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**OPTICAL MASS MEMORY INVESTIGATION**

**CONTRACT NUMBER NAS8-30564**

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INVESTIGATION Final Report (Harris Corp.,  
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**FINAL REPORT**

**(CDRL 005)**

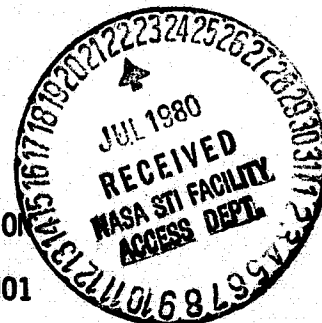
**PREPARED FOR**

**GEORGE C. MARSHALL SPACE FLIGHT CENTER  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812**

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P.O. BOX 94000, MELBOURNE, FLORIDA 32901**



**2 MAY 1980**



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## 1.0 INTRODUCTION AND SUMMARY

This report represents a summary of the work performed on Contract NAS8-30564. Since the thrust of the effort was to evaluate and subsequently design an advanced working model of an optical mass memory, this report will concentrate on the results of that work, rather than review in detail all the steps in evolving the final design approach. However, a summary of previous development accomplishments is presented for completeness.

### 1.1 HOLOGRAPHIC RECORDER/REPRODUCER - HOLOMEM

During the first phase of the optical mass memory investigations program, a breadboard holographic memory was designed and successfully tested. This system consisted of an acousto-optic page composer, a rotary disk recording media transport, a galvanometer data scanning system, and a self-scanned photo diode array. With this system, we successfully demonstrated recording and readout of holographic data on Kodak SO-253 film at a data rate of slightly less than 1 mega bit per second.

As a result of this phase of our investigations, we developed the  $\text{TeO}_2$  crystal as a mass produceable acousto-optic device. This device is currently being implemented in the AMM-13 system.

A second major component investigation involved a series of recording media studies. As a result of these studies we have eliminated photoplastic and thermoplastic as viable media alternatives because of inconsistencies in their performance. Electro-photographic and diazo materials show further promise as media alternatives, but silver halide media is the only existing recording material which will satisfy the requirements for high resolution recording and guarantee archival data stability.

## 1.2 DIGITAL RECORDER/REPRODUCER SYSTEM (DIGIMEM)

This approach, the recording of digital data in the form of spots, met with considerable success and resulted in several significant accomplishments:

- o A successful floppy disk film transport utilizing air platens which held the  $6\mu$  focus requirement.
- o Photodetector array readout of recorded spots at 1 Mb/s.
- o The production of high quality, reversal processed, optical spots, readable at rates of 1 Mb/s and up.
- o Development of clock and sync- recovery schemes for high speed data transfer via optical techniques.
- o The successful demonstration of optically recording and reading of 2.5 spots on  $3.5\mu\text{m}$  centers at 10 Mb/sec.

It was this first successful demonstration of direct spot recording and reading at high rates that led to the final phase of this contract - the Advanced Working Model.

## 1.3 ADVANCED WORKING MODEL (AWM)

The objectives of the AWM were to exploit the findings of the previous phases of work and to design and test breadboard models of optical storage and retrieval devices which would be capable of:

- o No less than  $10^{12}$  bits total storage
- o 10 sec or less random access to any one of 1000 records
- o Record and read rates of 30 Mb/s
- o Modular expandibility to  $10^{13}$  bits
- o  $10^9$  bit data record capacity
- o  $10^8$  bits/in<sup>2</sup> storage density
- o Achievable BER of  $10^{-6}$  or better

The design presented in the following sections satisfies or exceeds all but the third objective. A record rate of 30 Mbs was accomodated in the Recorder design; 5 Mbs in the Reader design. This change was made to demonstrate the viability of lower rate (and hence lower cost) reader concepts. Since procurement action for a deliverable  $10^{13}$  bit system prototype intervened, the fabrication and test phases were not completed, thus no test data is presented. However, it is worthy of note that the prototype system design is virtually the same as that presented in the following narrative.

## LIST OF FIGURES

<u>Section</u>	<u>Description</u>	<u>Page</u>
2.1	Recorder Subsystem Breadboard Configuration	2-3
2.1	S&R Reproducer Subsystem Prototype Configuration	2-4
2.1	MASTAR I Advanced Working Model Key System Parameters/Features	2-5
2.1	MASTAR I Advanced Working Model Recorder Subsystem Features and Parameters	2-6
2.1	MASTAR I Advanced Working Model S&R REPRODUCER Subsystem Features and Parameters	2-7
2.2	MASTAR I System Functional Block Diagram	2-8
2.2	Data Sources to Recorder Subsystem	2-10
2.2	Data Formatter Functions	2-11
2.2	MASTAR I Advanced Working Model Data Sources and Format	2-13
2.2	Recorder Optics Functional Block Diagram	2-14
2.2	Fiche Data Format Overview	2-15
2.2	S&R Reproducer Optics Functional Block Diagram	2-17
2.2	Data Deformatter Functions	2-19
2.2	Error Detection and Collection Functions	2-20
2.2	Error Statistics Printout	2-22
2.3	Advanced Working Model Format/Transport Trade-Off Considerations	2-24
2.3	Advanced Working Model Format/Transport Trade-Off Considerations (continued)	2-25
2.3	Advanced Working Model Format/Transport Trade-Off Considerations (continued)	2-27
2.3	Advanced Working Model Format/Transport Trade-Off Considerations (continued)	2-28

LIST OF FIGURES  
(continued)

<u>Section</u>	<u>Description</u>	<u>Page</u>
2.3	Advanced Working Model Format/Transport Trade-Off Considerations (continued)	2-30
2.3	Fiche Storage Capacity Requirement	2-32
2.3	Fiche Spatial Data Format	2-33
2.3	Guard Bands Permit Readout Beam Overscan	2-34
2.3	Fiche Format Information/Data Content Distribution	2-35
2.3	Spot Space Allocation Within Each Track	2-37
2.3	Lateral Misalignment Compensation With Readout Beam Overscans	2-38
2.3	Decentering Results in Line Skew Relative to the Readout Beam Trace	2-39
2.3	Readout Beam Scan Accuracy Tolerance Effects	2-41
2.3	Effects of Misalignment of Readout Beam Relative to Recorded Spot	2-42
2.3	Net System Tolerances Record and Read Processes	2-44
2.3	Important Tolerance Considerations	2-45
2.3	Important Tolerance Considerations (continued)	2-46



## LIST OF TABLES

<u>Section</u>	<u>Description</u>	<u>Page</u>
3.1.1.2.0	Media Specifications	3-7
3.1.1.2.0	Comparison of Recording Media Types for Optical Spot Recording	3-8
3.1.1.2.0	MASTAR -- Candidate Recording Media	3-16
3.1.2.2	The Recorder AOM Specifications	3-22
3.1.2.2	Recorder AOB D Specifications	3-23
3.1.2.2	Recorder ATWL Specifications	3-25
3.1.2.2	The Recorder Optics Lens Layout	3-29
3.2.2	Acousto-Optic Beam Deflector Characteristics	3-40
3.2.2	The Reader Optics Lens Layout	3-43
3.2.3	The Reader Lenses	3-45
3.2.4	Track-To-Track Step Tolerancing	3-52
3.2.4	Recorder-To-Reader Decentration Tolerancing	3-53
3.2.4	Transport Mechanisms and the Carousel Access Sequence (Worst-Case)	3-55
3.2.4	Transport Mechanisms and the Carousel Access Sequence (Worst-Case) (Continued)	3-56

## LIST OF FIGURES

<u>Section</u>	<u>Description</u>	<u>Page</u>
3.1.2.2	The MASTAR Recorder Subsystem Conceptual Layout	3-19
3.1.2.2	The Recorder Acousto-Optic Devices Schematic	3-26
3.1.2.2	The Acoustic-Traveling Wave Lens Recording System	3-28
3.1.3	The AOBD Driver Electronics	3-31
3.1.3	The Recorder Electronics Subsystem	3-32
3.1.3	The Recorder Transport Mechanism	3-35
3.1.3	The MASTAR Recorder Subsystem Packaging	3-36
3.2.2	The Acousto-Optic Beam Deflector Optics Schematic	3-38
3.2.2	The Acousto-Optic Beam Deflector Reader Optical System	3-41
3.2.3	The Optical Receiver Electronics	3-46
3.2.3	Data, Clock, and Error Statistics Recovery	3-48
3.2.4	The Storage and Retrieval Carousel Mechanisms Assembly	3-50
3.2.4	Reader and Storage and Retrieval Module	3-57
3.2.4	The Storage and Retrieval Carousel Reader	3-58
3.2.4	Rack Details for Storage and Retrieval Reader	3-59



**SECTION 2.0**

**AIM SYSTEM DESCRIPTION**

## 2.0 AWM SYSTEM DESCRIPTION

The objectives of the MASTAR I Optical Mass Storage System Advanced Working Model (AWM) were twofold: (1) to establish the technologies and design approaches for an operational system that would meet the requirements of a NASA Mass Storage System for applications such as the NEEDS Program (2) to provide a test-bed for determining raw error statistics under various conditions so that forward error correction coding techniques and hardware can be defined to ensure achievement of the required bit error rate for these applications in an operational system. This test-bed was intended to be used during the development of the operational system to help refine the design parameters of the forward error correction coding electronics.

In summary, the MASTAR I Advanced Working Model has been designed to demonstrate recording and playback of imagery data and to enable quantitative data to be derived as to the statistical distribution of raw errors experienced through the system. It is this latter capability that will continue to be invaluable throughout the development of future Optical Mass Storage Systems. Quantitative data about the statistical distribution of the raw bit error rate experienced in optical recording is essential to enable the definition and design of forward error correction coding techniques to achieve extremely low bit error rates (less than one part in  $10^9$ ).

### 2.1 AWM Key System Features and Parameters

The Advanced Working Model System consists of two subsystems: the Recorder and the Storage and Retrieval (S&R). The Recorder Subsystem utilizes key technologies such as an Acoustic-Traveling Wave Lens to achieve recording of digital data on fiche at a rate of 30 Mbits/sec, whereas the S&R Reproducer Subsystem utilizes a less complex optical system that employs an Acousto-Optical Beam Deflector to achieve data readout at a 5 Mbits/sec rate.

The Recorder Subsystem is an operational breadboard as depicted in Figure 2.1-1, whereas, the S&R Reproducer Subsystem is a rack mounted prototype configuration is illustrated in Figure 2.1-2. Some key system features and parameters are listed in Figure 2.1-3. These will be discussed in greater detail throughout the remainder of this report. However, note that the system has the built-in capability for detecting and collecting error statistics. Some of the key features and parameters of the Recorder and S&R Subsystems are listed in Figures 2.1-4 and 2.1-5 respectively.

It is important to note that the Recorder and S&R Subsystems operate independent of one another. Furthermore, each of the Subsystems are constructed in modular form with each module performing independent functions. The operation of each module and its interface to other modules is controlled by a Controller for both the Recorder and S&R Subsystems. These, as well as other features, of the Advanced Working Model can best be described by referring to Figure 2.2-1.

## 2.2 AWM System Description

Figure 2.2-1 shows a functional block diagram of the MASTAR I Advanced Working Model. The lower half of the figure depicts the Recorder Subsystem, and the upper half of the figure depicts the S&R Reproducer Subsystem. Although both subsystems are shown in this Figure, they are functionally and physically separable. The system operation can be explained by tracing the data flow through the Recorder, to the formation of the recorded fiche, to the reading of the fiche in the S&R Reproducer Subsystem, and outputting the data to the display or to the error detection and collection electronics.

BREADBOARD

RECORDER CONFIGURATION SUBSYSTEM

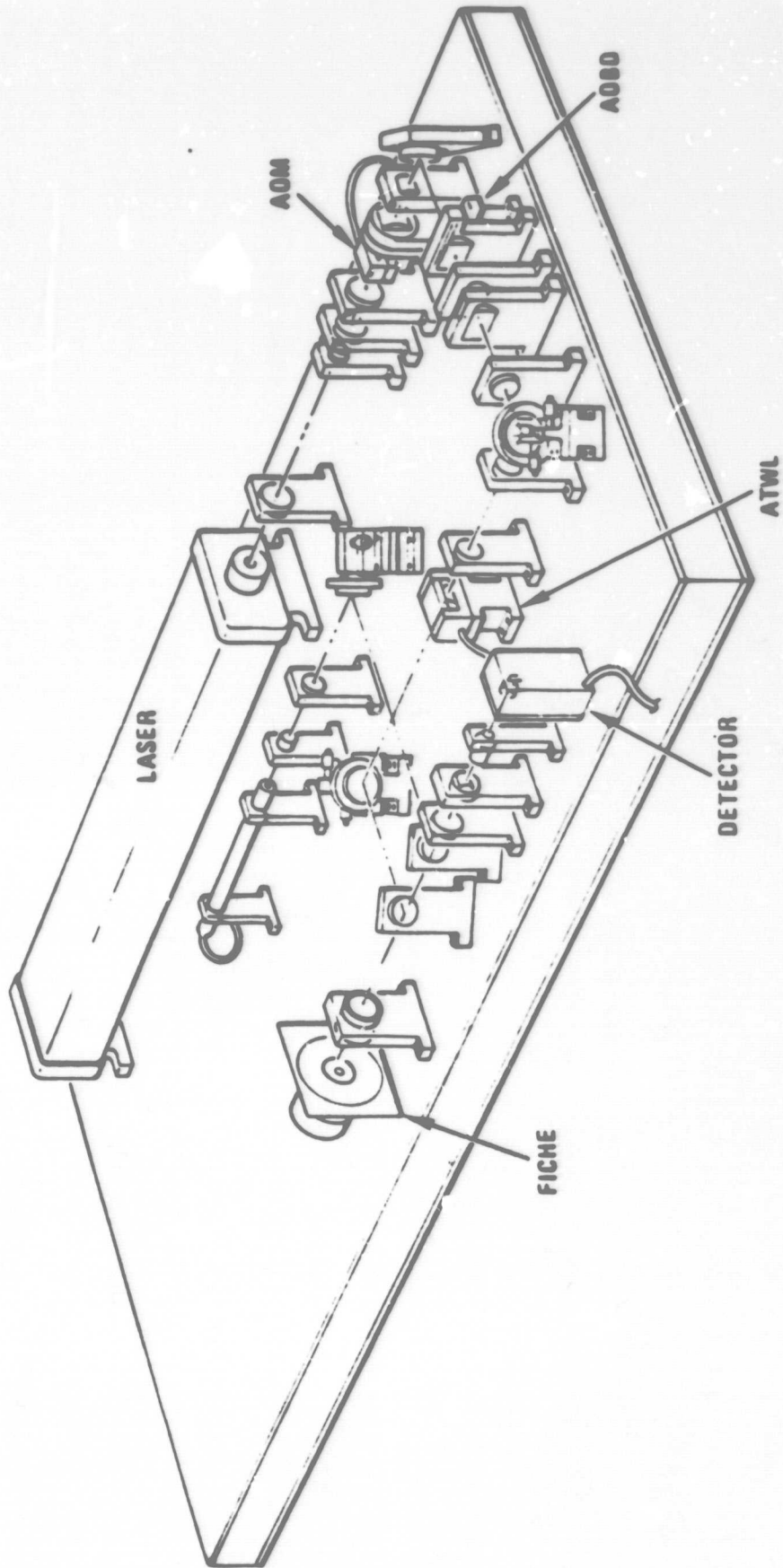


Figure 2.1-1

S&R REPRODUCER PROTOTYPE SUBSYSTEM CONFIGURATION

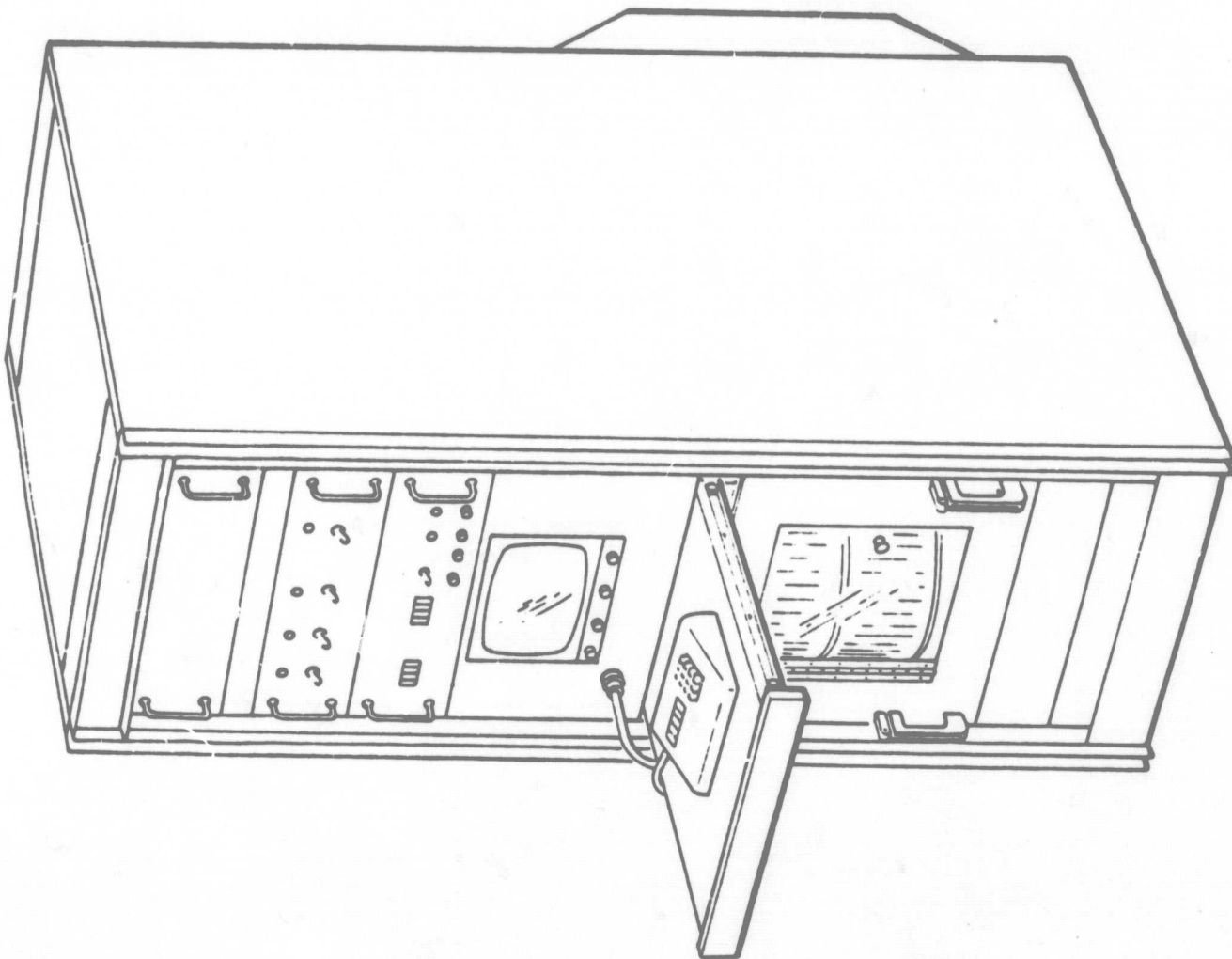


Figure 2.1-2

**MASTAR I**

**ADVANCED WORKING MODEL**

**KEY SYSTEM PARAMETERS/FEATURES**

- **DATA RECORD CAPACITY:  $10^8$  USER BITS PER FICHE**
- **AVERAGE STORAGE DENSITY:  $10^8$  USER BITS/IN<sup>2</sup>**
- **RECORD RATE:  $3.0 \times 10^7$  b/s**
- **READ RATE:  $5.0 \times 10^6$  b/s**
- **RANDOM ACCESS TIME: 10 SEC AVERAGE**
- **BIT ERROR RATE:  $10^{-6}$  OR BETTER (SHOW HOW WHEN EDAC IS IMPLEMENTED)  $10^{-9}$  GOAL**
- **OFF-LINE FILM PROCESSING**
- **SYSTEM SHALL INCORPORATE ERROR DETECTION AND COLLECTION ELECTRONICS**
- **THE SYSTEM SHALL BE AN END-TO-END OPERATIONAL RECORDER/REPRODUCER ADVANCED WORKING MODEL**



## MASTAR I

### ADVANCED WORKING MODEL

#### RECORDER SUBSYSTEM

#### FEATURES AND PARAMETERS

- OPERATIONAL BREADBOARD—MODULES ARE BENCH MOUNTED
- EACH MODULE IS SELF-CONTAINED AND OPERATES INDEPENDENT OF OTHER MODULES WITH ONLY COMMAND SIGNALS FROM THE CONTROLLER
- EACH MODULE IS INDEPENDENTLY TESTABLE BEFORE INTEGRATION INTO THE SYSTEM
- DATA SOURCES ARE TV IMAGES AND PN SEQUENCE-SWITCH SELECTABLE
- ELECTRONIC DATA STORAGE: FULL TV IMAGE (3 BIT QUANTIZATION) IN RECORDER SUBSYSTEM— $10^6$  BITS
- RECORD RATE: 30M BITS/SEC USER RATE  
144M PIXELS/SEC DURING ACTIVE SCAN
- MANUAL FILM HANDLED TO THE FILM PROCESSOR
- LINE SCAN TIME: 5.5 MICROSECONDS ACTIVE SCAN  
11.0 MICROSECONDS AVERAGE  
(90.91K LINES/SEC)
- SCAN LENGTH: 792 SPOTS ACROSS 1.11 mm LINES
- FICHE FORMAT: 36 ANULAR TRACKS ON 1.25 mm CENTERS  
EACH TRACK MADE UP OF 1.11 mm LINES ON  
2.6 MICROMETER CENTERS

**MASTAR I**

**ADVANCED WORKING MODEL**

**S AND R REPRODUCER SUBSYSTEM**

**FEATURES AND PARAMETERS**

- **STAND ALONE SUBSYSTEM-OPERATIONAL PROTOTYPE**
- **CONTAINED IN A 19-INCH RACK**
- **OPERATES INDEPENDENT OF THE RECORDER SYSTEM**
- **HAND LOAD FICHE IN CAROUSEL**
- **DATA CAPACITY: 10<sup>12</sup> USER BITS STORED ON 1000 FICHE**
- **UPON COMMAND THE SYSTEM RETRIEVES A FICHE, READS THE DATA, DEFORMATS THE DATA AND DISPLAYS THE RESULTING IMAGE ON THE CRT**
- **WHEN PIN SEQUENCE DATA IS RECORDED ON FICHE--ERRORS IN THE DATA ARE DETECTED ON A BIT-BY-BIT BASIS**
- **ERRORS ARE COLLECTED FOR ERROR ANALYSIS--PAPER TAPE PRINT-OUT**
- **READ RATE: 5M BITS/SEC USER DATA**  
12M SPOTS/SEC AVERAGE RATE  
24M SPOTS/SEC DURING ACTIVE SCAN
- **SCAN LENGTH: >865 SPOTS TO OVERSCAN**  
792 SPOTS 1.11 mm RECORDED LINE

Figure 2.1-5



MASTAR I SYSTEM  
FUNCTIONAL BLOCK DIAGRAM

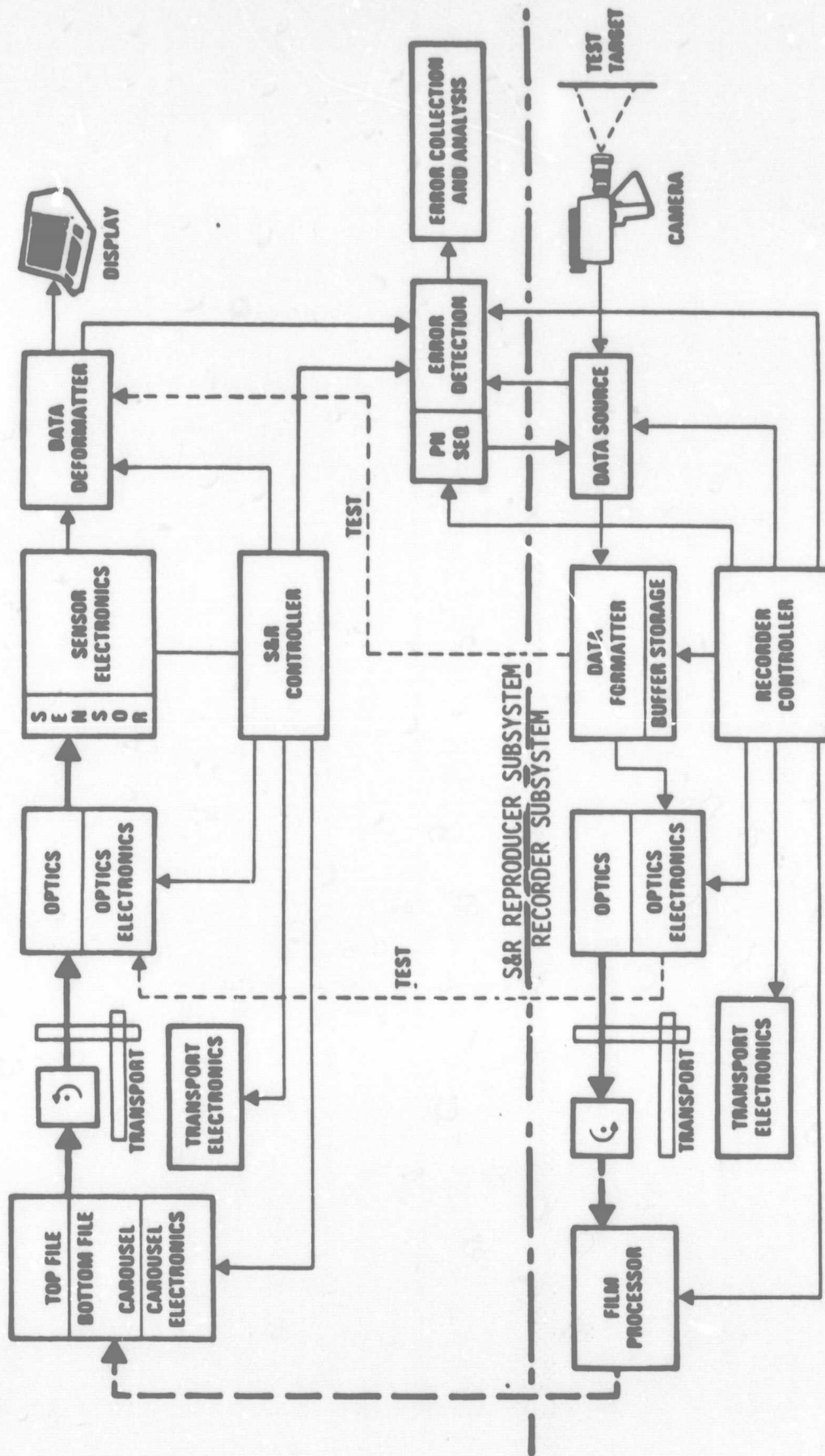


Figure 2.2-1

### 2.2.1 Recorder Subsystem

The data to be recorded are derived from one of two sources: a television (TV) camera, that views a test target, or a PN sequence generator. The TV (video) camera is utilized for demonstration purposes, whereas the PN sequence generator is used as a reference data source from which readout errors can be examined and detected to determine the statistical distribution of the raw bit errors. Figure 2.2-2 shows how the data to be recorded by the Recorder Subsystem is derived from either the TV camera or the PN sequence generator, and formatted into 33 bit parallel output words at a serial equivalent rate of 30 Mbits/sec.

The data formatter accepts the 33 bit parallel input and reads it into memory as depicted in Figure 2.2-3. The formatter ingests data into memory until  $10^6$  bits have been stored: this is equivalent to one TV frame of video. Also, if the PN sequence generator is used, the process is the same with  $10^6$  bits of data stored into memory before the recording process begins. After the memory is filled, the data is read out of memory and formatted into individual lines to be recorded on the fiche. First, the TV camera video data is bandwidth limited to approximately 4.5 MHz and sampled at 10 M/samples per second. This sampled signal is then quantized to 3 bits providing 30 Mbit/sec output data into the formatter. One complete TV frame ( $10^6$  bits) are stored in memory in the formatter as previously described. The pseudo-random sequence used for error detection and collection is derived from an 11 stage PN sequence generator. This signal is formatted into the 33 bit parallel output and shifted at 30 Mbits/sec to the data formatter.

The formatting process, see Figure 2.2-3, starts with Manchester encoding of the user data which yields 660 spots for 330 (ten 33 bit words) user bits in each line. The encoded data stream is then

DATA SOURCES  
TO RECORDER SUBSYSTEM

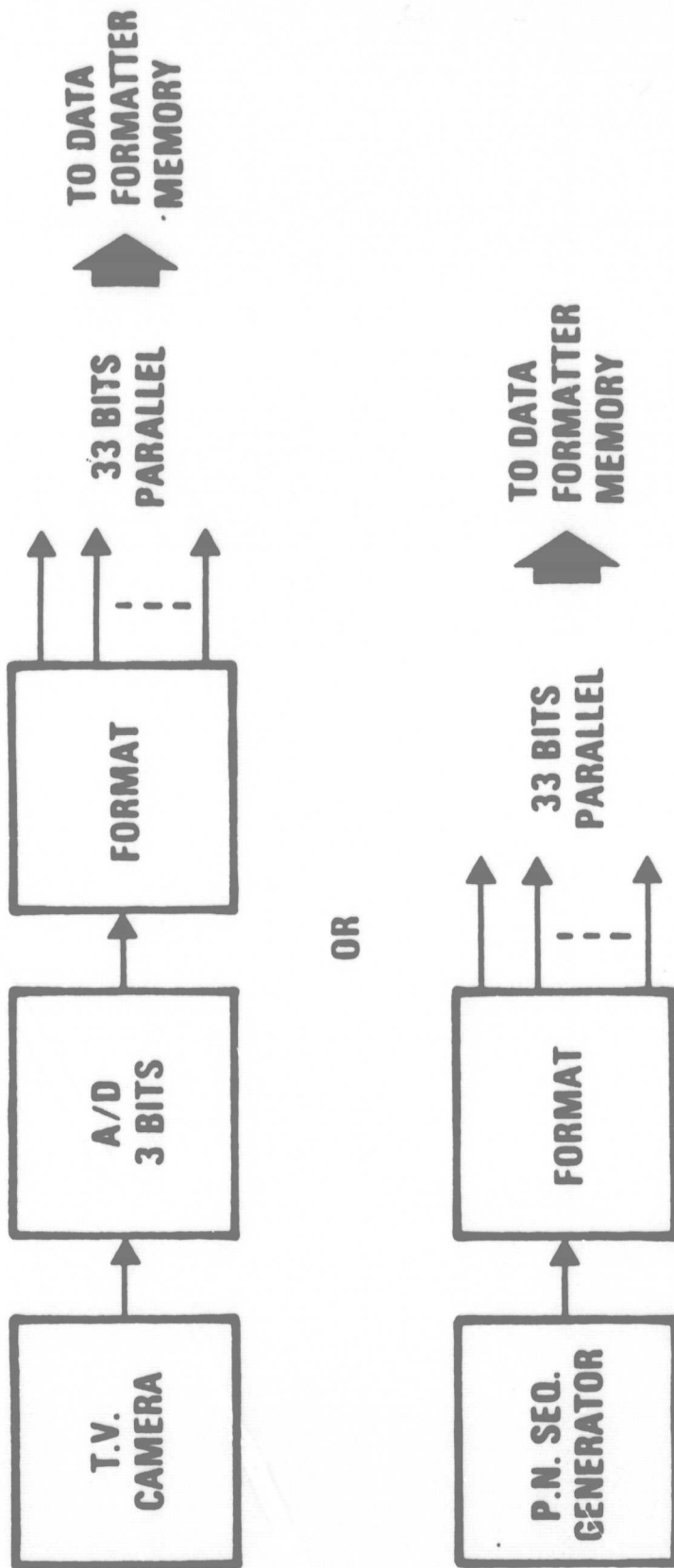
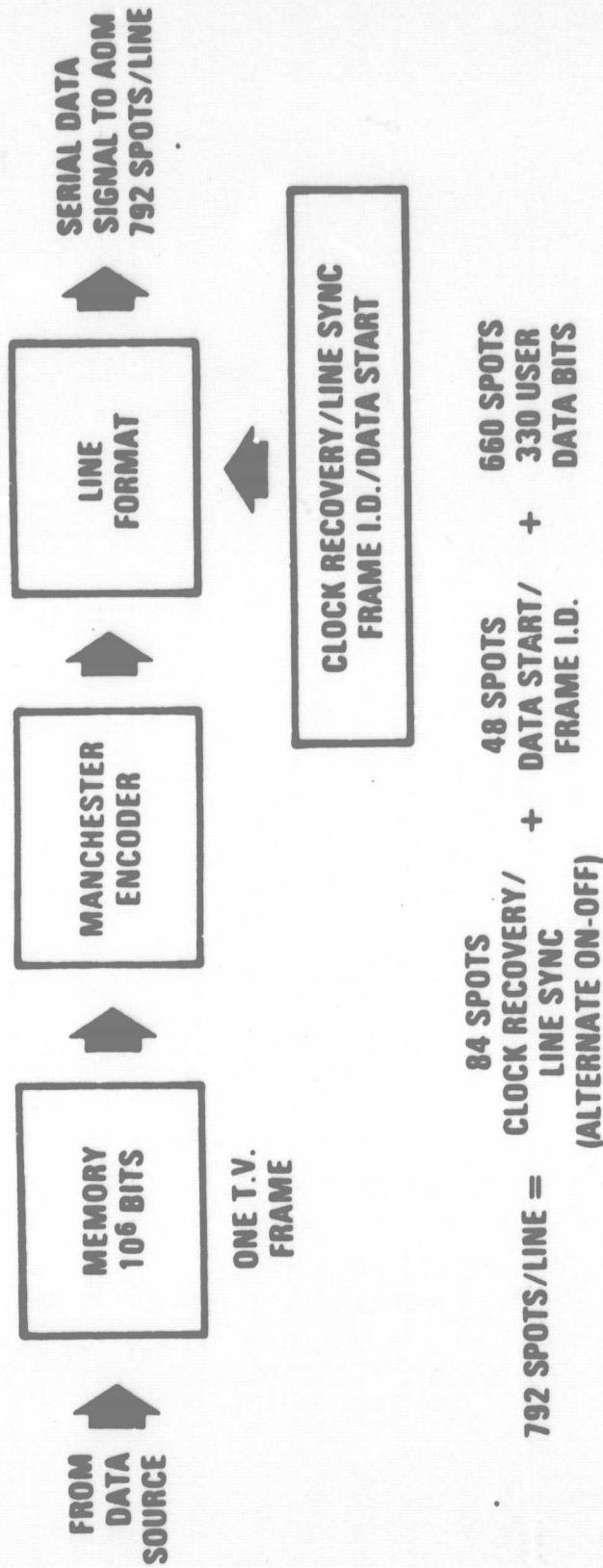


Figure 2.2-2

DATA FORMATTER FUNCTIONS



multiplexed with 84 spots at the beginning of each line for clock recovery and 48 spots following the clock recovery for data start/frame I.D. This makes a total of 792 spots per line that are recorded on the fiche. The modulated data signal is then outputted from the data formatter to the optics module at an average rate of 72 Mspots/sec, or an instantaneous rate of 144 Mspots/sec at a 50% duty factor. The 50% duty factor is utilized to provide sufficient time for retrace of the optical scanner which utilizes an Acousto-Optical Beam Deflector (AOBD) and an Acoustic-Traveling Wave Lens (ATWL). A summary of the data formatting process is shown in Figure 2.2-4.

The serial data signal is transferred from the formatter to the Recorder Optics Module depicted in Figure 2.2-5. As described, this serial data signal consists of 792 pulses from which 792 individual spots are recorded on the fiche each time the optical system scans the beam across 1.11 mm of line length. The recording process is as follows: the Laser Beam is modulated by the data signal via the Acousto-Optical Modulator (AOM). From the AOM the amplitude modulated Laser Beam is expanded and projected through the Acousto Optical Beam Deflector (AOBD). The AOBD, in conjunction with the optics immediately following it, scans the modulated beam across the Acoustic-Traveling Wave Lens (ATWL). The ATWL demagnifies the scanning spot to produce an output near its surface of 792 spots. The optics immediately following the ATWL are used to re-image the 792 spots onto the 1.11 mm line length at the fiche. Hence, as the fiche rotates, individual lines, each containing 792 spots, are sequentially recorded. This is depicted in Figure 2.2-6. After sufficient lines have been recorded to complete a single fiche track, the fiche is mechanically translated to the next track location and recording of lines of data continues. This process is repeated until all of 36 tracks are recorded. At this point the recording process ceases and the fiche is



MASTAR I

ADVANCED WORKING MODEL

DATA SOURCES AND FORMAT

IMAGERY DATA

DATA SOURCE: TV CAMERA  
VIDEO BANDWIDTH: = 4.5 MHz  
SAMPLE RATE: 10M SAMPLES/SEC  
QUANTIZATION: 3 BITS  
BIT RATE TO RECORDER: 30 Mb/s  
DATA PER TV FRAME: 10<sup>6</sup> BITS  
DEMULTIPLIED DATA: 33 BITS PARALLEL TO RECORDER  
(11, 3 BIT PIXELS)

FIXED DATA FOR ERROR DETECTION

DATA SOURCE: 11 STAGE PN GENERATOR  
DATA RATE: 30 Mb/s  
DEMULTIPLIED DATA: 33 BIT WORDS PARALLEL  
TO RECORDER

MODES: 1. REPEAT EACH 330 BITS (10 WORDS)  
2. CONTINUOUS RUN 2<sup>11</sup> - 1 BITS

LINE FORMAT

USER BITS/LINE: 330 (10-33 BIT WORDS)  
USER SPOTS: 660 (MANCHESTER BIPHASE)  
DATA START WORD: 24 - 48 SPOTS  
CLOCK RECOVERY: 84 SPOTS  
TOTAL SPOTS/LINE: 792  
AVERAGE SPOT RATE: 72M SPOTS/SEC  
ACTIVE SPOT RATE: 144M SPOTS/SEC (50%  
DUTY FACTOR)  
LINE LENGTH: 1.11 mm  
GUARD BAND: 0.14 mm  
NUMBER OF TRACKS: 35

RECORDER OPTICS  
FUNCTIONAL BLOCK DIAGRAM

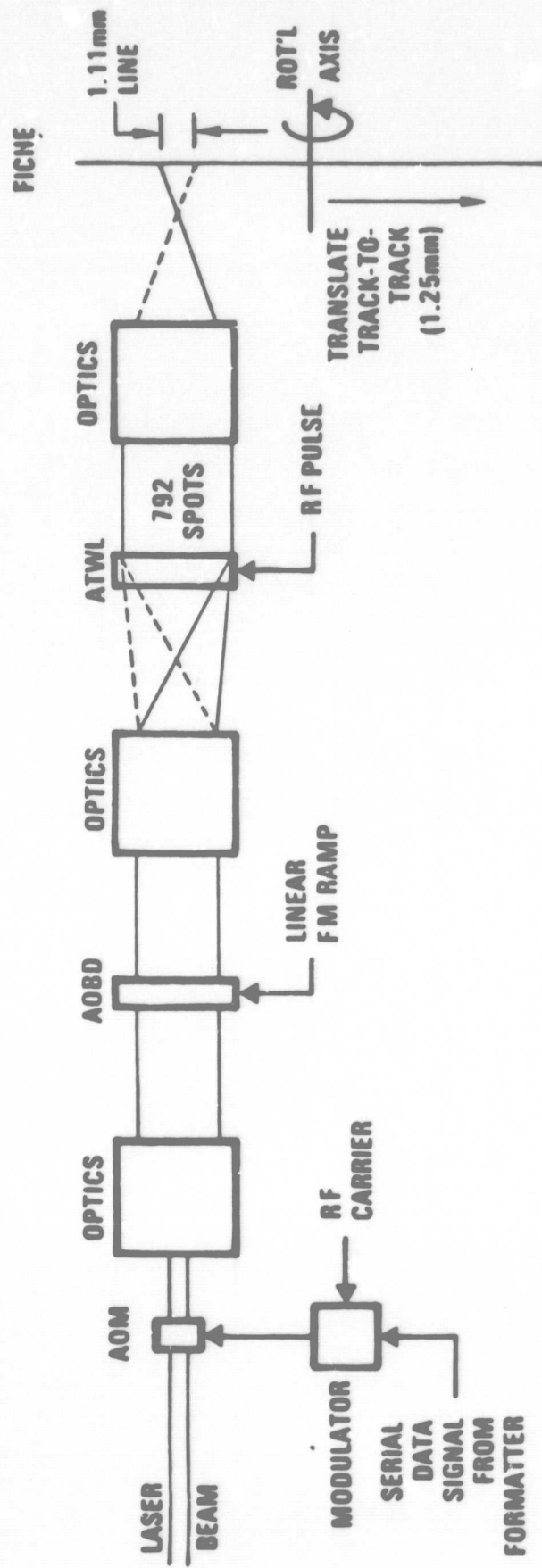


Figure 2.2-5

FICHE DATA FORMAT OVERVIEW

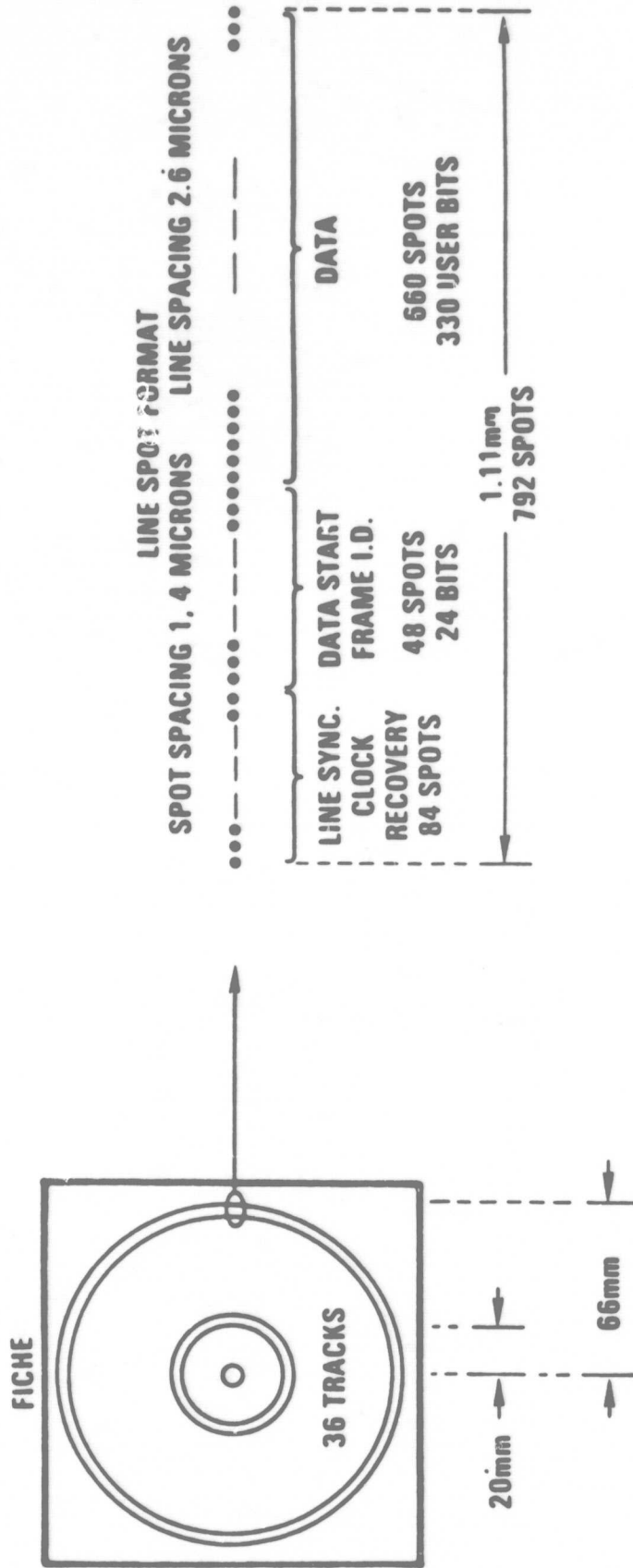


Figure 2.2-6



removed and chemically processed in the Film Processor as illustrated in Figure 2.2-1. From the film processor, the fiche is manually removed and inserted into a pre-defined storage location in the Storage Module (Carousel). The fiche can now be automatically retrieved and read by the S&R Subsystem.

#### 2.2.2. S&R Subsystem

The operation of the S&R Subsystem begins with an operator input via the keyboard. This input instructs the S&R Subsystem to retrieve a requested pre-defined fiche and to read data from a pre-defined track on that fiche. With this instruction, the S&R Controller causes the rotation of the carousel to a specified fiche location. The fiche is extracted by the extractor head part of the Transport Module. It is then translated by the Transport Module and positioned onto the rotary shaft of the Rotary Transport. At this point the fiche is rotated up to speed and when the track start location is reached, reading of the data begins. The individual lines of data within the track are scanned and read out, utilizing the Reader Optics Module, illustrated by the block diagram shown in Figure 2.2-7. The scanning Laser Beam, that illuminates the individual lines of data as the fiche rotates, is produced by the AOBDO optics configuration shown to the left of the fiche in Figure 2.2-7. In addition to the scanning beam, a stationary beam is produced that illuminates the first 84 spots of the line continuously. As the fiche rotates, this illumination is modulated as the lines of data pass through it. The light from both the scanning and stationary beams are collected by the optics shown to the right of the fiche in Figure 2.2-7 and brought to focus on the optical detectors. The scanning beam is focused onto one detector from which the data signal is derived. The stationary beam, which is modulated by the fiche rotation, is focused onto the second detector. The resulting signal from this detector is utilized to synchronize the scanning beam with

S&R REPRODUCER OPTICS  
FUNCTIONAL BLOCK DIAGRAM

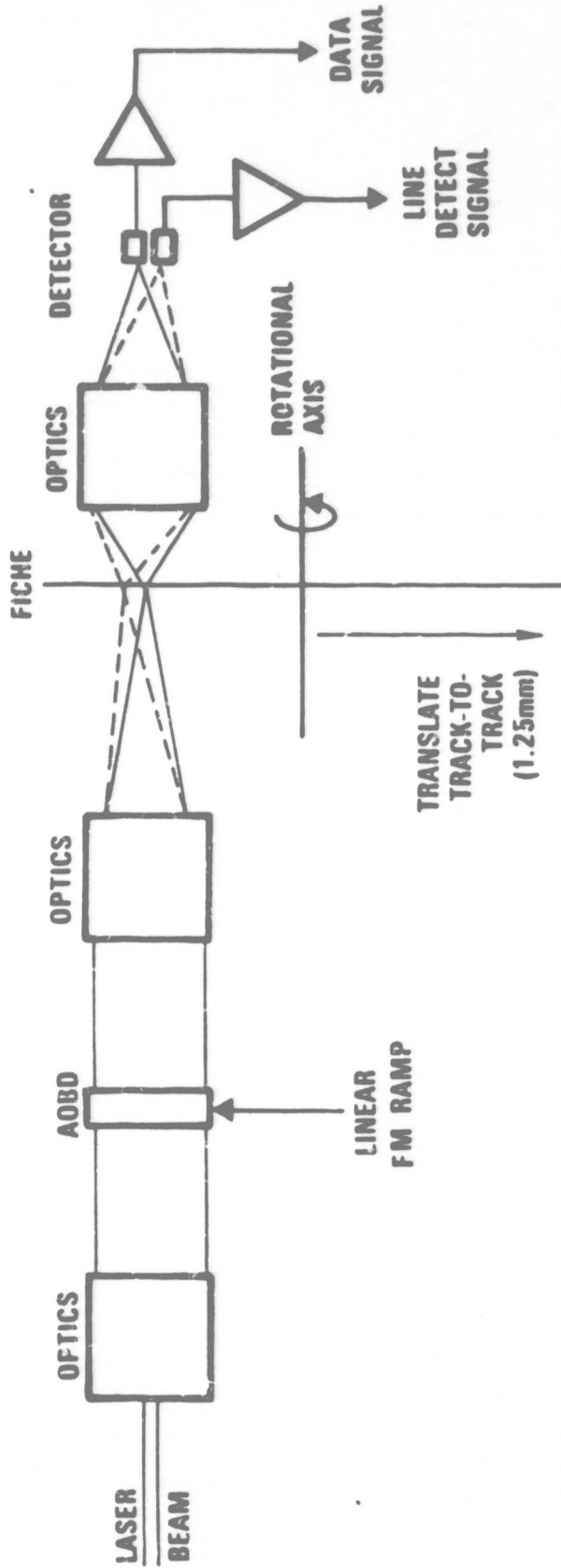


Figure 2.2

the fiche rotation so that the individual lines are tracked by the scanning beam. Synchronization and timing is achieved in the S&R Controller Module. The output data signal from the S&R Optics Module is inputted to the Data Deformatter Module. From this signal, data clock is recovered and it is decoded to strip the Manchester biphasic baseband code as illustrated in Figure 2.2-8. Further, the overhead data is removed (the first 84 spots for clock recovery and the next 48 spots or 24 bits for data start and frame I.D.). The output from the deformatter is therefore user data and clock. This data is clocked into a buffer memory ( $10^6$  bits). From memory the data is read out and is converted to an analog signal after which it is displayed on a TV Monitor. In this way, the entire Recorder and S&R Subsystems (Advanced Working Model) can be demonstrated by displaying imagery data. On the other hand, if the data that was originally recorded came from the PN sequence generator, the output from the deformatter is compared on a bit-by-bit basis to the original PN sequence as illustrated in the bottom part of Figure 2.2-8. When an error is detected it is stored and printed out on a paper tape printer for use in error data analysis. More details about the error data print-out will be described later in this section.

### 2.2.3 Error Detection and Collection

The important features of the Error Detection and Collection Module are set forth in Figure 2.2-9. First, the retrieved data are compared on a bit-by-bit basis to the PN sequence from which the data was originally generated; hence all errors are detected. Second, a sliding window goes high once an error is detected and stays high for  $n$  bits where  $n$  can be selected to be 2, 4, 8, 16, etc. Further, the high state will remain as long as an error is within the window. This state is called an error event.

DATA DEFORMATTER  
FUNCTIONS

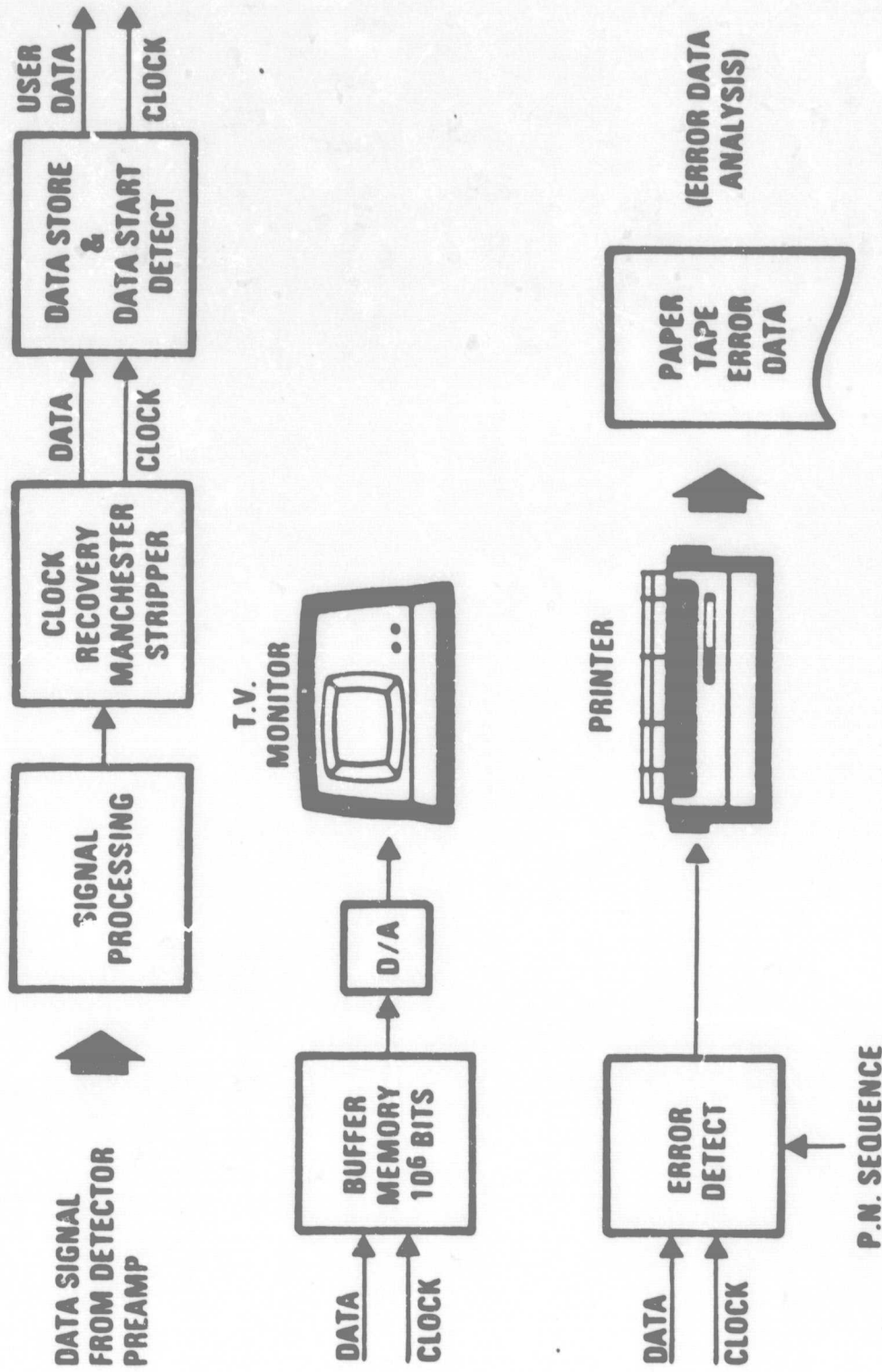


Figure 2.2-8



**ERROR DETECTION AND COLLECTION FUNCTIONS**

- **THE RETRIEVED DATA IS COMPARED BIT-BY-BIT TO THE ORIGINAL P.N. SEQUENCE**
- **A SLIDING ERROR WINDOW, N BITS LONG, (N IS SELECTABLE 2, 4, 8, 16 . . . ) ESTABLISHES ERROR EVENTS**
- **EACH ERROR EVENT IS RECORDED ALONG WITH THE NUMBER OF ERRORS DETECTED IN EACH EVENT**
- **EACH LINE WHERE AN ERROR EVENT OCCURRED IS IDENTIFIED**

An error event may have any number of errors. Further, since we are dealing with binary data, on the average half of the errors will be interpreted as correct data. Therefore, a burst error is detected by the length of the error event in which the sliding window passes at least one error. Each error event is recorded on the paper tape print-out. Further, the number of errors in each event, is also printed out. This allows the Analyst to determine the statistical distribution of errors generated in the system. For reference purposes the print-out also contains an identification of the individual lines within a track where an error event occurs. This will enable an error to be referenced directly to a specific location on the fiche. Hence, a careful examination of the recorded data on the fiche can be achieved under a microscope. Figure 2.2-10 is an illustration of a typical error print-out. The left hand column shows the line number where an error event was detected. The center column shows the length of the error event, i.e., the number of bits from the beginning of the error event to the last error in the event. The last column shows the actual number of errors measured in the event. With the errors printed out as shown in this figure the Analyst can determine the statistical distribution of the raw bit error rate, and from this be able to define forward error correction coding techniques which will substantially improve the bit error rate.

ERROR STATISTICS PRINTOUT

LINE ID #	EVENT LENGTH	ERROR COUNT
75	9	3
95	3	2
130	1	1
203	14	8
214	1	1
320	1	1
327	NO DATA CLOCK	
328	18	8
328	54	30
328	51	16
328	85	41
329	NO SYNC WORD	
406	1	1
437	1	1
529	13	7
766	5	4
938	1	1
1037	10	6
1153	3	2
1268	15	8
1447	14	7
1594	18	5
1818	12	7
2024	7	4

Figure 2.2-10

## 2.3

### AWM System Design Considerations

The AWM subsystem design approaches resulted from fundamental system design considerations, some of which are discussed here.

#### 2.3.1

#### Data Format/Rotary Transport Speed Trade-Off Considerations

First, it must be recognized that two-dimensional spot recording is a necessity to achieve a recording rate of 30 Mbits/sec or higher while maintaining a practical film rotational speed. Figure 2.3-1 illustrates the two-dimensional recording process where  $N_s$  individual spots are recorded in each line while the film moves a distance  $\delta_\ell$ . The film velocity is given by the fundamental equation shown in the figure. The parameters in this equation can be definitized from a combination of system requirements and practical design considerations.

The average spot recording rate  $\bar{R}_s$  is determined from the user data rate of 30 Mbits/sec and the derived design requirement for internal overhead consisting of 84 spots for clock recovery and 48 spots for data start and frame identification. This derivation is illustrated in Figure 2.3-2 with a result of 72 Mspots/sec. To achieve this average spot recording rate, the selected design approach utilizes an optical scanning technique with a 50% duty factor. This means that half the line scan period is utilized in the process of recording spots on film whereas the other half is taken up in the process of resetting the optical scanner for the next scan. Thus, the instantaneous spot recording rate  $R_s$  becomes 144 Mspots/sec.

Next, the total number of spots to be recorded in each line is dependent upon the scanning technique selected, the mechanical and optical tolerances that are realistic and the overhead required for data recovery. The acousto-optical scanning technique was selected because it is electronically controllable with no moving parts. This selection, along with a

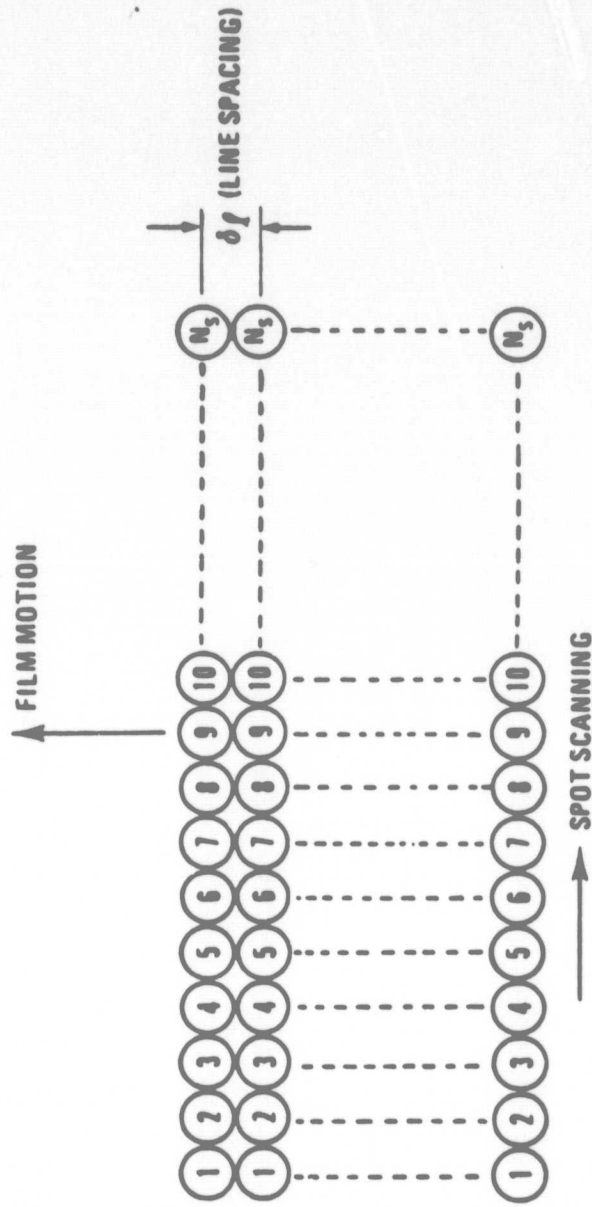


ADVANCED WORKING MODEL

FORMAT/TRANSPORT

TRADE-OFF CONSIDERATIONS

START WITH THE PRACTICAL ASSUMPTION OF  
TWO DIMENSIONAL RECORDING/READING



THE FILM SPEED IS

$$S_f = \delta l R_f = \frac{\delta l \bar{R}_s}{N_s}$$

WHERE

$R_f$  = LINE RATE

$\bar{R}_s$  = AVERAGE SPOT RATE

Figure 2.3-1

ADVANCED WORKING MODEL

FORMAT/TRANSPORT

TRADE-OFF CONSIDERATION  
(CONTINUED)

$$S_f = \frac{\delta f \bar{R}_s}{N_s}$$

THE AVERAGE SPOT RATE IS ESTABLISHED FROM THE USER DATA RATE

30 M BITS/SECOND



MANCHESTER BIPHASE  
BASEBAND CODING

60 M SPOTS/SECOND



OVERHEAD  
LINE SYNC, CLOCK RECOVERY  
AND DATA START

$\bar{R}_s = 72$  M SPOTS/SECOND  
AVERAGE RATE



$R_s = 144$  M SPOTS/SECOND

ACTIVE RATE WITH  
50% DUTY FACTOR

Figure 2.3-2

30 Mbit/sec input data rate (72 Mspots/sec average spot rate), imposed the use of an Acoustic-Traveling Wave Lens (ATWL) operating in combination with an Acousto-Optic Beam Deflector (AOBD). For this combination, the number of spots per line is directly proportional to the time-bandwidth product (TB) of the AOBD and the length of the ATWL. Also, the instantaneous spot recording rate  $R_s$  is inversely proportional to the acoustic velocity in the ATWL. The trade-off between these parameters, while considering available acousto-optical materials and fabrication techniques, lead to the conclusion that the total number of spots per line should not exceed approximately 900. This assumes that the center spacing between spots is equal to the  $1/e^2$  diameter of the spots; a comfortable spacing to provide a high quality output modulated signal when scanned by a similar beam. These considerations are highlighted in Figure 2.3-3. To provide an adequate design margin, the number of spots per line was selected to be 792. This selection provides ten 33 bit user words (or 330 user bits) in each line after Manchester encoding and data recovery overhead is added. Some additional trade-off considerations that influenced the selection of 792 spots per line will be discussed in Section 2.3.2 of this report.

The third parameter in the fundamental equation presented in Figure 2.3-1 is  $\delta_l$ ; the center spacing between adjacent scan lines. The selection of the value for this parameter was based upon the practical optical, mechanical and electronic design considerations set forth in Figure 2.3-4 and considered in Section 2.3.2 of this report. However, the basic trade-off considerations were the level of intersymbol interference that could be tolerated between the readout beam and the adjacent lines on the film and the depth of modulation achievable on the recording material versus recording and readout beam sizes. Based upon the analysis a

ADVANCED WORKING MODEL  
 FORMAT/TRANSPORT  
 TRADE-OFF CONSIDERATIONS  
 (CONTINUED)

$$S_f = \frac{\delta / \bar{R}_s}{N}$$

THE NUMBER OF SPOTS PER LINE IS CONTROLLED OR INFLUENCED BY THE FOLLOWING:

- THE SCANNING TECHNIQUE
    - ACOUSTO-OPTICAL SCANNING TECHNIQUE SELECTED: ELECTRONICALLY CONTROLLABLE AND NO MOVING PARTS
    - NUMBER OF OUTPUT SPOTS (AT  $1/e^2$  POINTS):  
 $N \sim T \cdot B$  OF AOB  
 $N \sim$  LENGTH OF ATWL
    - SCAN RATE (72M SPOTS/SEC AVERAGE REQUIRED):  
 $R_s \sim \frac{1}{T}$  FILL TIME OF AOB  
 $R_s \sim V_a$  ACOUSTIC VELOCITY IN ATWL
    - DEPENDENT UPON SELECTION OF AO MATERIAL, TRANSDUCER AND FABRICATION TECHNIQUES
  - MECHANICAL AND OPTICAL TOLERANCES IN RECORDER AND READER SUBSYSTEMS
  - OVERHEAD DATA REQUIRED FOR READOUT
    - CLOCK RECOVERY - 84 SPOTS
    - DATA RECOVERY - 48 SPOTS
- > 132 SPOTS
- SELECTION: 792 ( $1/e^2$ ) SPOTS,  $T = 5.5 \mu\text{SEC}$  ACTIVE SCAN TIME AND 50% DUTY FACTOR

Figure 2.3-3

ADVANCED WORKING MODEL  
FORMAT/TRANSPORT  
TRADE-OFF CONSIDERATIONS  
(CONTINUED)

$$S_f = \frac{\phi R_s}{N_s}$$

THE CENTER SPACING BETWEEN ADJACENT LINES IS DEPENDENT UPON OR INFLUENCED BY THE FOLLOWING:

- VARIATIONS IN THE ROTARY DRIVE SPEED (RECORDER AND READER)
- PRACTICAL TOLERANCE IN THE LINE SYNC CLOSED LOCK LOOP - READER
- MECHANICAL AND OPTICAL TOLERANCES:
  - VARIATIONS FROM A STRAIGHT LINE IN THE RECORD PROCESS
  - TRACKING THE LINE IN THE READOUT PROCESS
- SPOT SIZE PRODUCED IN THE RECORD PROCESS - INTERSYMBOL INTERFERENCE BETWEEN LINES ON THE FILM
- SIZE OF THE READOUT BEAM - INTERSYMBOL INTERFERENCE DUE TO PARTIAL ILLUMINATION OF ADJACENT LINES

- SELECTION: 1.4 MICRON SPOTS (1/6<sup>2</sup> POINTS) ON 1.4 MICRON CENTERS ALONG EACH LINE WITH 2.6 MICRON LINE CENTER SPACING



a  $1/e^2$  spot size of 1.4 microns and a line-to-line center spacing of 2.6 microns were selected.

Now, with values for the three parameters in the fundamental equation established, the film velocity is determined to be 23.637 cm/sec (9.306 in/sec) as set forth in Figure 2.3-5. This is considered to be approaching the practical upper limit for precision linear mechanical film transport systems. Thus, to provide room for growth to higher data rate systems, the rotary film transport approach was selected for the MASTAR I Advanced Working Model.



ADVANCED WORKING MODEL  
FORMAT/TRANSPORT  
TRADE-OFF CONSIDERATIONS  
(CONTINUED)

## FILM SPEED REQUIREMENT

$$S_f = \frac{\delta l \bar{R}_s}{N_s}$$

WHERE  $\delta l = 2.6$  MICRONS  
 $\bar{R}_s = 72$  M SPOTS/SEC  
 $N_s = 792$  SPOTS

THUS

$$S_f = 23.637 \text{ cm/SEC} \quad (9.306 \text{ IN./SEC})$$

THIS IS AT THE UPPER LIMIT CONSIDERED PRACTICAL FOR A LINEAR TRANSPORT WITH NO ROOM TO GROW FOR HIGHER SPEED REQUIREMENTS

HOWEVER, THIS IS COMFORTABLY WITHIN THE LOW SPEED RANGE OF A ROTARY TRANSPORT

SELECTION: **ROTARY TRANSPORT**

Figure 2.3-5

### 2.3.2 Data Storage Capacity, Data Format and System Tolerances

The data format on the fiche must provide the required user storage capacity of  $10^9$  bits per fiche and be compatible with practical design approaches involving realizable optical, mechanical and electronic tolerances.

Starting with the  $10^9$  user bits/fiche requirement, the following paragraphs discuss the basic fiche data format as reflected in Figures 2.3-6, 7, 8 and 9. First, the  $10^9$  user bits/fiche requirement causes a derived requirement of  $2.4 \times 10^9$  spots/fiche to satisfy the overhead for Manchester biphasic baseband coding, clock recovery and data start/line identification. This is illustrated in Figure 2.3-6. Additional external imposed overhead for data organization will increase the overhead depending upon the user applications. An additional 13% overhead margin has been provided in deriving the fiche format that is shown in Figure 2.3-7. This will be further discussed later. An exploded view of a single 1.11 mm wide track is illustrated by Figure 2.3-8.

The number of scan lines, each containing 792 spots, varies from track-to-track with 48,332 on the inner track (Track Number 1) and 142,217 on the outer track (Track Number 36). Figure 2.3-9 illustrates the number of scan lines on each track along with the cumulative number of lines from the first track. As shown in the figure, a single 148 mm by 148 mm fiche contains a total of 3,429,891 recordable lines. The  $10^9$  user bits/fiche requirement utilizes only 3,030,303 lines, leaving 399,590 lines for additional system overhead margin. Therefore, as long as the application requires less than 13% external overhead, a fiche will be capable of storing a full  $10^9$  bits of useful data. It is expected that Landsat Images from the NASA NEEDS Program would require substantially less than 13% external overhead.

FICHE STORAGE CAPACITY  
REQUIREMENT

10<sup>9</sup> USER BITS/FICHE



MANCHESTER BIPHASE  
BASEBAND CODING



2 X 10<sup>9</sup> USER SPOTS/FICHE



OVERHEAD PER LINE  
LINE SYNC, CLOCK RECOVERY  
AND DATA START WORD



2.4 X 10<sup>9</sup> SPOTS/FICHE



TRACK OVERHEAD  
LINE PHASE LOCK, SECTOR ID,  
END OF SECTOR



FICHE FORMAT

Figure 2.3-6

FICHE SPATIAL DATA FORMAT

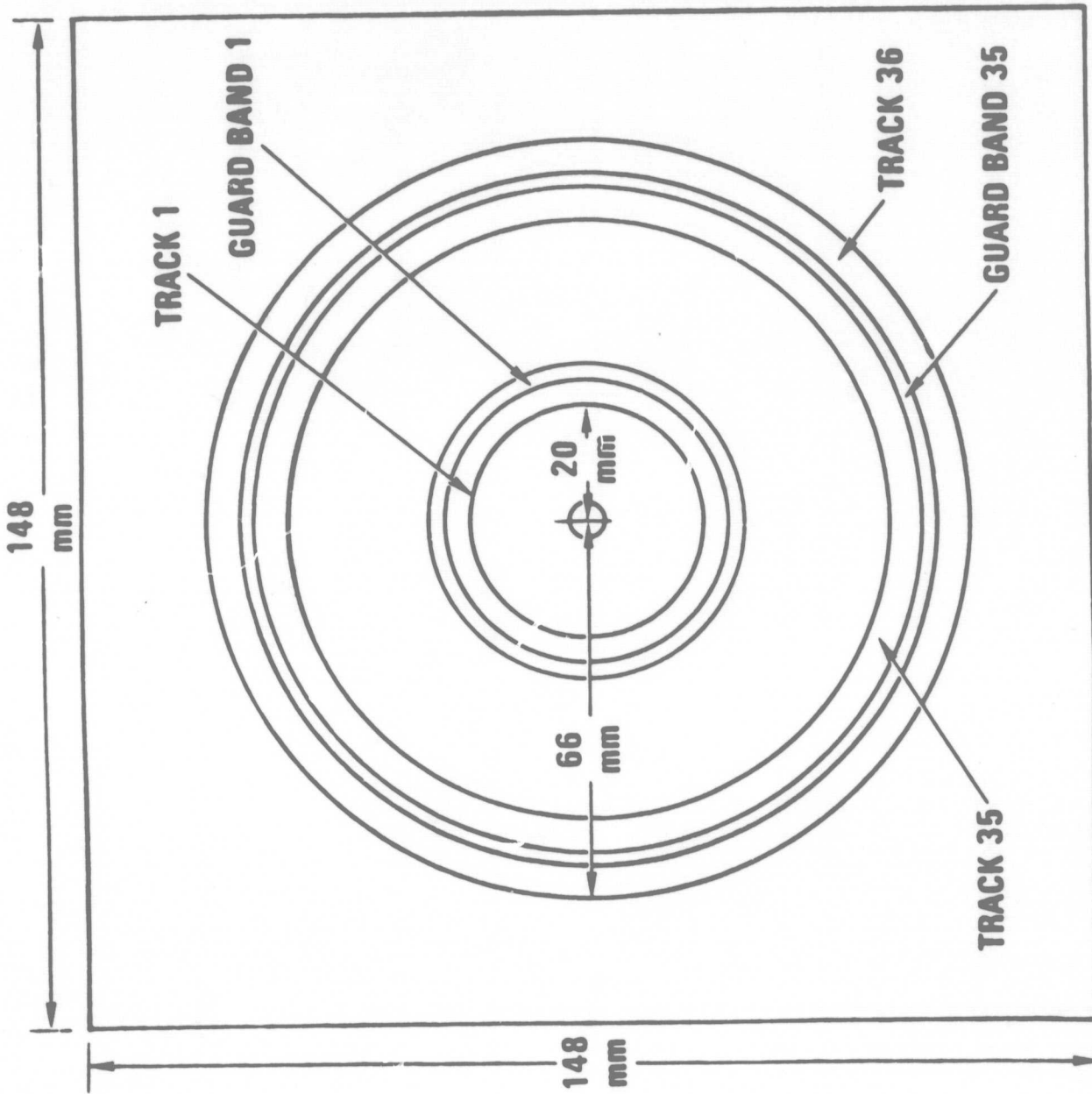
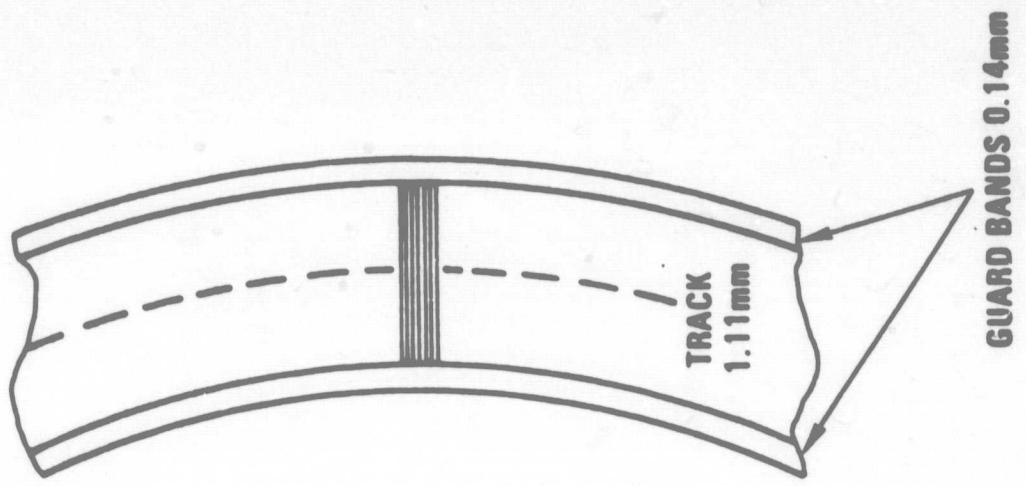


Figure 2.3-7

GUARD BANDS PERMIT READOUT BEAM OVERSCAN



FICHE  
ROTATION  
CENTER

Figure 2.3-8





Hence, a fiche would be capable of storing in excess of  $10^9$  bits of imagery.

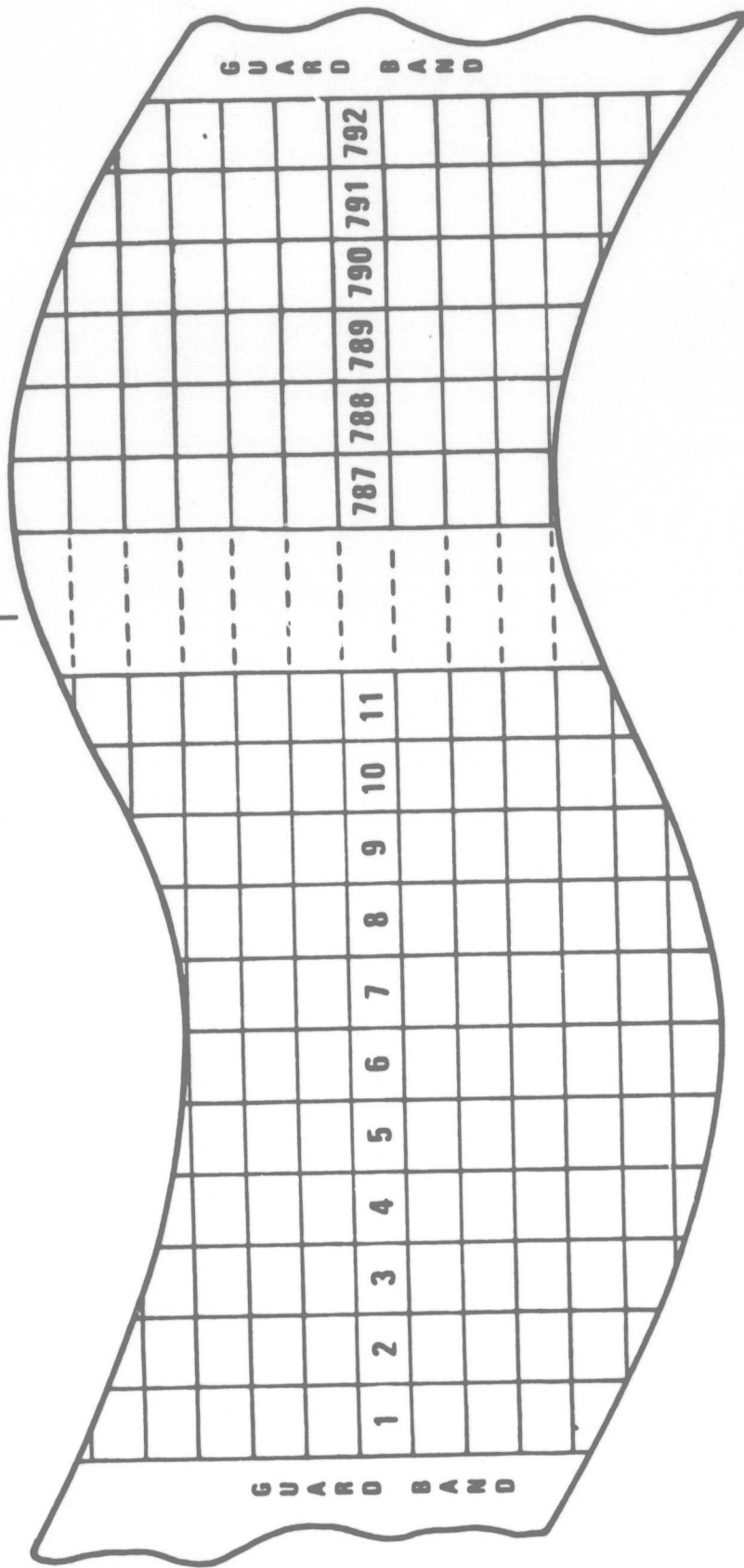
At this point let us begin with the fiche spatial data format described above and examine some of the factors that influenced the subsystem designs and in turn imposed constraints upon the fiche spatial data format. Figure 2.3-10 illustrates the allocation of space on a fiche for the individual spots across each line. A basic concern that was addressed is the recorded spot positional accuracy required for data (spot) recovery during the readout process and the resulting constraints that this places on the subsystem designs.

First consider the relative position of the readout beam to the recorded spots in the radial direction as illustrated in Figure 2.3-11. The 0.14 mm guard band between tracks permits the readout beam to overscan the individual lines at the line beginning and ending by an amount of up to 0.07 mm (50 spot diameters). This means that the individual lines of recorded data may be radially misaligned relative to the scanning readout beam track by this amount. This allocation is shared between the Recorder Subsystem and the S&R Subsystem. Nevertheless, a 50 spot tolerance radially is a comfortable margin.

However, some contributions to the radial misalignment translates into a tangential effect. One example of this is decentering of the rotational axis between the Recorder Subsystem and the S&R Subsystem. Regardless of the cause, decentering has the most significant effect on data readout that results from skew between the recorded line and the trace of the readout beam. This is illustrated in Figure 2.3-12. Although the figure shows alignment of the two at the start of scan position, proper synchronization would cause alignment near the center of the line; thus,

SPOT SPACE ALLOCATION WITHIN EACH TRACK

FILM MOTION



11076-21

Figure 2.3-10

LATERAL MISALIGNMENT COMPENSATION WITH  
READOUT BEAM OVERSCANS

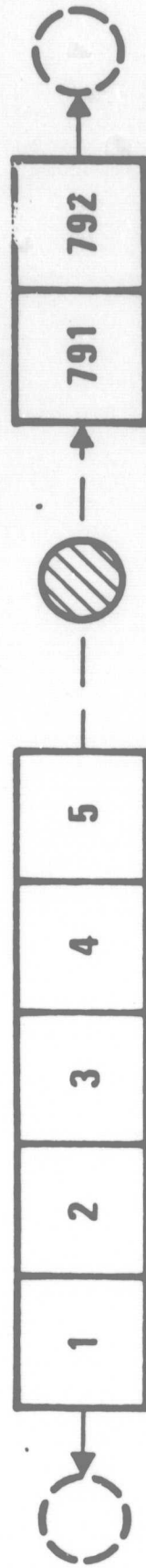


Figure 2.3-11

DECENTERING RESULTS IN LINE SKEW  
RELATIVE TO THE READOUT BEAM TRACE

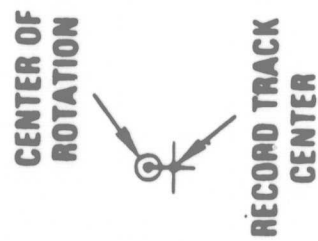
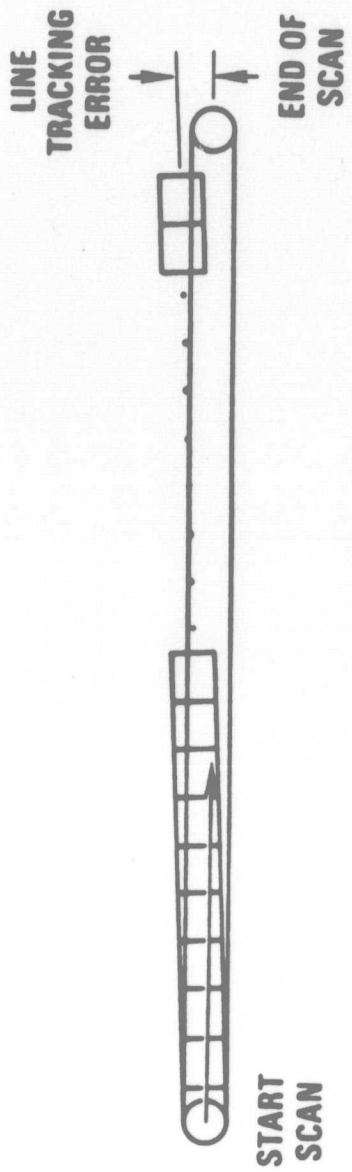


Figure 2.3-12

reducing the tangential misalignment by a factor of two.

When both the radial and tangential contributions are considered jointly and our attention is directed to the readout process of the individual spots, the level of modulation and the degree of intersymbol interference are the effects to be carefully examined. Figure 2.3-13 illustrates two conditions for data recovery. The top half of the figure illustrates perfect alignment between the scanning readout beam and the recorded spots. Further, perfect timing (data clock strobe) is shown so that data readout occurs when the readout beam is perfectly aligned horizontally with the recorded spots. The bottom half of the figure shows both an off axis scan and a jittery clock strobe signal. In this case, the amplitude of the signal is reduced and interference is experienced with the adjacent line of recorded data.

Using Figure 2.3-13 as a model and assuming a Gaussian profile for both the recorded spots and the intensity distribution across the readout beam, a computer analysis was performed to determine the degree of misalignment in both directions that could be tolerated in the readout process. The misalignment was referenced as a phase error with  $0^0$  phase error being referenced at the ideal recorded spot center. This is shown in Figure 2.3-14. The solid circle represents the recorded spot and the dotted circle represents the readout beam at the instant the readout data clock strobe occurs. Hence, the misalignment between the center of the two is represented by a phase error  $\Delta \phi$ . This phase error is derived vectorially from three components;  $\Delta \phi_c$  a phase error contribution that results from inaccuracy in the strobe clock,  $\Delta \phi_m$  a phase error contribution that is directly related to the mechanical tolerance between the recorded spot and the readout beam and  $\Delta \phi_\ell$  a phase error contribution that is directly

READOUT BEAM SCAN  
ACCURACY TOLERANCE EFFECTS

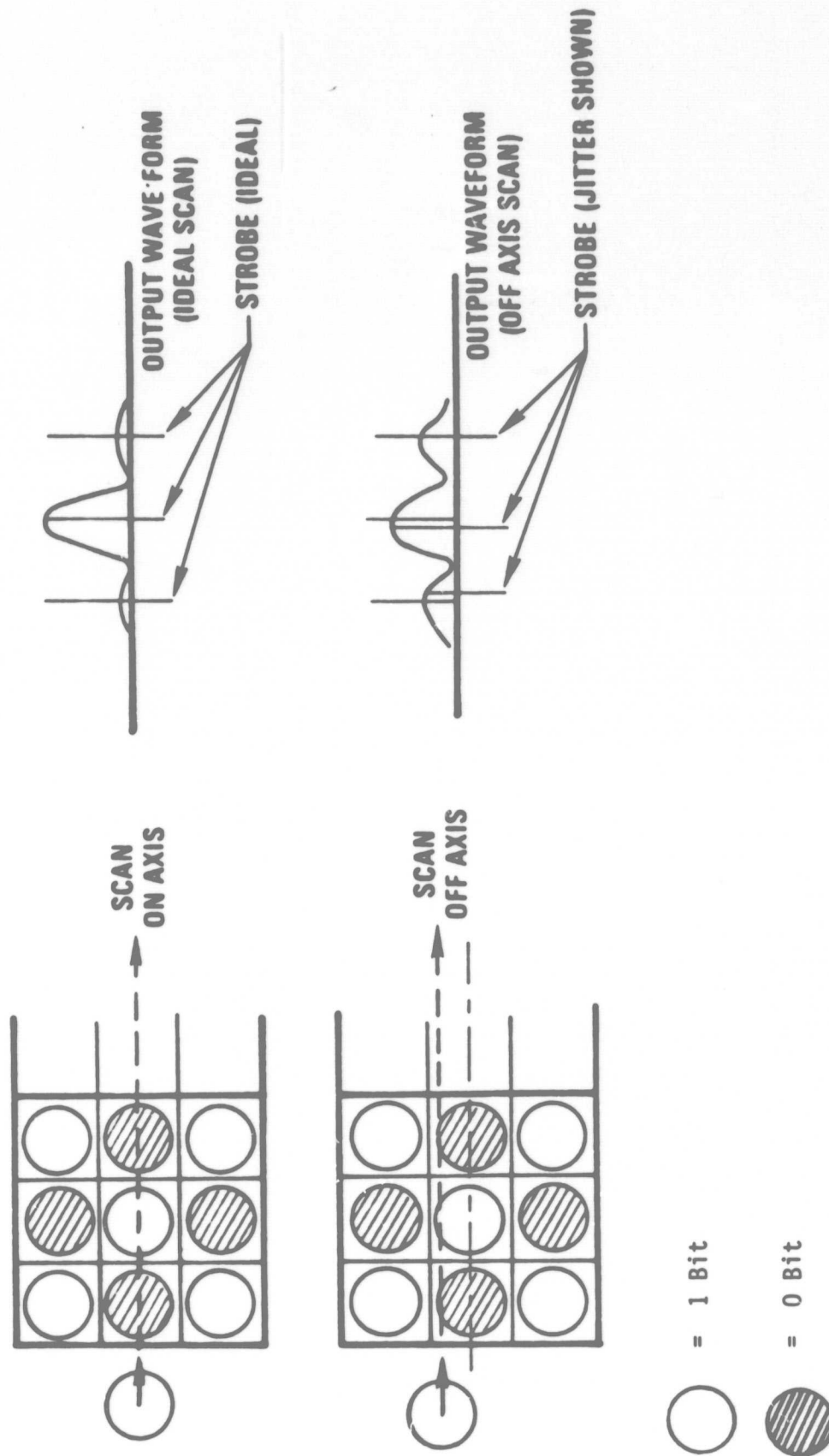


Figure 2.3-13



EFFECTS OF MISALIGNMENT OF READOUT  
BEAM RELATIVE TO RECORDED SPOT

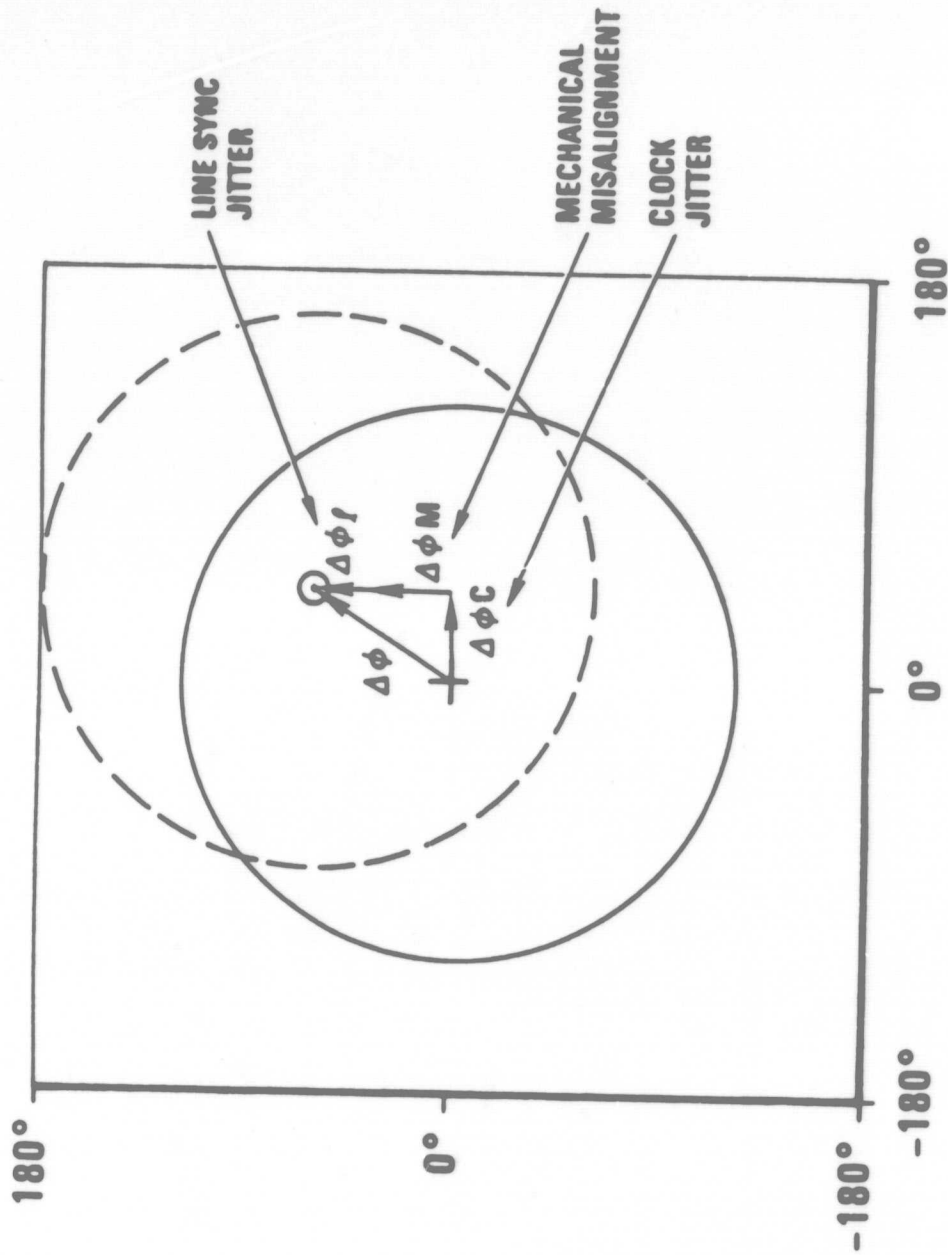


Figure 2.3-14

related to the inaccuracy in the synchronization between start of the scanning beam and the rotational position of the individual line to be scanned (line sync. jitter).

The results obtained from the computer analysis are summarized in Figure 2.3-15. As in Figure 2.3-14, the horizontal direction in this figure represents the phase error contribution due to spot misalignment in the radial direction (in the direction of beam scan), whereas, the vertical direction corresponds to the phase error associated with spot and beam misalignment in the tangential direction. The dotted elliptical shaped area in the center of the figure represents the region within which the readout must occur to ensure data recovery. The C M and L vector components represent the corresponding phase errors illustrated in Figure 2.3-14.

Figures 2.3-16 and 2.3-17 summarize the important tolerance considerations and the corresponding phase error budgets for the three fundamental phase contributors; line synchronization, data clock strobe and the integrated mechanical tolerances. Timing and control of the readout beam relative to the recorded data is considered to be reasonably straight forward where conventional design approaches can readily satisfy the budgets allocated of  $\pm 3.6^{\circ}$  phase accuracy for line synchronization and  $\pm 7.2^{\circ}$  phase accuracy for data clock strobe. A budget of  $\pm 79.2^{\circ}$  phase accuracy which corresponds to a mechanical misalignment as illustrated in Figure 2.3-12 is slightly less than 0.001 inch; a practical number where the majority of the budget can be allocated to misalignment of the center of rotation in the readout process compared to the center of rotation during the record process. Most other mechanical errors can be adjusted out during the system alignment process.

NET SYSTEM TOLERANCES  
RECORD AND READ PROCESSES

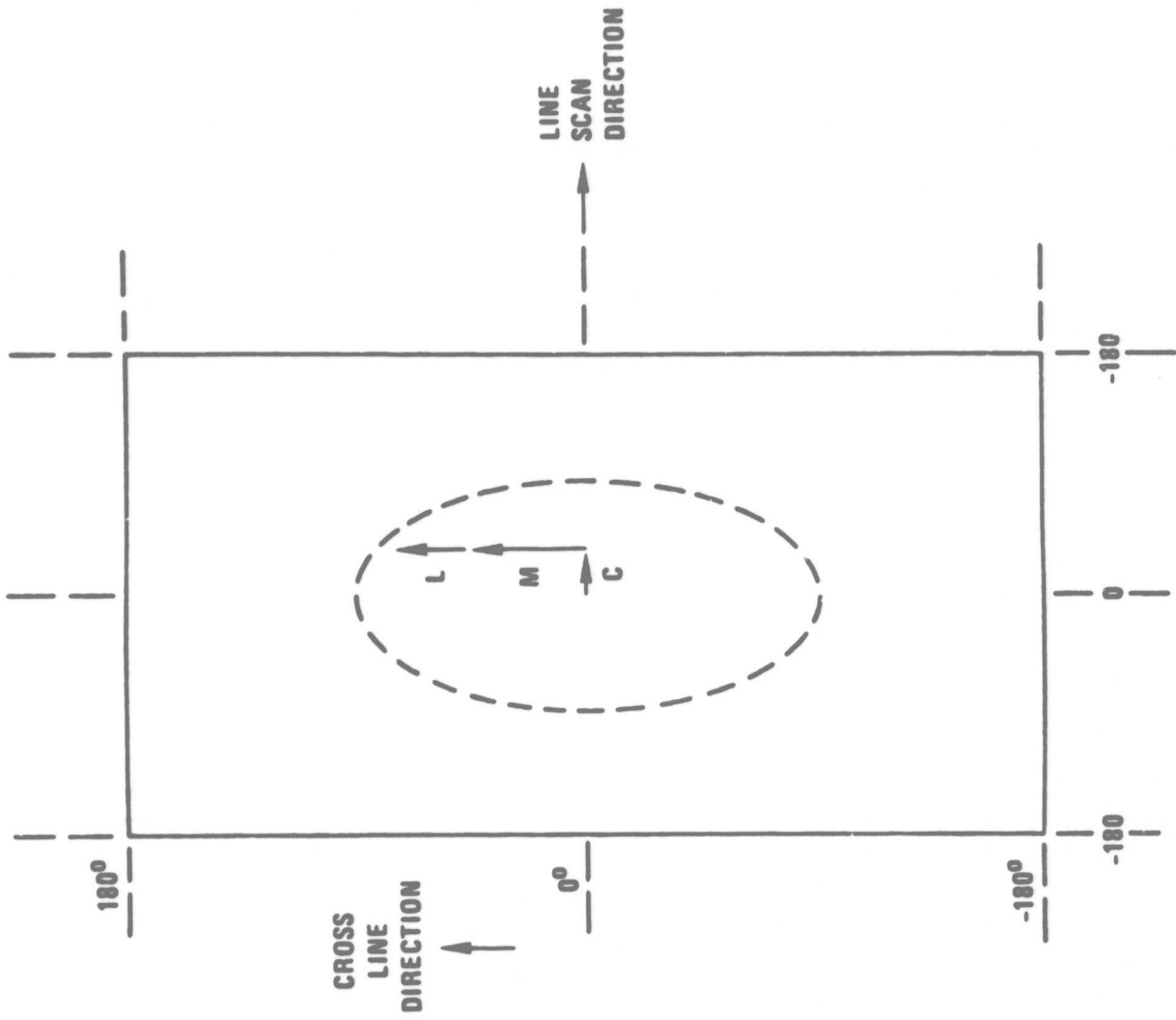


Figure 2.3-15

IMPORTANT TOLERANCE  
CONSIDERATIONS

- ROTATIONAL SPEED VARIATIONS AND LINE SYNC:
  - LONG TERM SPEED DRIFT IS EASILY CORRECTED BUT AFFECTS OUTPUT DATA RATE
  - SHORT TERM SPEED VARIATIONS AFFECT:
    1. LINE SPACING DURING RECORD
    2. LINE SYNC DURING READOUT
  - LINE SYNC LOOP BANDWIDTH MUST BE KEPT ONLY AS LOW AS NECESSARY TO TRACK THE VARIATIONS SO THAT SYNC CAN BE MAINTAINED OVER MANY LINES
  - BUDGET FOR SPEED VARIATIONS:  $< \pm 1\%$  TOTAL PEAK-TO-PEAK ( $\pm 3.6^\circ$  PHASE)
- DATA CLOCK STROBE:
  - AN ACCURATE CLOCK IS MAINTAINED DURING RECORD; THUS, ONLY NONLINEARITIES IN SCANNING IS EMBEDDED IN THE DATA
  - THE LOOP BANDWIDTH OF THE READOUT CLOCK STROBE IS KEPT LOW TO ENSURE THAT CLOCK IS MAINTAINED EVEN IF BURST OF DATA IS LOST
  - THE BANDWIDTH IS ONLY SUFFICIENT TO TRACK SLOWLY VARYING NONLINEARITIES ACROSS THE LINE
  - BUDGET FOR STROBE VARIATIONS:  $< \pm 7.2^\circ$  PHASE

IMPORTANT TOLERANCE  
CONSIDERATIONS (CONTINUED)

- MECHANICAL TOLERANCES
  - STATIC ALIGNMENT OF RECORD AND READ HEADS RELATIVE TO FICHE CENTER WILL BE AUGMENTED WITH FINE ADJUSTMENTS AND ELECTRONIC FEEDBACK
  - A PRECISION ALIGNMENT OF THE READ HEAD RELATIVE TO THE DATA LINES IS ESSENTIAL
  - TRANSLATIONAL ALIGNMENT FROM TRACK-TO-TRACK IS NOT CRITICAL DUE TO THE 0.14 mm GUARD BANDS AND READOUT BEAM OVERSCAN
  - FICHE ROTATIONAL CENTER DIFFERENCES BETWEEN RECORD AND READ TRANSLATE INTO LINE SKEW RELATIVE TO THE READOUT BEAM THAT VARIES AROUND THE TRACK
  - OPTICAL SCAN TRACK VARIATIONS BETWEEN RECORDED LINE AND READOUT SCAN LINE IS A POTENTIAL ERROR SOURCE
  - BUDGET FOR TOTAL STATIC AND DYNAMIC LINE SKEW AND LINE TRACK VARIATIONS IS  $< \pm 79.2^\circ$  PHASE

This analysis and the corresponding results form the basis for the electrical, optical and mechanical design for both the Recorder Subsystem and the S&R Subsystem operating in conjunction with each other. How these budgets influence the designs of the subsystems will be further discussed in Section 3 of this report.



SECTION 3.0

DESIGN ENGINEERING

### 3.0 DESIGN ENGINEERING

#### 3.1 Recorder Design

##### 3.1.1 Recording Materials

###### 3.1.1.1 Tradeoff Issues

The recording medium selected for an optical digital storage and retrieval system is perhaps the most significant single component in the entire system. Its wavelength sensitivity and resolution are closely tied to the selection of the laser wavelengths for the recorder and reader subsystems, its sensitivity is directly inter-related with the efficiency of the optical systems and drive power of the acousto-optic devices used, and the noise characteristics of the medium have major implications on the modulation transfer function requirements and error detection and correction overhead for the reader. In addition, the film format and mechanical stability are intimately involved with the detailed specification and design of the carousel, microfiche handler and rotary transport mechanisms. As a result, the selection of the medium requires considerable care to properly optimize the entire optical digital data storage and retrieval system design.

This section describes the basic considerations used in the selection of an optical recording medium for an optical digital recording system, and concludes with specific recommendations for this and future versions of the present system.

###### 3.1.1.2.0 Basic System Requirements

###### Sensitometry

The first of the critical recording medium parameters required for the present optical mass storage system is that of sensitometry. To establish the system requirements in this area, first consider that the target record rate is 30 Mb/s (user), which implies at least a 60 Mpixel/s equivalent bit rate when overhead is added. In addition, the spot size is 1.4 microns nominally. Using this as a baseline, we can calculate the recording media exposure requirements. Assume a 50 mw laser and 1% system optical efficiency (this is a somewhat conservative estimate) then the power available at the film

### Sensitometry (continued)

plane  $P_f = 0.5$  mw and the exposure/spot is:

$$\begin{aligned} \frac{E}{A} &= \frac{P_f t}{A} = \frac{0.5 \text{ mW/bit} \cdot 1.67 \times 10^{-8} \text{ s/bit}}{(1.4 \times 10^{-4})^2 \text{ cm}^2/\text{bit}} \\ &= 426 \text{ } \mu\text{J/cm}^2 = 4260 \text{ ergs/cm}^2 \end{aligned}$$

Since we expect a drift downward in laser power as the tube ages, we require a safety margin on the film exposure requirement of about a factor of 5 and specify  $E/A \approx 800 \text{ ergs/cm}^2$  to Achieve  $D_{\text{max}}$ . Since most film exposure sensitivities are specified for  $D = 1$ , we will look for films requiring  $\approx 100 \text{ erg/s cm}^2$  to achieve  $D = 1$ . If more exposure is required, it will be necessary to use a larger laser for recording.

The spectral sensitivity of the recording material must match the output of the record laser. There are system advantages to using a HeNe laser to record. These include reliability - (Since HeNe lasers have a proven history of reliability for long terms in system applications) simplicity - (A 50 mw HeNe laser can be air cooled and operates off normal line voltages) and cost - (Since HeNe lasers are typically less expensive than Argon or HeCd lasers). However, it is not possible to get a HeNe laser more powerful than 50 mw, and most high resolution recording materials are orthochromatic rather than panchromatic. Therefore, we have selected the recording material primarily on the basis of sensitometry, exposure and frequency response and recommend use of a laser which matches the requirements of the film.

### Modulation Transfer Function Response

For a  $1.5 \mu\text{m}$  spot with Manchester biphase baseband coding, the maximum recorded frequency is 350 cy/mm. At that spatial frequency, we want minimal effects due to the recording material MTF. Therefore, we require materials with 70% or better MTF at 350 cy/mm. With considerations of MTF rolloff, this converts to an equivalent resolving power (the cutoff frequency for the medium) of about 800 cycles/mm.

### Film Density

In prior systems we found that the maximum film density for acceptable signal-to-noise in data recovery must be  $D > 3$ . In addition, the highest contrast possible between the data and background was found to be desirable. As a result of this analysis, we have specified  $D_{\max} \geq 3$  and  $D_{\min} \leq 0.1$  for the present system, and will require  $\gamma$  to be  $\geq 3$ .

### Acutance

Acutance is related to contrast and resolution. High contrast films will have sharp well defined edges out to the resolution limit. For well defined spots, we require an edge density gradient  $> 4.50/\mu\text{m}$ .

### Granularity

Granularity is measured with a  $48 \mu\text{m}$  aperture for normal recording materials and with a  $6 \mu\text{m}$  aperture for very high resolution materials. It is not measured with the resolution necessary to be directly relevant to the readout of  $1.5 \mu\text{m}$  spots. We therefore require as low a granularity as possible (i.e.,  $\leq 5$ ) when measured with a  $6 \mu\text{m}$  aperture.

### Reciprocity

Reciprocity effects the laser power. For a full record rate per channel of 60 Mb/sec, the time per bit is 16.7 nsec, well into the region of reciprocity law failure. It is not realistic to specify a recording material with no reciprocity effects for 16 nsec exposures, but we can specify that reciprocity effects be small enough that they can be compensated for by increasing the exposure power.

### Latent Image Decay

Latent Image Decay relates to the time between exposure and processing. The time to record 10 user/bits/record at 30 Mb/sec is 3.3 sec. Therefore, the requirement that there be negligible latent image decay for a 30 min. period after recording is a conservative specification assuming each fiche is processed immediately after recording.

### Shelf Life

Shelf life affects the storage facilities prior to recording. Normally, recording materials are stored at either room temperature and humidity or under refrigeration. Preliminary data suggests that most recording materials have a shelf life of many months at  $-20^{\circ}\text{C}$ , and some will remain stable for years at this temperature. However, at room temperature ( $20^{\circ}$ ), the dark reaction rates that govern recording material degradation can increase by orders of magnitude. For long term storage, the recording material should be stored under refrigeration, but we specify at least one year safe shelf life under normal office conditions.

### Ferrotyping

Ferrotyping is caused by improper storage of the unrecorded film. Some silver halide materials show fog due to pressure or friction between adjacent layers when they are stored for long periods. We specify that the recording material show no ferrotyping or other anomalous effects due to storage conditions.

### Archival Properties

The archival life of the recording material after processing affects the required off-line storage environment. Many recording materials deteriorate under conditions of extreme temperature and humidity. Some materials are unstable even in protected, room-temperature storage. We specify that the selected recording material be stable at room temperature and relative humidity for at least 10 years. Protective measures will still be required to minimize the deposition of dust and particulate matter which will increase the scatter light and therefore degrade the bit error rate on readout.

### Response to High Illumination Levels

The stored data is expected to be retrievable from the recording medium a large number of times. Many recording materials do not permit unlimited data readout. For example, dry silver and diazo are known to show image degradation under conditions of extended playback or under high intensity illumination. We specify that the recording material remain stable under extended data recovery at the system level of readout irradiance.

### Dimensional Stability and Curl

Most recording materials are coated on thermoplastic substrates which unfortunately lack dimensional stability. Thermoplastic substrates shrink or swell with changes in ambient temperature and relative humidity by relatively large amounts. In addition, these materials show hysteresis effects when environmental variables are cycled. Processing is also known to produce irreversible dimensional changes.

Thermoplastics substrates exhibit a wide range of dimensional instability. Cellulose acetate has a very low level of dimensional integrity, while polyesters are relatively stable. Thick substrates are more stable than thin substrates. The most stable substrate appears to be preshrunk polyester. That is, a polyester that is cycled through extreme temperature and humidity variations prior to coating. This appears to stress relieve the polyester, and thus minimizes potential dimensional changes. For these reasons, we specify a >7 mil polyester substrate for all optical storage and retrieval applications.

Curl is the effect of non-balanced forces which cause the film to deviate from flatness. Curl has two primary causes: 1) the difference in behavior between support and emulsion under variations in relative humidity; and 2) core-set, plastic flow induced when the substrate material is wound into a roll before it is coated. Curl can be minimized by coating a gelatin layer on the back of the substrate to balance the emulsion and by requiring a large diameter core when the polyester is stored prior to coating. In the system, curl increases the probability that the film will be scratched by the transport.

### Packaging Requirements and Medium Handling

For a system that operates 24 hours a day, the film will have to be stored in a cartridge and loaded automatically. For a 30 Mbit/sec data rate and 109 bits/record a recording takes about 33 seconds; with film loading, assume approximately 36 seconds per fiche. We specify that the cartridges be changed every 30 minutes to allow processing before latent image decay degrades the image, the cartridges must be loaded with about 50 fiche. These should be loaded flat with no interleaving paper and preferably should be loaded well in advance of use. Therefore, the material must show no ferrotyping due to stacked storage.



### Packaging Requirements and Medium Handling (continued)

The recording material should be packaged at Kodak in flat sheets with 100 sheets per box. When they are received, each box should be loaded into a light tight cartridge in the dark or under appropriate safe lights. For operator convenience, at least one days' supply (and up to one weeks' supply) of cartridges could be loaded at one time and stored until required.

After recording, the entire cartridge will be processed at one time. The time allowed between recording and processing will depend on the rate of latent image decay, (i.e., the film must be processed before the image degrades). In the system as specified, this implies processing every 30 minutes. However, when a final film is selected, experiments can be performed to determine the allowable time between exposure and processing.

### Medium Specification

Based on the above considerations, we have developed a detailed recording medium specification for the present optical mass storage system. It is presented in Appendix A, and a summary of the key specifications appears in Table 3-1.

#### 3.1.1.3.0 Medium Tradeoffs

#### Recording Medium Alternatives

In order to determine the type of recording material which is optimum for the present system, we must first compare the sensitometric and systems-related characteristics of selected candidate recording medium requirements. In this section we will discuss and evaluate each of the presently-available candidate media shown in Table 3-2.

TABLE 3-1 MEDIA SPECIFICATIONS

- Exposure Sensitivity:  $< 800$  ergs/cm to achieve  $D_{\max}$
- Spectral Response: Matched to the record system laser
- Frequency Response: Desire no MTF effects at the spot frequency - interpretation, resolving power 800 cycles/mm
- Sensitometry:  $D_{\max} > 3.0$   
 $D_{\min} \leq 0.1$   
 Contrast ( $\gamma$ )  $> 3$
- Acutance: Edge density gradient  $> 4.50/\mu\text{m}$
- Granularity:  $\leq 5$  measured with  $6 \mu\text{m}$  aperture
- Reciprocity: Negligible or compensatable for exposure times in the 10 to 100 nsec range
- Latent Image Decay: Negligible for 30 min or more
- Performance Consistency: Random samples fiche to fiche or within one fiche should have  $< 5\%$  RMS variation in sensitometric characteristics
- Archival Life:  $> 10$  years in an office environment
- Image Permanence: Stable for repeated or extended exposure to high irradiance levels ( $> 100\text{w}/\text{cm}^2$ )
- Shelf Life:  $> 1$  year in an office environment
- Ferrotyping: None
- Processing: None, or dry, on-line preferred; machine processing using standard chemistry is a permissible alternative
- Handling Durability: The material should not be damaged or contaminated by ordinary handling or by automatic processing
- Availability: Standard product,  $\leq 30$  days ARO delivery
- Film Base: 7 mil polyester
- Curl: No more than 7 mil across the fiche in either direction. In curl units ( $100/R(\text{in})$ ), 0.3 over  $60^{\circ}$  to  $90^{\circ}\text{F}$ , 40% to 60% R.H.
- Format: 1) Standard Microfiche -  $148 \times 105$  mm  
 2) Square disk -  $148 \times 148$  mm die cut with rounded edges
- Dimensional Stability:  $\leq \pm 0.05\%$  change due to processing  
 $\leq \pm 0.06\%$  change when stored at 60-90%F  
 40-60% R.H.

TABLE 3-2 COMPARISON OF RECORDING MEDIA TYPES FOR OPTICAL SPOT RECORDING

MEDIA TYPE PARAMETER	SILVER HALIDE	DRY SILVER	ELECTRO- PHOTOGRAPHIC	DIAZO	THIN METAL FILMS	THERMO- PLASTICS	PHOTO- CHROMIC	PHOTOGRAPHIC RELATIVE
SPEED	1-100 $\mu\text{J}/\text{cm}^2$	1-100 $\mu\text{J}/\text{cm}^2$	1-100 $\mu\text{J}/\text{cm}^2$	10-500 $\text{mJ}/\text{cm}^2$	1-200 $\text{mJ}/\text{cm}^2$	1-100 $\mu\text{J}/\text{cm}^2$	10-500 $\text{mJ}/\text{cm}^2$	?
SPECTRAL RESPONSE	350-750 nm	350-700 nm	350-680 nm	350-480 nm	ALL $\lambda$	350-1000 nm	350-700 nm	ALL $\lambda$
RESOLVING POWER (CYCLES/nm)	100-5000	100-1000	100-1000	100-1000	500-5000	50-1000	200-1000	200-2000
STORAGE CAPACITY (MBITS/ $\text{cm}^2$ )	100	10	10	10	100	10	10	15
MINIMUM SPOT SIZE	1 $\mu\text{m}$	3 $\mu\text{m}$	3 $\mu\text{m}$	3 $\mu\text{m}$	1 $\mu\text{m}$	3 $\mu\text{m}$	3 $\mu\text{m}$	2.5 $\mu\text{m}$
SPOT CONTRAST	10:1	10:1	5:1	10:1	10:1	NA	?	10:1
PROCESSING	WET CHEM.	HEAT	TONER AND HEAT FIX	AMMONIA VAPOR OR HEAT	NONE	HEAT	NONE	NONE
UPDATABLE	NO	NO	YES	NO	YES	YES	YES	YES
DIRECT READ AFTER WRITE	NO	YES	?	NO	YES	YES	YES	YES
COMMERCIALY AVAILABLE	YES	YES	YES	YES	NO	NO	NO	NO

### Dry Silver Film

Dry silver film is similar in many ways to conventional silver halide materials, but is heat processed rather than requiring wet chemical processing. Many dry silver films consist of a light-sensitive organic silver salt sandwiched between two polyester supports. When exposed to light, a latent image is formed that is developed by heating the film to 260°F for 20 seconds. No fixation is possible, therefore the developed film must be protected from heat and high light levels to prevent printout. Pre-exposure storage conditions are also critical since high storage temperatures will generate fog. Dry silver films have a wide range of sensitometric properties, but in general  $D_{max}$  is  $>2.5$ . In summary, the relative advantages and disadvantages of dry silver films are as follows:

#### ADVANTAGES

- 1) High exposure sensitivity
- 2) Simple, fast heat processing
- 3) Relatively low cost
- 4) Commercially available

#### DISADVANTAGES

- 1) Limited shelf life
- 2) Not archival
- 3) Lack of long term image permanence
- 4) Insufficient  $D_{max}$

In spite of the advantages of this medium, in our judgment the low  $D_{max}$  and limited archival life of this medium make dry silver film a poor choice for the present system.

### Electrophotography

A transparent electrophotographic (TEP) film consists of a polyester substrate, an electrically conductive layer, and a transparent photo-conductive top coat. To record, the TEP film is charged and then exposed to light creating an electrostatic latent image that is subsequently developed by toner deposition.

### Electrophotography (continued)

The visible image is stabilized by heat fusing the toner particles. Since the material is not light sensitive until it is charged, it has a long shelf life. The archival life is good because the fusing step causes the toner particles to be integrated into the photoconductive layer. However, the resolving power is limited by the properties of the toners, 1000 cycles/mm resolution has been measured on unfused samples only. For fused images, 800 cycles/mm is about the limiting resolution. In addition, the fused image tends to be very grainy resulting in a low signal-to-noise ratio. Because of the limitations in the toner technology, we do not recommend use of an electrophotographic material at this time, however, progress in the field should be monitored since it may be desirable at some future date to convert to electrophotographic films. The following table lists the major advantages and disadvantages of electrophotographic films.

#### ADVANTAGES

- 1) Relatively high exposure sensitivity
- 2) Excellent pre-exposure and post-exposure stability
- 3) Simple processing in liquid toners
- 4) Low cost and commercial availability

#### DISADVANTAGES

- 1) Electrostatic interfaces are required
- 2) Limited spatial frequency response
- 3) Excessive scatter noise

### Diazo

In diazo materials, a diazomium salt is converted into a highly colored, diazo dye after exposure to light and development in an ammonia atmosphere. Since there are no grains involved, the resolving power is relatively high and the noise characteristics are good. Diazo materials are relatively slow and are in general UV to blue sensitive. While the image may be any color desired, in general for blue-black images which have the highest density when read with red light,  $D_{\max}$  is  $\leq 2.5$ . In addition, the image tends to bleach out

### Diazo (continued)

under extended readout. Because of its slow speed, low  $D_{\max}$  and questionable image stability we do not consider diazo materials to be optimum for the present system. The following table summarizes their advantages and disadvantages.

#### ADVANTAGES

- 1) Excellent shelf and archival life for ordinary environmental conditions
- 2) High resolving power
- 3) Low noise
- 4) Low cost and commercial availability

#### DISADVANTAGES

- 1) Very low exposure sensitivity
- 2) Ammonia vapor processing
- 3) Limited image permanence
- 4) Relatively low  $D_{\max}$

### Ablative Films

Thin ablative films have the major advantage of requiring no processing. Thin films of low melting point metals or metallic compounds are easily melted by a focussed laser beam. Surface tension causes pits to form exposing a reflective layer. Spots on the order of 0.1 to 0.5  $\mu\text{m}$  have been recorded making resolutions of up to 5000 cycles/mm feasible. However, they are not a standard product at this time. Coating such films on glass is a tricky procedure, and significant adhesion problems have been reported by Philips, RCA and Optical Coating Laboratory, Inc. To ensure a long archival life, the coatings will have to be made on glass substrates and overcoated with a protective silicon dioxide layer. Plastic substrates tend to oxidize degrading the quality of the recording in about 2 years. Because of the experimental nature of thin metal films, we do not recommend their use at this time. However, the continuing work in the field should be monitored so that the system can be converted to ablative media if and when they become reliably and commercially



### Ablative Films (continued)

available. The following table summarizes the advantages and disadvantages of thin metal films.

#### ADVANTAGES

- 1) No processing required
- 2) High spatial frequency response
- 3) Low noise

#### DISADVANTAGES

- 1) Not commercially available as a standard product
- 2) Questionable pre-exposure and post-exposure life
- 3) Glass substrate is required
- 4) Known adhesion inconsistency

### Thermoplastics

Thermoplastic film is a planar phase recording medium on which optical information is recorded as surface deformations. It is an electro-photographic material that is completely dry-working, heat only is required for processing.

Thermoplastic film consisted of a polyester substrate, an electrically conductive layer, a transparent photoconductor and a deformable thermoplastic layer. To record, the thermoplastic layer is charged and then exposed to light creating an electrostatic latent image. The image is developed by heating the forms which corresponds to the latent image. The surface deformation is frozen by cooling the thermoplastic. Since a phase image is formed, Schlieren readout optics are required.

Thermoplastic films are a highly sensitive material with a bandpass frequency response which can be optimized anywhere in the 50 to 1000 cycle/mm range. However, they have a limited archival life. Since they are heat processed, the deformations tend to smooth out at temperatures over 80°F. Even at normal room temperature, we have found that cold flow occurs which tends to reduce the deformations. In addition, they are not at this time a commercially

### Thermoplastics (continued)

available standard product. We do not recommend thermoplastics for the present application. The following table summarizes their advantages and disadvantages.

#### ADVANTAGES

- 1) Relatively high exposure sensitivity
- 2) Simple, fast heat development
- 3) Good frequency response which can be matched to the system

#### DISADVANTAGES

- 1) Electrostatic interfaces required
- 2) Poor archival life
- 3) Schlieren readout optics required
- 4) Inconsistent large area performance
- 5) Not commercially available as a standard product

### Photochromic

Photochromic materials change color when illuminated by the proper wavelength of light. Most photochromic materials considered for optical storage are reversible, i.e., they revert to the original color either naturally in the dark or under illumination by a different wavelength of light than that causing the original color change. They require relatively high exposures to initiate the color change, but no post exposure processing is required. They have good spatial frequency response and low noise levels. They are not commercially available in a standard format suitable for the present system. The following table summarizes the advantages and disadvantages of photochromic materials.

#### ADVANTAGES

- 1) Good Frequency response
- 2) No processing is required

Photochromic (continued)

DISADVANTAGES

- 1) The color change is reversible, therefore non archival
- 2) High exposures are required
- 3) Not available as a standard product

Silver Halide

Silver Halide materials have all the properties desired for this application, except that they require wet chemical processing. They are available with good exposure sensitivity and high resolutions. Densities greater than 4 and gamma values greater than 9 are possible using the proper chemistry. They have good shelf life when properly stored, and images have been stored for 50 years or more although some image degradation occurs for very long storage times. The overall quality of photographic films make them superior to present alternative recording media types for mass data storage. The following table summarizes the advantages and disadvantages of silver halide films.

ADVANTAGES

- 1) Very high exposure sensitivity
- 2) Very high storage capacity
- 3) Good shelf life and archival life
- 4) Established product commercially available
- 5) Relatively low cost

DISADVANTAGES

- 1) Wet, multi-step chemical processing required

In consideration of the characteristics of the alternative media available today (and in spite of the one disadvantage of silver halide film) we recommend the use of silver halide film for the present system.

### Silver Halide Media

Having determined that high resolution silver halide recording media was the best choice, we surveyed individual silver halide film specifications to select those films that meet the specifications in Table 1. The films listed were selected primarily by the resolution. Kodak literature was searched for films with a resolving power of at least 500 cycles/mm. The resulting list of candidate silver halide films plus a summary of their relevant properties is given in Table 3-3.

Comparing the film parameters to the previously determined system specifications, we find that 3414 and 5069 do not have the resolution required and are too granular for digital spot recording with 1.5 mm spots. The exposure requirements of 649F and S0 343 are higher than desired, but the proper choice of a high contrast developer such as Prostar will bring their exposure requirements within range.

We must now consider the system-related parameters. One requirement for the S & R carousel was that the film base be 7 mil ester. While any of these emulsions technically could be coated on 7 mil ester, it would require a QX order to Kodak, which is undesirable.

This limits our silver halide film selection to S0 343 and 4468 which are normally coated on 7 mil ester. However, in-house testing, later confirmed by Kodak, has shown that 4468 has three separate layers of matte particles, on the surface of the emulsion, between the emulsion and the substrate and on the back of the base. Matte particles are fine grain transparent particles which, unfortunately, scatter coherent light. Therefore, 4468 is not suitable for any application using coherent laser illumination. S0 343 has two disadvantages: It will have to be reversal processed to give a direct positive image and it has relatively poor exposure sensitivity. Depending on EDAC and baseband coding clocking considerations, a direct positive image may not be required, making this a potential area for future study. In addition, because of the lower sensitivity of this S0 343 medium, it will require more laser power for optimum media exposure.

TABLE 3-3 MASTAR -- CANDIDATE RECORDING MEDIA

PRODUCT	EXPOSURE D = 1 ergs/cm <sup>2</sup> 633 488	RESOLVING POWER cycles/mm 10 <sup>3</sup> :1 TOC 1.6:1	GRANULARITY AT D=1 48 μm 6 μm	CONTRAST γ	EMUL THICK	BASE TYPE MILS THICK
KODAK 649 F	900	2000+	<5 10	4	6	ESTAR 4 MIL
KODAK SO 173	400	2000+	<5 10	4	6	ESTAR 4 MIL
KODAK SO 253	0.5	1250	<5 14	7	9	ESTAR 4 MIL
KODAK SO 285	30	1250	<5 14	-2	<4	TRIACETATE 5.5
KODAK 3414	2	630	9 33	4	<4	ESTAR 2.5 MIL
KODAK 5069	6	630	9 43	>9	<4	TA 5.5 MIL
AGFA 10E75	25	2000		>4		
AGFA 8E75	75	3000		>4		
KODAK SO 343	1500	2000+	<5 <10	8	6	ESTAR 7 MIL
KODAK SO 424	50	1250	<5 13	4	<3	TA 5.5 MIL
KODAK SO 332	50	1250	<5 13	4	<3	ESTAR 4 MIL
KODAK 4468	100	1000	<5 17	-1.9	3	ESTAR 7 MIL
KODAK 6451	20	1500		≈4	<6	TA 5.5 MIL
AGFA 10E56	7	2000		>4		
AGFA 8E56	75	3000		>4		

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### Recommendations and Conclusions

The two critical and limiting factors in the recording media trade-off are resolution and the need to have a 7 mil estar film base. These two criteria plus the matte particles found in 4468 narrow the recording media selection to S0 343. If the resolution requirement is reduced, a new survey of Kodak literature will be necessary to determine if any other films are available. If the storage and retrieval carousel can be designed to handle 4 mil bases, then several alternative films become available. These are, in order of preference based on past experience, S0 332, S0 173 and 649F. However, for a generalized storage and retrieval media applicable to all our potential applications, S0 343 is the best current selection.

The advantages of S0 343 are:

- . Resolving power far beyond our requirements
- . Very low granularity
- . High is possible though with proper processing, good grey scale rendition results.
- . Currently coated on 7 mil estar - therefore, no QX coating is required
- . Available in 30 to 60 days ARO depending on packaging requirements

The disadvantages of S0 343 are:

- . Exposure at 488 to yield  $D = 1$  is  $1500 \text{ ergs/cm}^2$
- . Kodak claims the film ferrotypes if packaged without interleaving paper

In spite of these disadvantages, however, we believe S0 343 film is the optimum choice for the baseline digital optical recording medium and recommend it for use in all near-term storage and retrieval product applications.



### 3.1.2 OPTICAL SUBSYSTEMS

#### 3.1.2.1 Summary of Specifications

Before beginning the detailed discussion of the MASTAR optical subsystems design, a brief review of the recorder specifications described in Section 2 of this report is appropriate. First, the user data transfer rate requirement for the recorder is 30 Mb/s. As was outlined in Section 2, this must be multiplied by a factor of 2 to allow for the user of a Manchester biphasic baseband coding scheme. The addition of overhead bits at the front end of the scan for line sync, clock recovery, and frame sync, adds an additional 20% to the effective pixel rate. This means that the net recording rate required for the optical subsystems is  $30 \times 2 \times 1.2 = 72$  Mpixels/s.

After data transfer rate, the next key consideration is the data formatting requirement. Without repeating the complete outline of the data format from Paragraph 2.3, the major elements of importance in this data format to be considered here are the number of spots per line and the spot profile within that line. Based on the initial considerations described above, the design has centered on a format with 792 spots per line. This includes 330 user bits (or 660 spots, when the Manchester baseband is added), plus an overhead of 132 spots. Out of this 132 spots of overhead, 84 spots have been set aside for line sync (or frame sync, if a sector is being accessed) and clock recovery; the remaining 48 spots provides a 24 bit Manchester-coded word for data start and the identification of the frame number (when appropriate). To achieve the necessary  $10^9$  user bits of data capacity per 148 mm x 148 mm floppy disc, the spot spacing across the line has been chosen to be 1.4 microns, and the line-to-line spacing is 2.6 microns.

#### 3.1.2.2 The Optical Recorder Subsystem

##### Overview

The basic concept for the optical recorder subsystem is shown in Figure 3-1. In this baseline system, a helium-cadmium laser provides the 441.6 nm wavelength light required to illuminate the MASTAR recording medium. A Harris wide bandwidth acousto-optic modulator provides high-speed modulation of the laser

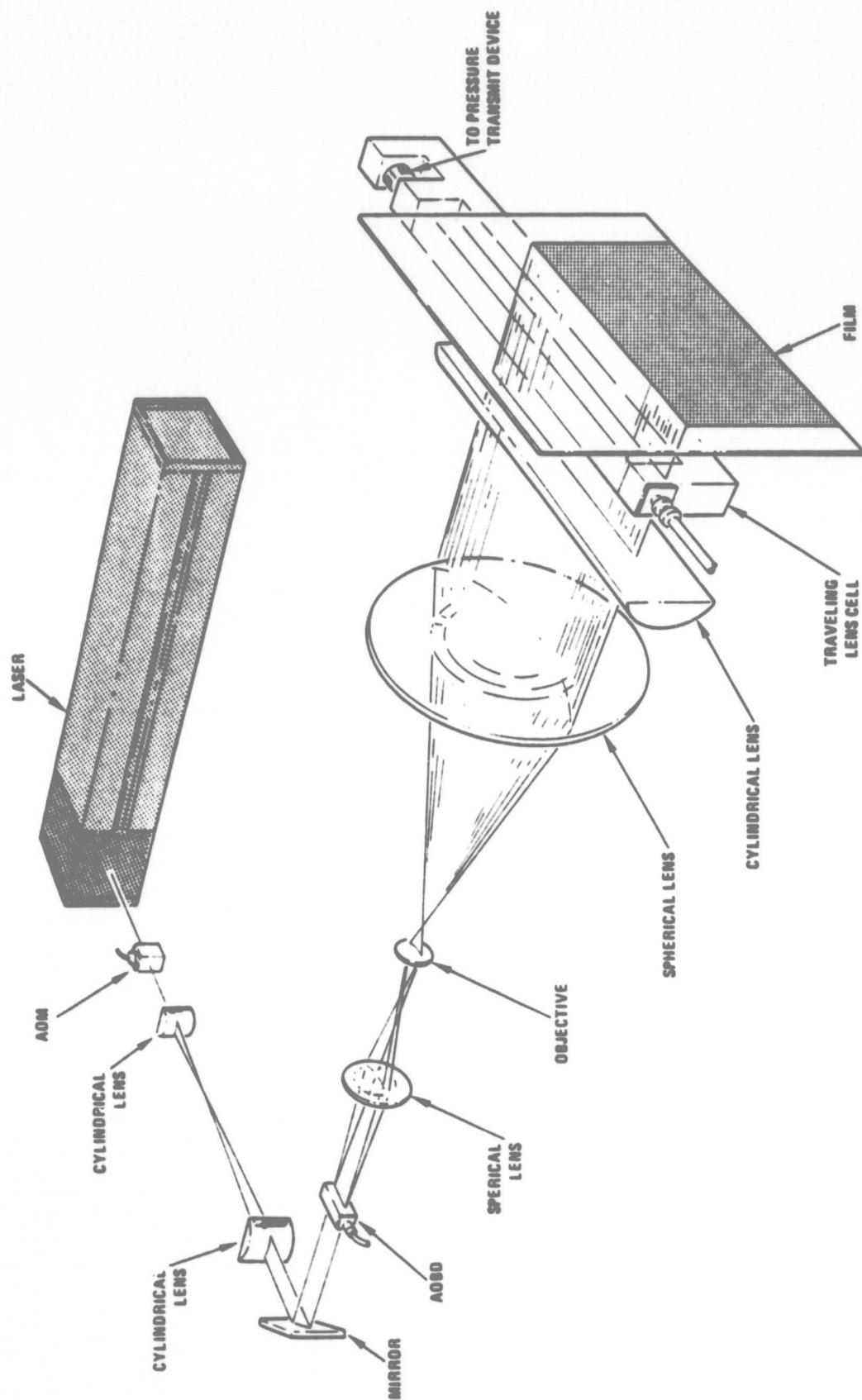


FIGURE 3-1 THE MASTER RECORDER SUBSYSTEM CONCEPTUAL LAYOUT

### Overview (continued)

beam, and an anamorphic optical system shapes the beam to illuminate the acousto-optic beam deflector. This deflector takes a pre-programmed frequency "ramp" electronic input, converts this signal into a changing acoustic frequency in the AOB cell, and diffracts the laser beam over a range of diffraction angles corresponding to the range of acoustic frequencies present in the cell. A scan lens then focusses this scanning optical wavefront into a line of spots in the focal plane between the spherical lens and the objective shown in the figure.

This scan can cover, at most, only a field size of a few hundred spots, since the AOB is limited in its time-bandwidth product. As a result, a second stage of scan magnification, the acoustic travelling-wave lens, is needed to provide the necessary number of spots per scan. To make this possible, a telescope optical system, conceptually shown in the figure as an objective and a spherical lens, magnifies the scan to illuminate the acoustic travelling-wave lens cell with a focussed, but larger, spot. The ATWL functions by taking a shaped RF impulse as the input to its transducer and converting that impulse into a high-gradient acoustic "bubble" in the glass. This "bubble" acts like a low  $f$ -number precision lenslet which can travel across the cell length at high speed. The result is that, as the acousto-optic beam deflector's scan tracks with the ATWL lenslet, the ATWL focusses the beam down to an even smaller size, thereby magnifying the number of spots per scan by as much as a factor of 20. With Harris devices, as many as 20,000 spots per scan have been achieved at pixel rates of 200 MHz.

### Acousto-Optic Devices

With the basic concept established for the recorder, the next step is the specification of the acousto-optic devices required for the system. Once their frequencies, bandwidths, scan angles, and spot sizes have been established, the rest of the optical subsystem and the electronic interfaces to these subsystems can be developed. To begin, consider the specifications for the acousto-optic beam deflector subsystem. The input wavelength of light is 441.6 nm, corresponding to the helium-cadmium laser line used in the system.

### Acousto-Optic Devices (continued)

The data transfer rate requirement is 72 Mp/s. Next, if we restrict the selection of acousto-optic devices to single-sweep devices, we simplify and lower the cost of the system; this is because we do not have to have duplicate electronics for driving the acousto-optic drivers if double-sweep devices are used. At the same time that we simplify the acousto-optic devices, however, we have cut the acousto-optic duty cycle to at most 50%, this is because the system will have to fill the device cell length completely and then wait for the cell to empty completely before the next line of data can be written. This means that our acousto-optic devices duty factor is now 50%, which in turn results in an effective 144 Mp/s data rate for the entire system. If we required sampling in the system by at least a factor of two, the modulator must then provide a rise time of less than 3.5 nanoseconds, and the electronics must provide a similar capability.

Once the above initial analysis was completed, an integrated acousto-optic device design approach was carried through to determine the optimum combination of acousto-optic modulator, beam deflector, and travelling-wave lens system for the MASTAR recorder. The AOM selected for the system is a tellurium-dioxide longitudinal mode device operating at a center frequency of 550 MHz. Its design has been optimized for 80% diffraction efficiency with a drive power of 800 mW, and it provides a rise time of well under 4 nanoseconds in the design. (In experimental results, risetimes of less than 2 nanoseconds have been achieved, indicating the practical capabilities of the device are more than acceptable for the intended application). The optical beam diameter required for the AOM is a  $1/e^2$  spot diameter of 18 microns. The remaining specifications for this device and those discussed above are tabulated in Table 3-4.

To provide the AOBBD requirements for the system, a device has been selected with the characteristics listed in Table 3-5. This device provides a scan angle of 1.07 degrees with a 50 MHz bandwidth and a center frequency of 100 MBz. As shown, it will produce a minimum scan size of 150 spots, when

TABLE 3-4 THE RECORDER AOM SPECIFICATIONS

	RECORDER	AOM
• MATERIAL		TeO <sub>2</sub> LONG
• OPTICAL WAVELENGTH		441.6 nm
• OPTICAL BEAM DIAMETER		18 μm (1/e <sup>2</sup> )
• CENTER FREQUENCY		550 MHz
• TRANSDUCER SIZE		0.07 X 0.7 mm <sup>2</sup>
• AO Q		15
• RISE TIME (10% TO 90%)		< 4 ns
• DIFFRACTION EFFICIENCY		0.4%/mW
• DIFFRACTION WITH 800 mW		80%
• DEFLECTION ANGLE		3.3°

TABLE 3-5 RECORDER AOBBD SPECIFICATIONS

RECORDER AOBBD

MATERIAL	TeO <sub>2</sub> (OFF-AXIS SLOW SHEAR)
OPTICAL WAVELENGTH	441.6 nm
OPTICAL BEAM WIDTH	3.5 mm
TRANSDUCER SIZE	0.9 X 3 mm <sup>2</sup>
CENTER FREQUENCY	100 MHZ
BANDWIDTH	50 MHZ MIN
NO. OF SPOTS WITH 5.5 us SCAN	150 MIN
FILL TIME	5 μs
VCO RESET TIME	0.5 μs
DUTY FACTOR	50%
A0 Q	29
DEFLECTION ANGLE	2°
SCAN ANGLE (AT 50 MHZ)	1.07°
DIFFRACTION EFFICIENCY	0.2%/mW
DIFFRACTION WITH 1W	80%
PACKAGE AND MATCHING	NON CRITICAL



### Acousto-Optic Devices (continued)

illuminated by an optical beam 3.5 mm wide and at most 0.9 mm high. Diffraction efficiencies of 0.2%/mW have been designed into the device and have been demonstrated in experimental evaluations.

Since the AOBBD provides at most 150 spots, the ATWL lenslet must provide a gain of a minimum of  $792/150 = 5.28$ . The baseline design for the present ATWL has been optimized to minimize the acoustic drive power requirements (thereby cutting heat buildup in the device and minimizing crystal strain), and produces a gain of 8.2, which is more than sufficient for the system. The input drive power is 160 watts, and the tellurium dioxide longitudinal-mode device takes an input 210 micron spots to compress into a 25.6 micron spot. Its other significant characteristics are summarized in Table 3-6.

The final acousto-optic device schematic is shown in Figure 3-2.

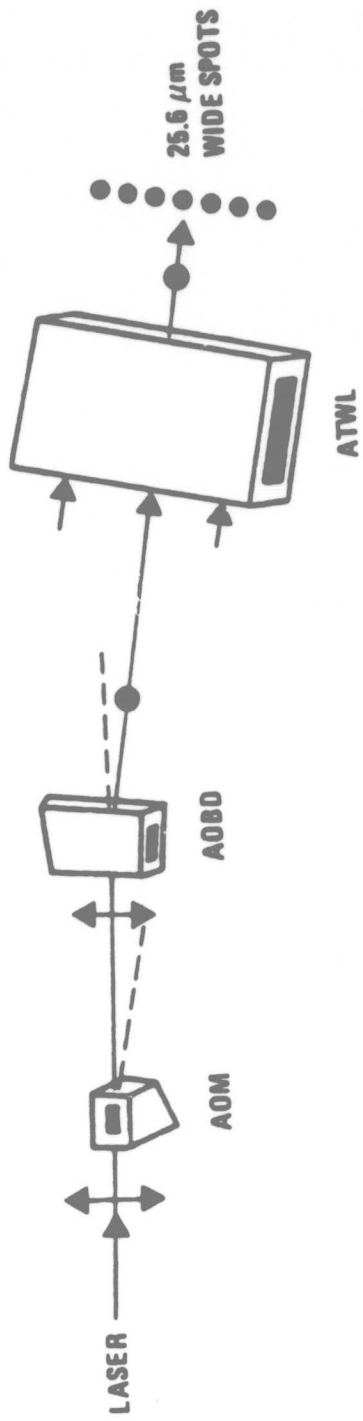
#### The Lens System

The lens system used to properly illuminate the AOM, relay and shape the beam for the AOBBD, magnify the beam to the ATWL and form the final reduction from the ATWL's 25.6 micron spot size down to the 1.4 micron spots at the film plane is shown in Figure 3-3. At the front end of the system is a Liconix 4050 Helium-Cadmium laser, which is capable of producing more than 50 milliwatts of output laser power. A half-wave plate rotates the polarization of the output wavefront from the laser to provide proper illumination of the AOBBD later on in the system. Lens  $L_1$  is a 10 mm EFL microscope objective which takes the input 0.91 mm ( $1/e^2$  beam width), focusses it, and causes it to diverge. By Gaussian beam propagation calculations, lens  $L_2$ , a 40 mm EFL spherical lens, collimates this beam at a 3.64 mm beam waist. Lens  $L_3$  is an 80 mm focal length lens, and it in turn focusses the beam at the AOM to 12.4 microns, well below the necessary 18 micron spot size specified for the necessary 3.5 microsecond risetime.  $L_4$ , a second 80 mm spherical lens, recollimates the beam to form a 3.64 mm collimated wavefront; this propagates down to illuminate the necessary 3.52 mm aperture of the AOBBD. In the cylindrical direction, the  $C_1$  (100 mm) and  $C_2$  (22.2 mm) lens system demagnifies the wavefront to create a 0.81 mm wide beam in the other optical dimension at the AOBBD's entrance pupil.

TABLE 3-6 RECORDER ATWL SPECIFICATIONS

	RECORDER	ATWL
•	MATERIAL	TeO <sub>2</sub> (LONG)
•	OPTICAL WAVELENGTH	441.6 nm
•	SCAN VELOCITY	4.2 mm/μs
•	ACOUSTIC FREQUENCY	5.13 MHz
•	TRANSDUCER SIZE	19 mm L X 5 mm H
•	PEAK STRAIN LEVEL NEEDED	1.39 X 10 <sup>-4</sup>
•	AVERAGE POWER WITH 50% DUTY FACTOR AND 20% FILL LENGTH	160 W
•	ACTIVE CELL LENGTH	23.1 mm
•	SPOT COMPRESSION GAIN	8.2
•	INPUT SPOT SIZE	210 μm
•	OUTPUT SPOT SIZE	25.6 μm

FIGURE 3-2 THE RECORDER ACOUSTO-OPTIC DEVICES SCHEMATIC



### The Lens System (continued)

To shape the AOBBD scanning spot, first note that in the long dimension of the AOBBD plane, the combination of the relatively large scan angle (1.07 degrees) and the relatively short AOBBD length (3.52 mm) results in the AOBBD itself acting as a lens. The focal length of this lens is  $3.52/1.07^{\circ}$ , or 188.5 mm. This "lens" focusses the 3.52 mm aperture to a 0.030 mm aperture. In the other dimension, the combination of two 22.2 mm EFL lens ( $C_3$  and  $C_4$ ) focusses the .82 mm beam down to 4.1 microns.

To relay and shape the spots from the AOBBD scan plane to the ATWL, a three lens system is used.  $L_5$  is a 50 mm lens which acts as a collimator of the diverging spot wavefront, and effectively acts as a fourier transform lens for the scanning system. Lenses  $L_6$  and  $L_7$  convert the transform back into a linear scan of spots, and telecentrically image the AOBBD scan onto the ATWL. The Gaussian spot profile of these imaged spots at the ATWL is 197 microns in the across-scan direction, and 26.9 microns in the opposite direction.

The final optical element in the spot imaging system is the 50 mm reduction lens  $L_8$  which takes the ATWL's 25.6 micron output spot and reduces it down to a nominal 1.2 micron ( $1/e^2$ ) spot diameter in the across-scan dimension, while at the same time producing a 1.4 micron spot-to-spot spacing and an across-scan 1.3 micron diameter.

A simplified version of the above discussion, along with the specified lens spacings and all Gaussian beam waists, is listed in Table 3-7.

### The Focus Servo Subsystem

In order to maintain focus as the recorder rotary transport steps from track-to-track in the system, a separate optical subsystem has also been integrated into the recorder. This system begins with a helium-neon laser (selected because the medium used in the recorder is insensitive to the 632.8 nm helium-neon laser light), which is focused by the 5 mm focal length microscope objective  $L_9$ , and imaged by the 150 mm spherical lens  $L_{10}$  and the reduction lens  $L_8$  onto the film plane. This spot of light reflects back from the recording medium to be focussed by lenses  $L_{11}$  (150 mm),  $C_5$  (a 10 mm cylindrical lens), and  $L_{12}$  (a 5 mm microscope objective) onto the output quadrant

FIGURE 3-3 THE ACOUSTIC-TRAVELING WAVE LENS RECORDING SYSTEM

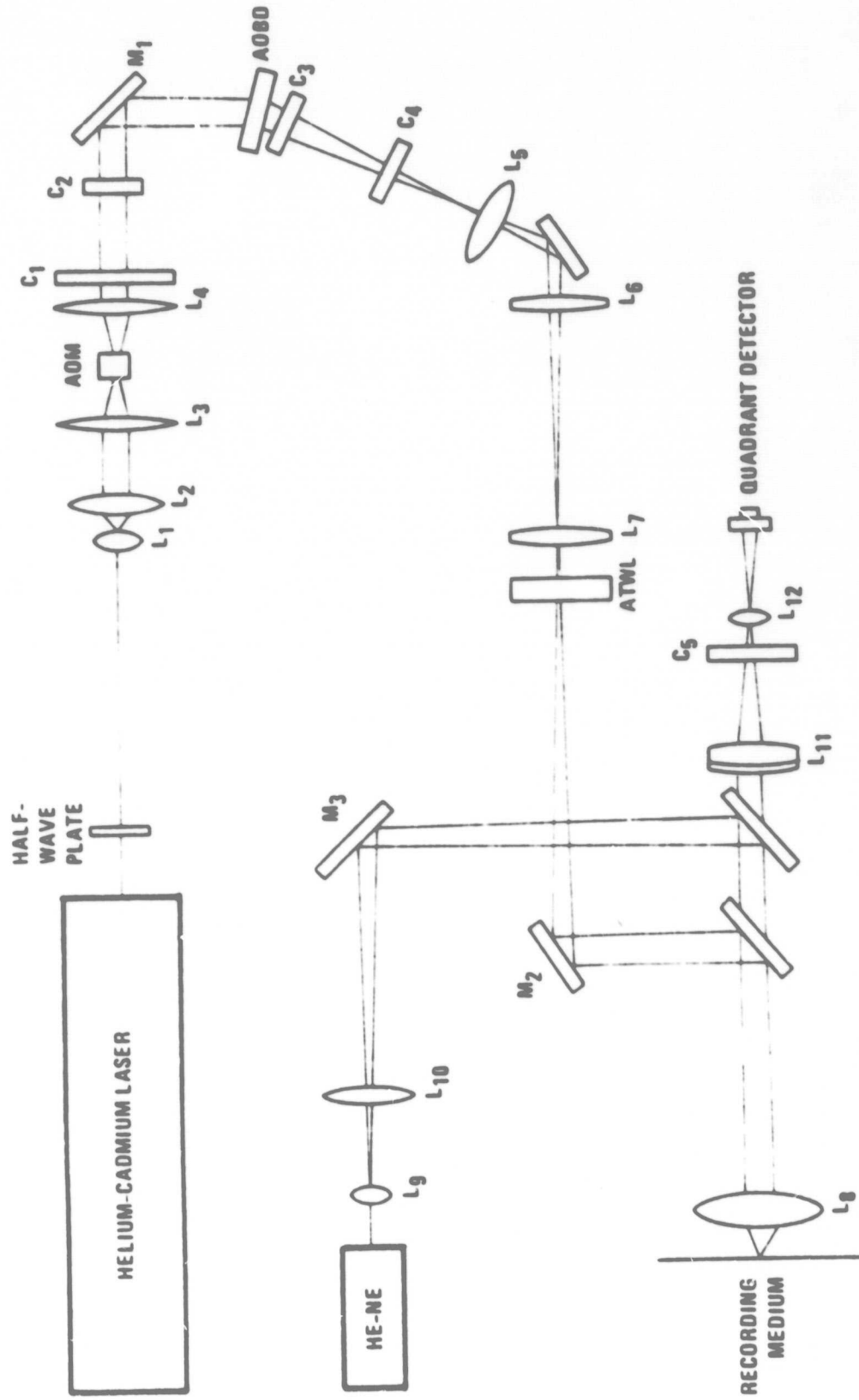


Table 3-7. The Recorder Optics Lens Layout

Input Wavefront from He-Cd Laser =  $0.91\text{mm}^{-2}$  ( $0.442\text{nm} =$  )

Lens Name	Type (C or S)	Focal Length (mm)	Separation to Next Element (mm)
L <sub>1</sub>	S	10	50
Beam Waist = 3.64 mm	S (at L <sub>2</sub> )		
L <sub>2</sub>	S	40	
Beam Waist = 3.64mm	S ( $\frac{1^2}{e}$ )		120
L <sub>3</sub>	S	80	
Beam Waist at AOM = 12.4 um = spherical			80
<hr/>			
AOM			
Beam Waist at L <sub>4</sub> = 3.64 mm	S		
L <sub>4</sub>	S	80	
C <sub>1</sub>	C	100	30
Beam Waist at C <sub>2</sub> = 3.64 mm X 0.81 mm			122.2
C <sub>2</sub>	C	22.2	200
Beam Waist at AOB = 3.64 mm X 0.82 mm, aperture to 3.52 mm X 0.82 mm			
Focal power of AOB in 'length' dimension = $\frac{3.52}{1.07^0} = 188.5$ mm EFL			
Distance from AOB to C <sub>3</sub> is:			34 mm
C <sub>3</sub>	C	22.2	127.3
C <sub>4</sub>	C	22.2	28.1
"Focus" of AOB/C <sub>3</sub> /C <sub>4</sub> System: 0.030 mm X 0.0041 mm			50
L <sub>5</sub>	S	50	122
L <sub>6</sub>	S	400	312
L <sub>7</sub>	S	400	72
"Focus" at ATWL is: 0.197 mm X .0269 mm			1091.50
L <sub>8</sub>	S	50 mm	52.4
"Focus" at final image plane is: 1.2 um X 1.3 um			



### The Focus Servo Subsystem

detector. This detector sees the spot focus error transformed into a line of light which is oriented either horizontally or vertically, depending on the direction of focus error. A "best focus" system will have a circle focussed on the detector.

#### 3.1.3 ELECTRONIC SUBSYSTEM

##### Data Sources

The data source for the MASTAR recorder can be either a digitized video data source or a known pseudorandom data sequence. The digitized video data source is taken directly from the output analog video source from a low-resolution TC-100A RCA camera, sampled at 100 ns intervals, and assigned 3 bits of user data per sample, resulting in a  $2^3 = 8$  grey-level depiction of the analog video scene. The net data rate for the video is therefore  $10 \text{ MHz} \times 3 = 30 \text{ Mb/s}$ . For the pseudorandom sequence, a preformatted selection of 330 user bits (and up) is available as the input data source for the system. The selection of input data source is controlled by a manual switch which must be thrown prior to recording.

##### Data Formatter

The data formatter, which consists of the baseband encoder and line formatter shown in Figure 3-4, takes a 33-bit parallel input from the data source, adds Manchester baseband coding in the front end, and adds the introductory line sync, clock recovery, and frame sync information from PROMs in the line formatter electronics. The format is merged and converted into the necessary 792 spot line for buffering and input to the acousto-optic modulator drive electronics.

##### Optics Electronics

Each of the acousto-optic devices require special drive electronics for their specific functions. The acousto-optic modulator utilizes a custom-designed, ultra-stable fixed-frequency oscillator as the driver for that component. The AOB, in order to provide a linear scan, utilizes a more complicated arrangement, as shown in Figure 3-5. Once a line of data is ready

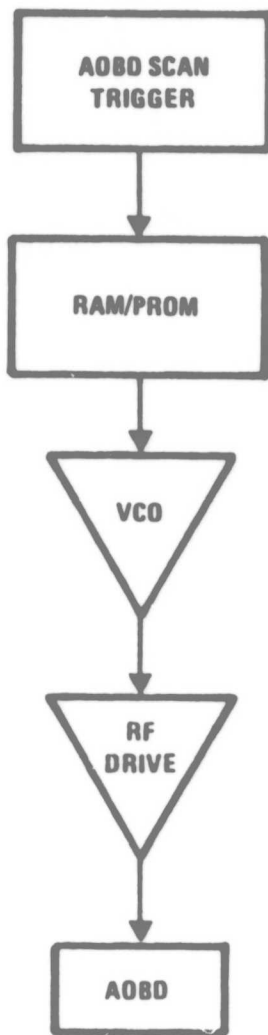


FIGURE 3-5 THE AOBD DRIVER ELECTRONICS

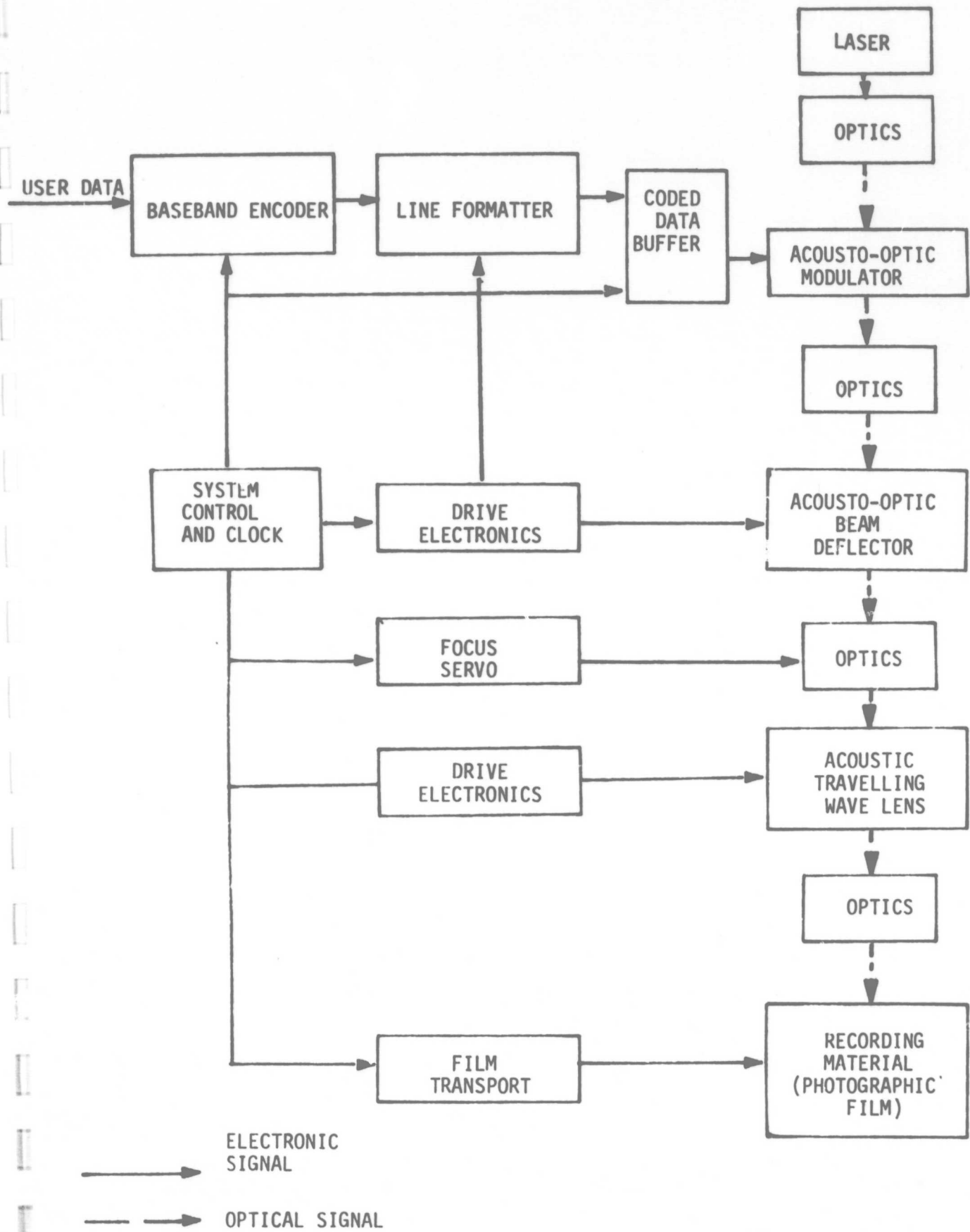


FIGURE 3-4 THE RECORDER ELECTRONICS SUBSYSTEM

### Optics Electronics

to be dumped into the AOM, this signals the AOBD scan trigger to start scanning. Then a voltage-controlled oscillator (VCO) takes the pre-programmed input from a RAM/PROM electronics subsystem to produce an analog drive signal for the AOBD's RF drive. This drive signal must be linear within less than 0.5% across the scan, and the RAM/PROM subsystem is designed to correct the normal VCO nonlinearities to provide this linear scan. Once the AOBD is triggered, the ATWL is triggered to scan along with it. The ATWL is driven by a RAM/PROM programmed shaped "RF" pulse to form the acoustic impulse in the cell. This pulse is shot into the cell at a rate of once per scan.

The focus servo electronics are the only other part of the optical subsystem which requires electronics inputs of an unusual nature. The output of the quadrant detector is used by these electronics to provide an error-correction analog drive signal for a piezoelectrically-driven mechanical transducer. This transducer is mounted on the final reduction lens  $L_8$ , and is capable of correcting up to 40 microns of movement in the servo subsystem.

The helium-cadmium laser is purchased from Liconix with its own prepackaged drive electronics and power supply.

### Transport Electronics

The rotary transport mechanisms are controlled by a Z-80 micro-processor from the recorder controller electronics. The PROMs in the controller have preprogrammed information which includes data on the appropriate drive speeds for each of the tracks in the rotary transport. A stepper motor drive package is included in the rotary transport subsystem, which provides efficient and rapid stepping from track-to-track. The DC Motor/Tachometer assembly to drive the rotary transport is controlled by a servo/encoder feedback loop electronics package mounted directly on the motor tachometer.

### Control Electronics

The rest of the control electronics shown in Figure 3-4 have been designed so that, once the command to record has been given, the mechanisms can automatically mount a fiche in the rotary vacuum chuck, bring the fiche up to speed, trigger writing and scanning of complete frames, and stop recording at the end of a track. This is accomplished using a self-contained Z-80 micro-

### Control Electronics (continued)

processor system and PROM-stored firmware in the controller. Stepping from track-to-track is initiated from the controller following a manually-operated switch command to move to the next track.

### The Rotary/Track Transport

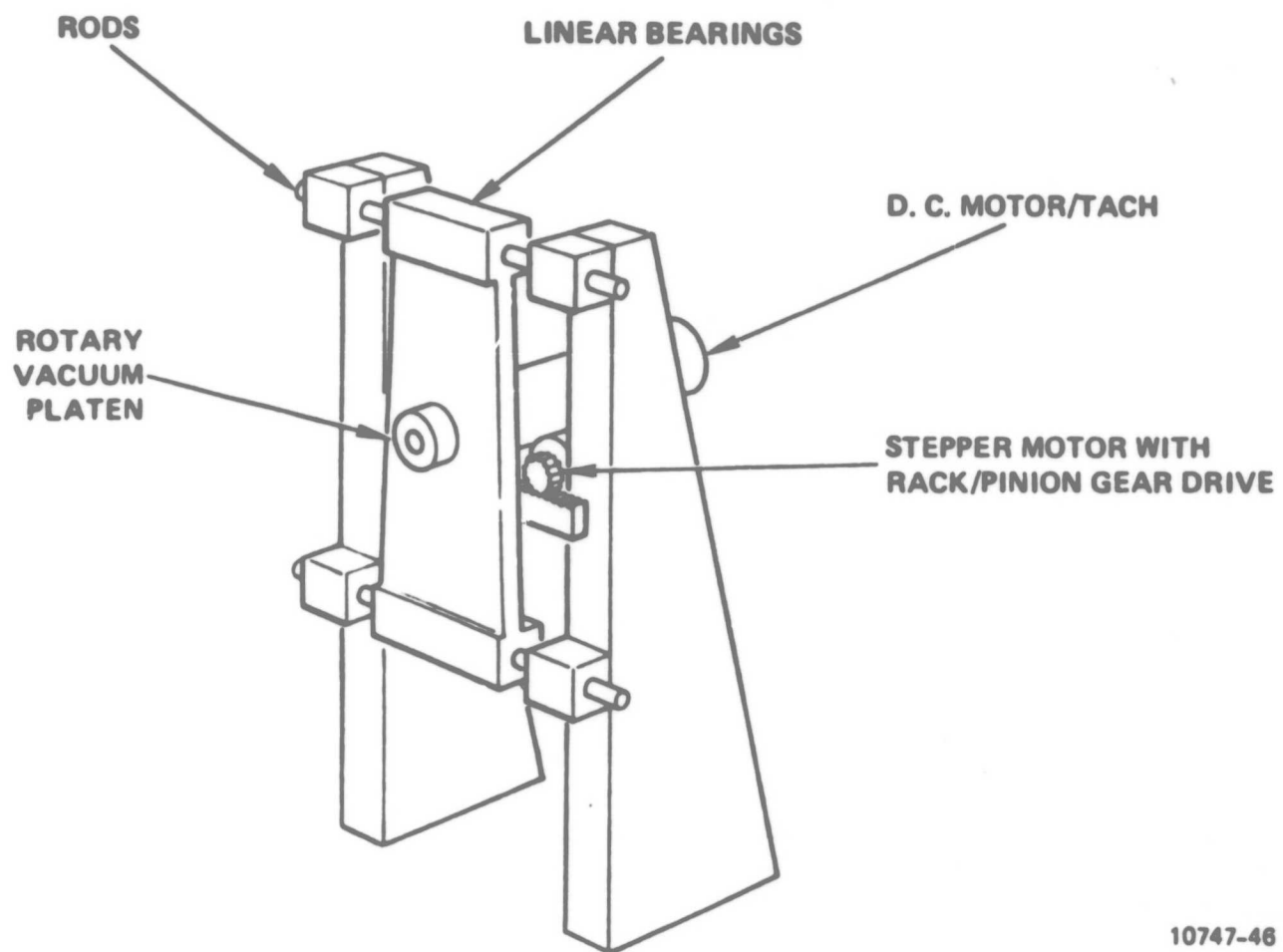
The rotary/track transport is shown in Figure 3-6. It consists of a rotary drive with a D.C. motor and tachometer mounted on a solid aluminum plate. Motion from track-to-track is accomplished using a stepper motor and rack and pinion gear drive shown in the figure. The steps are controlled in 1.25 mm steps. The rotary transport is capable of speeds in excess of 1000 cycles per minute, which is well beyond the present system requirements for the recorder of just over 34 rpm (for the 66 mm radius) or 113 rpm (for the 20 mm inner radius).

### The Vacuum Chuck Subsystem

The vacuum chuck clamps the film in the center using a punched hole alignment. Once the film is positioned and the vacuum switched on (a manual process in the present breadboard), the pin for hole positioning is automatically removed and the film allowed to spin.

### Optics Packaging

The recorder optics packaging configuration is shown in Figure 3-7.



10747-46

FIGURE 3-6 THE RECORDER TRANSPORT MECHANISM



RECORDER SUBSYSTEM

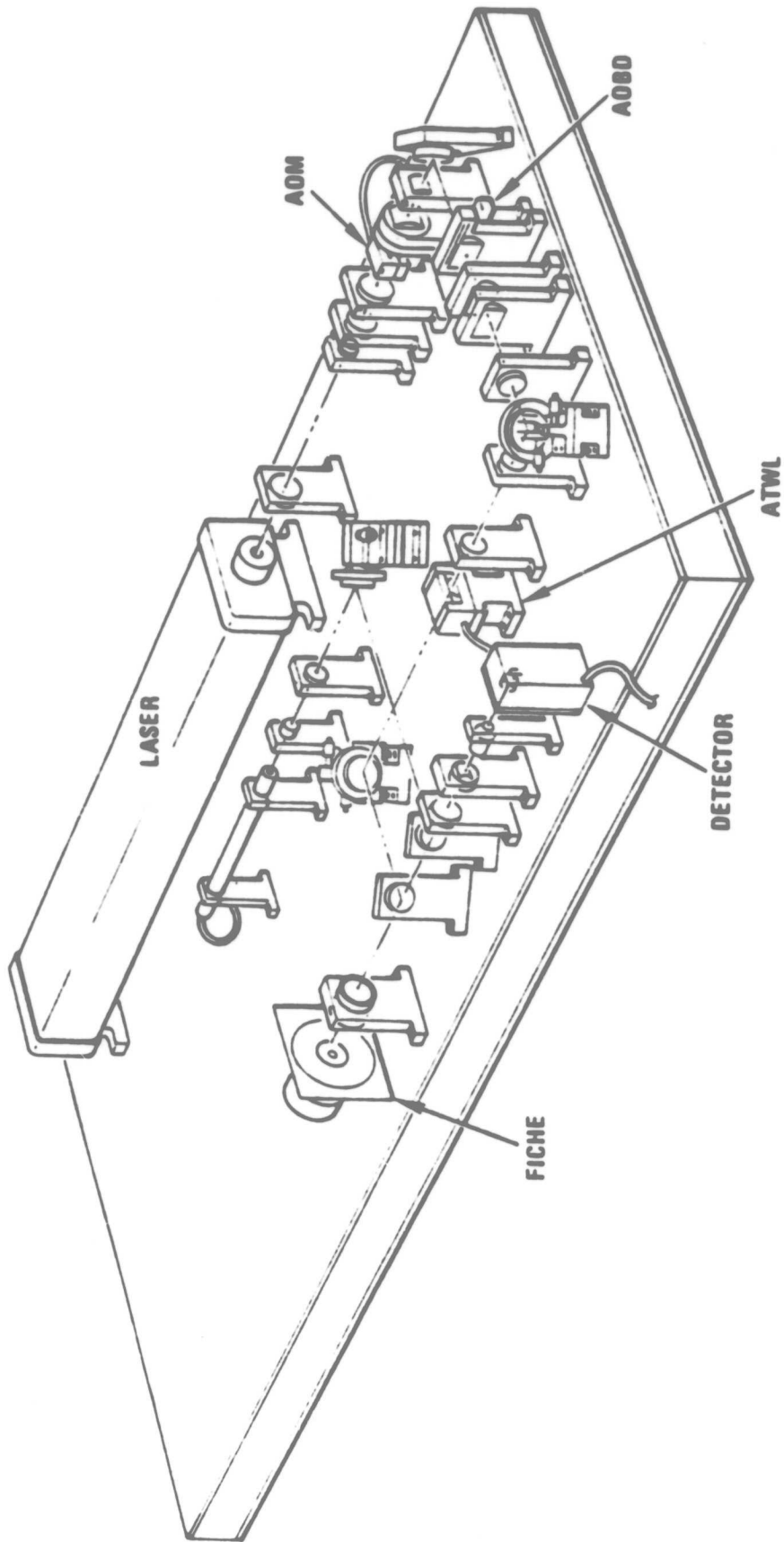


FIGURE 3-7 THE MASTER RECORDER SUBSYSTEM PACKAGING

## 3.2 Reader Design

### 3.2.1 Review of Specifications

As in the case of the recorder subsystems, the appropriate place to begin in discussing the reader is with a brief review of the reader specifications. The first key specification is the data transfer rate. With a user data rate of 5 Mb/s, a factor of 2 utilized for the baseband coding, and an additional 20% for line sync, clock recovery, and frame sync, the effective subsystem read rate is  $5 \times 2 \times 1.2 = 12$  Mpixels/s. Note that here, as in the previous case, since we are interested in using single-chirp acousto-optic deflection devices, the duty cycle of 50% (for single-chirp systems) results in an effective instantaneous data rate of 24 Mpixels/s.

As for data formatting, the original 792 spots per line recorded on film must, of course, be scanned by the reader subsystem. In addition to this data, however, a tolerance analysis of the mechanisms involved in the recorder indicates that the alignment of the optics with the data tracks may vary as much as  $\pm 50$  microns. (This is discussed in paragraph 3.2.4). With a spot spacing of 1.4 microns across the track, this amounts to a total of  $\pm 36$  spots additional to be scanned by the optics, for a total of  $792 + 72 = 864$  spots.

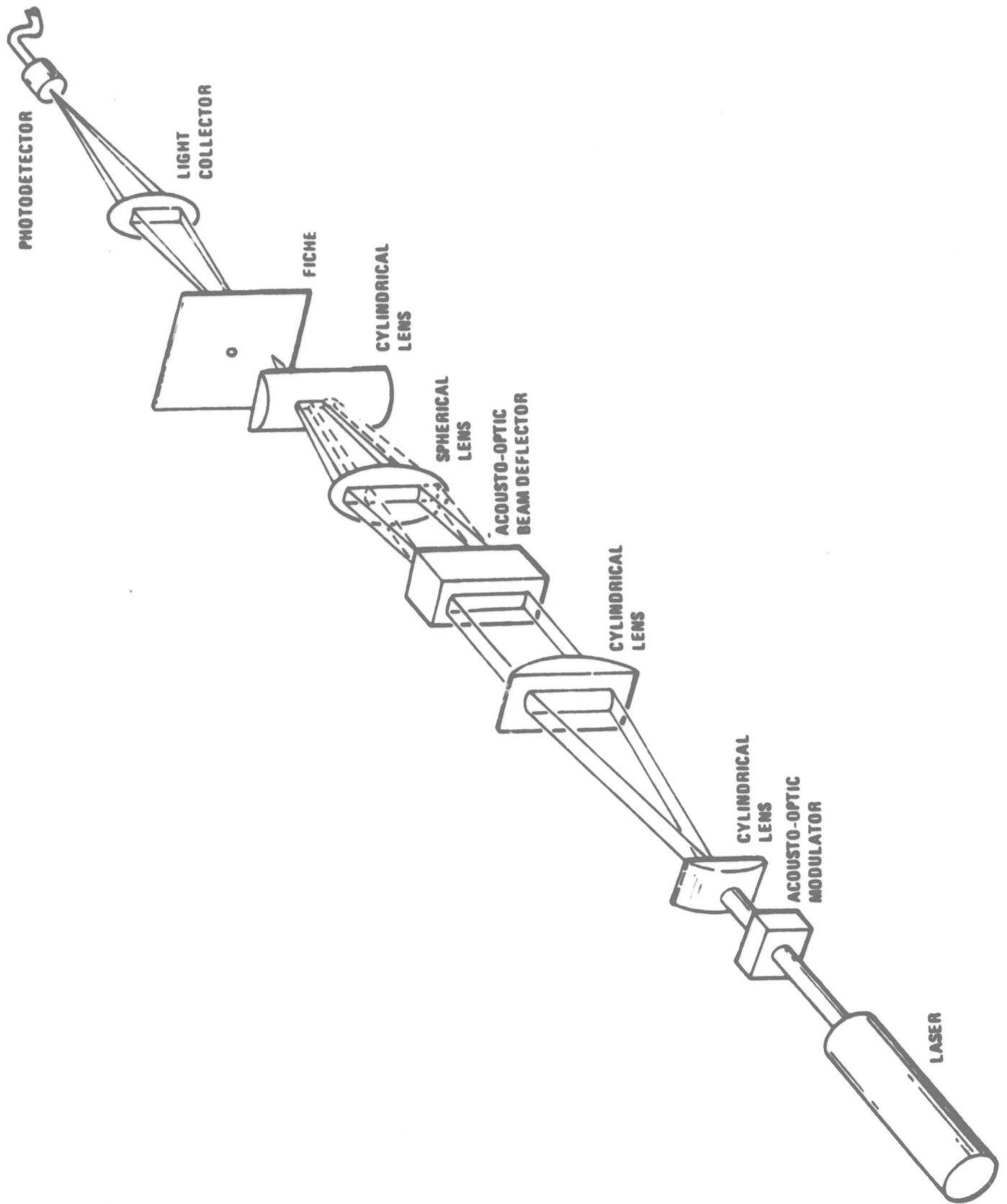
The remaining specifications to be demonstrated by the reader are those of access time, bit error rate, and on-line storage capacity. The access time from the ending of readout of any data block on any fiche to the beginning of readout of any other data block on any other fiche is required to be 10 seconds or less. The bit error rate requirement is that the system demonstrate raw bit error rate statistics sufficiently low that a corrected BER of less than  $10^{-6}$  is possible, using appropriate error detection and correction hardware. Finally, the reader must prove its access time with a minimum on-line data storage capacity of  $10^{12}$  user bits of information.

### 3.2.2 Optical Subsystems

#### Overview

The optical subsystems concept for the reader (shown in Figure 3-8) is simpler and more compact than the recorder subsystem. Because of the lower data transfer rate of the reader, an acousto-optic beam deflector is sufficient to provide the 5 Mb/s user data transfer rate and still scan the

FIGURE 3-8 THE ACOUSTO-OPTIC BEAM DEFLECTOR OPTICS SCHEMATIC



### 3.2.2 Overview (continued)

necessary field of 864 1.4 micron spot centers. At the front end of the reader, a helium-neon laser beam (chosen for its compatibility with detector sensitivities, low cost, high reliability, and compact size) is passed through a cylindrical lens beam expander to illuminate the AOBD entrance pupil. The AOBD output beam scans across selected cylindrical and spherical elements to focus down a line scan across the spots on the fiche. The light modulated by the recorded spots is then gathered by a light collector to converge on a photodetector.

#### The Acousto-Optic Beam Deflector

The deflector selected for the MASTAR reader is a slow-shear tellurium dioxide device similar to that in production use for commercial printer systems. With a center frequency of 90 MHz and a bandwidth of 50 MHz, it is capable of scanning more than 900 spots at an effective data transfer rate of over 24 Mpixels/s. The scan angle produced by the AOBD for these 900 spots is 1.47 degrees, and the diffraction efficiency of this scan is better than 80% with an input drive power of 2 watts. The complete set of specifications for this device is listed in Table 3-7.

#### The Lens System

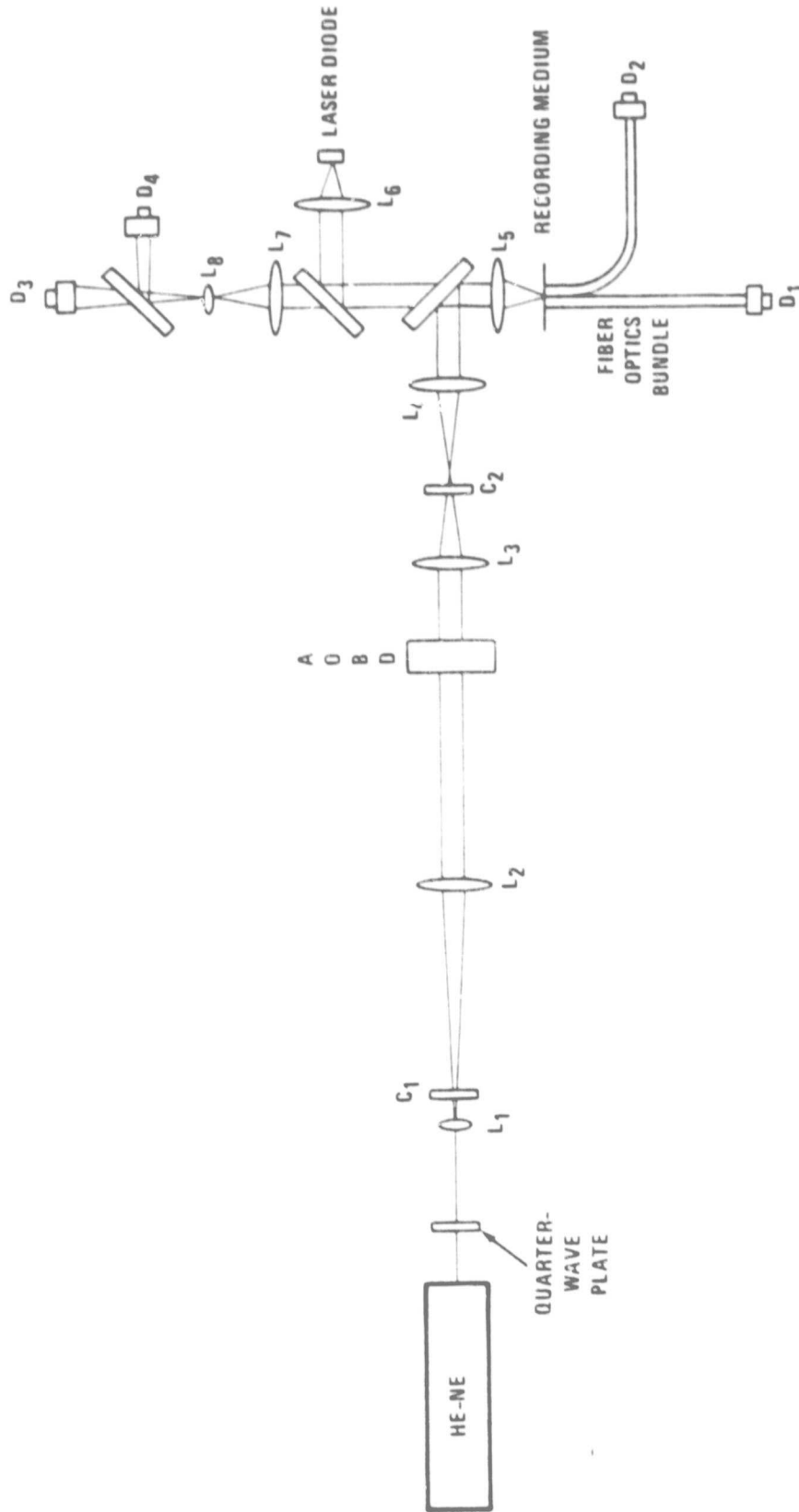
The lens system used for the reader is shown in schematic form in Figure 3-9. A 4 mW Hughes Helium-Neon laser with an output Gaussian beam waist of 0.81 mm (at the  $1/e^2$  power points) is the light source for the reader. Immediately following the laser is a quarter-wave plate, which is used to convert the linearly polarized helium-neon source to a circularly polarized beam for proper illumination of the AOBD. The beam then passes through lens  $L_1$ , a 5 mm EFL microscope objective, is focussed down and diverges 50 mm from the focus to illuminate  $C_1$ , a 50 mm cylindrical lens. This lens forces a collimation of the beam to 8.1 mm in the direction of cylindrical power. When this beam passes through  $L_2$ , a 250 mm lens, it converges to a 0.65 mm beam in the AOBD 230 mm away, and comes to a focus 20 mm beyond the AOBD. In the other dimension,  $C_1$  has no effect on lens  $L_1$ 's converging wavefront, so that it illuminates a 40.5 mm aperture at  $L_2$ .  $L_2$  collimates the beam and the AOBD's input aperture is allowed to truncate the beam to a 19.8 mm aperture.

TABLE 3-7 ACOUSTO-OPTIC BEAM DEFLECTOR CHARACTERISTICS

MATERIAL	TeO <sub>2</sub> (SLOW SHEAR)
OPTICAL WAVELENGTH	632.8 nm
POLARIZATION	CIRCULAR
CENTER FREQUENCY	90 MHz
BANDWIDTH	50 MHz MIN
FILL TIME	32 μs
SCAN TIME	33 μs
RESET TIME (VCO)	1 μs
DUTY FACTOR	50%
NUMBER OF SPOTS	> 900
TRANSDUCER SIZE	0.7 X 2 mm <sup>2</sup>
OPTICAL BEAM SIZE	20 X <1 mm <sup>2</sup>
A0 Q	26.2
DIFFRACTION WITH 2W	80%
DEFLECTION ANGLE AT CENTER FREQUENCY	5.2°
SCAN ANGLE FOR 50 MHz BANDWIDTH (900 SPOTS)	1.47°

C-2

FIGURE 3-9 THE ACOUSTO-OPTIC BEAM DEFLECTOR READER OPTICAL SYSTEM





### The Lens System (continued)

After the AOBBD, the combination of lens  $L_3$ , a 100 mm spherical lens, and  $C_2$ , a 10 mm cylindrical lens, focusses the 19.8 mm x 0.65 mm wavefront into a 2.8 micron x 2.6 micron beam. This is also a scan plane of the system. Lenses  $L_4$  and  $L_5$ , a 100 mm to 50 mm telescope reduction system, then convert this to a nominal 1.4 micron x 1.3 micron beam. This propagation process is tabulated in more compressed form in Table 3-8.

To provide information for line synchronization (the signal to start the AOBBD scan), a separate optical path is used. A Nippon Electric Company (NEC) laser diode is placed in the system so that its 0.85 micron wavelength wavefront diverges and is collimated by lenses  $L_6$  and  $L_5$ , and is focussed by lens  $L_5$  as a line of light illuminating the line sync portion of the line of recorded spots.

To collect the light for line sync detection or data detection, a special fiber optic bundle is used. This bundle is a 0.177" circular grouping of 0.002" diameter glass fibers, and it is placed 0.125" away from the focal plane in the system. 20% of the fibers (arranged randomly within the bundle) are collected and routed to the detector for line sync, and 80% of the fibers are routed to the data photodetector. Special optical interference filters are placed in front of each photodetector to prevent the .85 micron line sync beam and .6328 micron data beam from adding noise to the detection process for line sync or data recovery.

The final optical subsystem used in the reader is the focus servo system. Because of packaging constraints, the reader focus servo works somewhat differently than that used in the recorder. In this approach, the signal from the laser diode is used to illuminate the film as before for line sync detection. For use as a focus servo signal, however, the reflected wavefront from the film is passed through the beamsplitter to be imaged via  $L_7$  (a 50 mm EFL lens) and  $L_8$  (a 5 mm microscope objective) to image the film plane. Detector  $D_3$  is placed slightly in front of the focal plane, and  $D_4$  in back of the focal plane, with the result that a detector signal comparator can be used to determine the exact focal shift of the system.

TABLE 3-8 THE READER OPTICS LENS LAYOUT

Input Wavefront from He-Ne Laser is  $0.81 \text{ mm e}^{-2}$

Lens Name	Type (C or S)	Focal Length	Separation to Next Element (mm)
$L_1$	S	5	55
$C_1$	C	50	200
Beam Waist at $L_2 = 40.5 \text{ mm} \times 8.1 \text{ mm}$			
$L_2$	S	250	230
Aperture at AOB (shaped) = $19.8 \text{ mm} \times 0.65 \text{ mm}$			
(Beam is converging in cylindrical direction; focus is 20 mm towards $L_3$ )			
$L_3$	S	100	100
$C_2$	C	10.0	76.9
	SCAN PLANE		10.3
Beam Size at Scan Plane is: $2.8 \mu\text{m} \times 2.6 \mu\text{m}$			
$L_4$	S	100	100
$L_5$	S	50	150
	FINAL SCAN PLANE		50

### The Lens Systems (continued)

The complete list of lenses used in the reader optics appears in Table 3-9.

### Light Budget

To calculate the available light budget for data detection, first note that the most significant losses in the system are the 80% to 90% loss in the AOBBD (including the factor of 2 for overillumination and allowance for rolloff), a maximum of 50% in the fiber bundle from attenuation, and a maximum of 40% for film reflection. Adding in other optical losses, a worst-case nominal system of efficiency of 10% overall can be estimated. This means that, with the 4 mW laser available for the reader, 400 microwatts of transmitted optical power can be expected at the data detector.

## 3.2.3 ELECTRICAL SUBSYSTEMS

### Acousto-Optic Beam Deflector Electronics

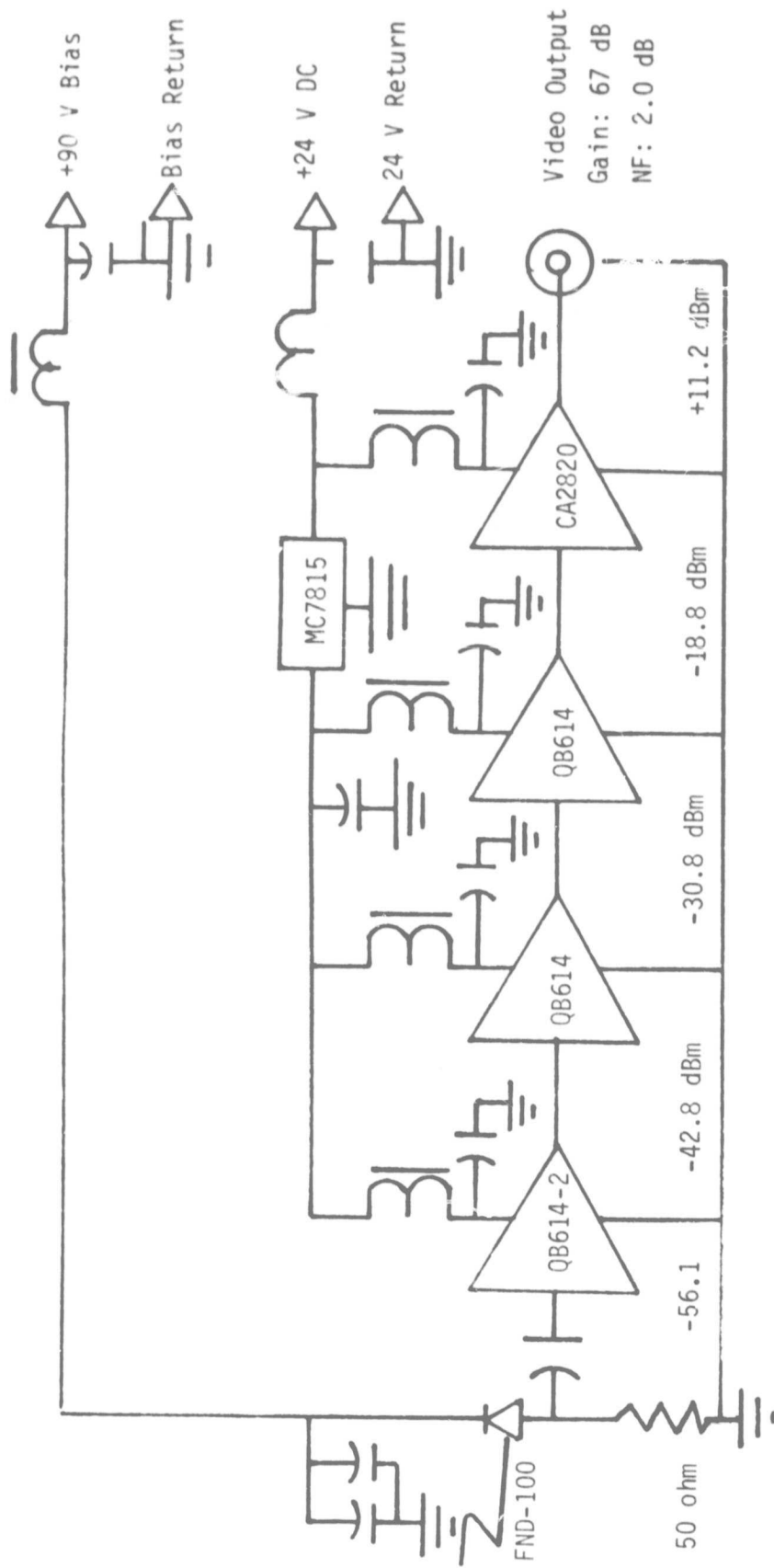
The AOBBD electronics for the reader are functionally identically to these used in the recorder, and as described in paragraph 3.1.3. As additional specifications, the requirements for accurate data recovery and spot uniformity are a linearity of less than 1% (peak-to-peak) and a stability of less than 0.1% (peak-to-peak) in the AOBBD driver. The 66 microsecond AOBBD drive cycle time includes a voltage-controlled oscillator settling time of 1 microsecond, a fill time of 32 microseconds, and an active scan time of 33 microseconds.

### Sensor Electronics

The optical receiver uses a high speed PIN silicon photodiode as the transducer, followed by a low noise amplifier chain to amplify the analog signal to a video level suitable for transmission to the data recovery module. The input photodetector is an EG&G FND-100 PIN photodiode, as shown in Figure 3-10. Its output is discharged through a 50 ohm load resistor, and is amplified by a low noise RF amplifier chain consisting of three QB614-2 amplifiers and a final CA2820 amplifier. The gains, bandwidths, and amplifier powers of the devices are listed in the Figure. The output of the sensor electronics is a signal with a net SNR of 28 dB, putting the effective bit error rate contribution of the device at less than  $10^{-8}$  with the 400 microwatts of input optical power.

TABLE 3-9 THE READER LENSES

L <sub>1</sub> :	5 mm SPHERICAL
C <sub>1</sub> :	50 mm CYLINDRICAL
L <sub>2</sub> :	250 mm SPHERICAL
L <sub>3</sub> :	100 mm SPHERICAL
C <sub>2</sub> :	10.0 mm CYLINDRICAL
L <sub>4</sub> :	100 mm SPHERICAL
L <sub>5</sub> :	50 mm SPHERICAL
L <sub>6</sub> :	50 mm SPHERICAL
L <sub>7</sub> :	50 mm SPHERICAL
L <sub>8</sub> :	5 mm SPHERICAL



DEVICE	GAIN	BANDWIDTH	NF (MAX)	POWER
QB 614-2	13.3 dB	5-20 MHz	1.8 dB	+3 dBm
QB 614	12.0 dB	2-30 MHz	3.8 dB	+8 dBm
CA 2820	30.0 dB	1-52 MHz	8.0 dB	+26 dBm

FIGURE 3-10 THE OPTICAL RECEIVER ELECTRONICS

### Data Deformatting and Error Detection

The data deformatter and error detection modules take the detected data and convert it into either a video display signal or as the input for the error detection circuit. As shown in Figure 3-11, once the data has been detected, it is buffered in a line buffer to first extract clock data from the Manchester-encoded bits. Once clock has been recovered, the means to start separating recovered at the beginning of the scan, it is used as the means to start separating user data out of the pixel stream. The Manchester baseband code is extracted, and, for the video case, a full frame of data is clocked out (and counted out using a line counter). The frame of data is stored in a solid-state RAM buffer memory with 1 Mb of user data per video frame, where it can be run through a high-speed digital-to-analog converter, and used as the refresh for a television monitor.

For the pseudorandom(p/n)sequence case, the output data is compared to the expected pseudorandom sequence, with errors collected and printed out as they are detected. As was already described in section 2.0 of this report, the printout includes the track number, frame number, line number and number of errors in a line for each line of data as it is read. Misreads of the entire line are also flagged as error signals, to distinguish this event from the error statistics to be gathered on the actual spot detection process.

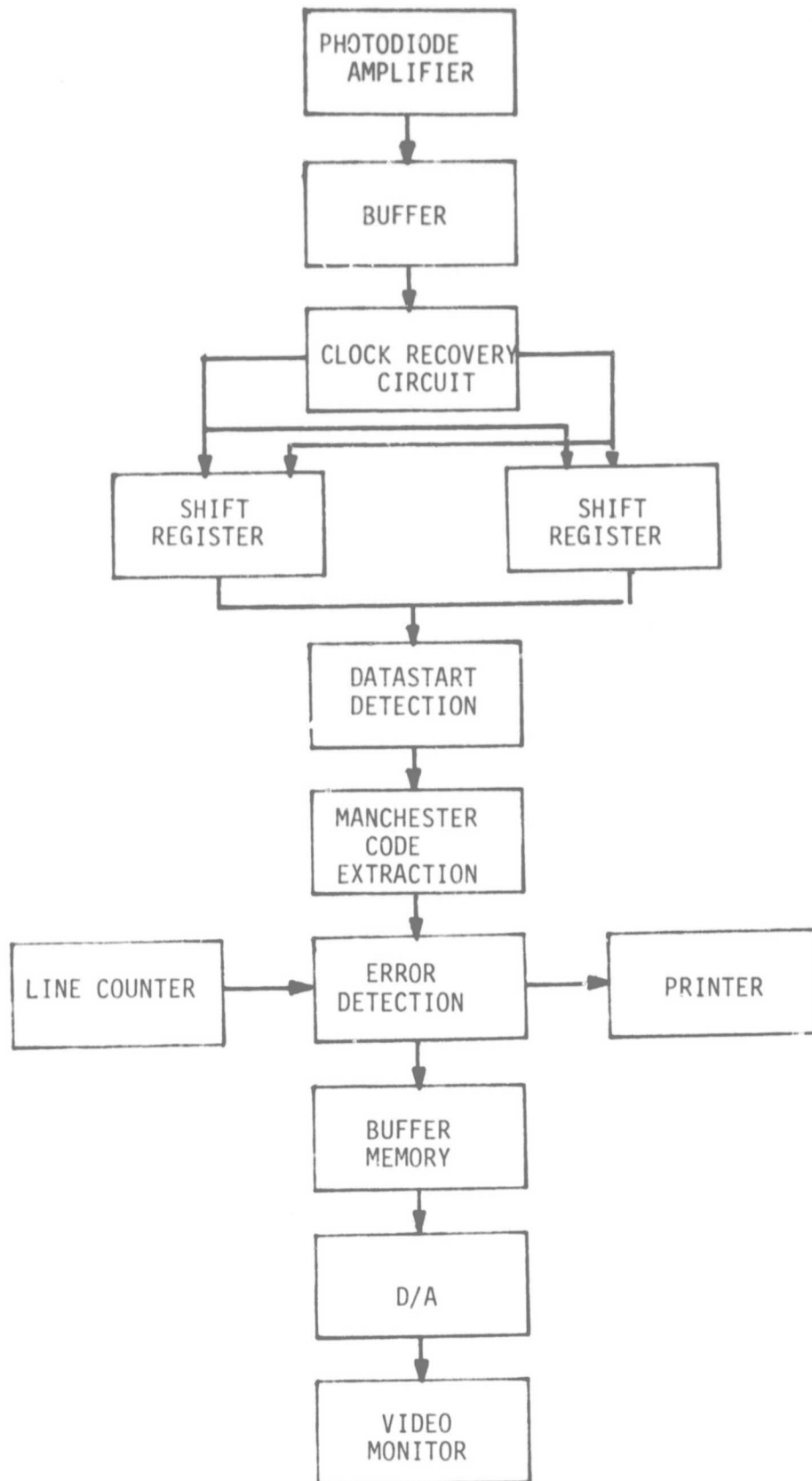
### Mechanisms Control

The rotary transport and track transport control are identical to those subsystems used in the recorder, with the exception that the input drive signals from the controller run the rotary transport at a rate only one-sixth as fast as in the recorder.

For the x-y transport, a stepper motor driver system with electronic feedback is responsible for accurate positioning of the fiche in the center position between the two levels of the carousel, and for retrieval to the top or bottom level. An air piston system with simple vacuum actuation is used to position the fiche in the hole for the vacuum chuck to clamp the fiche, and a simple electromechanical valve acts as the electronic-to-mechanical transducer for this control system.



FIGURE 3-11 DATA, CLOCK, AND ERROR STATISTICS RECOVERY



### Controller

The storage and retrieval subsystem controller, like that in the recorder, consists of a Z-80 microprocessor and firmware subsystem. The controller automatically regulates all functions in the reader, so that once a command has been given to read a given frame on any of the carousel fiche, the controller takes over and accesses from that point without human interaction. The complete mechanism and readout sequence is described in the access time discussion in paragraph 3.2.4.

#### 3.2.4 MECHANICAL SUBSYSTEMS

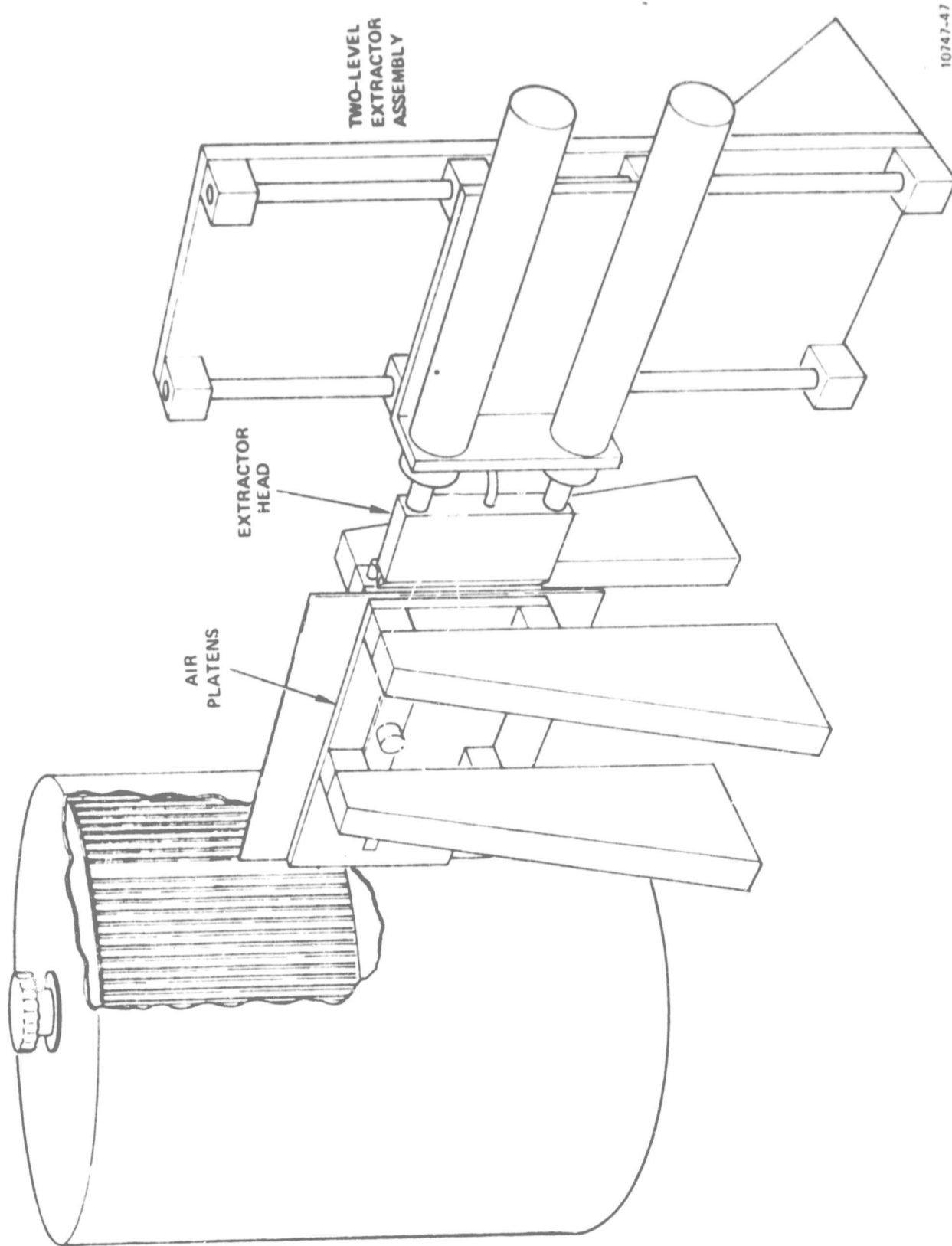
##### The Transport Subsystems

The transport subsystems for the reader consist of an x-y transport, the vacuum chuck for handoff to the rotary transport, the track transport, and the rotary device itself. The x-y transport is a combination of stepper motors and air pistons as described in the electronics subsystem above which provides accurate positioning of the microfiche within the air platens, into and out of the slots for fiche retrieval, and onto the vacuum chuck for handoff to the rotary transport. In use, the transport is positioned by stepper motor to one of two levels in the carousel. Then the air pistons push the extractor head above or below the air platens to push the head against the fiche (see Figure 3-12). When contact is made, the vacuum is applied to the extractor, and the head clamps around the fiche. The pistons retract, the stepper motors move the fiche down to the vacuum chuck, and the steppers stop. A pin is engaged in the hole in the center of the fiche, the vacuum on the vacuum chuck is switched on, and the extractor head is released. The pin is removed from the fiche, and the fiche is ready for rotation. Once the fiche has completed readout on one track, the fiche is stepped from track-to-track by a rack-and-pinion gear assembly (on 1.25 mm centers) exactly as in the recorder.

For the reverse operation, the track stepper is moved to its extreme position and the rotary transport is moved to a zero position. The extractor head then clamps on the fiche, the vacuum chuck is released, and the fiche is returned to its slot in the carousel.

##### Tolerancing

The actual tolerances achievable with the key elements of the transport mechanisms include a reader/recorder rack-and-pinion error, pinion concentricity, and gear tooth/tooth errors, as well as recorder-to-reader decentration considerations, such as concentricity of the bore, bore diameter



10747-47

FIGURE 3-12 THE STORAGE AND RETRIEVAL CAROUSEL MECHANISMS ASSEMBLY

### Tolerancing (continued)

matching in the center hole, and hole punch matching to the bore. These tolerances are gathered in Tables 3-10 and 3-11, and amount to a total tolerance of  $\pm 1.9 \times 10^{-3}$  inches error in track positioning. This has been accounted for in allowance of overscan on the part of the reader optics.

### The Carousel Subsystem

The storage and retrieval carousel is a two-level assembly with 512 dedicated slots cut from the inside out radially on each level of the carousel. The fiche are stored in the carousel in slots in a pair of plates for each level, with 8 slots per level used for supports to hold dimensional tolerances of the carousel levels. The plates themselves are cut from Lexan, a high-rigidity plastic used in injection-molded production packaging. Fully loaded, the Lexan plates and the entire carousel module stores a total capacity of  $504 \times 2 = 1008$  fiche per module. At over  $1 \times 10^9$  user bits per fiche, this amounts to a total of over  $10^{12}$  user bits per module.

The carousel itself is driven by special drive gear mounted on a loaded precision stepper motor. An encoder is also tied to the electronics to keep track of the position of the carousel relative to its zeroed position.

### Access Sequence and Access Time

To access any given block of data, once a request for a new frame is received at the controller, the readout electronics first checks the number of the frame it is currently reading and compares it against the last frame number in that track. Based on this comparison, the readout electronics calculates the optimum acceleration/deceleration rotary drive waveform to move the transport from its current frame, past the last frame in the track, and to a stop at the zero position between the end of the track and the beginning of the track. The y-axis of the x-y transport then moves it to the edge of the fiche, the vacuum is applied to the extractor head, and the vacuum chuck on the rotary transport releases the fiche. The extractor and x-y transport replaces the fiche in the carousel, the carousel rotates to the proper new slot position, and the process is reversed to replace the fiche in the rotary transport. The proper track is accessed, and once again the reader accelerates the transport to access the proper frame and achieve the proper speed at the same time.

TABLE 3-10 TRACK-TO-TRACK STEP TOLERANCING

- READER/RECORDER RACK-AND-PINION ERROR:  
 $\pm 2 \times 10^{-4}$  INCHES
- PINION CONCENTRICITY:  $\pm 2 \times 10^{-4}$  INCHES  
(RECORDER OR READER)
- GEAR TOOTH/TOOTH ERROR:  $\pm 2 \times 10^{-4}$  INCHES (NET)
- TOTAL ERROR:  $< 1 \times 10^{-1}$  INCHES (=0.025 mm)

TABLE 3-11 RECORDER-TO-READER DECENTRATION TOLERANCING

- CONCENTRICITY OF SERVO BORE:  $< \pm 3 \times 10^{-4}$  INCHES  
(RECORDER OR READER)
- BORE DIAMETER MATCHING (RECORDER-TO-READER):  
 $\pm 1 \times 10^{-4}$  INCHES
- HOLE PUNCH MATCHING TO BORE:  $\pm 1 \times 10^{-4}$  INCHES  
(RECORDER OR READER)
- NET DECENTRATION:  $< \pm 9 \times 10^{-4}$  INCHES  
( $\cong \pm 0.022$  mm)



### Access Sequence and Access Time (continued)

The complete access sequence is shown in detail in Table 3-12. The final access time, based on experimental measurements of the actual mechanism response times, is 8.06 seconds maximum, from the end of readout of any frame to the beginning of readout of any other frame in the  $10^{12}$  bits of user data which are on-line.

### Packaging

The reader packaging concept has been to place all the optics, electronics, and mechanisms for the storage and retrieval reader subsystem in a single 61" x 30" standard rack, with some accommodation for the carousel mechanisms. The placement of the optics relative to the mechanisms themselves is shown in Figure 3-13, which illustrates the relative physical size of the reader optics as well as showing how the mechanisms for extraction and transport of the fiche have been designed integral to the optics. This package is incorporated in a single rack as illustrated in Figure 3-14, with a door for accessing the carousel/optics assemblies, a mounting panel for the video display, and a table for the keyboard controller. This table will also be used for an error statistics printer. As further detail as to the configuration inside the rack, Figure 3-15 is helpful. The control electronics and power supplies have been mounted in the upper part of the rack to allow easy human interaction with the external controls, and to prevent heat dissipation from the electronics from passing up through the optical beam paths. The mechanisms have been organized to place the x-y transport in the rear chamber of the rack, with the rotary transport optics, and carousel mounted up close to the access door. Finally, the table mounted in front of the rack can be lifted up and out of the way with a special folding mount to allow easy access to the carousel and optics.

TABLE 3-12 TRANSPORT MECHANISMS AND THE CAROUSEL  
ACCESS SEQUENCE (WORST-CASE)

	TIME REQUIRED (SECONDS)
1. COMPLETED READOUT OF A FRAME; ROTATE TO "0" POSITION AND STOP	0.5
2. Y-AXIS OF TRANSPORT POSITIONS TO ENGAGE FICHE	0.32
3. VACUUM APPLIED TO EXTRACTOR	0.10
4. SERVO PLATEN RELEASES	0.10
5. Y-AXIS POSITIONS TO RETRACT POSITION	0.32
6. X-AXIS POSITIONS TO CAROUSEL LEVEL	0.45
7. EXTRACTOR EXTENDS INTO CAROUSEL	0.50
8. VACUUM DROPPED OUT ON EXTRACTOR	0.10
9. EXTRACTOR RETRACTS TO "START"	0.50
10. CAROUSEL ROTATES TO SLOT POSITION	1.69
11. X-AXIS POSITIONS EXTRACTOR TO CAROUSEL	0.45
12. EXTRACTOR EXTENDS, ENGAGING FICHE	0.50

TABLE 3-12 TRANSPORT MECHANISMS AND THE CAROUSEL  
 (continued) ACCESS SEQUENCE (WORST-CASE)

	TIME REQUIRED (SECONDS)
13. VACUUM APPLIED TO FICHE	0.10
14. EXTRACTOR RETRACTS	0.5
15. X-AXIS POSITIONS TO CENTER FICHE ON ROTARY TRANSPORT	0.23
16. LOCATOR PIN ENGAGES FICHE	0.10
17. VACUUM TO EXTRACTOR DISENGAGED	0.10
18. LOCATOR PIN FULLY ENGAGES SERVO PLATEN	0.10
19. VACUUM APPLIED TO SERVO PLATEN	0.10
20. Y-AXIS POSITIONS TO RETRACT POSITION	0.32
21. SERVO ACCELERATES TO PROPER SPEED	0.30
22. TRACK STEPPER POSITIONS TO PROPER TRACK	0.18
23. ROTARY TRANSPORT ACCELERATES TO PROPER FRAME; DATA IS NOW READY FOR READOUT	0.50
TOTAL ACCESS TIME	8.06 SECONDS

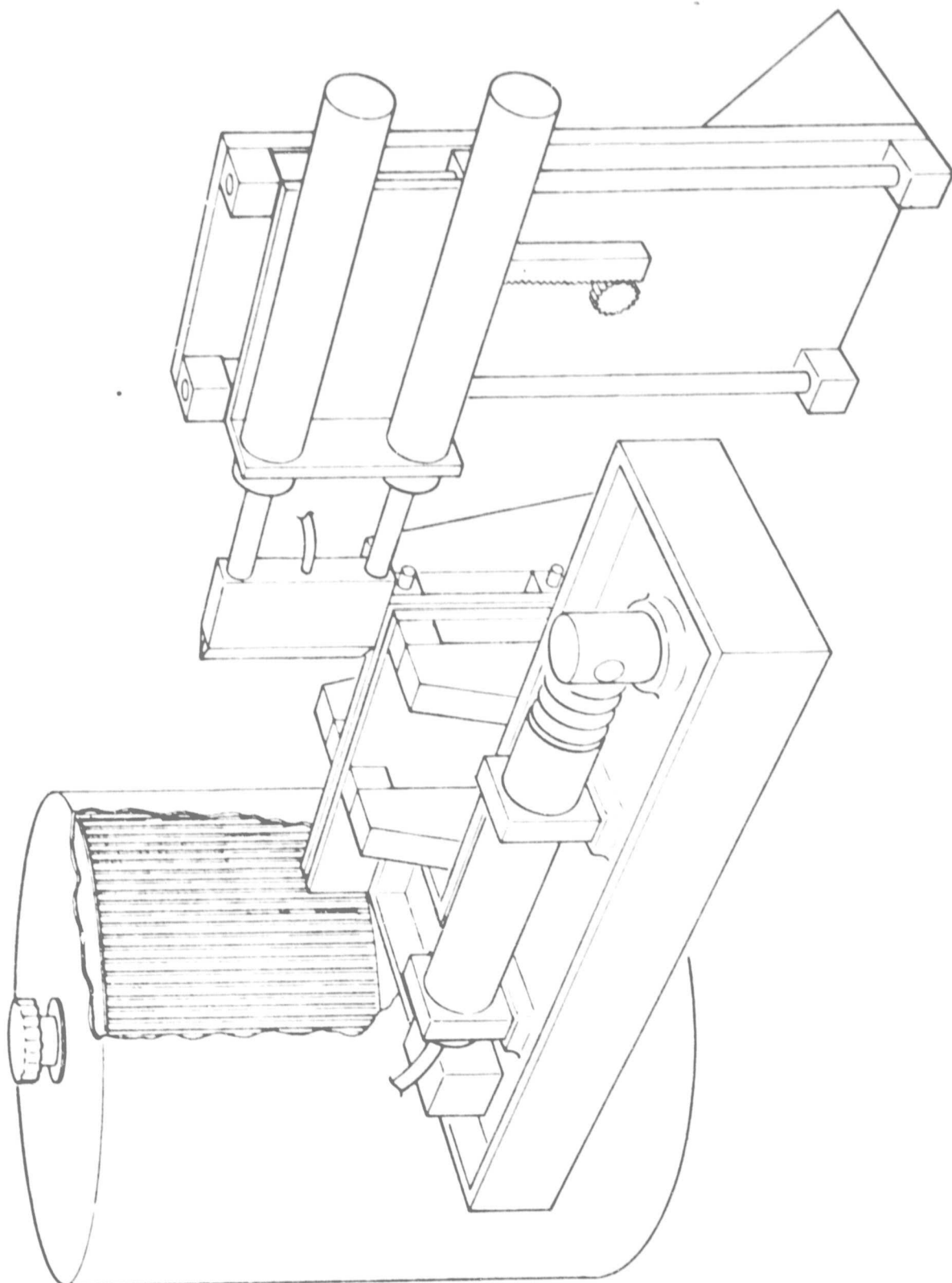


FIGURE 3-13 READER AND STORAGE AND RETRIEVAL MODULE

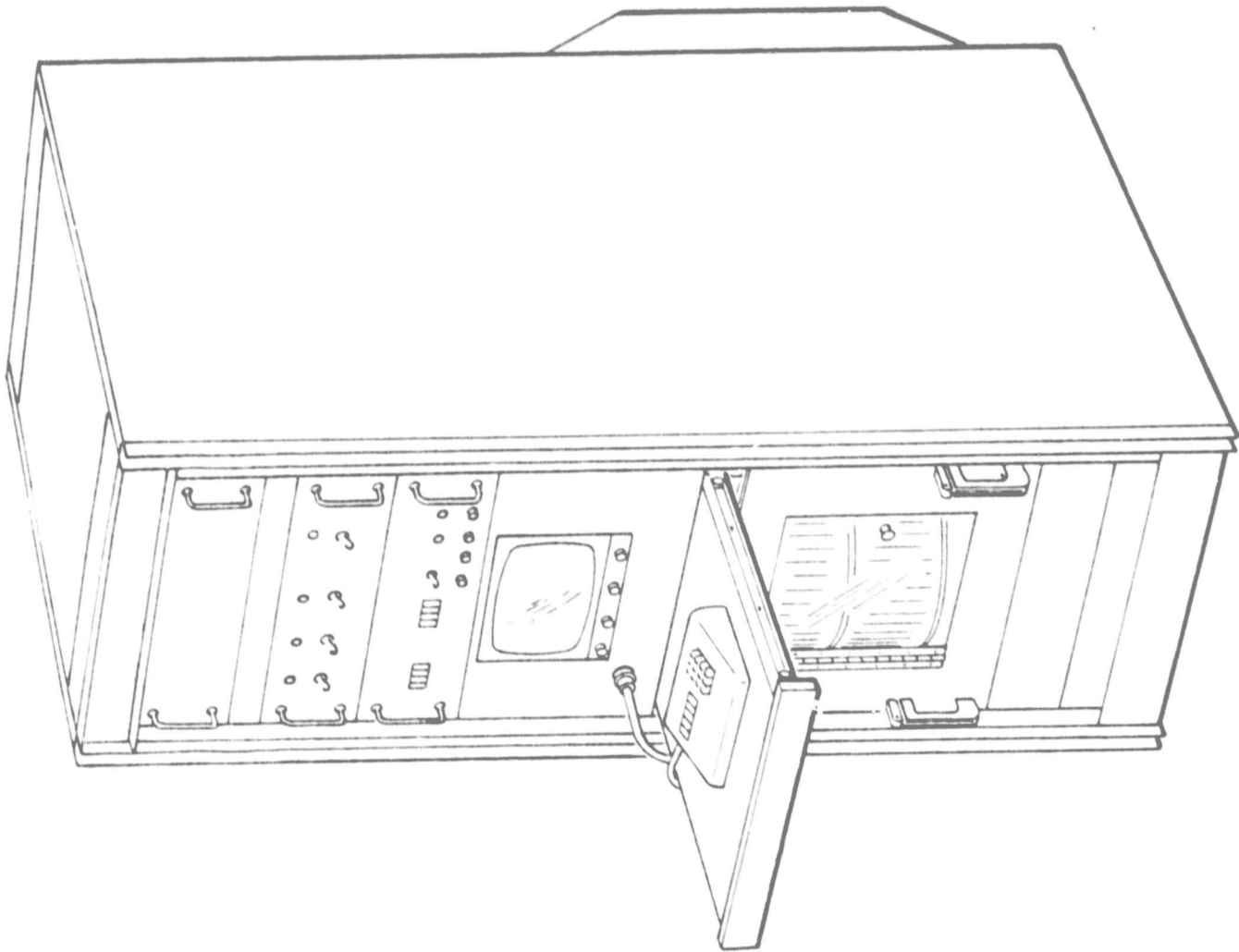


FIGURE 3-14 THE STORAGE AND RETRIEVAL CAROUSEL READER

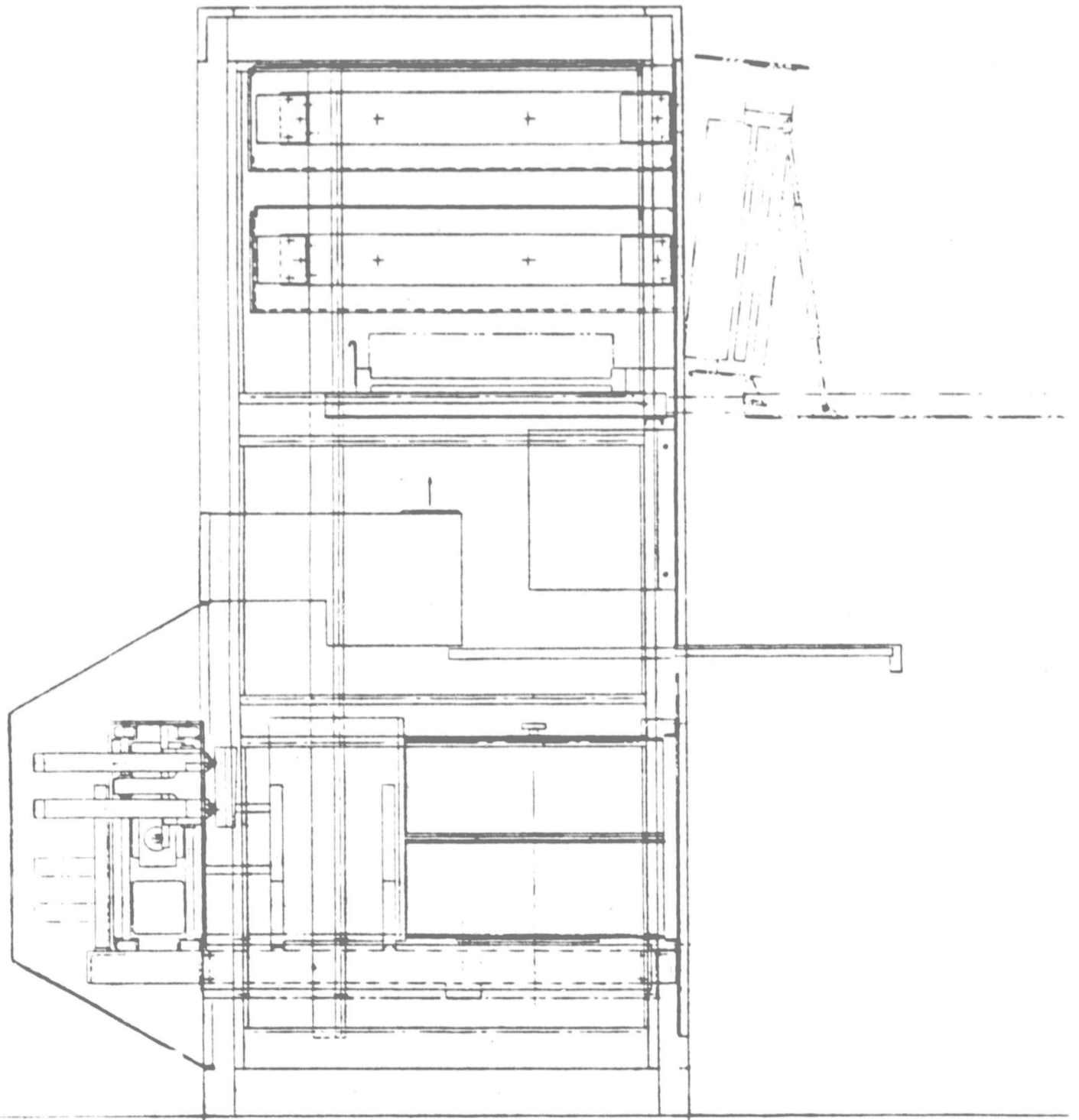


FIGURE 3-15 RACK DETAILS FOR STORAGE AND RETRIEVAL READER

APPENDIX A

OPTICAL MASS MEMORY RECORDING MEDIUM SPECIFICATION

(HARRIS PRINT CONTROL NUMBER 142716,  
REVISION 0)



## OPTICAL MASS MEMORY RECORDING MEDIUM SPECIFICATION

### 1.0 SCOPE

This specification shall cover the minimum functional and physical requirements of the material. These requirements shall be complete and to the level of detail necessary to reproduce the same material without recourse to the original manufacturer.

### 2.0 SPECIFICATION SUMMARY

The material shall have operational and performance requirements to allow it to perform as the optical recording medium for the Archival Mass Memory System for NASA's Marshall Space Flight Center.

#### 2.1 Dimensional Specifications

##### 2.1.1 Film format: 148 mm x 148 mm + 0.0 mm, -1.57 mm, die cut with rounded corners.

The radius of curvature of the corners shall be 1.57 mm, + 0.0 to -0.2 mm. A circular hole with diameter =  $6.35 \text{ mm} \pm 0.025 \text{ mm}$  shall be punched in the film. This hole shall be centered on the centerline of each dimension  $\pm 0.025 \text{ mm}$ . This specification shall hold at  $20^{\circ}\text{C}$  and 50% R.H.

##### 2.1.2 Squareness and Edge Straightness:

The squareness and dimensions of any given sheet of film shall be limited by two perfect rectangles, one made to the minimum dimensional tolerance specified, and the other to the maximum tolerance. No point on the perimeter of the sheet shall fall within the smaller rectangle, nor shall any point fall outside the larger rectangle. The areas removed during corner rounding shall not violate this test.

##### 2.1.3 Film Dimensional Stability:

Film dimensional stability effects shall be no greater than:

- 1) Processing dimensional change:  $\pm 0.01\%$
- 2) Thermal coefficient of expansion:  $\pm 0.002\%$  per  $1^{\circ}\text{C}$
- 3) Humidity coefficient of expansion:  $\pm 0.002\%$  per 1% RH
- 4) Aging size change:  $\pm 0.01$  to  $-0.02\%$  after 1 year  
 $\pm 0.01$  to  $-0.03\%$  after 10 years

- 2.1.4 Film Curl:  $\leq 0.178$  mm across the fiche in either direction  
( $\leq 0.3$  curl units\*) from 16<sup>0</sup> to 32<sup>0</sup>C, 40 to 55% RH.
- 2.1.5 Film Base: The film base shall be 7 mil +0.8 mil to -0.3 mil polyester coated on the back with an antihalation layer soluble during processing. The antihalation layer shall be  $\cong 0.5$  mil thick.
- 2.2 Film Sensitometry and Storage Performance
- 2.2.1 Maximum Density:  $\geq 3.00$
- 2.2.2 Minimum Density:  $\leq 0.10$
- 2.2.3 Contrast Ratio ( $\gamma$ ):  $\geq 3.0$
- 2.2.4 Exposure Sensitivity:  $E \leq 800$  ergs/cm to produce  $D_{max}$  for the required region of spectral response.
- 2.2.5 Spectral Response: Orthochromatic (400-530 nm) or panchromatic (400-640 nm); selectable by vendor.
- 2.2.6 Reciprocity Failure: Loss of less than 0.05D from a standard density of 1.0D for exposure times of 10 nsec to 100 nsec.
- 2.2.7 Latent Image Decay: The change in achievable  $D_{max}$  after exposure shall be  $\leq 0.2D$  for 30 minutes before processing.
- 2.2.8 Film Performance Consistency: There shall be  $< 5\%$  RMS variation in sensitometric characteristics within a single fiche or between any two fiche.
- 2.2.9 Processing: Wet processing by automatic machine using developer, stop bath, fixing agent, wash and dry stations. The processing time shall be no more than 2 minutes dry to dry.
- 2.2.10 Image Permanence: (Processed) There shall be  $< 5\%$  rms variation in sensitometric characteristics after exposure to 100W/cm white light for a total of 12 hours at 15<sup>0</sup> to 25<sup>0</sup>C, 40 to 55% RH.
- 2.2.11 Shelf Life: (unexposed) The material shall withstand storage for 1 year at 15<sup>0</sup> to 25<sup>0</sup>C, 40 to 55% RH with all sensitometric and dimensional parameters within the specification.
- 2.2.12 Image Archival Life: There shall be  $< 5\%$  rms variation in sensitometric characteristics after 10 years storage at 15<sup>0</sup> to 25<sup>0</sup>C, 40 to 55% RH.
- 2.2.13 Emulsion Type: To be selected by vendor (to be consistent with other specifications).
- 2.2.14 Emulsion Thickness:  $6 \mu\text{m} \pm 0.5 \mu\text{m}$
- 2.2.15 Film Acutance: The edge density gradient shall be  $\geq 200/\text{mm}$

\* A curl unit is defined as  $1/R$  where R is the radius of curvature in inches of the arc the film naturally assumes when under no constraints.

- 2.2.16 Film Frequency Response: The film MTF shall be  $> 75\%$  at 350 cycles/mm and the film resolving power shall be  $> 800$  cycles/mm when measured with a target with 1000:1 Test Object Contract (TOC).
- 2.2.17 Film Granularity: The film granularity shall be  $\leq 5$  ANSI granularity units when measured with a 6  $\mu\text{m}$  aperture on film exposed to a uniform density of 1.0.
- 2.3 Film Availability, Quality Control and Packaging
- 2.3.1 Material Availability:  $< 30$  days ARO
- 2.3.2 Material Packaging: The material shall be packaged 25 sheets per double light tight box. Film manufacturing date, quantity, dimensions, and emulsion type labeled on the box.
- 2.3.3 Quality Control: The film shall be inspected prior to packaging and shall have no more than 1 pinhole of maximum size 1  $\mu\text{m}$  per fiche. In addition, there shall be no more than 1 scratch of maximum size 1  $\mu\text{m}$  wide by 10  $\mu\text{m}$  long by 0.2  $\mu\text{m}$  deep and no more than 1 dig with maximum depth of 0.5  $\mu\text{m}$  per fiche.

3.0 APPLICABLE DOCUMENTS

The following references were used in the preparation of the specification. They are available from the issuing organization noted.

PH 1.51 (new), Draft proposed to the American National Standards Institute -

"Dimensions for Micrographic Sheet and Roll Films"

Ps-1, Kodak Corporation Photographic Products Catalog, 1978-1979

4.0 GLOSSARY OF TERMS

## GLOSSARY OF TERMS

Acutance - The objective measure of edge sharpness.

Archival Life - A measure of the post-exposure stability of a recorded image for a prescribed set of storage conditions.

Curvature - Curvature is a measurement of the deviation of the recording material from flatness. As a result, the film assumes an arc-like shape when under no restraints. Curvature is expressed in units of  $100/R$  where  $R$  is the radius of curvature of the arc in inches. Curvature has 2 primary causes: (1) differences in the dimensional changes of the base and the emulsion due to changes in relative humidity; and (2) plastic flow in the base when the polyester is wound in a roll and stored (core-set).

Dimensional Stability - Most thermoplastic substrates shrink or swell with changes in ambient temperature and relative humidity. Processing may also cause irreversible dimensional changes. The result is a shift in the location of recorded information.

Exposure Sensitivity - The exposure required to produce a prescribed absorption change for a given set of conditions. In industry this is generally defined for a density,  $D = 1.0$ .

Frequency Response - A measure of the difference between the recorded image and the input signal as a function of spatial frequency. Typically, the ratio of output to input density modulation is plotted as a function of spatial frequency; the resulting curve is called a modulation transfer (MT) curve. The ratio of output to input modulation is called the modulation transfer function (MTF). The objective measure of resolving power is the frequency at which  $MTF = 0.03$  (3%).

Graininess - The subjective impression of non uniformity in an image produced by the granular structure.

Granularity - An objective measurement which correlates with the subjective appearance of graininess. Kodak defined granularity numbers represent 1000 times the standard deviation in density produced by the granular structure of the material when a uniformly exposed and developed sample is scanned by a micro-densitometer having an optical system aperture of  $F/2.0$  and with a defined circular scanning aperture. Standard apertures are  $48 \mu m$  and  $6 \mu m$ .

Image Permanence - A measure of the inherent capability of the recording material to undergo extended data recovery at some prescribed level of readout irradiance without serious loss of information content or detectability.

Latent Image Decay - A measure of the change in the density resulting from a given exposure as a function of the time delay between exposure and development.

Reciprocity - The exposure required to produce a certain density equals the intensity of the light times the duration of exposure. In general, this is a constant over a broad range of exposure times, however, for very long (hours), or very short, (nanoseconds), exposure times the exposure required to produce a certain density may be larger than normal. This is the region of reciprocity law failure.

Resolving Power - A subjective measure of the finest detail a recording material can unambiguously record as a spatial variation of absorption.

Sensitometry - The experimental measurement of absorption changes as a function of exposure with processing and wavelength as parameters. For absorptive type materials the only measurable quantity is the intensity transmittance  $T_i$ , the ratio of transmitted to incident power. Defined quantities are  $D$  and  $T_A$ :

$$D = -\log_{10} T_i \quad 0 \leq T_i \leq 1 \text{ (Optical density)}$$
$$T_A = T_i \quad 0 \leq T_i \leq 1 \text{ (amplitude transmittance)}$$

Sharpness - The subjective measure of edge sharpness.

Shelf Life - A measure of the pre-exposure stability of a recording material for a prescribed set of storage conditions.

Spectral Response - A measure of exposure as a function of wavelength required to produce a given density. Orthochromatic spectral response implies exposure sensitivity in the blue-green region of the visible spectrum while panchromatic spectral response indicates some sensitivity to red light in addition to blue-green light sensitivity.