \times 10^{16}$ e/m^2 in 3 minutes and then decayed to its value at 1000 EDT. At the same time, N_T increased by approximately the same amount. On 5 July between 1730 and 1745, N_I increased by $\sim 1.9 \times 10^{16}$, while N_T increased by $\sim 2.3 \times 10^{16}$. The rapid increases started at 1740 EDT with N_I increasing by $\sim 2.1 \times 10^{16}$ in 6 minutes; N_T increased similarly.

The equivalent signal-delay time at 1.6 GHz (in the navigation frequency band) corresponding to the vertical electron content distribution was always below 15 nanoseconds for the time period reported. On different days, the time delay varied by as much as 60%. Between maximum and minimum on any one day, the largest factor was 12. Superimposed on the normal diurnal variations of the content were quasi-sinusoidal variations which usually occur near the time period of maximum content of the daily cycle. These variations are caused by ionospheric irregularities.

The dispersive-group-delay technique measures the total electron content from observer to satellite, whereas the Faraday technique yields the content only in the vicinity of the earth (i.e., up to $\sim$1200 km). The difference between the two yields the content above $\sim$1200 km, which is referred to as the plasmaspheric content, N_P.

It follows that

$$N_P = N_T - N_I. \tag{8}$$

N_P is plotted in Fig. 2 for the same time intervals and for the same time period as that of Fig. 1. The plasmaspheric content ranged from 1 to $\sim$8 TEC units, or equivalently from $\sim$0.5 to over 4 nanoseconds for a 1.6 GHz signal. Generally, the minimum of the plasmaspheric content occurred near ionospheric sunrise while its maximum occurred near ionospheric sunset. During any one day, the diurnal variation was not as pronounced as the corresponding variation of the total or ionospheric electron contents. The maximum variation (by a factor of ∿3.4) was observed on 5 July. This is compared to a total content variation by a factor of 12 for the same day. The day-to-day variability exhibited changes of up to 300% during comparable local time periods (e.g., on 4 and 7 July during nighttime hours).

Of great importance to the applicability of global time-delay models based on TEC data obtained by the Faraday rotation technique, is the magnitude and variation of the ratio of plasmaspheric to the ionospheric time delays, or equivalently (N_P/N_I). This ratio (see Fig. 3) shows a diurnal as well as a day-to-day variability. Between 0100 and 0700 EDT, the ratio was nearly always above 50% and on occasions exceeded 100%. After this time-period, the ratio decreased to its minimum at ∿1100 EDT, after which time it increased with the time of day. From 0700-0100 EDT, the ratio average increased from ∿30 % to ∿40 %.

The ratio of the plasmaspheric to the total time-delays due to free electrons along the signal's path, or equivalently N_P/N_T, is shown in Fig. 4. The diurnal and day-to-day variability of this ratio is similar to that of N_P/N_I. During the night the ratio was high, reaching a value up to 70%. During the day, the ratio was lower, averaging from ∿25% to 30%.

CONCLUSIONS

Preliminary results of the radio beacon experiment of the ATS-6 indicate the magnitude and variation of the plasmaspheric electron content. The group path delay of a navigation signal due to free electrons in the plasmasphere cannot be neglected when it is compared to the delay due to the ionosphere. Group path delay prediction models based on Faraday data do not adequately compensate for the total delay; at night, they may be off by more than 50%, and during the day by an average of ∿35%. This is in addition to other prediction errors, i.e., differences between observed and predicted values of the delay times. Furthermore, ionospheric (Faraday) prediction models cannot be corrected by adding a constant offset to account for the plasmaspheric delay, since the plasmaspheric content exhibited a diurnal and day-to-day variation. Fortunately, the highest ratio of plasmaspheric-to-ionospheric delay time occurs at night, when the total delay time is relatively small.

The data reported here was taken at a mid-latitude station during the quiet phase of the solar cycle. During such a phase at such a location, the group delay is generally small and modeling schemes yield corrections within the accuracy requirements of the proposed navigation systems. It remains to be seen if the observed ratios of plasmaspheric-to-ionospheric delays will be maintained at other geographic locations, and when delay times will be large, such as during the maximum phase of the solar cycle. If such ratios are maintained during the maximum of the cycle, neglecting the plasmaspheric content will cause errors exceeding the accuracy requirement of the system.

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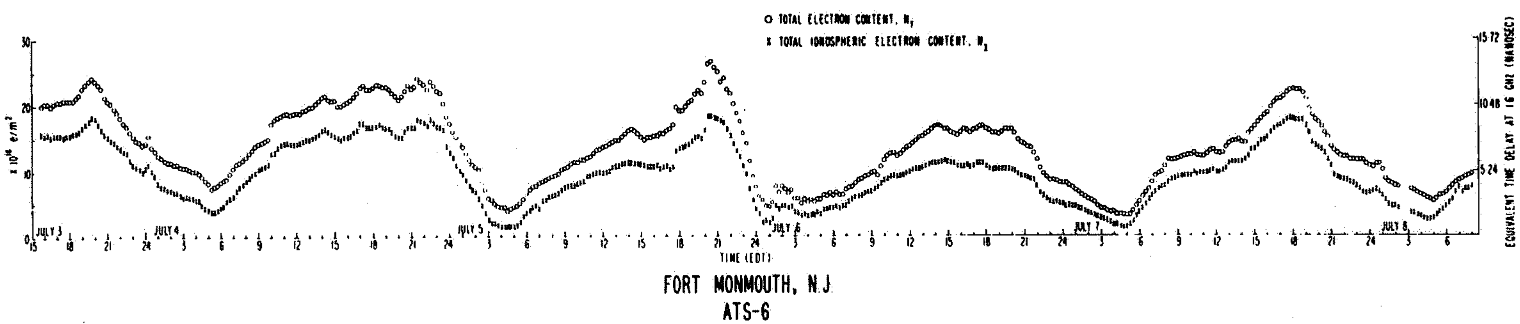
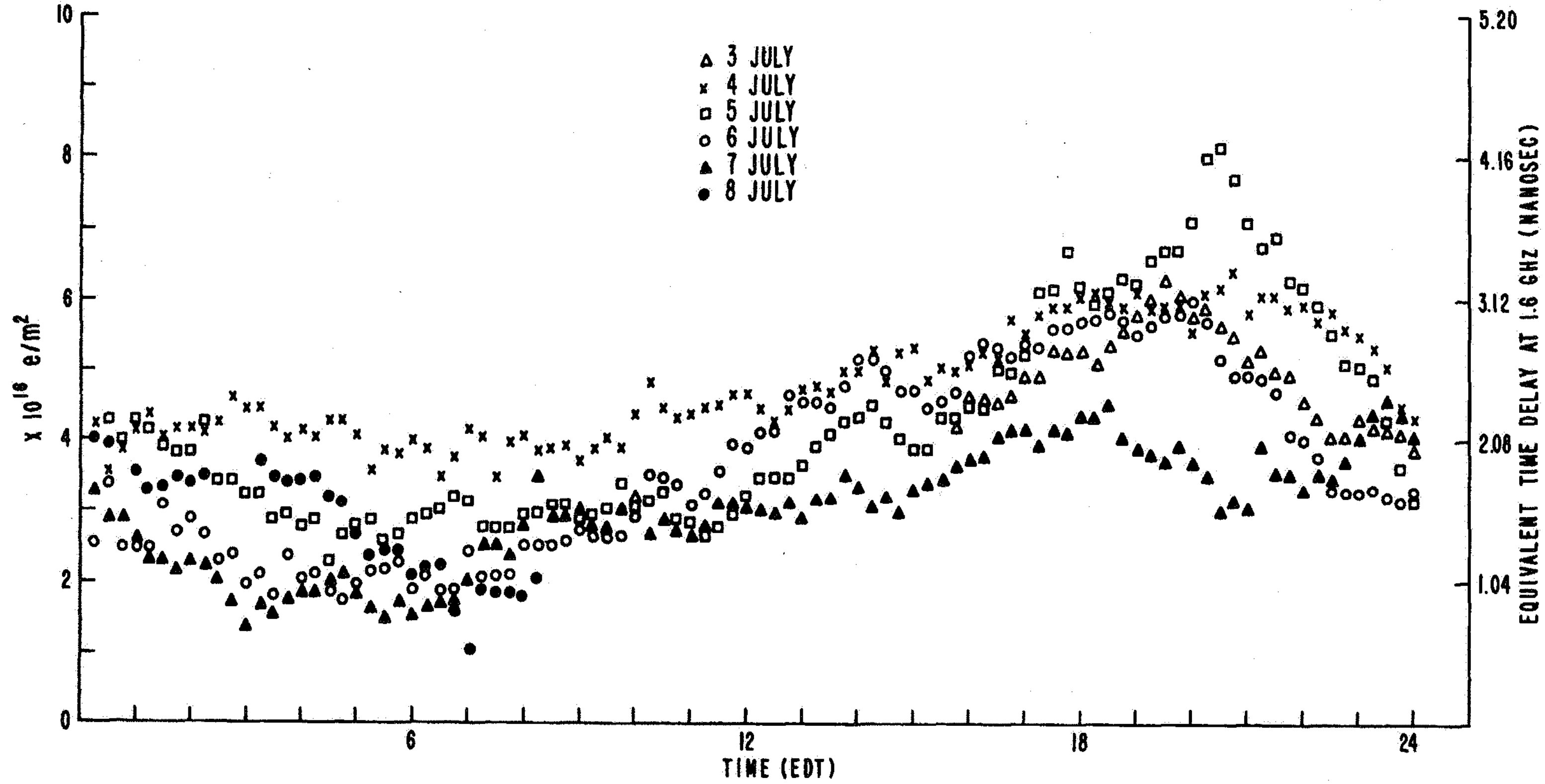


Fig. 1. Variation of total electron content, $N_T^{(\odot)}$, and ionospheric electron content, $N_I^{(x)}$, at 15-minute intervals from 1600 EDT, 3 July 1974, to 0800 EDT, 8 July 1974, at Fort Monmouth, N. J. (equivalent time-delay for 1.6 GHz signals are also indicated).

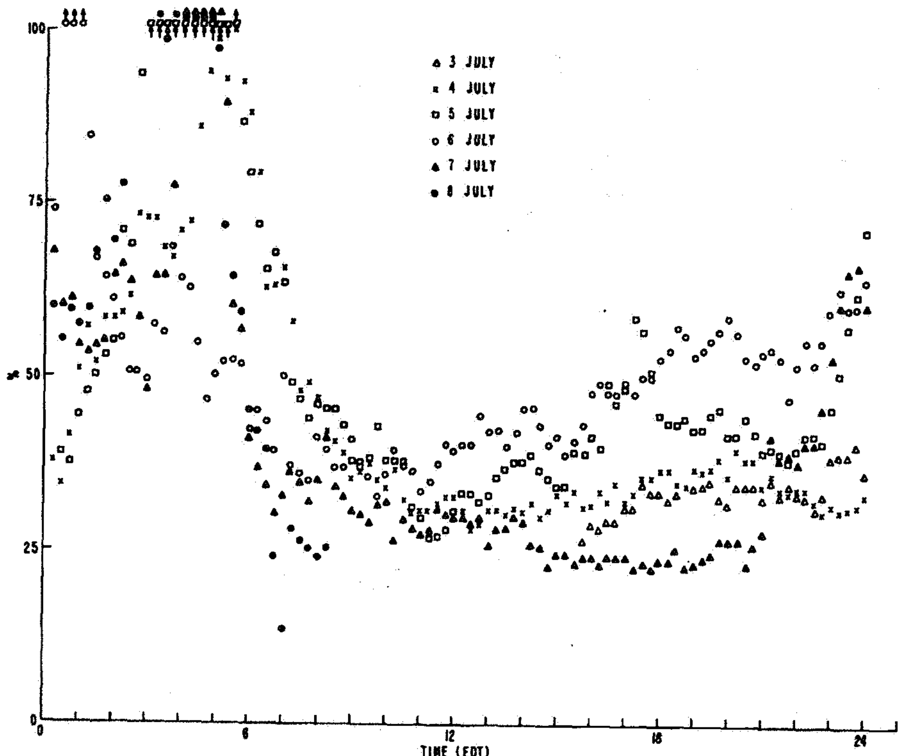


PLASMASPHERIC TOTAL ELECTRON CONTENT

FORT MONMOUTH, N.J.

ATS-6

Fig. 2. Variation of the plasmaspheric electron content at 15-minute intervals for same time period as in Fig. 1.



% OF PLASMASPHERIC TO IONOSPHERIC CONTENTS $\left(\frac{N_p}{N_I}\right)$
FORT MONMOUTH, N.J.
ATS-6

Fig. 3. Variation of the ratio of plasmaspheric to ionospheric electron contents (in percent) at 15-minute intervals for same time period as in Fig. 1.

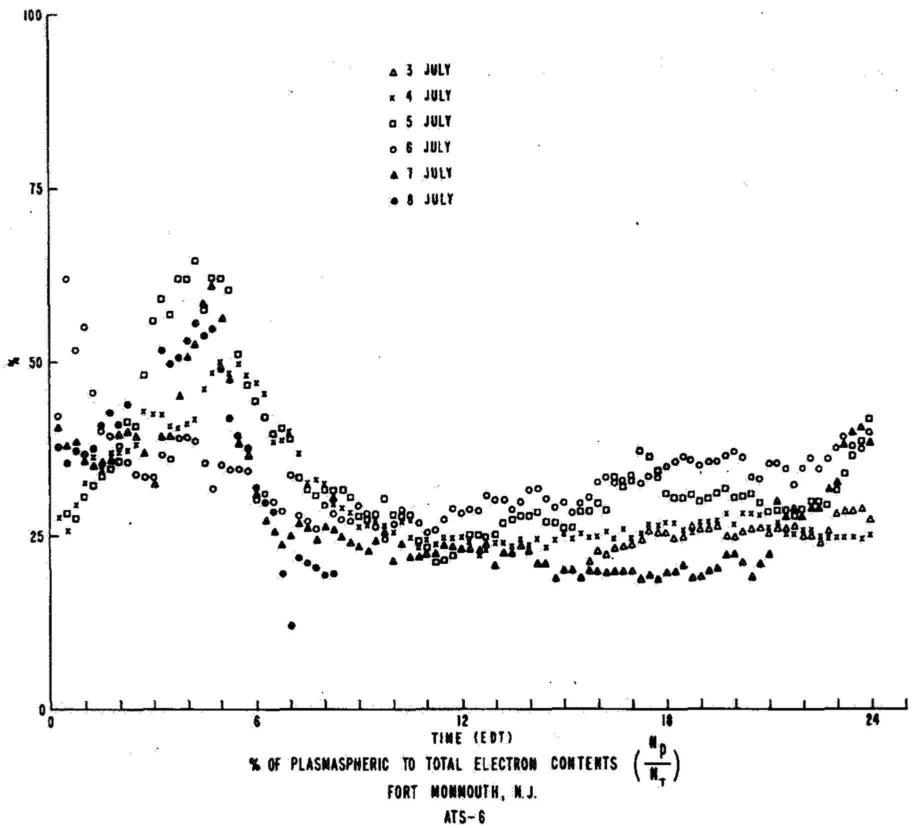


Fig. 4. Variation of the ratio of plasmaspheric to total electron contents (in percent) at 15-minute intervals for same time period as in Fig. 1.

QUESTION AND ANSWER PERIOD

MR. CALLAHAM:

Is there any significant contribution at all to the delay due to tropospheric effects? Is there any significant contribution due to the presence of gases aside from the electron content?

DR. SOICHER:

I understand the GPS people are not concerned about the tropospheric delays because they're certainly an order of magnitude smaller than ionospheric effects.

N75 27201

A PASSIVE SUBMICROSECOND TIME DISSEMINATION SYSTEM

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ABSTRACT

A submicrosecond Time Dissemination System has been developed by the Johns Hopkins University Applied Physics Laboratory. The System is composed of an experimental transit improvement satellite (TRIAD), TRANET Satellite Tracking System, and special satellite signal receivers each tied to separate cesium clocks. The 400 MHz signal from the satellite is phase modulated $\pm 45^{\circ}$ by a pseudo-random noise (PRN) digital code with a bit rate of 5/3 MHz.

Evaluation of this system has shown that satellite oscillator frequency instabilities are the major source of error. During a three day observation of the satellite, the maximum excursion of the satellite oscillator frequency from a straight line fit to the observed frequency was 7×10^{-12} $\left(\frac{\Delta f \text{ diff}}{f}\right)$. Experiments indicate that Global time transfers can be made with errors less than 100 nanoseconds.

INTRODUCTION

Improvement of the Navy Navigation (Transit) Satellite System has led to the development of a new series of satellites which incorporate the following improvements:

1. Wide Band Pseudo-Random Noise (PRN) Phase Modulation of the carrier for range navigation and precise dissemination of time.

2. Disturbance Compensation System (DISCOS) which compensates for the aerodynamic drag forces and solar radiation pressure.

3. Programmable frequency synthesizer which compensates for frequency drift of the satellite quartz crystal reference oscillator.

This paper shall discuss nanosecond clock experiments utilizing the improvement mentioned under number 1. With the implementation of broad bandwidth digital pseudo-random noise (PRN) high frequency phase modulation on the carrier frequencies of the new Transit Improvement Satellite, TRIAD, came the ability to resolve timing marks with greatly increased precision using practical electronic circuitry. One key advantage of the Transit Satellites for disseminating time is that these satellites transfer time in a passive mode (one way signals from satellite to user). The advantages of this passive time dissemination system over an active or two way timing system are the following:

1. No limit to number of simultaneous terrestrial users.

2. User need not compromise his position by transmission of radio signals.

3. Use of portable omni-directional antennas.

DISCUSSION

The purpose of the nanosecond clock experiment was to determine what level of accuracy time can be disseminated using PRN signals which are broadcast from the TRIAD Satellite. The task was to investigate how accurately the Clock Epoch Difference between two cesium beam clocks could be determined using the PRN modulation transmitted from the TRIAD Satellite. The various sources of errors were examined and their order-of-magnitude contributions to the total were determined.

The experimental system is shown in Figure 1. The experiment was to determine the clock epoch difference or error between two cesium clocks when they are used as recovery system clocks for receivers monitoring

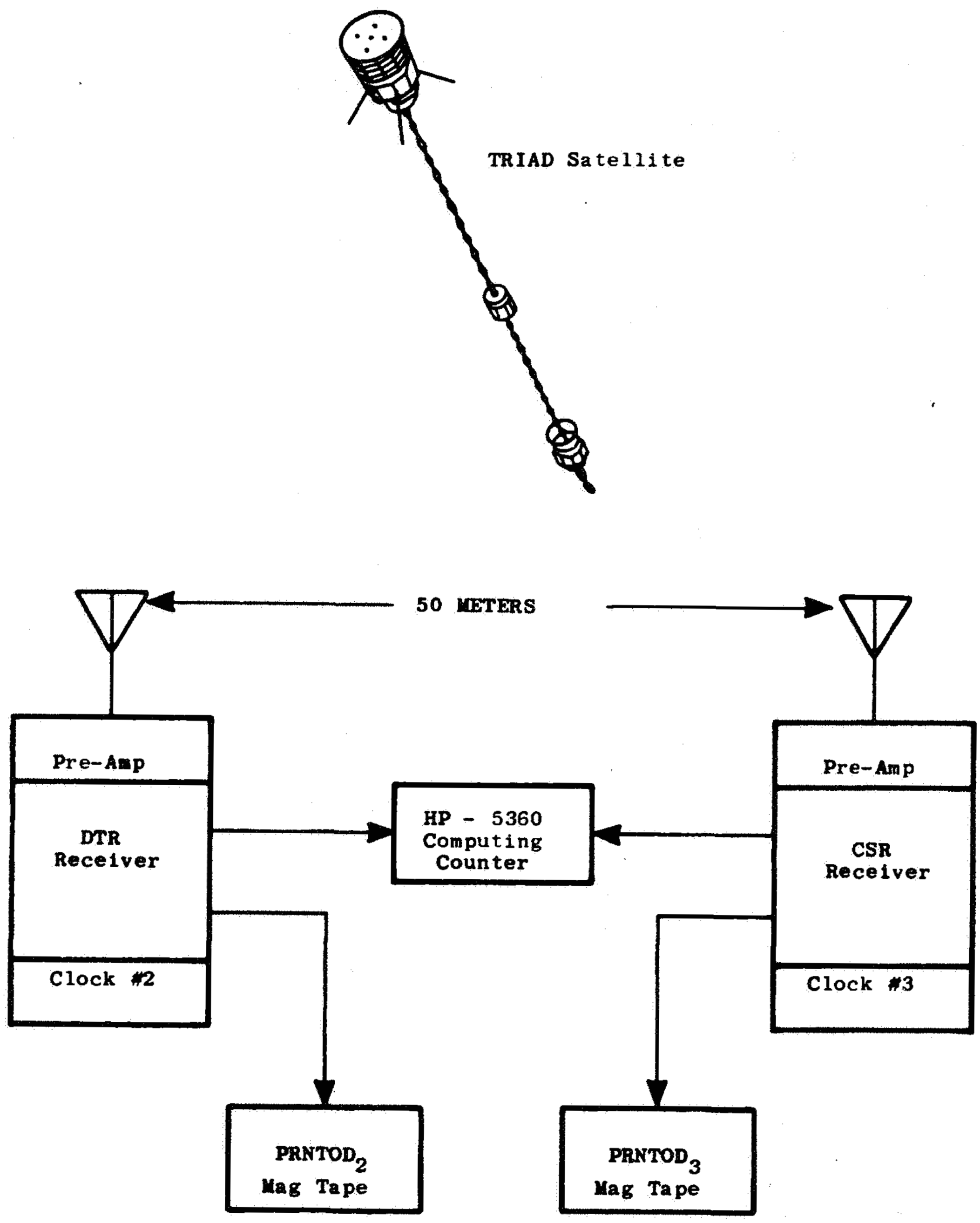

FIG. 1 SATELLITE AND RECEIVER EQUIPMENT DIAGRAM

the TRAID Satellite PRN digital code modulations on the 400 MHz signal. The two modes for determining the clock epoch error were the Regional Clock Transfer Mode and the Global Clock Transfer Mode. For the Regional Clock Transfer, both receivers monitor the same satellite signal simultaneously. For the Global Clock Transfer, measured PRN epoch times of arrival using one receiver are compared with predicted PRN epoch times of arrival using data from previous satellite passes measured with the other receiver. Satellite oscillator drift predictions are essential for predictions of PRN epoch times of arrival. Slant range propagation delays, ionospheric and tropospheric refraction delays, and equipment delays must be determined in order to determine the clock epochs error between the two cesium clocks on the ground. These time delays and their variation during a satellite pass are schematically shown in Figure 2. By subtracting these delays from the PRN times of arrival, one can determine the PRN times of transmission from the satellite. The PRN times of transmission are determined using two different clocks. The difference in time is the clock epoch difference between the two cesium clocks.

The clock epoch differences as determined by ground simulation of satellite signals and when the two receivers are simultaneously viewing the orbiting satellite (Regional Clock Synchronization) are shown in Figure 3. The maximum variation between these two methods to determine the clock epoch error is 43 nanoseconds with a mean bias of +22 nanoseconds for the satellite passes compared to the ground simulated satellite signals. The standard deviation of the satellite data from the general curve is only nine nanoseconds, however.

The bias in the Regional Clock Synchronization Data compared to the satellite simulator could come from several sources. Differences in antenna delays for the two receivers could account for part of the bias and/or dynamic response differences between the two receivers.

Data for the Global Clock Transfer Mode are generated by using PRN epoch receipt times as measured by the BRN-3 receiver for one pass to predict when PRN epochs should arrive at the SRN-9 receiver for the next pass and comparing the measured times of arrival with the predicted

CLOCK SYNCHRONIZATION METHOD

COMPARE PRN SATELLITE TRANSMISSION TIMES USING DIFFERENT CLOCKS

PRN TRANSMISSION TIME, CLOCK #1

PRN TRANSMISSION TIME, CLOCK #2

CLOCK EPOCH DIFFERENCE

TIME OF TRANSMISSION = TIME OF RECEPTION $-\rho/c - \Delta t_{ion} - \Delta t_{trop} - \Delta t_{eq}$

ρ SLANT RANGE, FROM SATELLITE EPHEMERIS AND RECEIVER COORDINATES.

Δt_{ion} FROM REFRACTION CORRECTION FREQUENCY DERIVED BY MIXING THE 150 and 400 MHz CARRIERS TOGETHER.

Δt_{trop} FROM TROPOSPHERIC MODEL USING TEMPERATURE, PRESSURE, AND HUMIDITY.

Δt_{eq} FROM EQUIPMENT DELAY CALIBRATIONS.

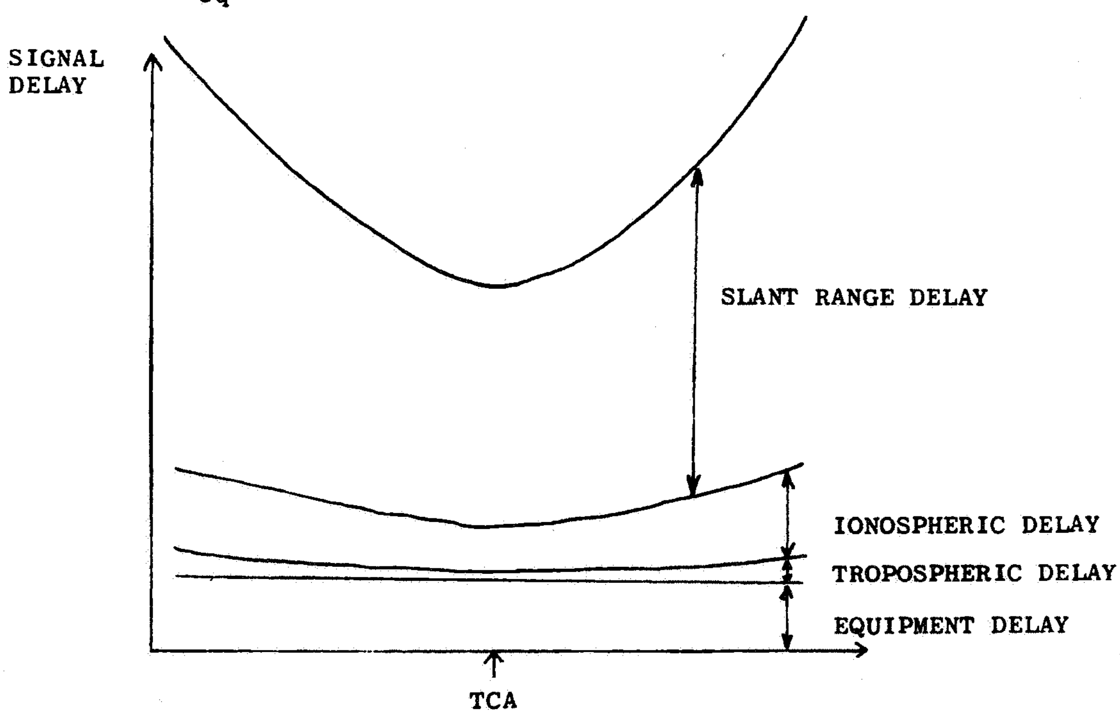

FIG. 2 CLOCK SYNCHRONIZATION METHOD

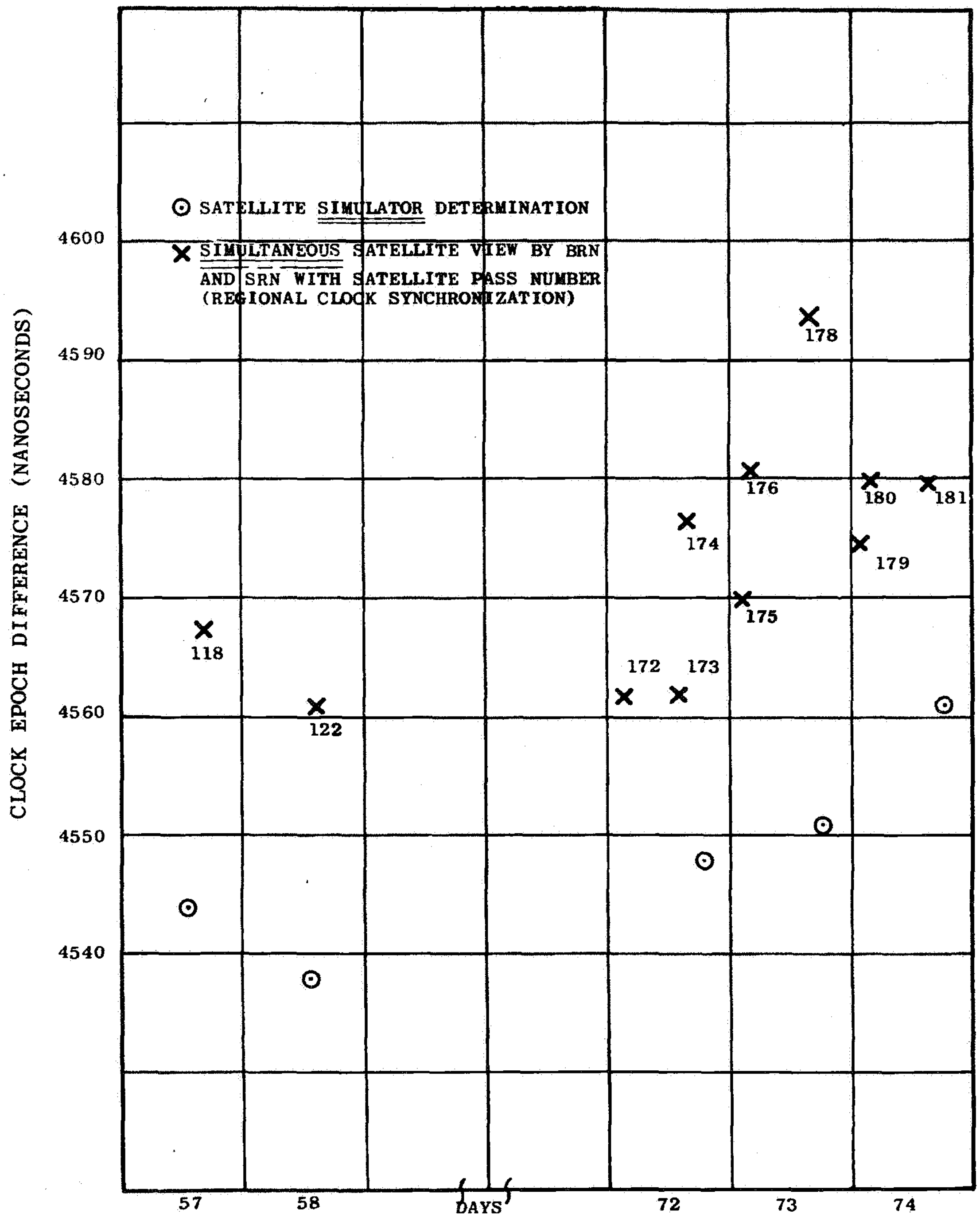

FIG. 3 REGIONAL CLOCK SYNCHRONIZATION DATA

times. The difference between these predicted times and the measured times is the clock epoch difference, determined in the Global Clock Transfer Mode (See Figure 4). The predicted PRN times of transmission from the satellite are based upon estimates of the satellite oscillator frequency drift. The measured TRIAD oscillator frequency between days 72 and 74, 1974 is shown in Figure 5. The largest departure of the measured frequency from a straight line fit was 7×10^{-12} $\left(\frac{\Delta f \text{ diff}}{f}\right)$.

Prediction errors can also be generated by BRN-3 to BRN-3 predictions just like the BRN-3 to SRN-9 predictions (Global Clock Transfer Mode). From such predictions and the data shown in Figure 4, we learn that clock synchronizations on a global basis can be made with errors less than 75 nanoseconds when the time transfers between the satellite and the two clocks being synchronized are made within 100 minutes. The largest error observed during this experiment was 200 nanoseconds for twelve hour prediction times. The mean bias error for the twelve hour predictions was 90 nanoseconds.

One of the purposes of this experiment was to generate the error budget shown in Table 1. This error budget was generated from the data used to generate Figure 4, ephemeris determinations for the TRIAD Satellite, ground equipment noise analysis, and a theoretical study of error sources.

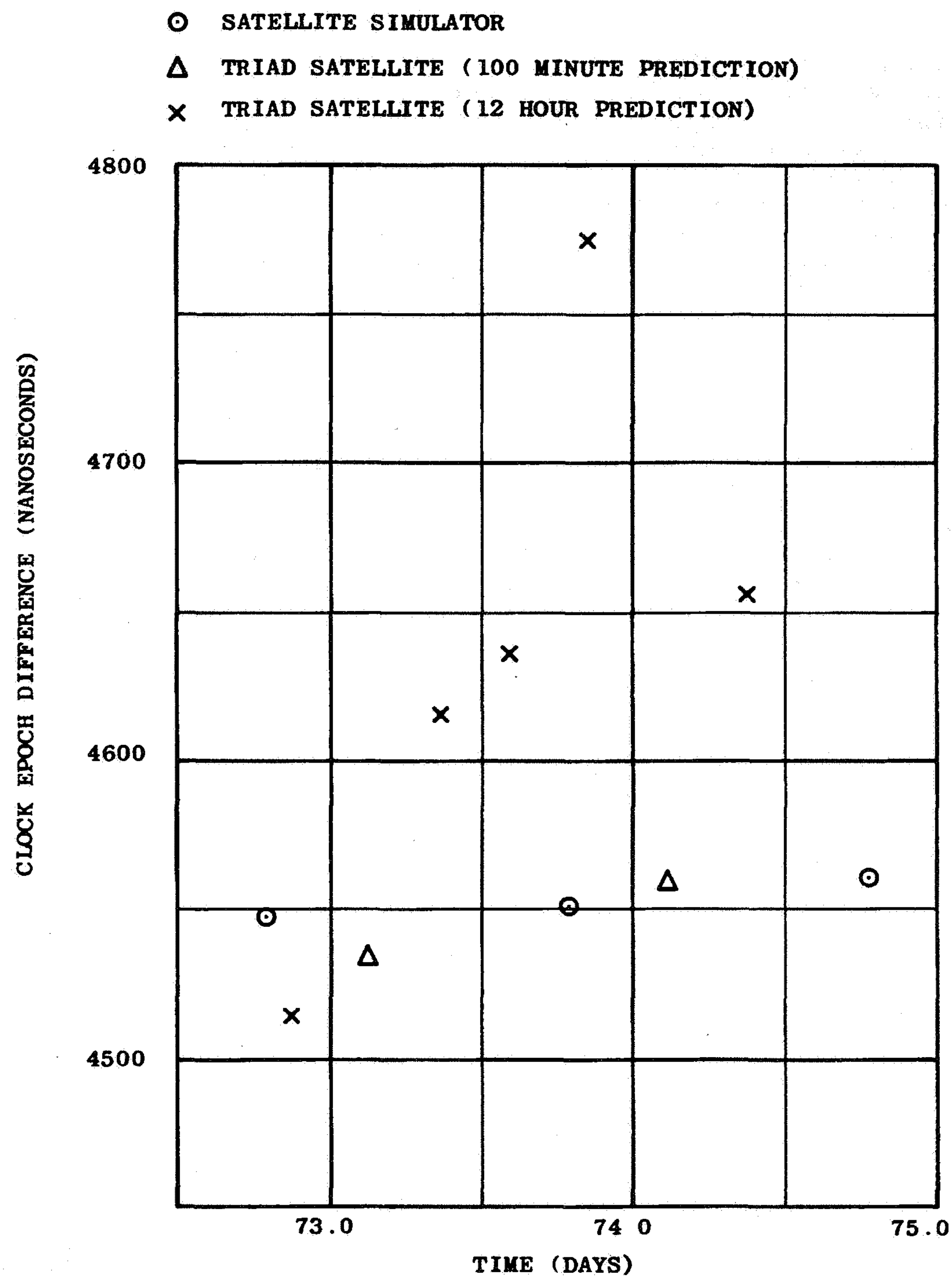

FIG. 4 GLOBAL CLOCK SYNCHRONIZATION DATA

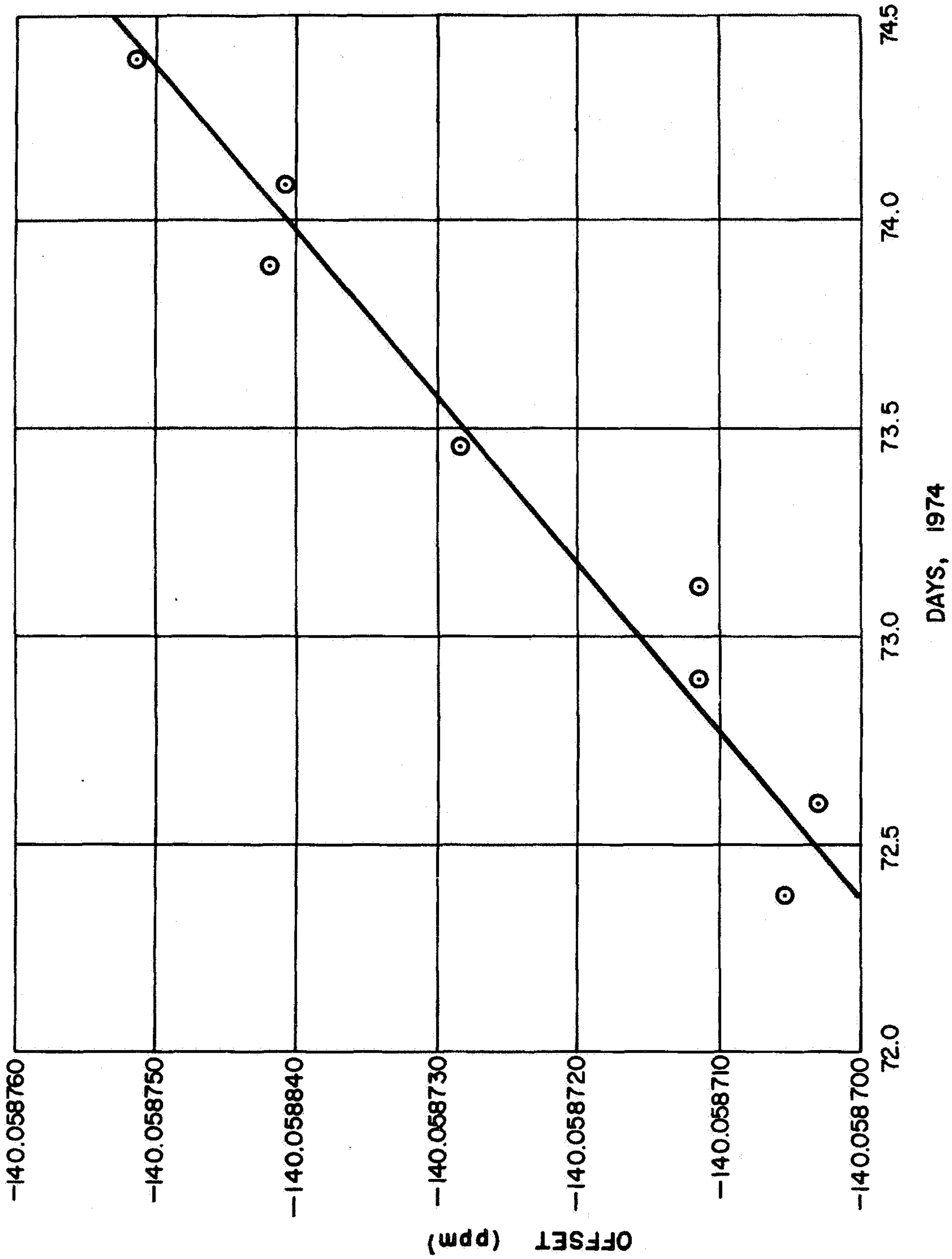

FIG. 5 SATELLITE OSCILLATOR FREQUENCY OFFSET

GLOBAL CLOCK SYNCHRONIZATION
ERROR BUDGET

A.	**Scientific Problems:**	**Time Error**
	1. Satellite Position	~ 75 ns
	2. Refraction	< 30 ns (90% Prediction)
	3. Gravity Red Shift[1]	10 ns
B.	**Engineering Problems:**	
	1. Satellite Oscillator	200 ns/12 hrs.
	2. Receivers (Two)	~ 20 ns

TABLE 1 GLOBAL CLOCK SYNCHRONIZATION ERROR BUDGET

[1]While orbiting the earth, the satellite experiences a varying gravitation field and thus the magnitude of its velocity fluctuates. Because of this, the satellite oscillator frequency changes during each revolution. These fluctuations were not modeled during this experiment, thus they contributed to the error budget.

FUTURE DIRECTION

During the next year experiments involving receivers spread over a greater geographic distribution should be initiated to confirm the indicated global capability. An experiment tying the Naval Observatory to Hawaii would be of great experimental value as the data can be confirmed by an existing active time link. Future satellites are planned which will incorporate the use of PRN modulation on their signal at higher power and with less uncertainty of orbit position. One of the satellites in this series is TIP II, which will broadcast on approximately 2.25 watts CW and PRN component on the 400 MHz channel and the 150 MHz channel will have .9 watts CW and PRN component. This increased power should increase the received signal by approximately 10 dB on the ground. The advantages of TIP II should be the following:

1. Greater frequency stability and frequency control.

2. Higher orbit, thus decreasing the satellite position uncertainties from the gravitational model at least by a factor of two.

3. Stronger signal level decreasing PRN TOD jitter.

ACKNOWLEDGEMENT

Those who planned, organized, built equipment, took data, analyzed results, and contributed to the success of this work are the following: C. W. Anderson, A. G. Bates, R. E. Bateman, E. H. Beck, R. J. Danchik, C. G. DeLoriea, R. E. Dove, R. F. Gavin, G. S. Hartong, E. W. Hix, H. S. Hopfield, E. E. Mengel, E. F. Osborne, E. F. Prozeller, L. J. Rueger, T. A. Schonhoff, B. W. Shaw, R. C. Slegel, R. J. Stellabuto, D. W. Stover, R. R. Yost, and P. A. Zirkle.

APPRECIATION

The author and all those who worked and contributed to the success of this program wish to thank ARPA for the funding which made this research possible.

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4. E. F. Osborne and T. A. Schonhoff, "Delay-Locked Receivers with Phase Sensing of the Correlation (Error) Function". National Telecommunications Conference, Atlanta, Ga., Nov. 1973.

N75 27202

NAVSTAR:

GLOBAL POSITIONING SYSTEM AN EVOLUTIONARY RESEARCH AND DEVELOPMENT PROGRAM

By: Col. B. W. Parkinson
U.S. Air Force
Space and Missile Systems Organization

ABSTRACT

The Global Positioning System has recently been renamed the NAVSTAR Global Positioning System. It was known as System 621B or Defense Navigation Satellite System, and within the Navy it was known as TIMATION. NAVSTAR represents a combination of the concepts that were known as TIMATION and those knonw as System 621B into a Joint Program. This combination was directed by Secretary Clements on 17 April 1973. A DSARC review was held on the 13th of December and a final decision was made to approve this program on the 22nd of December by Secretary Clements. NAVSTAR is a multi-service program (See Figure 1) with the Joint Program Office at SAMSO which is proceeding into its Phase I Concept Validation Program. I would like to describe the system and the Concept Validation Program with you at this time.

The current status of satellite navigation systems within DOD is described in Figure 2. The existing operational system is called TRANSIT. For a host of reasons, it does not satisfy a broad base of users (See Figure 3). Particularly, anyone with dynamics in their positioning or navigation problem. Therefore, we are motivated to move ahead to a Global Positioning System that potentially can eventually replace TRANSIT and serve a host of other users as well (See Figures 4 and 5). The initial operational capability would be achieved in about 1984. The Phase I Program incorporates the efforts of the Naval Research Laboratory, with their Navigation Technology Satellites (NTS), NTS-1 and NTS-2. The Joint Program Office will develop prototype Navigation Development Satellites (NDS) that will be described later. The basic system capability is three dimensions of position, three dimensions of velocity and very precise system time.

I'd like to now discuss that systems concept which consists of a Space Segment, a ground based Control Segment, and the User Segment (See Figure 6). The operational system would

GPS ORGANIZATION

JOINT PROGRAM MANAGER	COL B. W. PARKINSON
DEPUTY PROGRAM MANAGERS	
AIR FORCE	LTC S. W. GILBERT
AFLC	MAJ R. O. BYRNE
ARMY	LTC P. WEBER
DEFENSE MAPPING AGENCY	MR P. E. FREY
MARINE CORPS	LTC J. BARRY
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FIG 1

DOD NAVIGATION SATELLITE SYSTEMS

OPERATIONAL GPS OBJECTIVES

- PRECISE GLOBAL NAVIGATION CAPABILITY
  - 3 DIMENSIONAL LOCATION
  - 3 DIMENSIONAL VELOCITY
  - TIME

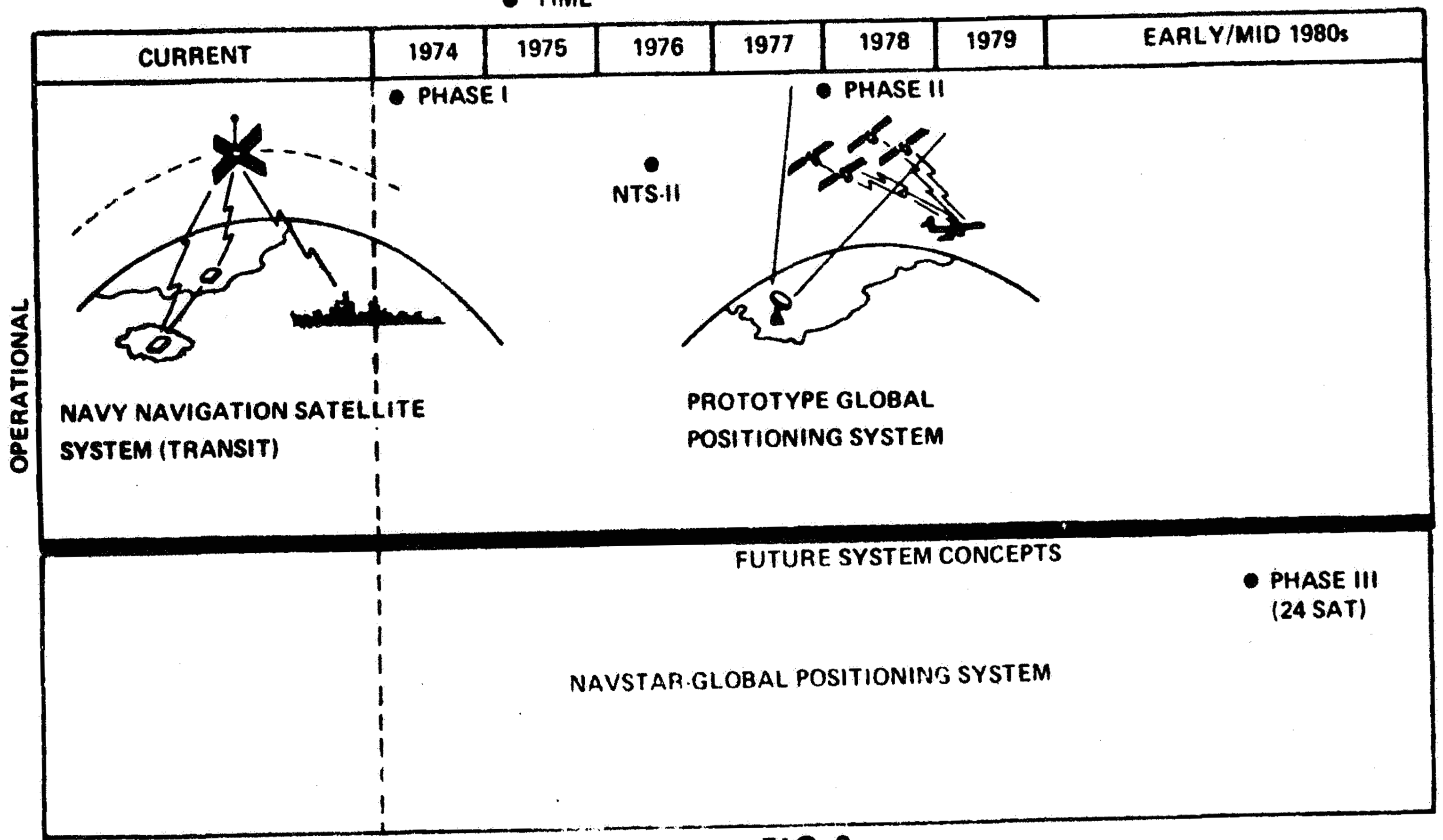


FIG 2

THE NEED FOR A UNIVERSAL NAVIGATION SYSTEM

- UNIVERSAL PERFORMANCE

  INCREASE EFFECTIVENESS & CAPABILITY

- LOWER COST

  REDUCE PROLIFERATION OF POS/NAV SYSTEM[S]

FIG 3

AIRCRAFT NAVIGATION AVIONICS

AIRCRAFT TYPE	NAVIGATION				
	TCN	LRN	ILS	DF	VOR
AIE	X		X	X	X
A7A/D		X	X	X	
B52	X	X	X	X	X
C5	X	X	X	X	X
C7A	X		X	X	X
C119	X	X	X	X	X
C123	X	X	X	X	X
C124	X	X	X	X	X
C130	X	X	X	X	X
KC135	X	X	X	X	X
C141	X	X	X	X	X
F4C/E	X			X	
F4D/RF4C	X	X		X	
F102	X		X	X	X
F104	X		X		X
F105		FEW	X	X	X
F106A/B	X		X	X	
F111				X	
OV10A				X	
NO. DIFF. TYPES	(9)	(10)	(23)	(21)	(8)

FIG 4

NAVIGATION AVIONICS COSTS

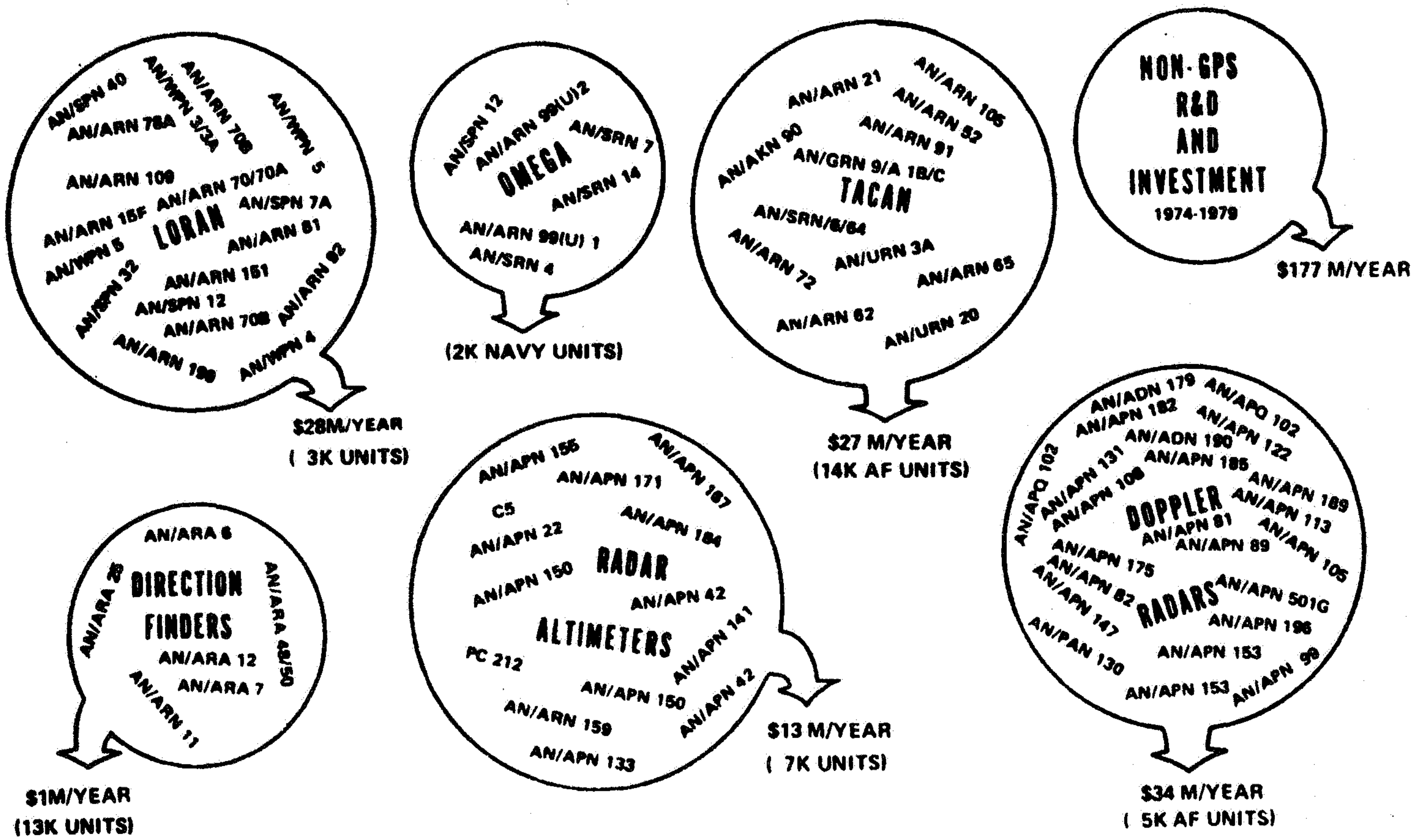


FIG 5

470

GPS CONCEPT

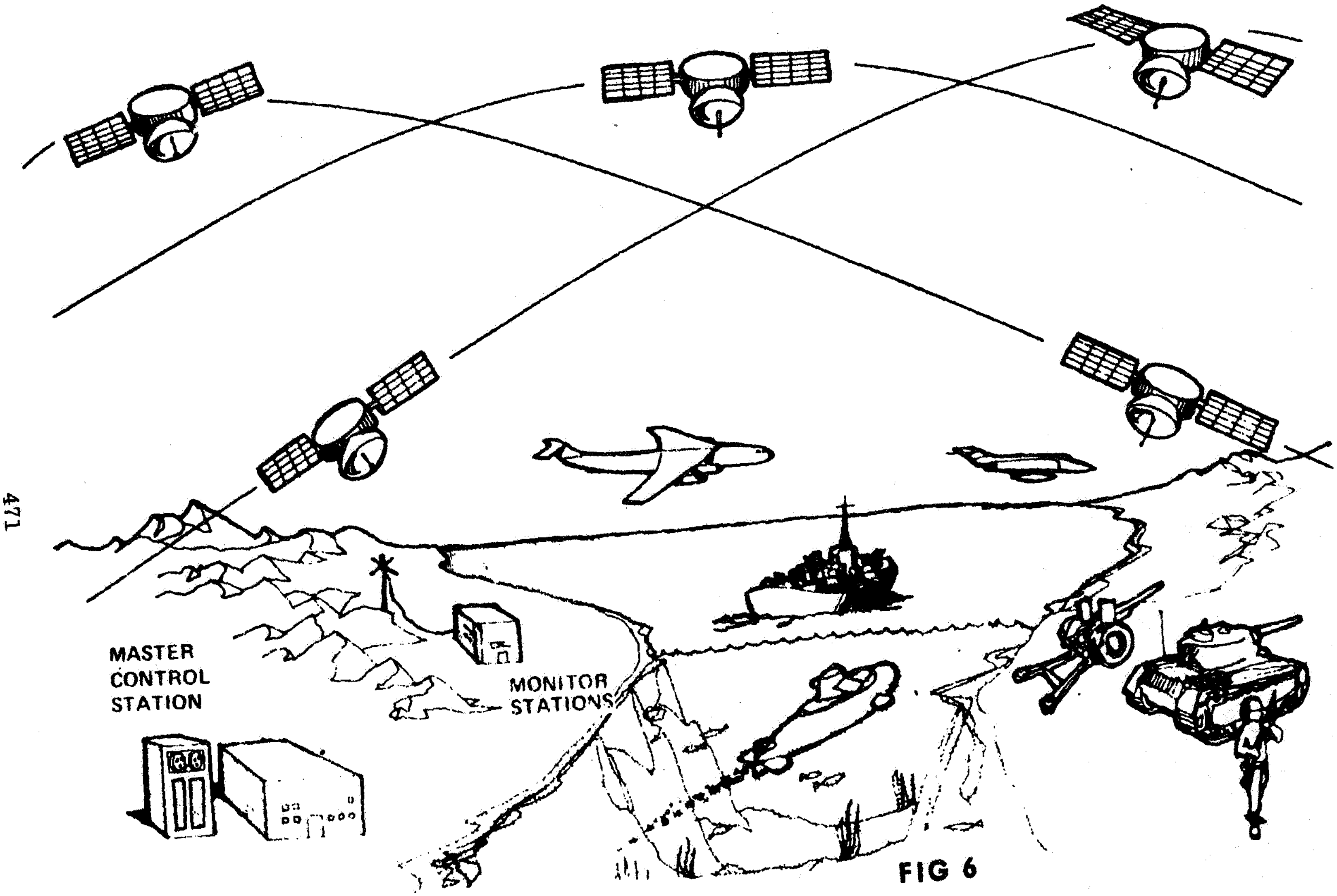


FIG 6

deploy three planes of satellites in circular, 10,000 nautical mile orbits with an inclination of 63°. Each plane would contain eight satellites. This deployment insures that at least six satellites are continuously in view from any point on the earth. The Master Control Station would be located in the United States with four monitor stations located on United States territory. The user equipment classes would satisfy a host of DOD users and will also be offered to the civilian community. We expect the spacecraft weight to be 800 pounds, with 300 watts end-of-life power. It would employ a dual-frequency pseudo-random noise navigation signal. For general use, only the primary NAV signal at 1600 MHz would be used. The basic tracking technique for the Control Segment is one-way tracking. A unique feature of the system is that the satellite employs an atomic spaceborne clock. We are projecting an operational clock of about 10^{-13} seconds per second drift rate. This is the state-of-the-art for cesium clocks as exemplified by the Hewlett-Packard Laboratory standards.

The basic system technique is described in Figure 7. The Control Segment tracks the satellites and predicts their future position as well as the future behavior of these clocks. It periodically uploads that information into the satellite's memory. The satellites continuously transmit their signal which is a spread-spectrum L-Band signal with a 10 MHz chipping rate and a 20 MHz bandwidth. If a user has a clock which is synchronized to these satellite clocks, he can measure the time difference between transmission and reception. This is then multiplied by the speed of light to find the range. Thus, contact with three of these satellites would determine three spheres and his location would be at the intersection of those three speres. Unfortunately, the assumption of the user's synchronized clock would be very expensive. To satisfy that problem, he listens to a fourth satellite, thereby giving him four pieces of information from which he derives three coordinates of position and one coordinate of time. This really represents synchronizing his very crude, by flight qualified atomic standards, crystal-based clock. So the basic technique of listening to four satellites to derive the user's coordinates is more economically attractive.

The orbital configuration for the operational system is depicted in greater detail in Figure 8. There will be three orbital planes, each inclined approximately 63° to

System Technique

PSEUDO-RANGING TO FOUR SATELLITES

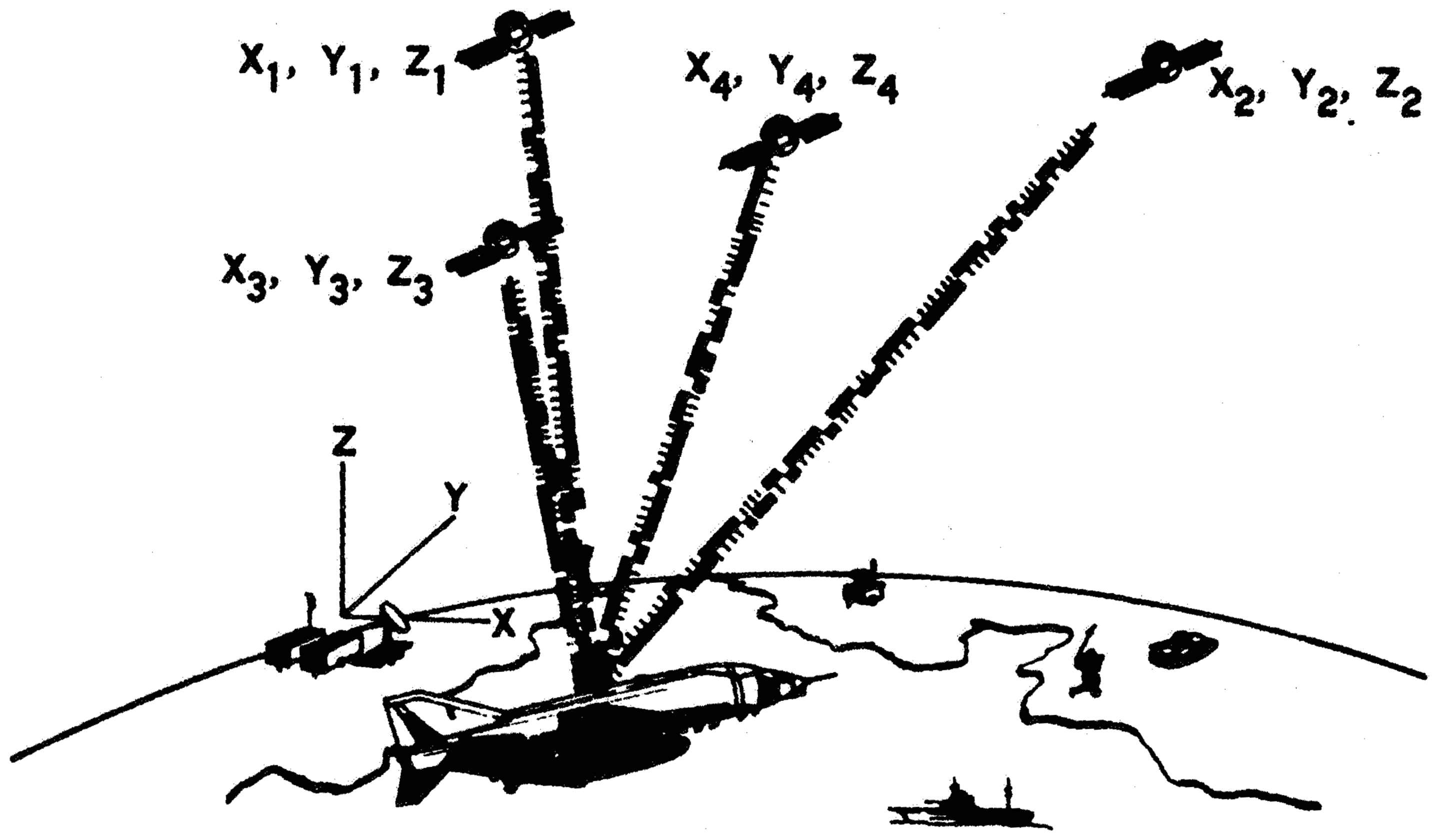
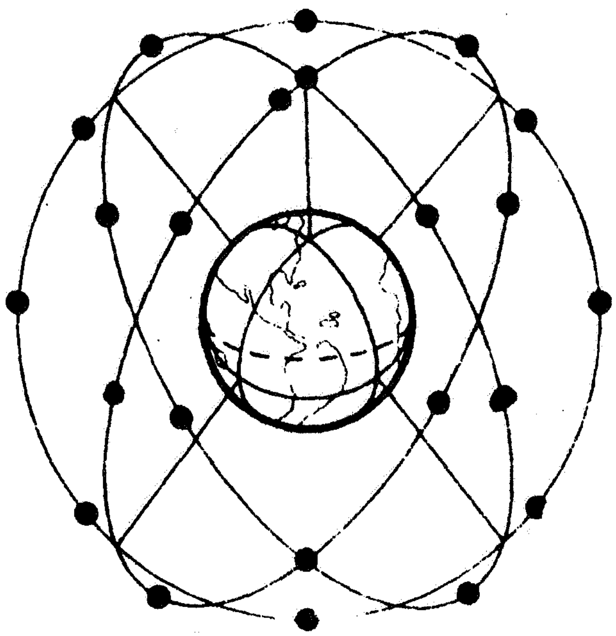


FIG 7

ORBITAL CONFIGURATION



SPACECRAFT CONFIGURATION

PHASE 1	OPERATIONAL
6 SATS	24 SATS
800 LBS	900 LBS
400 WATTS	450 WATTS
NAV. SIGNALS	
–1200 MHZ	SAME
–1600 MHZ	SAME
ONE WAY TRACKING	SAME
10^{-12} CLOCK STABILITY	10^{-13} CLOCK STABILITY

FIG 8

the equator. The 24 satellites will have an orbital period of 12 hours. This will give a minimum of six satellites in view continuously at all global locations and on the average there will be 8 or 9 satellites in view. Approximate upper bounds on the satellite weight and power as well as other spacecraft parameters are listed on the right.

The baseline global positioning system will rely on Master Stations in the United States only (See Figure 9, 10 and 11). The Master Station and computing facilities will be located at one of several alternative locations, each of which already has a computing facility or a spacecraft control and telemetry system. During the first phase of development, overseas Monitor Stations would be used to help develop the worldwide ionospheric model.

We don't require the accurate clocks in any of these applications. It's cheaper for everyone to simply listen to four satellites. In fact, the user who knows his altitude can get by with just listening to three satellites, and again, he doesn't have to have an accurate clock. Even a user with a cesium clock would get out of synchronization by the end of a week. That is, the navigation function would be somewhat impaired, if the requirement was for 100 foot accuracy. If that's not a problem, he can get by with a three-channel receiver, for example, and at a potential cost saving. On the other hand, it may be to your advantage to listen to all four satellites and synchronize your cesium clock to a world-wide standard.

The six user classes that we project in the operational system are portrayed in Figure 12. These are the major classes with the cost of user equipment for unit buys in thousands of dollars. Class A is for the dynamic user in a potentially high jamming environment that demands the ultimate in precision. The two parellel definition efforts that we undertook have estimated the costs to be between $28,000 and $29,500. Class B is for the high dynamic user. Class C is an interesting class. Here we're addressing low acquisition cost with Low Life Cycle cost as well. The range we now project for a complete piece of Class C user equipment is $15,000 to $16,000. Class D is for surface vehicles.

Class E is a man-pack which also has applications for

CONTROL SYSTEM SEGMENT EQUIPMENT

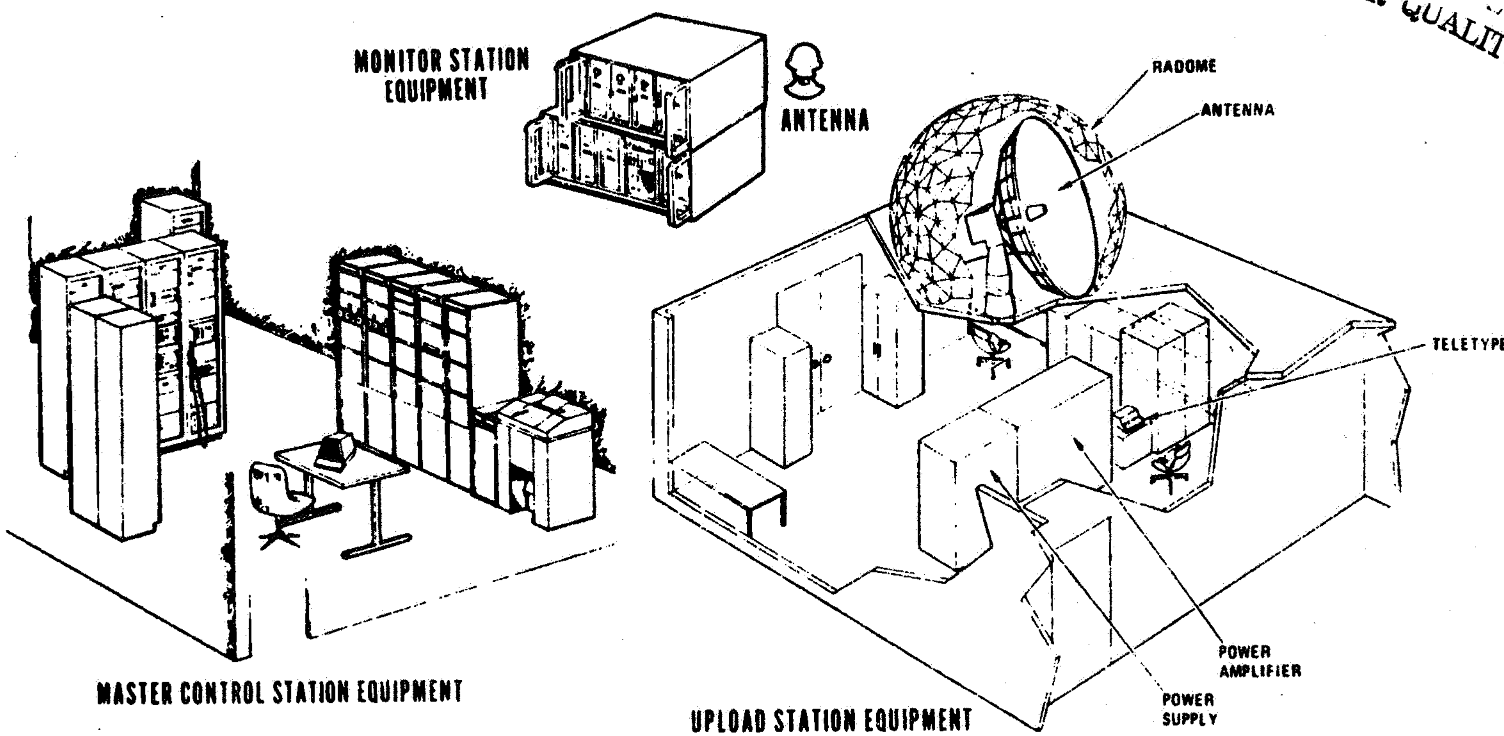


FIG 9

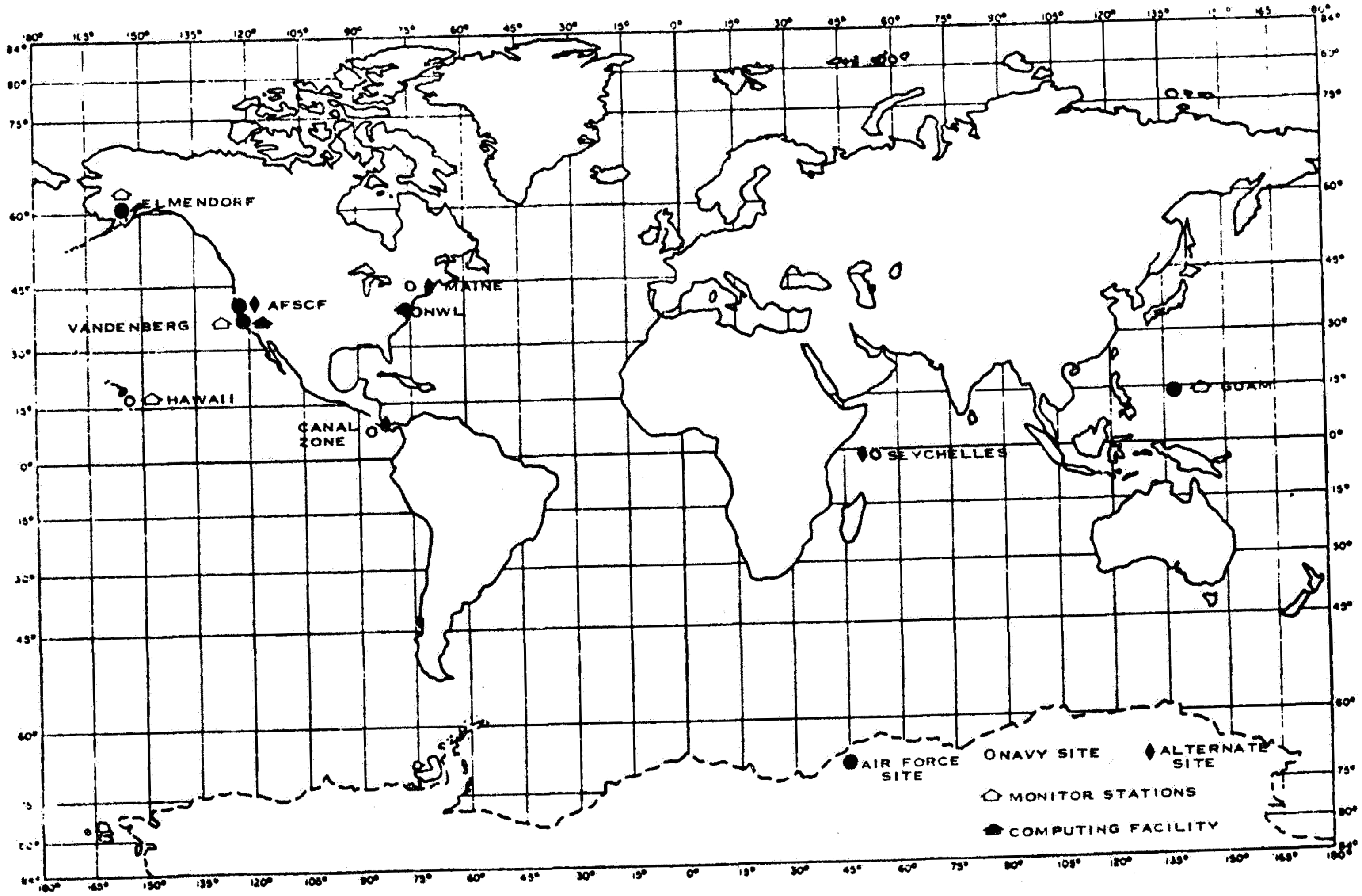

ELMENDORF
AFSCF
VANDENBERG
MAINE
NWL
HAWAII
CANAL ZONE
SEYCHELLES
GUAM
AIR FORCE SITE
NAVY SITE
ALTERNATE SITE
MONITOR STATIONS
COMPUTING FACILITY

FIG 10

BASELINE USER EQUIPMENT

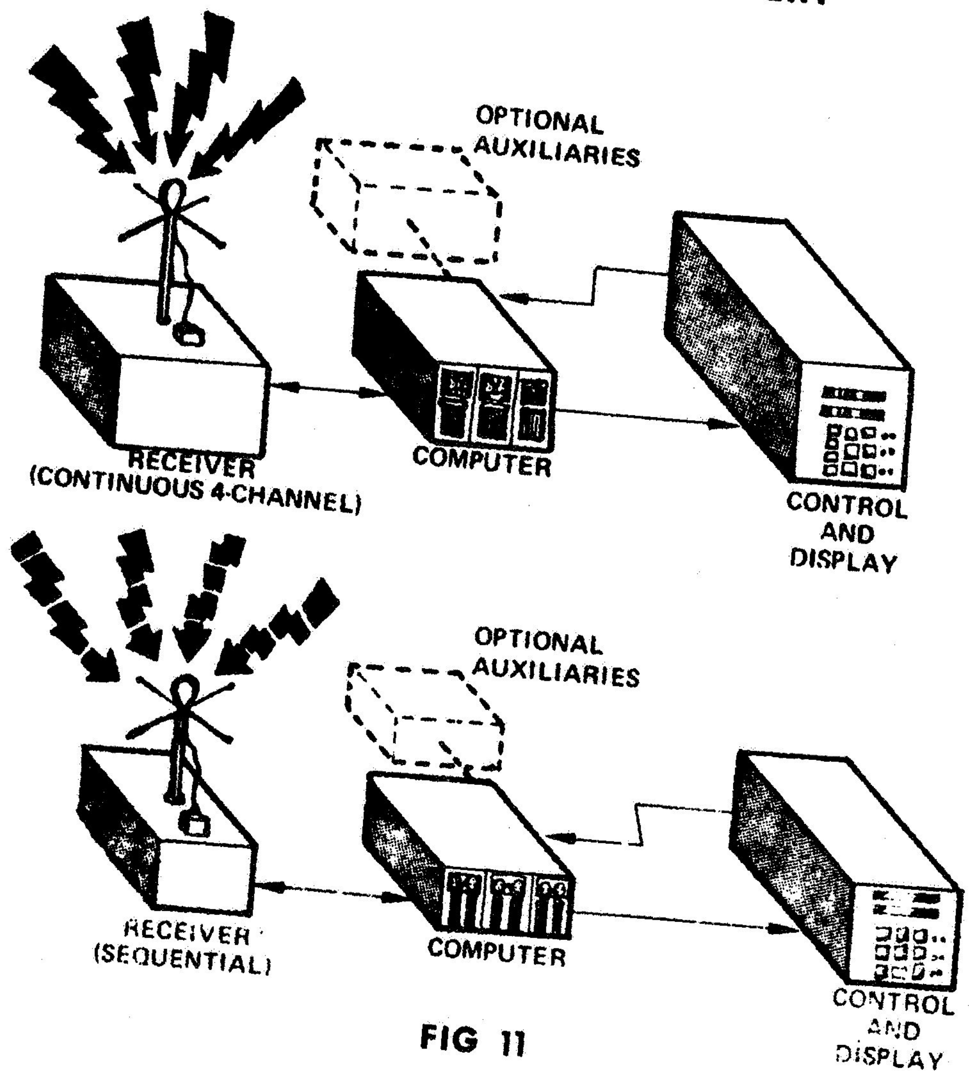


FIG 11

GPS User Classes

1000 UNIT BUY DOLLARS IN $1,000

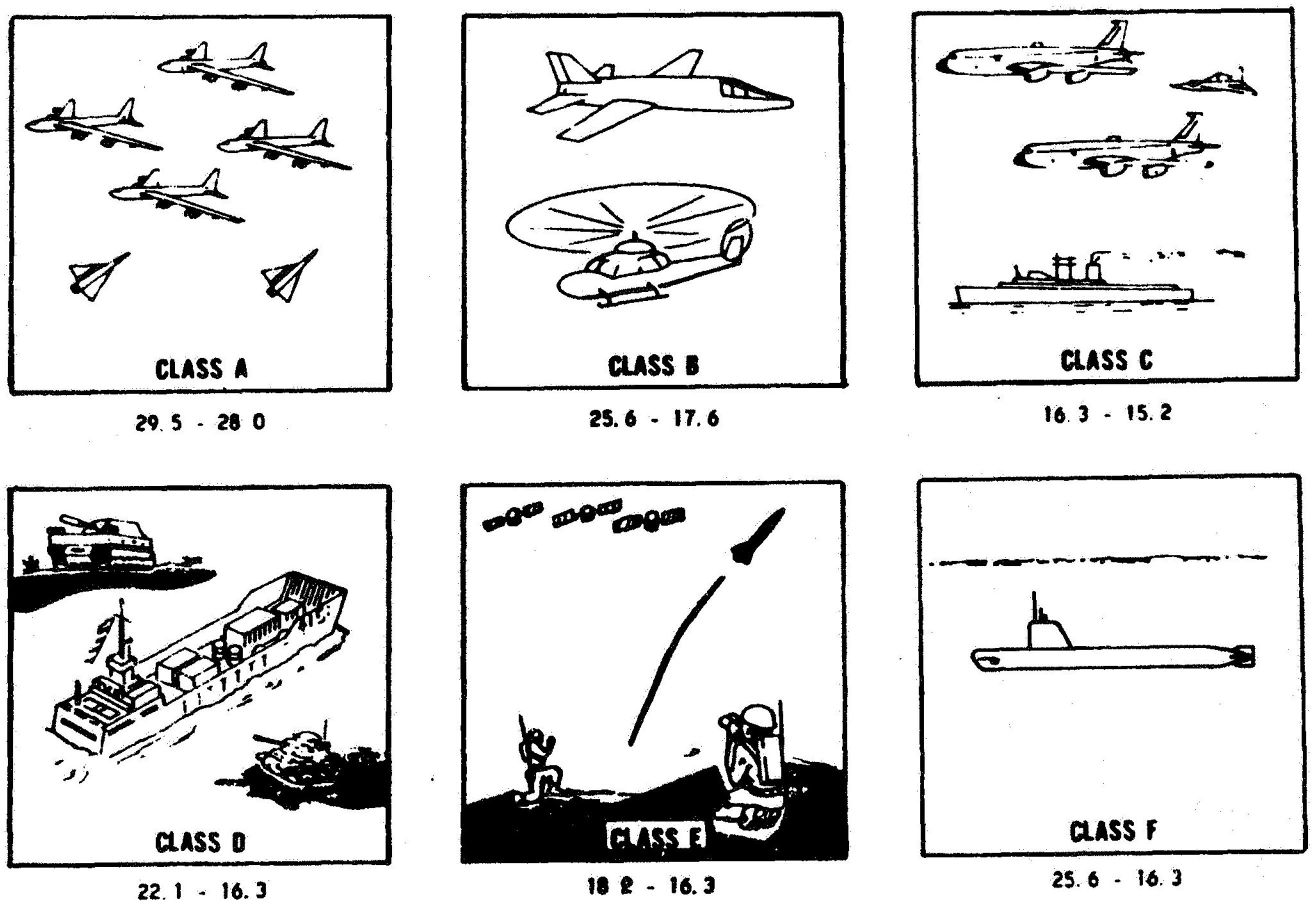


FIG 12

self-navigation of satellites. It also has application to the midcourse guidance of missiles because it is small, light weight and rugged. Class F is for submarines. Further consolidation efforts seem possible with savings to DOD by reducing logistic requirements.

In Figure 13 is shown the expected system accuracy for the mature operational system. Fifty percent of the time in the horizontal plane it is 16 feet; and in the vertical plane it is 20 feet. These figures are the result of extensive simulations by The Aerospace Corporation in Los Angeles, The Analytical Sciences Corporation in Massachusetts as well as the Naval Weapons Laboratory, who have performed analysis of the TRANSIT program. In fact, we intend to use the Naval Weapons Laboratory orbit determination in our ephemeris determination.

This is an unclassified system except for two aspects. The measured performance capability of the full-up system would be Confidential. The quantitative evaluation of survivability/vulnerability will be Secret. The projections I'm showing you are not classified. We have done our best to make this system as unclassified as we can. It makes it a lot easier to develop the system. As soon as the first person gets a piece of user equipment, the capability of the system would be pretty obvious. We didn't see much point in needlessly over classifying it.

The characteristics of the system I've described are very interesting, (See Figure 14) giving accurate three-dimensional position as well as velocity. The velocity is considerably better than a foot a second. These accuracies are available as a world-wide common grid. As a result of having the pseudo-random noise transmission, the system has the ability to be made secure and have a good anti-jam capability. It is passive with a continuous readout system available instantaneously to every user. It is unsaturable and therefore can service any number of users.

We are also addressing life cycle cost very early in the development. We have had a Deputy Program Manager for Logistics since the beginning of this program, and our efforts in that direction I think are significant.

The applications are very wide ranging from precision weapons delivery through search and rescue, (See Figure 15).

EXPECTED GLOBAL POSITIONING SYSTEM ACCURACY

	HORIZONTAL	VERTICAL
50% OF TIME	5m	7m
90% OF TIME	8m	10m

FIG 13

UNIVERSAL POSITIONING SYSTEM CHARACTERISTICS

- ACCURATE 3 DIMENSIONAL POSITION & VELOCITY
- WORLD WIDE COMMON GRID
- SECURE/AJ CAPABILITY
- PASSIVE & ALL WEATHER OPERATION
- REAL-TIME CONTINUOUS
- UNSATURABLE
- LOW LIFE CYCLE COST
    - SYSTEM
    - USER

FIG 14

GLOBAL POSITIONING SYSTEM
APPLICATIONS

MISSIONS	SPECIAL USES
● LAND	
● TROOP MOVEMENT ● CONVOY ● ARMOR ● MOBILE ARTILLERY ● GEODESY	● ARTILLERY SURVEY ● FIRE SUPPORT ● TROOPS IN CONTACT ● CLANDESTINE FORCES
● SEA	
● PATROL ● PASSIVE RENDEZVOUS ● TASK FORCE OPERATIONS ● HARBOR CONTROL	● SSBN ● ASW ● SAR ● PILOTAGE ● BUOY/SHOAL/REEF LOCATIONS ● BEACH HEAD
● AIR	
● CLOSE AIR SUPPORT ● FERRYING ● TACTICAL DEPLOYMENT ● REFUELING ● RECONNAISSANCE ● APPROACH/LANDING	● BLIND/VISUAL AIDED BOMBING ● MISSILE INITIALIZATION/INERTIAL UPDATE ● MIDCOURSE GUIDANCE ● CARP/HARP ● RPV/RCV ● BARE BASE
● SPACE	
● SATELLITE EPHEMERIS ● SPACE VEHICLE POSITION	● SPACE TRANSPORTATION SYSTEM ● SATELLITE TRACKING
● SPECIAL OPERATIONS	
● INTELLIGENCE ● RANGE INSTRUMENTATION	● PASSIVE ELINT ● PHOTO RECCE/MAPPING ● TARGETING ● SENSOR IMPLACEMENT ● COR/WEAPON SYSTEM TEST SCORING

FIG 15

We recently briefed the Commandant of the Coast Guard and some of his staff, and they suggested some additional applications that we had not previsouly considered. In the area of pilotage they were very interested in the man-pack. They suggested that the harbor pilot arrive onboard ship with a man-pack which gives him both position and velocity.

He can take it to the bridge and simply read out the coordinates of the ship as it is coming into the harbor and thereby be able to navigate in fog or darkness without any difficulty. There is an application in Anti-Submarine Warfare (ASW) in which the Navy is very interested.

Now, I want to briefly describe the results of the Holloman Test program (See Figure 16). Holloman tests were conceived as a simulation of the satellite system. Four L-Band pseudo-random noise spread-spectrum transmitters were placed on the desert floor. The mobile calibration station was also placed there which has the same function as a tracking station, but it was only tracking the clock in this case, because of course, the transmitters weren't moving. We placed two competing types of receivers in a C-135 and overflew this complex. We recorded their inputs and then compared that with the location of the airplane as determined by the White Sands Missile Range Tracking complex.

The comparisons that you see in Figure 17 are comparisons between NAVSTAR-indicated aircraft location and the location as assessed by the White Sands Missile Range Tracking complex. The test simulates satellite-type geometry from about 40 to 120 seconds on the graph. I have three axis of data, up, north and east. Again, it is a 3-D system - zero to fifty feet.

To show that these weren't simply pathological results, here is the cumulative distribution as a percent of time. Errors were measured through this area navigation test for each of the competing receivers (See Figure 18). Ninety percent of the time, the Magnavox receiver on all three axis was within about 15 feet and 90 percent of the time the Hazeltine receiver was within about 22 feet. This is a summary of the test results which demonstrated performance of both continuous and sequential receivers. I didn't show you the velocity comparison, but it demonstrated accuracies which were better than a foot per second. We also ran a

USER EQUIPMENT DEFINITION AND EXPERIMENTS PROGRAM

HOLLOMAN AFB - WHITE SANDS MISSILE RANGE

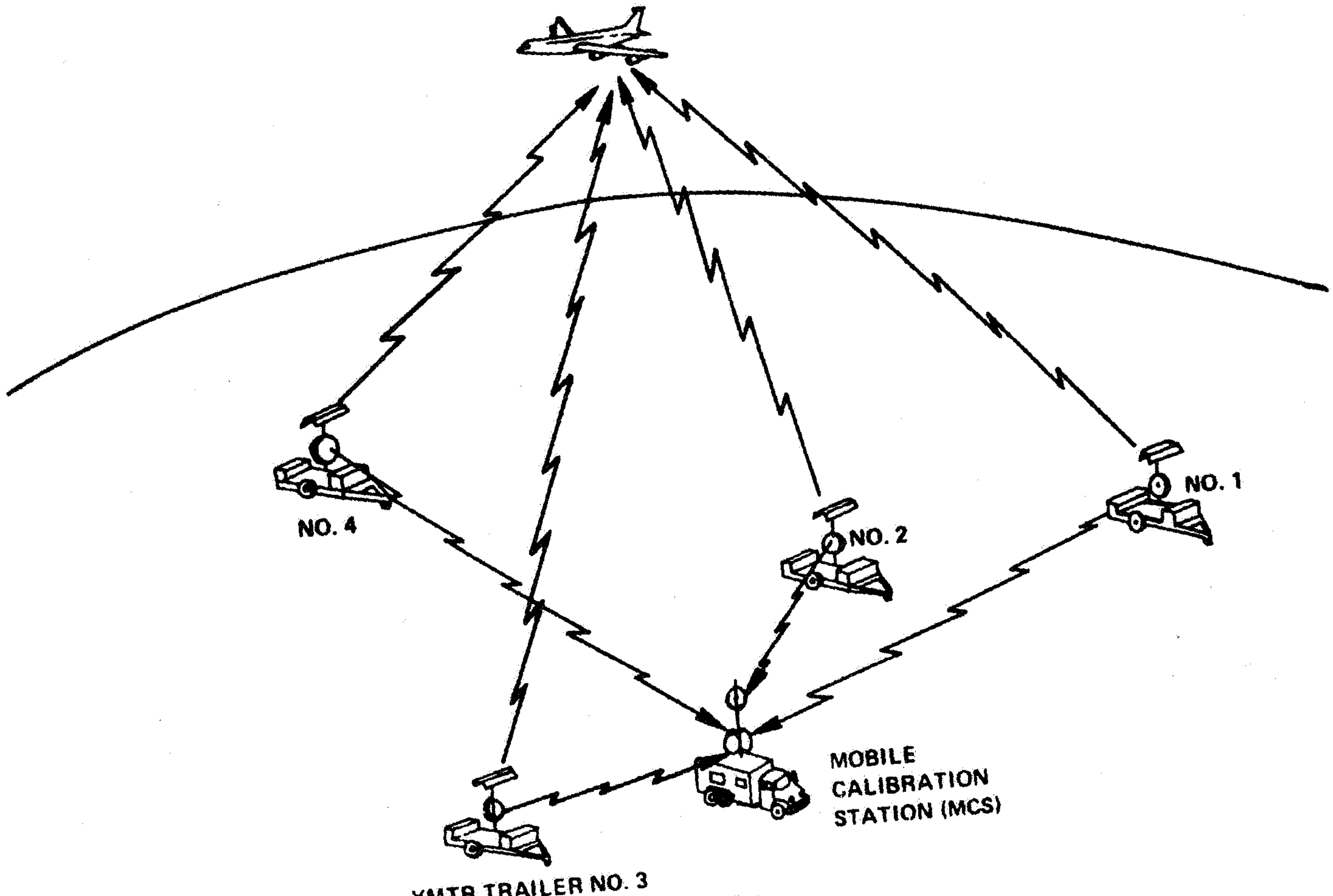


FIG 16

HAFB FLIGHT TEST
POSITION RESULTS AREA NAV

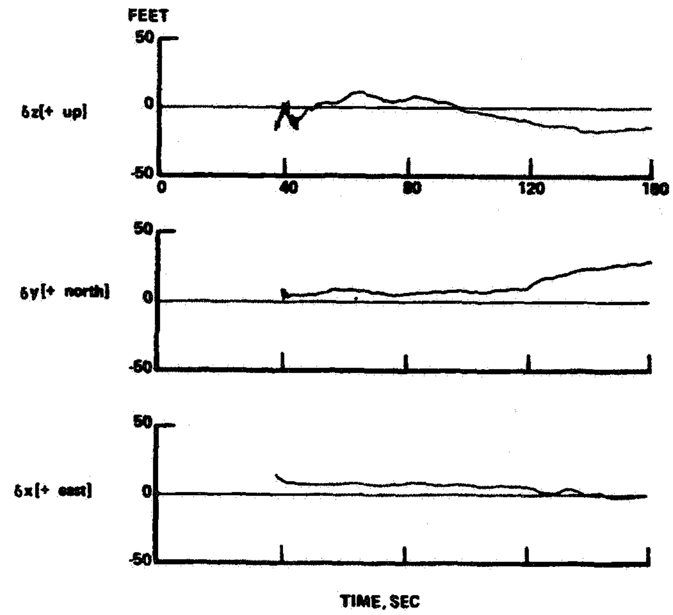


FIG 17

CUMULATIVE DISTRIBUTION OF POSITION ERRORS (AREA NAV TEST)

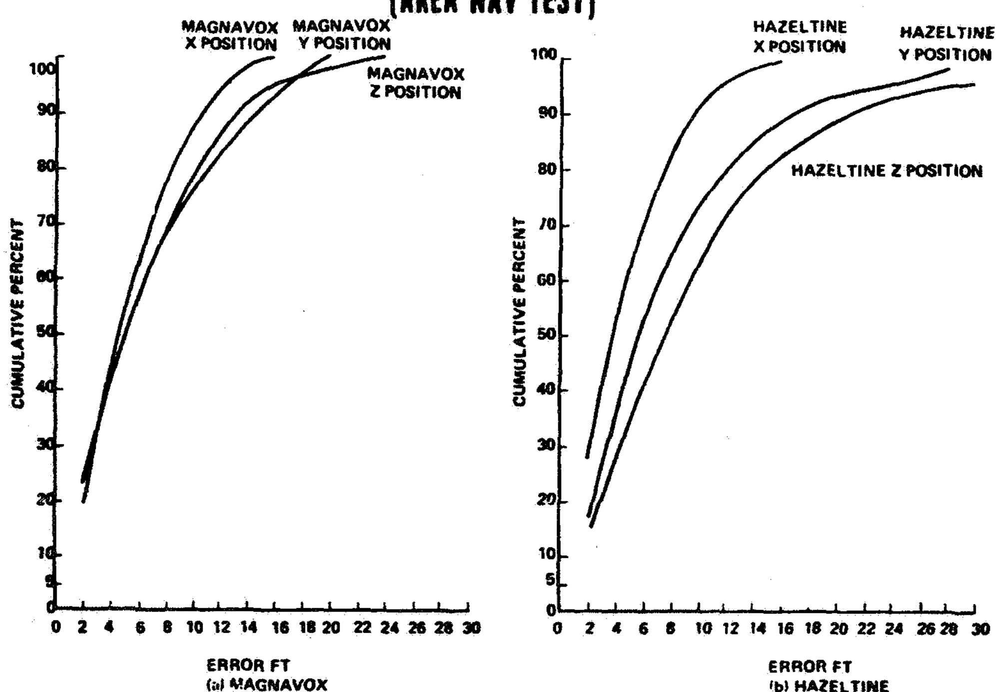


FIG 18

second series of tests which were called our ILS tests. In this test we were flying approaches to the runway as shown in Figure 19.

For this ILS purpose, our position accuracy is better than 5 feet (See Figure 20). One of the more important results here is engineering feedback to the next generation of receiver design.

The major test results are summarized in Figure 21. The Holloman Tests verified the system error budget through actual flight tests. Both continuous and sequential receivers were demonstrated. The continuous receiver simultaneously receives the navigation signals from four satellites; the sequential receiver listens to the satellites one at a time. Accuracies better than 15 feet in position and 1 FT/SEC in velocity were achieved. The most significant result is that data is already available to feed into user equipment design improvements.

The first phase of this program to arrive at a Global Positioning System is a Concept Validation Phase (See Figure 22). Its objectives are four-fold: to be certain that the basic concept is sound; to make such adjustments in that concept as necessary to get to the best design; to pin down the system cost, both for the user considering life cycle cost, and the cost of overhead; and, to demonstrate the military value in selected operations demonstrations.

The method of achieving these objectives will also evolve into the operational system (See Figure 23). This will be done using prototype operational satellites deployed in operational orbits with five satellites developed by the Global Positioning System Program Office. For the sixth satellite, we're relying on the Naval Research Laboratory to put up a follow-on experimental satellite (NTS-2) which would also have our signal structure on board. By time-phasing these six satellites to arrive over the test area, we get up to three hours of good geometry. This permits very good development tests for the receivers we will be developing. The Master Control Station will be a prototype of the Operational Master Station. The Monitor Stations, which are really no more than a piece of user equipment, would be prototypes of the operational system as well. We have a program for developing user equipment for all the user classes shown. It's an orderly phased approach that

ILS APPROACH TESTS

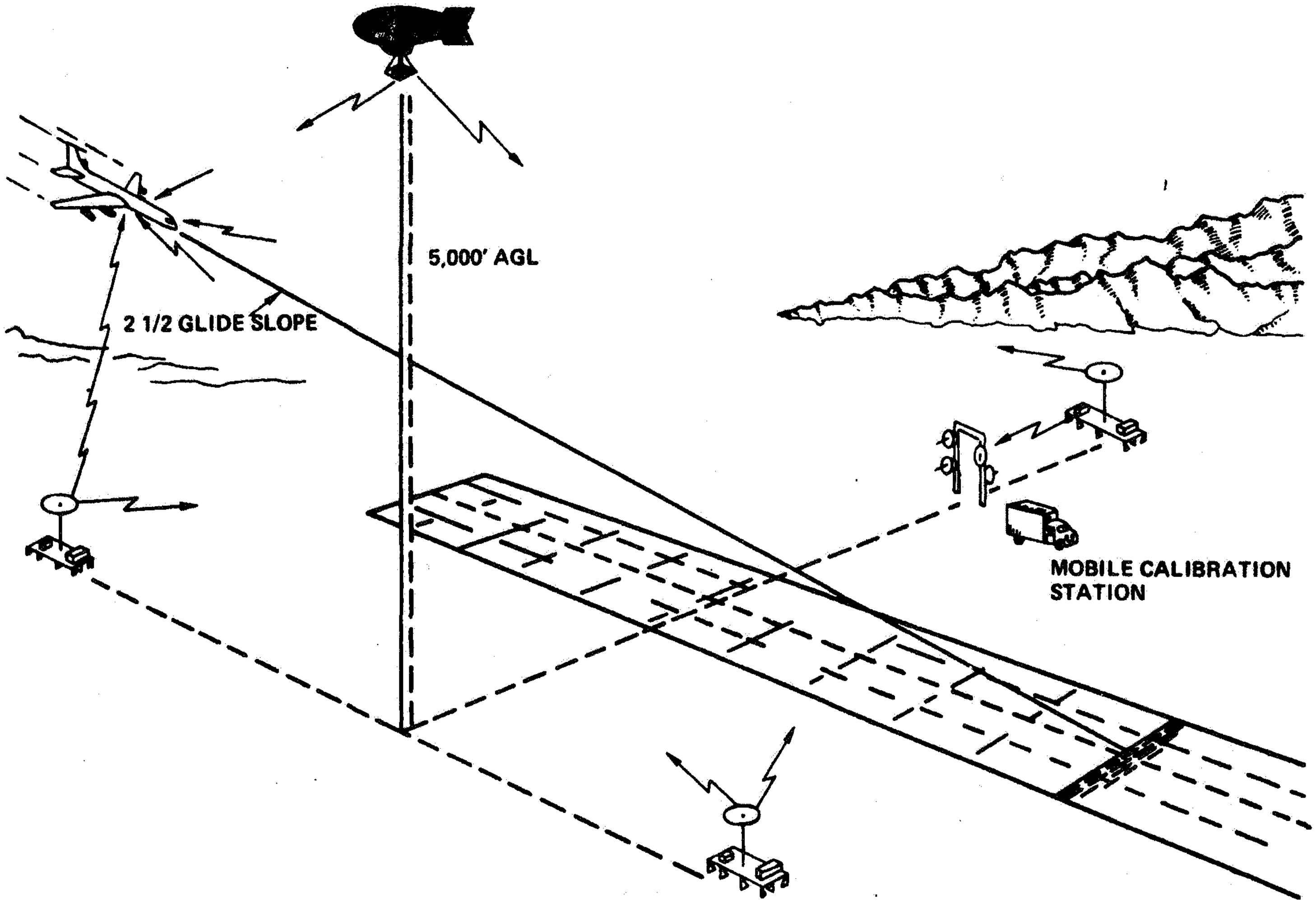


FIG 19 TRANSMITTER SITE

HAFB FLIGHT TESTS TYPICAL ILS RESULTS

11 STATE FILTER SOLUTION WITH INITIALIZATION

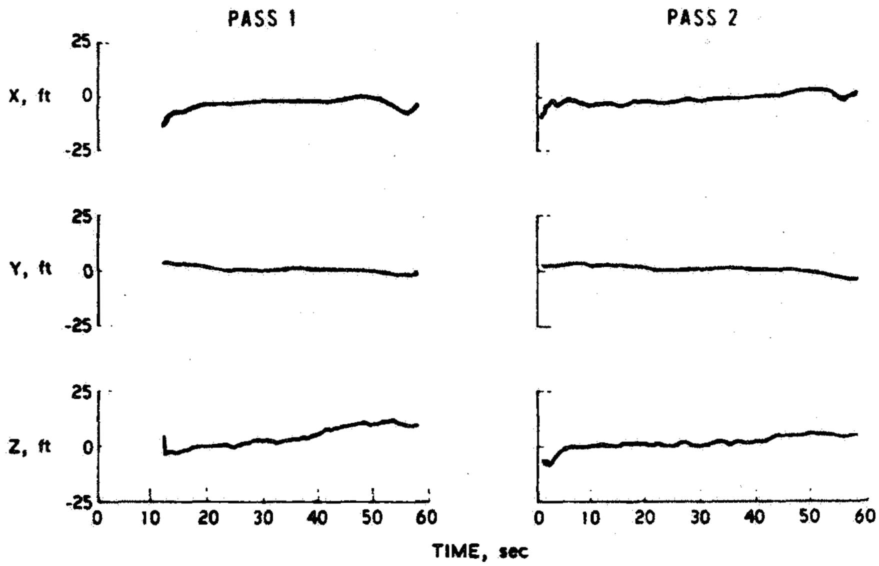


FIG 20

TEST RESULTS

HOLLOMAN NAVSAT SIMULATION/INI

- DEMONSTRATED PERFORMANCE OF BOTH CONTINUOUS & SEQUENTIAL RECEIVERS
- CONTINUOUS RECEIVER ACCURACIES

• AREA NAV	–	POSITION:	LESS THAN 15 FEET
	–	VELOCITY:	LESS THAN 1 FOOT/SECOND
• ILS	–	POSITION:	LESS THAN 5 FEET

- ENGINEERING FEEDBACK TO THE DESIGN

FIG 21

GPS VALIDATION PROGRAM OBJECTIVE

PROVIDE INFORMATION TO MAKE THE NEXT DECISION

- VALIDATE THE GPS CONCEPT
- VALIDATE THE PREFERRED DESIGN
- DEFINE SYSTEM COSTS
- DEMONSTRATE MILITARY VALUE

FIG 22

GPS-PHASE 1

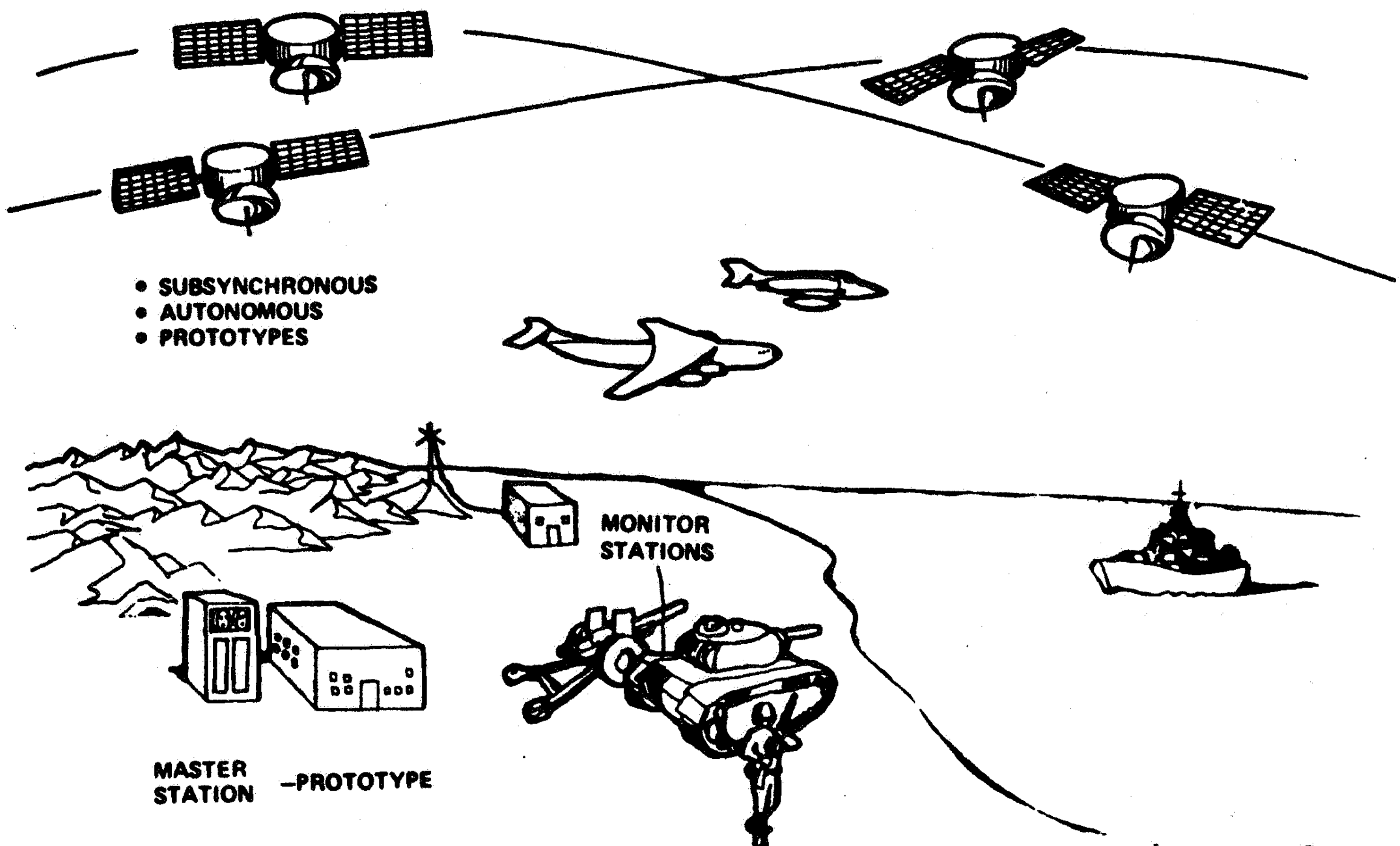


FIG 23

first goes through advanced development models and then proceeds into engineering development.

The orbital configuration by phases evolves into our total capability as shown in Figure 24. Phase I has the five satellites that I've just described, with a sixth one from the Naval Research Laboratory. Phase II, which would begin with a DSARC II decision, augments these satellites out to three satellites in each of three rings. Fully operational spacing time phases arrival over the test area, and gives us a full operational test for about eighteen months. At the end of that period, which would be about 1981, we reposition these satellites, spacing them uniformly in their orbits giving us a world-wide, continuous, limited operational capability. That means that there is a line of position available for anyone at all times instantaneously. As a matter of fact, eighty percent of the time, the user who knows his altitude can get a complete fix. This is a very significant capability, and I think makes a real step forward in terms of the program legacy.

In Figure 25 is shown the program schedule by calendar year. The first evolutionary step was approved with DSARC I in December. It is a Concept Validation Phase, with the user equipment split into two broad categories: the low-cost user (which is designated as Class C) and the more sophisticated classes. In Phase I the low-cost receiver will progress into a prototyping status. The sophisticated user will be lagging slightly, still being in the development status during Phase I. In 1978 we complete development test and evaluation. The satellites to support it are the six that I've just described. The Ground Control Segment moves forward as a prototype. Our system capability, initially, would be ground testing using a simulated satellite complex we developed at Holloman Air Force Base and then proceeding on with periodic 3-D capability as the four satellites arrive over our test area.

Phase II is the system validation phase. The low-cost equipment will be in production so it is available for the world-wide limited operational capability in 1981. The more sophisticated classes would be brought forward to the prototype status, i.e., just before production; they could be called preproduction models. IOT&E, initial operational tests, will be carried out using those user models. Six additional satellites will give us nine and allow for spares. These would actually be production, Block-1 satellites.

Orbital Configurations by Phase

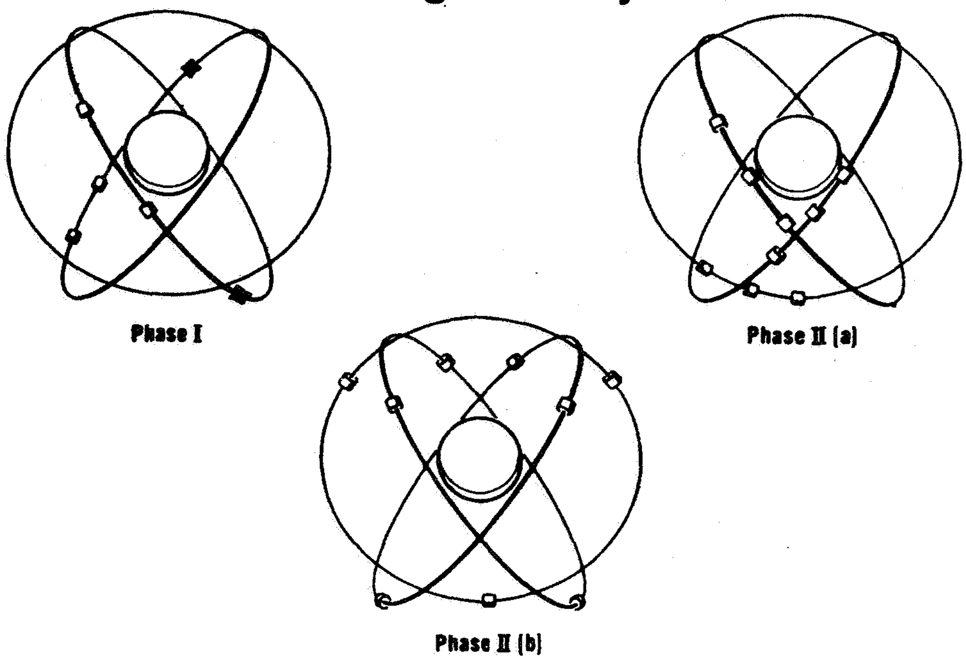


FIG 24

GPS PROGRAM SCHEDULE

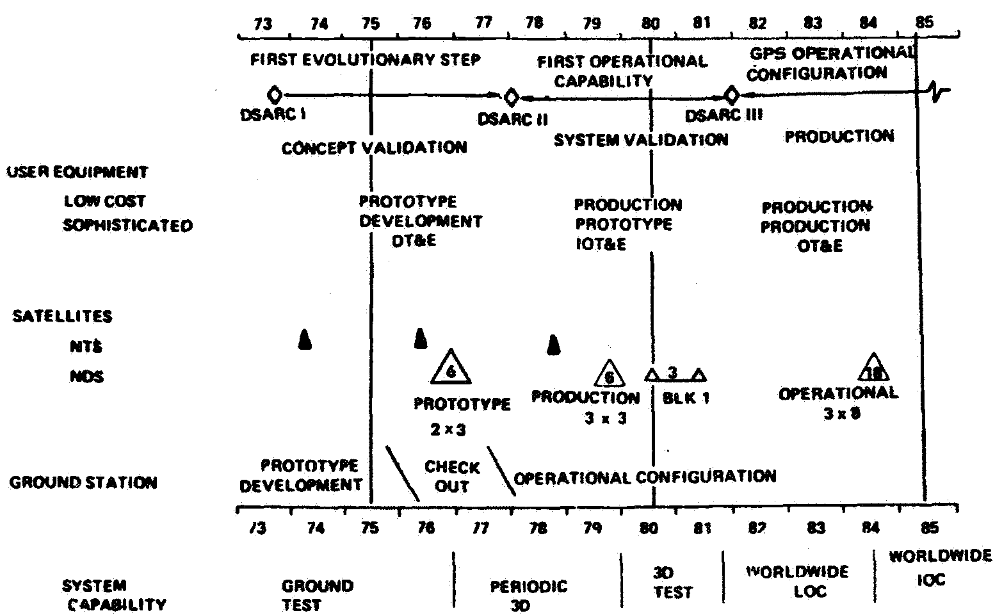


FIG 25

Three-dimensional testing would occur for about eighteen months, then the limited operational capability would be implemented by respacing the satellites using the onboard propellant capability.

A favorable decision at DSARC III would move ahead with full production of the system, achieving initial operational capability in 1984. All user equipments would be in production at this point, and we would complete our operational test and evaluation.

In Figure 26 is shown some of the future test work that will be ongoing during Phase I. The demonstration of performance, through the demonstration of selected operational missions, Naval surface vessels are certainly included. All along the Air Force has had user command participation. I've asked my Navy Deputy to insure that we also get Navy user command participation in the design and overseeing the results of these initial tests, because we feel it is quite important.

There's an application for replacing range instrumentation and the accuracies available are equivalent to roughly the kinds of accuracies expected from very sophisticated ranges. Furthermore, you're not pinned down to a single geographic area. You could achieve these accuracies anywhere. Then you have two options, you could either telemeter back that position or your could record it on tape for later recovery via some other technique. That application is clear. It would be premature to do it during Phase I.

SPECIAL FEATURES
DT&E AND LIMITED IOT&E
PHASE I

- EARLY DEMONSTRATION OF PERFORMANCE
- DEMONSTRATION OF OPERATIONAL MISSIONS

  COORDINATE BOMBING
  APPROACH LANDING NAVIGATION
  AERIAL REFUELING
  ARMY LAND OPERATIONS
  NAVAL SURFACE VESSELS
  SPECIAL TECHNIQUES ANTIJAM AND VULNERABILITY

- USER COMMAND PARTICIPATION

FIG 26

QUESTION AND ANSWER PERIOD

MR. FISCHER:

On the slide showing the landing test results, I noticed it mentioned an 11 state filter. I wonder if there's a simple description what those 11 state are? I was assuming 9 states for vehicle motion and two for clocks, is that anywhere near correct?

COL. PARKINSON:

No. I think it's 6 states for vehicle motion and something like 5 states for clock or perhaps 4 states for clock because you see, you have to also model all the individual clocks in this case. I'm not certain what all the states were anymore, but the important thing is he had to not only model the position of the receiver itself, he also had to model the error that was being generated from our transmitters because they were not all locked in. They were running open loop. So he had to accept that as part of the model.

DR. COHEN:

This is a very bold and exciting project and one which will get a lot of use, but you should be made aware that the radio astronomers will receive it as a mixed blessing. There will be doubt with 1,200 and 1,400 megahertz radiation which will fall on them continuously and maybe forever.

1,200 megahertz is in the red shifted hydrogen band from external galaxies which receive some use and will receive even more. It's not a radio astronomy protected band, but it is one which will be very useful in scientific research and one which clearly will become unusable, at least within some number of your megahertz. I don't know what the effects of band widths of your transmissions would be.

COL. PARKINSON:

At that frequency, 20 megahertz. But you have to recognize that the signal itself is below the noise floor in an omni antenna.

I'm not certain that it's quite the problem here.

DR. COHEN:

Well, I don't know. , I think you said 400 watts.

COL. PARKINSON:

That's 400 watts DC power, but the actual power that's being radiated could be as much as 100 watts.

DR. COHEN:

Haven't there been some experiments with some other satellites in the 1,600 megahertz region and rather far away from your nominal band that found that the interference is very, very strong and wiped out radio astronomy measurements? The point is that radio astronomers detect and work with signals which are very much below the noise floor by a factor of 1,000 or 10,000.

COL. PARKINSON:

Well, I certainly register your comment. Assuming that you have a degree of directivity in those antennas, I personally don't think that the spread spectrum signal can be a lot of trouble.

DR. COHEN:

In these same experiments that I described it was found that when they were within three degrees of pointing at a satellite, they were wiped out entirely. For some extremely sensitive measurements they were wiped out whenever the satellite was above the horizon.

After 1984 your system will have from 6 to 9 satellites in view at all times from every point on the earth. I think that that will reaffirm that systems are getting more sensitive all the time. My guess is that there will be some bands which will become closed, in a sense, to very sensitive radio astronomy use.

I'd be delighted, sir, to send you a report that the National Radio Astronomy Observatory has just written on this particular interference problem.

DR. ALLEY:

If you assume a reasonable circularity of orbit, that you might hope to achieve, there will be a modulation with a 12-hour period having an amplitude of 12 nanoseconds in the ability to transfer time due to the potential effect of general relativity.

COL. PARKINSON:

Well, of course that's a highly predictable thing. Therefore, it doesn't show up in an error budget since we would be calibrating it out. The effect is on the order of 2,200 nanoseconds times the eccentricity of the orbit and it is a sizeable effect and one that we have to correct our clocks for.

We'll correct our clocks in such a way that the user is insensitive to that effect and doesn't even know it's there. The very fast moving user still has to worry about his own relativistic problem.

MR. KEATING:

You mentioned minimization of the proliferation of global navigation systems. How does your system relate to other systems which are global such as OMEGA, and perhaps loran, which may possibly some day become global? Are you in completion with them?

COL. PARKINSON:

Yes, I guess my feeling right now is that the competition is not one that I'm involved in. I'm offering up and building a system, and then the user community will have some choices to make.

If I could hold down the cost of user equipment, provide a highly accurate worldwide grid which is reliable and always available, then the user community will have a choice to make. And I think that's the best way to look at the problem, rather than looking at it as though I'm trying to turn off all the loran transmitters in the world—because I'm not.

NAVIGATION TECHNOLOGY SATELLITE I

Charles A. Bartholomew
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ABSTRACT

The NTS-1 satellite was launched on July 14, 1974. This spacecraft is one of a series of technology satellites to be launched in support of the NAVSTAR GPS Program. NTS-1 was designed to verify the error budget and measure related performance factors including a commercial rubidium vapor frequency standard modified for space conditions. A description of this spacecraft and preliminary performance data will be discussed.

Paper was not received.

QUESTION AND ANSWER PERIOD

MR. CALLAHAM:

I observed that you had a very high rate of clock drift in terms of microseconds, before you issued a tuning command to the satellite. And after you issued the tuning command that you had calculated, I assumed you stopped the drift. You overshot and got a drift of roughly equivalent magnitude in the opposite direction. Since this was unexpected and since it took you 12 hours at least, to figure out that this was what the clock was doing, what would the poor user do if he got this sort of information and didn't know that's what the clock was doing?

MR. EASTON:

What we plan to do in operation, of course, is adjust the clock much closer and have it synthesized so that we can adjust for any drift in the clock. So it won't have these big changes in operation.

DR. SOICHER:

Are both frequencies on all the time? In the ionospheric experiment that you conducted, did you conduct amplitude scintillations? Who has the data available, and have you seen any significant scintillations at L band?

CAPTAIN HOLMES:

To answer your first question I presume you mean when you say both frequencies, you mean are both the L band and the UH frequencies on all the time? The answer to that is no, the reason for it is that because of the tumble of the satellite we have not achieved the temperature stabilization in the satellite that we had hoped for. As a result, we have peak temperatures in excess of 30 degrees centigrade and we don't feel that we can operate or that we should operate at least at this time, both frequencies continuously.

With regard to whether we have seen any significant scintillation data, I would have to say that right now because of the tumble rates and because of the changing rates that have been introduced into the satellite in order to translate the spin into a tumble mode, we would not I don't think right now that we want to say that the data is such that we would be sure that we've achieved significant results.

DR. SOICHER:

I'd like to suggest that the GPS people that L band may exhibit amplitude scintillation and of worse magnitude especially in equatorial regions and Arctic regions.

I'm sure that some work is being done along these lines, but it ought to be done in view of the power of this other system.

CAPTAIN HOLMES:

We would agree 100 percent with that.

DR. HELLWIG:

You show the tuning curve for the rubidium—how is the tuning done?

MR WHITE:

Dr. Hellwig, I'm not actually sure I understand your question. How do we calculate the tuning we did? Why did we do it? It was a C field command. We changed the current to C field. The reason we didn't hit the right spot was because we were using some tuning curves that we had generated on the ground for it under some different conditions, and it turns out that the temperature in the satellite was sufficiently different and when I guessed the new word, I guessed the wrong word.

We intend, in later work, to generate the tuning curve in the satellite and see what we can expect in the way of a Delta F change and see what happens then.

DR. ALLEY:

Is it possible to predict when the satellite will stabilize sufficiently to allow laser ranging to be done to the reflectors?

CAPTAIN HOLMES:

We're in the process of assessing what impact the current tumble rate will have on the experiment. Our feeling is that we will probably be able to do the laser ranging experiments even under the present conditions.

DR. ALLEY:

What was the period of tumble? How long might they be facing the earth?

CAPTAIN HOLMES:

The period is roughly 35 minutes, and that will provide probably on the order of 10 minutes of laser viewing time.

DR. ALLEY:

But you know the phase of that tumble sufficiently well that one could predict?

CAPTAIN HOLMES:

Yes.

RESULTS OF THE FIRST 150 DAYS OF THE NTS-1 SOLAR CELL EXPERIMENTS

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ABSTRACT

Twelve solar cell experiments were on the Naval Research Laboratory NTS-1 satellite launched on 14 July 1974, into a 13,620 km circular orbit at an inclination of 125°. The experiment comprises: 2 ohm-cm n/p, lithium-diffused p/n, violet n/p, p^+ back-surface field, and ultra-thin wrap-around contact cells. The short-circuit current of the experiments ranged from 2 to 12 percent higher in space than under solar simulators. During the 5 year life of the satellite, the experiments will be exposed to radiation equivalent to 2 x 10^{15} 1-MeV electron cm^{-2} and to nearly 5500 thermal cycles.

INTRODUCTION

The NTS-1 satellite is a forerunner of the NAVSTAR Global Positioning System being developed to provide extremely accurate world-wide navigational capability for ships, aircraft, and ground forces. Two earlier TIMATION satellites have proven this concept of passive and accurate position-fixing, and demonstrated through a joint British - U. S. experiment in 1972 that the system is ideal for transferring precise time around the world.

The payload also contains twelve solar cell experiments from the Royal Aircraft Establishment, Comsat Laboratories, and the Naval Research Laboratory.

The satellite viewed from the top (Fig. 1) is an octagon with a 48 inch diameter (122 cm) and is 22 inches high (56 cm). The solar array consists of 4 paddles made up of 2 x 4 cm n/p solar cells of 2 ohm-cm resistivity, placed on both sides. Each side has 10 strings of 81 cells in series connection. The coverslips are 12 mil (0.030 cm) Corning 7940 fused silica with blue-filters, cemented to the cells with Sylgard R6-3489 adhesive. Interconnects are 2 mil (0.005 cm) silver-plated molybdenum attached by reflow soldering.

OBJECTIVES OF THE SOLAR CELL EXPERIMENTS

The NRL and COMSAT Experiments are designed to compare the performance and degradation in time of various types of experimental solar cells with the reference experiment consisting of conventional cells of the same type used in the main array. The NTS-1 orbit is in a severe radiation environment which is equivalent to a 1-MeV electron fluence of 4×10^{14} electron cm^{-2} $year^{-1}$ incident on a solar cell shielded by 12 mils (0.030 cm) of fused silica. The specific objectives of these experiments are:

(1) To compare performance and radiation resistance of the Comsat and Centralab violet cells manufactured in 1973 to a reference cell.

(2) To compare the performance and radiation resistance of the Spectrolab "Helios" cell to a reference cell.

(3) To observe radiation resistance of lithium-diffused cells in orbit at temperatures near 50°C where annealing can occur.

(4) To observe performance and radiation degradation of a very thin solar cell (100 μm) having a p^+ diffused layer at the back contact.

The RAE experiment on the satellite represents a further stage in the process of proving and demonstrating the spaceworthiness of British components and techniques for the construction of advanced lightweight deployable arrays of thin silicon solar cells. The first flight experiments, embodying the thin cells, coverslips and flexible panel assembly techniques, were flown on the Prospero (X3) technological satellite and are still working satisfactorily after nearly three years in orbit (1). Miranda (X4) launched earlier this year, demonstrated the soundness of the fold-up stowage and telescopic deployment systems which have been developed for such arrays (2).

The aims of the present experiment are:

(1) To demonstrate the spaceworthiness of Ferranti 125 μm wrap-around solar cells of the latest 24-finger design, solder interconnected and mounted without cement on a flexible substrate.

(2) To compare Czochralski (CZ) and float zone (FZ) cells of the same type, with particular reference to any photon-induced degradation.

(3) To compare the performance and radiation resistance of 1 and 10 ohm-cm thin cells.

(4) To check initial performance and radiation damage predictions.

(5) To compare integral and discrete coverslips.

DESCRIPTION OF EXPERIMENTS

The experiments consist of the 12 types shown in Table 1. Fig. 2 is a photograph of experiments 1 through 4. The Helios cell experiment is shown in Fig. 3 and the reference array is shown in Fig. 4. The NRL and Comsat experiments are all series-wired patches, for which I-V curves are obtained from the telemetered data in orbit. The I-V curve is produced by the electrical circuit shown in Fig. 5. A ramp voltage with a time length of 30 seconds is applied to each experiment in sequence through a clock operated switching gate, and data is recorded at intervals of 2.56 seconds, yielding about 12 points of the IV curve during each sampling period.

All of the experiments are fixed to the satellite through thermally insulating stand-off legs. As a result of this and because the NTS-1 will be a three-axis stabilized spacecraft, the solar cell patches are calculated to reach temperatures of 70°C for the NRL and Comsat experiments, and 90°C for the RAE experiment. A Fenwall Type GB35P52T5 thermistor is attached to the rear surface of one cell on each of the NRL and Comsat experiments to measure temperature.

CALIBRATION OF EXPERIMENTS

Measurement of the NRL panels under solar simulator conditions was performed in part at the following locations: Air Force Aero Propulsion Laboratory, Hughes Aircraft Company, Jet Propulsion Laboratory, NASA Goddard Space Flight Center, and the Naval Research Laboratory. The calibration of the Comsat experiment was performed by Comsat Laboratories, and the RAE experiment was calibrated with the RAE Large Area Pulsed Solar Simulator (LAPSS).

Also, temperature coefficients for the experimental patches were determined at NRL and the Air Force Aero Propulsion Laboratory.

The short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and maximum power (P_{max}) obtained from the solar-simulator measurements are shown in Table I.

CALCULATION OF SPACE RADIATION FLUENCE

The effect of the natural trapped radiation environment was calculated from data available from the National Space Science Data Center, NASA (5,6). Computerized calculations were made of solar cell I-V curves as a function of temperature and coverslip thickness, using a program developed for NASA Goddard Space Flight Center (7).

The electron spectrum flux was calculated to be equivalent to 3 x 10^{14}

1-MeV e $cm^{-2}yr^{-1}$, while the proton spectrum flux was 1 x 10^{14} 1-MeV e $cm^{-2}yr^{-1}$, for a solar cell array with 0.030 cm of fused silica shielding at a circular orbit of 7500 n.m. (13,900 km). In a total radiation fluence of 4 x 10^{14} 1-MeV e cm^{-2} yr^{-1} the 2 ohm-cm solar cells in the main array will lose 19 percent of their maximum power in one year, and 35 percent after 5 years.

MEASUREMENT IN ORBIT

NTS-1 was launched on 14 July 1974 at 04:55:00 hours GMT. The four solar paddles of the main array were commanded to deploy in the first revolution; two of them indicated positive latch-up during Rev 1, the other two latched into final position during Rev 18 and Rev 19 after 6 days in orbit. During this time the spin rate of the satellite was slowed down to about 18 minutes per revolution. After Rev 20, high quality data was received from the solar cell experiments, with sun aspect angle varying from 0 to 15 degrees from normal incidence. The orbital period is 468.73 minutes, resulting in slightly more than 3 revolutions per day. The perigee is 12,193 km and the apogee is 13,606 km. The inclination is 125.11 degrees. Solar cell experiment data is recorded in real-time during a 2½ hour period as the satellite is in view of the Naval Research Laboratory Satellite Tracking Facility at Blossom Point, Maryland, located 50 km south of Washington, D.C.

The experiments are mounted on the top surface of the satellite, from which extends an 18.3 m gravity-gradient boom and a 56 cm magnetic boom. Thus, at certain solar aspect angle and rotation angle it is possible for partial shading to occur on the experiments. A computer program is being prepared which will predict the shading and reject data from shaded panels during processing. In the meantime, shading effects are obvious when the entire I-V curve is measured.

The temperature of the NRL experiments ranged from -13°C to +32°C during the first weeks while the spacecraft is rotating. The Comsat panel temperature ranged from -16°C to +19°C. The RAE patches are operating at temperatures somewhat higher than these. After several months the NRL and Comsat solar panel temperatures went as high as 60°C.

The results of measurements during Rev 30 (tenth day in orbit) are shown in Table 1. The I_{sc}, V_{oc}, and P_{max} have been corrected to a cell temperature of 25°C. The pre-launch solar simulator data are shown in this table for comparison.

A general observation of the space data shows that the short-circuit current (I_{sc}) of all the NRL and Comsat experiments is higher in space than under the solar simulators. Of the two lithium-doped cell experiments, the Centralab cell indicated a loss in P_{max} of 7 percent from ground to space. The power loss of four of the experiments is shown in Fig. 6 as a function of time in orbit for the first 5 months. No data is available prior to the tenth day because of the unfavorable sun angles during maneuvers to achieve final flight configuration and orientation. The reference panel is performing as predicted. The high efficiency arrays also degraded as expected for the first 100 days; from that point to 150 days the degradation rate for the Comsat violet was much more than had been predicted from electron accelerator experiments. The Helios panel is performing as expected. The lithium-diffused silicon panel improved slightly in power output between the third and fifth month. This annealing of radiation damage can be accounted for since the solar cell average temperatures increased during this period to as much as 50° Centigrade for many hours. This is sufficient to anneal some of the radiation damage from the first few months, as well as to reduce the present rate of damage below that for the other types of cells.

CONCLUSIONS

The NTS-1 solar cell experiments are operating very successfully; good quality data in the form of twelve-point IV curves is being obtained from the NRL and Comsat experiments. The results indicate higher initial output for all experiments than had been measured under solar simulators. The cells having the highest P_{max} are, in descending order: (1) Comsat violet, (2) Centralab violet, and (3) Heliotek "Helios" solar cells. Because of the orbital constraints, data will be obtained at semiannual periods lasting for 20 to 30 days. A shadowing program will be completed to assist in data reduction.

The NTS-1 experiment is of significant importance, because it permits the continuing evaluation of several types of high-efficiency solar cells and lithium-doped cells in a hard radiation environment with a direct comparison to a flight-quality conventional solar cell.

ACKNOWLEDGEMENT

This work is supported by the Naval Electronic Systems Command. The success of the solar cell experiments is due largely to the assistance of the Space Metrology Branch, NRL, to the dedicated efforts of the Spacecraft Technology Center, NRL, and to the cooperation of the Air Force Aero Propulsion Laboratory, the Jet Propulsion Laboratory and Comsat Laboratories.

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Table 1

PHOTOVOLTAIC MEASUREMENTS OF THE NRL AND COMSAT EXPERIMENTS

Experiment No.	Cell Type	Cell Size (cm)	Coverslip (cm)	Measured AMO performance per cell at 25° C					
				Solar Simulator			Rev 30 in Orbit		
				I_{sc} mA	V_{oc} mV	P_{max} mW	I_{sc} mA	V_{oc} mV	P_{max} mW
1	CEN Radial Grid n/p, 10 ohm-cm	2 X 2 X .01	Fused silica .015	141	576	61.1	151	558	55.5
2	CEN Violet n/p	2 X 2 X .03	Fused silica .015	157	582	68.1	169	574	73.0
3	HEL Lithium p/n	2 X 2 X .02	Fused silica .015	131	600	60.5	143	587	63.2
4	CEN Lithium p/n	2 X 2 X .02	Fused silica .015	125	606	57.0	144	589	56.0
5	CEN Violet n/p	2 X 2 X .03	Fused silica .030	149	570	65.6	172	569	73.3
6	HEL Helios n/p, 10 ohm-cm	2 X 2 X .03	Fused silica .030	159[1]	581[1]	69.7[1]	168	562	68.6
7	CEN n/p 2 ohm-cm	2 X 4 X .03	Fused silica .030	250	591	115	282	573	122.2
8	Comsat Violet	2 X 2	Ceria glass .015	162[2]	594[2]	74.3[2]	185	578	83.3

[1]Measured by Spectralab.
[2]Measured by Comsat Laboratories. All other measurements by Naval Research Laboratory.

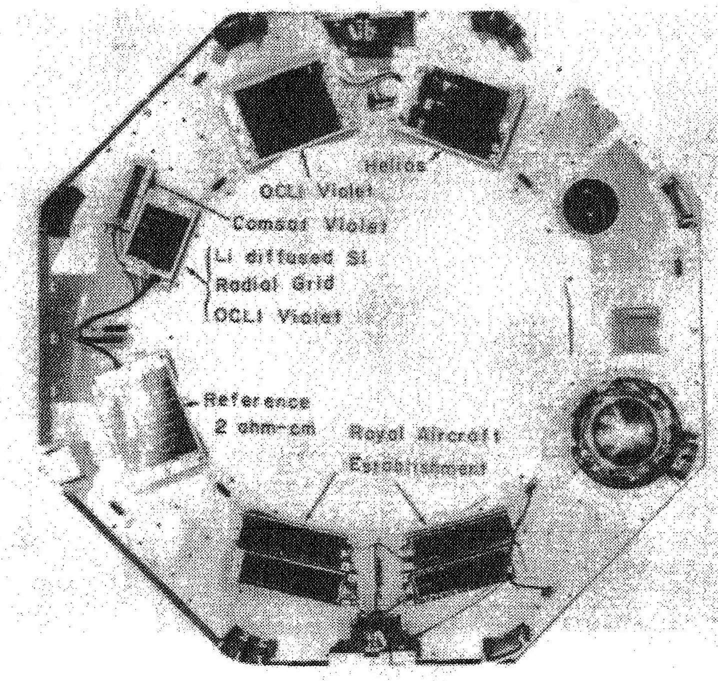

Fig. 1 Solar cell experiments on the top deck of NTS-1.

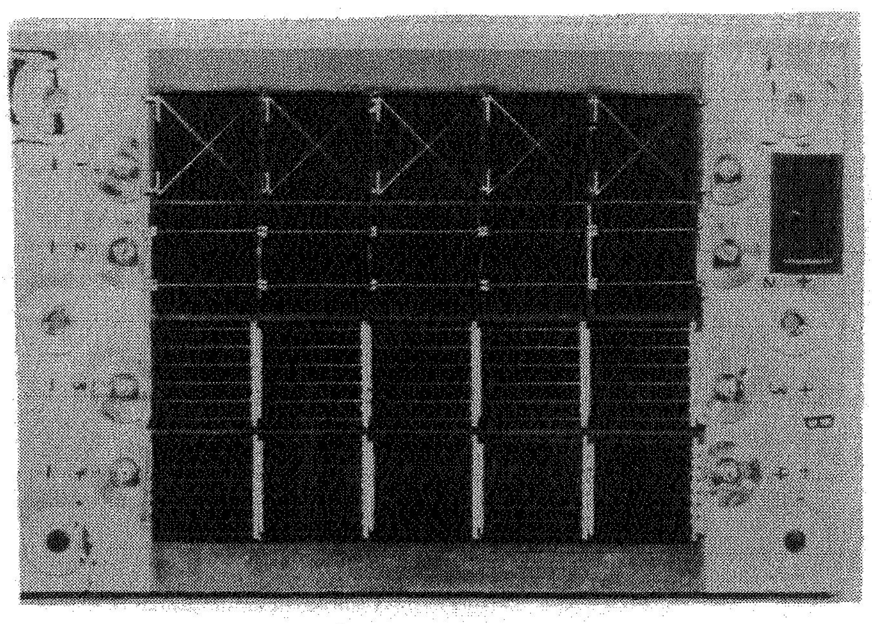

Fig. 2 Solar cell panel containing experiments 1 through 4.

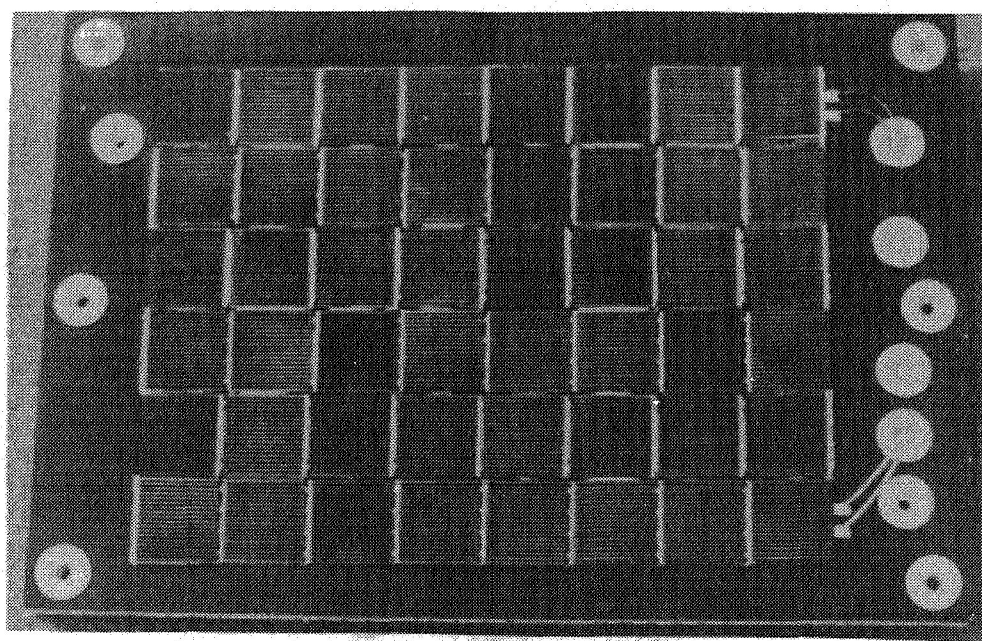

Fig. 3 The Spectrolab "Helios" solar cell experiment on NTS-1.

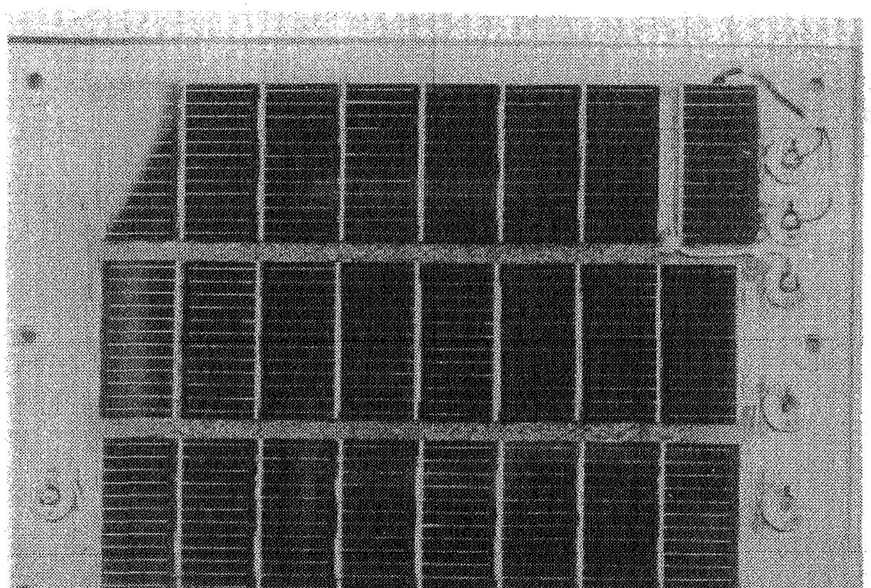

Fig. 4 The reference solar cell panel containing 2 ohm-cm N-on-P cells.

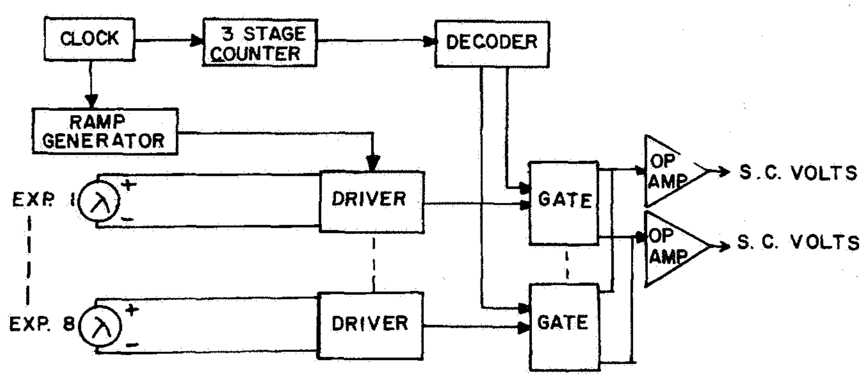

Fig. 5 The photovoltaic current-voltage measuring circuit on NTS-1.

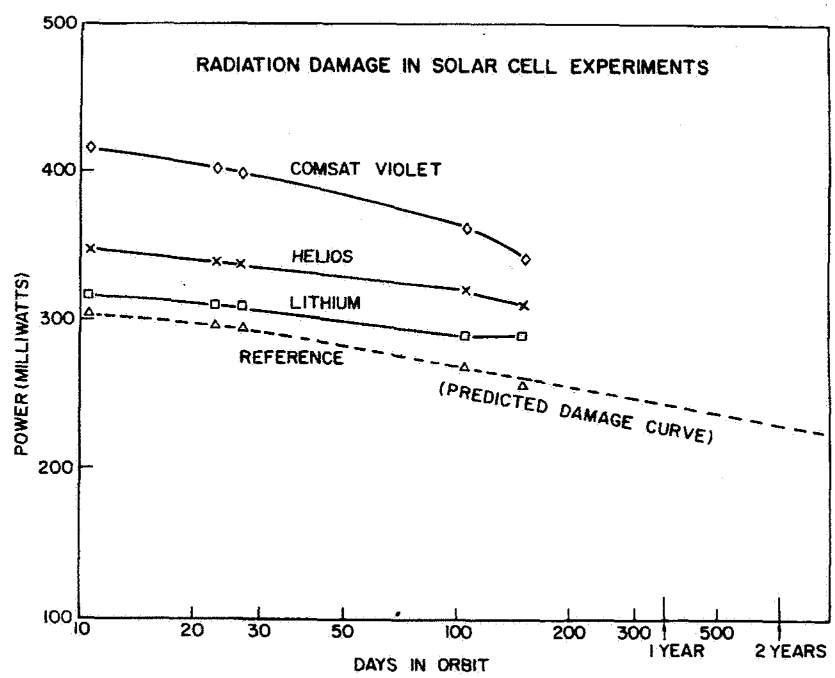

Fig. 6 The effect of trapped radiation damage on the maximum power output of the solar cell experiments on NTS-1.

N75 27204

STATISTICAL ANALYSIS OF TIME TRANSFER DATA FROM TIMATION II

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A.C.T., Australia

ABSTRACT

Between July 1973 and January 1974, three time transfer experiments using the Timation II satellite were conducted by the Division of National Mapping, A.C.T., Australia and the US Naval Research Laboratory, Washington, D.C., to measure time differences between the US Naval Observatory and Australia. Statistical tests showed that the results are unaffected by the satellite's position with respect to the sunrise/sunset line or by its closest approach azimuth at the Australian station. Further tests revealed that forward predictions of time scale differences, based on the measurements, can be made with high confidence.

Measurements Against the Satellite Clock

The results of the first two time transfer experiments between NRL and Australia have already been presented (Easton, Smith and Morgan, 1973, 1974).

The first series of statistical tests examined the residuals from a quadratic fit of the results TII-AUST, where TII represents the satellite on-board oscillator and AUST represents the local Australian time standard, in this case the National Mapping portable cesium standard DNM590 whose performance was linear with respect to a four component mean time scale. The measurements in July showed that the on-board oscillator had a constant aging rate during the experiment, and the residuals were normally distributed, while during the September run the residuals were not normally distributed. The oscillator was evidently much less stable in the January 1974 run, and a simple curve could not be fitted.

The curves fitted were:

July run: $\text{TII-AUST} = 5.371 + 4.7616(t-\bar{t}) + 0.25214(t-\bar{t})^2$ microseconds,

where t was the day of the year and $\bar{t}$ was the midpoint of the run (199.153). The standard deviation of the 38 residuals was 0.585 microseconds.

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September run: TII-AUST = $38.940 + 3.9779(t-\bar{t}) - 0.00956(t-\bar{t})^2$ microseconds, where $\bar{t}$ was 265.544. The standard deviation of the 42 residuals was 1.653 microseconds.

For each run, the residuals were analyzed by a two-way analysis of variance with unequal cell sizes (Hamilton, 1964), the classifications being:

(1) Effect of sunlight, to see if it affected either the satellite clock through temperature variation, or the signal travel time.

This classification was sub-divided by the time of closest approach:

- (i) more than 2 hours before sunrise or more than 2 hours after sunset;
- (ii) 1 to 2 hours before sunrise or 1 to 2 hours after sunset;
- (iii) 0 to 1 hours before sunrise or 0 to 1 hours after sunset;
- (iv) 0 to 1 hours after sunrise or 0 to 1 hours before sunset;
- (v) 1 to 2 hours after sunrise or 1 to 2 hours before sunset;
- (vi) more than 2 hours after sunrise or more than 2 hours before sunset.

(2) Effect of azimuth, to see if the local surroundings had any effect. This classification was sub-divided by the azimuth at closest approach:

- (i) in the quadrant North to East;
- (ii) in the quadrant East to South;
- (iii) in the quadrant South to West;
- (iv) in the quadrant West to North.

The number of observations falling into each cell, and the row and column means, are given in Tables I and II. The residuals from the fitted curves are shown in Figure 1.

The analyses of variance presented show that there is no statistical evidence for effects due to the amount of sun illumination on the satellite-station path, or on the quadrant of observation; nor is there any significant interaction between these two factors. No data were available to the authors for testing more precisely the effects of temperature and proton bombardment on the satellite oscillator.

January 1974 Results

A third run was conducted in January 1974, principally to provide an interpolating line for calibrating the Timation system against a USNO flying clock which visited National Mapping on 7 December 1973. On this run, oscillator instability, the restriction to one transmission frequency, and turning the oscillator on and off during the run degraded the results of TII-AUST to the extent that comparisons with the satellite clock could not be statistically analyzed. The time transfer comparisons with USNO were also degraded, as can be seen from Figure 2, but the mean of the observations still proved useful. The results of fitting straight lines to the January measurements of USNO-AUST, together with combinations of all three runs, are given in Table III.

Inter-run Statistics

Three series of tests were conducted to establish whether the runs, and their combinations, were statistically equivalent.

In the following descriptions, the σ^2 are variances of residuals after fitting straight lines of form

$$\text{USNO} - \text{AUST} = \alpha + \beta(t-\bar{t}),$$

and the σ_β^2 are the variances of the observed rates β. The number of observations in each data set is denoted by n.

(1) The first series compared the results obtained, on the one hand, by subtracting direct Australian observations from points interpolated between NRL observations, and on the other hand, by subtracting interpolated Australian observations from direct NRL observations. The tests were:

(i) Equivalence of Sample Populations, i.e. whether NRL-interpolated samples were drawn from the same population as AUST-interpolated samples.

Null hypothesis H_o : $\sigma_1^2 = \sigma_2^2$

Alternative H_1 : $\sigma_1^2 \neq \sigma_2^2$

Test statistic : $f = \sigma_1^2/\sigma_2^2$ (Fisher's F)

Evaluation : Accept H_o if $0.60 < f < 1.67$.

The f-column of Table IV shows that the populations were statistically equivalent at the 95% level for all except the September runs, which were nearly equivalent.

(ii) Non-zero Significance of Rates, i.e. whether the rates of each run were statistically equal to zero.

Null hypothesis $H_o : \beta = 0$

Alternative $H_1 : \beta \neq 0$

Test statistic $: t = [\beta]/(\sigma_\beta^2)^{\frac{1}{2}}$ (Student's t)

$:$ Accept H_o if $t < 1.96$.

The t-columns of Table IV show that the rates were very different from zero in all runs except January. This is due in part to the large standard error and small data set; but reference to Table III shows that the rate was indeed small, which is possibly explainable by the vagaries of the satellite oscillator which made the interpolation scheme unstable. It will be shown in a later test that the January rates were different from the rates determined from the other runs.

(iii) Equivalence of Rates, i.e. whether rates obtained by interpolating NRL observations equalled AUST-interpolated rates.

Null hypothesis $H_o : \beta_1 = \beta_2$

Alternative $H_1 : \beta_1 \neq \beta_2$

Test statistic $: T = (\beta_1 - \beta_2)/S$ (Student's t)

where $S = \{[(n_1-2)\sigma_1^2 + (n_2-2)\sigma_2^2][\sigma_{\beta 1}^2/\sigma_1^2 + \sigma_{\beta 2}^2/\sigma_2^2]/[n_1+n_2-4]\}^{\frac{1}{2}}$

Evaluation $:$ Accept H_o if $T < 1.96$.

The T-column of Table IV shows that the two interpolation schemes gave the same rates.

(2) The second series of tests evaluated whether the midpoint of one run (α at time $\bar{t}$ in Table III) coincided with the value at $\bar{t}$ on the line fitted through another run, i.e. whether runs gave consistent values when extrapolated.

Null hypothesis: $\alpha_1 = \alpha_2 + \beta_2(t-\bar{t})$

Alternative : $\alpha_1 \neq \alpha_2 + \beta_2(t-\bar{t})$

Test statistic : $t = \alpha_1 - [\alpha_2+\beta_2(t-\bar{t})]/S$ with

d-2 degrees of freedom, where $S = [\sigma_1^2/n_1 + \sigma_2^2/n_2]^{\frac{1}{2}}$,

$$d = S^4/[\sigma_1^4/n_1^2(n_1+1) + \sigma_2^4/n_2^2(n_2+1)].$$

This statistic is approximately distributed as Student's t - it is the incomplete Fisher-Behrens statistic (Welch, 1937; Hamilton 1964).

Evaluation : Accept H_o if $t < 1.96$.

Table V shows that forward extrapolation of the NRL-interpolated samples is valid - even extrapolating from the July run into January is satisfactory at the 2% level. The fact that the AUST-interpolated samples do not give such good extrapolation characteristics is attributed to the sparser Australian data sets - otherwise it is a little puzzling.

(3) The third series tested the hypotheses that, for the NRL-interpolated samples, the sample populations and rates from each run and combination were equivalent; and similarly for the AUST-interpolated samples. All single runs satisfied a χ^2 goodness-of-fit test for normality.

(i) Equivalence of population variances.

Null hypothesis $H_o : \sigma_1^2 = \sigma_2^2$

Alternative $H_1 : \sigma_1^2 \neq \sigma_2^2$

Test statistic : $f = \sigma_1^2/\sigma_2^2$ (Fisher's F)

Evaluation : Accept H_o if $0.60 < f < 1.67$.

The f-column of Table VI shows clearly that the July run had significantly lower variance than any other run or combination, but that the other runs were, by and large, from the same population.

(ii) Equality of rates.

Null hypothesis $H_o : \beta_1 = \beta_2$

Alternative $H_1 : \beta_1 = \beta_2$

Test Statistic $: T = [\beta_1 - \beta_2]/S$ (Student's t)

where $S = \{[(n_1-2)\sigma_1^2 + (n_2-2)\sigma_2^2][\sigma_{\beta_1}^2/\sigma_1^2 + \sigma_{\beta_2}^2/\sigma_2^2]/[n_1+n_2-4]\}^{\frac{1}{2}}$

Evaluation : Accept H_o if $t < 1.96$.

The T-column of Table VI shows that, for the NRL-interpolated samples, the rate determined from the January run was statistically different from the rates determined from all other runs and combinations, which were in turn statistically equal to each other. This confirms the result found in test (ii) of the first series. The poorer results obtained from the AUST-interpolated samples confirm the second series tests wherein extrapolation between some run combinations was not valid.

Comparison of Time Scales

The tests described above all used a single cesium standard, DNM590, for the time scale denoted AUST. To demonstrate that the out-of-character results of the January run were not due to a change of rate in this clock, a special Australian artificial time scale (AATS) was constructed, comprising the four cesium standards DNM590, the original Mount Stromlo standard DNM205, the newer standard NSL338 of the National Standards Laboratories, CSIRO, Sydney, and standard HP052 maintained by Hewlett Packard (Australia) Limited, Melbourne. These clocks are all compared daily by ABC television comparisons (Miller 1970) and were not stopped or adjusted in the period between 8 February 1973 and 23 May 1974. No other cesium standard in Australia satisfied both these conditions. The time scale was a simple unweighted mean of the four clocks, offset (in phase only) so that it agreed approximately with UTC (USNO) determined by flying clocks.

An extrapolating ephemeris for AATS was constructed, using least squares straight line fits, in which:

$$E[\text{USNO-AATS}] = \sum_{i=1}^{4} E[\text{USNO-Clock}_i]/4$$

and

$E[USNO-Clock_i] = E[USNO-DNM590]$ (by Timation)$+E[DNM590-Clock_i]$ (by Television).

Selected points on the graphs of the clocks against the artificial time scale are shown in Figure 3. It can be seen that no significant rate change occurred in DNM590. Assuming that no such rate change occurred in UTC (USNO), the poor results in rate from the January run would reflect deficiencies in the Timation II technique.

Table III includes the result of a visit by USNO flying clock PC572 in December 1973, and, in the column headed USNO-AUST, gives the values obtained by inserting t = 7 December 1973 in the various formulae obtained for different Timation II runs and combinations. For each interpolating system, the July-September combination gave the best agreement, which was 0.31 microseconds for NRL-interpolations and 0.17 microseconds for UAST-interpolations. The 95% confidence interval at 7 December for the NRL-interpolated July-September combination was ±0.27 microseconds, and for the AUST-interpolated combination ±0.20 microseconds. Thus, on the assumption that no error was attached to the flying clock result, the former set gave almost statistically correct results, while the latter set showed excellent agreement. When the quoted error of ±0.2 microseconds from the USNO certification was taken into account, the NRL-interpolated result also became acceptable.

Extrapolating the July-September combinations backwards to the date of the previous USNO flying clock visit on 8 February 1973, the differences were 3.03 microseconds with ±0.05 microseconds 95% confidence interval for USNO-interpolates, and 3.12 microseconds with 0.37 microseconds 95% confidence interval for AUST-interpolates. When the errors of the flying clock measurements are taken into account, these results are not unsatisfactory. On the other hand, the agreement between USNO-AATS by the extrapolating ephemeris and USNO-AATS by the flying clock measurement was 0.8 microseconds, which is regarded as very satisfactory over such an interval. It is unfortunate that no subsequent definitive flying clock trip has been made, as a further test of the predictive power of Timation would have been very beneficial, especially as time keeping in Australia during 1974 has been plagued with breakdowns both in a number of cesium standards and in the television network system.

On the basis of the consistency of the NRL-interpolated July-September combination in both the extrapolative and interpolative senses, its agreement with USNO flying clock measurements, and its consistency with a selected Australian time scale, the formula 4 in Table III was adopted as the definitive comparison between Australian clocks and UTC(USNO MC), and was accordingly made the sole interpolating link between UTC(USNO MC) and the regular television-compared Australian mean time scale UTC(Aus).

Conclusions

The foregoing statistical analysis shows quite clearly the value of the Timation satellite for intercontinental time transfer at the sub-microsecond level. The major areas requiring particular attention are:

(i) Long runs are required to establish rates reliably. The durations of the three runs were thirteen, seventeen and twelve days in July, September and January respectively, and even then the sparser results in January produced anomalies.

(ii) The stability of the satellite oscillator must be good enough to carry interpolations over several hours. The poor January results establish this point forcibly.

(iii) The superior results from the July run show that dual frequency transmissions (150 MHz and 400 MHz) do indeed reduce errors.

(iv) Every effort should be made to have the data set as dense as possible.

(v) There are factors affecting the stability of the oscillator which we do not yet understand, since an analysis of variance failed to reveal two possible causative, or perhaps correlated, effects. It is significant here that the residuals AUST-TII were not normally distributed yet the residuals from USNO-AUST = (USNO-TII)-(AUST-TII) were normally distributed, thus indicating the presence of a perturbing influence in the region of the satellite. No data was available to test accurately the hypothesis that the temperature around the crystal caused it to fluctuate.

The Timation II results presented here have been incorporated into UTC(AUS), so that predictions of the relationship between Australian clocks and USNO can be made with confidence at the microsecond level. It is hoped that regular observations of Timation III can be carried out - its improved clock should improve the statistics considerably and enable our geographically isolated clocks to contribute to International Atomic Time.

Acknowledgements

The authors particulary thank Mr. R. Easton of the Naval Research Laboratory, Washington, D.C. for his enthusiastic collaboration in the project. They also thank Mr. R.J. Bryant and Mr. R. D. Craven of the Division of National Mapping for their assistance with the calculations for this paper, and Miss M. Dowhy, Miss M. Schussig and Miss J. Thurling of the Division for preparing the manuscript.

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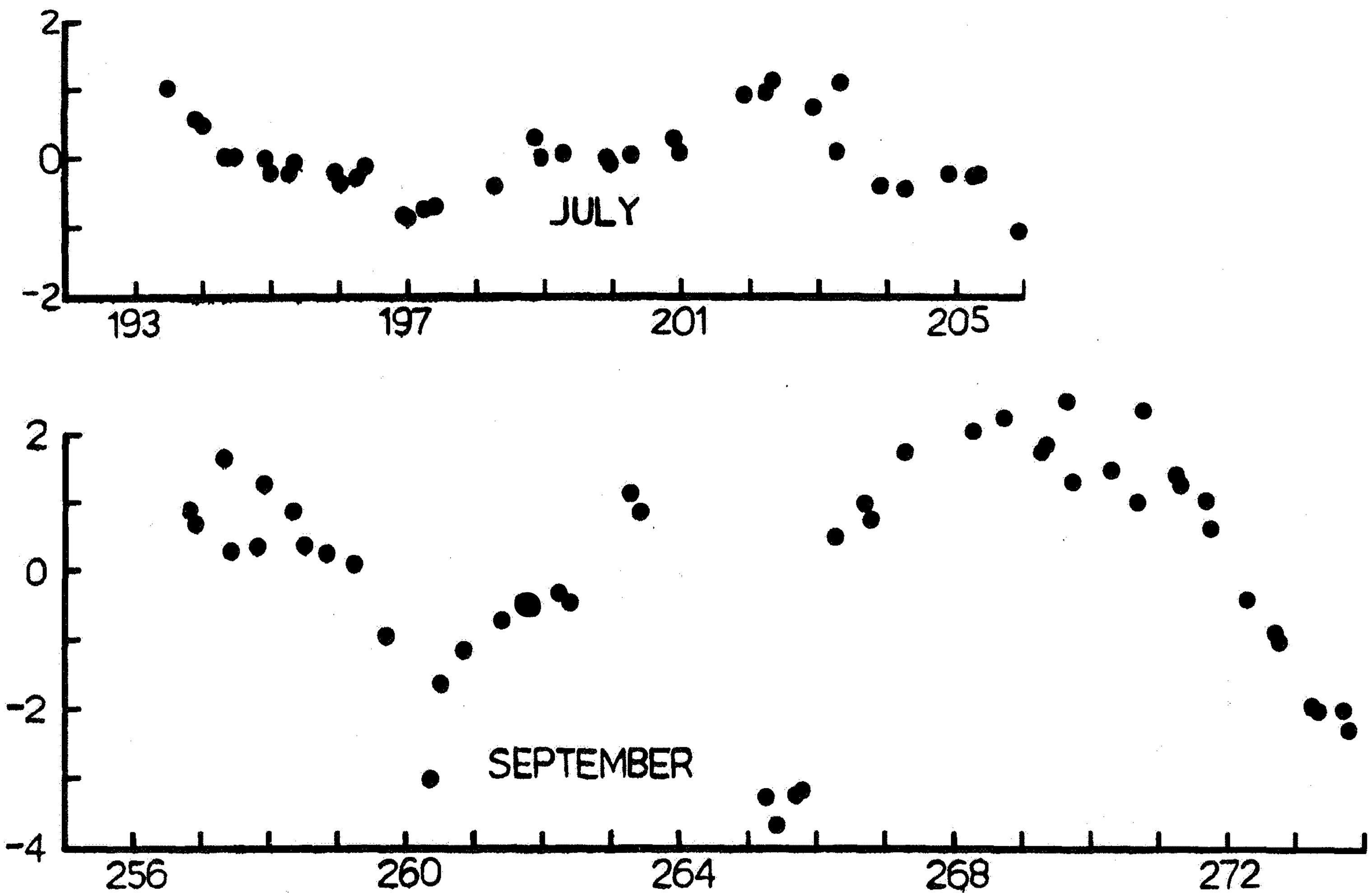

Figure 1: Residuals from Quadratic Fits of TII-AUST (NRL-Interpolated), July and September 1973. The Horizontal Scale is Marked in UT Days. The Vertical Scale is Marked in Microseconds.

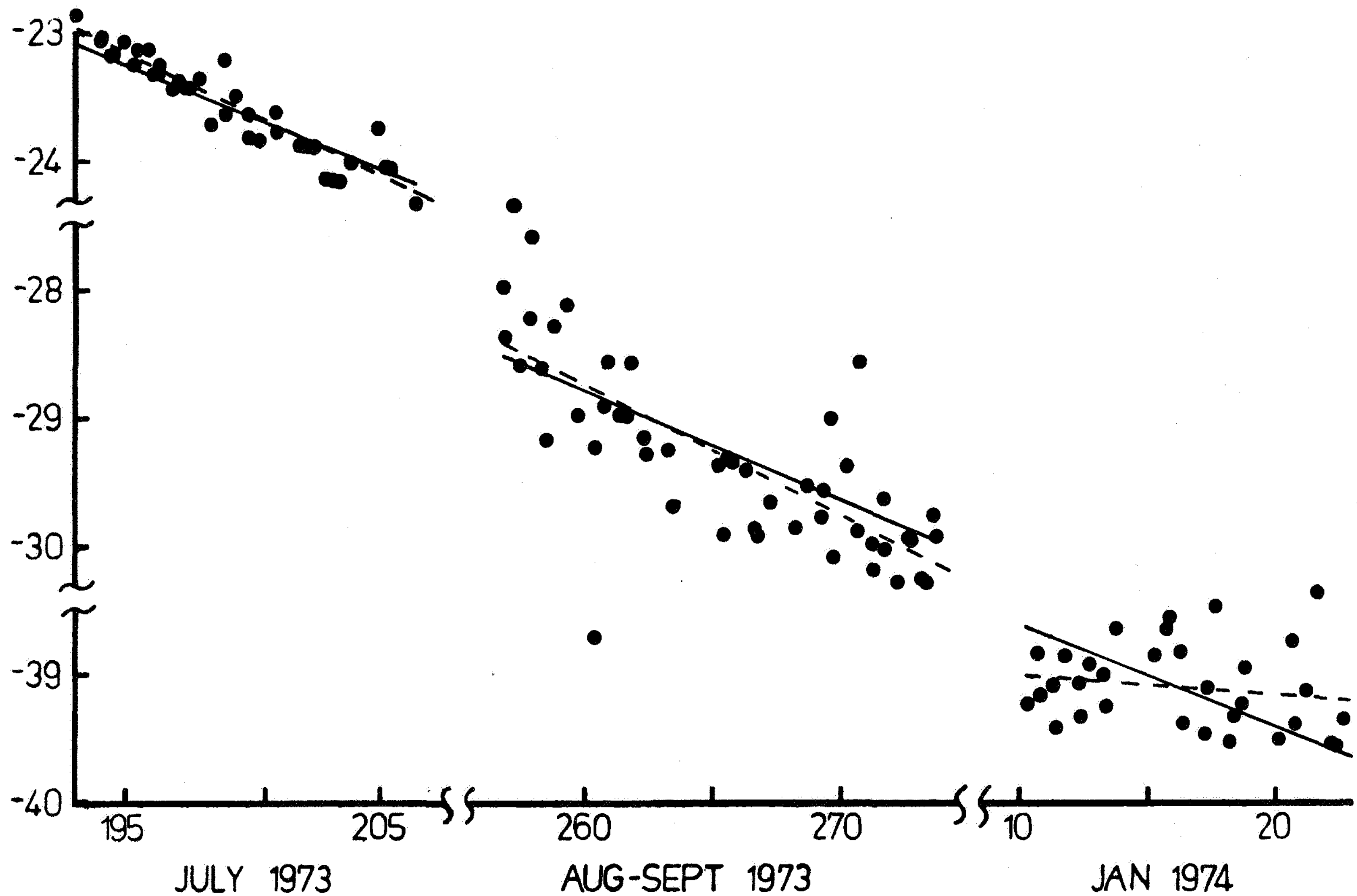

Figure 2: USNO-Aust (NRL-Interpolated).
The Full Line is Line 6 of Table III, i.e. Combination of All Three Runs.
The Dashed Lines are Lines 1,2,3, of Table III, i.e. Individual Runs.
The Horizontal Scale is Marked in UT Days. The Vertical Scale is Marked in Microseconds.

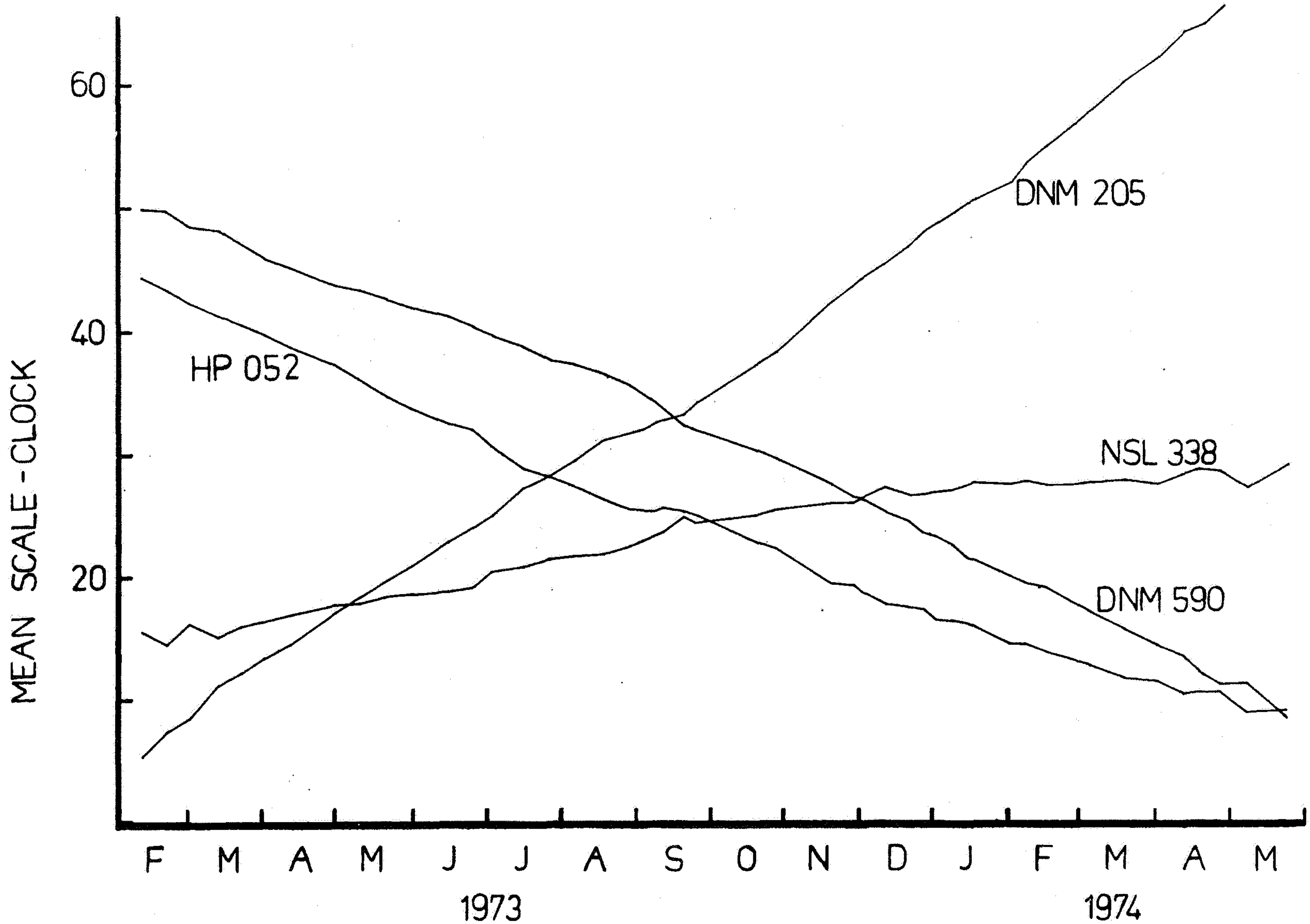

Figure 3: Australian Artificial Mean Time Scale (AATS)-Clock for Each Component Clock. The Vertical Scale is Marked in Microseconds; its Origin is Arbitrary.

TABLE I

Analysis of Variance, July 1973 Run

Number of Observations and Cell Sums

Illumination at t.c.a.	Quadrant of c.a. NE	SE	SW	NW	Row Sums
1. $>2^h$ before sunrise or $>2^h$ after sunset (dark)	0 -	0 -	0 -	5 0.215	0.215
2. 1^h to 2^h before sunrise or after sunset	1 0.176	1 -0.846	1 0.027	2 2.279	1.636
3. 0^h to 1^h before sunrise or after sunset (twilight)	1 0.117	4 -1.720	2 -0.682	0 -	-2.285
4. 0^h to 1^h after sunrise or before sunset	3 0.466	2 1.114	1 0.734	0 -	2.314
5. 1^h to 2^h after sunrise or before sunset	3 0.349	1 -0.283	4 -1.887	0 -	-1.821
6. $>2^h$ after sunrise or before sunset (daylight)	0 -	0 -	7 -0.057	0 -	-0.057
Column Sums Total Sum of Squares	1.108	-1.735	-1.865	2.494	0.002 11.974034

Residual Mean Square:	0.3851 with 14 degrees of freedom
Illumination Mean Square:	0.5196 with 5 degrees of freedom
F-statistic (calculated):	1.349
Critical Value for rejection:	2.96 for $F_{5,14}$ (5%)
Quadrant Mean Square:	0.5500
F-statistic (calculated):	1.428
Critical Value for rejection:	3.34 for $F_{3,14}$ (5%)

TABLE II

Analysis of Variance, Aug/Sept Run

Number of Observations and Cell Sums

Illumination at t.c.a.	Quadrant of c.a. NE	SE	SW	NW	Row Sums
1. $>2^h$ before sunrise or $>2^h$ after sunset (dark)	1 -2.095	6 1.385	4 -4.709	0 -	-5.419
2. 1^h to 2^h before sunrise or after sunset	3 2.580	3 -4.481	5 3.737	4 3.297	5.133
3. 0^h to 1^h before sunrise or after sunset (twilight)	3 -2.459	2 1.313	0 -	3 -4.772	-5.918
4. 0^h to 1^h after sunrise or before sunset	5 7.283	0 -	3 -1.217	3 -1.241	4.825
5. $>1^h$ after sunrise or before sunset (daylight)	2 -0.551	0 -	0 -	2 1.929	1.378
Column Sums Total Sum of Squares	4.758	-1.783	-2.189	-0.787	-0.001 132.343029

Residual Mean Square:	2.881 with 29 degrees of freedom
Illumination Mean Square:	2.8490 with 4 degrees of freedom
F-statistic (calculated):	0.989
Critical Value for rejection:	2.70 for $F_{4,29}$ (5%)
Quadrant Mean Square:	0.786 with 3 degrees of freedom
F-statistic (calculated):	0.273
Critical Value for rejection:	2.93 for $F_{3,29}$ (5%)

TABLE III

USNO-AUST for each run, and combinations of runs.

The time scale designated AUST is the portable caesium standard DNM590. Units are in microseconds or microseconds/day. t is measured in UT days from 1970 Jan 0; $\bar{t}$ is the mean date of observation in each run. n is the number of observations in each run.

Run	USNO-AUST $=\alpha+\beta(t-\bar{t})$			USNO-AUST	n	standard deviation	
	α	β	$\bar{t}$	1973 Dec 07		σ_α	σ_β
A. Australian observations to NRL interpolates							
1. July 1973	-23.566	-0.09864	199.0	-37.57	38	.0221	.00600
2. Sept 1973	-29.320	-0.10195	265.4	-37.03	50	.0710	.01296
3. Jan 1974	-39.102	-0.01470	381.4	-38.51	32	.0590	.01528
4. July - Sept 1973	-26.835	-0.08686	236.7	-35.89	88	.0418	.00126
5. Sept 1973 - Jan 1974	-33.137	-0.08437	310.7	-35.69	82	.0528	.00093
6. July - Sept - Jan	-30.106	-0.08511	275.3	-35.70	120	.0369	.00053
B. NRL observations to Australian interpolates							
7. July 1973	-23.649	-0.10202	199.6	-38.07	43	.0223	.00620
8. Sept 1973	-29.403	-0.10021	265.5	-36.97	62	.0489	.01009
9. Jan 1974	-39.004	-0.02308	381.8	-38.06	47	.0500	.01363
10. July - Sept 1973	-27.046	-0.08762	238.5	-36.03	105	.0305	.00094
11. Sept 1973 - Jan 1974	-33.543	-0.08249	315.7	-35.63	109	.0380	.00066
12. July - Sept - Jan	-30.744	-0.08399	282.8	-35.63	152	.0292	.00041

UTC(USNO MC) - DNM590 (by USNO PC572): $-36.2 \pm 0.2\ \mu s$, 73 Dec 07.

TABLE IV

Comparison Between NRL-Interpolated and AUST-Interpolated Runs

Run	Hypothesis			
	1(i) Equal Variances	1(ii) Zero Rate		1(iii) Equal Rates
	f	t (NRL-Int)	t (AUST-Int)	T
July	0.868	16.440*	16.455*	0.390
Sept	1.700*	7.867*	9.932*	0.107
Jan	0.948	0.962	1.693	0.407
July-Sept	1.568	68.937*	93.213*	0.531
Sept-Jan	1.450	90.720*	124.985*	1.695
July-Sept-Jan	1.259	160.585*	204.854*	1.697

* Hypothesis rejected.

TABLE V

Validity of Extrapolating Between Runs

Run: Extrapolated from	to Midpoint of	Diff (Extrap. – Mean)	Number of Points (n_2)	s.d. of Extrap. Value (σ_2)	t
<u>NRL – Interpolated</u>					
July	Sept	–0.800	38	0.400	1.969
July	Jan	–2.454	38	1.095	2.238 §
Sept	Jan	–2.035	50	1.504	1.352
July–Sept	Jan	–0.294	88	0.187	1.499
Sept–Jan	July	–0.146	82	0.117	1.137
<u>AUST–Interpolated</u>					
July	Sept	–0.964	43	0.409	2.340 *
July	Jan	–3.233	43	1.130	2.858 *
Sept	Jan	–2.059	62	1.175	1.751
July–Sept	Jan	–0.600	105	0.138	4.087 *
Sept–Jan	July	0.324	109	0.085	3.687 *

§ Hypothesis accepted at 2% level.

* Hypothesis rejected.

TABLE VI

Evaluation of Inter-Run Consistency

Run 1	Run 2	Hypothesis	
		3(i) Equal Variances f	3(ii) Equal Rates T
<u>NRL - Interpolated</u>			
July	Sept	0.073 *	0.166
July	Jan	0.166 *	5.356 *
July	Sept-Jan	0.081 *	0.800
Sept	Jan	2.259 *	3.733 *
Jan	July-Sept	0.726	4.164 *
July-Sept	July-Sept-Jan	0.941	1.263
July-Sept	Sept-Jan	0.673	1.521
Sept-Jan	July-Sept-Jan	1.400	0.724
<u>AUST - Interpolated</u>			
July	Sept	0.144 *	0.117
July	Jan	0.181 *	5.068 *
July	Sept-Jan	0.135 *	1.327
Sept	Jan	1.260	4.408 *
Jan	July-Sept	1.201	5.023 *
July-Sept	July-Sept-Jan	0.756	2.161 *
July-Sept	Sept-Jan	0.622	4.171 *
Sept-Jan	July-Sept-Jan	1.216	1.980 §

§ Hypothesis accepted at 2% level.

* Hypothesis rejected.

QUESTION AND ANSWER PERIOD

DR. WINKLER:

I think there are several impressions which I have gotten, particularly yesterday and today when systems applications were discussed and performances have been disputed.

One fact came out very strongly this morning was that apparently people talking about the same subject can claim directly opposite extremes and yet both may be right. One radio astronomer said that the time limitation of experimentation is the atmosphere and not the clocks. The second said it's the clock, not the atmosphere and I believe that both are right and points out the fact that it is not sufficient to specify simply the performance of an atomic clock, for instance. That there are so many parts, ten to 12th or 10 to the 13th is useless unless one also specifies environment or specifies the timing that is required and a lot of other additional things.

APPENDIX

LIST OF ATTENDEES AND REGISTRANTS

6th PTTI PLANNING MEETING

U. S. Naval Research Laboratory

December 3-5, 1974

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LIST OF ATTENDEES AND REGISTRANTS

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