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REDUNDANCY MANAGEMENT OF MULTIPLE KT-70 INERTIAL MEASUREMENT UNITS APPLICABLE TO THE SPACE SHUTTLE

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16. ABSTRACT

This test program was designed to demonstrate that Failure Detection and Isolation (FDI) can be accomplished with three redundant KT-70 Inertial Measurement Units (IMU) and a single 4π-CP2 computer. Each of the three KT-70 IMUs are mated to an interface unit and each interface unit is connected to the processor interface unit via a serial data bus operating at 10 mHz.

A brief description of the major components that comprise the total system is given. Problems encountered with the hardware and software are discussed in addition to the solutions and modifications.

Test results for Velocity FDI for 3-IMU and 2-IMU configurations are presented. The failure detection and isolation algorithm performance was highly successful and most types of velocity errors were detected and isolated. The failure detection and isolation algorithm also included attitude FDI but was not evaluated in this test program because of the lack of time and low resolution in the gimbal angle synchro outputs. The Shuttle KT-70 IMUs will have dual-speed resolvers and high resolution gimbal angle readouts. It was demonstrated by these tests that a single computer utilizing a serial data bus can successfully control a redundant 3-IMU system and perform FDI.

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Duane White was instrumental in correcting problems and coding software changes for the 4π-CP2 computer. Edward Moore played an important part in trouble shooting the interface hardware and maintaining the equipment. Mr. White and Mr. Moore are with the Sperry Rand Corporation.

Major contributions to this program were made by Dennis Ellsworth and Collier Rawls of NASA. Mr. Ellsworth was indispensable in isolating and correcting software problems.

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REDUNDANCY MANAGEMENT OF MULTIPLE KT-70 INERTIAL MEASUREMENT UNITS APPLICABLE TO THE SPACE SHUTTLE

I. INTRODUCTION

This document is the final report on a task agreement with the Johnson Space Center (JSC) to develop a redundancy management scheme and to demonstrate failure detection and isolation (FDI), using three redundant KT-70 Inertial Measurement Units (IMU) and a single 4π-CP2 computer.

The Marshall Space Flight Center (MSFC) entered into this activity initially under the Shuttle booster flyback studies. A contract was let with the Charles Stark Draper Laboratory (CSDL) to define an experiment program to implement onboard checkout, failure detection, isolation and redundancy management for multiple IMU systems. As a result of the task agreement with JSC, the contract with CSDL was amended to add several additional modifications to make the hardware and software meet the Shuttle program requirements. Although the hardware used in this test program does not meet all Shuttle baselines, it is sufficiently similar to the Shuttle inertial hardware to permit it to be used as a test bed in the interim until the Shuttle hardware is operational (Figs. 1, 2, and 3).

CSDL developed the software programs and fabricated the interface hardware required to operate the multiple IMU system. System software developed by CSDL was delivered on two "tapes". Tape 1 contained system operational programs and tape 2 contained the 19 parameter calibration program. The CSDL calibration program was written from the single IMU calibration program developed by the Sperry Rand Corporation for MSFC. All IMUs were calibrated with the single IMU calibration program, using a Singer Test Station and 4π-CP2 computer. This was done so that the 3-IMU test station could be free for other operations while the individual IMUs were being calibrated.

A considerable amount of hardware and software debugging and correction was required after the equipment was delivered to MSFC. It should be noted, however, that CSDL had only one IMU available and limited time to verify the software and to make hardware corrections. Due to the excessive time required

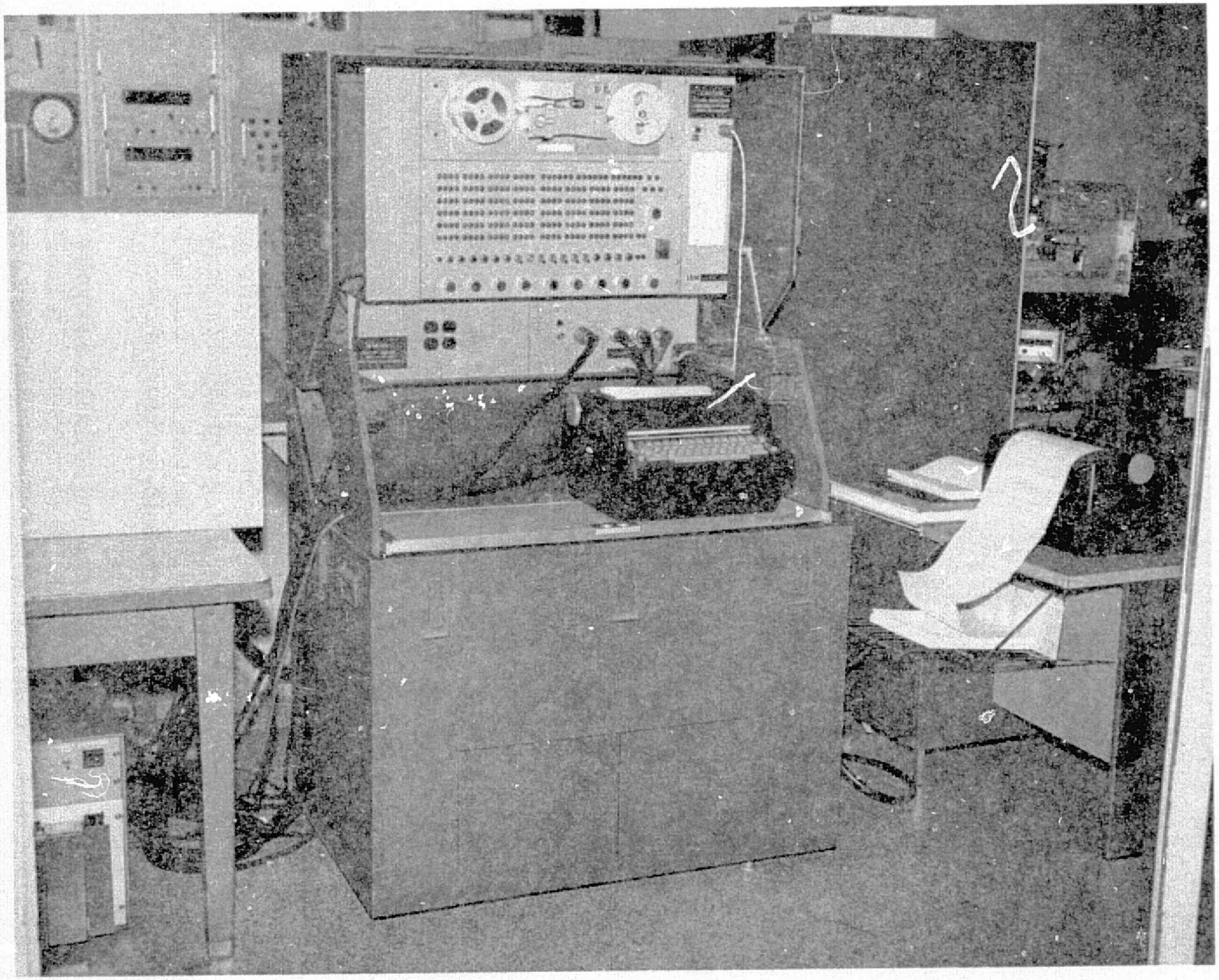

Figure 1. Field operating unit-CP2 computer input/output console.

Figure 2. Hewlett Packard computer console (part of PAINTS).

Figure 3. Three KT-70 IMU platforms, adapter power supplies, and interface units.

to correct the hardware and software problems encountered, the overall goals of the original test program were curtailed and confined primarily to 2-IMU FDI. This decision was made by mutual agreement between MSFC and JSC because of the greater value of the 2-IMU FDI tests with the presently baselined Space Shuttle configuration.

II. SYSTEM OVERVIEW

A view of the overall system may be gained by examining Figure 4. The laboratory test system employs three off-the-shelf Singer Kearfott KT-70 IMUs operating under the control of a single IBM 4π-CP2 computer. Each of the three KT-70 IMUs are mated to an interface unit (IU) which distributes power to the IMU and encodes and decodes its communication with the computer. Each IU is connected to the processor interface unit (PIU) via a serial data bus operating at 10 MHz. The PIU encodes and decodes communications and serves as an interface between the single 4π-CP2 computer and the individual IMU/IUs. The PIU also serves as the interface with MSFC's Programmable Automatic Inertial Navigation Test Station (PAINTS) (Figs. 2 and 3). All communication links are bidirectional.

III. SYSTEM COMPONENT DESCRIPTION

The following paragraphs provide brief descriptions of the major components that comprise the total system.

A. IMU and Adapter Power Supply (IMU/APS)

The redundant IMU system was designed to employ three off-the-shelf Singer Kearfott KT-70 (AN/ASN-90) IMUs with their adapter power supplies (APS).

The KT-70 IMU is a four gimbal platform containing two, 2-degree-of-freedom, dry flexure-mounted wheel gyros. The redundant gyro axis is slaved to null. The platform also contains a single, and a 2-degree-of-freedom, dry flexure accelerometer. The three gimbal angle readout signals are derived from single speed synchros. The outer roll gimbal is slaved to the inner roll gimbal and gimbal-flip occurs at pitch angles approaching ±90°, which assures pitch/azimuth gimbal orthogonality to prevent gimbal lock.

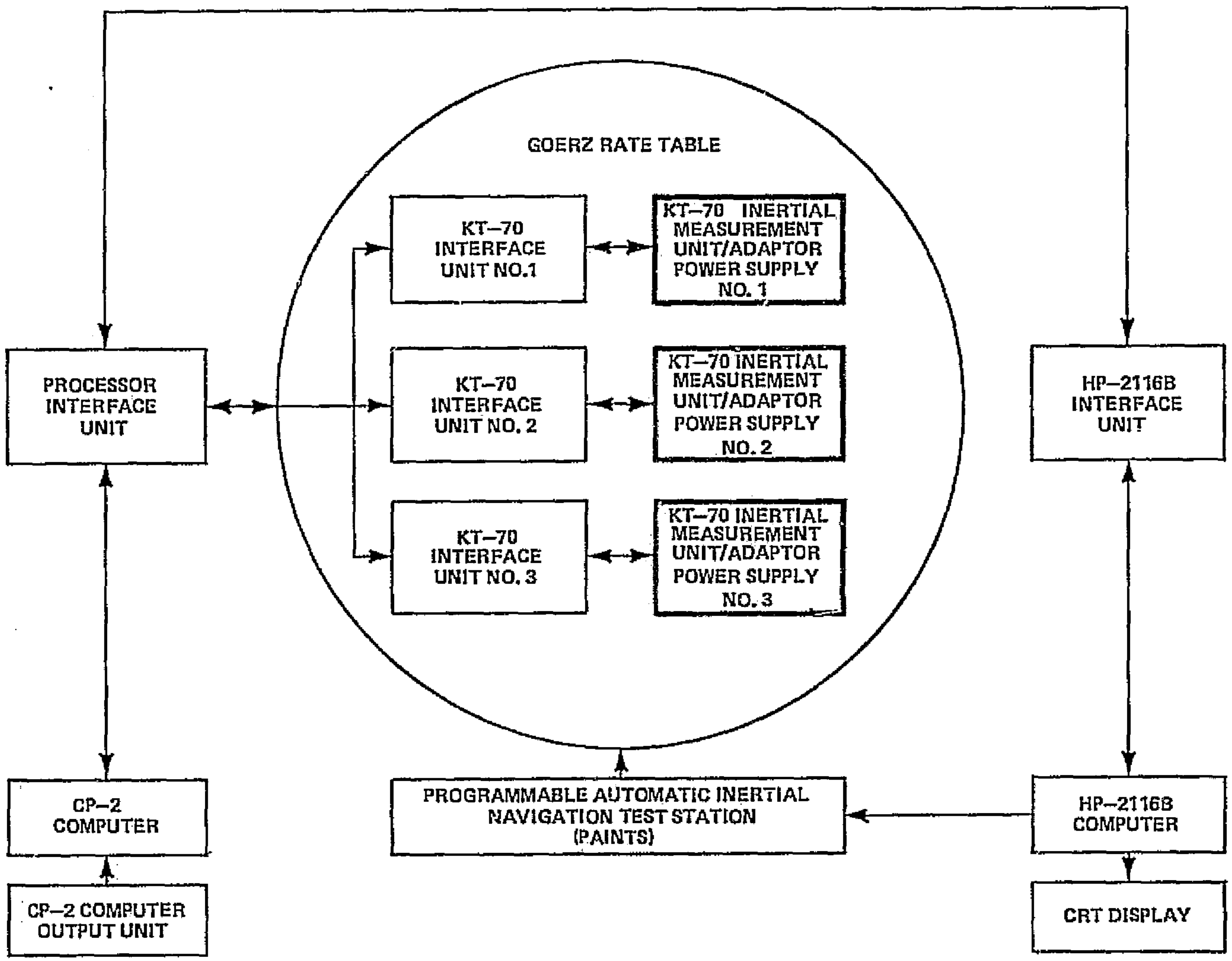

Figure 4. IMU redundancy management test configuration.

Accelerometer output pulses represent quantized increments of integrated rebalance current, and are characteristically asynchronous. The accelerometer output ΔV pulse scale factor is 0.032 fps/p. The gyros may be torqued either digitally or by analog commands. The APS requires 115 V, 3 phase, 400 Hz power from an external source, and provides all dc and ac voltage levels required by the IMU. A battery pack is mated to the APS to provide transient protection, for a limited duration, in the event of a dropout of the primary power source.

B. IBM 4π-CP2 Computer and Ancillary Equipment

The IBM 4π-CP2 computer is a general purpose, stored program, parallel, fixed point, binary computer with auxillary memory. External control and input/output (I/O) is accomplished through use of a field operating unit (FOU). The FOU is equipped with a typewriter, paper tape reader and paper tape punch. The computer stores 8 K, 32-bit words (or 16 K, 16-bit words); the capacity of the auxillary memory doubles this figure. The memory cycle time is 2.5 μs. The computer is configured for externally controlled input and output, i.e., PIU controls all data transfer. The computer cycle times are determined by an external interrupt driven by the PIU's 10 MHz master oscillator.

C. Processor Interface Unit (PIU)

The PIU is the interface between the 4π-CP2 computer and the four data bus addresses. It functions to encode and decode communications for the computer, and to serve as an I/O buffer. Parallel data transfers, at 60 K words/s, are used between the computer and PIU. Data transfers to the HP-2116B computer (PAINTS), one of the bus addresses, are also accomplished by a parallel bus at low rate. The other addresses to the three IUs are reached by a 10 mHz serial data bus. The PIU is required to encode and decode data bus communications, perform master timing for the system (including the 4π-CP2 and HP-2116B computers), and control of the 4π-CP2 I/O.

The PIU's 10 MHz master oscillator provides all timing for the system, from the 10 MHz bus clock to the 50 Hz minor cycle control. The 10 MHz pulse train drives a 9 bit (18 state) Johnson counter which provides the timing pattern required for data bus encoding and decoding. It also provides the clock for the finite state controller, which directs the PIU in carrying out its assigned tasks. The PIU has a manual push-button ABORT switch, which functions to reset the finite state machine to state "O" and to issue a discrete interrupt to the computer, causing a restart. The PIU employs TTL logic in standard 14 and 16 pin dual-inline-pack integrated circuits, and it contains three data bus drivers and receivers.

D. Data Bus

The bidirectional data bus consists of four twisted and shielded wire pairs, each with a single function. The functions are transmit clock, transmit data, receive clock, and receive data. Words in the data bus messages are 18-bits, or 1.8 μs long. The bidirectional data bus was designed by CSDL according to NASA/MSFC's breadboard data bus specification. It has been demonstrated by these tests that a single computer using a serial data bus can successfully control a redundant 3-IMU system.

E. Interface Unit

The IU decodes data bus transmissions and serves as the interface between the IMU/APS and the PIU. These transmissions can synchronize accelerometer readings, command (IMU and gyro pulse torque commands) or demand (read accelerometers, read synchro/digital (S/D) converters, read IMU/IU status, etc). On read demands, the IU encodes a reply acknowledging receipt of the message and encodes any requested data. The IU also must act on commands, which include mode changes (i.e., ground align to gyrocompass mode), resetting discretes and analog torquing sense discretes. The IU contains three S/D converters to convert the gimbal synchro outputs from analog to digital. The S/D output signal is 14-bit, parallel, and is TTL compatible. The IU employs TTL logic in standard 14 and 16 pin dual-inline-pack integrated circuits.

The KT-70 IMU gyros are dithered with a 200 pps 1:1 binary torquing pattern. In other applications, a single IMU is mated directly to a dedicated computer and each torque pulse is commanded individually. In this system, a single computer services nine gyros on the three IMUs and the time requirement for individual torque commands would require too much time of each computer cycle. This system was designed so that the torque command to each gyro is stored in a shift-register and the command is constant until an up-date is received from the computer. The shift-register for each axis receives torquing information 50 times/s.

The accelerometer ΔV pulses are accumulated in registers which are 12-bit, up-down counters. The counters are located in the IU and are read in response to a command from the PIU/computer.

F. Programmable Automatic Inertial Navigation Test Station (PAINTS)

This test facility is a part of the MSFC Electronics and Control Laboratory. It comprises a Goerz rate table, HP-2116B computer, magnetic tape storage, line printer, CRT display, and a single pin plotter. The PAINTS was used to monitor all three KT-70 IMU systems simultaneously on the CRT in real time. The HP-2116B computer was programmed to change data formats for the different modes of platform operation. The HP computer also converted the KT-70 data into engineering units for display and recording. This test facility was invaluable in troubleshooting hardware and software problems and in evaluating the KT-70 performance in real time.

G. PIU/HP-2116B Interface

The first major problem encountered was an attempt to send data from the PIU to the HP-2116B computer for data retrieval. One of the problems was due to noise spikes on the PIU/HP-2116B interface cable. This was corrected by shortening the interface cable from 50 to 15 ft and terminating each end of the cable wires with the proper matching impedance. The line driver chips in the PIU were also changed to a different type to improve the data transmission.

There was also a compatibility and timing problem in communications between the PIU and HP computer. This was corrected by making some changes in the PIU output logic circuits to the HP computer.

IV. MODIFICATIONS TO CSDL HARDWARE

A. KT-70 Torque Commands

Each time the KT-70 is commanded to enter the ground alignment mode, the platform slews to the -90° position and computes the Y gyro drift term (DY). The IMU then slews back to the 0° heading where the X gyro drift term (DX) is computed. It was noted after several ground alignment runs that the DX and DY drift terms were not repeatable to within the desired limits. The ground alignment computer program was analyzed and several changes were patched into the program in an effort to solve the problem, but these changes were unsuccessful. The hardware was not immediately suspect, since it was functional. After observing the gyro torquing commands on an oscilloscope, it appeared that the torque pulses were not stable. This signal is difficult to analyze visually since the torque pulses are normally changing under dynamic closed loop conditions. A review of the Singer Kearfott IMU specifications revealed a requirement that the command/clock pulse rate be 200 pps with a clock stability of 100 ppm. It was found from examining the IU prints that the 200 pps command/clock pulses were derived from a 400 Hz free running oscillator, which was incapable of maintaining the stability required by the specification. The original design had attempted to synchronize the nominal 400 Hz clock by resetting the oscillator every 20 ms with the request accelerometer update (RAU) signal, which was available in the IU.

To correct the gyro torquing problem, a crystal controlled 400 Hz Gyro Pulse Torque (Gypto) clock was fabricated and installed in IU SN-1. This clock was derived from a 128 kHz crystal oscillator which was accurate to 10 ppm. With this crystal controlled Gypto clock, several ground alignment tests were made and the DX and DY drift measurements were repeatable.

Rather than add a crystal oscillator in each IU, a modification was made to run the 400 Hz signal from the master timing count-down chain in the PIU to each of the three IUs over separate lines. This provided a 400 Hz signal synchronized to the signals used for the 4π-CP2 interrupt and minor cycle timing. The addition of synchronizing the Gypto clock to the 4π-CP2 computer minor cycles improved the accuracy of the Gypto pulse commands. This modification corrected the Gypto commands and the DX and DY drift terms were computed during each ground alignment run with good repeatability.

B. Interface Unit Parity Errors

One of the most perplexing and troublesome problems encountered throughout this program was the issuance of parity errors by the logic circuits. When the 4π-CP2 computer received a parity error, the computer ceased to function and the test run had to be aborted. This occurred frequently and on numerous occasions an abort was given after a test run had been in progress for 3 or more hours. The problem was intermittent and seemed to be caused by two sources. One source was the parity bit generator in the IUs. At one point in the program, only one IU was consistently operational without issuing parity errors. The problem was eventually isolated to the parity bit generator. This circuit has a pulse feedback loop and the time delay in the loop was extremely critical due to the high pulse rate. Integrated circuit chips were changed out to correct the problem, although the integrated circuits performed normally. It was found that the parity generator circuit would function only if the integrated logic chips were made by a particular manufacturer. The time lag in the integrated circuits varied between manufacturers by a few nanoseconds, which was enough to cause a slight phase shift in the feedback pulses. This caused a mismatch with the input pulses and, therefore, a parity error was issued.

The second source of parity bits was in the PIU +5 Vdc power supply. The power supply was heavily loaded and a constant +5 V output could not be maintained because of insufficient voltage regulation. A voltage transient on the 60 Hz power line would cause a parity error and a resulting abort. The +5 Vdc supply was replaced by connecting an external dc supply to the PIU bus. This power supply had more capacity and better voltage regulation than the smaller PIU supply.

V. MODIFICATIONS TO THE CSDL SOFTWARE

A. Ground Alignment

The first sequence in the ground alignment mode is to slew the platform -90° about the azimuth or Z axis. The platform is then leveled and the azimuth offset angle is computed. The offset angle will depend upon the initial heading of the platform before the slew and the accuracy of the analog slew rate. The offset angle is slewed out and the Y gyro drift (DY) is computed. When the offset angle is large, the platform tilt can be affected during the offset slew. A change was made in the ground alignment program to relevel the platform after the offset angle was slewed out. This change resulted in better repeatability in the Y gyro drift rate computation when the offset angle was relatively large.

After the DY computation is complete, the platform is slewed +90° back to the nominal 0° heading. The platform is leveled and the X gyro DX drift rate is computed without correcting for the azimuth offset, which is usually small. A change was made in the alignment program to correct the azimuth offset at the conclusion of the DX computation and the DX computation was repeated with the corrected azimuth. This made a slight improvement in the computation of the DX term.

B. Gyrocompass

The gyrocompass mode is entered automatically at the conclusion of ground alignment. Azimuth offset correction at the conclusion of the DX computation in ground alignment also minimized the heading offset prior to entering the gyrocompass mode. This reduced the time required to gyrocompass to the desired azimuth.

The gyrocompass program was written to run for a preset time and then automatically enter the navigation mode. It was found to be desirable to determine in real time when gyrocompassing had reached an acceptable level. To provide this capability, a switch was added to the front panel of the PIU. The switch was wired to the 4π-CP2 interrupt DIN 22.

The computer program was modified to monitor DIN 22 and it remained in gyrocompass until the switch was placed in the NAV position. The program then entered the navigation mode. The time required to complete a gyrocompass run ranged from 30 min to 1 h.

C. Navigation Program Changes

The navigation program computed the earth's radius as a function of computed latitude. Since the test site was fixed, a change was made in the program to maintain a constant earth radius.

The navigation program was written assuming that the gravitational acceleration vector, due to mass attraction, pointed to the geometric center of the earth. In reality, this vector points to a point below the geometric center of the earth and it has two components. One component is perpendicular to the equatorial plane and the second component lies in the equatorial plane and in a plane containing the test site and the polar axis.

A change was made which computed the earth-centered inertial X and Y acceleration, due to mass attraction, as a function of the component in the equatorial plane and the angle through which the test site had rotated since the platform had gone inertial. The Z component was set equal to the component perpendicular to the equatorial plane. The result was that these accelerations were computed independently of the latitude and longitude as originally computed by the navigation program.

The equations which clamped altitude, in the navigation program, were eliminated to give a better insight into the velocity errors. The altitude error remained within an acceptable range for all tests after a correction was made in the computation, which is discussed in the following paragraph. With the altitude clamp, altitude errors were used to correct (or drive in a direction to correct) the velocity errors which caused the altitude errors. In effect, the velocity corrections were distributed onto the earth-centered inertial axes as a function of the direction cosines of the test site radius vector in earth-centered inertial coordinates. This made it difficult to determine the instrument errors which had caused the velocity behavior because of the erratic changes in velocity due to the clamp.

It was found that the major portion of the altitude error was generated by computational inaccuracy. The computation of altitude from the position components was accomplished by floating point, with a 32-bit machine. The first 9 bits were used for sign and exponent, leaving 23 bits for data. This gave only 7 place accuracy, which resulted in position error build-up. A change was made to perform fixed point computation of the position components, with scaling to obtain 8 place accuracy. The result was a greatly reduced altitude error, which was due primarily to platform hardware errors.

The navigation program computed velocities in the earth-centered inertial reference frame. The velocities were then transformed to the local vertical reference frame defined by the computed latitude and longitude. Changes were made to the navigation program so that the velocity errors were displayed in the actual earth-fixed reference frame at the test site.

D. Three-IMU Navigation with Velocity FDI

It was found that when an attempt was made to navigate with 3 IMUs in the average filter, midpoint filter, Kaufman filter, or in the multinavigator mode with velocity FDI active, sudden shifts in velocity errors occurred. Analysis revealed that insufficient time was available to perform all of these computations in a major cycle (200 ms). Changes were made so that the computations were performed in different major cycles (200 ms time periods). This meant that FDI was performed with slightly different data than that used in navigation, but was skewed apart by only 200 ms. The velocity and attitude FDI scheme is shown in Figure 5.

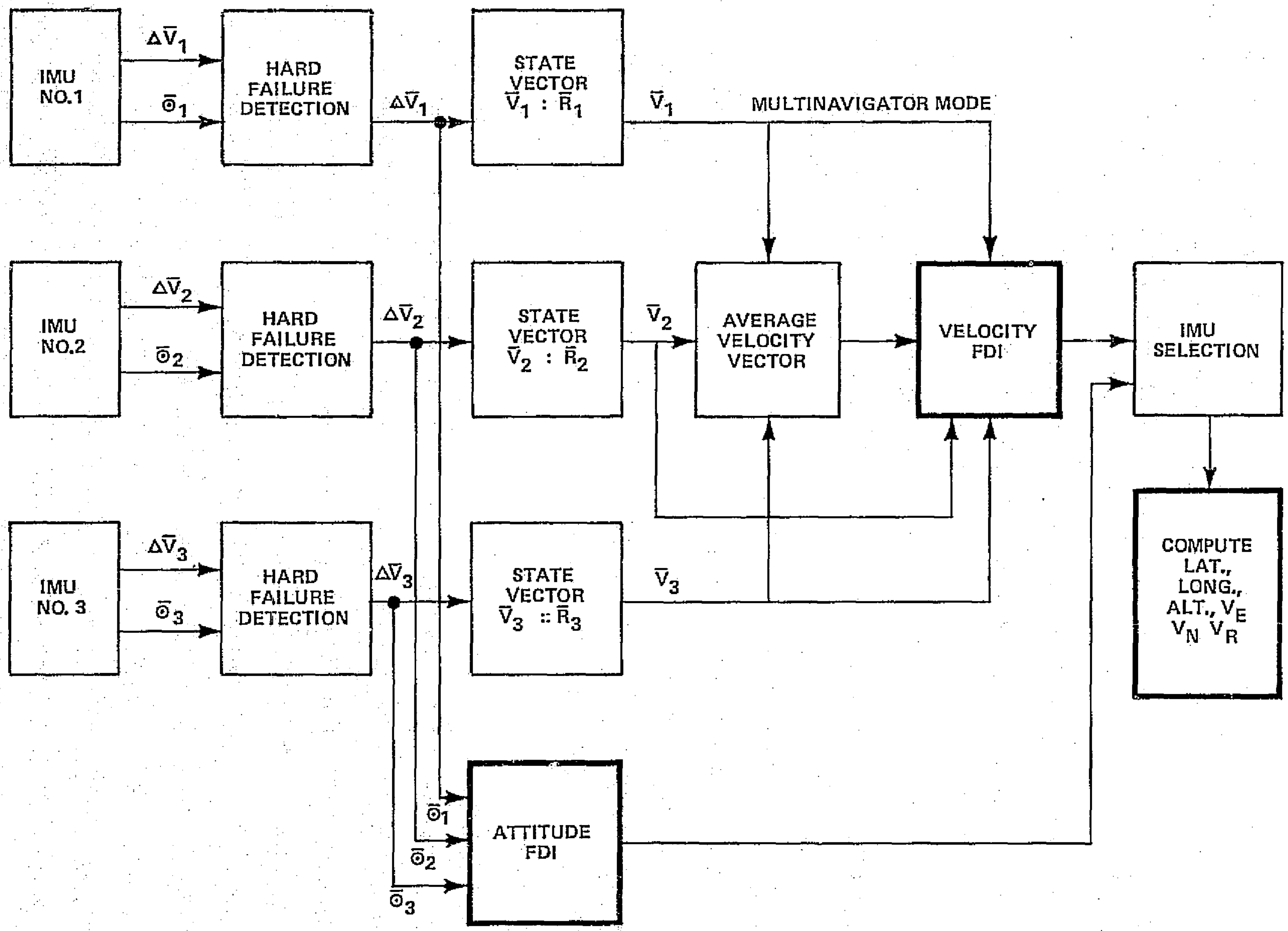

Figure 5. Multiple IMU velocity and attitude FDI scheme.

E. Three-IMU Navigation with Attitude FDI

A similar problem to that encountered with velocity FDI was found. Again, the computations were skewed apart by one major cycle. This problem occurred only when attitude FDI was performed every 200 s. Since no navigation values are used in attitude FDI, no problem existed in skewing the computations.

F. Two-IMU Navigation with Velocity FDI and Attitude FDI

A problem similar to that encountered with 3-IMU velocity FDI and 3-IMU attitude FDI was uncovered with 2-IMU navigation with velocity and attitude FDI. Again, this was corrected by skewing these computations by one major cycle. Thus, velocity FDI was performed in one major cycle followed by navigation in the next major cycle and every 50 s the navigation cycle was followed by attitude FDI in the next major cycle.

A change was made in the 2-IMU velocity FDI algorithm because the gyro errors could not be detected. This was caused by the fact that the transformation relating the skewed and non-skewed IMU reference frames was continually updated by current gimbal angle information. Therefore, the velocity transformation from skewed to non-skewed space and from non-skewed to skewed space was always in agreement and gyro drift would not cause the velocities to diverge, even though the platforms drifted apart. A change was made to compute the transformation initially (after skewing one of the IMUs) and this was used to transform velocities from one space to another in all subsequent velocity FDI computations. The result was that gyro drifts would perturb the 2 s sum of velocity and the skewed and non-skewed IMU velocity would drift apart when compared to the same reference frame and detection was accomplished. The navigation computations continued to use the transformation obtained from current angle information.

Navigation performance was poor in the 2-IMU configuration due to the gimbal synchro error (±6 min) and to the error in the S/D converters. The gimbal synchro output is used in the transformation for rotating the accelerometer velocity outputs of the skewed IMU into the non-skewed reference frame. This results in an error in the computed position of the skewed IMU. This same type navigation error is introduced by, and is very sensitive to, misalignment between IMU cases. The IMU case-to-case alignments were made while the IMUs were in the gyrocompass mode so that they could be aligned together as closely as was practical.

A further effort to minimize the IMU case-to-case alignment error was made using a software fix. This consisted of a transformation matrix for case-to-case alignment. The element values for this transformation matrix were determined from errors obtained during the first few seconds of a navigation run and they were held constant for all subsequent runs.

The accuracy of the instrument compensation values was another factor in the poor navigation for the 2-IMU configurations (this was a factor in all navigation modes). The instrument compensation values were obtained from calibration runs using the Singer Kearfott single IMU test station. The calibration program was coded for the 4π-CP2 computer from Kearfott equations and calibration of gyro mass unbalance was added to the program by MSFC. The Kearfott calibration program was written for vertical IMU navigation in aircraft applications. In this program, the IMUs were inertial during the navigation runs. Inertial navigation in a 1 g field requires highly accurate instrument compensation. It was demonstrated that small percentage changes in a single compensation term produced significant error velocity changes during a navigation run. The results of this test program indicate that the present calibration program does not have the capability to produce compensation terms to the required accuracy for inertial navigation. It is our understanding that an improved calibration program has been implemented by Kearfott.

VI. FAILURE DETECTION, ISOLATION AND REDUNDANCY MANAGEMENT FOR THREE COLINEAR IMUs

The following is a description of the velocity FDI program for the single navigator mode as implemented by CSDL. The velocity FDI program accumulates accelerometer output data over a 2 s time interval.

$$\overline{\Delta V_{AVE}} = \frac{1}{3} \sum_{I=1}^{3} \overline{CAP_I}$$

where I = IMU number and $\overline{CAP_I}$ = compensated CAPRI data for IMU 'I' accumulated for 2 s.

The (3X3) velocity error ratio matrix is given by

$$VER \equiv (VER_{IJ}) = \left(\frac{\Delta V_{AVE,J} - CAP_{IJ}}{|\overline{\Delta V}_{AVE}|} \right)$$

where I = IMU 1, 2, 3 and J = Axis X, Y, Z .

The total squared error for each axis is computed from the components of the velocity error ratios as follows:

$$VTE_J = \sum_{I=1}^{3} (VER_{IJ})^2$$

for J = Axis X, Y, Z.

The (3X3) isolation ratio matrix is then computed as follows:

$$ISR \equiv (ISR_{IJ}) = \left[\frac{(VER_{IJ})^2}{VTE_J} \right]$$

for I = 1, 2, 3 and J = X, Y, Z.

Two levels of FDI are performed for velocity errors, 3σ and redline. A failure must be detected and isolated at both levels before the affected IMU is soft failed and removed from the navigation process.

The first test performed is for 3σ failure detection. If no error is detected, the program is exited. If a failure is detected, then 3σ isolation is attempted. Whether or not a successful 3σ isolation is accomplished, a redline failure detection is attempted. If the redline failure is not detected, the program is exited. If detection is made, redline isolation is attempted. Only if the redline failure isolation is successful will the affected IMU be soft failed, thereby removing it from the navigation process.

A failure on axis J is detected if the following relation holds:

$$VTE_J > KD_J$$

where KD_J is the appropriate detection level, 3σ or redline, for axis J. A failure detected on axis J is isolated to IMU I if the following holds:

$$ISR_{IJ} > KI$$

where KI is the isolation level constant, which is the same for both 3σ and redline isolation.

VII. FAILURE DETECTION, ISOLATION AND REDUNDANCY MANAGEMENT FOR TWO SKEWED IMUs

With two skewed IMUs, velocity FDI compares the measured ΔV of each IMU with that of the other IMU transformed into its own space. This two velocity FDI iteration is made every 2 s. A change was made in the computer program to compute the velocity transformation matrix on the first pass after skewing one of the IMUs. This transformation was then used to transform velocities from one space to the other for all subsequent velocity FDI computations in that particular run.

Performing velocity FDI at the IMU level with only a 2 s velocity accumulation limits the error level that can be detected. The accumulated error for 2 s is small and it makes the detection of gyro and accelerometer bias shifts difficult. Therefore, unless the bias shift is large, it will not trip the detection level and the bias will go undetected while the velocity error increases. There also is a limit on the minimum detection level that can be set without experiencing unwanted detections due to normal deviations.

Performing velocity FDI at the state vector level would not limit the type of errors that could be detected. FDI at this level would be accomplished with errors that had accumulated from the start of the navigation computation and the algorithm would be more sensitive to errors of all types.

VIII. NAVIGATION AND VELOCITY FDI TEST MODES

Test data were taken from three modes of navigation:

1. Three-IMU single navigator, using an average filter

2. Three-IMU multinavigator, using the mid-value filter

3. Two-IMU FDI, average filter.

In the single navigator, the three operating IMUs are in a colinear configuration. The velocity outputs from all three IMUs are averaged and the resultant average state vector is used by the navigator. Velocity FDI is performed as discussed in Section VI.

The multinavigator also operates with all three IMUs in the colinear configuration. A state vector is computed for each IMU, the average state vector obtained, and the mid-point filter then selects the IMU that is in best agreement with the average value. The state vector for this IMU alone is used for the navigation output. If the selected IMU deviates from the midpoint value, another IMU is selected to replace it. Velocity FDI is performed at the state vector level as described in Section VI; however, the velocity used is the total velocity instead of only a 2 s sum from the IMUs.

The 2-IMU FDI mode is automatically selected when 1-IMU has a soft or hard failure. The higher numbered of the two remaining on-line platforms is slewed to the skew position. The velocity from the skewed platform is then transformed into the non-skewed reference frame, where the two ΔV vectors are averaged for use by the navigator. Single instrument errors (such as accelerometer biases) in the skewed platform are propagated on all navigation axes because of the skew geometry. Similar errors in the reference platform are propagated on only one axis.

Every test starts in the ground alignment mode which requires approximately 20 min to complete. The gyrocompass mode begins automatically at the completion of ground alignment. Gyrocompassing continues until terminated manually by operating a switch which sends an interrupt to the computer. The time required to complete gyrocompassing depends upon the initial azimuth heading and platform tilt at the time of entry. Time in the gyrocompass mode ranged from 30 min to 1 h and was determined by monitoring the IMU outputs on the system display CRT. When the NAV switch was operated, the computer switched from gyrocompassing to navigation, whereupon the IMUs went inertial and navigation computation began.

To simulate a soft failure, an instrument miscompensation value was stored in the computer memory. At a preset time during the navigation test, a miscompensation routine altered the normal compensation parameters of a specified instrument of a specified IMU by a predetermined amount. In this series of tests only one parameter was altered during any particular run. The program had the capability of altering several parameters at various times as specified. In all runs in this series, the miscompensation routine was set to start at either 10 or 20 min after the start of navigation.

IX. TEST DATA SUMMARY

The 3-IMU test data are plotted for runs 1 through 8 (Appendix). The conditions under which the tests were performed are given on each graph, and the miscompensation was applied 10 min after entering the navigation mode. It should be noted that the time given on the graphs for error detection and isolation is from the start of navigation. Therefore, 10 min (or 600 s) should be subtracted from the time stated to determine the time required to detect and isolate the applied miscompensation. Test runs 1 through 5 were made in the single navigator mode using the average filter. Test runs 6 through 8 were made in the multinavigator mode using the mid-value filter. The error detection level and isolation ratios suggested by CSDL were used in all 3-IMU test runs.

Navigation runs 9 through 22 are plotted from data taken during the 2-IMU test configuration. Test results for these and all other 2-IMU test runs are tabulated in Tables 1-4. Data from all test runs have not been plotted since the curves are repetitious. The test data for all 3-IMU test runs have been tabulated in Table 5. The test data for all 2-IMU test runs have been tabulated in Table 6.

Miscompensation parameters were introduced in skewed and non-skewed IMUs and were applied at a preset time from the start of navigation. The preset time was 10 min in most runs but some were timed for 20 min. The error detection level was reduced by 20/1 from the value suggested by CSDL and some other values were also tried. These changes were made to reduce the time for valid detection and isolation without receiving erroneous error detections. The isolation ratio of 0.93 was the value suggested by CSDL and it was held constant for all 2-IMU runs. The velocity errors listed in the test results Ve, Vn, Vr, are the East, North, and radial error velocities respectively, referenced to the earth-fixed reference frame at the test site.

X. CONCLUSIONS

The FDI algorithm performance was generally good. As was expected, some miscompensations were more easily detected than others. In the gyro bias miscompensation runs, the errors were correctly detected in almost all cases. There were a few runs where the error was not detected because the gyro bias caused a platform rotation about an axis that was near the local vertical. This resulted in small changes in velocity errors that were at or near the threshold of detection.

In the low gain accelerometer bias (BLX, BLY, BLZ) miscompensation runs, the large bias errors of 0.1 m/s^2 were readily and correctly isolated. The 0.05 m/s^2 miscompensation runs demonstrate that the miscompensation can improve the IMU performance to a degree in some cases. As can be seen in runs 39 and 40 (Table 2), the +0.05 m/s^2 error was detected immediately and the -0.05 m/s^2 error was detected in 210 s. This can also be seen in runs 44 and 45. The disparity in detection time is due to the imprecise IMU calibration parameters with which we had to work and to the gimbal angle readout errors. These tests show that an accelerometer bias of 0.05 m/s^2 is easily detected and that accelerometer biases of 0.025 m/s^2 are for all practical purposes undetectable, even though large errors accrue.

In the low gain accelerometer scale factor (KLX, KLY) miscompensation runs, the algorithm was ineffective in detecting X and Y accelerometer errors on the non-skewed platform. This was expected because the X and Y accelerometers sense acceleration almost entirely in the horizontal plane. When the IMU goes inertial, small accelerometer outputs build up, but they are relatively small and a large scale factor error is required to generate detectable errors. The Z accelerometer, however, senses almost 1 g on the non-skewed IMU and an error of 9.1×10^{-5} m/s/p (3×10^{-4} ft/s/p) was detected immediately. It should be noted that this is equivalent to approximately 0.09 m/s^2 (0.03 ft/s^2) bias error, since the Z accelerometer on the non-skewed IMU has an output of approximately 1000 p/s/g. On the skewed IMU, all accelerometers sense components of 1 g and an error of 0.42×10^{-4} m/s/p (1.3815×10^{-4} ft/s/p) was detected immediately in the X accelerometer. The X accelerometer scale factor error on the skewed IMU is significant, since this accelerometer senses a large component of g.

The 2-IMU FDI gyro scale factor test runs show that detection and isolation were ineffective except for very large scale factor errors. In fact, the navigation errors due to this type miscompensation were relatively small.

To optimize the FDI test results, a substantial amount of time and effort was expended to improve the accuracy of the IMU calibration parameters before the FDI tes[illegible]n. Unfortunately this effort had to be cut short because of the time required and the approaching termination of the project. The number of 3-IMU test runs were limited due to the shift in emphasis to the 2-IMU configuration. Another consideration was the large number of variables to be evaluated in the 2-IMU configuration and the fact that each test run requires 2 to 3 h to complete.

Time did not permit all possible miscompensations to be evaluated, but a representative number of runs were made in the most error sensitive parameters. After the selection of 0.075 for the error detection ratio, further variations were made to increase the sensitivity of detection to reduce the time required to detect an error. The error detection ratio was reduced as far as possible, but the improvement in error detection over the 0.075 value was not significant. The isolation ratio of 0.93 was used throughout these tests and it was very effective in isolating the applied errors to the proper IMU and to the proper axis. Time did not permit evaluating changes in this parameter.

The 2-IMU velocity FDI test results are considered to be highly successful, even with the limitations in the IMU calibrations and the gimbal angle readouts. Miscompensations applied in the sensitive axes were detected and isolated in a timely manner and the velocity error build-up in the process was held to a minimum.

XI. RECOMMENDATIONS

Run 5 demonstrates a serious problem encountered when performing velocity FDI at the IMU ΔV level with colinear IMUs in the single navigator mode. With only a 2 s sum of velocity to work with, accelerometer bias and scale factor errors will not be detected unless they are sufficiently large to trip the detection level. The only accumulative effect of the error will be through the IMU mass unbalance compensation, which will cause a platform drift. This requires a long time to build up sufficiently large errors to trip the detection level, although, the velocity errors increase rapidly.

Three solutions are possible for this problem:

1. Lower the detection level.

2. Perform FDI using a ΔV accumulated over a longer time interval.

3. Perform FDI downstream of the navigation computations at the state vector level.

The first solution would lead to more false failures due to transients, vibrations, etc., and would probably lead to unsatisfactory results.

The second solution means that velocity FDI would be performed less frequently unless special precautions were taken. One means of getting around this would be to make the computations on a sliding time scale or moving ΔV value. This solution could have promise, however.

The third solution makes the system more sensitive to all errors and should be seriously considered if the IMUs are kept colinear in the Shuttle system.

Run 8 demonstrates a serious problem with the multinavigator mode of navigation using the mid-value filter. As the mid-value filter switches from IMU to IMU, transients result in the velocity error output. These transients could cause perturbations in the guidance algorithm unless filtered out. A solution to this problem would be to use the average value of the three IMU state vectors in the guidance algorithm.

The 2-IMU velocity FDI runs demonstrate that gyro errors are readily detectable when performing FDI at the ΔV level with the changes made as previously discussed. However, accelerometer bias errors and scale factor errors may or may not be detected, depending upon the magnitude of the error. To increase the potential to detect these errors, velocity FDI should be performed at the state vector level. This would increase the sensitivity of the algorithm to all errors. To detect gyro errors, it is necessary to transform the velocities through a transformation determined after the skewed orientation is obtained. The transformation is invariable in all subsequent processing. The transformation used in the navigation process must be the current one obtained from current gimbal angle information.

The navigation system is less sensitive to errors in the skewed IMU. This results from the fact that the individual instrument errors are distributed on all three axes of the non-skewed system. It would prove advantageous then to navigate with the IMUs in a skewed configuration if the gimbal angle information is accurately known.

TABLE 1. 2-IMU FDI TEST, GYRO BIAS MISCOMPENSATION

RUN NO.	MISCOMPENSATION APPLIED: IMU					ERROR DETECTION LEVEL	RESULTS: ERROR LOCATION: IMU			TIME TO ISOLATE ERROR (SEC)	V_E (M/S)	V_N (M/S)	V_R (M/S)
	SKEWED	NON-SKEWED	BIAS OF GYRO	TIME FROM START (MIN.)	VALUE °/HR.		SKEWED	NON-SKEWED	AXIS				
10		X	X	10	1	.075		X	Y	500	4.0	– 1.02	– .148
11	X		X	10	1	.075	X		Y	470	– 1.30	– 1.31	– .342
12		X	Y	10	1	.075		X	X	545	– 1.24	3.99	– .048
13	X		Y	10	1	.075	X		X	560	– .874	– 198	– .087
14		X	Z	10	1	.075	NOT DETECTED			–	8.57	14.29	1.73
15	X		Z	10	1	.075	X		Y	1565	3.08	– 4.05	.798
16		X	Z	10	–1	.075		X	X	2300	6.16	–14.09	2.68
17		X	X	10	–1	.075		X	Y	750	–13.62	.554	– .015
18	X		X	10	–1	.075	X		Y	535	– 1.63	– .912	– .158
19		X	Y	10	–1	.075		X	X	850	– 2.03	–18.0	.101
20	X		Y	10	–1	.075	X		X	3350	78.44	42.3	8.6
21	X		Z	10	–1	.075	X		Y	1470	1.31	1.58	.841
22		X	Z	10	1	.075	X		Y	2910	16.3	33.3	4.13
81		X	X	20	1	.06		X	Y	465	1.23	.11	.33
82	X		X	20	1	.06	X		Y	485	– 1.64	– .087	.16
83		X	Y	20	1	.06		X	X	535	.071	9.05	1.44
84	X		Y	20	1	.06	X		X	510	– 1.67	– .115	.472
86	X		X	20	1	.05	X		Y	410	– 1.82	.98	.335
87		X	X	20	1	.06		X	Y	295	– 1.44	– 2.11	.55
88		X	X	20	1	.045		X	Y	130	– 1.29	– 1.31	.24
89		X	X	20	1	.045		X	Y	175	– 2.39	– 0.35	– .053
90		X	Y	20	1	.045		X	X	560	– 1.04	.099	.219
92		X	Z	20	1	.045	NOT DETECTED			–	1.13	2.96	1.56
93		X	Y	20	1	.045		X	X	280	– 1.89	1.79	.44
106	X		Y	10	–1	.06	X		X	965	– 2.37	– .16	.38

TABLE 2. 2-IMU FDI TEST, LOW GAIN ACCELEROMETER BIAS MISCOMPENSATION

RUN NO.	MISCOMPENSATION APPLIED: IMU: SKEWED	MISCOMPENSATION APPLIED: IMU: NON-SKEWED	ACCELEROMETER BIAS	TIME FROM START (MIN.)	VALUE M/S²	ERROR DETECTION LEVEL	RESULTS: ERROR LOCATION: IMU: SKEWED	RESULTS: ERROR LOCATION: IMU: NON-SKEWED	RESULTS: ERROR LOCATION: AXIS	TIME TO ISOLATE ERROR (SEC)	V_E (M/S)	V_N (M/S)	V_R (M/S)
23		↓	(1) BLX	20	.1	.075		↓	X	0	− 1.28	− .81	.32
24			BLX	20	.05	.075			X	1940	4.3	−27.4	3.41
25			BLX	20	.025	.075			X	2850	16.5	−18.8	4.9
26			BLX	20	.0125	.075			X	2860	16.1	− 5.3	1.13
27			BLX	20	.00625	.075		NOT DETECTED		−	15.6	3.73	4.74
28			BLX	20	−.00625	.075		NOT DETECTED		−	75.4	16.6	17.1
29			BLX	20	−.0125	.075		NOT DETECTED		−	50.6	39.9	11.9
30			BLX	20	.0125	.075		NOT DETECTED		−	40.2	3.4	9.7
31			BLX	20	−.025	.075		NOT DETECTED		−	30.6	35.3	5.85
32			BLX	20	.025	.075		•	X	1720	3.4	−14.5	1.49
33			BLX	20	−.05	.075		•	X	0	− 2.15	− .825	− .10
35			BLX	20	−.1	.075		•	X	0	− 2.99	− .64	.11
36			BLX	20	−.1	.075		•	X	0	− 2.25	− .82	− .18
37			(2) BLY	20	−.1	.075		•	Y	0	− 3.00	.20	.07
38			BLY	20	.1	.075		•	Y	0	− 2.94	− .513	− 1.32
39			BLY	20	.05	.075		•	Y	0	− 2.12	.053	.104
40			BLY	20	−.05	.075		•	Y	210	− 5.89	− .586	.168
41			BLY	20	.025	.075		NOT DETECTED		−	74.4	13.9	21.6
42			BLY	20	−.025	.075		NOT DETECTED		−	10.7	24.3	1.4
43	↓		BLX	20	.1	.075	•		X	0	− 2.9	− .93	− .01
44			BLX	20	.05	.075	•		X	410	2.57	2.10	− 2.99
45			BLX	20	−.05	.075	•		X	0	− 2.56	− 1.41	− .092
46			BLX	20	.025	.075	•		X	3310	44.28	15.64	− 4.75
47			BLX	20	−.025	.075		NOT DETECTED		−	10.7	.11	17.1
48			BLY	20	.1	.075	•		Y	0	− 2.4	− 1.2	− .123
49			BLY	20	−.1	.075	•		Y	0	− 2.3	− 1.16	− .213

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TABLE 2. (Concluded)

RUN NO.	MISCOMPENSATION APPLIED: IMU SKEWED	IMU NON-SKEWED	ACCELEROMETER BIAS	TIME FROM START (MIN.)	VALUE M/S^2	ERROR DETECTION LEVEL	RESULTS: ERROR LOCATION: IMU SKEWED	IMU NON-SKEWED	AXIS	TIME TO ISOLATE ERROR (SEC)	V_E (M/S)	V_N (M/S)	V_R (M/S)
50	•		BLY	20	.05	.075	•		Y	0	– 2.2	– .68	– .25
51	•		BLY	20	–.05	.075	•		Y	0	– 2.3	– 1.13	.196
52	•		BLY	20	.025	.075	NOT DETECTED			–	10.2	31.3	3.22
53	•		BLY	20	–.025	.075	NOT DETECTED			–	12.3	–10.7	2.75
54		•	③BLZ	20	.1	.075		•	Z	0	– 1.97	– .743	.637
55		•	BLZ	20	–.1	.075		•	Z	0	– 2.1	– .169	.628
56		•	BLZ	20	.05	.075		•	Z	0	– 2.9	– .89	.218
57		•	BLZ	20	–.05	.075		•	Z	0	– 2.46	– .47	.03
58		•	BLZ	20	.025	.075	NOT DETECTED			–	33.0	9.5	–18.2
59		•	BLZ	20	–.025	.075	NOT DETECTED			–	12.0	6.9	24.0
60	•		BLZ	20	.1	.075	•		Z	0	– 2.47	– .37	.37
61	•		BLZ	20	–.1	.075	•		Z	0	– 2.8	– 5.36	.026
62	•		BLZ	20	.05	.075	•		Z	0	– 2.5	– .618	.006
63	•		BLZ	20	–.05	.075	•		Z	0	– 2.5	– 1.14	.235
64	•		BLZ	20	.025	.075	NOT DETECTED			–	9.6	14.11	–13.6

① X AXIS LOW GAIN ACCELEROMETER BIAS
② Y AXIS LOW GAIN ACCELEROMETER BAIS
③ Z AXIS LOW GAIN ACCELEROMETER BIAS

TABLE 3. 2-IMU FDI TEST, LOW GAIN ACCELEROMETER SCALE FACTOR MISCOMPENSATION

RUN NO.	MISCOMPENSATION APPLIED: IMU SKEWED	MISCOMPENSATION APPLIED: IMU NON-SKEWED	ACCELEROMETER SCALE FACTOR	TIME FROM START (MIN.)	VALUE FT/SEC²/ PULSE	ERROR DETECTION LEVEL	RESULTS: ERROR LOCATION: IMU SKEWED	RESULTS: ERROR LOCATION: IMU NON-SKEWED	RESULTS: ERROR LOCATION: AXIS	TIME TO ISOLATE ERROR (SEC)	V_E (M/S)	V_N (M/S)	V_R (M/S)
65		•	① KLX	20	.003	.075	NOT DETECTED			–	15.7	8.4	6.4
66	•		KLX	20	.003	.075	•		X	0	– 1.99	– .358	.442
67	•		KLX	20	.0015	.075	•		X	0	– 1.78	– .240	.670
68	•		KLX	20	.00075	.075	•		X	0	– 1.97	– .280	.290
69	•		KLX	20	.00037	.075	•		X	0	– 2.7	– .197	.235
70	•		KLX	20	.000185	.075	•		X	0	– 2.81	.330	.049
71	•		KLX	20	.0000925	.075	NOT DETECTED			–	– 1.23	– 2.05	10.3
72	•		KLX	20	.00013815	.075	•		X	0	– 2.39	– .590	– .016
73		•	② KLY	20	.0006	.075		•	Y	1540	20.1	– 2.14	4.78
74		•	KLY	20	.0003	.075	NOT DETECTED			–	35.4	3.00	9.27
75		•	KLY	20	-.0003	.075		•	Y	3945	5.68	19.42	.94
76		•	③ KLZ	20	.0006	.075		•	Z	0	– 1.96	.0186	.0138
77		•	KLZ	20	.0003	.075		•	Z	0	– 1.72	– .076	.201
78		•	KLZ	20	-.0003	.075		•	Z	0	– 2.03	– .390	– .130

① X AXIS LOW GAIN ACCELEROMETER SCALE FACTOR
② Y AXIS LOW GAIN ACCELEROMETER SCALE FACTOR
③ Z AXIS LOW GAIN ACCELEROMETER SCALE FACTOR

TABLE 4. 2-IMU FDI TEST, GYRO SCALE FACTOR MISCOMPENSATION

RUN NO.	MISCOMPENSATION APPLIED					ERROR DETECTION LEVEL	RESULTS						
	IMU		GYRO TORQUER SCALE FACTOR	TIME FROM START (MIN.)	VALUE NOMINAL ± ( )%		ERROR LOCATION			TIME TO ISOLATE ERROR (SEC)	V_E (M/S)	V_N (M/S)	V_R (M/S)
	SKEWED	NON-SKEWED					IMU SKEWED	IMU NON-SKEWED	AXIS				
95		•	①KGX	10	+10	.045	NOT DETECTED			–	2.45	2.47	2.16
96		•	KGX	10	+20	.045	NOT DETECTED			–	– .571	–1.91	1.00
97		•	②KGY	10	+10	.045	NOT DETECTED			–	–2.80	–2.28	.074
98		•	KGX	10	–50	.06	NOT DETECTED			–	–2.50	–1.12	.517
99		•	KGX	10	–100	.06		•	Y	0	–1.82	2.07	– .160
101	•		KGX	10	–100	.06	•		Y	30	–1.94	–1.62	–1.44
102		•	③KGZ	10	–100	.06		•	X	390	–2.77	–5.15	– .086

① X GYRO TORQUER SCALE FACTOR
② Y GYRO TORQUER SCALE FACTOR
③ Z GYRO TORQUER SCALE FACTOR

TABLE 5. 3-IMU FDI TEST VELOCITY DATA (UNITS M/S)

TIME IN SECONDS	RUN NO. 1			RUN NO. 2			RUN NO. 3			RUN NO. 4			RUN NO. 5			RUN NO. 6		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	.0028	.0051	.009	.0006	.006	– .004	– .001	.006	– .002	.0028	.0027	– .0098	.0028	.0028	.0084	– .007	– .0012	– .0136
300	–.038	.036	.046	– .0397	.0333	.132	– .032	.033	– .267	– .0421	.0333	– .29[illegible]	– .042	.0032	– .1199	.0975	.0297	– .268
600	–.036	.117	.091	– .0395	.1037	.341	– .0236	.0936	– .4812	– .0245	.1034	– .538	– .077	.0009	– .192	.2076	.1163	– .441
900	–.023	.252	.219	.670	.192	.577	.0058	.1977	– .359	.0317	.2164	– .729	– .1281	– .986	– .146	.316	.276	– .536
1200	–.007	.459	.394	2.79	.266	.882	.0281	.365	– .1754	.0872	.3854	– .857	– .249	–1.95	– .0533	.393	.516	– .549
1500	–.022	.731	.576	6.25	.269	1.34	.0059	.593	.0783	.1345	.6304	– .9355	– .459	–2.86	+ .0787	.393	.849	–.457
1800	–.097	1.107	.888	11.04	.176	1.91	– .0353	.901	.372	.1099	.9710	– .9607	– .756	–3.95	.251	.228	1.29	– .290
2100	–.212	1.593	1.25	①			– .1776	1.308	.738	.0527	1.406	– .9167	–1.19	–4.53	.478	.0021	1.89	– .0584
2400	– .395	2.20	1.642	13.9	1.63	3.39	– .398	1.817	1.14				–1.74	–5.22	.756	② .543	– .461	– .731
2700	–.714	2.96	2.08				– .693	2.45	1.61				–2.44	–5.89	1.078	2.79	–3.58	– .319
3000							–1.14	3.21	2.11									
3300																		
3600																		
3900																		
4200																		
4500																		
4800																		

FOOTNOTE SYMBOLS INDICATE THE OCCURRENCE OF ERROR DETECTION & ISOLATION, THE TIME & VELOCITY VALUES OF WHICH ARE BELOW

	TIME	V_E	V_N	V_R
1	2000	14.9	.0713	2.32
2	2260	NOT RECORDED		

TABLE 5. (Concluded)

TIME IN SECONDS	RUN NO. 7			RUN NO. 8			RUN NO. __			RUN NO. __			RUN NO. __			RUN NO. __		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	.0063	−.0037	−.0132	.00037	.0075	− .0057												
300	.1428	.00247	−.272	.102	.033	− .232												
600	.363	.0722	−.461	.281	.1245	− .393												
900	.509	.209	−.566	−.0536	−.0695	−1.15												
1200	①			.146	−.695	− .523												
1500				②														
1800																		
2100																		
2400																		
2700																		
3000																		
3300																		
3600																		
3900																		
4200																		
4500																		
4800																		

FOOTNOTE SYMBOLS INDICATE THE OCCURRENCE OF ERROR DETECTION & ISOLATION, THE TIME & VELOCITY VALUES OF WHICH ARE BELOW

	TIME	V_E	V_N	V_R
①	1075	.2336	4.94	−1.27
②	1375	.1290	− .222	−1.41

TABLE 6. 2-IMU FDI TEST VELOCITY DATA

TIME IN SECONDS	RUN NO. 9			RUN NO. 10			RUN NO. 11			RUN NO. 12			RUN NO.__			RUN NO.__		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	.0005	– .00127	– .0049	.003	– .004	.0006	.0062	– .006	– .009	– .002	– .0026	– .0048						
300	– .516	– .486	– .324	– .492	– .522	– .273	– .485	– .564	– .317	– .497	– .517	– .214						
600	– 1.21	–1.37	– .334	–1.16	–1.57	– .300	–1.12	–1.71	– .368	–1.21	–1.45	– .211						
900	– 1.58	–1.18	– .315	.54	–1.54	– .250	–1.44	–1.81	– .364	–1.52	– .086	– .145						
1200	– 1.42	.118	– .233	① 3.03	– .893	– .0054	② –1.3	–1.3	– .4	③ –1.47	3.83	.0086						
1500	– .86	.479	– .082	.728	– .157	.365	–1.3	–1.65	– .47	–2.36	3.39	.277						
1800	.033	.673	.0912				–1.3	–1.89	– .45									
2100	.96	1.11	.350				–1.3	–2.14	– .30									
2400	2.71	1.62	.690				–1.3	–2.3	– .075									
2700	5.2	2.3	1.14				–1.45	–2.4	.23									
3000	7.75	3.3	1.67															
3300	10.5	4.3	2.26															
3600	14.4	5.9	2.95															
3900																		
4200																		
4500																		
4800																		

FOOTNOTE SYMBOLS INDICATE THE OCCURRENCE OF ERROR DETECTION & ISOLATION THE TIME & VELOCITY VALUES OF WHICH ARE BELOW

	TIME	V_E	V_N	V_R
①	1100	4.0	–1.02	–.148
②	1070	–1.3	–1.31	–.342
③	1145	–1.24	3.99	–.048

ORIGINAL PAGE IS OF POOR QUALITY

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 13 V_E	RUN NO. 13 V_N	RUN NO. 13 V_R	RUN NO. 14 V_E	RUN NO. 14 V_N	RUN NO. 14 V_R	RUN NO. 15 V_E	RUN NO. 15 V_N	RUN NO. 15 V_R
0	.0029	.00619	.00064	– .0038	– .0065	– .0092	.00299	.00612	– .0096
300	– .44	– .49	– .25	– .513	– .596	– .279	– .462	– .555	– .263
600	– .889	–1.467	– .248	–1.073	–1.58	– .238	– .980	–1.67	– .243
900	–1.12	–1.39	– .194	–1.26	–1.52	– .164	–1.17	–1.75	– .182
1200	① – .873	– .206	– .095	– .874	.077	– .036	– .813	– .601	– .073
1500	– .799	– .296	– .127	.111	1.15	.170	.0932	– .465	.093
1800				1.4	2.70	.427	1.38	– .613	.37
2100				2.88	5.47	.750	2.74	– .48	.71
2400				5.29	9.24	1.18	② 3.15	– .45	1.078
2700				8.57	14.29	1.73			
3000									
3300									
3600									
3900									
4200									
4500									
4800									

TIME IN SECONDS	RUN NO. 16 V_E	RUN NO. 16 V_N	RUN NO. 16 V_R	RUN NO. 17 V_E	RUN NO. 17 V_N	RUN NO. 17 V_R	RUN NO. 18 V_E	RUN NO. 18 V_N	RUN NO. 18 V_R
0	– .0071	– .0039	.00063	.0062	.0035	.00914	– .0021	– .0026	– .0047
300	– .500	– .54	– .133	– .462	– .583	– .247	– .547	– .65	– .271
600	–1.13	– 1.69	– .0169	– 1.05	–1.64	– .184	–1.22	–1.69	– .275
900	–1.51	– 1.97	.131	– 3.34	–1.50	– .088	–1.64	–1.71	– .222
1200	–1.31	– 1.35	.318	– 9.53	.0295	– .0196	⑤ –1.66	– .944	– .185
1500	– .625	– 2.07	.575	④ –14.14	– .74	.0664	–1.83	–1.11	– .227
1800	.285	– 3.46	.90						
2100	1.21	– 5.36	1.32						
2400	2.72	– 8.03	1.75						
2700	5.06	–12.09	2.33						
3000	③ 6.7	–12.6	2.8						
3300									
3600									
3900									
4200									
4500									
4800									

FOOTNOTE SYMBOLS INDICATE THE OCCURRENCE OF ERROR DETECTION & ISOLATION, THE TIME & VELOCITY VALUES OF WHICH ARE BELOW

	TIME	V_E	V_N	V_R
①	1160	– .8742	– .1978	– .0872
②	2165	3.08	– .405	.798
③	2500	6.16	–14.09	2.68
④	1360	–13.62	.554	– .015
⑤	1135	– 1.63	– .912	– .158

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 19 V_E	RUN NO. 19 V_N	RUN NO. 19 V_R	RUN NO. 20 V_E	RUN NO. 20 V_N	RUN NO. 20 V_R	RUN NO. 21 V_E	RUN NO. 21 V_N	RUN NO. 21 V_R	RUN NO. 22 V_E	RUN NO. 22 V_N	RUN NO. 22 V_R	RUN NO. 23 V_E	RUN NO. 23 V_N	RUN NO. 23 V_R	RUN NO. 24 V_E	RUN NO. 24 V_N	RUN NO. 24 V_R
0	.0037	– .0029	– .034	– .0021	– .0026	.0055	.0005	– .0012	– .0049	.0029	– .0039	.0006	.0005	– .0013	– .0049	– .00213	– .0026	– .0047
300	– .568	– .624	– .288	– .523	– .48	– .187	– .54	– .49	– .26	– .552	– .610	– .213	– .51	– .61	– .18	– .599	– .69	– .2'
600	–1.25	– 1.52	– .226	– 1.26	– 1.46	– .049	–1.25	–1.4	– .202	– .012	– .017	– .140	–1.24	–1.68	– .106	–1.36	– 1.71	– .067
900	–1.79	– 4.18	– .113	– 1.61	– 1.34	.169	–1.62	–1.09	– .083	– 1.5	– 1.65	.0302	–1.54	–1.81	.066	–1.81	– 1.68	.148
1200	–1.94	– 9.8	– .021	– 1.38	– .05	.385	–1.39	.525	.053	– 1.269	– 0.842	.2104	⑤ –1.28	– .81	.32	–1.79	– .314	.432
1500	① –2.6	–18.8	.193	– .671	.424	.675	– .812	.912	.231	– .555	1.07	.455				–1.42	– 4.68	.79
1800	–4.74	–21.1	.572	1.54	1.36	1.03	.303	1.13	.530	.597	2.55	.810				– .91	– 9.38	1.17
2100				5.6	3.52	1.47	③			2.22	5.85	1.29				– .57	–13.7	1.56
2400				12.3	7.3	2.15				3.82	8.40	1.62				.457	–17.9	2.02
2700				21.4	12.4	2.96				6.66	13.1	2.18				2.06	–21.9	2.49
3000				30.7	17.5	3.82				9.70	19.28	2.81				3.69	–25.6	3.10
3300				43.0	24.3	5.03				13.2	26.8	3.53				⑥ 4.2	–27.4	3.75
3600				58.0	32.1	6.48				④ 16.7	38.1	4.69				4.1	–27.2	4.6
3900				75.0	40.7	8.2				17.4	40.9	5.66				4.4	–26.2	5.3
4200				②														
4500																		
4800																		

FOOTNOTE SYMBOLS INDICATE THE OCCURRENCE OF ERROR DETECTION & ISOLATION, THE TIME & VELOCITY VALUES OF WHICH ARE BELOW

	TIME	V_E	V_N	V_R
①	1450	– 2.03	–18.0	.101
②	3950	78.4	42.3	8.6
③	2070	1.31	1.58	.841
④	3510	16.3	33.3	4.13
⑤	1200	– 1.28	– .81	.32
⑥	3140	4.3	–27.4	3.41

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 25			RUN NO. 26			RUN NO. 27			RUN NO. 28			RUN NO. 29			RUN NO. 30		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	.0005	.0087	– .0049	.00439	– .0078	– .0359	– .0057	– .0078	– .0140	.00012	.00097	– .0087	– .007	– .0039	– .0095	– .0038	.0035	– .00915
300	– .60	– .70	– .270	– .641	– .588	– .674	– .64	– .67	– .25	– .589	– .606	– .1187	– .878	– .676	– .262	– .68	– .506	– .265
600	– 1.42	– 2.02	– .186	– 1.56	–1.61	– .855	– 1.72	–1.97	– .15	– 1.00	–1.10	– .1187	– 1.72	– 1.45	– .222	– 1.86	–1.585	– .269
900	– 1.92	– 2.26	– .105	– 2.2	–1.41	–1.07	– 2.42	–2.11	.017	– 1.17	– 1.68	.33	– 2.44	– 1.32	– .137	– 2.72	–1.72	– .232
1200	– 1.88	– 1.41	.054	– 2.22	– .449	–1.13	– 2.76	–1.14	.184	– .45	– .50	.63	– 2.50	.106	– .032	– 3.06	– .5	– .162
1500	– 1.47	– 3.75	.26	– 1.86	–1.39	–1.21	– 2.28	–1.11	.456	.97	.14	.99	– 2.05	1.79	.238	– 3.06	–1.38	– .04
1800	– .81	– 6.42	.543	– 1.18	–2.81	–1.21	– 1.67	–1.31	.735	3.19	.694	1.47	– 1.16	3.21	.516	– 2.7	–2.5	.114
2100	– .18	– 8.88	.833	– .61	–3.8	–1.14	– 1.01	–1.25	1.05	5.05	1.09	1.97	– 1.17	4.89	.855	– 2.3	–3.5	.33
2400	1.25	–11.1	1.21	.69	–4.8	–1.02	.49	– .98	1.45	8.37	1.77	2.67	1.8	6.81	1.27	– 1.3	–4.25	.579
2700	3.37	–13.3	1.69	2.76	–5.4	– .82	2.93	– .585	1.93	12.24	2.61	3.33	4.4	8.83	1.74	.73	–4.8	.95
3000	5.4	–15.1	2.22	5.78	–6.2	– .41	5.15	.078	2.44	16.3	3.5	4.13	7.3	11.1	2.34	2.5	–5.3	1.36
3300	7.8	–16.8	2.9	7.12	–6.29	– .24	8.19	1.066	3.179	21.0	4.3	5.14	10.5	13.4	3.03	4.7	–5.6	1.8
3600	11.0	–17.8	3.5	10.4	–6.0	.17	11.4	2.21	3.82	27.3	5.6	6.38	14.9	16.3	3.87	7.9	–5.5	2.4
3900	14.7	–18.7	4.4	14.2	–5.7	.76	15.6	3.73	4.74	33.8	6.87	7.68	19.8	19.3	4.85	11.5	–5.2	3.1
4200	① 16.7	–16.7	5.3	② 17.0	–2.7	1.59				40.7	8.40	9.2	24.7	22.8	5.99	15.2	–4.5	3.9
4500	17.5	–12.0	6.1							48.3	10.1	10.9	30.2	26.6	7.22	19.2	–3.6	4.8
4800	18.7	– 7.1	6.9							56.9	12.1	12.7	36.7	30.6	8.67	24.28	–2.38	5.86
										65.8	14.3	14.8	44.23	35.68	10.44	29.5	– .78	7.05
										75.4	16.68	17.1	50.6	39.9	11.9	34.7	1.07	8.3
																40.2	3.4	8.7

FOOTNOTE SYMBOLS INDICATE THE OCCURRENCE OF ERROR DETECTION & ISOLATION, THE TIME & VELOCITY VALUES OF WHICH ARE BELOW

	TIME	V_E	V_N	V_R
①	4050	16.5	–18.8	4.9
②	4060	16.1	–5.3	1.13

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 31			RUN NO. 32			RUN NO. 33			RUN NO. 35			RUN NO. 36			RUN NO. __		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	.006	.003	– .019	– .0038	– .0065	– .009	.0036	– .0003	– .023	.006	.009	.0013	– .002	.007	– .005			
300	– .67	– .64	– .32	– .68	– .66	– .21	– .66	– .739	– .271	– .70	– .62	– .19	– .63	– .65	– .24			
600	– 1.64	– 1.73	– .37	–1.78	–1.95	– .20	–1.51	–1.80	– .22	–1.91	–1.64	– .15	–1.63	–1.85	– .21			
900	– 2.31	– 1.85	– .36	–2.51	– 2.25	– .17	–1.97	–1.90	– .10	–2.65	–1.74	– .04	–2.17	–1.96	– .14			
1200	– 2.44	– .59	– .31	–2.6	– 1.39	– .079	* –2.15	– .825	– .11	* –2.99	– .64	.11	* –2.25	– .82	– .18			
1500	– 1.91	2.10	– .20	–2.3	– 3.8	– .050	–5.38	–2.10	.57									
1800	– 1.03	4.46	– .04	–1.67	– 6.5	– .25												
2100	– .049	7.11	.17	–1.15	– 8.85	– .49												
2400	1.82	9.91	.49	– .062	–11.1	.8												
2700	4.52	12.9	.91	2.07	–13.4	1.18												
3000	7.42	16.14	1.42	* ①														
3300	10.73	19.35	2.04															
3600	15.09	22.91	2.78															
3900	20.07	26.8	3.66															
4200	25.02	30.09	4.68															
4500	30.6	35.3	5.85															
4800																		

NOTES:

* INDICATES ERROR DETECTION & ISOLATION OCCURRENCE

① ERROR DETECTION & ISOLATION OCCURRED AT T = 2920 – SEE VELOCITY VALUES BELOW

	TIME	V_E	V_N	V_R
①	2920	3.4	–14.5	1.49

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 37			RUN NO. 38			RUN NO. 39			RUN NO. 40			RUN NO. 41			RUN NO. 42		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	− .002	− .0026	.0055	− .0038	.0035	− .009	.0063	.0035	− .009	− .010	.0009	− .0087	.006	.0035	− .009	− .004	− .005	− .004
300	− .73	− .511	− .272	− .77	− .49	− .29	− .81	− .75	− .28	− .66	− .69	− .13	− .72	− .51	− .19	− .59	− .57	− .23
600	−1.61	−1.41	− .233	−1.86	−1.28	− .28	−1.55	−1.43	− .17	− .02	− .18	− .43	− 1.65	− 1.39	− .10	− 1.43	− 1.78	− .125
900	−2.29	−1.17	− .176	−2.58	−1.04	− .23	−2.11	−1.34	− .075	−2.56	−1.89	.087	− 2.41	− 1.31	− .02	− 1.82	− 1.97	.014
1200	*−3.00	.20	.07	*−2.94	− .513	−1.32	*−2.12	.053	.104	−2.74	− .026	.258	− 2.52	− 1.08	.19	− 1.70	− .88	.217
1500										①			1.00	.20	1.00	− 3.45	− .52	.28
1800													3.2	.449	1.17	− 4.8	− .075	.32
2100													6.34	.645	1.80	− 6.14	.682	.338
2400													10.2	.865	2.78	− 6.63	1.79	.372
2700													14.9	1.24	3.77	− 6.35	3.06	.378
3000													19.9	1.74	5.04	− 6.01	4.62	.370
3300													24.8	2.28	6.33	− 5.24	6.44	.41
3600													31.0	3.22	7.95	− 3.56	8.69	.42
3900													37.2	4.2	9.6	− 1.27	11.39	.54
4200													43.7	5.6	11.6	.256	13.2	.632
4500													50.6	7.4	13.77	2.79	16.5	.832
4800													58.4	9.1	16.1	6.4	20.1	1.08
													66.2	11.2	18.8	10.7	24.3	1.40
													74.4	13.9	21.6			

*OCCURRENCE OF ERROR DETECTION & ISOLATION

OCCURRENCE OF ERROR DETECTION AND ISOLATION AT OTHER THAN NOMINAL TABLE TIMES

	TIME	V_E	V_N	V_R
①	1410	−5.89	−.586	.168

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 43			RUN NO. 44			RUN NO. 45			RUN NO. 46			RUN NO. 47			RUN NO. 48		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	– .004	.005	– .004	.003	– .004	.0006	.0062	.0035	– .0091	– .006	– .0003	– .0136	.005	– .005	– .0145	– .004	– .005	– .004
300	–1.3	–1.4	– .18	– .71	– .69	– .20	– .867	– .915	– .251	– .725	– .625	– .291	– .58	– .64	– .25	– .746	– .734	– .214
600	–1.85	–1.9	– .17	–1.75	–1.85	– .1837	–1.70	–2.04	– .234	– 2.01	– 1.91	– .309	– 1.48	–1.78	– .17	–1.62	–1.94	– .228
900	–2.63	–2.03	– .11	–2.46	–2.00	– .100	–2.44	–2.38	– .178	– 2.82	– 2.02	– .298	– 1.98	–1.86	– .05	–2.20	–2.10	– .199
1200	*–2.9	– .93	– .01	–2.12	– .614	– .273	*–2.56	–1.41	– .092	– 3.1	– .894	– .289	– 1.77	–1.62	.08	*–2.4	–1.2	– .123
1500				1.06	1.39	–2.25				– 1.25	.315	–1.41	– 2.78	–1.45	1.46			
1800				①						.973	1.15	–2.40	– 3.38	–2.46	2.89			
2100										3.28	2.25	–3.28	– 4.01	–3.15	4.37			
2400										6.43	3.47	–4.03	– 3.87	–3.65	5.85			
2700										10.48	4.86	–4.64	– 2.97	–3.91	7.35			
3000										14.83	6.34	–5.12	– 1.9	–4.00	8.9			
3300										19.31	7.79	–5.41	– .6	–3.86	10.4			
3600										25.0	9.58	–5.56	1.7	–3.2	12.0			
3900										31.15	11.3	–5.5	4.5	–2.4	13.7			
4200										37.35	13.4	–5.2	8.17	–1.01	15.8			
4500										* 44.39	15.64	–4.75	10.7	.11	17.1			
4800																		

*OCCURRENCE OF ERROR DETECTION AND ISOLATION

OCCURRENCE OF ERROR DETECTION & ISOLATION AT OTHER THAN NOMINAL TABLE TIMES

	TIME	V_E	V_N	V_R
①	1610	2.57	2.10	–2.99

ORIGINAL PAGE IS OF POOR QUALITY

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 49			RUN NO. 50			RUN NO. 51			RUN NO. 52			RUN NO. 53			RUN NO. 54		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	– .004	.005	– .004	.005	– .005	.004	– .0043	.0052	– .0043	– .006	.002	– .014	.003	.006	.0006	– .005	.0022	– .0038
300	– .63	– .657	– .265	– .714	– .665	– .295	– .65	– .69	– .141	– .69	– .68	– .26	– .725	– .660	– .179	– .618	– .626	– .167
600	–1.58	–1.88	–2.97	–1.64	–1.74	– .313	–1.57	–1.87	– .05	– 1.68	– 1.94	– .27	– 1.88	– 1.86	– .111	–1.45	–1.90	.071
900	–2.2	–2.17	– .268	–2.2	–1.81	– .310	–2.2	–2.1	.048	– 2.48	– 2.26	– .23	– 2.67	– 2.13	– .021	–1.96	–1.84	.33
1200	*–2.3	–1.16	– .213	*–2.2	– .68	– .25	*–2.3	–1.13	.196	– 2.95	– .95	– .14	– 2.8	– .93	.102	* –1.97	– .743	.637
1500										– 3.95	.93	– .02	– 1.26	– 2.6	.276			
1800										– 4.65	2.88	.126	– .64	– 3.46	.541			
2100										– 5.28	5.03	.287	2.54	– 6.29	.902			
2400										– 5.12	7.48	.478	5.36	– 7.85	1.38			
2700										– 4.1	10.2	.70	9.28	– 9.60	2.10			
3000										– 3.1	12.9	.97	12.3	–10.76	2.75			
3300										– 1.8	15.8	1.2						
3600										.70	19.2	1.68						
3900										3.6	22.9	2.11						
4200										6.7	27.0	2.62						
4500										10.2	31.3	3.22						
4800																		

*OCCURRENCE OF ERROR DETECTION & ISOLATION

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 55			RUN NO. 56			RUN NO. 57			RUN NO. 58			RUN NO. 59			RUN NO. 60		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	– .004	– .0052	– .0425	– .002	– .002	.005	.0079	– .0026	– .0040	.0036	– .0003	– .0136	– .0038	.0035	– .009	– .002	– .003	.006
300	– .714	– .77	– .19	– .689	– .63	– .245	– .69	– .59	– .28	– .72	– .77	– .24	– .656	– .587	– .309	– .68	– .61	–.14
600	–1.50	–1.66	– .03	–1.80	–1.76	– .160	–1.71	–1.62	– .27	– 1.76	–1.85	– .207	– 1.67	–1.73	– .314	–1.70	–1.55	.001
900	–2.0	–1.61	.248	–2.55	–1.79	– .059	–2.36	–1.69	– .20	– 2.49	–1.91	– .095	– 2.31	–1.75	– .255	–2.34	–1.57	.16
1200	*–2.1	– .169	.628	*–2.9	– .89	.218	*–2.46	– .47	.03	– 2.5	– .71	.0109	– 2.35	– .512	– .167	*–2.47	– .37	.37
1500										– 2.0	– .51	– 2.0	– 2.07	– .079	2.72			
1800										– .96	– .54	– 4.1	– 1.5	– .059	4.83			
2100										.24	– .24	– 6.1	.97	.41	7.7			
2400										2.29	.18	– 8.06	.19	.94	10.1			
2700										5.2	.703	– 9.86	1.90	1.68	12.7			
3000										8.23	1.44	–11.16	3.8	2.68	15.8			
3300										11.7	2.43	–13.2	6.18	3.81	18.6			
3600										16.4	3.89	–14.6	9.13	5.17	21.4			
3900										21.2	5.7	–16.1	12.0	6.9	24.0			
4200										27.0	7.5	–17.1						
4500										33.0	9.5	–18.2						
4800																		

*OCCURRENCE OF ERROR DETECTION AND ISOLATION

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 61 V_E	RUN NO. 61 V_N	RUN NO. 61 V_R	RUN NO. 62 V_E	RUN NO. 62 V_N	RUN NO. 62 V_R	RUN NO. 63 V_E	RUN NO. 63 V_N	RUN NO. 63 V_R	RUN NO. 64 V_E	RUN NO. 64 V_N	RUN NO. 64 V_R	RUN NO. 65 V_E	RUN NO. 65 V_N	RUN NO. 65 V_R	RUN NO. 66 V_E	RUN NO. 66 V_N	RUN NO. 66 V_R
0	– .004	.005	– .004	.00012	– .0042	– .028	.00012	.00096	– .0087	.003	– .004	– .009	.004	.0022	– .0038	– .0057	.00226	– .0140
300	– .72	– .579	– .214	– .632	– .602	– .234	– .72	– .676	– .212	– .66	– .52	– .21	– .657	– .657	– .0382	– .749	– .682	– .154
600	–1.82	–1.62	– .174	–1.65	–1.74	–1.61	–1.69	–1.89	– .161	–1.613	– 1.51	– .09	– 1.51	–1.88	.232	–1.467	–1.53	.0026
900	–2.57	–1.72	– .100	–2.37	–1.88	– .717	–2.43	–2.02	– .041	–2.33	– 1.88	.158	– 2.00	–1.92	.566	–2.01	–1.53	.197
1200	*–2.8	–5.36	.026	*–2.5	– .618	.006	*–2.50	–1.14	.235	–2.33	– 1.75	.305	– 1.92	– .743	.890	*–1.99	– .358	.442
1500										–2.9	– .495	– 1.31	– 1.40	– .645	1.288			
1800										–3.12	– 1.136	– 3.01	– .42	– .58	1.78			
2100										–3.19	– 1.47	– 4.97	1.5	.65	2.33			
2400										–2.55	– 1.59	– 6.34	2.5	.758	2.89			
2700										–1.00	– 1.52	– 7.90	5.1	1.98	3.61			
3000										+ .546	– 1.18	– 9.5	8.02	3.6	4.5			
3300										2.7	– .74	–10.9	11.3	5.6	5.4			
3600										5.9	2.3	–12.3	15.7	8.4	6.4			
3900										9.6	14.11	–13.[illegible]						
4200																		
4500																		
4800																		

*OCCURRENCE OF ERROR DETECTION AND ISOLATION

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 67			RUN NO. 68			RUN NO. 69			RUN NO. 70			RUN NO. 71			RUN NO. 72		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	– ,007	,006	,0006	,0005	– ,001	– ,005	– ,007	– ,004	,0006	,0005	– ,001	– ,005	– ,0058	,0022	– ,0038	– ,002	– ,0026	,0055
300	– ,55	– ,55	– ,126	– ,618	– ,58	– ,195	– ,798	– ,696	– ,119	– ,745	– ,515	– ,191	– ,66	– ,64	– ,22	– ,688	– ,619	– ,256
600	–1,32	–1,56	,121	– ,015	– ,016	– ,067	–1,79	–1,59	– ,0289	–1,97	–1,36	– ,159	–1,67	–1,68	– ,20	–1,67	–1,74	– ,216
900	–1,86	–1,49	,422	–2,07	–1,42	,119	–2,5	–1,49	,089	–2,70	–1,15	– ,085	–2,37	–1,72	– ,12	–2,33	–1,85	– ,151
1200	*–1,78	– ,24	,67	*–1,97	– ,28	,29	*–2,7	– ,197	,235	*–2,81	,33	,049	–2,47	– ,48	– ,015	*–2,39	– ,59	– ,0168
1500													–3,65	–1,38	1,49			
1800													–4,32	–2,18	2,62			
2100													–5,03	–2,71	3,92			
2400													–4,9	–3,08	5,21			
2700													–3,87	–3,17	6,55			
3000													–2,81	–3,09	7,76			
3300													–1,32	–2,77	9,07			
3600													–1,23	–2,05	10,3			
3900																		
4200																		
4500																		
4800																		

*OCCURRENCE OF ERROR DETECTION AND ISOLATION

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 73			RUN NO. 74			RUN NO. 75			RUN NO. 76			RUN NO. 77			RUN NO. 78		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	.006	– .005	– .004	– .0038	– .0035	– .0091	.0005	– .001	– .005	– .0038	.0035	– .009	– .004	.004	– .014	– .004	.003	– .009
300	.606	– .70	– .17	– .647	– .617	– .217	– .31	– .72	– .12	– .729	– .608	– .251	– .55	– .56	– .239	– .62	– .55	– .28
600	– 1.47	–1.86	– .0689	– 1.52	–1.58	– .135	–1.87	– 1.83	.042	–1.51	–1.49	– .212	–1.41	–1.57	– .14	–1.56	–1.59	– 28
900	– 2.04	–2.02	– .0709	– 2.09	–1.56	.0285	–2.63	– 1.95	.229	–2.02	–1.36	– .144	–1.84	–1.44	.04	–2.09	–1.59	– .23
1200	– 2.00	– .90	.298	– 2.07	– .28	.20	–2.86	– .909	.449	*–1.96	.0186	.0138	*–1.72	– .076	.20	*–2.03	– .39	– .13
1500	.726	–1.01	.766	– .53	.03	.51	–3.61	– .612	.657									
1800	4.2	–1.45	1.41	1.67	– .11	.96	–4.10	– .597	.826									
2100	8.2	–1.68	2.26	4.11	.05	1.57	–4.9	– .234	.974									
2400	13.7	–1.96	3.36	7.57	.21	2.31	–5.3	.246	1.072									
2700	①			12.06	.52	3.26	–5.0	.899	1.15									
3000				16.59	.91	4.37	–4.9	1.85	1.30									
3300				21.79	1.41	5.74	–4.7	2.9	1.36									
3600				28.27	2.16	7.35	–3.57	4.72	1.42									
3900				35.44	3.00	9.27	–1.28	8.39	1.33									
4200							– .03	10.8	1.32									
4500							1.38	12.9	1.25									
4800							4.51	17.6	.99									
							②											

*OCCURRENCE OF ERROR DETECTION & ISOLATION

OCCURRENCE OF ERROR DETECTION AND ISOLATION AT OTHER THAN NOMINAL TABLE TIMES

	TIME	V_E	V_N	V_R
①	2740	20.1	– 2.14	4.78
②	5145	5.68	19.42	.94

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 81			RUN NO. 82			RUN NO. 83			RUN NO. 84			RUN NO. 86			RUN NO. 87		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	– .0053	– .0016	– .0184	.008	– .003	– .005	– .004	– .005	– .004	– .005	.0022	– .014	– .004	.005	– .004	– .00012	.0009	– .0087
300	– .650	– .57	– .235	– .59	– .60	– .26	– .64	– .64	– .652	–1.02	– .75	– .232	– .68	– .511	– .225	– .71	– .78	– .208
600	–1.66	–1.6	– .221	–1.55	–1.61	– .27	–1.38	–1.80	.157	–1.90	–1.63	– .175	–1.72	–1.33	– .175	–1.84	–2.38	– .117
900	–2.26	–1.56	– .137	–2.22	–1.63	– .20	–1.77	–1.93	.406	–2.60	–1.61	– .071	–2.34	–1.15	– .105	–2.67	–2.88	.058
1200	–2.34	– .42	– .028	–2.46	– .387	– .19	–1.68	– .75	.724	–2.7	– .26	.1021	–2.51	– .28	.033	–2.97	–2.16	.26
1500	.49	– .28	.16	–2.10	– .037	.02	– .99	3.09	1.10	–2.3	– .038	– .31	–2.13	.81	.231	⑥		
1800	①			②			③			④			⑤					
2100																		
2400																		
2700																		
3000																		
3300																		
3600																		
3900																		
4200																		
4500																		
4800																		

FOOTNOTE SYMBOLS INDICATE THE OCCURRENCE OF ERROR DETECTION & ISOLATION, THE TIME & VELOCITY VALUES OF WHICH ARE BELOW

	TIME	V_E	V_N	V_R
①	1665	1.23	.11	.33
②	1685	–1.64	– .087	.16
③	1735	.071	9.05	1.44
④	1710	–1.67	– .115	.472
⑤	1610	–1.82	.98	.335
⑥	1495	– 1.44	–2.11	.55

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 88			RUN NO. 89			RUN NO. 90		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	.0057	− .005	− .0043	− .007	− .004	.0006	− .004	.0048	− .0042
300	− .61	− .69	− .151	− .702	− .656	− .264	− .676	− .701	− .278
600	−1.48	−2.14	− .099	−1.7	−1.63	− .224	−1.69	−1.83	− .273
900	−1.95	−2.39	− .004	−2.27	−1.49	−1.61	−2.34	−1.86	− .224
1200	−1.77	−1.43	.14	−2.00	−1.10	− .130	−2.47	− .678	− .137
1500	①			②			−1.93	.030	.018
1800							③		
2100									
2400									
2700									
3000									
3300									
3600									
3900									
4200									
4500									
4800									

TIME IN SECONDS	RUN NO. 92			RUN NO. 93			RUN NO. 95		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	− .0036	− .0003	− .0136	.0005	− .001	− .005	− .006	− .008	− .004
300	− .741	− .777	− .188	− .66	− .75	− .21	− .63	− .77	− .17
600	−1.76	−2.18	− .1080	−1.77	−2.3	− .11	−1.72	−2.25	− .0747
900	−2.46	−2.39	.035	−2.29	−2.49	− .01	−2.31	−2.43	.05
1200	−2.61	−1.38	.231	−2.33	−1.43	.21	−2.59	−1.18	.234
1500	−2.12	−1.05	.451	④			−2.13	− .86	.485
1800	−1.37	− .67	.78				−1.41	− .81	.779
2100	− .57	+ .707	1.11				− .49	− .51	1.19
2400	1.13	2.96	1.56				1.03	.0195	1.62
2700							2.45	2.47	2.16
3000									
3300									
3600									
3900									
4200									
4500									
4800									

FOOTNOTE SYMBOLS INDICATE THE OCCURRENCE OF ERROR DETECTION & ISOLATION, THE TIME & VELOCITY VALUES OF WHICH ARE BELOW

	TIME	V_E	V_N	V_R
①	1330	−1.29	−1.31	.24
②	1375	−2.39	− .035	−.053
③	1760	−1.04	.0996	.219
④	1480	−1.89	1.79	.44

TABLE 6. (Continued)

TIME IN SECONDS	RUN NO. 96			RUN NO. 97			RUN NO. 98			RUN NO. 99			RUN NO. 101			RUN NO. 102		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	−.0065	−.0029	−.023	.006	−.006	−.009	−.00714	−.0039	.006	.0001	.0010	−.019	−.006	−.0003	−.0136	−.006	−.008	−.014
300	−.703	−.782	−.204	−1.05	−1.03	−.248	−.661	−.699	−.179	−.80	−.92	−.22	−.785	−.631	−.1903	−.96	−.94	−.25
600	−1.81	−2.18	−.134	−1.86	−2.0	−.199	−1.7	−2.03	−.048	• −1.82	−2.07	−.16	• −1.94	−1.62	−1.44	−1.01	−1.78	−.21
900	−2.49	−2.6	−.005	−2.6	−2.3	−.113	−2.5	−2.12	.16							−2.55	−4.20	−.13
1200	−2.64	−1.61	.15	−2.8	−2.28	.074	−2.7	−1.09	.371							①		
1500	−2.21	−1.74	.364				−2.3	−1.12	.517									
1800	−1.49	−1.97	.612															
2100	−.571	−1.91	1.00															
2400																		
2700																		
3000																		
3300																		
3600																		
3900																		
4200																		
4500																		
4800																		

• OCCURRENCE OF ERROR DETECTION AND ISOLATION AT OTHER THAN NOMINAL TABLE TIMES -

	TIME	V_E	V_N	V_R
①	990	−2.77	−5.15	−.086

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TABLE 6. (Concluded)

TIME IN SECONDS	RUN NO. 106			RUN NO. ___			RUN NO. ___			RUN NO. ___			RUN NO. ___			RUN NO. ___		
	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R	V_E	V_N	V_R
0	−.004	−.005	−.004															
300	−.75	−.65	−.15															
600	−1.91	−1.73	−.10															
900	−2.70	−1.72	−.004															
1200	−2.80	−.39	.15															
1500	−2.49	−.25	.31															
1800	①																	
2100																		
2400																		
2700																		
3000																		
3300																		
3600																		
3900																		
4200																		
4500																		
4800																		

FOOTNOTE SYMBOLS INDICATE THE OCCURRENCE OF ERROR DETECTION & ISOLATION, THE TIME & VELOCITY VALUES OF WHICH ARE BELOW

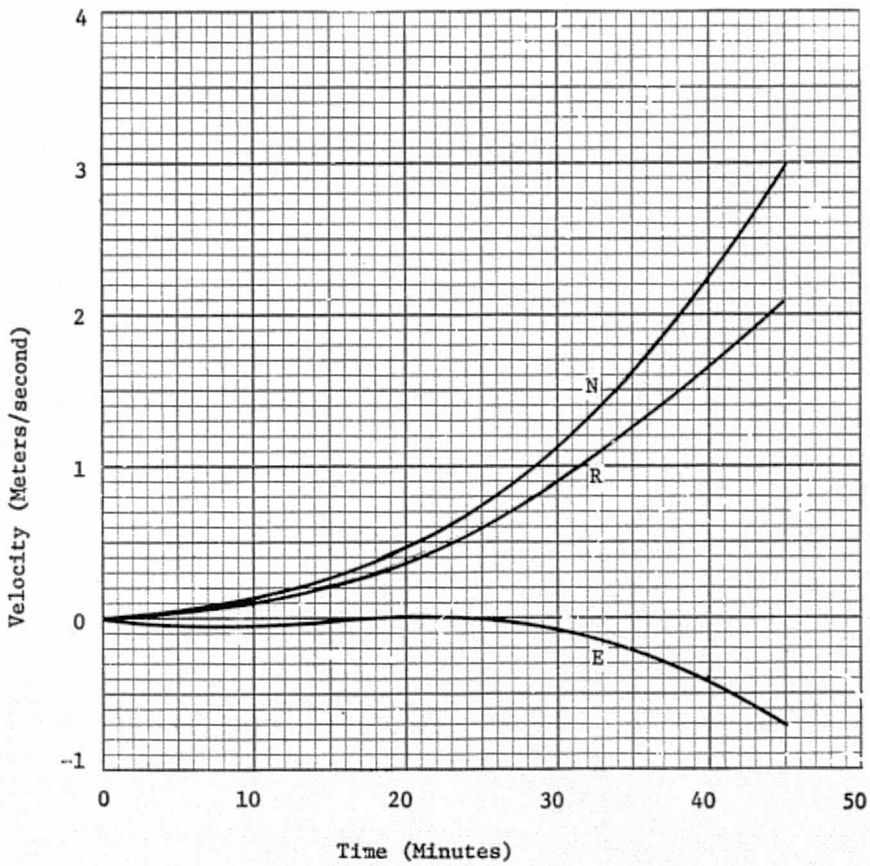
	TIME	V_E	V_N	V_R
①	1565	−2.37	−.16	.38

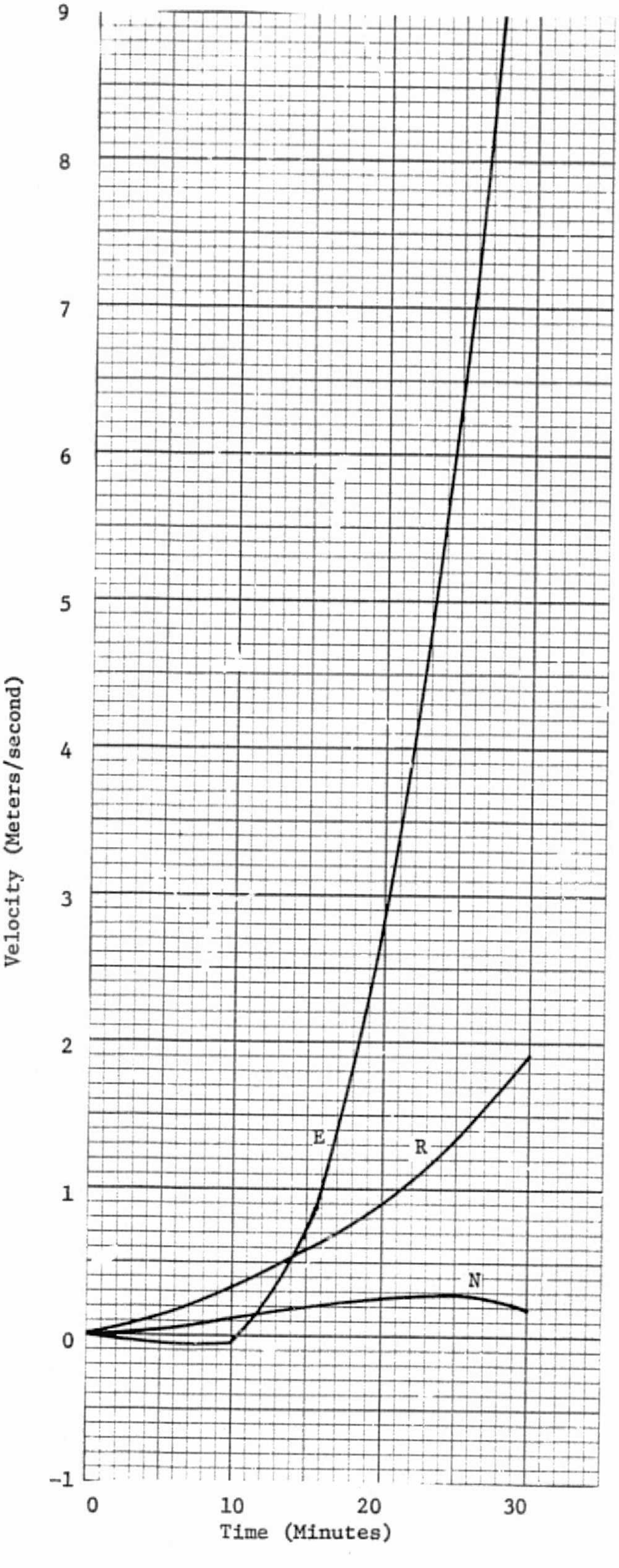
APPENDIX

TEST DATA CURVES

RUN #1
Single Navigator
Average Filter

VFDI
No Miscompensation
Error Not Detected





RUN #2
Single Navigator
Average Filter

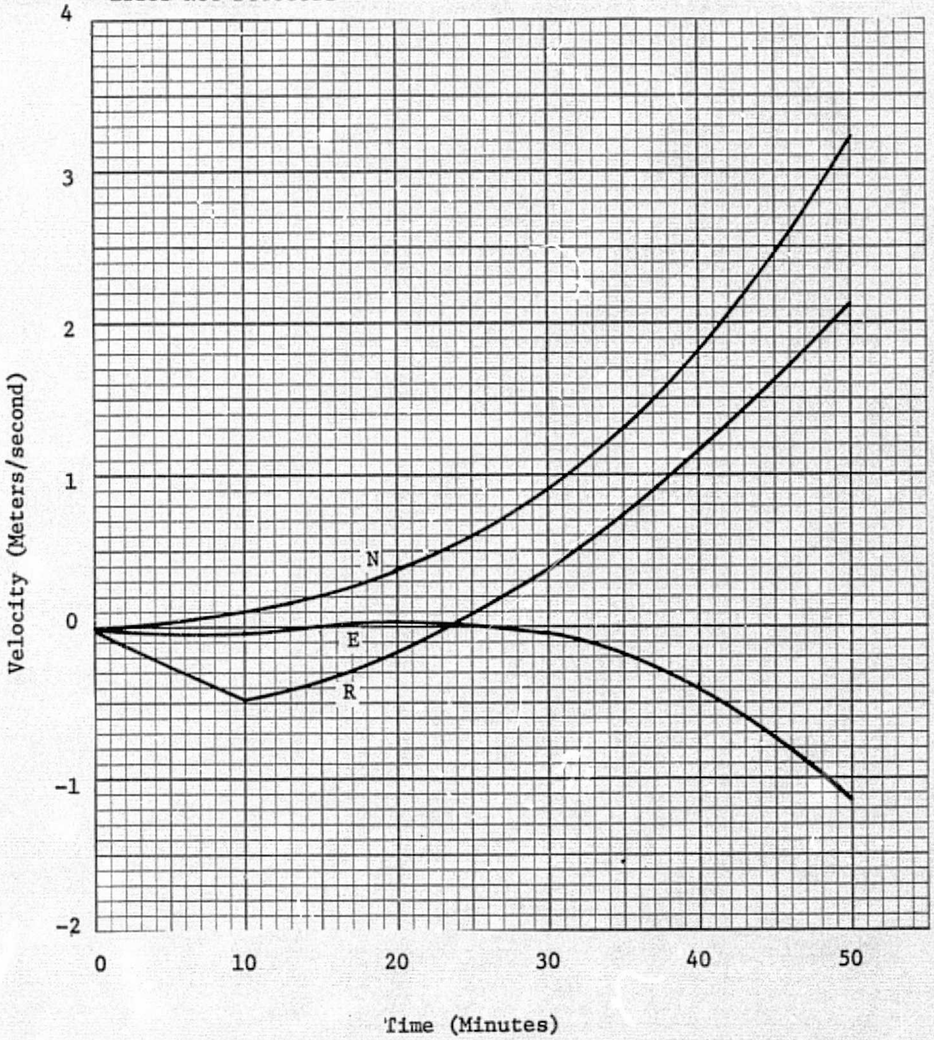
VFDI
1°/hr X Gyro Bias
On IMU #2
10 Minutes into
Navigation

Error Detected and
Isolated @ 2000 seconds

RUN #3
Single Navigator
Average Filter

VFDI
+0.03% Z Accelerometer Scale Factor Shift
on IMU #1
10 Minutes into Navigation

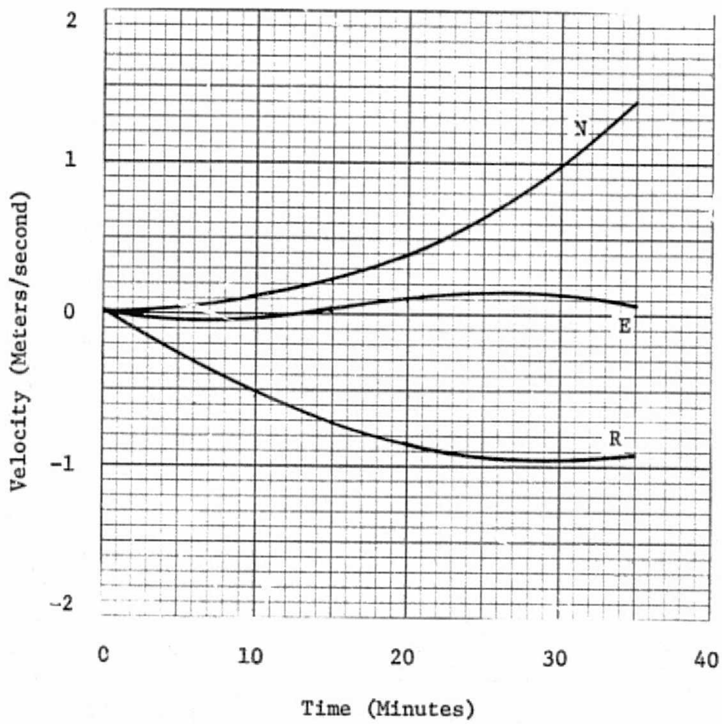
Error Not Detected



RUN #4
Single Navigator
Average Filter

VFDI
+0.03% Y Accelerometer Scale Factor Shift
on IMU #3
10 Minutes into Navigation

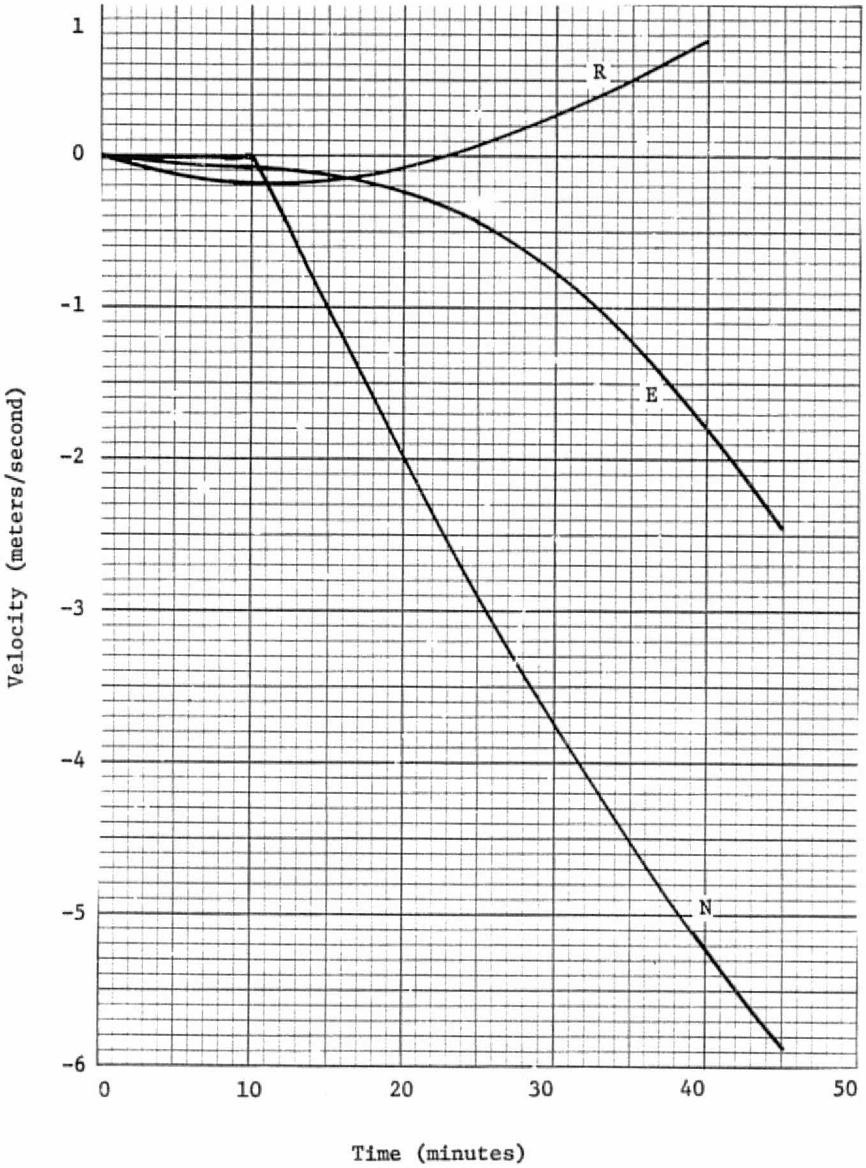
Error Not Detected



RUN #5
Single Navigator
Average Filter

VFDI
0.01 M/S^2 X Accelerometer Bias
on IMU #2
10 Minutes into Navigation

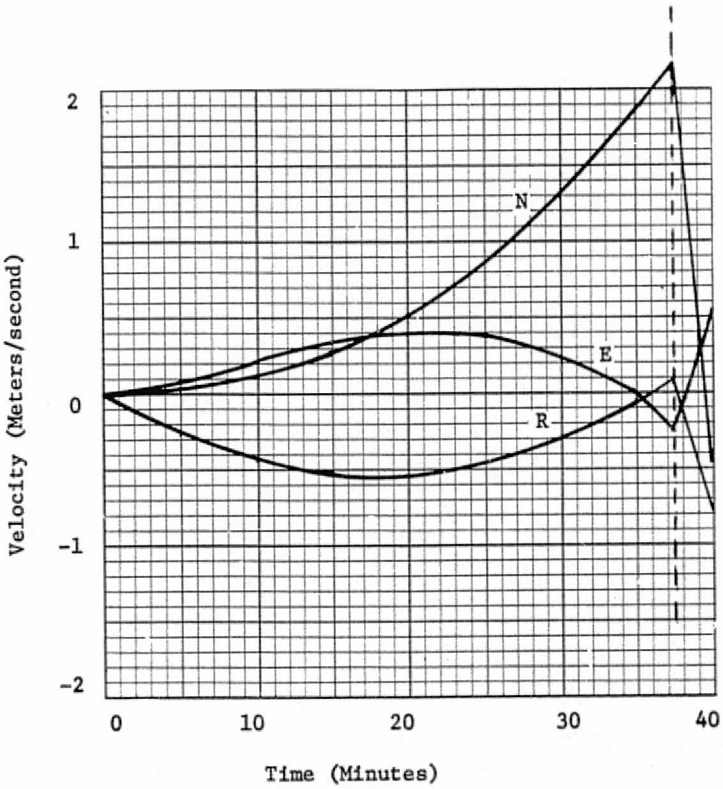
Error Not Detected



RUN #6
Multinavigator
Mid-Value Filter

VFDI
No Miscompensation

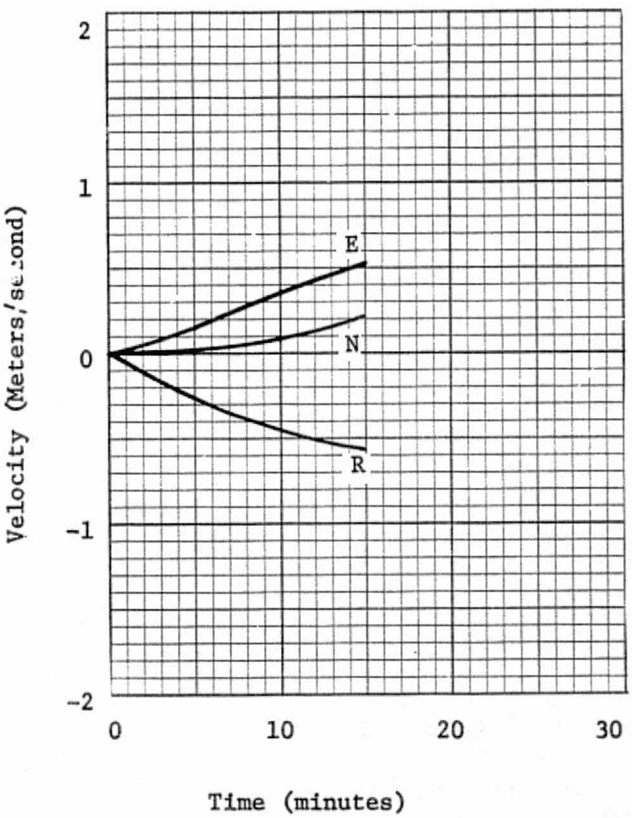
Error Detected and Isolated @ 2260 Seconds



RUN #7
Multinavigator
Mid-Value Filter

VFDI
1°/hr Y Gyro Bias
on IMU #1
10 Minutes into Navigation

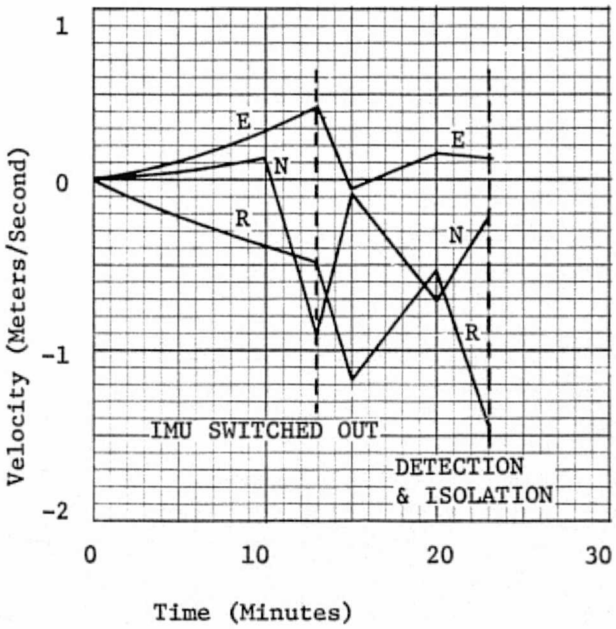
Error Detected & Isolated @ 1075 Seconds



Run #8
Multinavigator
Mid-Value Filter

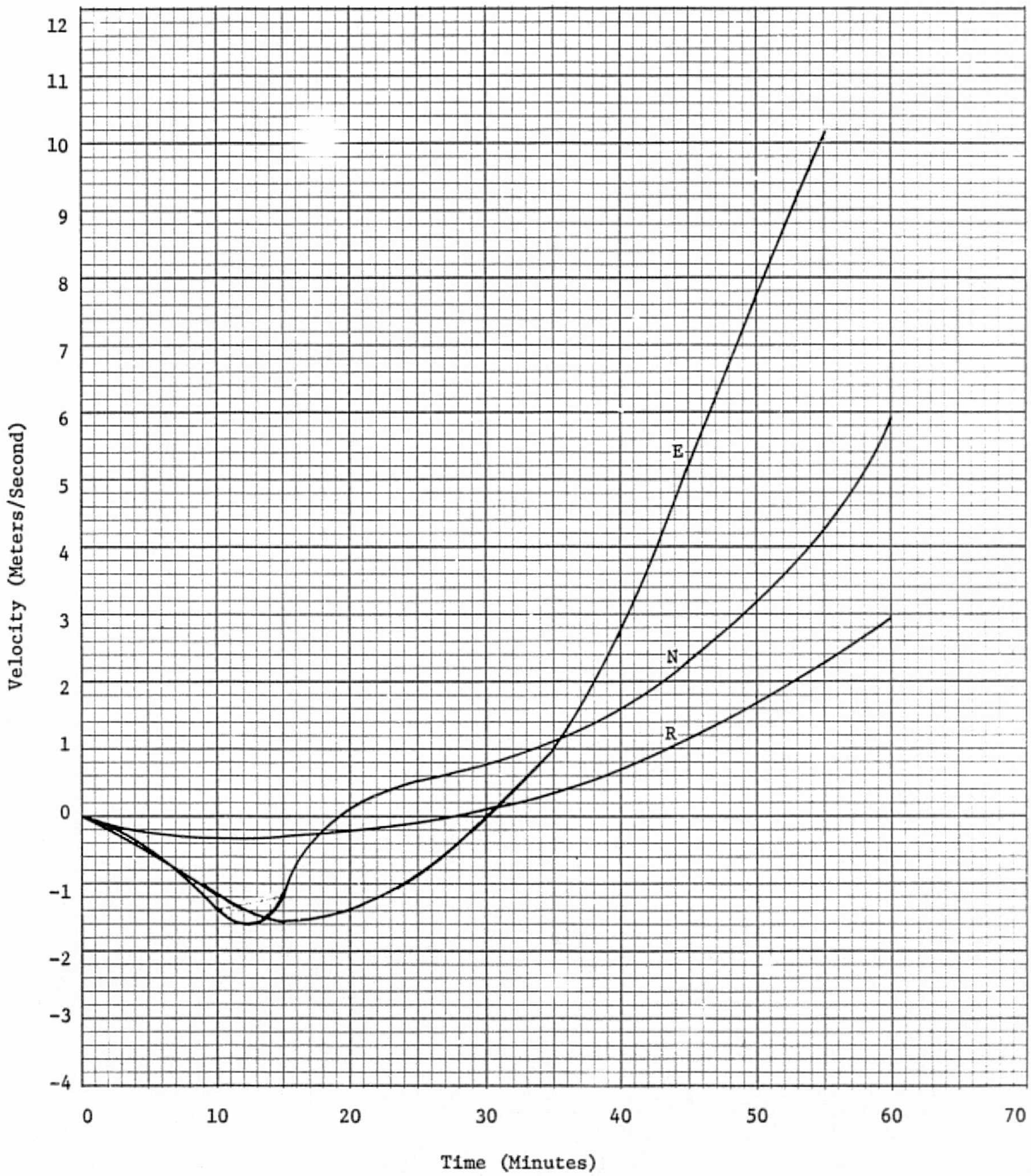
VFDI
+0.01 m/s^2 X Accelerometer Bias Shift
on IMU #2
10 Minutes into Navigation

Error Detected & Isolated @ 1375 seconds
Error Isolated to Y Axis, IMU #2



Run #9
2 IMU FDI

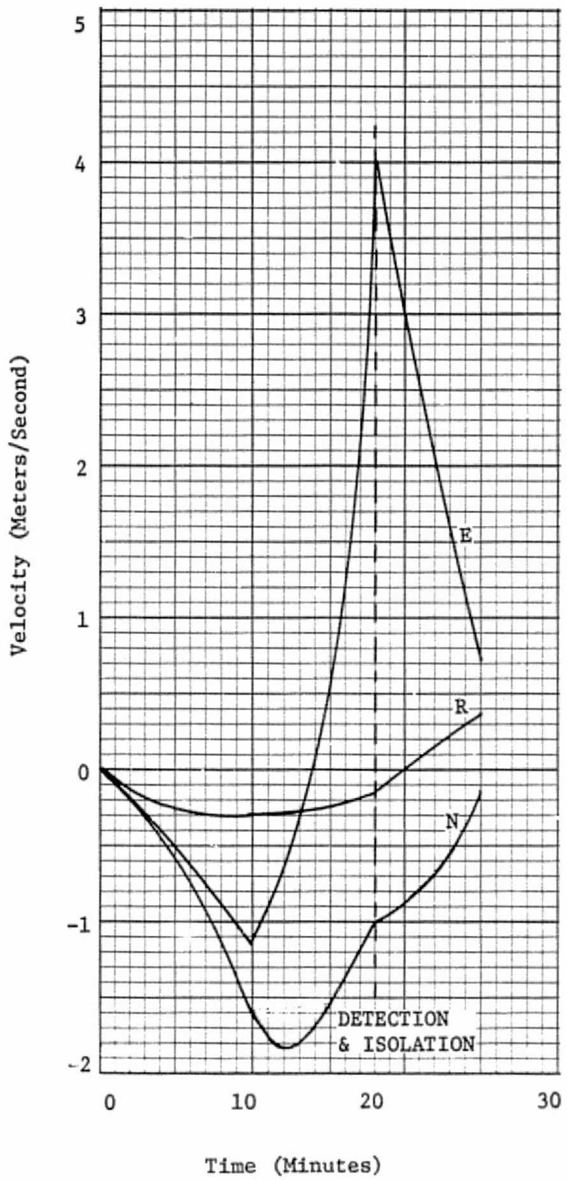
VFDI
No Miscompensation
Error Not Detected



Run #10
2 IMU FDI

VFDI, EDV = 0.075
+1°/hr X Gyro Bias Shift
on Non-Skewed IMU
10 Minutes into Navigation

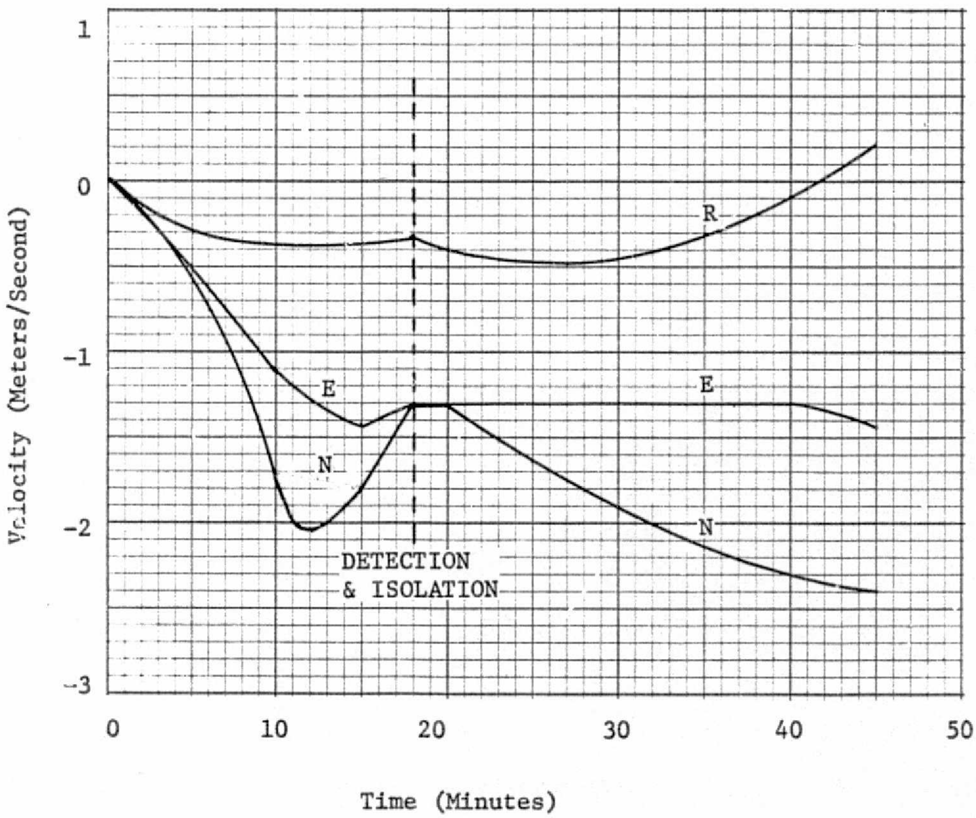
Error Detected & Isolated @ 1100 Seconds
Error Isolated to Y Axis, Non-Skewed IMU



Run #11
2 IMU FDI

VFDI, EDV = 0.075
+1°/hr X Gyro Bias Shift
on Skewed IMU
10 Minutes into Navigation

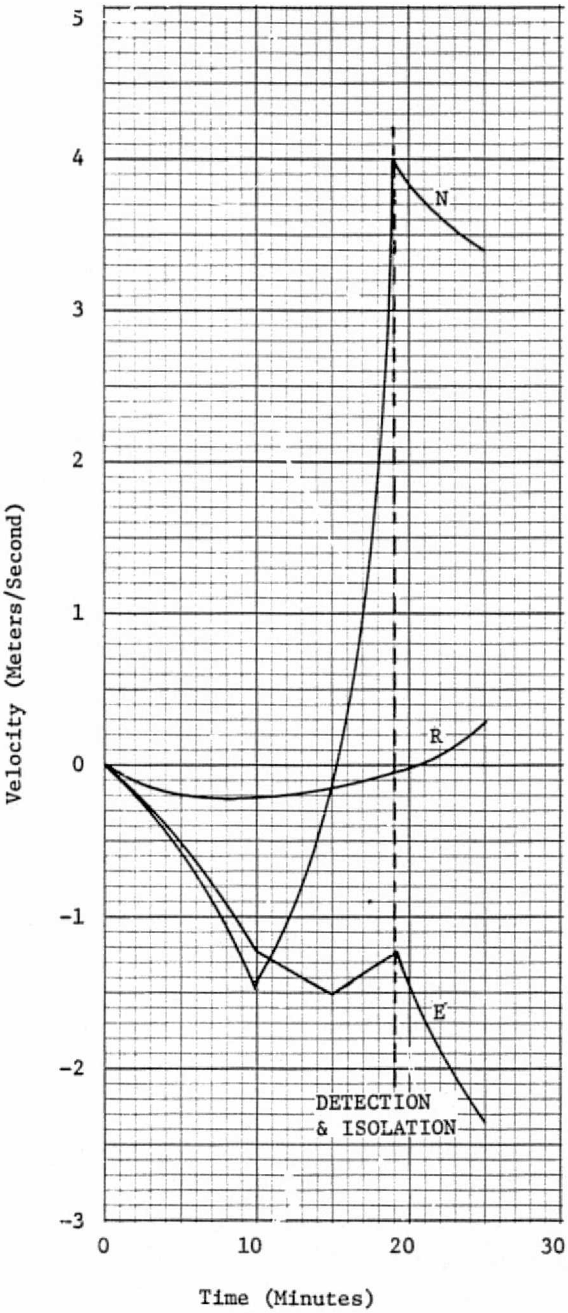
Error Detected & Isolated @ 1070 seconds
Error Isolated to Y Axis of Skewed IMU



Run #12
2 IMU FDI

VFDI, EDV = 0.075
+1°/hr Y Gyro Bias Shift
on Non-Skewed IMU
10 Minutes into Navigation

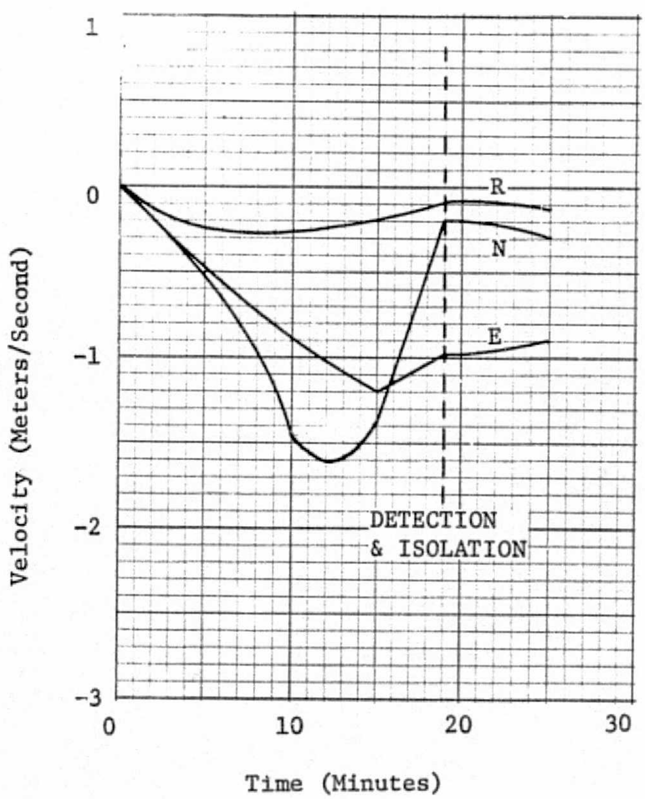
Error Detected & Isolated
@ 1145 seconds
Error Isolated to X Axis
of Non-Skewed IMU



Run #13
2 IMU FDI

VFDI, EDV = 0.075
+1°/hr Y Gyro Bias Shift
on Skewed IMU
10 Minutes into Navigation

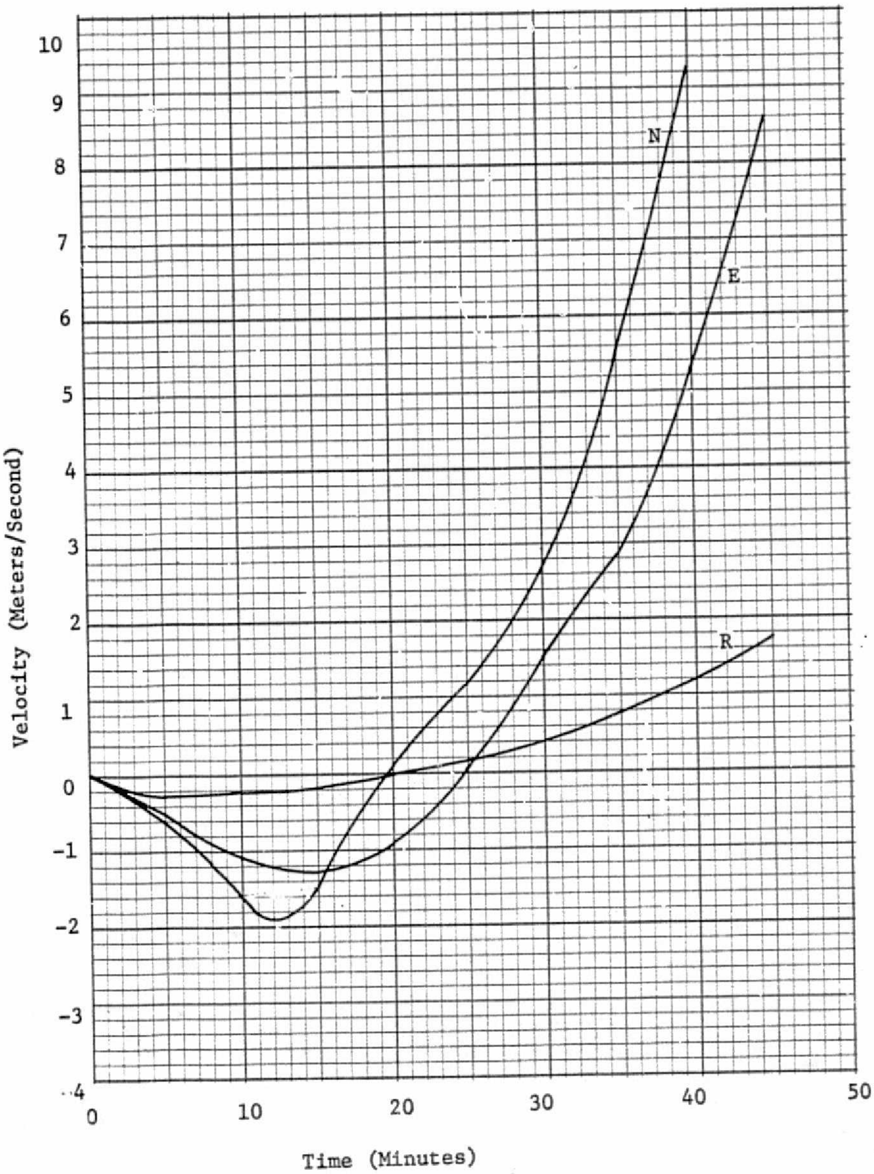
Error Detected & Isolated @ 1160 seconds
Error Isolated to X Axis of Skewed IMU



Run #14
2 IMU FDI

VFDI, EDV = 0.075
+1°/hr Z Gyro Bias Shift
on Non-Skewed IMU
10 Minutes into Navigation

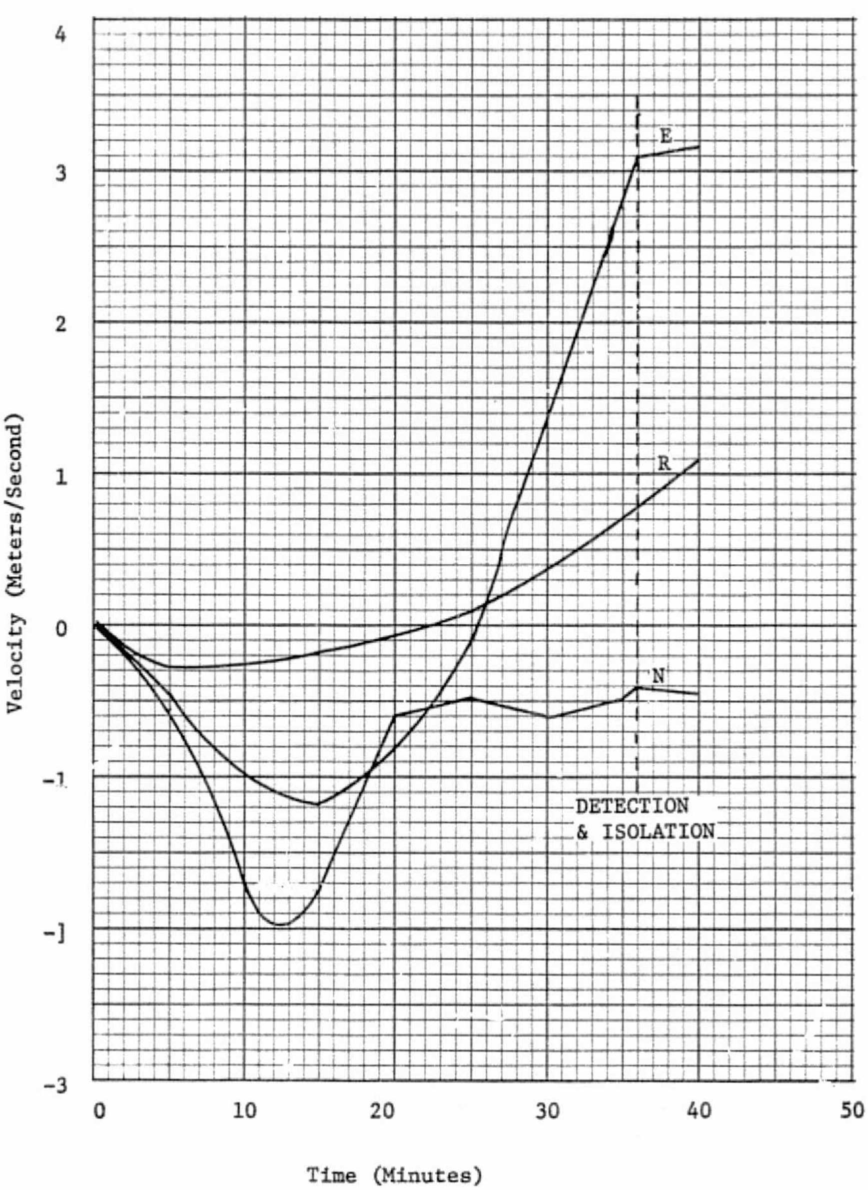
Error not Detected



Run #15
2 IMU FDI

VFDI, EDV = 0.075
+1°/hr Z Gyro Bias Shift
on Skewed IMU
10 Minutes into Navigation

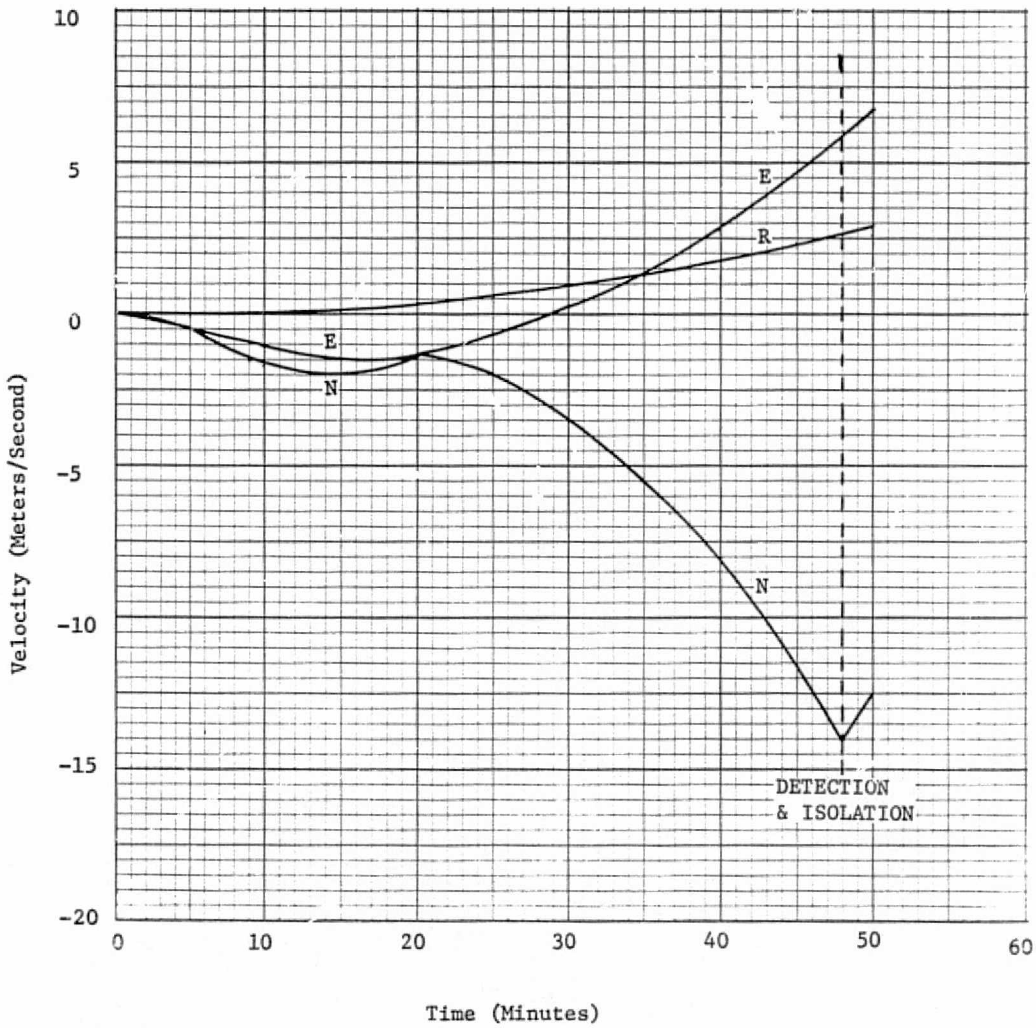
Error Detected & Isolated @ 2165 Seconds
Error Isolated to Y Axis of Skewed IMU



Run #16
2 IMU FDI

VFDI, EDV = 0.075
-1°/hr Z Gyro Bias Shift
on Non-Skewed IMU
10 Minutes into Navigation

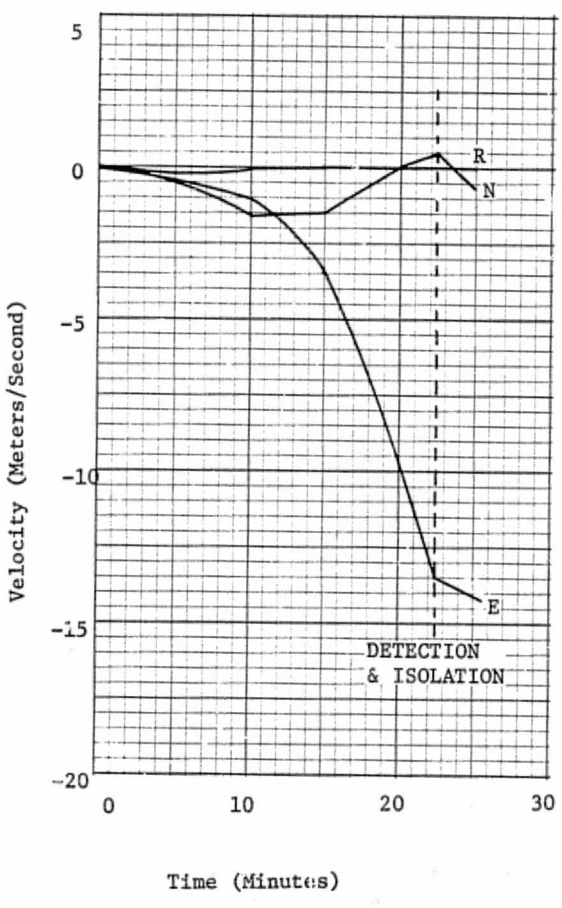
Error Detected & Isolated @ 2900 seconds
Error Isolated to X Axis of Non-Skewed IMU



Run #17
2 IMU FDI

VFDI, EDV = 0.075
-1°/hr X Gyro Bias Shift
on Non-Skewed IMU
10 Minutes into Navigation

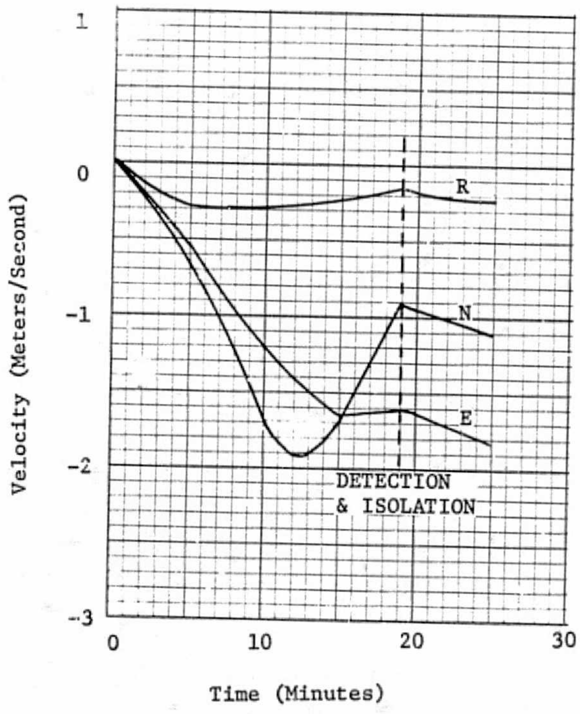
Error Detected & Isolated @ 1350 Seconds
Error Isolated to Y Axis of Non-Skewed IMU



Run #18
2 IMU FDI

VFDI, EDV = 0.075
-1°/hr X Gyro Bias Shift
on Skewed IMU
10 Minutes into Navigation

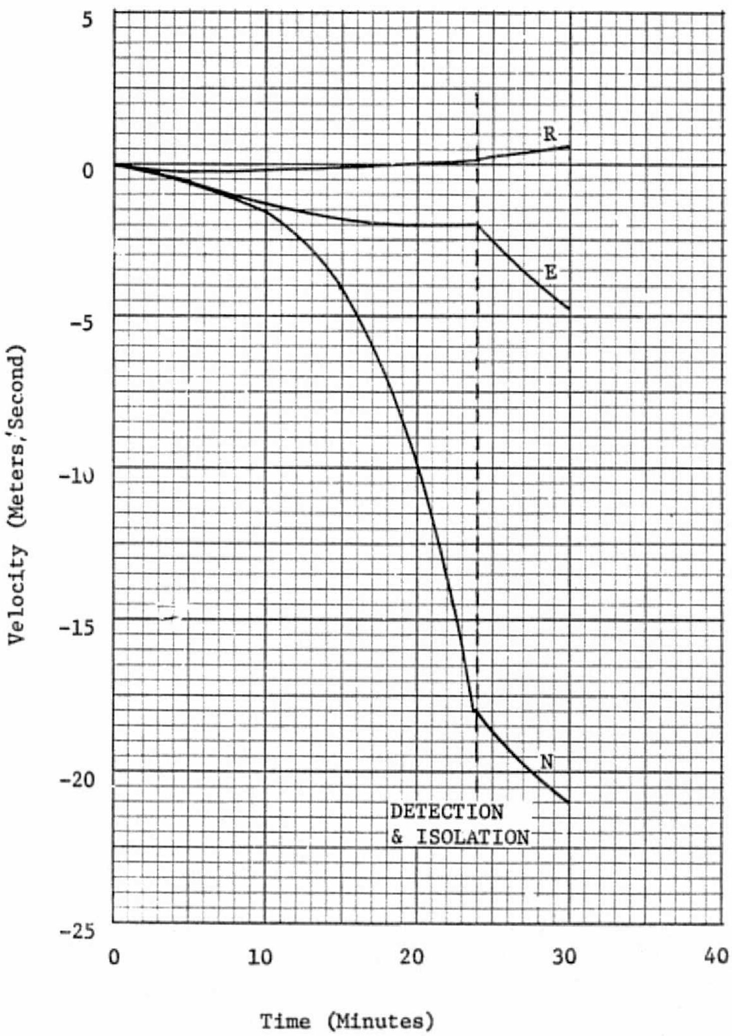
Error Detected & Isolated @ 1135 Seconds
Error Isolated to Y Axis of Skewed IMU



Run #19
2 IMU FDI

VFDI, EDV = 0.075
-1°/hr Y Gyro Bias Shift
on Non-Skewed IMU
10 Minutes into Navigation

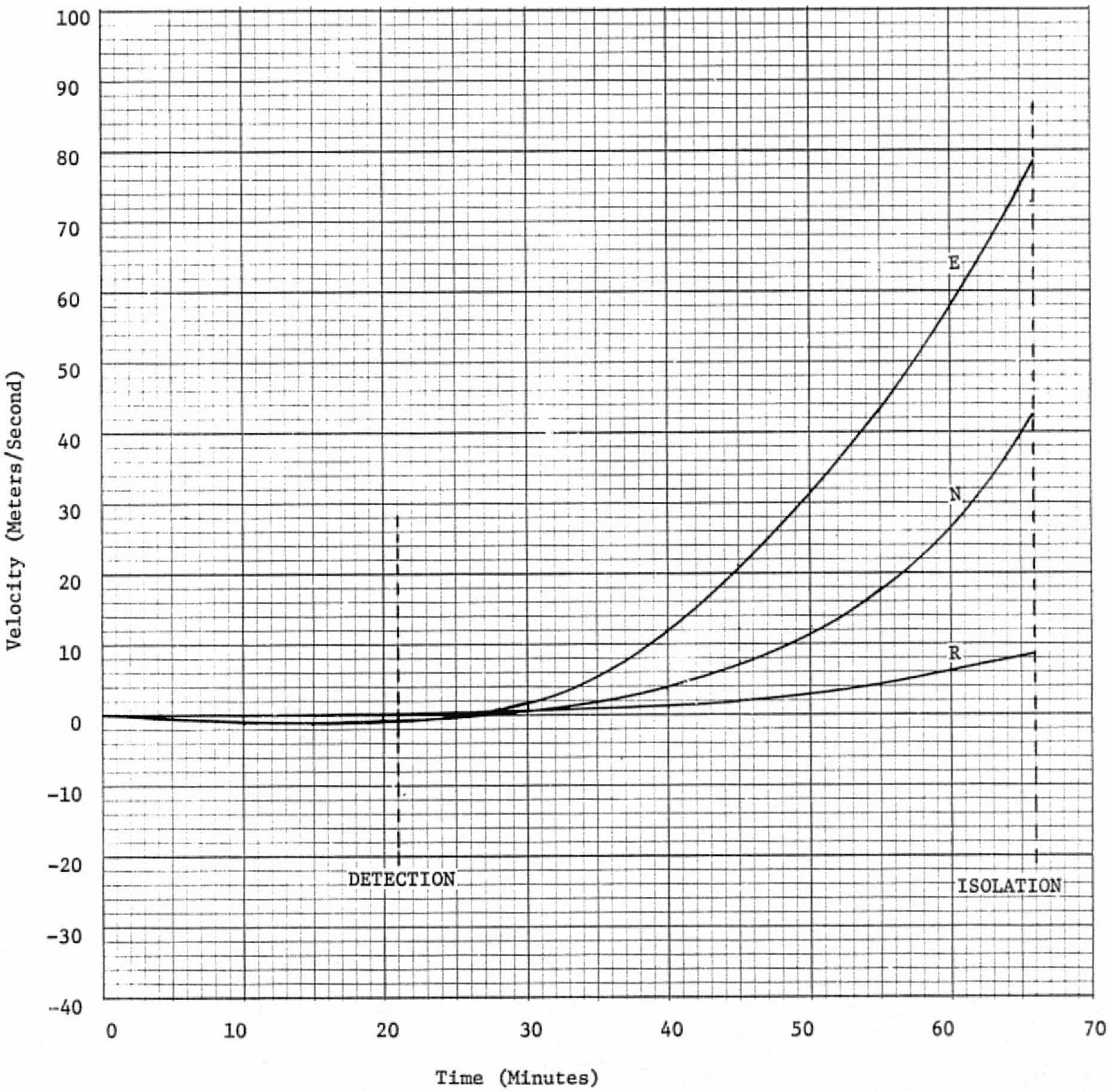
Error Detected & Isolated @ 1450 Seconds
Error Isolated to X Axis of Non-Skewed IMU



Run #20
2 IMU FDI

VFDI, EDV = 0.075
-1°/hr Y Gyro Bias
on Skewed IMU
10 Minutes into Navigation

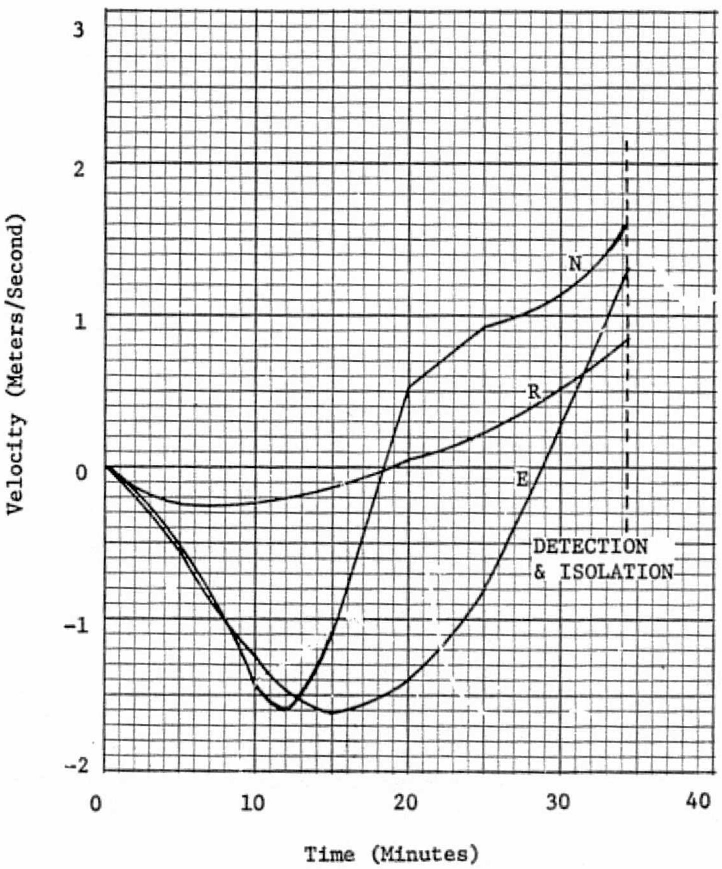
Error Detected @ 1255 Seconds
Error Isolated @ 3950 Seconds



Run #21
2 IMU FDI

VFDI. EDV = 0.075
-1°/hr Z Gyro Bias Shift
on Skewed IMU
10 Minutes into Navigation

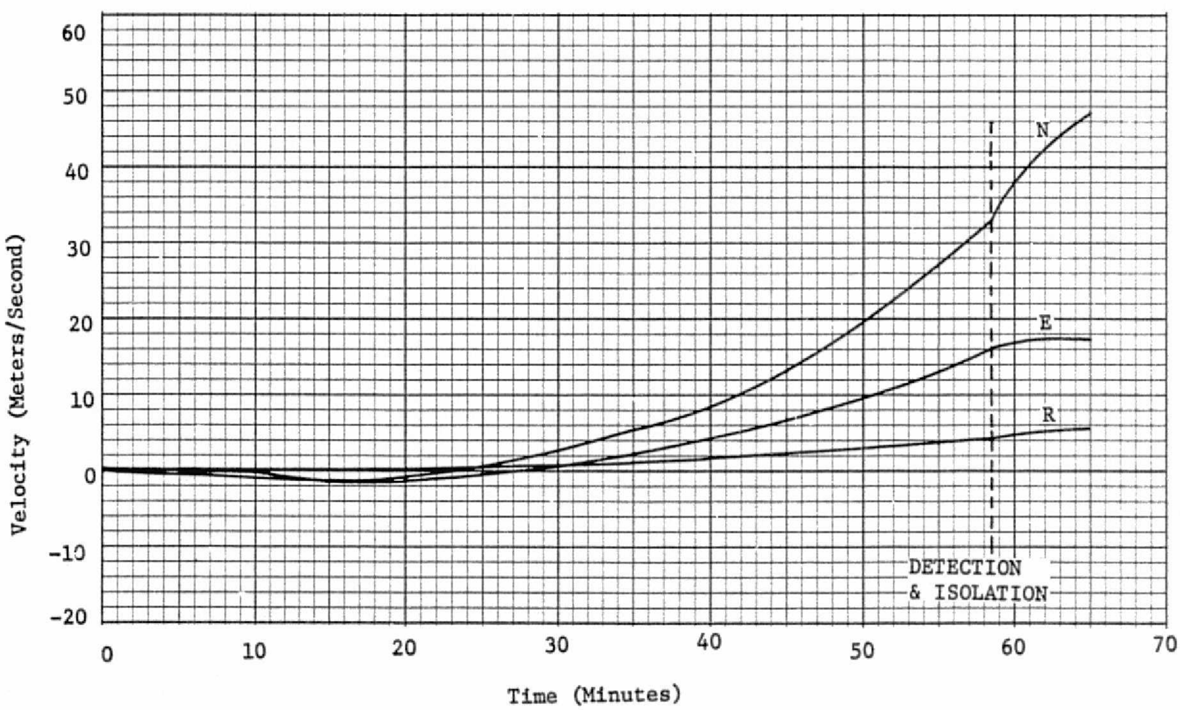
Error Detected & Isolated @ 2070 Seconds
Error Isolated to Y Axis of Skewed IMU



Run #22
2 IMU FDI

VFDI, EDV = 0.075
+1°/hr Z Gyro Bias Shift
on Non-Skewed IMU
10 Minutes into Navigation

Error Detected & Isolated @ 3510 Seconds
Error Isolated to Y Axis of Skewed IMU



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APPROVAL

REDUNDANCY MANAGEMENT OF MULTIPLE KT-70 INERTIAL MEASUREMENT UNITS APPLICABLE TO THE SPACE SHUTTLE

By Lewis J. Cook

The information in this report has been reviewed for security classification. The report, in its entirely, has been determined to be unclassified and contains no information concerning Department of Defense or Atomic Energy Commission programs.

This document has also been reviewed and approved for technical accuracy.

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