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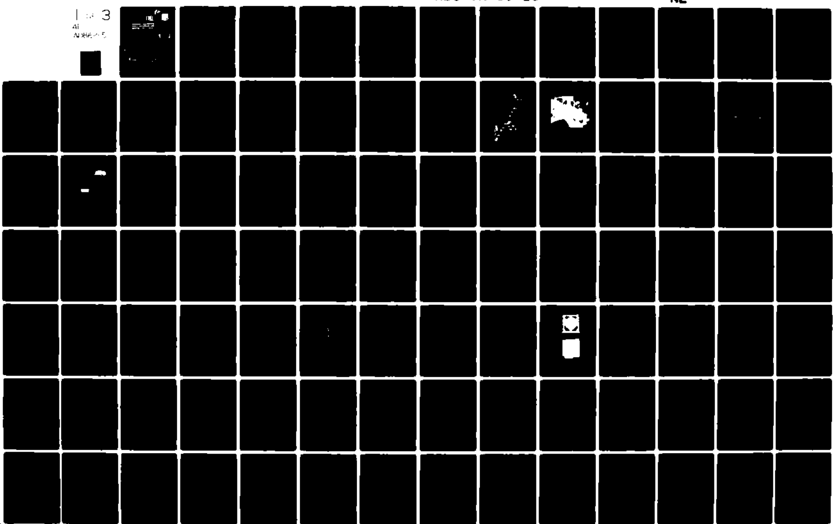

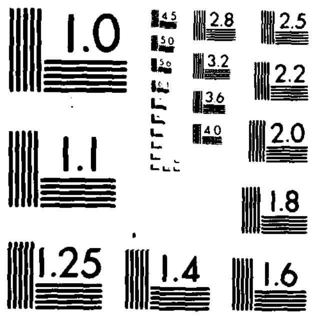
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This study effort evaluates potential improvements to the performance of the Wideband Recorder (WBR) system. These potential improvements are in the areas of bit error rate (BER), data packing density, and system optical power efficiency. Improvements to corrected BER which can be obtained by deeper interleaving of the recorded codewords are described and data from experiments simulating this process are documented. A potential data packing density increase from a modification of the intensity profile of the recording beam (Cont'd)

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is described and experimental results are presented. A reduction in raw BER which can be obtained by reduced data crosstalk is predicted, and the results of testing a new, low-crosstalk Acousto-Optic Page Composer (multichannel optical modulator) are presented. Finally a modification to the system's optical path which can reduce the optical power required for data recording is discussed.

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LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ABBREVIATIONS

AO	ACOUSTO-OPTIC
AOM	AO MODULATOR
AOPC	AO PAGE COMPOSER
BCH	BOSE-CHAUDURI-HOCQUENGHEM
BER	BIT-ERROR RATE
DC	DIRECT CURRENT
ECC	ERROR CORRECTION CODING
EDM	EXPLORATORY DEVELOPMENT MODEL
Gb/s	GIGABITS PER SECOND
Mb/s	MEGABITS PER SECOND
PN	PSEUDORANDOM NOISE
RF	RADIO FREQUENCY
SNR	SIGNAL-TO-NOISE RATIO
WBR	WIDEBAND RECORDER

PREFACE

This report was prepared by the Digital & Optical Processing Department of the Government Communications Systems Division of Harris Corporation. It documents the results of the technical effort in the fourth phase of development of a high-rate optical data recorder; the contract title is "Wideband Holographic Digital Recording and Reproduction (Phase IV)". This work was performed between September 1978 and September 1979.

The program manager was W. F. Quinlivan, Jr. The System Engineer and Principal Investigator was Dr. C. A. Shuman. The principal technical contributors to this report are L. M. Ralston and Dr. C. A. Shuman.

The publication date of this report is October 1979.

EVALUATION

The vast and varied command and control information available as a result of the evolution of high data communication and reconnaissance systems will cause gross changes in data management techniques.

The technologies exploited under this program offer the ability to accommodate input/output data transfer rates in excess of one (1) gigabit per second.

More specifically, the holographic recorder concept has demonstrated the versatility of accommodating full throughput read, write and expanded time base (slow down) capabilities of one (1) gigabit, 900 megabits, 600 megabits, 400 megabits and 40 megabits per second user data, digital data handling. Bit Error Rates of 1×10^{-8} using error correction schemes have been achieved at a packing density of 3.5 megabits per square inch.

This report culminates several years of RADC involvement in the development of this technology for unique applications in data handling and data management.

Albert A. Jamberdino

ALBERT A. JAMBERDINO
Project Engineer

SECTION I

INTRODUCTION

1.0 INTRODUCTION

This report documents the technical results of the FOURTH phase of a multiphase program to advance the state-of-the-art of wideband digital recording using holographic techniques. In this introductory section we provide a brief summary of the overall program goals, a synopsis of the accomplishments of the previous phases of the program, and a description of the organization of the report.

1.1 Program Goals

The basic objective of the Wideband Recorder (WBR) program is to develop optical techniques and hardware for the recording and playback of digital data at rates above 1 Gb/s. This is made necessary by the limitations associated with other, more conventional, data recording techniques. For example, much effort has gone into the development of electron-beam, laser, and magnetic recorders; however, currently reported results indicate that these technologies fall somewhat short of the rates required for today's highest-speed information systems. Furthermore, future increases anticipated in the rates required of high-speed recorders assure that the slower technologies will continue to require the parallel operation of multiple recorder units to handle the data rates. For many mission requirements, parallel operation of multiple recorders may be undesirable due to the problems associated with re-establishing bit-to-bit time integri y between machines during playback. Additional negative features of parallel recorder systems include tighter alignment requirements, diluted volume packing density capabilities, and machine-to-machine incompatibility of data records.

Optical holographic techniques offer attractive solutions to all of these problems. Distributed data storage inherent in the optical holographic format provides simultaneously the relaxed positioning tolerances needed for practical high-speed mechanisms and the relatively high packing density required for single recorder support of gigabit per second data rates. Additional advantages of multichannel holographic recording include reduced "bit dropout" from storage medium defects, relaxed mechanical tracking accuracy requirements due to holographic shift invariance, increased lifetime of stored data due to noncontact readout techniques, and full rate or greatly reduced playback capability resulting from the speed-independence of optical systems.

To exploit these attractive features of optical holographic data storage, Harris has undertaken a multi-phase development program involving experimental and analytical evaluations of the necessary technologies. This program has included both the design, fabrication, and testing of a system capable of recording and playback at raw data rates up to 750 Mb/s, and the investigation of the components and subsystems needed to extend that rate to 1024 Mb/s. The evolution of this system and the accomplishments of each phase of the development program are detailed in the following paragraph.

1.2 Program History

The Wideband Recorder program at Harris has progressed since 1971 through a feasibility study contract, Phases I and II (single contract), Phase III, and now the current Phase IV activity. A brief history of these contract activities is provided here, with a summary overview presented in Table 1.2.

On the Feasibility Study for RADC in 1971, Harris performed breadboard experiments to show that one- and two-dimensional digital (on-off) data patterns could be recorded as Fourier transform holograms on film with acceptable signal-to-noise ratios ($\sim$20 dB) in the recovered data patterns. A 15-faceted polygonal mirrored scanner was used to record and recover one-dimensional holograms along a scanned path on high-resolution silver halide film at equivalent rates above 100 Mb/s. The positive results of this activity led to a proposed design concept for an Exploratory Development Model; this proposal resulted in a single contract to Harris from RADC for a Phase I and Phase II, calling for 70,000 hours of engineering effort.

During the Phase I activity a tradeoff study, with supporting breadboard experiments with one-and two-dimensional hologram recording

TABLE 1.2

SUMMARY OF WIDEBAND RECORDER PROGRAM HISTORY

Program Phase	Dates	Key Events
WBR Feasibility Study (RADC)	1971	Demonstrated that 1-d and 2-d holograms containing digital data could be recorded on and recovered from film with acceptable SNR using a multi-faceted spinner.
Phase I WBR (RADC)	1973-74	Selected 1-d approach, completed EDM, and recorded at 400 Mb/s with readout at 40 Mb/s.
Phase II WBR (RADC)	1974-76	Upgraded EDM for 600 Mb/s (user) record and readout at 10^{-6} - 10^{-7} corrected BER.
Phase III WBR (-)	1976-77	Completed design for 900 Mb/s (user) record and readout, including design validation (Note: Planned experimental activity was cancelled by customer, largely because of reluctance to use silver halide film.)
Phase IV WBR (RADC)	1978-79	Performed EDM testing to develop hard design tradeoff data, installed and tested a new TeO_2 page composer to improve BER by about 2X, achieved a position of being ready to build a deliverable prototype WBR.

approaches, led to the selection of the one-dimensional approach because of somewhat relaxed mechanical precision requirements and greater availability of key components (e.g., the photodetector array and the scanner). The Exploratory Development Model (EDM) of the Wideband Recorder was then designed, fabricated, assembled, adjusted, and tested, leading in 1974 to demonstrations of 400 Mb/s recording and 40 Mb/s readout. Reduced rate recording and readout was also demonstrated.

The Phase II activity commenced immediately with the design of improved opto-mechanical layouts, key components, and control electronics. All upgrades were then incorporated into the EDM. In 1976 the upgraded EDM was operated at 600 Mb/s (user) record and readout rates (750 Mb/s total), yielding 10^{-6} to 10^{-7} corrected bit-error-rates. The Phase II EDM was also operable at reduced record and readout rates.

The Phase III activity called for the design of a 900 Mb/s (user) record and readout WBR system (~ 1.2 Gb/s total) based on the concept proven during Phases I and II. The original intent of the Phase III activity was to update the Phase II EDM to test all major revisions to key components and subsystems (especially the film transport and the page composer). However, before new components and subsystems were ordered, the customer down-scoped the original contracted effort by about 50%, leaving only the design and documentation tasks (no hardware updates with experiments). The main reason for this change in the customer's position was a reluctance to base an operating system on the use of silver halide film. Subsequently, RADC funded a study at Harris to test three specific electrophotographic film alternatives for WBR; this study program is in progress at the time of this writing.

The Phase IV activity (the program on which this report has been prepared) grew out of recommendations in the Phase III final report. The activities described herein for Phase IV were considered to be essential tests and EDM refinements to complete a base of tradeoff and design support data for any future prototype WBR system. The refinements are proven and all needed design support data is assembled; we are now in a position to design, fabricate, and deliver a prototype WBR system for up to 900 Mb/s record and readout rates.

1.3 Organization of the Report

Beyond this introductory section, this report is divided into four sections. Section II provides a description of the Wideband Recorder system and some of its key technologies. This description is brief, in keeping with the scope of the current contract and because this material has been widely distributed in previous reports. The reader interested in further description and more detailed analysis of the system's operation is referred to the Phase II and Phase III final reports (References I and 14), as well as the data published in the other references.

Section III contains a fairly comprehensive summary of the Phase III program. The Phase III final report, which was not widely distributed, is the source for nearly all of this material. The subsections of Section III are parallel to the major chapters in the Phase III report, and summarize their contents.

In Section IV we report on the technical results achieved during the current Phase IV program. Each area of experimental investigation is covered in a separate section, and the application of the new results to the overall system design is discussed.

Finally in Section V we describe some of the important tradeoffs which must be made when configuring a system for wideband recording. These are then related to the design choices made during the Phase III system design, and to some other systems which could be achieved using the technologies developed on the WBR program. The section concludes with a description of some of the technology areas in which further development would rapidly advance the capabilities of optical data storage systems, and with recommendations for the future.

SECTION II

SYSTEM ENGINEERING

2.1 The Wideband Recorder System - Introduction

2.1.1 System Functional Description

The fundamental approach to the problem of gigabit/second digital data recording taken by the Harris Wideband Recorder program involves the raster-scanning of holographically coded data onto reel-format photographic film. Figure 2.1.1-1 is a functional representation of the optical configuration required in this approach, while Figure 2.1.1-2 shows the actual hardware.

The optical path begins at the laser which provides the coherent light required for holographic recording. The beam-forming optics block represents those components that separate the beam into signal and reference beams. The signal beam is formed into a line source of light which illuminates a one-dimensional, multichannel page composer.

The formatting of high-rate data into 128 parallel channels, and the modulation of the data in those channels onto the optical signal beam are accomplished by the demultiplexer and the page composer. The demultiplexer (the feasibility of which was demonstrated by an earlier program) converts the high-rate, serial bit stream to 128 low-rate parallel

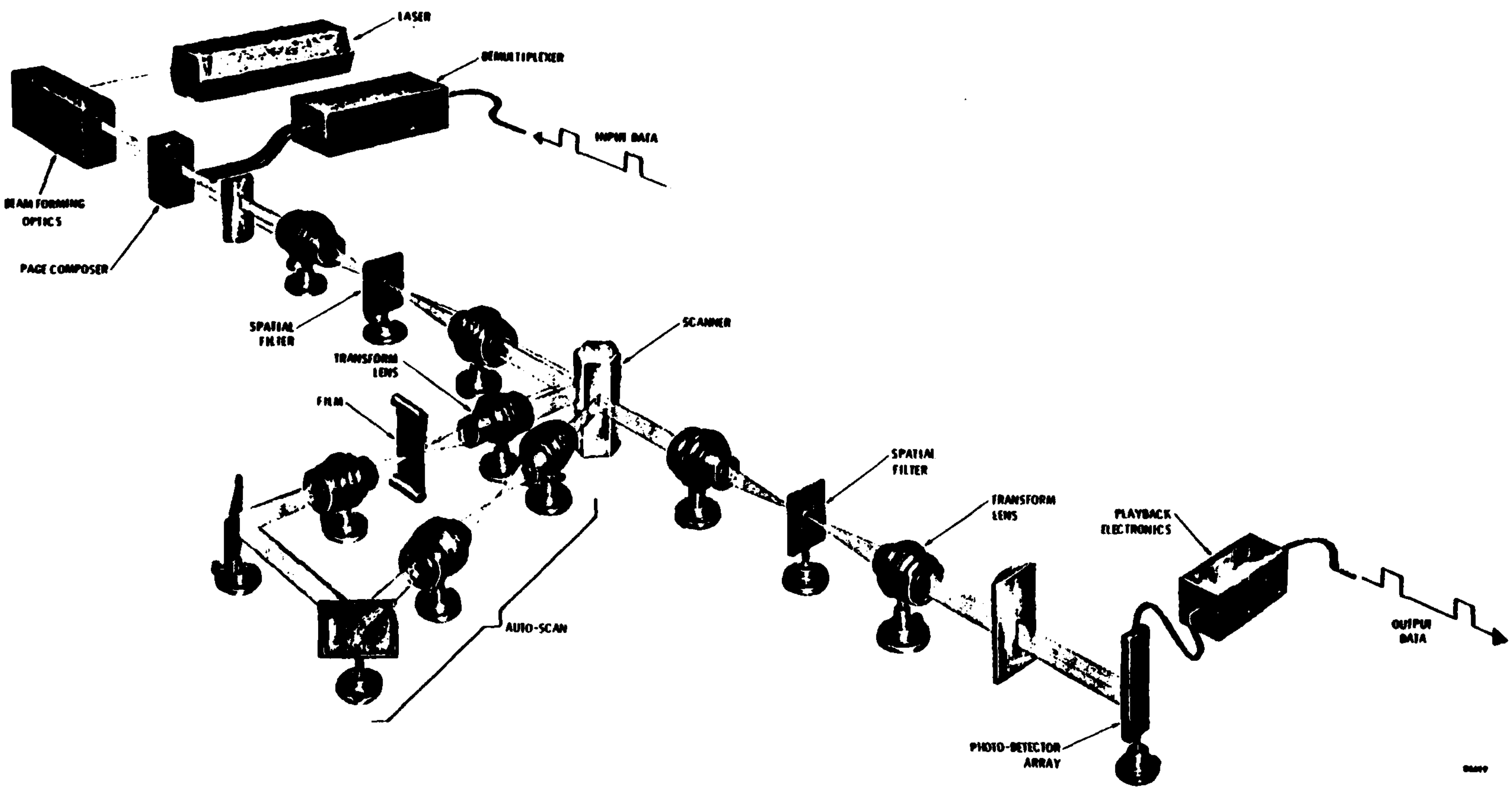


Figure 2.1.1-1. Wideband Holographic Recorder/Reproducer

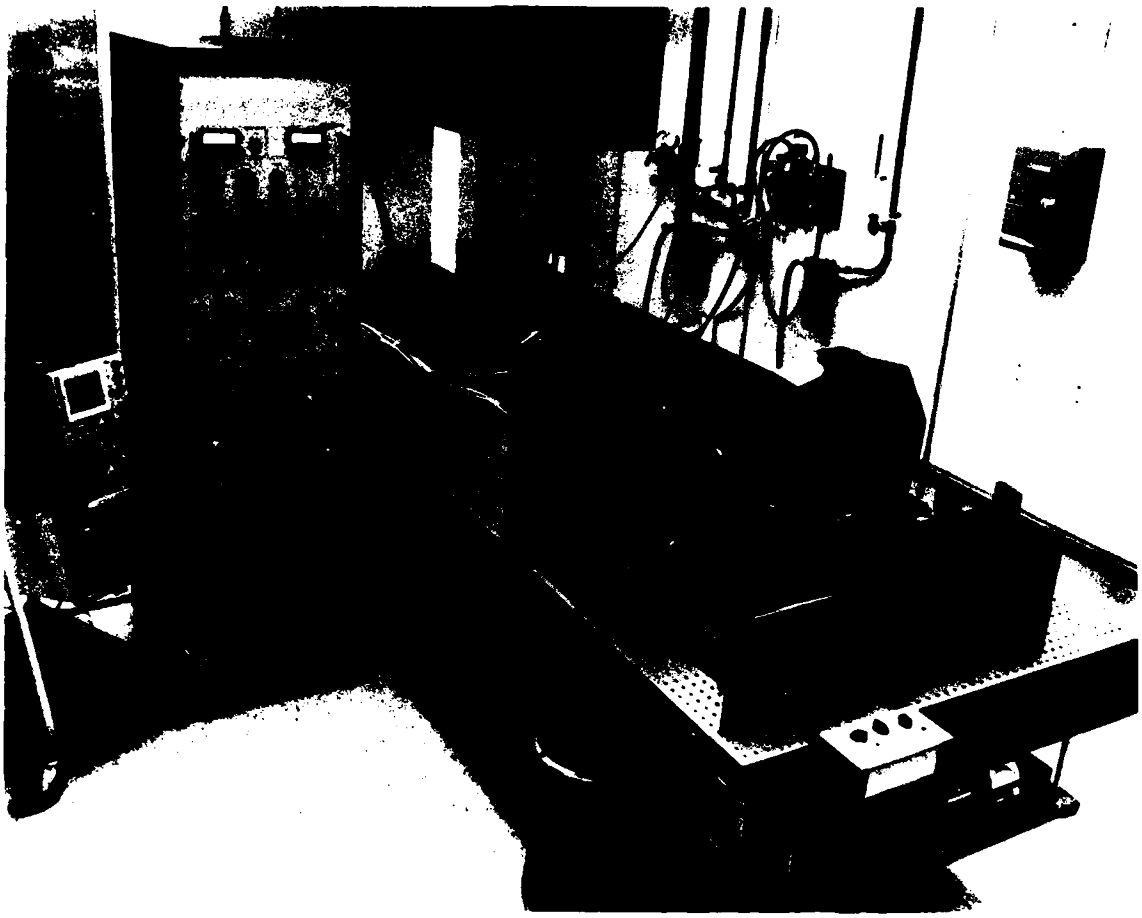


Figure 2.1.1-2. Wideband Holographic Recorder/
Reproducer Hardware

bit streams. These bit streams are modulated onto RF carriers and sent to the page composer, which is a linear array of 128 acousto-optic elements. The electrical energy is converted to acoustic waves within a glass crystal, so that when the light passes through the crystal, it is modulated by the acoustic waves to produce 128 optical data channels.

The next step is to produce the Fourier transform of the optical bit pattern at a spatial filter plane, where the reference and signal beams are brought together. Optical noise is removed at this stage, and the beam size is adjusted as required. To record the hologram, the light distribution at the spatial filter plane is imaged to the film by way of a multifaceted spinning mirror (the scanner). As the film is transported through the film plane, the beam scans laterally across it, recording rows of holograms.

After the film is developed, it is replaced in its original position and is illuminated by the reference beam. The holographically diffracted data is brought back to the spinning mirror by an "autoscan" arrangement. The second reflection from the moving mirror, removes the angular scanning motion so the data can be imaged onto a stationary detector. After the data is reflected from the moving mirror optical noise is removed at a second spatial filter plane and the data is imaged onto individual photodetectors by means of an array of fiber-optic elements (not shown in the figure).

Finally, threshold decisions are made on the detected signals and the resulting binary data is sent to verification circuitry to check the fidelity of the readout process. Remultiplexing of the data for playback in a single full-rate bit stream, while not implemented in the Phase II system, would be done at this point.

2.1.2 Data Storage Format

A clearer understanding of the advantages of a holographic recording system can be gained from a more detailed description of the format in which the data is stored on the film. Consider first Figure 2.1.2-1, where holographic and direct-spot recording formats are compared. In the spot recorder, the single optical beam is modulated at the full incoming data rate and then scanned across the film to record spots, each of which represents one bit of information. The holographic recorder instead separates the incoming data into a number of channels (at a proportionally slower data rate), and uses a multichannel modulator to produce multiple modulated optical beams. These beams, along with a single optical reference beam, are then overlapped at the film to produce the holograms (interference patterns), each of which represents a number of bits equal to the number of channels in the modulator array. The "side view" of Figure 2.1.2-2 shows how the overlap and later separation of the data channels is done. Each signal wave forms an interference pattern with the reference wave at the film, and each interference pattern has a

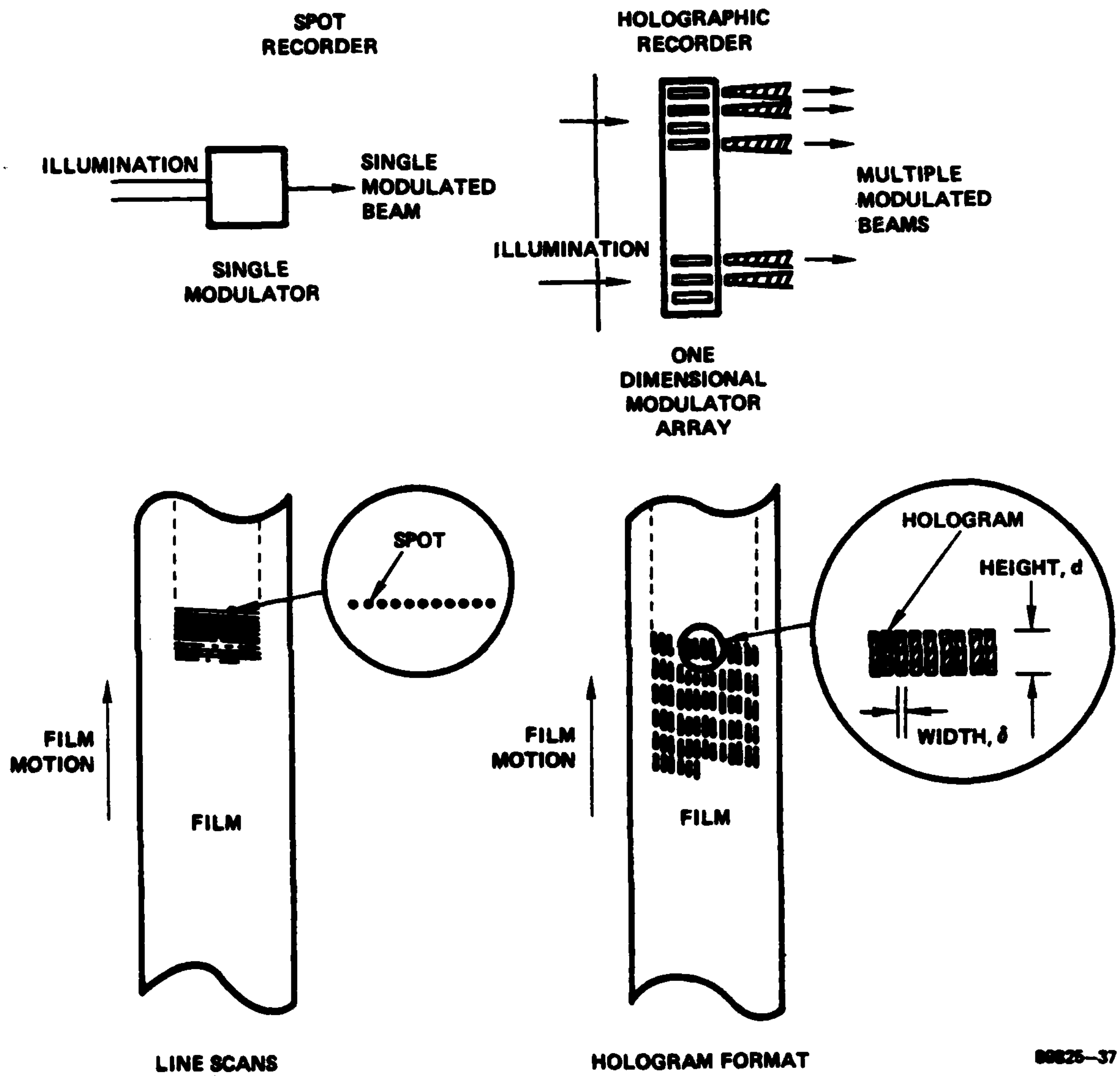


Figure 2.1.2-1. Comparison of Holographic and Direct Spot Recording Formats

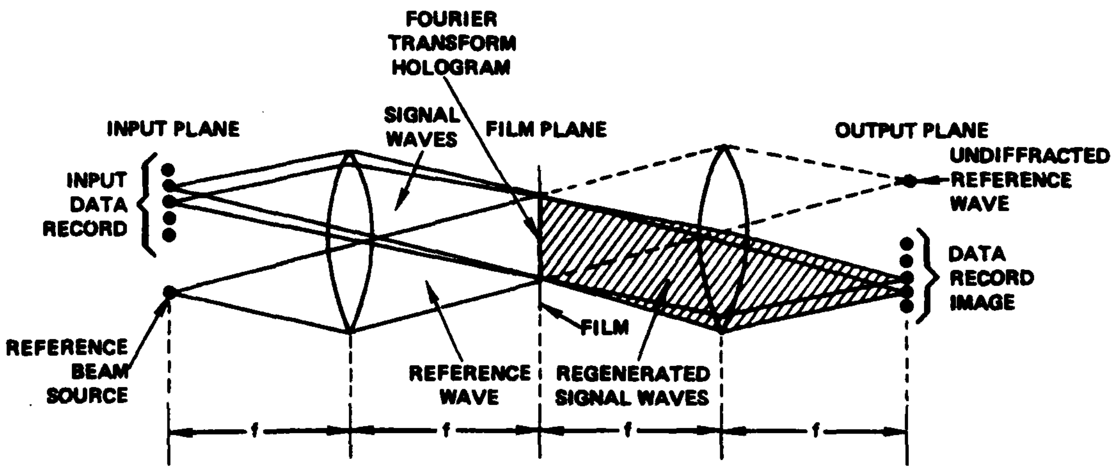


Figure 2.1.2-2. Holographic Recording and Readout

slightly different frequency since the various signal waves are incident at different angles. Thus, the hologram contains frequencies corresponding to each data channel that was "on" when it was recorded. For readout, the developed film is replaced in the film plane and reilluminated with a copy of the original reference wave. The various grating components of the hologram then diffract some of the reference wave at angles corresponding to their frequency. These regenerated signal waves, because of their angular dispersion, can be separated by the output lens and collected in the data image plane for detection and processing.

The storage format in which these holograms are recorded by the Wideband Recorder system is shown in Figure 2.1.2-3. The dimensions involved (hologram length, width, etc.) are important trade-off parameters affecting the system's packing density and bit error rate; specific trade-offs will be discussed below in Section V. As nominal values, we may say that the holograms are approximately 1 mm high by 15 μm wide, and that the film may be 35 or 70 mm wide and up to 3000 feet long (longer if the system design accommodates splices).

Additional details of the recording and readout process, as well as the specific data formatting and parameter values that were used in the Phase II system can be found in the Phase II Final Report (Reference 1).

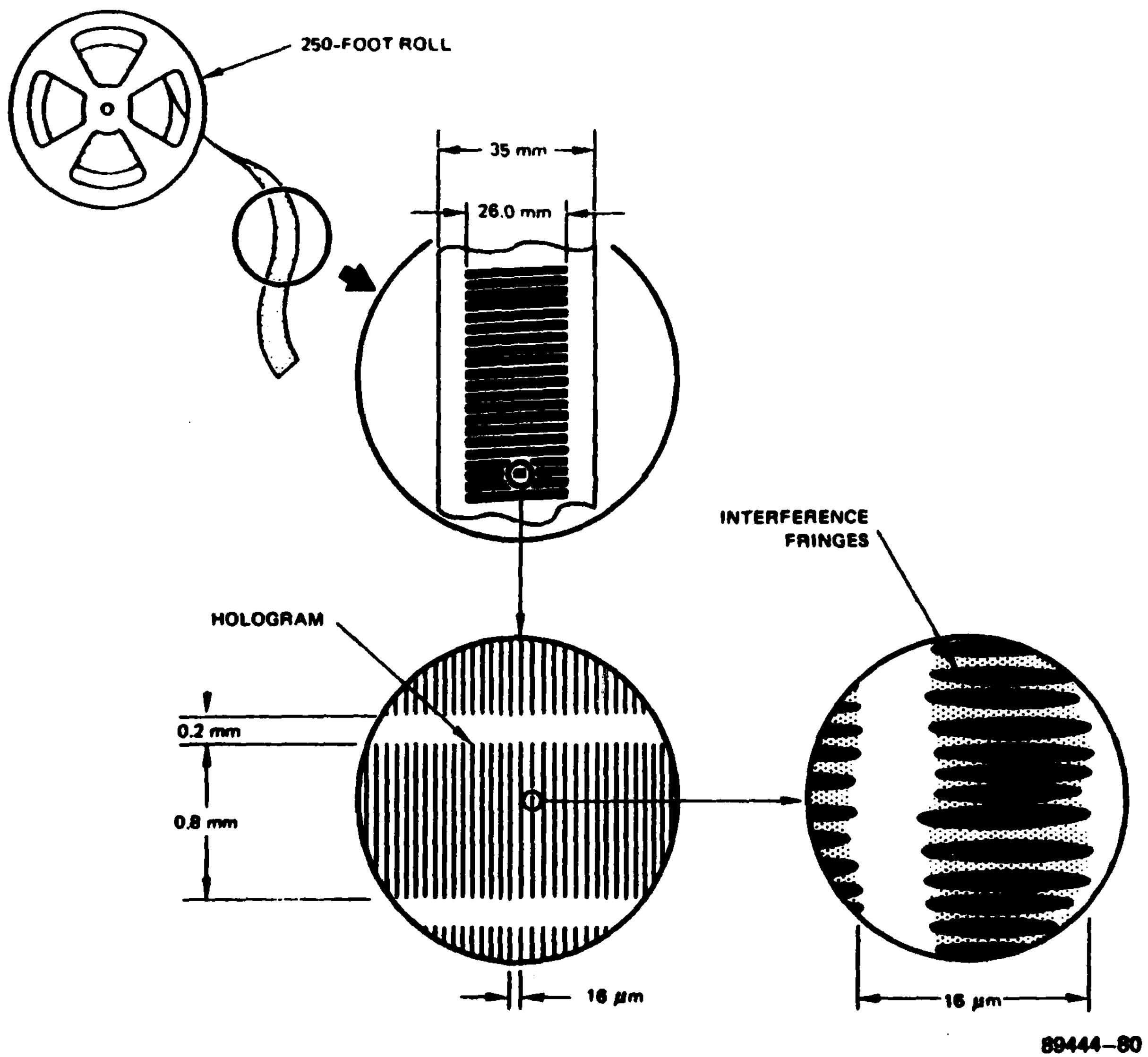


Figure 2.1.2-3. Holographic Storage Format

2.1.3 Acousto-Optic Devices

Acousto-Optic (AO) devices perform several important functions in the WBR system. These functions include (temporal) modulation, beam splitting, and page composition. The performance of the page composer, in fact, is so critical to the overall system that a page composer hardware development activity was included in the Phase III program, and is reported on below in Section III. Because of their importance to the system and to understanding its operation, we will now briefly review the operation of AO devices, and give some examples of their application to the Phase II and (projected) Phase III systems.

An AO device is a block of transparent material (various types of glass, for example) through which we pass the laser beam that we want to modulate or deflect. In the crystal, the light beam interacts with an acoustic wave. Devices used in the WBR system operate in the "Bragg" diffraction mode (see Reference 2) which produces two main output beams as shown in Figure 2.1.3. The undiffracted component has not interacted with the acoustic wave and is usually discarded, the diffracted component has interacted with the acoustic wave. Temporal modulation of the acoustic wave amplitude can be used to temporally modulate the amplitude of the diffracted light wave. Frequency modulation of the acoustic wave will produce an angular scan of the light wave, since the diffraction angle is proportional to the spatial frequency of the acoustic wave. The acoustic wave is introduced into the crystal by means of an electromechanical

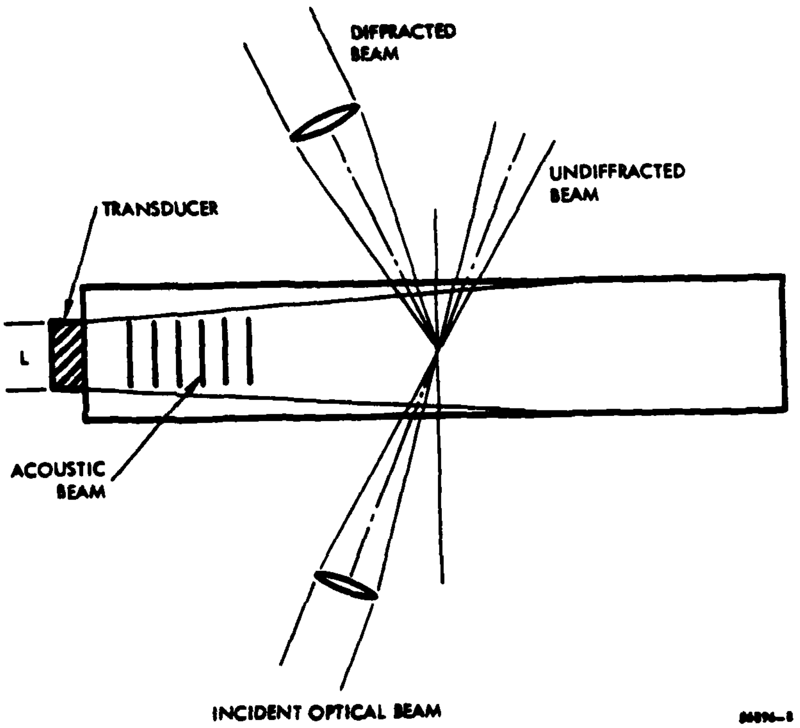


Figure 2.1.3. Details of Acousto-Optic Interaction

transducer bonded to one face of the crystal which in turn is connected to an appropriate source of RF electrical energy and associated control circuits for amplitude or frequency modulation.

Example 1 - Modulation

The transitions in light level which are used to record holograms and guardbands are produced by passing the beam through an AO modulator (AOM). High-rate recording requires that the rise time associated with these transitions be as short as possible. The rise time of a change in light level produced by an AOM depends on the time required for the acoustic waves to propogate through the optical beam which can be minimized by using a very small light beam. This is achieved in the main light-modulating AOM of WBR by focusing the beam inside the AOM (as in Figure 2.1.3).

Example 2 - Beam Splitting

To produce the two beams necessary for holographic recording, the WBR Phase II system used an AO beamsplitter. Since the signal to this device was constant, rise time considerations were not important. However because the light wave interacts with a moving acoustic wave, a Doppler-like frequency shift (equal in magnitude to the RF acoustic frequency) is induced in the diffracted light. Since holographic recording requires complete coherence between reference and signal wave, this frequency shift would ordinarily prevent such recording. To solve this problem, the WBR system uses the diffracted, frequency-shifted light as the reference beam, and uses the undiffracted light to illuminate another AO device, the page composer. Driven by the same RF source as the beamsplitter, the page composer imparts to the signal beam a frequency shift identical to that of the reference. Thus, coherence is preserved and interference can take place.

Example 3 - Modulation/Beamsplitting

The separate AO devices for modulation and beamsplitting described above worked well in the Phase II system, but the loss associated with the devices (each is about 50 percent efficient) was not negligible. An important simplification can be made to the Phase III system design to improve this situation: the use of a single beamsplitter and AO modulator. In this case, the AOM both provides temporal modulation of the reference beam and frequency-shifts it to correspond to the signal beam's page-composer-shifted frequency. The passive beam splitter/AOM combination provides improved light efficiency. Additional discussion of this new technique will be included in the Phase IV results reported in Section IV.

Example 4 - Page Composition

To produce simultaneously many optical channels of data, a multichannel AO device is needed. The operation of this device is essentially identical to the modulator described in Example 1 above. The AO page composer used in the WBR system has 128 channels arranged in a linear array. To minimize signal rise time, the line source of light is focused through the crystal. Further details of the construction and performance characteristics of the page composer, including test data of a new unit built during the Phase III activity, will be found in Sections III and IV.

2.1.4 Summary of Key System Features

The fundamental approach and storage format described above provide several important advantages over other types of digital data recording systems. These advantages are inherent in the method, and generally do not depend strongly on the particular system specifications chosen. We will now list some of these features and their impact on the system design requirements to be discussed in later sections.

- Multichannel Formatting of Data.

  By demultiplexing the high-rate data into many parallel channels (current systems use 128), the speed requirements of several electrical and mechanical subsystems are reduced. Examples include film transport and scanner velocities, and electronic and acousto-optic modulation bandwidths.

- **Raster-Scan Recording.**

  Scanning perpendicularly to the multichannel data dimension permits distribution of the data across a wide recording material (e.g., 70 mm film), further reducing film transport speed requirements.

- **Holographically Distributed Information Storage.**

  Since each bit is represented in the hologram by a relatively long (currently 1 mm) fringe pattern, small film defects, which would destroy several direct-spot-recorded data bits, merely reduce the readout signal level by a small amount; the probability of "bit dropout" is thereby reduced. An additional benefit of distributed information is that the system which reaccesses the hologram for data retrieval must accurately position the hologram with respect to the read beam only to within a fraction of the relatively large) hologram's size, rather than a fraction of a single bit location.

- **Holographic Shift Invariance.**

  In a Fourier-hologram recording system, the output in the data image plane (as in Figure 2.1.2-2) does not shift when the film moves vertically in the film plane.

This further reduces the "tracking accuracy" with which the film transport must position the hologram relative to the read beam.

- <u>Simultaneous Multichannel Recording.</u>

  By recording, and later reproducing, all channels simultaneously using a single recording medium, the temporal integrity of the data is automatically maintained, eliminating the "skew" problems featured in some other systems.

- <u>One-Dimensional Linear Array.</u>

  In addition to permitting the use of well-developed technologies in data formatting (for recording) and detection (for readout), the use of a one-dimensional linear data array can provide a simple method of making user-selectable packing density/bit-error-rate (BER) trade-offs. Specifically, hologram width, because it interacts with few other system parameters, can be varied over nearly a two to one range to shift emphasis from low BER to high packing density or vice-versa.

- <u>Photographic Recording Medium.</u>

  Other storage media may eventually become available which eliminate the only significant disadvantage of film (its processing requirement). Currently, however, it is the best choice for the WBR system. Once processed, film provides long-term archival storage and immunity to some environmental influences (e.g., shock, vibration, moderate temperatures, and magnetic fields) to which other media may be sensitive.

- Noncontact Read Capability.

  In a holographic data storage and retrieval system, nothing touches the film during readout except the laser light itself. There are, therefore, no read heads to be damaged or limited in lifetime; furthermore, the film can be read out many (i.e., several hundred) times without significant BER degradation.

- Speed-Independent Signal Level.

  Since the readout signal is an optical beam intensity (as modulated by each hologram), it is not dependent on the speed of readout. Thus, readout can be done at either high (i.e., full-record rates and vicinity) or low (e.g., computer-compatible) speeds.

- High Density Storage.

  An additional feature of high-resolution holographic film is its ability to achieve higher packing densities than most other storage media. Packing densities of nearly 15 Mb per linear inch of 70 mm film are currently being projected.

- Machine-to-Machine Data Record Compatibility.

  Some recording techniques have recording "signatures" or alignments which require readout on the same machine that did the recording. The reduced tracking and alignment requirements mentioned above make absolute (rather than relative) alignment specifications achievable in a Wideband Holographic Recorder system. This in turn makes possible the readout of the stored data at remote facilities on machines other than that used to record it.

SECTION III

3.0 THE PHASE III PROGRAM - A SUMMARY

3.1 Program Objectives

By the completion of Phase II, wideband holographic recording and playback had been successfully demonstrated at user data rates of 600 Mb/s with effective information packing densities 5 times greater than those of high-speed (e.g., 80 Mb/s) magnetic tape recorders and bit-error-rates better than 1×10^{-6}. Detailed technical results of these earlier phases are documented in report number RADC-TR-77-153, copies of which may be obtained through the National Technical Information Service (NTIS).

The THIRD phase of the program, the results of which are summarized in this section, constituted an 11-month experimental and analytical investigation into the feasibility of an operational 900 Mb/s wideband holographic digital recording and reproduction system (with a BER of 10^{-6} or better), and a design trade-off study to assess the technical risk and define the probable performance of such a prototype system.

The major program objectives of Phase III included:

- Advancement of the state-of-the-art technology of wideband recording and reproduction

- Establishment (experimentally and analytically) of the feasibility of developing a prototype 900 Mb/s recorder/reader that will meet operational requirements
- Further development of the technology required to enable the conceptual design and configuration of a 900 Mb/s prototype system
- Establishment of reliable subsystem/device and component/material sources (vendors) for future prototype procurement.

The accomplishment of these objectives represents a major step in the development of feasibility-model equipment into operational hardware, and provides an expanded baseline from which any one of several viable wideband recorder systems may be configured to match various operational requirements and scenarios.

3.2 Areas of Investigation

The final report for the Phase III program was divided into nine chapters, detailing the results of eight separate investigations and an overall summary. The following subsections of this report are condensed from the Phase III report to provide a full status update on the WBR program. The excerpts given here are necessarily abbreviated, therefore for technical details the interested reader should refer to the original Phase III final report.

3.2.1 Autoscan Subsystem

One of the goals of the Phase III activity was to investigate all areas of the system which would be affected by the wider film format projected for the follow-on system. The wider format (70 mm as compared to Phase II's 35 mm) will reduce both the film transport speed required for a given data rate and the film length needed for a given record time; some increase in data packing density will result from the width increase.

The group of components (multifaceted spinning mirror and transform lenses) known as the Spinner/Autoscan system is crucial to the wider recording format. The lenses which perform the Fourier transform and scanning operations must meet a complex set of specifications which interact with the parameters of the spinner unit.

The Phase II system, with its 40-faceted spinner and 80 mm focal length lenses, provided acceptable performance in terms of most optical criteria and extensive experience in designing and working with such a system. A few areas for potential improvement, such as spinner facet figure repeatability and lens distortion tolerances, were identified during Phase II, and considered during the Phase III study.

The main area of concern, however, was the need to produce lens and spinner designs which could satisfy the system specifications defined by the wider film format and be manufacturable using current technologies at an acceptable cost. The purpose of the Spinner/Autoscan task, then, was to perform trade-off evaluations of candidate spinner/lens combinations, and to obtain preliminary designs of these two critical components.

3.2.1.1 Task Organization

Initially the task was divided into four areas:

1. System Design. This was the initial analytical look at the family of viable Autoscan systems, from which several candidates were chosen for more extensive study.

2. Lens Design. This included the generation of a detailed specification for the transform lenses, and a (subcontracted) lens design activity to provide specific design parameters and feasibility recommendations.

3. Spinner Design. Similar to the lens design activity the spinner design was to provide (in coordination with the Lens Design task) detailed spinner specifications and an assessment of current manufacturability of such a spinner unit.

4. Autoscan Analysis. This was an analytical modeling of the entire Autoscan system (including all adjustments

and error sources) to aid in system tolerancing and provide data for writing a detailed alignment procedure.

Like many of the Phase III program tasks, the Spinner/Autoscan activity was affected by the changes in the program requirements/funding situation. Nevertheless, some significant results were achieved. Specifically, a set of preliminary lens designs were obtained which appear to meet all system goals and specifications. The associated spinners are similar enough to the Phase II unit that their producibility is not in doubt. Finally, the Autoscan analysis was completed through the linear-model stage, with some useful results.

In the following paragraphs we will summarize the results of this investigation.

3.2.1.2 Task Results

The results of the task, as fully documented in the Phase III final report, included: 1) detailed Spinner/Lens Design tradeoff calculations (including the areas of telecentricity, duty cycle, field size, external entrance pupil, field coverage, resolution requirements, aperture and focal length, spinner size, and spinner scan angle); and 2) computer matching of candidate spinner/lens sets.

To analyze potential spinner lens pairs, a computer program was written which produced matching spinner/lens sets for spinners of any number fo facets. The field size, resolution requirements, and external entrance pupil size and distance were the input parameters. Several spinner/lens pair candidates were developed from the computer program, and the manufacturability of the most promising pairs was investigated.

The manufacturer of the Phase II spinner (Speedring Systems) was contacted for an opinion on the feasibility of the candidate spinners. They indicated that the 45-facet unit would have to be attempted on an experimental basis, and the 36-facet and 40-facet units on a best-effort basis. However they expressed confidence that the 30-facet unit could be produced with a difficulty factor of only about 1.5 over the 40-facet Phase II spinner.

To determine if a corresponding transform lens could be designed a subcontractor (Optical Research Associates) was requested to begin lens designs to match the 30, 36, and 40-facet spinners. The important design considerations here are front and back focal plane clearances, input aperture, distortion, and wavefront quality.

As a result of the detailed design study, ORA, Inc. recommended one particular successful lens design, which is illustrated in Figure 3.2.1.2; its parameters are tabulated in Table 3.2.1.2.

3.2.1.3 Conclusions and Recommendations

As a result of this effort, it was determined that the manufacture of the components necessary for an Autoscan Subsystem capable

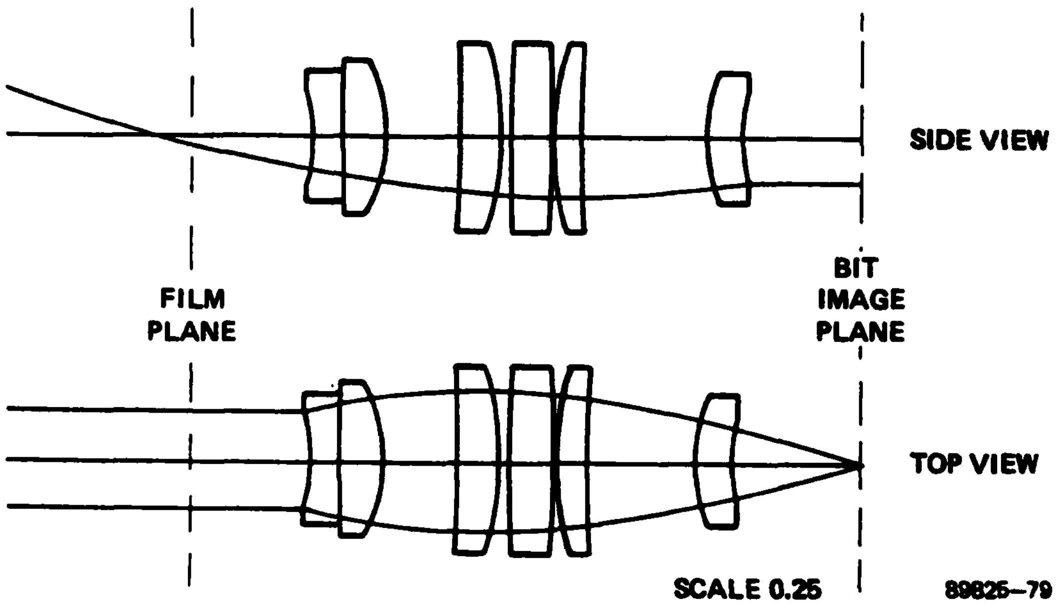


Figure 3.2.1.2. Preliminary Lens Design - Playback Mode, 131 mm EFL

Table 3.2.1.2 Design Characteristics of 131 mm EFL, 12°
6 Element Design

Characteristic	Goals	Design
Focal Length	131.0 mm	131.0 mm
Wavelength	514.5 nm	514.5 nm
Front Focal Plane Clearance	>60 mm	73.1 mm from lens ~60 mm from cell
Vignetting	None	None
Glass Type	Optional	SF6
Record Mode		
Input Aperture	14 mm x 52 mm	14 mm x 52 mm
Field Angle	±12.0 degrees	±12.0 degrees
Image Size	55 mm	55 mm
Image Displacement dh/dθ	f θ ±0.5% Constant ±2.0%	fθ ±0.38% Constant ±1.8%
Wavefront Quality	±.06 λ	±.05 λ
Wavefront Slope	.2 λ/mm	.10 λ/mm
Wavefront Parallelism	.13 λ	.10 λ
Playback Mode		
Input Aperture	55 mm x 2 mm	55 mm x 2 mm
Field Angle	±11.3 degrees	±11.3 degrees
Image Size	69 mm	69 mm
Image Displacement	Constant ±2%	Constant ±1.5%

Table 3.2.1.2 Design Characteristics of 131 mm EFL, 12°
6 Element Design
(con't)

Characteristic	Goals	Design
Wavefront Quality	$\pm.03\ \lambda$	$\pm.01\ \lambda$
Wavefront Slope	$1.00\ \lambda/mm$	$.25\ \lambda/mm$
Wavefront Parallelism	$.67\ \lambda$	$.28\ \lambda$

Table 3.2.1.2

of supporting the use of 70 mm film in the WBR system is feasible. Furthermore, the preliminary design indicates that the performance of the wide-format system can equal or exceed that of the Phase II autoscan system in all areas.

Several areas remain to be investigated which may ultimately help reduce the cost and alignment complexity of the system. Optical Research Associates suggested that the recurring lens cost may be reduced through the use of less expensive optical glasses and/or the elimination of one of the lens elements at a slight sacrifice in performance.

ORA's work has also shown that a 15° scan lens may be possible, an unexpected result. This wider scan angle could be used to reduce the spinner to a 24 faceted design which would significantly reduce its cost. Alternatively, the increased scan angle could be applied to achieving a field width beyond the 55 mm value providing some modest additional gains in packing density.

Finally, the autoscan analysis (not included in this summary) has been successful in modeling the system output to first order. It is recommended that any future effort carry the analysis to completion, generating sensible mechanical and optical design tolerances for the readout system, as well as a complete (and very probably simplified) readout system alignment procedure.

3.2.2 Film Transport Subsystem

One of the most significant changes in performance specifications contemplated for future systems is the increase in continuous data recording time from the previous (Phase II) value of about 15 seconds to a total of around 20 minutes. At a data rate of 900 Mb/s, this means that the data storage medium must have a capacity of over 1.0×10^{12} bits. We have seen in the previous section that the film width can be successfully increased to 70 mm; nevertheless, a record time of 10 minutes will require 3000 feet of such film, even at the increased packing density values achieved during the Phase III study.

At the beginning of the Phase III effort, obtaining a workable film transport concept seemed a formidable undertaking. Packing densities current at that time, combined with incomplete data format information, indicated that film lengths of 12,000 feet and operational speeds up to 3.1 meters/second would be required. During the course of the program, however, increased packing density and new data format information reduced these requirements to 3000 feet and 1.6 meters/second, putting the system well within the scope of current film manufacturing and film transporting technologies. Major changes to the Phase II film transport were still in order, but the task was more tractable.

The Film Transport Subtask, as originally envisioned, included generation of transport specifications, vendor survey, and subcontracted fabrication of a deliverable breadboard film transport subsystem. This would have demonstrated that this key element in the Wideband Recorder system was developed to a level appropriate for inclusion in the projected deliverable prototype (Phase IV) hardware. However, during the change in the Phase III program scope which occurred near the program midpoint, the fabrication task was eliminated.

In this section we will report on the results which this investigation had achieved at the time it was curtailed.

3.2.2.1 Film Transport Design Considerations

The storage capacity of a recording system is usually related to the surface area of the recording medium. Rapid access to a large surface area, as is required for high speed or high capacity memory systems, requires rapid transport of the storage medium past the record/read station. The current WBR requirements make it both a high speed (900 Mb/s) and high capacity (5 or 10 x 10^{11} bits) machine. Therefore, it will require a fairly sophisticated film transport mechanism to move the storage medium. In this paragraph we provide a summary of some of the considerations which (based on Phase II experience and future requirements) are critical to the design of the Film Transport Subsystem.

3.2.2.1.1 Film Dimensions

The film dimensions affect the film transport requirement in several areas. The reel inertia which is determined by the total mass of film that must be transported and the reel dimensions must be taken into account when the drive system (motor torque, etc.) is designed; start/stop time requirements are also affected by the reel inertia. For long film lengths, the film surface characteristics must be considered in conjunction with the acceleration requirements to define a radially programmed tension profile which will eliminate film slippage during acceleration or deceleration. If the start/stop requirements and the feasible acceleration profiles are not completely in accord, consideration of slack boxes or other inertial isolation devices will be necessary.

The increased width recommendations generate additional areas of concern. Film flatness in the focal plane must be maintained over the operational scan width. Wide films require more than ordinary care in the edge-guiding and support areas; the controlling parameter is the film's width to thickness ratio.

Reducing film thickness can help to minimize reel size and inertia. Thin films, however, require more sophisticated techniques to ensure adequate lateral tracking performance. Minimization of aerodynamic effects is also important for thin-base films.

3.2.2.1.2 Transport Speed Requirements

Maintenance of a high film speed once achieved is usually not difficult; inertia smooths the transport operation in that situation.

Attaining the required rates within the specified start/stop times, however, places stringent requirements on the torquer motors used to drive the transport; film slack takeup is also important.

In the WBR system, record and readout speeds are required to be the same, with slower readout speeds also available; thus the dynamic range of the readout system must be considered. Other operational modes which may be required for a WBR-type transport system include: rewind (or fast forward) speeds which may be substantially faster than the actual record and playback speeds; and hold mode operation, in which zero velocity with specified position holding tolerances must be achieved.

3.2.2.1.3 Readout Servo Requirements

To successfully readout the rows of holograms recorded on the film, the film transport must align each successive row (at the full readout rate) with the scanning readout reference beam. To do this, a row of timing marks, recorded on the film during recording, generates a signal which is used to phase-lock the film transport to the spinner (which generates the scanning beam). The design of the servo system which performs this function is critical to the film transport's operation. The allowed tolerance which controls the amount of misalignment between the scanning beam and the hologram rows, must be as small as possible to minimize the guardband space needed between rows (and hence increase data packing density).

The favorable effect of inertia in smoothing the transport's operation mentioned above can help achieve the required servo precision at the higher readout speeds. At low speeds, the servo design is generally more difficult; thus the required dynamic range of the readout system is an important design consideration.

3.2.2.1.4 Read Head Considerations

The design of the transport as it affects data readout is of course critical. The film must be maintained in the focal plane of the scanning lenses to a tolerance which is less than the depth of focus of the system in order for the read beam to remain small enough at the film to address the individual holograms. The film width over which this flatness must be maintained is a consideration; the Phase II system achieved excellent results over a 35 mm film width using a dual-sided air-bearing platen.

The position of the read beam must also be precisely aligned with the beginning and end of each hologram row; thus, the transport must limit the lateral wander of the film at the read (and record) station to some minimum. The lateral tracking capability determines the width of the required over scan, and therefore has a (small) impact on packing density. A larger consideration is that machine-to-machine compatibility of the recorded film spools (which is not a feature of other types of high-speed recorders) is possible if the lateral tracking tolerances are held to a minimum.

3.2.2.1.5 Additional Design Considerations

Some other areas are important enough to deserve mention in this summary. The preservation of film surface quality is crucial to maintaining a low system bit-error-rate. Any degradation caused by the transport's rollers, air platen, or acceleration effects can be damaging; Phase II experience showed that these can be avoided in a 35 mm WBR system; effort must go into designing the next transport to provide similar performance.

Some auxiliary marks must be placed on the film during the recording process. The sync marks which are used for phase-locked readout have been mentioned; another auxiliary mark required for almost any system application is an ID track for locating data blocks or other subdivisions within the film's length. These and any other required auxiliary marks must be generated and recorded on the film by the Film Transport Subsystem. One design consideration is that the sync marker record station should be as close to the hologram record station as possible to minimize the effects of film dimensional stability tolerances on the data/sync phasing.

Vibration is a potential problem when a large mass of film is accelerated. WBR, because its hologram exposure time is so short (of the order of 50 ns for the follow-on program), is not as sensitive to vibration as other holographic systems; nevertheless, good design practice requires some sort of mechanical isolation between the accelerating film and the recording station. This will minimize the stresses on the optical alignment and laser light source during system operation, thereby increasing the time between system maintenance and alignment procedures, etc.

Operational procedures should also be considered in a film transport's early design phase. Loading and unloading in room-light environment, bulk film spooling and formatting procedures, film threading techniques, splicing and splice handling procedures (if required), all should be included as important design considerations.

Finally the interface and control capabilities and requirements of the Film Transport Subsystem must be considered, especially in a fully operational recording system. In all likelihood, such a system will operate under the control of a preprogrammed microprocessor, and the transport must therefore be designed to respond to the commands input to it by the automatic control system, while maintaining its capabilities for manual operation during maintenance, loading, etc.

To conclude this paragraph, it is appropriate to note that all of the design considerations (potential problems, areas of concern, etc.) described above, as well as a number of others, were successfully implemented in the Phase II transport system. And although the film dimensions were considerably different than those contemplated for the next system, the experience gained from the Phase II transport greatly enhances the probability of solving these problems in future systems.

3.2.2.2 Vendor Survey and Selection Procedures

3.2.2.2.1 Introduction

Due to the anticipated system requirements of handling 3000 foot lengths of 70 mm wide film on 2.5 mil support at 1.6 meters/second record and read speed and 3 meters/second slew speed, an entirely new transport design was needed. The only part of the existing film transport system that was usable was the air platen, and it was not known how much improvement could be made in that area. Since many companies have already done extensive work in film transport design, it was decided to subcontract the design of the film transport subsystem.

3.2.2.2.2 Statement of Work

The Statement of Work for the film transport subtask was written recognizing Harris' limited knowledge of industry's capabilities in precision film transports. The task funds appeared sufficient to purchase a complete film transport if one were available off-the-shelf, but were probably not sufficient to fund development and construction of even major subsystems if an advancement in the state-of-the-art were required. Therefore, the Statement of Work was written to require best effort solutions to those problems requiring specialized knowledge beyond that of Harris engineering, while keeping in mind the rest of the subsystem requirements and its relationship to the Wideband Recorder. The problems to be addressed in detail were:

1. Supply and take-up spooling, including servo motor and drive, winding tension profile, and inertia isolation. Solution was to include detail design and all calculations.

2. The capstan drive, including rate and dynamic position accuracy. Solution was to include detail design, all calculations, and demonstration of breadboard model.

3. The film platen. The platen was required to hold the film flat, at record and playback speeds, without scratching the film at any speed. Also, the platen must have several degrees of freedom in adjustment, easy access for maintenance and modularity to permit design evolution. The solution was to include detail design and demonstration of a breadboard model, in conjunction with the capstan demonstration.

3.2.2.2.3 Vendor Contact and Results

Using inputs from RADC, Harris Purchasing, and Harris Engineering, a list of possible vendors was developed. After preliminary telephone conversations with each vendor, a request for a proposal and an accompanying Statement of Work was sent to each vendor. Four of the eight vendors contacted elected to bid to Harris requirements.

The proposals received from the four vendors were quite similar, generally involving about a dozen pages specifically addressing the Harris problem. The proposed solutions ranged from barely adequate to quite competent, and a broad range of related experience (or lack thereof) was shown. A disappointment is that none of the vendors recognized that the principal problem in the supply and take-up reel servo design is that the interaction between the winding tension profile and the film interlaminar friction limits the acceleration of the reels to a level which will not cause cinching. This affects everything, including the inertia isolation devices (slack boxes, etc.). A few weeks after receipt of the first proposal, Harris received an unsolicited proposal from one of the vendors, offering to extend the scope of the first proposal to include a breadboard of the entire film transport. Since the total dollar amount for this extended effort was still within the Harris budget, the up-scope was accepted.

The Statement of Work and the results of the vendor survey were presented at the Preliminary Design Review. Criticism was expressed about the narrowness of the scope of the effort, even though three of the four bidders were at the limit of the budget. In addition, the mission was more explicitly defined, allowing decreases in certain of the specifications, but requiring a full subsystem breadboard as an option. A re-bidding procedure was then undertaken. The highest bidder was excused from the bidding while the lowest bidder, who had already bid a full breadboard to the original specifications, decreased their bid slightly. The two remaining vendors increased their bids dramatically. Harris then presented the low bidder as the only viable choice. At this point the Phase III program was descoped, and all film transport activities were terminated.

3.2.2.3 Summary and Conclusions

The change in program funding clearly had a major impact on this subtask. Since no breadboard film transport was built, this remains as one of the few WBR subsystems without concrete evidence to support the feasibility of producing a system which meets future requirements.

The increase in packing density and modifications to the baseline system configuration that took place during the program have reduced the transport requirements from those specified initially. In addition, the considerable work done by Harris and the four competing vendors has (at least) served to produce a fairly firm preliminary design.

As presently envisioned, the film transport consists of two major structural elements: the reel assemblies and the capstan/platen assembly. The capstan/platen assembly is mounted firmly to the optics bench to preserve alignment, while the reel assemblies are isolated to keep vibration from the reel motors from coupling into the bench. Vacuum columns with air bearing turn-arounds are also attached to the bench. The capstans are urethane coated with no opposing pinch rollers. The film makes a 180° angle of wrap around the capstans and then around turn-arounds. The capstans are differentially driven from a single motor using a taut mylar belt. The differential action of the belt creates an accurate, calculable tension in the film between the capstans, regardless of the direction of motion. The platen is a two-sided air bearing platen with a polished chrome finish and discrete air holes. The reel drive uses direct drive printed circuit motors with fail-safe (spring applied) brakes. The capstan uses a Type II servo with position and velocity loops, and the reel motors are servoed to sensors in the vacuum columns. A conceptual illustration of the preliminary transport concept is given in Figure 3.2.2.3.

Finally, our recommendation is that film transport development be emphasized prior to or early in the deliverable system design activity. Preferably, a subcontracted deliverable breadboard film transport should be obtained and its performance evaluated in terms of the issues and considerations presented in this section.

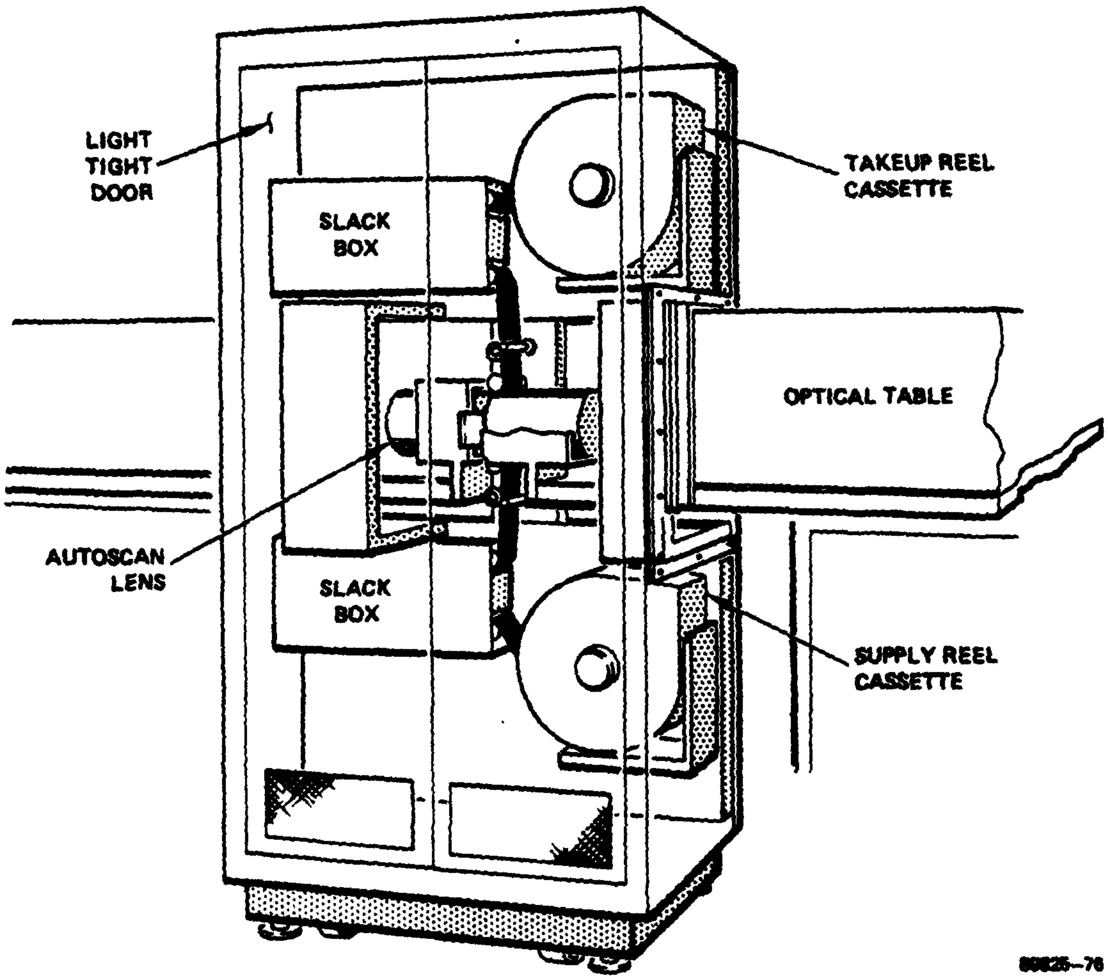


Figure 3.2.2.3. Conceptual Illustration of Film Transport Subsystem

3.2.3 AOPC/RF Subsystem

During the Phase II program, the technical performance of the Acousto-Optic Page Composer (AOPC) system (the Page Composer and its associated RF drive circuitry) was identified as one of the factors limiting overall system performance. Diffraction efficiency, which impacts the system light budget, and channel-to-channel crosstalk, which increases the system's minimum raw bit error rate, were particularly important. For this reason, the Phase III study included an activity to design/fab/test an improved AOPC/RF subsystem.

The original program plan called for the production and testing of an integrated AOPC/RF subsystem, with all specifications intended to apply to the subsystem as a whole. Changes in program funding, however, prevented the integration activity from being completed; this section, therefore, contains separate reports on the fabrication and testing of the AOPC unit and the RF drive electronics.

As we begin the description of the results of this investigation, we should point out that an Acousto-Optic Page Composer is frequently a useful part of other systems (direct-spot recorders, data processors, array scanners, etc.); thus, the achievements reported below are of interest to the wide range of optical storage and processing applications which they can support.

3.2.3.1 Acousto-Optic Page Composer Investigation

3.2.3.1.1 Design Goals and Specifications

The complete list of design goals and specifications for the AOPC/RF subtask is documented in Item 6 of the WBR Phase III Project Work Authorization; an excerpt from that list containing all the key items applying to the AOPC unit itself is reproduced below.

1.	Number of contiguous operating channels	32
2.	Transducer size	100 µm
3.	Center-to-center channel spacings	250 µm
4.	Rise Time (10% to 90%) of the optical flux with 90 m beam size	25 ns maximum with the design goal of achieving 18 ns maximum
5.	Diffraction efficiency with 200 mW drive power	50% minimum
6.	System crosstalk isolation	20 dB minimum with design goal of achieving 30 dB minimum
7.	Channel-to-channel deviation (time invariant)	±1.5 dB maximum
8.	Optical transmission at 0.514 m	92% minimum
9.	Center frequency nominal	150 MHz
10.	Material	TeO_2
11.	Beam position from the transducer surface	250 µm to 600 µm
12.	Clear aperture (measured from the transducer surface)	50 to 3000 µm
13.	Temperature range (ambient)	23°C ± 5°C
14.	Thermal interlock range	To be specified
15.	Expandable number of channels	128 minimum

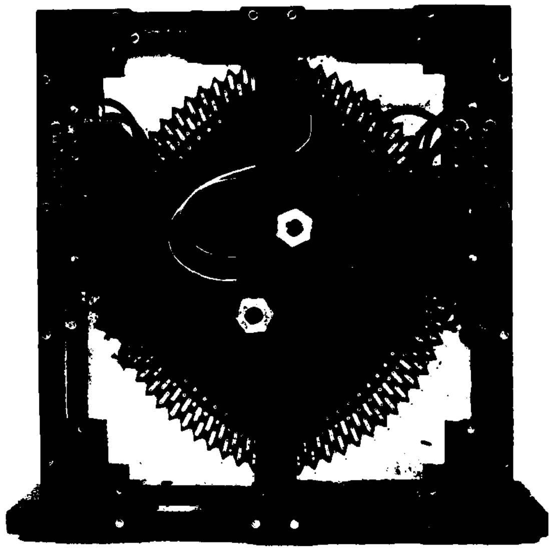
The AOPC will be wedged to allow the beam to pass through the cell without interfering with the circuit board and the mounting fixture. The mounting fixture will include a detachable RF connector for easy removal of the AOPC for servicing, and a provision for forced-air cooling with a thermal sensing mechanism.

3.2.3.1.2 Major Design Considerations

To meet the specifications, the AOPC design must consider several important parameters. These include the acousto-optic material and its properties, the transducer dimensions, and the mounting scheme used to connect the circuit card and drivers to the crystal (which is important because of its effect on crosstalk levels). Power dissipation in the AOPC (and the resultant temperature profile) is important to both the mechanical design and the optical performance of the unit; therefore, a thermal analysis was carried out to predict AOPC temperature profiles and recommend heat sinking techniques. Detailed discussions of these various design considerations are given in the Phase III report.

3.2.3.1.3 AOPC Fabrication

An AOPC device was fabricated according to the design and specification details given above, using procedures and techniques which are fully documented in the Phase III report. The finished unit, a 32-channel TeO_2 device, is shown in Figure 3.2.3.1.3. It was designed to



a. REAR VIEW, SHOWING CONNECTORS, PC CARD MICROSTRIP LINES, AIR COOLING VALVES

b. OUTPUT VIEW, SHOWING TeO_2 CRYSTAL, TOROIDAL IMPEDANCE MATCHING INDUCTORS

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Figure 3.2.3.1.3. The Phase III AOPC

be expandable to 128 channel operation, and to be compatible with the RF system described in the following paragraph. The performance achieved by the new AOPC was excellent, exceeding the design goals in the key areas of risetime, diffraction efficiency, and crosstalk. Performance of the device is summarized in Table 3.2.3.1.3.

3.2.3.2 RF Drive System Investigation

The RF drive system provides the AOPC with the digitally modulated RF signals which feed the array of transducers (128 in a full system, 32 for the Phase III study). Its inputs are the digital data for each channel, the system-generated modulation and timing signals, and any required master system control signals.

The Phase III RF system design divided the electronics into four basic modules, shown in block diagram form in Figure 3.2.3.2. They are:

1. The A module, which contains the master RF oscillator and the mixers which impose the system-generated modulation signals onto the RF signal.
2. The B module, which splits the RF into four mutually-orthogonal phases (i.e., 0°, 90°, 180°, and 270° phase angles with respect to the input), to permit "phase randomization" of the recorded data.

TABLE 3.2.3.1.3

Comparison of AOPC Specification with AOPC Performance

	Specification	Desired Goal	Experimental Results
10 - 90% Rise Time	25ns	18ns	17.97ns (Ave for 7 channels with $\sim 90\mu m$ spot)
Crosstalk ($\triangleq$ 20 log ($\sqrt{1-\Delta X}$-1)	-20dB	-30dB	-30.2dB (on the basis of 4 channels adjacent to A3
Diffraction Efficiency (200mW RF)	50%	50%	>60% @50mW RF
Channel Uniformity (on basis of DE)	$\pm$1.5dB	$\pm$1.5dB	$\pm$1.3dB or better

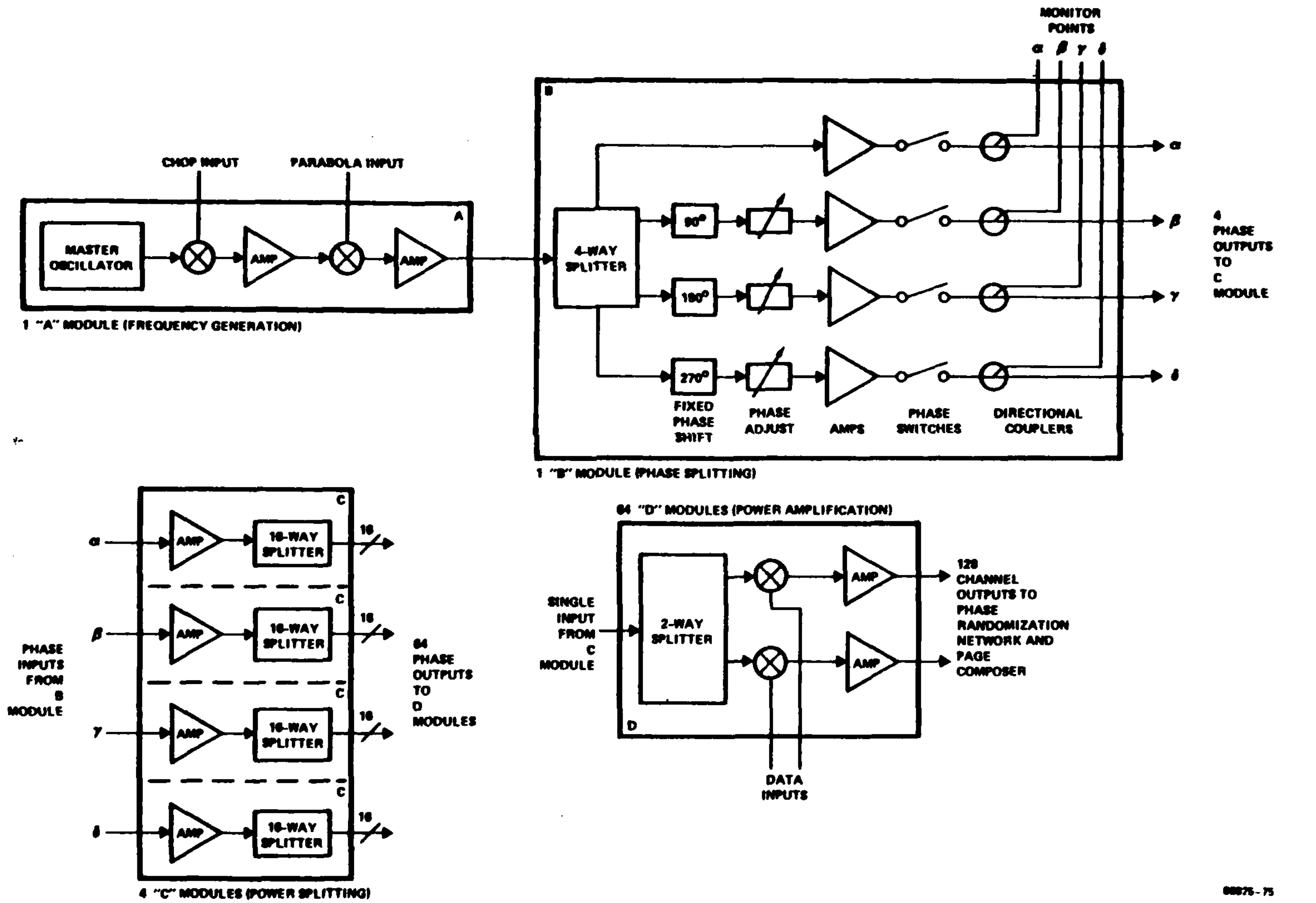

Figure 3. 2. 3. 2 RF Drive System for AOPC - Functional Diagram

3. The C modules, which split the RF signals and associated clock signals into a number of channels (16 for the Phase III study, 64 for a full system).

4. The D modules, each of which contains two channels for data modulation and final power amplification; the D module outputs are the AOPC transducer inputs.

The Phase III subtask plan called for the design, fabrication, and testing of the modules required to provide 32 channels of modulated data, with circuitry and housing designed to permit later expansion of the system to the full 128 channels. Due to the descope of Phase III, the completion and testing of the RF system was delayed until Phase IV, and is reported on below in Section IV.

3.2.4 Photodetection Subsystem

The performance of the detection and threshold electronics is critical to several key system areas, primarily light budget requirements for readout and BER performance. The Phase II system used fiber-optic elements to bring the light from each channel in the readout array to discrete PIN photodiodes. The SNR performance of these devices and the associated amplification and thresholding circuits was in general acceptable, though some areas for improvement were identified. The sensitivity of the detectors, however was a source of concern. By requiring a peak light input of 280 nW per detected "1" bit (for an electrical SNR consistent with a 10^{-6} BER), the detectors forced the Phase II system to operate with a fairly large power laser: 2 to 4 watts at a wavelength of 514.5 nm. A laser of this size is both bulky and voracious, requiring tens of kilowatts of input power, as well as 4 to 6 gallons per minute of water for cooling. Since these requirements could have a significant negative impact on the deployability and facilities requirements of the contemplated deliverable Wideband Recorder system, the Phase III activity included investigations into the availability and characteristics of detector devices, interfacing techniques, and threshold circuit designs which could provide better performance and reduced light input requirements.

The investigations undertaken in this subtask fall into three categories:

1. Photodetector and Filtering. This included a survey of available devices, selection of appropriate candidates that offer performance advantages, and signal-to-noise calculations for various device configurations, indicating the BER (electrical) performance to be expected for various light input levels.

2. Thresholding. An evaluation of the "adaptive threshold" scheme used in Phase II was made, and various

parameter choices and alternative schemes were considered in terms of potential performance improvements. This investigation was coordinated between the team concerned with item 1 above, and the System Analysis subtask responsible for mathematical system modeling (the System Analysis results and models are described in Section VIII).

3. Fiber-Optic Interface. The areas considered in this investigation include the fiber duty cycle (also in conjunction with the System Analysis results), the fiber type, interconnect schemes, especially as influenced by the structure of the most likely candidate devices identified in item 1, and optical filtering functions served by the fiber array.

3.2.4.1 Photodetector Evaluation

To provide a basis of comparison for evaluating new candidate photodetector devices, the first task performed was an analysis of the Phase II detector and processing electronics. The results of this could then be applied to define strictly comparable performance parameters for the new devices. The most significant results obtained are BER versus input power curves.

We should emphasize that the calculations assumed "ideal optical inputs". This means that the BER values discussed do not include major system noise sources described elsewhere in this report, such as AOPC crosstalk, film surface degradation, and film nonlinearity; even film grain noise is left out. Thus what we are concerned with here is the selection of detector devices which can detect ideal inputs with electrical noise limited BER's well below those at which the full system is designed to operate. This will assure that the detection electronics subsystem does not contribute significantly to the overall system error rate.

The result of the evaluation led to data on BER vs. input power for various devices, part of which is presented in Figure 3.2.3.1 1 & 2. The device recommended is No. 3 in the first figure; this is an RCA hybrid device capable of a 10^{-10} BER at only 5 NW of input power.

3.2.4.2 Thresholding Electronics Investigation

The analog data recovered by the photodetectors must be thresholded and sampled to make bit decisions. In the Phase II system several schemes for performing this function were implemented and evaluated. By far the best performance was obtained with the single-channel adaptive threshold. The operation of this circuit is described in detail in the Phase II final report (Reference 1).

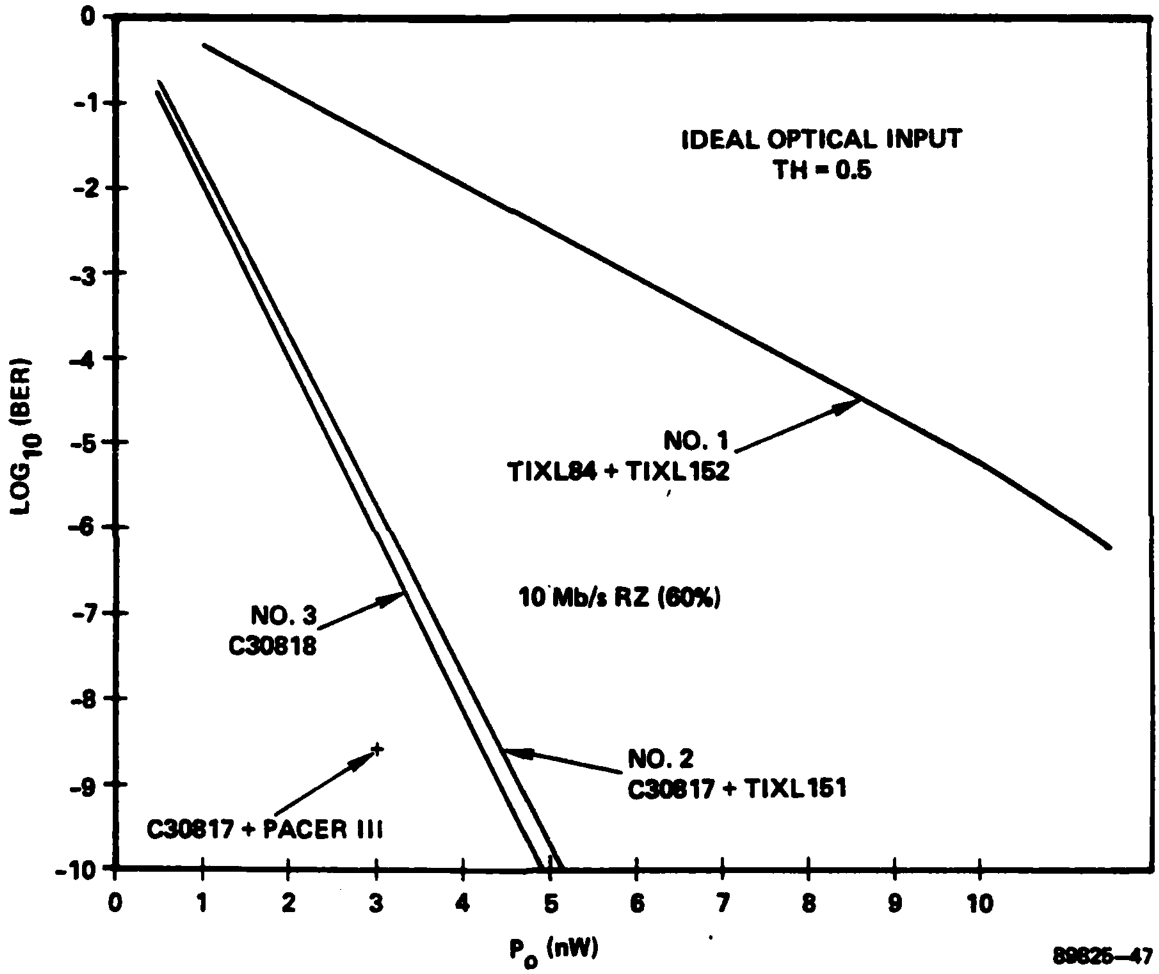

Figure 3.2.3.1-1. BER as a Function of Average Received Optical Power for Candidate WBR Avalanche Photodiode Receivers

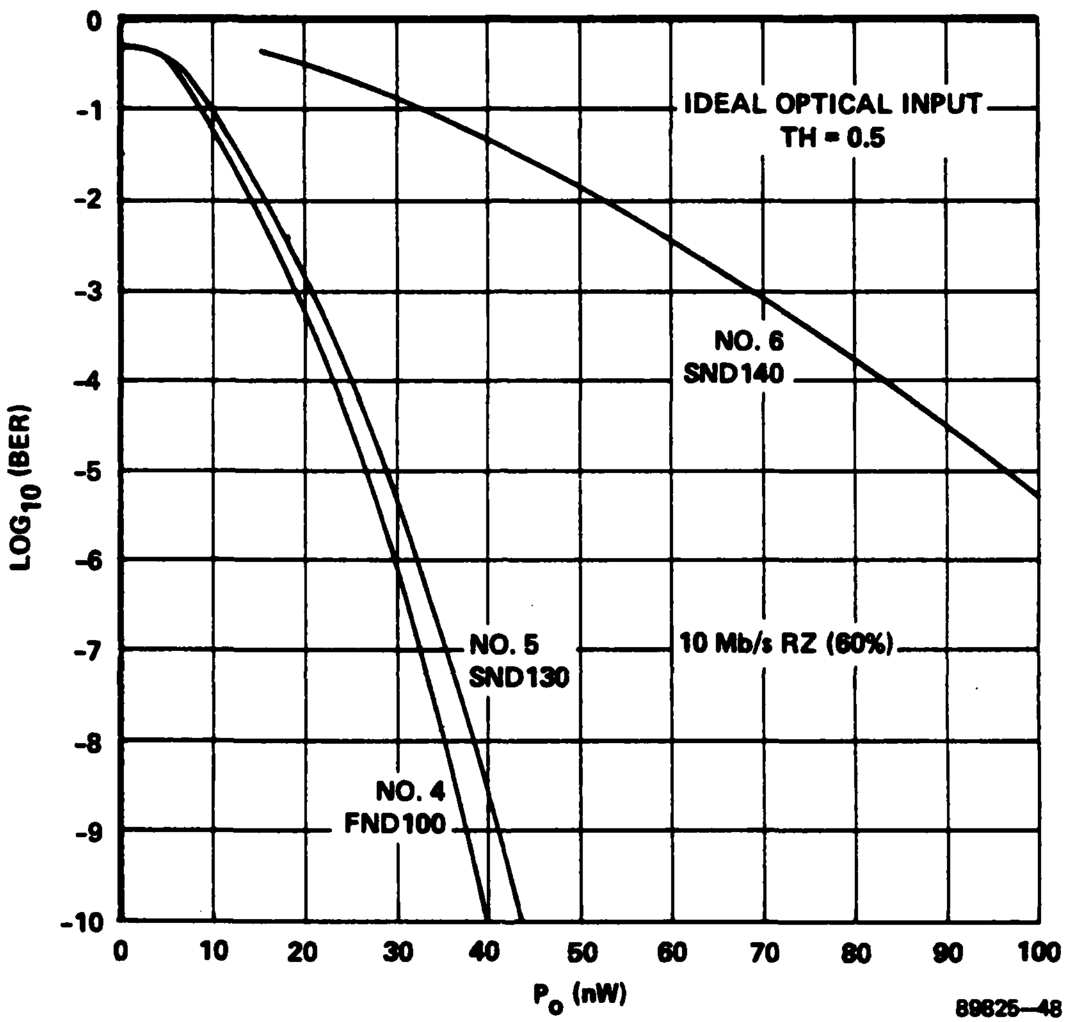

Figure 3.2.3.1-2. BER as a Function of Average Received Optical Power for Candidate WBR PIN Photodiode Receivers with PACER III Preamp

The original plan for the Phase III threshold evaluation activity was to first obtain comprehensive data and consistent models of the system's noise characteristics, an effort that was to be coordinated between the System Evaluation subtask (which was collecting data on the Phase II hardware), the System Analysis subtask (which was mathematically modeling the system), and the Threshold Investigation group. Then this information would be used to decide on a theoretically optimum approach to the thresholding process. As reported in Sections VII and VIII of the Phase III final report, however, substantial difficulty was encountered in matching the observed noise characteristics to the system models. As a result of this problem, and influenced by the changing program goals and funding (as well as the good results obtained by the System Evaluation subtask using the Phase II adaptive threshold circuitry), a decision was made to recommend an adaptive threshold for the follow-on system. By incorporating several variable components into the prototype circuits which should be tested early in the next phase, the threshold could be empirically adjusted to optimize BER performance; some of these adjustments could be economically placed in the final circuit for channel optimization, while others would be replaced by fixed components.

Thus, the threshold investigation became an investigation into the design considerations associated with several adaptive threshold circuits. The two leading candidates were voltage mode adaptive (VMA), and current mode adaptive (CMA, used in Phase II). Details of this evaluation will not be repeated here, but the conclusion reached was that the speed of response specification gives the current mode thresholding scheme some apparent advantages over the voltage mode.

Summary

Although still in the preliminary stages, the present indications from the threshold analysis appear to favor a current mode adaptive threshold similar to the one implemented in the Phase II system. Assuming that some such scheme is implemented, the design considerations that have emerged from this study include:

- Use of adjustable components in key areas to optimize channel performance.
- Use of a tracking rate which varies as a function of scan position: a fast-tracking "acquire" period at the beginning of scan, followed by a slower response during the data.
- Simplified implementation, since the follow-on system will not have the long 'hold' time requirements which were specified for Phase II.

Finally, modifications to the Phase II circuit have been suggested which would help to make it compatible with the next system's goals. These include: the use of a faster comparator to allow 10 Mb/s operation, the use of a balanced diode bridge to reduce potential error, the use of a bipolar input buffer to decrease cost, the use of simplified current source switching techniques, and the use of Schottky diodes to increase speed and decrease offsets.

3.2.4.3 Fiber-Optic Interface Investigation

The distribution of the individual optical channels to the detector devices is a critical step in the readout process since the advantage of a highly sensitive detector can be lost if an efficient coupling scheme cannot be found. The Phase II system used an array of plastic fibers (DuPont Crofon ^{R}), which were interfaced to the PIN photodiodes using a transparent silicon compound as a flexible coupling. A simplified diagram of a Linear Fiber-Optic Array is shown in Figure 3.2.4.3.

The fiber-optic interface investigation (as given in the Phase III report) provided 1) a recapitulation of the Phase II array performance and design criteria; and 2) a tabulation of the design considerations of interest for the follow-on system, including spatial duty cycle, transmittance uniformity, durability, and connectorization characteristics.

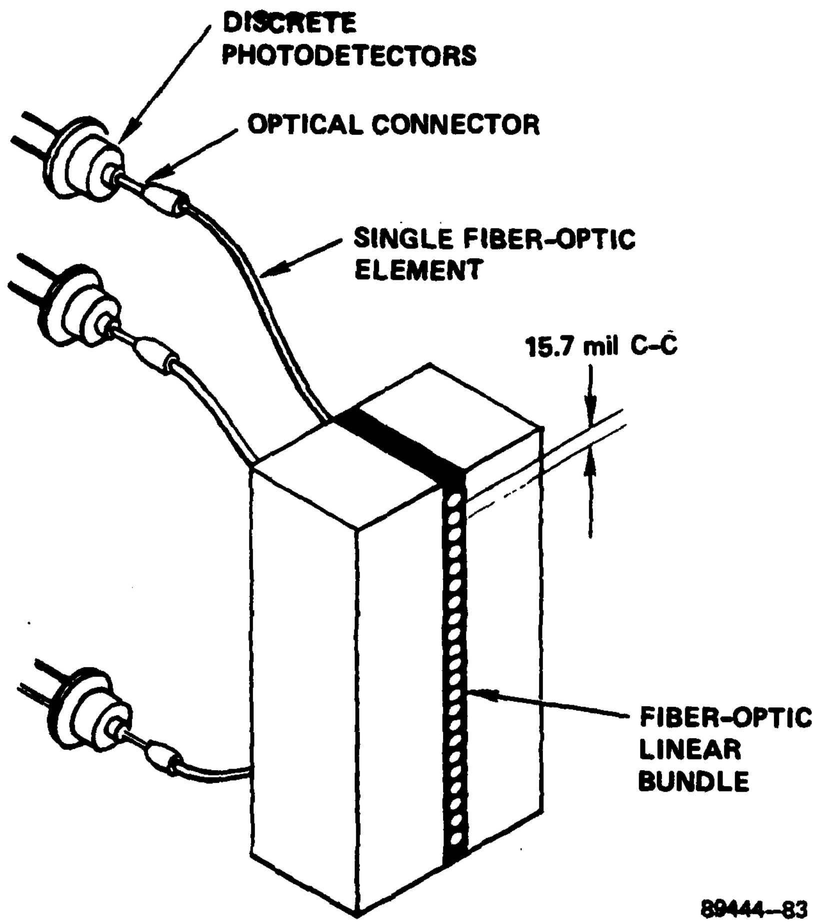

Figure 3.2.4.3. A Linear Fiber-Optic Array

3.2.4.4 Conclusions

Like several of the other Phase III subtasks, the Photodetector/Threshold investigation was affected by the changing program scope and schedule. The projected breadboard experiments could not be performed, and further investigations into the thresholding and fiber interface areas were also cut short. Nevertheless, several preliminary recommendations have emerged.

1. The RCA Avalanche Photodetector units are recommended for the prototype system. They provide a substantial increase in sensitivity over the devices previously studied, which should materially affect the size and power of the required readout laser. The selected hybrid APD device, which should provide some additional mechanical interface design flexibility because of its detector/amplifier combination, is capable of producing bit detection at an (electrical) BER of 10^{-6} with only 3 nW of light input.

2. Current mode adaptive thresholding appears to offer both high performance standards and design flexibility, and is recommended. Further investigation early in the next development cycle is also recommended.

3. The Fiber-Optic interface problem can be handled in several ways. Custom modification of the individual device packages, with manipulation capability for positioning the fibers with respect to the detectors, is a brute force solution. The Phase II scheme is not ruled out, especially for those systems which will include a reasonably large laser as a part of the record system. But the most attractive solution is an integrated detector/coupler unit, which may become available from RCA (or others) in the future. If available, this latter option would be the recommended interface for the Phase IV system.

4. Overall, the performance of the detector subsystem (in terms of SNR) is expected to exceed that of the rest of the system. Thus there will be more BER gains to be made from considering the optical filtering areas (at the fibers and elsewhere in the system) than from trying to squeeze the last ounce of performance from the detectors.

Finally, we must emphasize that the breadboard experiments which we were not able to include in this study will serve to confirm all the data gathered, and to increase the level of confidence which the system designers and users will be able to place in the conclusions presented. Such experiments are recommended for early in the prototype build phase.

3.2.5 Recording Material Investigation

The recording material plays a key role in the design and operation of a high data rate acquisition and processing system based on coherent optical techniques. Two particular areas related to the recording material must be considered during the initial system definition phase. First, a recording material must be identified and procured; the material should possess a high exposure sensitivity, provide good holographic recording properties, and permit a high volume packing density. Second, the processing requirements and support equipment for the recording material must be considered to ensure optimum system performance levels; the recording material must be compatible with high speed, automatic processing.

During the Phase III program we investigated these recording material issues. We have established baseline specifications for the recording material consistent with overall system performance goals, and initiated extensive discussion and interaction with Eastman Kodak in an effort to procure a material which performs to the specifications. We analyzed the operational requirements for a processor in both the near and far term, and surveyed existing processors and evaluated their performance in terms of overall system compatibility. Our results and recommendations on film procurement and processing are summarized in this section.

3.2.5.1 Film Procurement Activities

The recording material for the Wideband Recorder/Reproducer (WBR) system is the archival memory medium for the data storage system. In selecting an appropriate material, a comprehensive assessment of user requirements and the compatibility of commercially available photographic media with these requirements is necessary. The requirements represented by the WBR application were translated into a set of baseline photographic and material properties. We then contacted Kodak in an effort to obtain recording material samples with these baseline characteristics. The baseline material characteristics and the related film procurement activities are documented in the Phase III final report. The following paragraph excerpts the summary of the film procurement task.

3.2.5.1.1 Conclusions

The final result of the discussions was to accept Kodak's suggestion that Harris order a special "QX" film. The "QX" category refers to low quantity special orders from Kodak, and includes a setup charge added to the actual materials cost. The description of the material to be ordered would be Kodak Recording Film Type SO141 on a 2.5 mil ESTAR support with a clear-gel backing and balanced for curl control with a fine matte. The film will be wound on a 3-inch (inner diameter) tenite spool; this winding format is identified by Kodak as Specification Number SN 510. The minimum order in this format is 30 rolls of 70 mm x 3000 foot film. This minimum order ensures a good probability of obtaining ten rolls with no splices. The 35 mm film version of this, which Harris recommended be purchased for testing, would be in 35 mm x 250 foot rolls and is identified by SN 684.

At current (i.e., 1976) prices, the 70 mm film in such an order would cost approximately \$0.71 per square foot, while the 35 mm film would be nominally \$0.84 per square foot. With the inclusion of the QX (or setup) charge, the nominal material cost would be \$0.90 per square foot. Delivery of the product, according to Kodak, would be 30 to 60 days after receipt of the order. No film was procured or tested using this information, due to the scope change imposed upon the WBR program at this point.

3.2.5.2 Film Processor Requirements

Another major consideration in the implementation of a Wideband Recorder/Reproducer system is the method of film processing.

The processing techniques employed determine the diffraction efficiency of the recorded holograms, the signal-to-noise ratio of the reconstructed data patterns, and the archival quality of the processed film. The mechanical transport within the processor must provide film handling with no scratches or abrasions to the recorded surface to avoid causing an increase in detected error rate. Thus, the processor has a major influence on overall system performance levels.

During the course of the Phase III contract, we analyzed the operational requirements for a processor in both the near and far term. We also surveyed currently existing processors and evaluated their performance in terms of overall system requirements. In this paragraph, we summarize the general information obtained during the processor activity, and reprint the conclusions reached.

3.2.5.2.1 General Processor Comments

During the course of this processor survey, significant practical information was gathered. In particular, several aspects of processor sensitometric control and maintenance were covered. The comments in this paragraph outline these items. The procedures are applicable to the control and maintenance of any general processing facility. Close sensitometric control is required for the WBR processor. Two particular methods to ensure this control are commonly employed for automatic processing machines; these are sensitometric control strips and chemical monitoring. The sensitometric control strip is a film sample containing a calibrated step wedge exposure and is processed prior to each major film run. The developed densities of the control strip are measured and compared with the density levels obtained for optimum processing conditions. In addition, the strip is examined for surface quality. This test determines the general condition of processor performance. A processor log book, detailing processor conditions and the resulting sensitometric control strip data, can then be used to diagnose any problem areas identified.

Chemical monitoring is also necessary to maintain optimum processing performance. The monitoring should include, as a minimum, measurements of pH and replenishment rates. Replenishment is necessary to replace development chemicals consumed during processing. However, replenishment alone does not ensure pH maintenance. Thus, both the replenishment rate and pH level must be monitored and maintained. The processor log book containing the daily history of processor performance, pH levels, and replenishment rates can aid considerably in determining and rectifying problem areas.

Periodic processor maintenance is required to obtain processed film of high sensitometric and cosmetic quality. Cleaning of the developer racks and rollers must be included in this schedule. The racks can be cleaned by immersion in a silver solvent solution such as potassium dichromate or sodium sulfite, though commercially available cleaning solutions also work well. To remove chemical residues from the roller assemblies, agitation by ultrasonic transducers or manual scrubbing is effective if used with a subsequent water rinse step.

Because of the strict processing demands in the WBR application, a second recommended option for the processor is an infrared film viewer. Since the infrared illumination does not increase the fog level on the candidate film (Kodak SO-141), the viewer may be used to monitor film quality during any stage of the processing. With the viewer, processor-induced faults can be identified and corrected before the completion of a processing run. An additional infrared viewer could in fact be used to pre-inspect film before recording to ensure that no emulsion and base defects are present. Thus, the infrared film viewing station provides an effective method for monitoring quality before, during, and after film processing.

One last design recommendation which should be made is the incorporation of a silver recovery unit (SRU) in the processor. The SRU removes the silver ions generated in the fixer solution during processing. Two common techniques used for silver extraction are ion exchange and electrolysis. In the ion exchange process, the silver ions are removed by passage of the used fixing solution through a column of a suitable ion exchange resin. In the electrolysis technique, the silver ions are plated out of solution by passage between two charged electrodes. This second technique, adaptable to either intermittent or continuous operation, produces a recycled fixing solution which can be reused many times. An economic advantage of this process is that the recovered silver can help defray film costs and processing expenses. In addition, the recycled fixing solution, if not reused, can be discarded with minimal effect on the environment.

3.2.5.2.2 Summary and Recommendations

A summary of the processors surveyed and their key features is given in Table 3.2.5.2.2. In the table, the machines have been separated into high and moderate throughput rate classes. A wide range of machine features are represented. However, judging from user comments, we conclude that all of the processors, when properly maintained, produce high quality output film for their intended application.

The WBR application requires particularly high performance levels. The output film quality is critical, since film damage of any kind

Table 3.2.5.2.2. Summary Matrix of Automatic Film Processors

Processor Type	Throughput Rates (Max)	Development Method	Threading	Transport Path	Dimensions (l x w x h)
High Rate Processors					
Houston Fearless Model P-003	150 ft/min	Spray	Leader	Helical	17' x 3' x 8'
Triese Model MTV - 105 B/W	150 ft/min	Immersion	Leader	Serpentine	34' x 2' x 7'
Fultron Model III-B	50 ft/min	Spray	Leader	Serpentine	19' x 8' x 8'
Pako Standard Cine 215	52 ft/min	Immersion	Leader	Helical	15' x 3' x 7'
Moderate Rate Processors					
Kodak Versamat Model 1140	40 ft/min	Immersion	Self	Serpentine	8' x 2' x 5'
Oscar Fisher Model G12MA	24 ft/min	Immersion	Self	Serpentine	5' x 2' x 6'
Filmline Custom Line	40 ft/min	Immersion	Leader	Helical	22' x 2' x 7'

contributed to the system bit error rate. Another important requirement is that high throughput rates must be achieved to minimize the access time to recorded information.

In our judgement, only the Houston Fearless, Triese Engineering and Fultron processors currently have the capability to provide the necessary performance levels. These machines combine high quality film handling and processing with a high throughput rate. It is recommended that long-term program plans incorporate one of these machines as a dedicated processor.

Additional investigation of these processors is recommended. Specifically, exposed but unprocessed samples of film recorded on the WBR system should be supplied for processing on the three recommended machines. The processed film samples could than be evaluated quantitatively. The diffraction efficiency of the holograms, the signal-to-noise ratio of the reconstructed data pattern, and the film surface quality would be of particular interest in evaluating each processor's performance.

Finally, it is believed that a moderate throughput rate processor is the best choice for short range program needs. This is because this type of processor offers the flexibility of determining the effects of a variety of system requirements and is available on lease options or at moderate costs.

3.2.5.3 Film Testing Activities

The Phase II WBR system used Kodak SO-141 film as its storage medium. Good results were obtained from this film, which was available in 1000 foot lengths of 35 mm width, and 4 mil thickness; however, not all of the film characteristics important to holographic recording are specified by, or available from, the manufacturer. Thus, characterization of this film experimentally would provide a valuable baseline for comparing candidate replacement or backup films.

Also, discussions with Kodak produced several candidate replacement films, evaluation of which was then in order. Thus, a film testing activity was included in Phase III to establish the holographically relevant parameters of SO-141 and its (presumptive) competitors. In this paragraph we summarize the results of these tests.

3.2.5.3.1 Summary of Kodak SO-141 Results

We measured the sensitometric and holographic parameters of Kodak SO-141. An exposure of $1.3\ \mu J/cm^2$ at 514.5 nm is required to obtain a processed amplitude transmittance of 0.5; the contrast γ at this point is 1.85. This is the region of interest in holography. The spatial frequency response is 33 percent at 300 cycles/mm, decreasing to 20 percent at 600 cycles/mm. It is relatively flat above 600 cycles/mm.

The best data storage performance is obtained for K = 10; here, the SNR is 14 dB with a corresponding DE of 0.94 percent for a packing density of 1 Mb/cm^2. These parameters satisfy the requirements of the Wideband Recorder system. The performance of Kodak SO-141 is well matched to the Wideband Recorder/Reproducer system.

3.2.5.3.2 Summary of Kodak SO-192 and SO-391 Film Test Results

During film procurement discussions with Kodak, two recording materials were suggested as possible alternates for the Wide-band Recorder/Reproducer; these materials were Kodak SO-192 and Kodak SO-391. These films, intended for high resolution aerial duplication applications, have an orthochromatic spectral sensitivity. Normally supplied on 5 mil Estar^R (polyester) base, these films are available by special order in a variety of format sizes. The basic construction of both films incorporates internal antihalation layers and is compatible with automatic processing.

The sensitometric and holographic performance of the Kodak SO-192 and SO-391 films were measured to determine the suitability of their use as a recording material for the Wideband Recorder/Reproducer. The measurement series included densitometric parameters, such as the characteristic curves, and holographic performance, as indicated by diffraction efficiency and signal-to-noise ratio levels.

The first conclusion reached was that the overall holographic performance of Kodak SO-192 is not suited to high density data storage and retrieval applications. The film base scattering levels cause a significant degradation of SNR in the 400 to 600 cy/mm bandpass, the spatial frequency range used for WBR holograms. The decreased SNR results in higher, and therefore unacceptable, bit error rates. Although it has suitable recording properties for conventional imagery, Kodak SO-192 cannot achieve the performance levels required in the WBR application.

However, the holographic performance of Kodak SO-391 is acceptable. Overall, the sensitometric and data storage parameters of this film are nearly equivalent to those of Kodak SO-141, the film presently used in WBR. Thus, Kodak SO-391 is an alternate candidate for high data rate holographic recording. The possibility of procuring this film in the 70 mm thin base format should be investigated.

3.2.6 System Evaluation

Specification of an operational prototype Wideband Recorder system, the goal of the Phase III activity, required complete information about system capabilities and requirements. Testing on the Phase II Brassboard System provided extensive experimental data in many areas, as documented in the Phase II final report (RADC Contract No. F30602-73-C-0155). These experiments, in conjunction with certain user requirements and goals, indicated several areas for further investigation. The three major categories into which these additional areas fell were:

- Investigation of potential sources of increases in overall system data packing density
- Investigation of error statistics as related to optimum error correction coding choices
- Investigation of system performance in multichannel data readout experiments.

An overview summary of each of these areas and the motivations for their investigation will now be given. The section following will summarize the results obtained.

3.2.6.1 Packing Density

The Phase II Exploratory Development Model achieved an area packing density of approximately 4.8 Mb/linear inch or 3.5 Mb/in^2 on 35 mm wide film. This is an average value inclusive of all guardband and other overhead areas of the film, the local peak value was approximately two times larger. This value represents a significant improvement over the state of the art in digital data storage using other (non-photographic) technologies. It did not, however, closely approach the theoretical limits of photographic data storage. For this reason, an attempt to increase the packing density of the WBR system could be optimistically undertaken.

Packing density increases have two beneficial imp..ts on the overall system. First, the storage volume for a given quantity of data is reduced thereby reducing the space, time, and cost requirements associated with the maintenance of a large archival data store. Second, the dynamic requirements on certain electromechanical system components are reduced. That is, by minimizing the amount of the storage medium (film) required to store a fixed amount of data, the film transport mechanism (and any associated moving device, such as a scanning mechanism) can be slowed down for a given data rate. Or alternatively, for a given film transport speed range, the feasible system data rate will be increased.

The four key areas in which increases in packing density have been investigated are:

1. Horizontal (across scan) packing density
2. Vertical (along film) packing density
3. Spatial Frequency (bandwidth) packing density
4. Radial (film thickness) packing density

The first two are essentially two orthogonal components of "area packing density". The first three together define the effective "space-bandwidth product" of the film. When all four areas are taken together, they define the overall volume packing density of the storage process.

3.2.6.2 Error Characterization

Performance data taken on the Phase II WBR system indicated that significant improvements could be made in the achievable bit error rates (BER's) by the use of error correction coding (ECC). The basic trade-off to be made in the selection of an appropriate code is that of code efficiency versus error correcting "power". It is desirable to minimize the "overhead" to the user data while simultaneously providing enough error correcting "power" to keep the system BER below some required minimum. Since the efficiencies of the available codes are well known, the key question becomes, "which codes have the needed power". To answer this question in an optimum way requires a knowledge of the error statistics which affect the data.

In Phase II of the WBR program, where prior knowledge of the relevant error statistics was unavailable, a code was chosen for test purposes which was relatively easy to implement, and which provided a high probability of correcting both burst and random errors. This code (a BCH 63, 51 code interleaved to depth 4) provided significant BER reductions, but required the addition of a rather large percentage of error correction (parity) bits to the recorded data stream.

Improved performance on future systems may be obtained in two ways: 1) by using more sophisticated and efficient codes, and 2) by tailoring the code to the specific error statistics which are associated with the Wideband Recorder System. In both cases, the significant trade-off decision balances system BER performance against implementation complexity and cost. To provide information relevant to both of these areas, experiments were performed which characterize the nature and statistics of the Phase II system errors, and predict the performance of a variety of coding and formatting schemes.

3.2.6.3 Multichannel Bit Error Rate Measurements

During the final testing period in its development, the Phase II system was exercised in a variety of ways, and extensive performance data was tabulated and documented in the final report. Most of the data involved the relationship of system bit error rate to various other parameters. The BER data, however, was usually taken from one readout channel at a time; in fact, cost and schedule and considerations prevented simultaneous detection of errors on more than two channels. Some experiments were performed which measured BER data on various channels with purely electronic channel switching (i.e., no optical component realignment or optimization for individual channels), and the performance of all operational channels in the array was evaluated.

Nevertheless, simultaneous detection of errors on more than two channels would be beneficial in several areas: 1) the level of confidence in the overall system error rate would be increased; 2) the channel-to-channel error correlation statistics would be determined, abetting the error correction code selection process described above; 3) sensitivities of the system's BER performance to various optical and electronic alignment and synchronization parameters would be determined for the full array, further contributing to the final system design and tolerancing. For these reasons, a multichannel (up to five channels simultaneously) BER device was constructed and used in association with the WBR system.

3.2.6.4 Summary of System Evaluation Results

The System Evaluation Subtask evaluated the performance of the Phase II system in areas which are key to the near-term development of deliverable holographic digital data recorders. The three categories into which these areas fall and the motivations for investigating them are:

1. Data Packing Density Increases

   These were investigated to minimize data storage volume, reduce speed requirements of the opto-mechanisms, and increase record time for a given film length.

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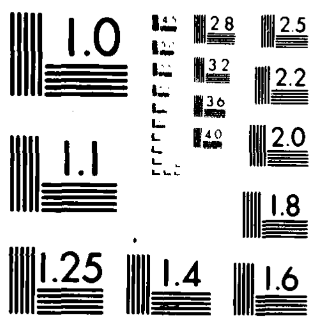

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2. Determination of Error Characteristics

This study provided information to optimize data detection and thresholding schemes, and to help match the system error statistics to appropriate data coding techniques.

3. Multichannel Data Collection

This completed the characterization of the Phase II hardware in terms of its BER performance.

The results obtained in each of these three areas can be summarized as follows:

1. Packing Density

Vertical Packing Density - The experiments showed that the originally stated goal (at least 10 percent increase in packing density with less than 20 percent increase in BER) could be met, but that the gain was only narrowly achieved. The conclusion was that, with current techniques, double-Rayleigh resolution is a practical minimum for systems in which low BER is an important goal. Additional conclusions were that no noticeable benefits accrue from over-illuminating the hologram during readout, but that row-to-row cross-read has little effect on the system as currently configured. This latter observation, with further study, may prove of importance in reducing the phase-lock accuracy requirements of future film transport subsystems.

Frequency Packing Density - Only small changes in spatial carrier frequency were possible, due to physical limitations of the Phase II system. At the maximum frequency increase (~ 12%), however, no appreciable BER increase was observed. This information, combined with the MTF data for Kodak SO-141 indicates that increases in spatial carrier frequency are a promising area for packing density increases. In fact, transform lens design considerations, rather than film capability, appear to be the limiting factor in this area. The Phase III design goal increases the frequency band to cover the 375-750 cycles/mm range, providing a 20 percent nominal packing density increase. The feasibility of this and further extension is covered in the Spinner-Autoscan section of this report.

Horizontal Packing Density - The first and most surprising result of these experiments was that reducing the interhologram guardbands, by giving more film area to the holograms themselves, produced a substantial BER decrease, while still providing enough hologram/guardband modulation for the operation of the clock and sync recovery circuits. This offered the opportunity to either accept the lower BER value at the original packing density, or maintain the original BER level while increasing packing density. Further experimentation produced a fairly well-defined BER versus packing density curve, which can be used in future system design exercises. An additional option for future systems is to build in a user-selectable BER/packing density option, permitting trade-offs between high-integrity and high-volume storage, as dictated by the nature of each new block of data.

Radial Packing Density - Only some fairly simple static and dynamic tests could be run with the thin-base film samples available, since the proper emulsion for recording and reproduction could not be obtained on 2.5 mil polyester base within the cost and schedule restrictions of the task. Also, performance of the experiments on the Phase II system necessarily restricted the investigation to the 35 mm width films used on that system. Still, it was shown that thin-base film in 35 mm format can be handled successfully in a WBR context. The air-bearing platen was able to restrict the film to within the required depth-of-focus tolerance limits, without scratching or otherwise degrading the film surface. Full-shoulder lateral edge-guiding was shown to be effective (although marginally so) in providing repeatable tracking performance during repeated transporting operations. And finally, the Phase II film processor was shown to be able to handle the thin-base film (although a different, more sophisticated processing system will be recommended for the follow-on system. Thus, these experiments provide some added confidence in the feasibility of a system using thin-base film. Early in the development of such a system, these experiments should be repeated and expanded in scope, specifically using the wide format and the particular emulsion which is chosen for the system.

2. Error Characterization

Data Statistics - The results of this series of experiments were curves closely related to cumulative probability density functions of the fluctuations in the heights on one-bits and zero-bits. The data were taken under a variety of system conditions, to isolate and separately examine the effects of optical and electrical crosstalk and film noise. This information, which once again confirmed the importance of crosstalk in limiting the BER performance of the Phase II hardware, was provided to the Photodetector/Threshold and System Analysis Subtasks to assist in modelling the noise environment of the detected data. These results will also be of use as controls for future systems, to verify that the various noise sources (especially page composer crosstalk) have been successfully reduced to acceptable levels.

Burst Error Characterizations - By simulating the "burst dissolving" power of various interleave depths, this experiment gave a fairly clear picture of the typical burst-type defects affecting the Phase II system. It was found that a significant improvement in BER performance of the error correcting code could be obtained by choosing the interleave depth to be greater than about 8 to 10. This is a very important result when considered in conjunction with the horizontal packing density studies, since it indicates that further BER/packing density trade-offs, as described in those studies, are possible, i.e., system limits in those areas have not yet been approached. Studies of the maximum useful codeword length indicated that a word length of 127 was adequate both in terms of correcting power and interleaving capability and should be the design choice for the next system. This would provide a 10 percent decrease in the necessary coding overhead data as compared with the Phase II system (and an equal increase in packing density).

Based upon the experimental data, the coding study provided extensive trade-off information on cost, memory requirements, circuit complexity, and theoretical code performance. The choice of a (127, 113) BCH double-error correcting code, full-scan interleaved, was supported, and the reasons documented. The LSI investigation showed that LSI implementation of the selected code was feasible and cost-effective within the current state of LSI technology, and preliminary circuit design descriptions were given. In summary, a (127, 113) BCH coding scheme, full-scan interleaved and implemented with LSI techniques, is recommended for the next system. This should provide corrected error rates one or more orders of magnitude below those achieved by the Phase II system, while requiring approximately 10 percent less overhead to be added to the recorded data.

3. Multichannel BER Measurements

A new subunit of electronic circuitry (including drawer, panel, and housing) was designed and fabricated to permit simultaneous error detection on five additional channels (bringing the system capability to a total of seven channels). Experiments consisted of recording and readout procedures, with the system alignment optimized for all five channels rather than any particular channel. The resulting BER values, while not identical to those recorded in Phase II, were well within the bounds of variation observed in Phase II to be normal to the system. Specifically, the average raw BER for the readouts with four or more channels operating was 1.6×10^{-4}, while the average corrected rate (which could only be measured on the two channels of the main readout system) was 2.0×10^{-8}. These values may be compared to the average Phase II value ranges of $BER_{RAW} = 1 \times 10^{-4}$ to 3×10^{-4} and $BER_{CORRECTED} = 2 \times 10^{-6}$ to 2×10^{-8}. The correspondence of these values clearly indicates that the prototype can be a fully operational, multichannel system.

3.2.7 System Analysis

As a separate subtask of the Phase III program, the Advanced Technology Department (ATD) of Harris undertook a theoretical look at several key areas of WBR system performance. The following paragraphs excerpt the introductory and concluding sections of the ATD report, as well as a few of the key results obtained.

3.2.7.1 Analysis Organization

The ATD system analysis subtask has been divided into 4 sections which are (1) interchannel interference, (2) hologram uniformity, (3) intersymbol interference, and (4) electronic processing. Each section addresses one major area of concern to WBR system engineers. A short discussion of each of these sections follows.

3.2.7.1.1 Interchannel Interference

The WBR has 128 parallel channels operating simultaneously. If the recorder/reader formed a perfect communications link, all the energy inputted to one channel of the AOPC would be recovered by the corresponding fiber when reading. This is not the case. For many reasons the energy from one channel is coupled into neighboring channels. Energy received by one channel's fiber that originated as some other channel's signal has been termed interchannel interference. This energy may be cross-coupled either electrically or optically and for reasons which will become obvious, distinction is made between electrical and optical crosstalk.

Optical interchannel interference arises from the light associated with one channel spreading into areas occupied by other channels. The majority of any channel's optical interference comes from adjacent channels (optical neighbors). The magnitude of interchannel interference experienced by one channel at some instant is a function of a channel's 'on' fiber plane light amplitude profile, the fiber size, and the data pattern (i.e., which channels are 'on'). Thus optical interchannel interference is a random variable which can assume one of a finite number of values for a fixed system. The exact way in which interchannel interference affects bit error rate is a function of the signal profiles, the ratio of interference to signal, and the phase relation between interference and signal. It is true that for a fixed phase difference and signal profile, as the interference-to-signal ratio increases the BER will also increase.

Parameters which establish the fiber plane 'on' amplitude profile for a channel are AOPC transducer duty cycle, the Rayleigh resolution of the system, and any apodizations which exist in the record or read paths. The way that this profile translates into signal and interference energies is dictated by the fiber duty cycle. Phase difference between signal and interference is a function of the channel phase assignment.

The only major source of electrical interchannel interference is AOPC crosstalk. Channels whose AOPC electrical feed lines are adjacent to each other are considered to be electrical neighbors. Since channels are fed alternately from opposite sides of a printed circuit card, electrical neighbors are not adjacent in the 128 channel data beam. Electrically adjacent channels have one channel (fed from the opposite side of the card) between them. For this reason electrical interchannel interference must be treated separately from optical interference. The magnitude of electrical interchannel interference is a function of the AOPC feed line isolation and the data pattern. The effects of the electrical interference on BER again depend on the channel phase assignment.

3.2.7.1.2 Hologram Uniformity

By recording data as holograms, the energy (thus intensity profile) of each 'on' channel is spread over the entire hologram. The energy is not spread uniformly, however. This non-uniformity of hologram intensity can create a problem if there is a large difference between maximum and minimum intensity. Recording parameters, such as laser power, must be set so that the maximum exposure does not significantly exceed the linear range of the film's T_a-E curve. If there is a large dynamic range in the hologram intensity, very low exposure levels must be recorded. Recording low exposure levels gives reduced film signal-to-noise ratios and may result in significant non-linearities. For these reasons it is desirable to keep the hologram intensity as uniform as possible.

Non-uniform hologram intensity results from two processes, one fixed and one random. The fixed process is the envelope of each of the cosines which add to make up the hologram. This envelope is a function of the AOPC duty cycle and the Rayleigh resolution of the recorded hologram as well as the shape of the reference beam used during recording. Increasing the page composer duty cycle (transducer height) or increasing the Rayleigh resolution (hologram height) will cause the edges of the hologram to be less intense than the middle, giving reduced signal-to-noise ratio at the edges.

The random process is the addition of the amplitude of the cosines from whatever channels are 'on'. If all channels are in phase, these cosines add constructively in the middle of the hologram causing a large intensity spike. Large intensity spikes are avoided in the Phase II system by assigning different phases to the various channels causing both constructive and destructive interference at all points in the hologram.

3.2.7.1.3 Intersymbol Interference

At one instant one hologram containing 128 bits is being read (or recorded). Some time later an adjacent hologram representing 128 different bits is read (or recorded). It is possible for the energy from the n^{th} channel of one hologram to be read (or recorded) as being energy associated with the n^{th} channel of neighboring holograms. This cross-coupling of energy between holograms has been called intersymbol interference. Since different holograms are read (or recorded) at different times, intersymbol interference appears to couple energy from previous and future signals on a channel into the present signal for the same channel.

Intersymbol interference is mainly a spot size problem. To prevent intersymbol interference, the energy in the spot of light used to record and re-illuminate the film should be unimodal and contained within a width that is small compared to a hologram width. The width of the spot actually obtained with the WBR is a function of the width of the illumination incident on the page composer, AOPC risetime, width of the spinner facets, and impulse response of the lenses. It is desirable to identify which of these parameters is dominant and determine parameter ranges which give acceptable spot sizes.

3.2.7.1.4 Electronic Processing

The term electronic processing is used here to denote the detection circuitry starting with the photodetector and continuing through the bit decision device. It does not include any error correction encoding/decoding or remultiplexing.

Photodetectors used in the Phase II WBR are Meret hybrid photodiode amplifier units. The ouptuts of these devices are linearly proportional to the energy incident upon the detectors. Since energy is the integral of light intensity and light intensity is equal to $|\text{amplitude}|^2$, the detector introduces a square law effect. This creates the problem of signal dependent noise in the detector outputs.

Outputs of the photodiode/amplifiers are filtered and compared to thresholds to obtain bit decisions. Optimal filtering is a function of intersymbol interference, random noise statistics, and signal (time) profile. The maximum likelihood threshold setting will be a function of the signal-to-noise ratio. Since laser intensity and film transmittance vary slowly in time, the threshold must have the ability to track these changes. Also, the filter/threshold function must be accomplished with low complexity circuitry since it is duplicated for each of the 128 channels.

This section of the system analysis subtask will be aimed toward modeling the noise encountered in the WBR, determining the optimum bit decision strategy, and finding a low complexity implementation giving near optimum performance. The statistical analysis associated with the noise model should give information about bit error rates to be expected. A more detailed discussion of the electronic processing used with Phase II of the WBR is given in the Phase II final report [1].

3.2.7.2 Analysis Results

3.2.7.2.1 Interchannel Interference

Single channel analysis assuming a point reference indicates that integer Rayleigh systems have no clear optimum values, while non-integer Rayleigh systems may. The AOPC duty cycle has little influence on signal energy (especially for τ_f, the fiber array duty cycle, $<50\%$) while the adjacent channel interference level increases fairly rapidly with decreasing page composer duty cycle, τ. Fiber duty cycle can be optimized only for non-integer Rayleigh systems. Generally a smaller τ_f results in a smaller interference to signal ratio, (ISR), so that τ_f should be the smallest size that will collect the required signal energy, and tolerate system jitter.

Gaussian apodization can be used to increase the light efficiency of the system and reduce interchannel interference. Apodization appears to be more useful for re-illumination than for recording, where a constant film bias is desirable. Total apodization resulting in a ratio of $1/e^2$ between the edge and the center intensities has little negative influence on the system and offers 92% efficiency with 6.3 dB sidelobe suppression for a 2 Rayleigh, $\tau = 0.4$, system.

There is a significant reduction in interchannel interference shown by multiple channel analysis when adjacent channels are excited in phase quadrature. Quadrature phasing does result in some channels exhibiting a lower BER than others which may or may not be desirable. It is also possible to further improve the performance of quadrature channels by using some form of equalization.

3.2.7.2.2 Hologram Uniformity

All the analysis in this report assumes that the transmittance of exposed and developed film is linearly proportional to the data intensity exposing the film. This will only be true if

(1) the film is 'biased' by some fixed intensity to be at a point within the linear region, and

(2) intensity variations associated with the data do not cause excursions from the bias point which are large enough to exceed the linear range limits.

In the WBR, the light necessary to bias the film comes mainly from the reference. To assure that excursions associated with the data are small relative to the bias value, the reference beam intensity is much greater than the intensity of a data beam.

Making the intensity variations associated with the data small relative to the bias avoids non-linearities but it also results in reduced signal-to-noise ratios. The film noise is a function of the bias and has a fairly constant value. Therefore any decrease in the recorded signal lowers the SNR, creating higher error rates. The most desirable situation is to have the film biased to the middle of its linear range and have data-related intensity variations cover (but not exceed) the entire linear region. To achieve this situation, the data channels must have phase assignments such that a minimum of local intensity peaks occur in the hologram. Candidate channel phase assignment schemes include:

Single Phase: This would be the case if the AOPC did not have the ability to introduce phase differences. The large spike in the middle of the hologram has a peak value of N, the number of channels. Any channel phase assignment that is one pattern repeated periodically along the channel array will create a spike of equal amplitude somewhere along the hologram.

Chirp: Out of all phase assignments investigated to date the chirp gives the most uniform envelope for $\tau(u)$. Channel phases were assigned by the equation

$$\phi_n = \frac{\pi}{N} \left(n - \frac{N}{2}\right)$$

Quantized Chirp: Implementation of chirp phase assignments requires that many different phases be generated by the transducer driver circuits. Quantizing the chirp to 4 levels makes implementation practical.

Optical Quadrature Chirp Assigned: This is the result of quantizing a chirp to four levels with the additional restriction that optically adjacent channels be in phase quadrature.

Optical quadrature assigned by PN sequences was also investigated but did not better the results obtained from the chirp assignment.

Electrical Quadrature Chirp Assigned: This results from quantizing a chirp to four levels with the additional restriction that electrically adjacent channels (every other channel) be in phase quadrature. This assignment might be used if AOPC crosstalk was a major problem.

WBR II: The Phase II Wideband Recorder used a channel phase assignment which made electrically adjacent channels be in phase quadrature.

It is desirable to bias the film as uniformly as is possible during the recording process. This permits achieving relatively large SNR's without introducing non-linearities. The most significant factor in achieving this uniformity is the shape of the reference beam which should be made as narrow as the light budget will allow.

The other factor in hologram bias uniformity is the channel phasing. Having all channels in phase creates a large bias spike in the center of the hologram and should be avoided. Chirp assigned channel phases produce maximum spike levels which are reduced by a factor of almost 10, the lowest level yet observed. Quantizing the chirp to 4 phases to allow practical implementation increases spike levels by a factor of 1.2 and adding the restriction that adjacent channels be in phase quadrature spikes up to 1.4 times those of a chirp. In considering these results it should be remembered that the effect that these spikes have on the film bias is a factor of data beam intensity/reference beam intensity less significant than the reference beam shape.

It is believed that the loss of uniformity due to a phase quadrature restriction is not as significant as the reduction in inter-channel interference that it allows. Thus a phase quadrature channel assignment appears most desirable at this time.

3.2.7.2.3 Intersymbol Interference

Intersymbol interference is mainly a function of the width of the spot used to record and read the holograms. One major question to be answered is which part of the system predominates in the spreading of this spot. The three most likely candidates are the AOPC ristime, spinner facet width, and lens impulse response.

The step response of the AOPC for the Phase III WBR was measured and the impulse response obtained by taking the derivative of the step response. Defining the standard deviation to be the distance between points where the response is down to $1/e^2$ gives $\sigma_{AOPC} = 21$ ns.

At a 1000 Mb/sec data rate, a 128 channel system would record holograms at a rate near $10 \cdot 10^6$ holograms/sec. Since each hologram is 12.5 μm wide (as modified by the packing density increases achieved during Phase III), the combined effect of the spinner and the lens must be translate time into position at a rate of

$$(12.5\ \mu\text{m/holo}) \cdot (10 \cdot 10^6\ \text{holo/sec}) = 1.25 \cdot 10^8 \mu\text{m/sec} \quad (4\text{-}1)$$

The effective σ of the AOPC is 21 ns which means that at the hologram plane

$$\sigma_{AOPC} = (2.1 \cdot 10^{-8}\ \text{sec}) \cdot (1.25 \cdot 10^8 \mu\text{m/sec} = 2.6\mu\text{m} \quad (4\text{-}2)$$

In regard to horizontal spot size, the point of concern is the width of the film area affected by the AOPC input at any instant. This width is given by the convolution of the AOPC impulse response with the spinner/lens impulse response. If both responses are nearly Gaussian, the value of σ for the result of this convolution will be

$$\sigma \approx \sqrt{\sigma^2_{AOPC} + \sigma^2_{S-L}} \quad (4\text{-}3)$$

Manufacturers data puts the value of σ_{S-L} (spinner and lens combined) around 7 μm. Using equation 4-3, the non-zero AOPC risetime causes additional spreading of the spot to 7.5 μm.

In summary, intersymbol interference was identified as a low priority area since it is not believed to pose as significant a problem to the WBR as the other areas of this investigation. The sole result of the intersymbol interference analysis was the determination that AOPC risetime does not pose any problem to the present system, and in fact current lens and AOPC performance could probably support a somewhat increased system data rate. It was suggested that the effects of intersymbol interference might be reduced by recording adjacent holograms with a reference whose phase is shifted by 90°. No analysis was performed to determine if this assertion is correct.

3.2.7.2.4 Electronic Processing

The photodetector develops an output current which is proportional to the light energy incident upon it. This light is composed of signal, interchannel interference, and noise. The output current is amplified and compared to a threshold to obtain bit decisions which results in a bit error rate that is a function of the signal and noise energies and how cleverly the threshold was chosen.

The first and most important step in determining the proper bit decision strategy is to properly model the noise source and detection process. This allows derivation of the detector current probability density function (pdf) which is the basis for all decisions. For this analysis, it was assumed that film grain noise is the major random noise component. Film base noise and spots or scratches were neglected partially due to inability to model them.

In addition to the mathematical modelling process, several experiments were performed in the System Evaluation subtask which were intended to determine the probability density function of the noise in the system. However, the results of these experiments did not agree with the model developed. (The experiments are documented in Section VII of the Phase III report, the model in Section VIII.)

Since determination of the probability density function for the detector's output is absolutely necessary for making BER predictions, and since the model believed to describe the system did not give results consistent with experimental results, the analysis of electronic processing was terminated. Both the system model and the experimental procedures were examined in detail and no inconsistencies could be identified. Therefore, until this dichotomy can be resolved it appears that experimentation, rather than theoretical analysis, must direct the development of electronic processing in the WBR.

3.3 Phase III Summary

All of the tasks and activities carried out during the Phase III study have produced positive results, essentially eliminating the technical risk which prior to this phase was attached to a fully operational prototype 900 Mb/s Recorder/Reproducer System. To provide a format for describing these results, we can note that most of them fall into one (or more) of three rather global system performance areas: BER performance, system packing density, and optical power requirements. These areas are certainly not independent of each other, and a few of the results may either belong in more than one or not fit well in any of them; this format will, however, serve to emphasize the interrelationships of the various results, as well as their relationships to the major system goals.

3.3.1 BER Performance

The goal of the Phase II system was a BER of 1.0×10^{-6} or less. With the aid of error-correction coding (ECC), that goal was achieved, but with very little margin. Raw BER performance was found to be limited primarily by AOPC crosstalk, while the corrected BER was seriously degraded by the burst errors associated with film surface damage. (Early in the program scratches arising in the film transport were a problem; after this problem was solved, the rather unsophisticated Phase II processing system was revealed as the major source of film surface damage.) The following Phase III results should produce future system BER's one or more orders of magnitude below 1.0×10^{-6}.

1. A new AOPC was fabricated and tested. This 48-channel TeO_2 device, in addition to its excellent rise time, diffraction efficiency, and channel uniformity, showed very low crosstalk. The 30 dB typical

crosstalk suppression represents a 13 dB improvement over the Phase II unit; this was achieved in a worst-case situation: while the Phase II adjacent channels were driven in phase quadrature, the new AOPC was tested with all channels driven in phase. Low cross-talk simulation experiments performed during Phase II (by recording partially-populated holograms) showed raw BER values around 1.0×10^{-5}; the Phase III AOPC could perform as well or better.

2. Burst errors caused by film surface damage were shown experimentally to be (typically) 10 bits or less in length. Thus the Phase II ECC interleave depth (4 bits) was inadequate, and the domination of the corrected BER performance by burst errors is explained. The new coding and interleave design uses full-scan interleaving (with interleave depth ranging from 22 to 36, depending on the selected packing density). Thus the full power of the ECC should be realized.

3. The film surface damage mentioned in Item 2 came primarily from the relatively unsophisticated and inappropriate (and inexpensive) Phase II film processor.

Better processors are on the market; our survey established that several of them can support the throughput requirements of future systems while maintaining film surface quality superior to that in Phase II.

4. A new connection scheme was devised for the AOPC transducers. Formerly, the interdigitiated AOPC circuit card layout forced a choice: one could place in phase quadrature either the electrically adjacent on the circuit card or the optically adjacent channels in the array, but not both. In Phase II, electrical quadrature was chosen, to minimize AOPC crosstalk; thus some readout channels were in phase with their neighbors, increasing any interchannel interference effects. With the new connection scheme, both optical and electrical neighbors can be driven in phase quadrature, aiding the suppression of both crosstalk (in recording) and interchannel interference (in readout).

<u>BER Summary</u>. In the future, raw error rate will be reduced by lowered crosstalk and interchannel interference. Corrected error rates will benefit from reduced burst error sources due to improved processing, and from interleave randomization of such bursts as still occur.

3.3.2 Packing Density

The local peak packing density in each Phase II hologram was about 5 Mb/in^2, with the average value (which takes into account the various guardbands and other overhead areas) being about half as large. For Phase III, increased packing density was a goal, subject to the previously described bit-error-rate requirements. Results from Phase III which can improve the packing density include the following:

1. Experiments were performed on the Phase II system which showed that data could successfully be recorded in smaller holograms with a higher spatial carrier frequency and narrower interhologram guardbands. An area packing density increase (from the Phase II values) of at least 70 percent can be achieved from these areas alone.

2. A lens and spinner autoscan design was achieved which meets the required optical specifications and can support the increased spatial carrier frequency mentioned in Item 1, as well as provide a 55 mm or greater scan width. This width will use the available storage area of 70 mm film more efficiently than was done with the 35 mm Phase II film, further increasing packing density.

3. The error characterization experiments and coding study results indicated that the system BER goals could be met using an error correcting code that uses only half the overhead of the Phase II code (11.0 percent versus 19.0 percent). This will provide a further increase in the packing density of user data of about ten percent.

4. Experiments on the Phase II system have shown that thin-base film (in 35 mm width format) can be transported at speeds up to 4.0 meter/second, maintaining both the lateral tracking accuracy requirement and the necessary flatness in the recording plane. If these results can be extended to the 70 mm film projected for the next system, the change from 4.0 mil film to 2.5 mil film would provide approximately an additional 40 percent increase in volume packing density.

Packing Density Summary. In the future, recorded holograms will be smaller, with an increased spatial carrier frequency and reduced inter-hologram guardbands. A more efficient error-correcting code will be used. Thin-base film will probably be useable, increasing overall volume packing density.

3.3.3 Optical Power Requirements

The importance of minimizing the optical power requirements of the system can be emphasized by considering the laser used in the Phase II system. Typically operated at output powers between 1 and 4 watts, it required a water supply (for cooling) of 6 gallons/minute, and up to 50 kW of electrical input power. The following Phase III developments will permit substantial reductions of the WBR system's optical power requirements, and consequently, of its power and water facilities requirements.

1. An improved optical design of the reference beam path has been devised, which will eliminate the need for one of the AOM's used in the Phase II system. Since these devices are typically only about 50 percent light efficient, this will effectively halve the optical input power required to deliver a given amount of light energy to the film plane.

2. The new AOPC has a total light conversion efficiency of around 30 percent (for continuous drive); this is several times greater than the performance of the Phase II unit (at equivalent RF drive power levels). This will further reduce the power output requirement

for the laser used to record the data in the new WBR system.

3. Currently available, system-compatible avalanche photodetectors have been identified which are at least 25 times more sensitive than the PIN devices used in the Phase II system. Analysis of these detectors has been performed which indicates that they will require as little as 5 nW per "1" bit to produce performance which is essentially electrically noise-free ($BER < 1 \times 10^{-9}$). This increased sensitivity will greatly reduce the power requirement of the readout laser in the next system.

4. Analysis of parameter sensitivities and tolerances in the mathematically-modeled WBR system suggested that strong apodization (beam shaping) of the readout reference beam would increase the readout system's light efficiency, while simultaneously reducing inter-channel interference (and hence BER). Experimental confirmation of this was obtained using the Phase II hardware. The result is a reduction of nearly 50 percent in the power output required from the readout lasers in both the Phase II and Phase III systems.

Optical Power Summary. Improved optical design and a more efficient AOPC will reduce the size of the record laser. More sensitive detectors and more effective apodization will reduce the size of the readout laser. Light budget calculations indicate a probable record laser power in the 150-200 mW range, and a read laser power in the 20-35 mW range. This latter result could be especially significant if a read-only subsystem becomes a part of future system requirements, since lasers in the 20 mW range can be lightweight, air-cooled, low power dissipation devices.

3.3.4 Other Phase III Achievements

Most of the items listed above are concerned directly with improvements in the technical performance of the WBR system. A few other achievements are worthy of inclusion in this summary, although they do not fit easily into any of the previous categories; they are concerned with such considerations as the feasibility, cost, operability, flexibility, and future potential of the system.

1. The conceptual design of a dual film transport system, with hand-over occuring during gaps in the incoming data stream, provides two important advantages. First, the length of the individual film segments is reduced to conform to those that are currently available. Second, the length of time the system can

continue recording using this technique is extended indefinitely.

2. A preliminary design of the electronics that control the data reception, encoding, and recording offers a unique and useful option: a user-selectable packing density versus BER trade-off. By varying the width of the holograms, the user of this system will be able to vary the data capacity of a given film spool by up to 2 to 1. Thus more storage space can be assigned to more important data units, decreasing their BER; or conversely, at the expense of some BER increase, extra long data units may be recorded on a standard length film.

3. A design and feasibility study was completed which confirmed the possibility of using Large Scale Integration (LSI) devices to perform the error-correction encoding and decoding.functions. This will reduce the complexity, parts count, etc., associated with applying ECC to the system's 128 channels. Furthermore, it was possible to include in the LSI design enough flexibility to support a variety of particular ECC choices; this will both increase the general applicability

and hence cost-effectiveness) of the new LSI devices, and permit ECC decisions for the WBR system to be tailored more easily (and at a later point in the design/fabrication process) to changing system requirements.

4. At data rates near 1 Gb/s, the main limitations to increasing this performance (in a holographic WBR-type system) are posed by the photodetector bandwidth and sensitivities, the film transport and spinner mechanical speed requirements, the film sensitivity, and the rise times of the acousto-optic devices. The increased packing density achieved during Phase III has cut in half the required film transport and spinner speeds; also, rise times achieved with the new AOPC and other currently available AOM's exceed those needed for a 1 Gb/s recorder, as do the parameters of the new avalanche photodetectors. The laser power has been substantially reduced by various Phase III results; thus a small increase to compensate for reduced film sensitivity would be easily tolerable. The conclusion which can be drawn from all of these considerations is: not only has the technical risk been

essentially eliminated from development of a 900 Mb/s system; it has also been substantially reduced for systems at rates of 1.5 Gb/s or more.

3.3.5 Preliminary Specifications and Design Values for a 900 Mb/s Holographic Digital Data Recorder/Reproducer System

The assumption made at the beginning of the Phase III study was that the system requirements could be met by a straightforward extension of the techniques and devices used in Phase II. This assumption was fully validated by the positive results achieved by all the Phase III subtasks. The current requirements were in fact exceeded in many areas, greatly extending the variety of system configurations to which the holographic WBR approach can be responsive.

We are now in a position to provide more detailed specifications for the system which meets the Phase III requirements. By combining the baseline parameters (given in Paragraph 3.2.8.2) with the results and recommendations of the various subtasks, we can calculate many of the necessary system values. The results appear in Table 3.2.9.5. Some of the items in the table will undoubtedly change during the final design stage of the next system, responding either to changing system goals or to further technical progress in one or more subsystem area; as of the date of this report, however, the stated values describe a workable system solution, and should provide a valuable data base for all future holographic WBR system synthesis activities.

Table 3.3.5 Preliminary Phase III System Specifications

Scan Format (horizontal)	
Scan Width	55 mm
Hologram Spacing	12.45 μm
Hologram Duty Cycle	75%
No. of overhead holograms/scan	98
No. of ECC holograms/scan	476
No. of user data holograms/scan	3842
Total number of holograms/scan	4416
Row Format (Vertical)	
Hologram length	0.85 mm
Hologram frequency band	375-750 cy/mm
Bits/hologram	128
Channel resolution	2.0 Rayleigh
Packing Density	
Local peak (all data)	1.5 Mb/cm^2
Average (user data)	0.83 Mb/cm^2
Average (user data, linear)	14.7 Mb/in.
Storage Medium (Kodak SO-141 or equivalent)	
Film thickness	2.5 mil
Film width	70 mm
Film length	3060 ft.
Capacity (user data)	5.4×10^{11} bits
Film Transport	
Type	dual
Top speed	1.56 m/s
Phase lock accuracy	$\pm 1\%$

Table 3.3.5 Preliminary Phase III System Specifications (con't)

Focal flatness technique	dual air platen
Flatness achieved	$\pm$ 15μm
Lateral tracking accuracy	$\pm$40μm
Start/stop time	1 second
Record time/3060 ft. reel	10 minutes

<u>Spinner</u>

No. of facets	30
Scan rate	1830/second
Speed	3660 r/min
Encoder pulses/facet	64,1
Facet size (height, width)	52 mm, 19 mm
Facet figure (absolute)	$\pm$ λ/20
Facet figure (matching)	$\pm$ λ/32
Facet-toaxis angular tolerance	$\pm$10 arc-seconds
Dynamic facet repeatability (low speed)	$\pm$30 arc-seconds
Dynamic facet repeatability (full speed)	$\pm$15 arc-seconds
Descan error (maximum)	$\pm$ 2 arc-seconds

<u>Transform Lenses</u>

Focal length	131 mm
Pupil dimensions (height, width)	52 mm, 13.4 mm
F# (maximum)	1.5
F# (working)	2.4
Field size (width, height)	55 mm, 2 mm
Wavefront quality	diffraction limited on hologram spacing and bit spacing

<u>Page Composer</u>

Material	TeO_2
No. of channels	128
Diffraction efficiency (average)	30%
Channel uniformity	$\pm$15%
Drive power (typical)	50 mW
Channel data rate	8 Mb/s

Table 3.3.5 Preliminary Phase III System Specifications (con't)

Rise time	18 ns
Crosstalk	-30 dB
Photodetectors (RCA 30818 or equivalent)	
Type	avalanche
Sensitivity	200 mA/W
Light requirement (electrical BER of 10^{-9})	5 nW
Interface	fiber array
Optical fibers	glass, 3 mil core
Error Detection and Correction	
Code type	BCH (127, 113)
Interleave depth (nominal)	34 (full scan)
BER (corrected, average, maximum)	10^{-7}
Laser Source	
Wavelength	514.5 nm
Record power requirement	175 mW
Read power requirement	30 mW
Coherence length (minimum)	2 cm

SECTION IV

4.0 PHASE IV RESULTS

The accurate specifications for an operational Wideband Recorder System can be established only after a thorough analysis of the system capabilities and requirements is complete. The WBR Phase II test results provided some of this data, while at the same time indicating additional areas for futher investigation. During Phase III, we carried out some of these studies by analyzing several ways of increasing the system packing density, investigating error statistics and error correction codes, and measuring system performance during multichannel data readout. The results reported in the Phase III final report, suggested some further desirable experimental investigations. These experiments, performed during the current program phase, fall into four categories:

1. Verification of the analytical coding study performed during Phase III.
2. Investigations into the effect on bit error rate (BER) of readout beam apodization.
3. Installation and testing of a new acousto-optic page composer (AOPC) designed for reduced electrical crosstalk.

4. Investigations into potential improvements in system optical efficiency by reducing the number of acousto-optic devices.

The results of these tasks are summarized below:

1. The coding study proved that the Phase III recommended error correcting codes have the ability to correct a raw random error rate of 10^{-4} to better than 10^{-8}.

2. A 1/e intensity apodization was determined to be optimum in terms of reducing BER.

3. The AOPC fabricated during Phase III was installed and tested in the WBR breadboard. The system crosstalk was reduced by about 6 dB and the system BER was reduced by about a factor of 2.

4. A factor of 5 improvement in optical efficiency resulted from implementing a simplified optical configuration.

This section presents the detailed results of the Phase IV experimental study.

4.1 Coding Study

4.1.1 Introduction

It is well known that large reductions in the overall bit error rate (BER) of a digital data recording system can be made by including a small percentage of data-dependent error detection and correction (EDAC) bits to the recorded data. This coding process can be done in a number of different ways and achieves its optimum effectiveness when the selected code is matched to the type of error sources present in the system. For example, some codes are particularly effective against burst errors, whereas others are designed to handle random errors which rarely occur in strings longer than two or three. Thus, a knowledge of the errors statistics that corrupt the reproduced data in a recording system is essential in choosing an EDAC code which simultaneously has sufficient "correcting power" to achieve a required minimum error rate and also introduces a minimum of overhead bits into the recorded data. The overhead is of importance because it is directly related to the system's total packing density. An additional consideration is the cost and complexity required to implement the EDAC circuitry in a multichannel configuration, such as the WBR system.

4.1.1.1 Error Correction Encoding

The Wideband Recorder system utilizes error correction codes to achieve greater packing density for a given bit error rate (BER). In general, increasing hologram size reduces the BER. This technique may be used to reduce the random errors due to film and optical system noise to any desired level. However, properly choosing an error correcting code and hologram size will provide a higher effective packing density for a given error rate than increasing the hologram area alone. This sole issue justifies the added complexity and expense of incorporating an error correction encoder and decoder. The previous statements were concerned only with errors associated with random noise in the system. Burst errors, associated with general film defects, scratches, or processing problems, are not effectively reduced by increasing hologram size, as the defects easily can be five to ten times the nominal size of a hologram. However, certain error correction coding techniques can effectively combat burst errors. For these reasons, error correcting codes are a cost-effective tool for realizing the desired system performance.

4.1.1.2 Code Choice Considerations

The choice of a proper coding scheme involves many factors; these include performance, cost reliability, simplicity, and overhead. One choice must be made immediately between block and convolutional codes. Convolutional codes are most effectively used in low rate ($<3/4$) systems with poor raw bit error rates ($>10^{-3}$). The Wideband Recorder system has a nominal raw BER below this level ($<10^{-3}$). More important is the desire to use a high rate code ($> 4/5$). The coding rate primarily determines the speed-up factor that the system must operate above the speed required for recording data alone. To achieve the desired overall user data rate of approximately 1 billion bits/second, the 128 channels of the system must be operated at a rate of approximately 8 million bits/second (Mb/s); a coding rate of 1/2 would increase the per channel data rate to 16 Mb/s. The cost and technical difficulty of obtaining photodetectors, acousto-optic devices, film transports, and spinners are very sensitive to data rate around this nominal 10 Mb/s operating point. Thus, block codes appear to be the best approach to pursue for the Wideband Recorder.

There are a number of block codes. In particular, the single and double error correcting Bose Chandri (BCH) codes offer good random-error correcting performance and high rate in the region of interest (raw BER around 10^{-4} or better). These codes can be interleaved to obtain any desired burst capability, and their implementation is relatively simple and inexpensive. Since encoder/decoder operation at the system data rate of approximately 1 Gb/s is not feasible, multiple channels of encoders and decoders are required. The most logical multiple channel configuration utilizes one encoder for each of the 128 channels in the acousto-optic page composer, and a decoder associated with each of the 128 photodetector channels. This also makes the coding scheme somewhat orthogonal to burst errors, since burst errors are generally caused by scratches which are parallel to the holograms. A defect causing an error in one channel position of a hologram would usually increase the probability of error in the other positions of the same hologram, however, since the coding scheme utilizes only one channel per hologram obliterating one entire hologram will not cause an uncorrectable error.

The choice of interleave depth is determined by the code performance and burst statistics. The technique of interleaving redistributes the burst among a number of codewords, effectively randomizing the burst. In the limit, as the interleave depth approaches infinity, the performance of the coding scheme should approach the random error capability of the basic code. Since the defects and scratches typically encountered in the Wideband Recorder are physically limited in size, a relatively small interleaving depth can be quite effective in randomizing burst errors.

The error-correcting code implemented in the Phase II Exploratory Development Model is a (63, 51) BCH code interleaved to depth 4. The basic (63, 51) code uses 12 bits of parity and 51 bits of data to yield a code word of 63 bits with a rate of 51/63 or 81 percent. This code can correct any single- or double-error pattern in the 63-bit block and in addition, due to the specific implementation chosen, is capable of correcting some selected triple-error patterns. The triple patterns chosen were the higher probability errors involving bursts. Interleaving, sometimes referred to as time spreading, improves the capability of the code for burst errors while maintaining the same random error-correction properties.

Interleaving is accomplished by the generation and combination of four codewords into a "superblock" of length 252. The basic code can correct a burst of length 3. A burst length of 12 or less occurring in the interleaved code will generate, at most, three errors in each of the four primary codewords and will, therefo e, be fully corrected.

The random error capability of this code can be approximated in the region of interest by the equation

$$BER_c = 3100 \times BER_r^3,$$

where BER_r is the raw bit error rate, and BER_c is the corrected bit error rate.

During the Phase II system evaluation, the efficiency of this code was measured. We found that for raw error rates in the range of 1.0 to 1.5×10^{-4}, most decoded error rates at interleave depth of 4 were in the range of 10^{-6} to 10^{-7}. For the (63, 51) BCH code interleaved to depth 4, a raw error rate of 1.5×10^{-4} was projected to decode with an error rate of 1.0×10^{-8}.

The failure of the error-correcting code to provide the full correcting power of which it is capable is an indication that burst type error patterns significantly limit the system performance. The fact that corrected error rates of only slightly better than 1.0×10^{-6} were observed indicated that significant bursting was taking place to "overload" the decoding circuits. This was confirmed on several occasions by the observation of repeatable bursts at specific film locations, which could then be isolated and determined to be film processing and (in rarer instances) manufacturing defects.

Two ways of attacking this problem are immediately apparent: (1) improving the quality of film processing and handling techniques; and (2) burdening the electronics and coding circuitry with the task of providing greater burst immunity. The importance of achieving and maintaining higher quality film processing techniques for Phase III and future systems has received strong emphasis during the entire WBR development program, and the conclusion that machines exist which can handle this important task is documented in the Phase III final report. The extent to which well-known electronic techniques for minimizing the effects of burst errors can be applied to systems of the level of development of the current WBR was investigated during Phase III.

4.1.2 Interleave Depth Investigations

4.1.2.1 Interleave Simulation Procedure

To provide the ability to investigate the effects of "code-word length" and "interleave depth" on the system bit error rate performance without building extensive additional electronic circuitry, several modifications were made to the Phase II hardware. These modifications permitted simulated decoding of readout data at a number of different codeword lengths and interleave depths. Here 'simulated' means that errors were not corrected, only detected, and that the output was not the number of errors, but rather the number of times that a particular coding scheme would have failed to correct all errors. To investigate a codeword length of 25 at an interleave depth of 10, the error detection electronics would check every tenth bit to determine the presence of an error. After checking 25 bits, the number of errors in that codeword would be recorded and a new codeword checked. Since the codeword length and interleave depth were variable, this provided a direct measure of the burst characteristics of the data being read out, as well as an indication of the minimum electronic complexity which can handle such bursts. The technique has the disadvantage that for long codewords and large interleave depths, it becomes a time consuming task to collect sufficient data to ensure the statistical validity of the results.

4.1.2.2 Phase III Results

The results obtained during Phase III are decoder failure probabilities, plotted against the interleave depth, with codeword length as a parameter. The first of these results in shown in Figure 4.1.2.2-1

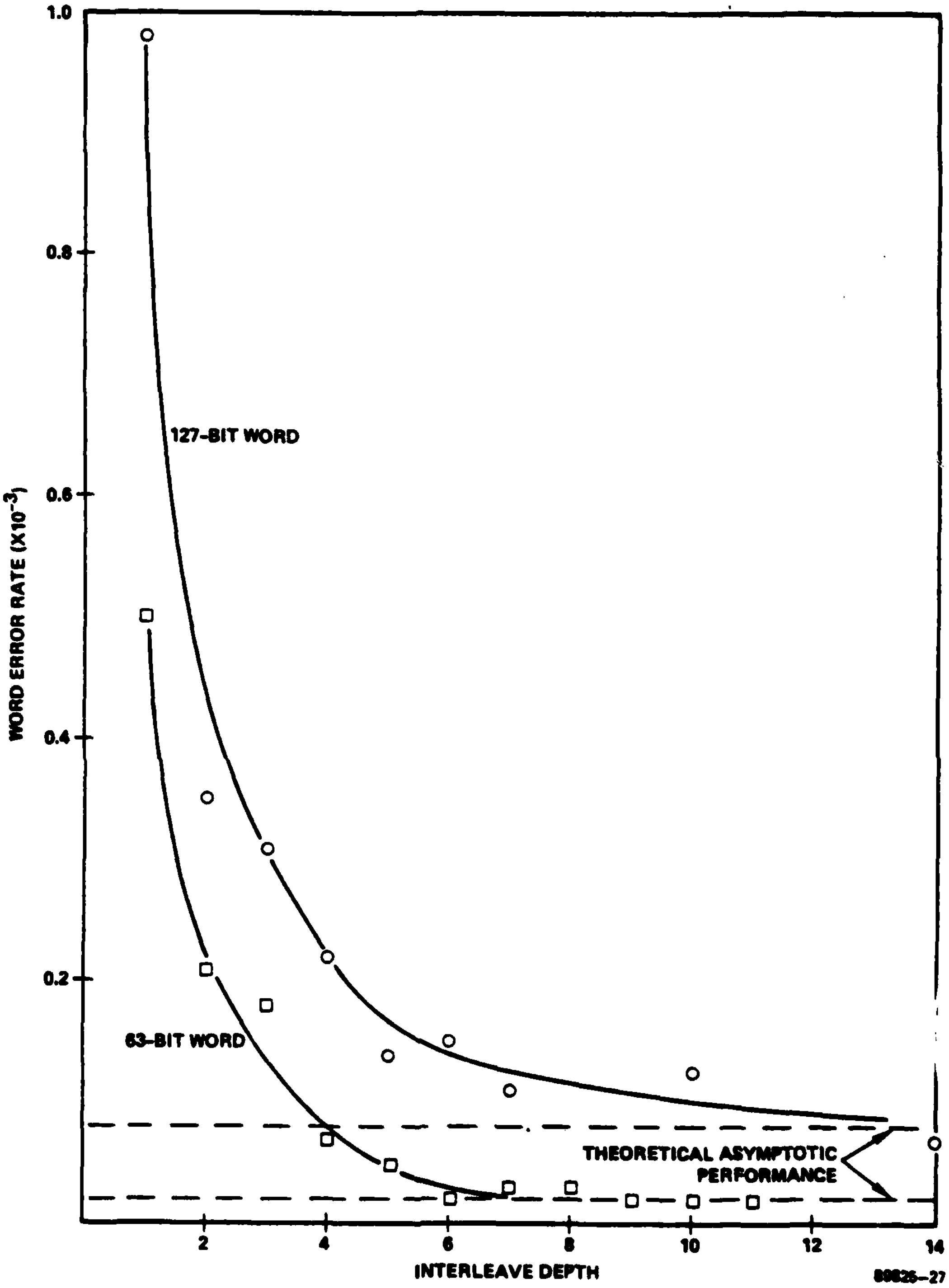


Figure 4.1.2.2-1 Single Error Correcting Code Performance - Phase III Results.

which shows a plot of a multichannel average word error rate (WER) for two different single-error-correcting codes. Two salient facts about these curves are that: (1) the WER decreases with interleave depth, indicating that burst errors do provide a limitation to the noninterleaved system performance; and (2) at an interleave depth between 6 and 10, the WER reaches a lower limit, indicating that most bursts are successfully "randomized" so that they cannot affect more than one bit in a given codeword. Furthermore, the asymptotic values of the WER in these two cases agree very well with theoreitcal limits calculated by using the experimentally determined raw BER of 1.0×10^{-4}. These limits are 8.0×10^{-5} and 2.0×10^{-5} for the 127 and 63 length codes, respectively, and are also shown in Figure 4.1.2.2-1.

Figure 4.1.2.2-2 shows the WER as a function of interleave depth for double-error-correcting codes. The behavior is similar to that of the single-error-correcting codes, except that no visible lower WER limit is reached due to the additional power of these codes. According to the formulae detailed in the Phase III final report, the theoretical limiting WER values for a 1.0×10^{-4} raw error rate are (for the 127 code) 3.2×10^{-7}, and (for the 63 code) 4.0×10^{-8}. At these low rates, and with only a few codewords being read from each scan at the higher interleave depths, collection of enough data for statistical validity was not possible beyond an interleave depth of about 7. Nevertheless, the

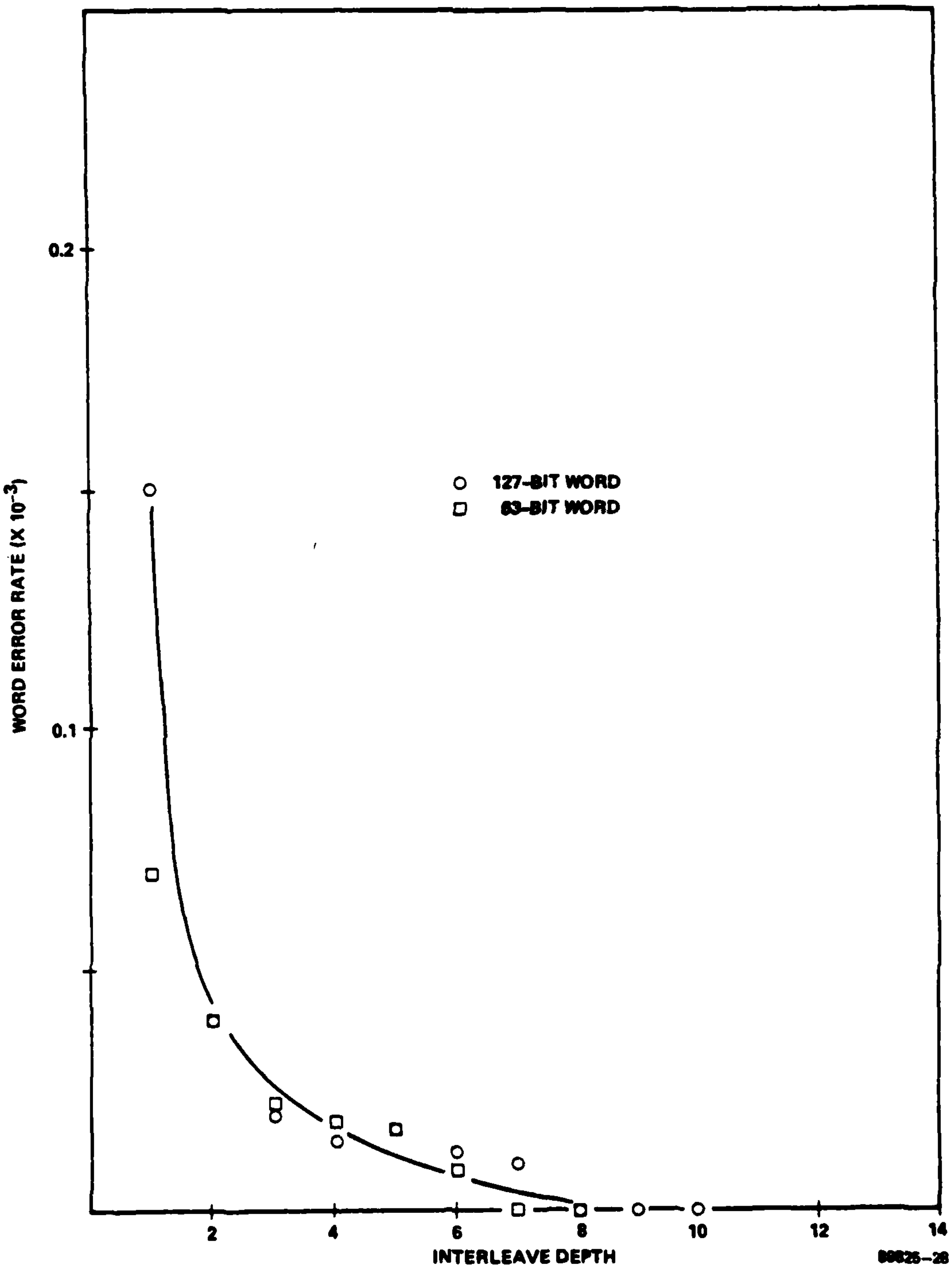


Figure 4.1.2.2-2 Double Error Correcting Code Performance - Phase III Results.

WER did become unreadable (i.e., go below about 1.0×10^{-6}) at the same interleave depth which was observed to produce fully random error performance with the single-error-correcting codes. This provides indirect evidence that random (i.e., burst-free) error correcting performance should be achieved with any of the codes studied if the interleave depth is 10 or greater.

4.1.2.3 Phase IV Experiments

During Phase III, the theoretical performance and the implementation costs both in overhead requirements and electrical complexity were investigated. The complete results are reported in the Phase III final report. In general, both the (63, 51) or the (127, 113) double error correcting codes meet the BER performance requirements of future systems. The (63, 51) code is theoretically more powerful, but is more costly to implement. Since there were advantages to both codes, each was investigated in the present study.

To determine the actual performance limits of the double error correcting codes at large interleave depths, a large amount of data must be collected. Using the interleave simulation procedure described in Section 4.1.2.1 and a film recorded during Phase III but infrequently read, data was collected on the (63, 51) code at an interleave depth of 25 and on the (127, 113) code at an interleave depth of 15 (the maximum possible for a total scan length of 1910 holograms). Channels with a nominal BER of about 10^{-4} were selected and the starting point in the scan was varied.

During data collection, uncorrectable errors caused by severe emulsion damage occurred twice. The cause of these errors was identified and the row containing the film damage was blanked out. In this way, these errors were counted only once rather than on each cycle of the film and since such emulsion damage is rare, counting the same error repeatedly would not be statistically valid.

The results of this task are summarized in Figure 4.1.2.1-1 in which the word error rate data from Phase III and Phase IV are plotted as a function of interleave depth. The theoretical limits for these codes assuming a rawbit error rate of 10^{-4} are also shown. During Phase III, the measured word error rate reached a lower bound of about 10^{-6} due to limited statistics. During Phase IV, data collected at interleave depths of 15 and 25 reduced this lower limit to the region of the theoretical code performance. The effective decoded BER can be calculated from the measured word error rate using formulas derived in the Phase III report.

$$P_c = \frac{D}{N} P_w$$

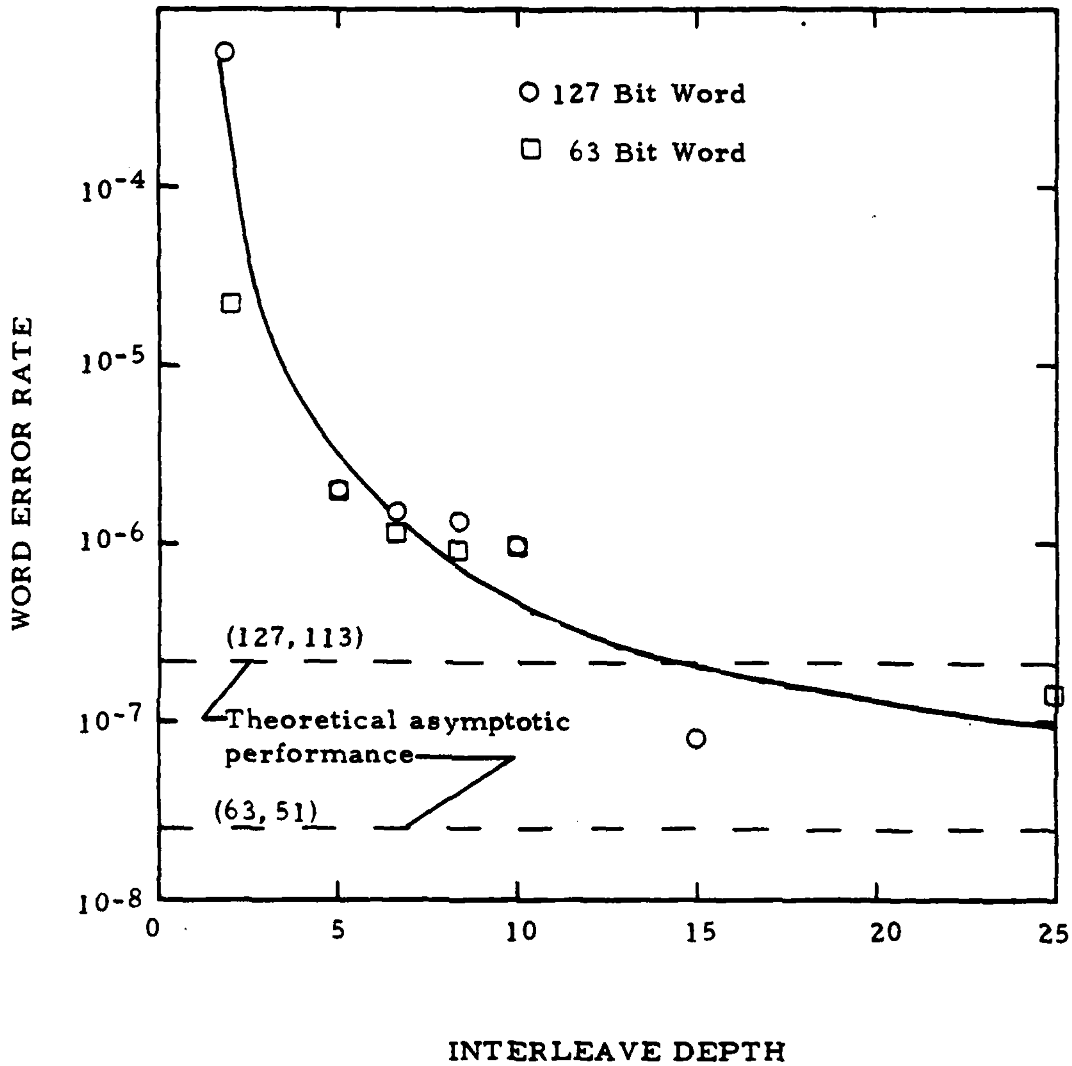


Figure 4.1.2.1-1 The Performance of the Double Error Correcting Codes Extended to High Interleave Depths.

where P_c is the corrected error rate provided the raw errors are random

P_w is measured word error rate

N is the word length

D is the distance of the code (=5 for a double error correcting code).

For the (63, 51) code, the effective decoded BER was 1.7×10^{-8}. For the (127, 113) code the effective decoded BER was 3.8×10^{-9}. The overall results of Phase IV demonstrate that future WBR system could be designed with raw BER's on the order of 3×10^{-5}. The resulting decoded bit error rates if the (63, 51) or (127, 113) code full scan interleaved were implemented would be 8.44×10^{-11} and 3.54×10^{-10}, respectively.

Our results show that, as predicted during Phase III, the (63, 51) or the (127, 113) double error correcting codes can meet future system requirements. For best results, in either case the code should be interleaved over the full width of the scan. Taking into consideration the extensive tradeoff in cost, memory requirements, and circuit complexity performed during Phase III the (127, 113) BCH double-error correcting code full scan interleaved is recommended for future systems.

4.2 Vertical Packing Density Study

4.2.1 Introduction

The average area packing density on the Phase III Exploratory Development Model was approximately 3.5 Mb/in^2 inclusive of all guardband and other overhead areas on the film. Although localized peak values were about twice the average, they remained well below theoretical limits. Therefore, during Phase III, techniques for increasing the system packing density were investigated.

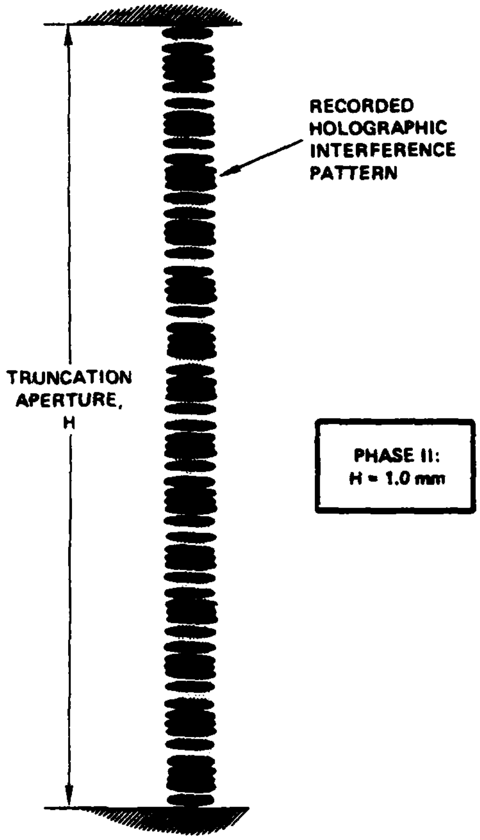
Packing density increases can be achieved only at the cost of increased bit error rate. Vertical packing density is increased by reducing the height of the hologram which increases the channel-to-channel crosstalk. Increasing the horizontal packing density is accomplished by reducing the hologram width. The temporal resolution of the hologram is reduced, with a corresponding BER increase. Spatial frequency increases in packing density are the result of shifting the spatial frequency range recorded in the hologram upward. This requires both better response from the Fourier transform lenses and improved film MTF response.

Useful increases in packing density improve overall system parameters in two areas. First, the volume required to store a given quantity of information is reduced thereby minimizing the space, time and cost requirements associated with maintaining a large archival data store. Second, the speed at which some of the electromechanical system components must operate is reduced.

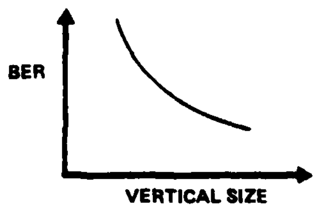
4.2.2.1 The Effect of Hologram Truncation

Figure 4.2.1.1 summarizes the considerations associated with vertical packing density. The hologram, as shown, is a superposition

VERTICAL PACKING DENSITY



- EACH HOLOGRAM CONTAINS 128 BITS
- EACH BIT IS REPRESENTED BY A COSINE FRINGE PATTERN
- PERFECT SPATIAL BIT RESOLUTION WOULD REQUIRE RECORDING OF INFINITE-LENGTH COSINES
- TRUNCATING THE HOLOGRAM:
  - DECREASES RESOLUTION
  - INCREASES PACKING DENSITY
- PERFORMANCE CRITERION: BIT ERROR RATE (BER)
- EXPECTED PERFORMANCE:



- GOAL: 10-20% INCREASE IN PACKING DENSITY FOR ≤20% INCREASE IN BER

89578-4

Figure 4.2.1.1 Vertical Packing Density Considerations of interference fringe patterns from 128 channels; each channel produces a cosinusoidal fringe pattern with a slightly different spatial frequency. In the Phase II system, the recorded frequencies range from 300 to 600 cycles per millimeter. The resolution of adjacent channels when the hologram is read out depends on the total number of cycles recorded for those channels in the hologram. Therefore, truncation of the hologram length (H) by recording the hologram rows closer together increases packing density in the along-film ("vertical") direction, but degrades the channel-to-channel separation, causing an increase in crosstalk and hence bit error rate.

4.2.2.2 The Effect of Apodization

Optical interchannel interference occurs when the light from one channel is smeared so that some of its energy is incident on neighboring fibers. During Phase III, the single channel light distribution during readout was analyzed. It was shown that by using a record reference beam and/or a readout reference beam with a Gaussian amplitude profile, the size of the sidelobes can be reduced. For optimum film response, a uniform intensity profile during recording is desirable. Therefore, if apodization is used, it must be implemented during readout.

As the edge intensity is reduced, less use is made of the information stored at the edges of the hologram. As a result, edge intensities due to the combination of record and read processes of less than $1/e^2$ were found to be impractical. Conversely, as the edge intensity decreases, the percentage of the beam energy which falls on the hologram increases and the percentage which passes through the Rayleigh filter increases. Therefore, for a perfectly illuminated hologram, most of the laser energy is wasted by the system.

4.2.3 Phase III Results

During Phase III, three basic experiments were carried out. First, readout experiments were done with a reference beam which varied in size. When the beam was smaller than the hologram height, this experiment simulated a packing density (PD) increase; when the beam was larger than the hologram height, the nature of the experiment was that of apodizing the read beam, as well as investigating the significance of adjacent-row crossread. Second, record/read experiments were performed with vertical PD increased by 11 percent. Finally, the recorded vertical PD was increased a total of 22 percent and additional BER readout data were taken.

The results of these experiments are summarized in Figure 4.2.3-1 which shows a plot of the average error rate change as a

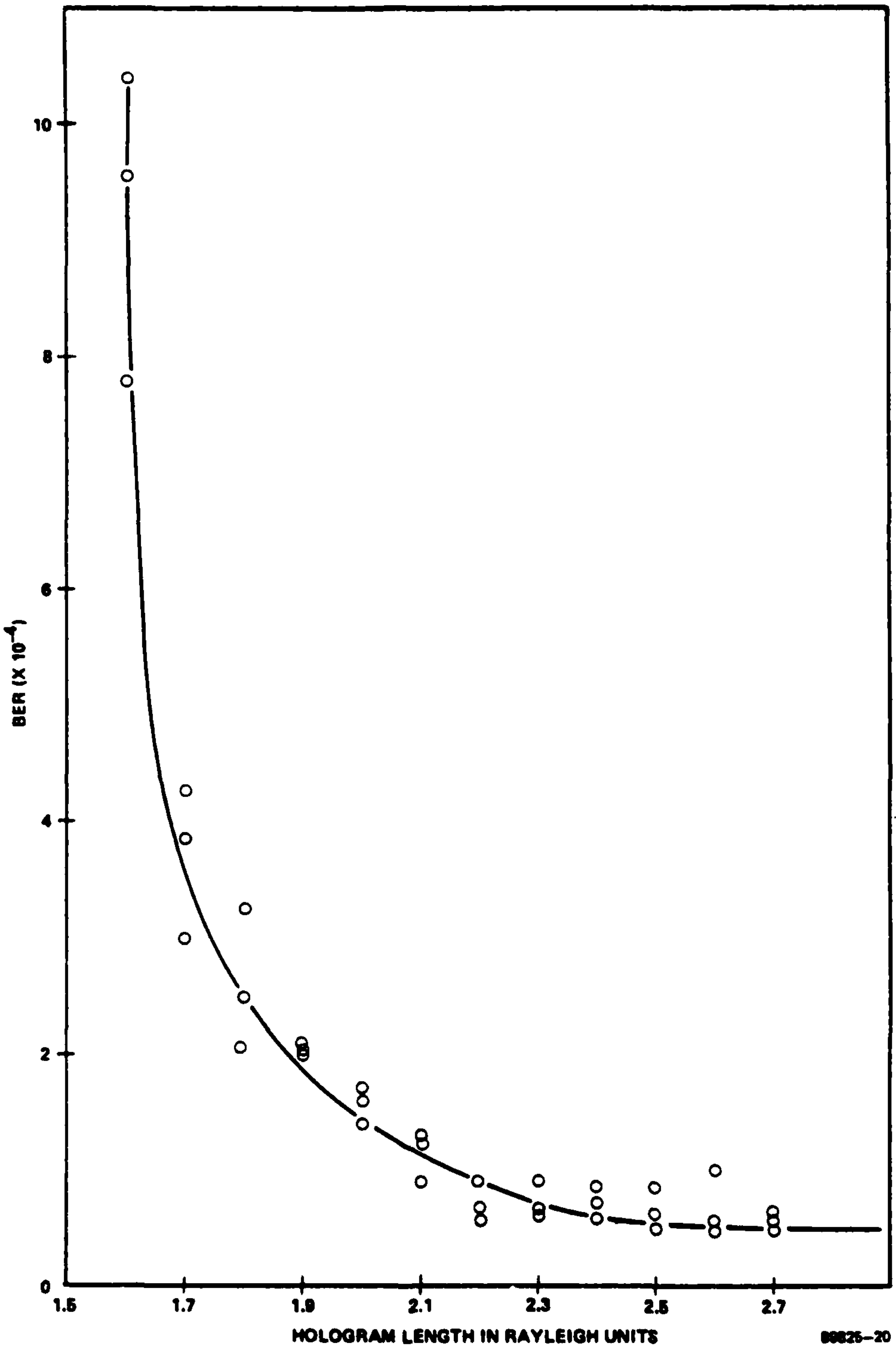


Figure 4.2.3-1 Vertical Packing Density - BER Versus Hologram Length

function of changes in the hologram's vertical size. The abcissa is labeled in units of "single-Rayleigh" resolution, with the Phase II nominal value of 2.3 Rayleigh indicated. The results show that a 10 percent increase in vertical packing density can be achieved at the price of about a 20 percent increase in BER, and that, with the Phase II hardware, the BER increases very rapidly as the length of the hologram is made smaller than that required for double-Rayleigh resolution of the channels. Vertical packing density increases will be relatively expensive in terms of BER.

A section of the Phase III System Analysis task investigated the effect of apodization on the hologram readout. The normalized signal energy and the channel-to-channel interference to signal ratio (ISR) were computed for several values of readout apodization. We found that the signal energy was fairly insensitive to apodization up to $1/e^2$, while the ISR decreased rapidly with increasing apodization. These results suggest that apodization during readout might be an effective means of reducing interchannel optical interference and that additional hologram shortening may be possible with proper choice of apodization.

4.2.4 Phase IV Experiments

As a result of the Phase III analysis, an experimental investigation into the effects of reference beam apodization during readout was performed during the Phase IV. study. A recording made during Phase III with increased horizontal and vertical packing densities was read out with a reference beam which was adjustable in both size and apodization.

The results are summarized in Figures 4.2.4-1 and 4.2.4-2. The figures show BER as a function of the falloff in light intensity from reference beam center to edge with reference beam size in units of single Rayleigh resolution as a parameter. Several channels were read out and some variations in BER performance were noted, but the basic pattern remained constant so two representational channels are presented for clarity. The plotted BER was measured with the reference beam centered on the holograms; however, it was noted that for readout beams providing less than 2 Rayleigh resolution, BER improvements of up to a factor of 2 could be achieved by offsetting the reference beam to either side.

4.2.5 Discussion and Conclusions

The current experiments have verified the predictions that apodization during readout can more efficiently utilize the hologram area and reduce sidelobe interference thereby reducing BER. At the 2.1 Rayleigh resolution recommended during Phase III for hologram length, a reference beam intensity apodization of 1/e results in approximately a 20% improvement in BER. As the apodization is increased beyond this,

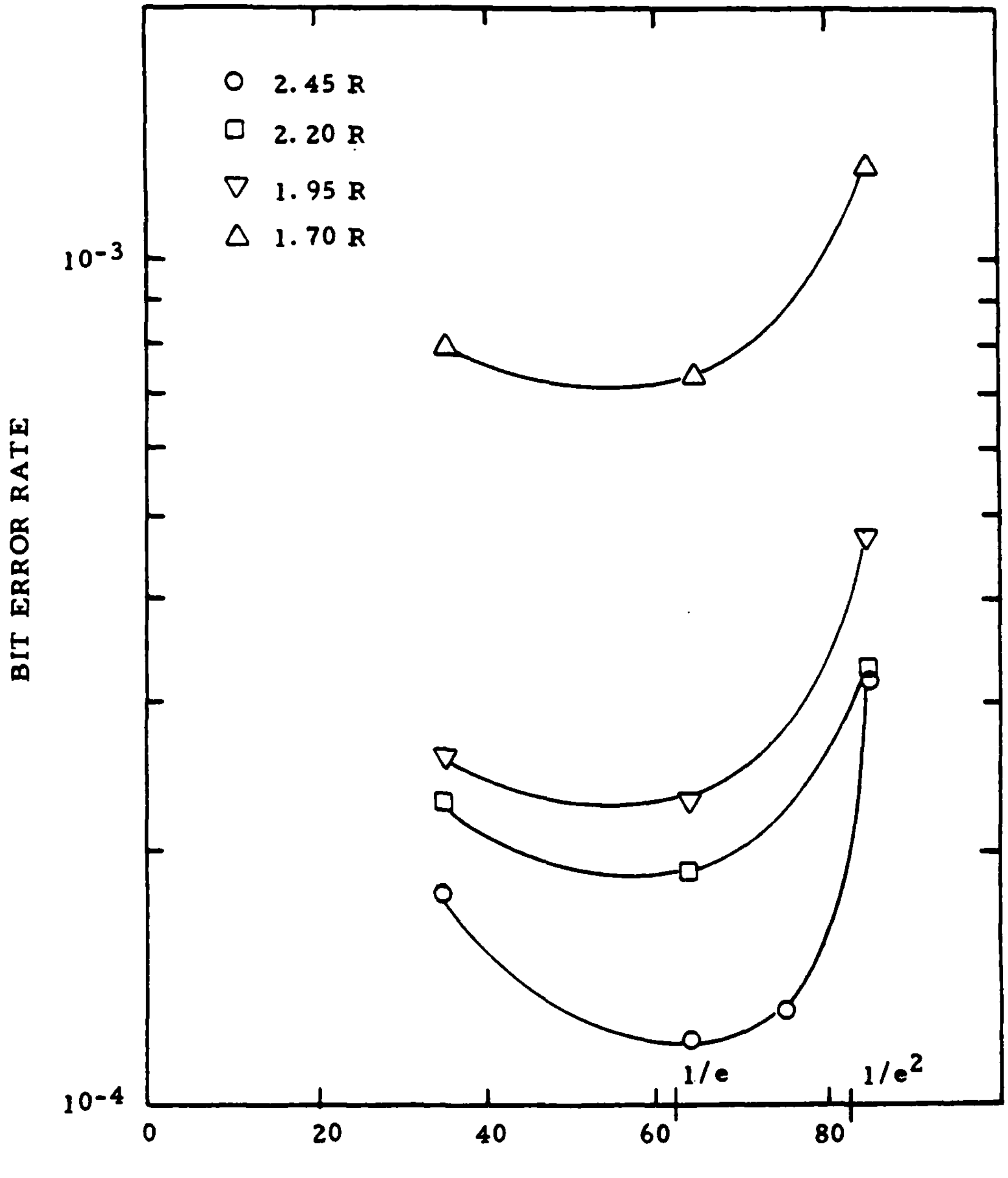


Figure 4.2.4-1 The Effects of Reference Beam Intensity Apodization - BER Versus Intensity Falloff, Channel 26.

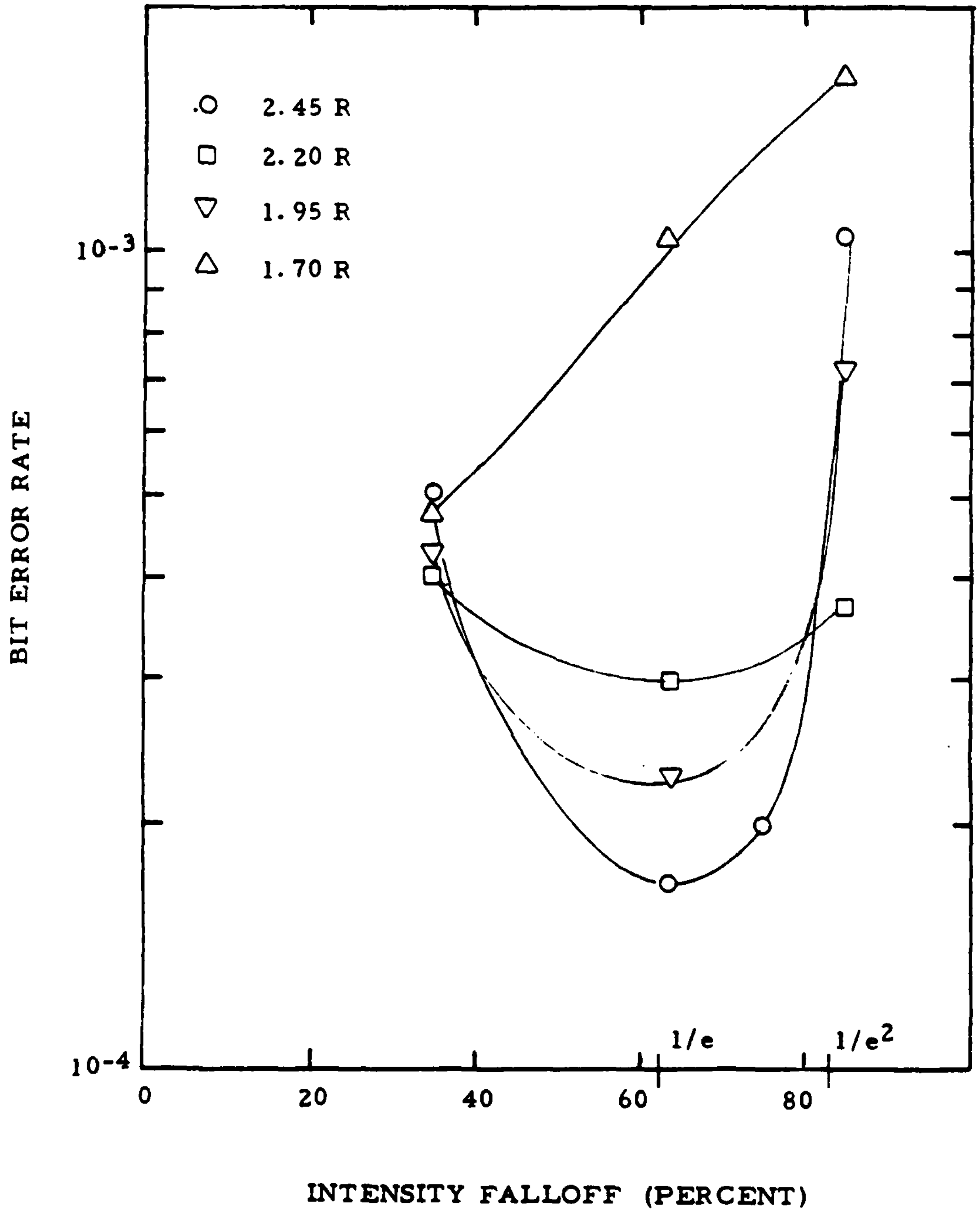


Figure 4.2.4-2 The Effects of Reference Beam Intensity Apodization - BER Versus Intensity Falloff, Channel 9.

the BER rapidly increases indicating that too much of the information stored near the edges of the hologram is being lost. At the 1/e apodization level, reducing the hologram size from 2.2 R to 1.95 Rayleigh resolution units results in a 20% increase in BER, whereas over-illumination during readout results in improved BER.

As a result of this investigation and the results of the Phase III study, we would recommend the hologram length should be 2.1 Rayleigh resolution units and the readout apodization should be 1/e.

4.3 Alternate AOM Configuration Study

4.3.1 Introduction

The light efficiency of the WBR optics is an important consideration in the design of future systems. In the Phase II EDM, a Coherent Radiation CR-12 argon ion laser is used. The facilities requirements for this laser include 3 phase 440 VAC power input and two water lines running at 2 gpm and 4 gpm to cool the power supply and head. With improved optical efficiency, future systems could be designed around a lower power laser which has a lower initial cost, requires simpler facilities to support it, and is less expensive to operate.

During Phase IV, the optical system was reconfigured to permit the use of a single modulator/beamsplitter acousto-optic device in the record system. The goal of this task was to show that the new configuration can provide benefits to the system's light budget while maintaining adequate light level control, SNR, and BER.

4.3.1.1 Original System Configuration

Acousto-optic (AO) devices perform several important functions in the WBR Phase II EDM, including temporal modulation, beam splitting, and page composition. Figure 4.3.1.1-1 shows a schematic diagram of the AO devices used during Phase II. The first device, the Parabola Acousto-optic Modulator (AOM), operates in the loss modulation mode to correct for reference beam intensity variations due to the scanning process. As more RF power is applied to this device, more energy is diffracted from the transmitted beam.

The modulated throughput beam from the parabola AOM illuminates the Main AOM which temporally modulates the reference beam during recording to generate the blanking region, the hologram-to-hologram guardbands, and the frame sync region. There are three levels of RF drive used by the Main AOM: Guardband, Hologram, and Off. In recording data holograms or checkerboards, the RF drive alternates between the hologram level and the guardband level. During blanking, the Main AOM operates at the guardband level. The frame sync region is generated by turning the Main AOM off during certain periods in order to produce clear regions on the film. During readout, the reference beam

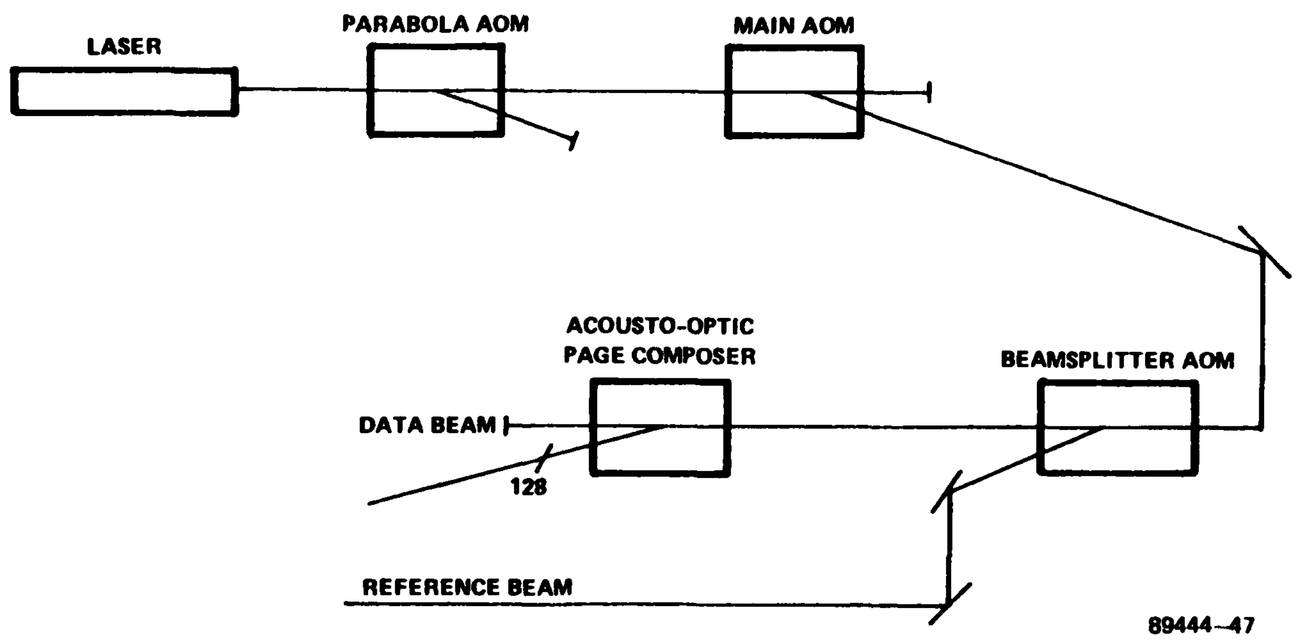


Figure 4.3.1.1-1 Acousto-Optic Devices in WBR Phase III System

illuminates these clear regions and is detected by the same detector used to recover bit sync. High-rate recording requires that the rise time associated with these transitions be as short as possible. Since the rise time of a change in light level produced by an AOM depends on the propagation time of the acoustic waves through the optical beam, the rise time can be minimized by using a very small light beam. This is achieved in the main light-modulation AOM of WBR by focusing the beam in the cell.

The temporally modulated beam from the Main AOM then enters the beam splitter AOM. Since the signal to this device is constant, rise time considerations are not important here. However, another characteristic of acousto-optic devices is very significant. That is the fact that, because the light wave interacts with a moving acoustic wave, a Doppler-like frequency shift (equal in magnitude to the RF acoustic frequency) is induced in the diffracted light. Since holographic recording requires complete coherence between reference and signal wave, this frequency shift would ordinarily prevent such recording. This problem is solved in the WBR by using the diffracted, frequency-shifted light as the reference beam, and using the undiffracted light to illuminate another AO device, the page composer. Driven by the same RF source as the beamsplitter, the page composer imparts to the signal beam a frequency shift identical to that of the reference. Thus, coherence is preserved and interference can still take place.

To produce simultaneously many optical channels of data, a multichannel AO device is needed. Except for its multichannel nature, this device, the acousto-optic page composer (AOPC) is essentially identical to the modulator described above. The AOPC used in the WBR Phase II EDM has 128 channels arranged in a linear array. To minimize signal rise time, a line source of light is focused through the crystal. The output of the AOPC is Fourier transformed and interferred with the reference beam to form the hologram.

4.3.1.2 New AOM Configuration

Since only the diffracted beam from the Main AOM is used during recording, this system does not have a high optical efficiency. Figure 4.3.1.2-1 shows a schematic diagram of the new AOM configuration investigated during Phase IV.

The parabola AOM serves the same purpose as previously, to compensate for variations in the reference beam intensity due to the scanning process. The modulated throughput beam is then incident on the second acousto-optic device which combines the functions of the Main AOM and the beam splitter AOM. The diffracted beam from this device becomes the system reference beam. During a recording it achieves three light

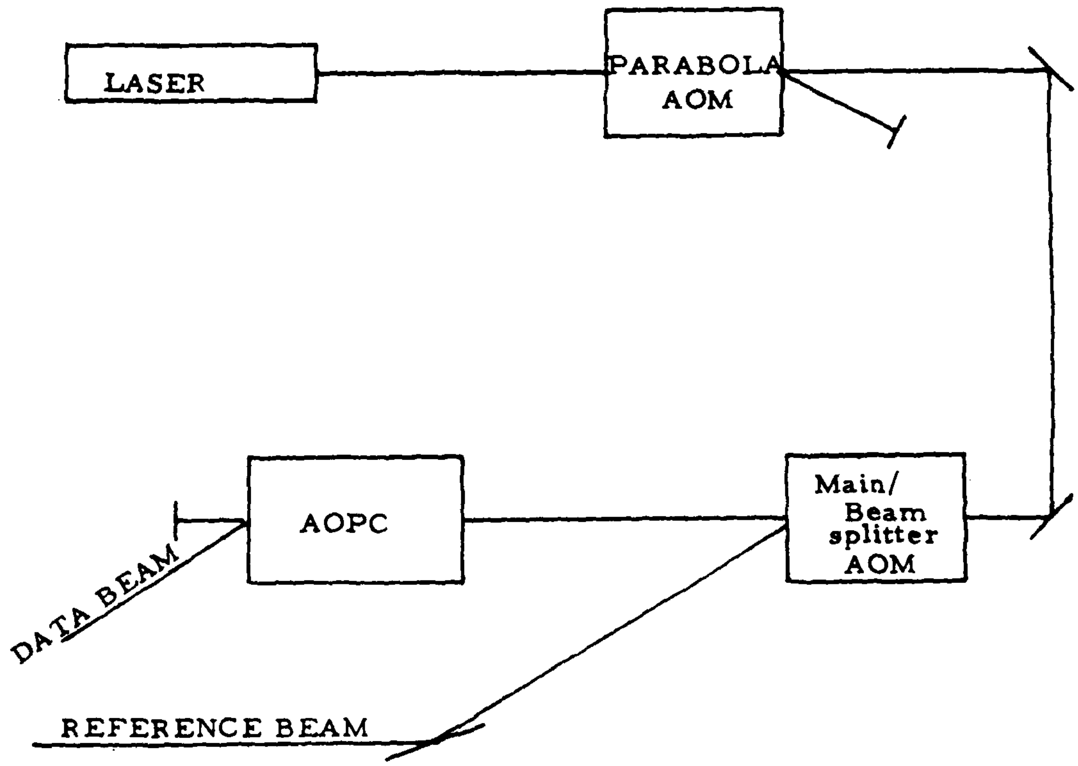


Figure 4.3.1.2-1 Acousto-Optic Devices in WBR Phase IV Simplified System.

levels: Guardband, Hologram, and Off. During a scan, the reference beam is turned to the guardband level during blanking, off to generate line sync, and alternates between hologram and guardband levels to record the data.

The undiffracted beam from this device illuminates the AOPC. The AOPC has only two levels, hologram record level and off. The AOPC is turned off except when data is being recorded. This allows the beam splitter to generate the guardband and line sync conditions since the AOM throughput beam is stopped by the AOPC during these periods.

In operation, the main AOM RF drive is used to drive the single modulator in the new configuration. The guardband light level is set using the main 60 dB attenuator in the RF control drawer. During guardband periods, the residual light which illuminates the page composer is blocked by turning the page composer off. The reference beam hologram level is set using the vernier attenuator in the system control electronics. The undiffracted light is incident on the AOPC and the signal level is set by attenuating the page composer RF drive. During line sync generation, both the AOM and the AOPC are turned off.

4.3.1.3 Expected Light Efficiency Changes

During the Phase II component evaluation, the optical efficiency of the major components in normal record mode, normal read-out mode, and with minimum light attenuation was measured.

An intensity loss of 56.6 percent was measured between the laser output and the input to the Main AOM; this light was lost in the parabola AOM and the servo system. In the record mode, with 1 dB of attenuation in the Main AOM, 7.4 percent of the input power was diffracted. With no attenuation, 38.5 percent of the incident light was diffracted. In the record mode (with a typical beamsplitter setting of 4) eighty percent of the input light was channeled into the signal path and 13 percent was diffracted into the reference beam with the remainder lost in reflections. With the beamsplitter control set at zero, seventy percent of the light went into the signal beam and 23 percent was diffracted into the reference beam.

During recording with 1 dB attenuation in the Main AOM and 4 dB in both the beamsplitter and page composer, 0.056 percent of the laser output reached the film plane. With no attenuation in the acousto-optic devices, 0.43 percent of the light reached the film. Most of the loss occurred in the page composer which had a diffraction efficiency on the order of 0.2 percent. The system efficiency during readout was 14.5 percent. During readout, the beam bypassed the high speed modulators and most of the optics.

As aresult of the new configuration, major efficiency improvements are expected in the record mode. With the old system, at worst 7.4 percent and at best 38.5 percent of the light reaching the Main AOM was used for the recording. With the new configuration, 100 percent of the light which reaches the AOM is available for the recording minus small losses due to reflections. The system efficiency is therefore expected to improve by a factor of 3 to 6 depending on the attenuation required to set the proper light levels.

4.3.2 Phase IV Results

To convert the EDM to the new configuration, the Main AOM was removed from the system and a mirror jog added to properly center the beam on the beam splitter. The RF drive to the Main AOM was then used to drive the beamsplitter.

Light level measurements were made at critical points in the optical path before and after the system change. Table 4.3.2-1 summarizes the old system power measurements when in record mode. The efficiency of the Main AOM was about 2% for hologram record level and about 10% for guardband level with 1 dB of attenuation in the system.

The system was then reconfigured as described above. The efficiency of the beam splitter was set to the same level as previously and the laser current was adjusted to set the reference beam power to the guardband level. The system was adjusted for a recording and the optical power was remeasured. The results are summarized in Table 4.3.2.2-2. Note the initial laser power required with the new configuration is about a factor of five lower than that required previously. With the present

Table 4.3.2-1. System Power - Old Configuration

	Optical Power	
	Guardband Level	Hologram Level
Laser Output Power	1.35 W	1.35 W
Main AOM Incident Power	635 mw	635 mw
Beamsplitter Incident Power	63 mw	12.6 mw
Beamsplitter Diffracted Power (Reference)	18 mw	3.9 mw
Beamsplitter Throughput Power (Signal)	37 mw	7.6 mw
Reference Beam Power at Film Plane	2.25 mw	0.52 mw
Signal Power at Film Plane	40 μw	8.2 μw

Table 4.3.2-2. System Power - New Configuration

	Optical Power	
	Guardband Level	Hologram Level
Laser Output Power	250 mw	250 mw
Beamsplitter Incident Power	110 mw	110 mw
Beamsplitter Diffracted Power (Reference)	24 mw	5.5 mw
Beamsplitter Throughput Power (Signal)	50 mw	70 mw
Reference Beam Power at Film Plane	2.2 mw	0.52 mw
Signal Power at Film Plane	7.2 μw	8.5 μw

acousto-optic modulator this is the largest power reduction possible since operation with less input power can be achieved only by increasing the diffraction efficiency of the AOM. This can be accomplished by increasing the RF drive power, however, higher RF power levels risk damaging the AOM. For a future system, the acousto-optic device would be designed to provide higher diffraction efficiency.

A standard recording was made with the new AOM configuration. The average BER was measured to be about 5×10^{-5}, a factor of two worse than for films recorded just prior to the system reconfiguration. The relatively poor performance can be attributed to two areas. First, operating the Coherent Radiation CR-12 laser which is capable of maximum 5W output at 250 mW required such a low current that the laser light output was not stable. Density variations due to the fluctuating laser power were apparent on the recorded film. Second, in the Phase II EDM readout electronics, a data strobe is generated to determine at what points the analog data is sampled for thresholding. The same strobe is used to sample both data bits and frame sync bits. Unfortunately, the optimum frame sync detection occurs when the frame sync bits are center sampled while the minimum BER occurs when the data bits are sampled from 20 to 30 percent after the analog center. With a 20 percent offset, frame sync is detectable, but as the strobe offset is increased to

30 percent, frame sync can not be recovered with the present electronics; thus, readout is not possible. For the sample recording, optimum BER occurs at a strobe displacement of greater than 28 percent. Therefore, the true minimum BER was not obtained due to the loss of frame sync. This problem is associated with the Phase II electronics and could be eliminated in future designs by decoupling the data strobe and the line sync strobe. It is not a fundamental system limitation.

The results of this task show that the system can be operated with a single AOM replacing the Main AOM and the beam splitter AOM. The 9W laser required in Phase II can be replaced by a 500 mW or possibly smaller argon ion laser. In the new configuration, light level adjustments for the signal and reference beams are independent as required for good system operability. Bit error rates on the order of 5×10^{-5} were measured. With a stable laser and optimized strobe positioning, error rates on the order of 2×10^{-5} are expected.

4.4 Acousto-Optic Page Composer Evaluation

4.4.1 Introduction

During Phase III of the Wideband Recorder program, a new acousto-optic page composer and associated RF drive electronics was designed, fabricated, and independently tested separate from the system.

The intent was to improve the technical performance of the page composer. In particular, diffraction efficiency and channel-to-channel crosstalk were identified during Phase III as factors which limited overall system performance. The purpose of the Phase IV task is to install the previously fabricated page composer in the system and determine the resulting effects on system performance.

4.4.1.1 Acousto-Optic Devices

An AO device is a block of transparent material (various types of glass, for example) through which a laser beam is passed that can be modulated or deflected. In the crystal, the light beam encounters the acoustic wave. Devices used in the WBR system operate in the Bragg diffraction mode which produces two main output beams as shown in Figure 4.4.1.1-1. One beam, the undiffracted component, has not interacted with the acoustic wave and is usually discarded. The other beam, the diffracted component, has interacted with the acoustic wave. Temporal modulation of the acoustic wave amplitude can be used to temporally modulate the amplitude of the diffracted light wave. Frequency modulation of the acoustic wave will produce angular variation of the light wave, since the diffraction angle is proportional to the spatial frequency of the acoustic wave. The acoustic wave is introduced into the crystal by means of an electromechanical transducer which is bonded to one face of the crystal, and which in turn is connected to an appropriate source of RF electrical

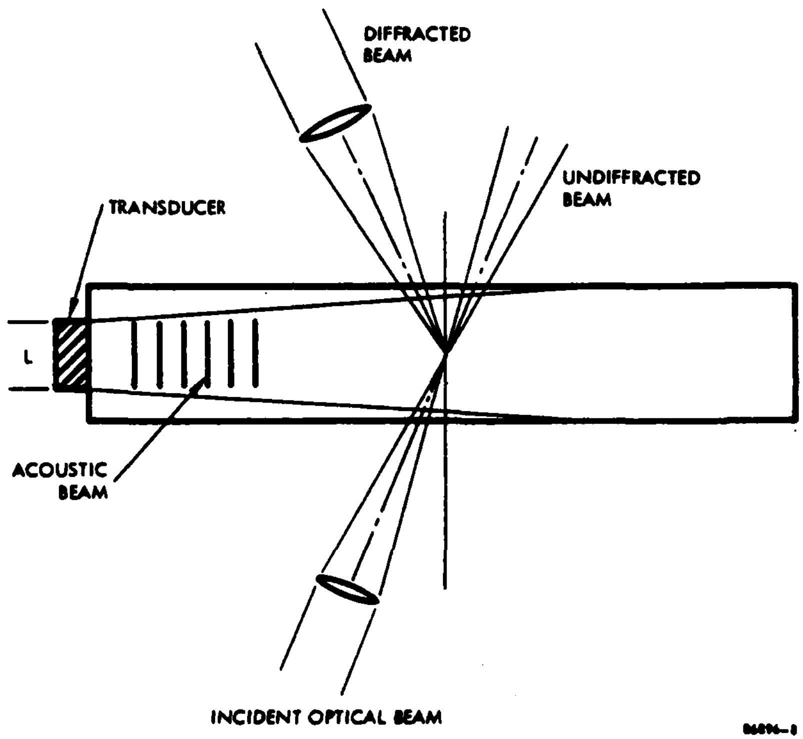


Figure 4.4.1.1-1 Details of Acousto-Optic Interaction.

energy and associated control circuits for amplitude or frequency modulation.

To produce simultaneously many optical channels of data, a multichannel acousto-optic modulator (AOM) is needed. High data rate recording requires that the rise time associated with turning on any channel of the page composer be as short as possible. Since the rise time of a change in light level produced by an AOM depends primarily on the propagation time of the acoustic waves through the optical beam, the rise time can be minimized by using a very small light beam. This is achieved by fucusing the line illumination of light through the crystal. The AOPC used on the Phase II EDM has 128 channels arranged in a linear array. The reduction to 32 channels was made to minimize fabrication costs rather than to meet any technical system needs. In any future model, a 128 channel page composer is required and can be fabricated using the same design techniques employed for the present AOPC.

4.4.1.2 The Phase II Page Composer

The design and mechanical construction features of the Phase II AOPC are detailed schematically in Figure 4.4.1.2-1. In this cutaway drawing, most of the important physical features can be seen in relationship to the unit as a whole. Important design considerations for a multichannel AOPC include: maximization of the diffraction

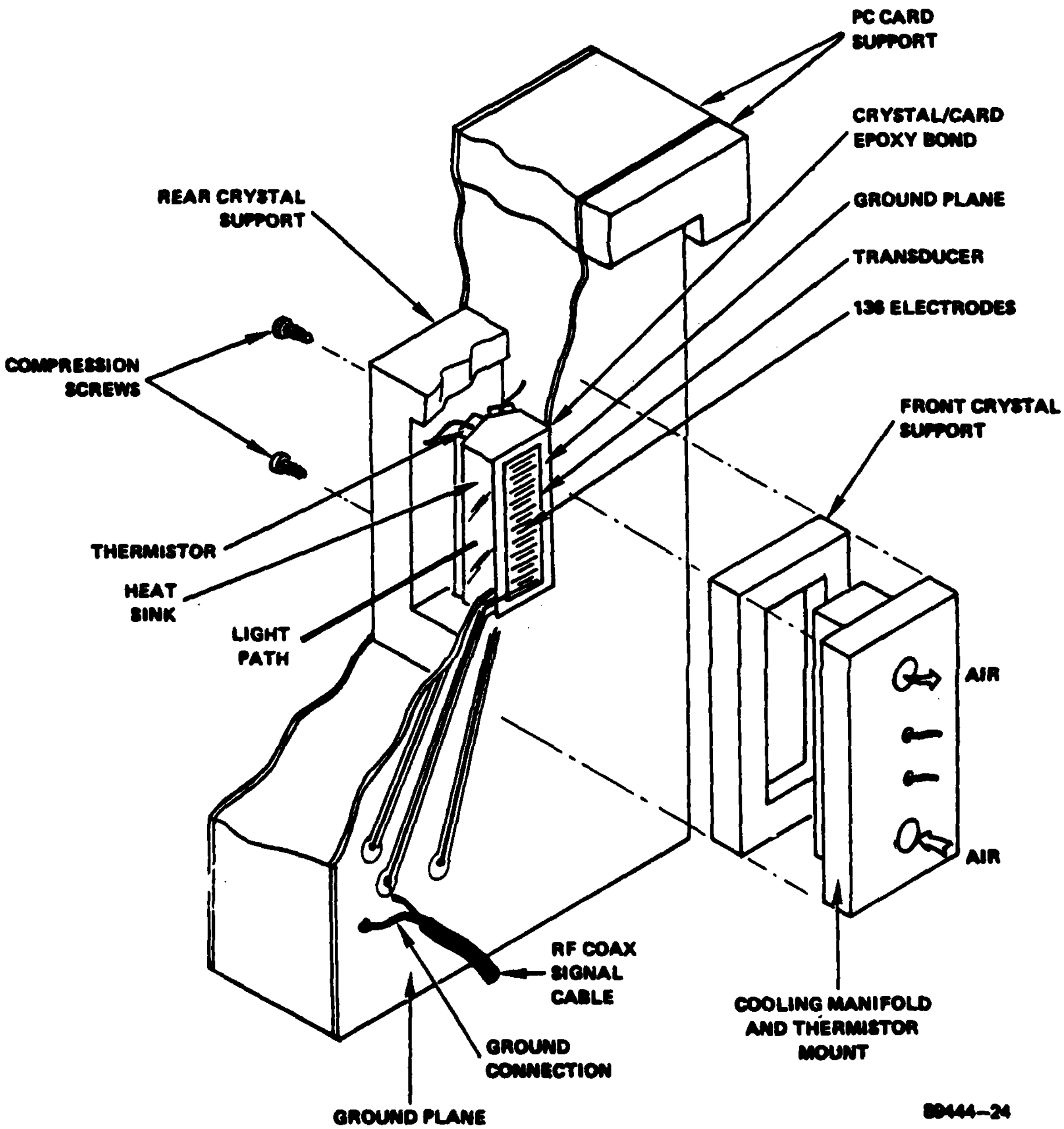


Figure 4.4.1.2-2 Phase II AOPC - Cutaway View

efficiency, extinction ratio, bandwidth, useful aperture, minimization of thermal effects, reflection losses, crystal aberrations, and channel-to-channel crosstalk. In addition, the monitoring of performance and heating effects, and properly adjustable mounting hardware are essential features of a successful design.

4.4.1.2-2 illustrates the beam/structure clearance consideration. The Phase II AOPC design requires that

$$\Theta_{in} - \Theta_{w} \geq 4^{\circ} \text{ for clearance.}$$

Since Θ_B is relatively small, $\sin \Theta_{in} \cong n \sin \Theta_{w}$. These two relations yield a minimum value for Θ_w of

$$\Theta_w \geq 6^{\circ}.$$

The value selected, $\Theta_w = 6^{\circ}$, provides structural clearance and produces a total beam deviation angle of 8°. The beam deviation in the WBR Phase II system is taken care of by inserting a "zig-zag" input device, which offsets the illumination beam input angle by such an amount that the diffracted beam can continue along the optical recording path.

The following table lists the complete specifications for the WBR Phase II AOPC. One explanatory note is needed. The Phase II unit was fabricated with a greater wedge angle than necessary. Therefore, the table below includes both the actual wedge and deviation angles and the minimum required angles.

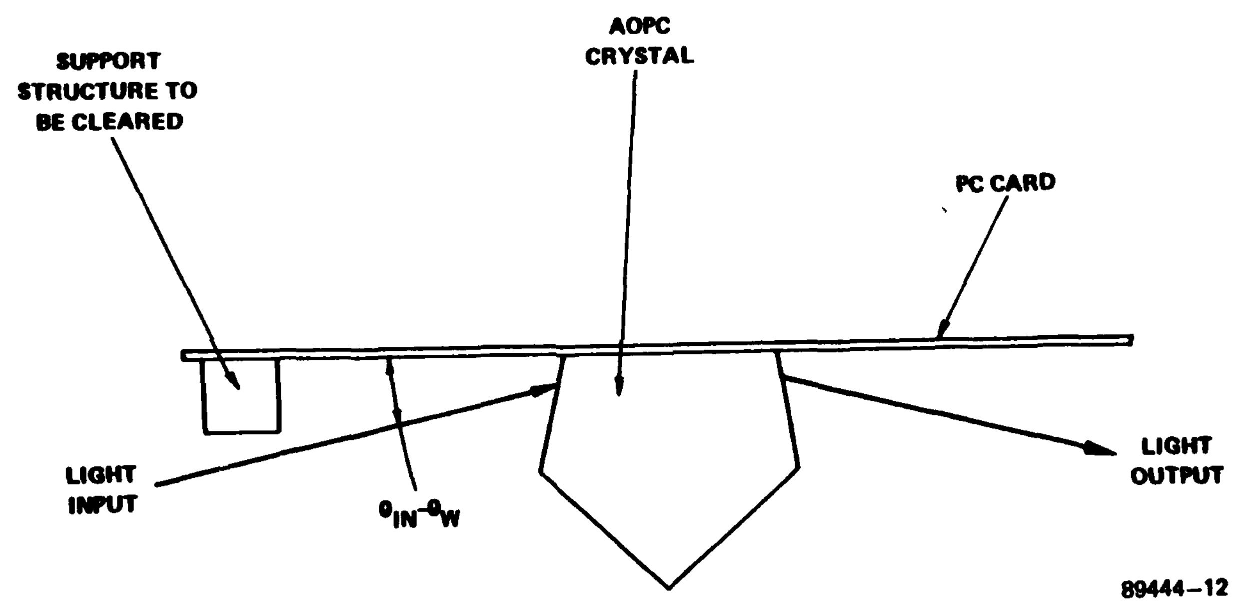


Figure 4.4.1.2-2 Structure Clearance by Crystal Wedging

Table 4.4.1.2-1. WBR Phase II AOPC Specifications

• **Crystal Physical Characterist.**	
Number of Elements (Electrodes)	136
Electrode Center-to-Center Spacing	250 μm
Electrode Height	125 μm
Interaction Length	6 mm
Material	SF 8 Glass
Transducer Size	10 mm x 35 mm
• **Optical Characteristics**	
Clear Aperture	35 mm x 10 mm
Optical Wedge (Actual)	15°/Surface
Optical Wedge (Minimum)	6°/Surface
Beam Deviation (Actual)	21°
Beam Deviation (Minimum)	8°
Coating	MgF for 514.5 nm
Reflectance after Coating	1.3%/Surface
• **Electrical Parameters**	
RF Carrier Frequency	130 Mhz
Card/Cable Interface Impedance	14 Ω
Digital Data Rate	6 M bit/second/ channel

Table 4.4.1.2-1. WBR Phase II AOPC Specifications (con't)

- Thermal Characteristics

Transducer Cooling	Forced Air
Crystal Cooling	Convective
Temperature Sensing	Matched Thermistor Pair

- Performance Levels

Insertion Loss (Including Absorption)	5.3%
Power Reflective Losses (Calculated from Interface Impedance Value)	32%
Nominal Diffraction Efficiency (λ = 514.5 nm)	50%/200 mW

During Phase III, an investigation was performed to characterize the types of system errors and their causes. The results documented in the Phase III final report showed that electrical crosstalk in the page composer was a major limitation on system performance and that a reduced crosstalk AOPC should provide a substantial decrease in raw BER.

4.4.1.3 The Phase III Page Composer

A summary of the key AOPC design parameters for the Phase III page composer is given in Table 4.4.1.3-1.

Since electrical crosstalk was determined to be a major noise source, special design considerations to minimize the electrical crosstalk were made. The crosstalk suppression goal was set at 30 dB in the WBR Phase III specification, with the minimum acceptable being 20 dB. Crosstalk is defined in Reference Data for Radio Engineers as "interference from other communication channels". In the WBR system, the crosstalk is taken to be any change in the optical intensity of a given channel due to acoustic beam interference or RF interference.

RF interference may come from any of several sources. A certain amount of crosstalk can be attributed to the coupling between the inductors used to tune the channels. In order to minimize the crosstalk

Table 4.4.1.3-1. Phase III AOPC Design Specifications

1.	Number of contiguous operating channels	32
2.	Transducer Size	100 μm
3.	Center-to-center channel spacings	250 μm
4.	Rise Time (10% to 90%) of the optical flux with 90 μm beam size	25 ns maximum with the design goal of achieving 18 ns maximum
5.	Diffraction efficiency with 200 mW drive power	50% minimum
6.	System crosstalk isolation	20 dB minimum with design goal of achieving 30 dB minimum
7.	Channel-to-channel deviation (time invariant)	± 1.5 dB maximum
8.	Optical transmission at 0.514 μm	92% minimum
9.	Center frequency nominal	150 MHz
10.	Material	TeO_2
11.	Beam position from the transducer surface	250 μm to 600 μm
12.	Clear aperture (measured from the transducer surface)	50 to 3000 μm
13.	Temperature range (ambient)	$23^{\circ}C \pm 5^{\circ}C$
14.	Thermal interlock range	To be specified
15.	Expandable number of channels	128 minimum

due to this source, the inductors were wound on toroidal cores, so that the magnetic field would be contained within the space of the core.

The grounding scheme selected for use in the AOPC can have a significant effect of the crosstalk. If any part of a multiple channel circuit requires a common path for the currents, severe crosstalk can be expected. In WBR II the transducer ground plane was connected to the circuit card by a wire bond which necessitated common current flow for all channels through the ground bond wire. This scheme appeared to be one of the major reasons for the excessive crosstalk levels observed in the WBR II AOPC; confirmation of this came when we used the same Phase II circuit card with the Phase III AOPC and the observed crosstalk level decreased from about -30 dB to -35 to -45 dB. The AOPC grounding scheme designed for the Phase III unit ensured that the transducer ground plane made effective RF connection to the circuit card ground plane very close to each transducer line. This design feature provided a significant reduction in channel-to-channel crosstalk.

Another source of RF crosstalk is coupling between microstrip lines. Since the transducer separation is specified to be 150 μm, the line spacing cannot be increased to decrease the amount of coupling. There is a tradeoff between reducing the voltage coupling factor and increasing the coupling region. Since the tradeoff curves must be emperically determined, this is not an easy tradeoff to analyze. One means of reducing the adjacent channel electrical crosstalk is to require that electrical neighbors be driven in phase quadrature. This was done on both the Phase II and Phase III page composers.

4.4.2 Phase III AOPC Results

This paragraph summarizes the test procedures and results from the Phase III AOPC task. All testing was performed off the Wideband Recorder EDM.

4.4.2.1 Diffraction Efficiency and Channel Uniformity

When used in the system, the AOPC was illuminated with a line source of light. Therefore, an effective diffraction efficiency (DE) was measured under line illumination conditions. For line illumination the width of the laser beam perpendicular to the acoustic propagation vector was roughly 90 μm to achieve the requisite rise times. This beam size was obtained by passing both the undiffracted and diffracted beams through a cylindrical lens. The optical configuration is similar to the one used in the WBR system. Both the diffracted and undiffracted beams were measured using a power detector whose active area was covered with an aperture to assure that the undiffracted beam width measured was the same width as the diffracted spot. Using the apertured photodetector, the undiffracted beam was measured with no RF applied to the AOPC to establish a zero level then, with power applied, the intensity of the diffracted spot was measured. The results of these effective diffraction efficiency measurements appear in Table 4.4.2.1-1; the value given is the ratio of the intensities of the diffracted spot to the apertured portion of the undiffracted beam. The average diffraction efficiency (DE) per channel was 24.94 percent with a standard deviation of 1.88 percent. This compares to the average DE per channel for the previous AOPC of about 8 percent.

DE uniformity was also measured using line illumination. Each of the channels was driven with roughly the same RF power; the DC and diffracted beams were measured for each channel. DE uniformity measurements were performed at a fixed illumination distance from the transducer; this data appears in Table 4.4.2.1-2.

The specification for DE uniformity was a channel-to-channel deviation of $\pm$ 1.5 dB max. This is taken to mean that the maximum channel DE must not be more than twice the minimum DE. The AOPC easily met this specification. With the incident beam positioned close to the transducer the maximum DE was 27.9 percent (channel B1), while the minimum DE was 18.6 percent (channel A7). With the incident beam positioned farther out in the crystal, the maximum DE was 46.0 percent (channel A10) and the minimum DE was 32.2 percent. Channel

Table 4.4.2.1 Channel Uniformity

Channel Number	Diffracted Power (mW)	DC Beam (mW)	Effective DE (Percent)
A13	16	40	40
A7	18.5	44.5	41.6
A6	21	52.5	40
A16	22	53	41.5
A5	26	61.5	42.3
A11	24	59	40.7
A4	26.5	67.5	39.3
A10	29	63	46.0
A16	21.5	56	38.4
A3	23.0	58.5	39.3
A9	28	68	41.2
A15	26	64	40.6
A2	23.5	57.5	40.9
A8	22	55	40
A1	19	49	38.8
A14	19	50	38
B14	15.5	38.5	40.3
B1	18	48	37.5
B8	21.5	51.5	41.7
B2	23.5	56.5	41.6
B9	25	60.5	41.3
B15	22.5	57	39.5
B3	25	62.5	40
B16	24	63	38.1
B10	24.5	62.5	39.2
B4	24	60.0	40
B5	24	58.5	41
B12	22.5	57.5	39.1
B11	23	56	41.1
B6	19.5	59.5	32.8
B13	19	59	32.2
B7	19	57	33.3

Remarks:

1. RF Drive Power (mW)
2. Background Illumination (mW)
3. Beam far out into the crystal 4 mm
4. Average DE = 39.60 percent, σ = 2.734 percent

Table 4.4.2.1 Diffraction Efficiency, Line Illumination

Channel Number	Diffracted Power (mW)	DC Beam (mW)	Effective DE (Percent)
B14	1.14	4.9	23.3
A13	1.36	5.4	25.2
A7	1.04	5.6	18.6
B1	1.56	5.6	27.9
B8	1.77	7.0	25.3
A6	1.9	7.4	25.7
A12	1.8	6.3	28.6
B2	1.85	7.0	26.4
B9	1.9	6.9	27.5
A5	1.75	7.4	23.6
A11	1.85	7.8	23.7
B15	1.79	7.2	24.9
B3	1.94	8.0	24.3
A4	2.05	8.3	24.7
A10	2.29	9.0	25.4
B16	1.82	7.5	24.3
B10	1.8	7.5	24.0
A16	1.75	7.2	24.3
A3	1.86	7.4	25.1
B4	1.82	7.2	25.3
B5	1.66	7.2	23.1
A9	2.1	8.9	23.6
A15	1.9	7.6	25.0
B12	1.6	7.0	22.9
B11	1.61	7.0	23.0
A2	1.75	7.0	25.0
A8	1.64	6.4	25.6
B6	1.5	5.9	25.4
B13	1.58	5.9	26.8
A1	1.54	6.0	25.7
A14	1.6	6.1	26.2
B7	1.37	4.9	28.0

Remarks:

1. RF Drive Power = 40 mW
2. Background Illumination = 0 mW
3. Beam slightly away from transducer for first 28 entries
4. Beam very near the transducers for last 4 entries
5. Average DE = 24.94 percent, σ = 1.879 percent

DE values were dependent on the distance from the transducer. The exact cause was not determined, but it is suspected that the surface scratches may have been responsible for these variations rather than acousto-optic variation.

The DE experiments were conducted to determine the sensitivity of the DE performance of the new AOPC to several variables. The DE was measured as a function of both illumination distance and RF power. The experimental setup was the one described previously but RF drive levels were increased. The DE specification was that the DE should be 50 percent minimum at a drive power of 200 mW. A DE of 60% was measured with only 50 mW RF input when the spot was near the transducer.

Using line illumination the DE was measured as a function of illumination distance; as is to be expected the DE does not vary appreciably with illumination distance. The reason for this is that regardless of illumination distance, all portions of the acoustic beam have light interactions and contribute to DE.

The DE as a function of RF power was measured with 7 channels driven simultaneously at the same power level. A cylindrical lens was used to focus the seven spots onto the photodetector. An aperture was placed on the cylindrical lens such that the undiffracted beam included all the light allotted in the system for seven channels; that is, the collected light passed beneath seven transducers and the corresponding seven areas between the transducers. This data could be called a system diffraction efficiency measurement, since it is representative of the way in which the AOPC would be implemented in the WBR system. The results are shown in Figure 4.4.3.2-2. At RF drive levels of 50 mW, approximately thirty percent of the incident light is diffracted into usable bit patterns.

4.4.2.2 Crosstalk Measurements

Crosstalk measurements were also made. A portion of the diffracted spot of the channel under observation was centered on a photodetector. Variations in the intensity of the center of the diffracted spot with the phase between the RF drives of the adjacent channels and the drive of the channel under observation were recorded as evidence of the crosstalk phenomenon. The phase relation was varied with a "line stretching" device. The crosstalk figure in dB is 20 log ($\sqrt{1 + \Delta x} - 1$), where Δx is half of the total observed variation in optical power of the diffracted spot, normalized to the mean optical power of the diffracted spot. The measurement of crosstalk in this manner represents a specification on the bit height fluctuations of the digital data retrieved from the AOPC.

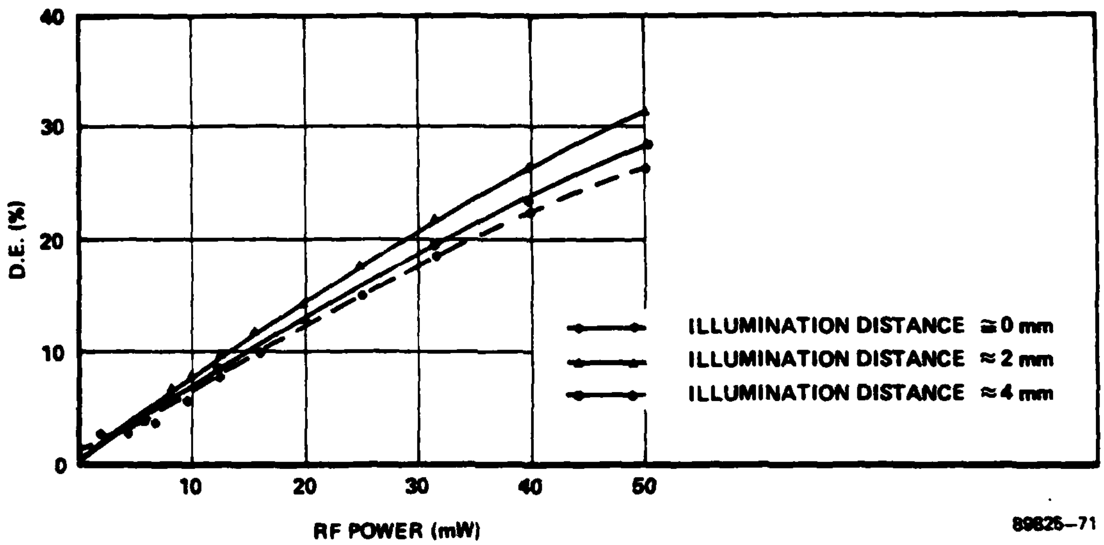


Figure 4.4.2.1-1 DE as a Function of RF Drive Power Using Line Illumination (7 Channels Driven).

The channels of the AOPC can be categorized into three basic types from a crosstalk standpoint: channels which are electrical but not optical neighbors, channels which are optical but not electrical neighbors, and channels which are neither optical nor electrical neighbors. Electrical neighbors are channels which have adjacent microstrip lines; optical neighbors have adjacent transducers. It was found that the phase relation for the maximum coupling between optical neighbors differs by 180° from the relation for the maximum coupling between electrical neighbors. The crosstalk figure for electrical but not optical neighbors was 32.3 dB. Crosstalk figure for optical but not electrical neighbors was 40 dB. The crosstalk figure for channels which were both electrical and optical neighbors was 31.6 dB. Hence the worst case crosstalk occurs between the channels which are both electrical and optical neighbors.

4.4.2.3 Summary of Phase III AOPC Study

The performance of the AOPC was quite satisfactory and in many cases exceeded the specification. However, its long term reliability and performance in the system remained undetermined. Any problems associated with the thermal stress could not be detected until all channels were excited to the full operational level. Table 4.4.2.3-1 summarizes the major achievements of the Phase III AOPC unit and a comparison of the measured values with the original specification.

TABLE 4.4.2.3-1

COMPARISON OF AOPC SPECIFICATIONS WITH AOPC PERFORMANCE

	Specification	Desired Goal	Experimental Results
10 - 90% Rise Time	25ns	18ns	17.97ns (Ave for 7 channels with ~90μm spot)
Crosstalk ($\cong 20\log(\sqrt{1-\Delta X}-1)$)	-20dB	-30dB	-30.2dB (on the basis of 4 channels adjacent to A3
Diffraction Efficiency (200mW RF)	50%	50%	>60% ● 50mW RF
Channel Uniformity (on basis of DE)	±1.5dB	±1.5dB	± 1.3dB or better

4.4.3 Phase III RF Drive System Results

The RF drive system provides to the AOPC the digitally modulated RF signals which feed the array of transducers (128 in a full system, 32 for this initial Phase III study). The required inputs for the RF system are the digital data for each channel, the system-generated modulation and timing signals, and the necessary master system control signals.

The Phase III RF system design divides the electronics into four basic modules:

1. The A module, which contains the master RF oscillator and the mixers which impose the system-generated modulation signals onto the RF signal.

2. The B module, which splits the RF into four mutually-orthogonal phases (i.e., 0°, 90°, 180°, and 270° phase angles with respect to the input) to permit "phase randomization" of the recorded data (more details on phase randomization appear in Section VIII and Reference 1).

3. The C modules, which split the RF signals and associated clock signals into a number of channels (16 for the Phase III study, 64 for a full system).

4. The D modules, each of which contains two channels for data modulation and final power amplification; the D module outputs are the AOPC transducer inputs.

The Phase III subtask plan called for the design, fabrication, and testing of the modules required to provide 32 channels of modulated data, with circuitry and housing designed to permit later expansion of the system to the full 128 channel requirement.

Table 4.4.3-1 summarizes the RF subsystem performance and compares the results to the original specifications. The RF subsystem performed to most of the specifications within the scope of the limited testing that was performed. The data and experience obtained will be beneficial in improving the performance of future systems. Characterization of the whole AOPC/RF subsystem performance as an integrated unit which could not be done during Phase III is reported in the next section as part of the Phase IV results.

4.4.4 Phase IV AOPC Test Results

The purpose of the Phase IV AOPC task was to integrate the page composer and RF drive electronics which were fabricated during Phase III and tested off the breadboard into the WBR Phase II EDM. The system performance with the new page composer was compared to that with the old page composer. To account for differences due to the

Table 4.4.3-1

RF SUBSYSTEM SPECIFICATIONS AND TEST RESULTS

Frequency	150 MHz	150 MHz
Frequency Stability	±0.1 percent	0.2 percent total after 3 hours warm up
Spectral Purity	100 KHz maximum	Not measured
Power Out	200 mW minimum	200 mW per channel 50 mW linear
Power Adjustment	Nominal set by pad 20 to 200 mW; adjustable 0 to 10 dB below nominal	>15 dB
Power Stability	±0.5 dB in 4 hours ±1.0 dB in 24 hours	±.4 dB for 4 hours ±.4 dB for 24 hours
Rise and Fall Times RF out	10 ns maximum	15 ns
Modulation Inputs		
Data Chop Extinction Ratio	30 dB below Nominal Power out minimum	-35 dB
Data Parabola Dynamic Range	10 dB minimum	>15 dB
Data in Extinction Ratio	30 dB below Nominal Power out minimum	-35 dB

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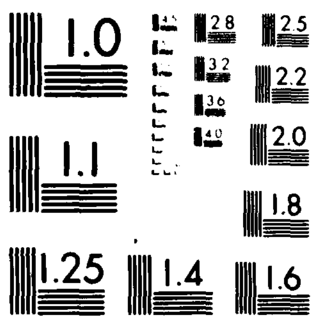

MICROCOPY RESOLUTION TEST CHART
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Table 4. 4. 3-1 (cont)

RF SUBSYSTEM SPECIFICATIONS AND TEST RESULTS

AOPC Attenuator	10 dB smooth dynamic range; repeatable within the system spec; see Power Stability	>15 dB
AOPC Off Switch	A switch will be provided to shut off all channel RF leakage >30 dB below nominal output	-35 dB
AOPC Overtemp Sensor	Circuitry for sensing AOPC temperature will be incorporated into RF Subsystem	deleted due to scope change
Phase Spacing (4 groups of 8 channels)	90^{o} nominal	90^{o}
Phase Adjust	Three groups will be adjustable $\pm 10^{o}$ about their nominal 90^{o}	$\pm 10^{o}$
Single Phase Shut Off	-30 dB extinction on any phase	-30 dB
Operating Temperature Range	$+23^{o}C \pm 5^{o}C$; all specifications to hold after 15 minute warmup	not measured

reduction in number of channels, control experiments were run using the old page composer with 128 channels operating. The same experiments were then repeated with the old page composer with 32 channels working; these experiments established a control for baseline comparison with the new AOPC. After all control experiments were complete, the old page composer was removed from the system and the new page composer installed. The final experiments were run and the results compared to the control data. The basic experiments included measurement of system BER and measurement of crosstalk. The procedure and results for this series of experiments are reported in the remainder of this section.

4.4.4.1 Page Composer Operation and BER Measurements

Standard recordings with 128 channels operating were made and the bit error rates of the 32 channels in the center of the page composer were measured. The center 32 channels were selected to avoid potential differences due to the spatial frequency of the data channels. During Phase II, a study was performed to determine if spatial frequency affected bit error rate. No effects were found, however, the film used during Phase IV, SO-332, has a different MTF than the previous film, SO-141. This will be discussed further in Section 4.5. The average measured BER for the 32 center channels was about 8.5×10^{-5}. Very good channels produced a raw bit error rate ranging from 2.0×10^{-5}

to 4.0 x 10^{-5}. However, several channels had error rates in excess of 10^{-4}; these higher bit error rates were caused by low diffraction efficiency and several very poor electrical contacts.

The next step was to determine how results obtained with a 32 channel page composer would relate to the normal 128 channel device. To do this, the RF drive to 96 channels of the old page composer were terminated into 50 Ω loads leaving only the center 32 channels operable. By terminating into 50Ω loads, electrical noise and crosstalk were minimized. The 32 operating channels were phase randomized using the same scheme employed for 128 channel operation.

Recordings were made with the old page composer limited to 32 channels. The optical power per channel was maintained constant so the overall signal level was one quarter what it was previously. This has the effect of raising the K-ratio of the recording, but keeps the DE per channel relatively constant. All 32 channels were reconstructed and measured for errors. The average bit error rate for this configuration was about 4 x 10^{-5}, roughly a factor of two better than with 128 channels operating. Several channels had bit error rates less than 2 x 10^{-5}, but most channels again fell between 2.0 to 4.0 x 10^{-5}. The relevant difference was the number of low BER channels.

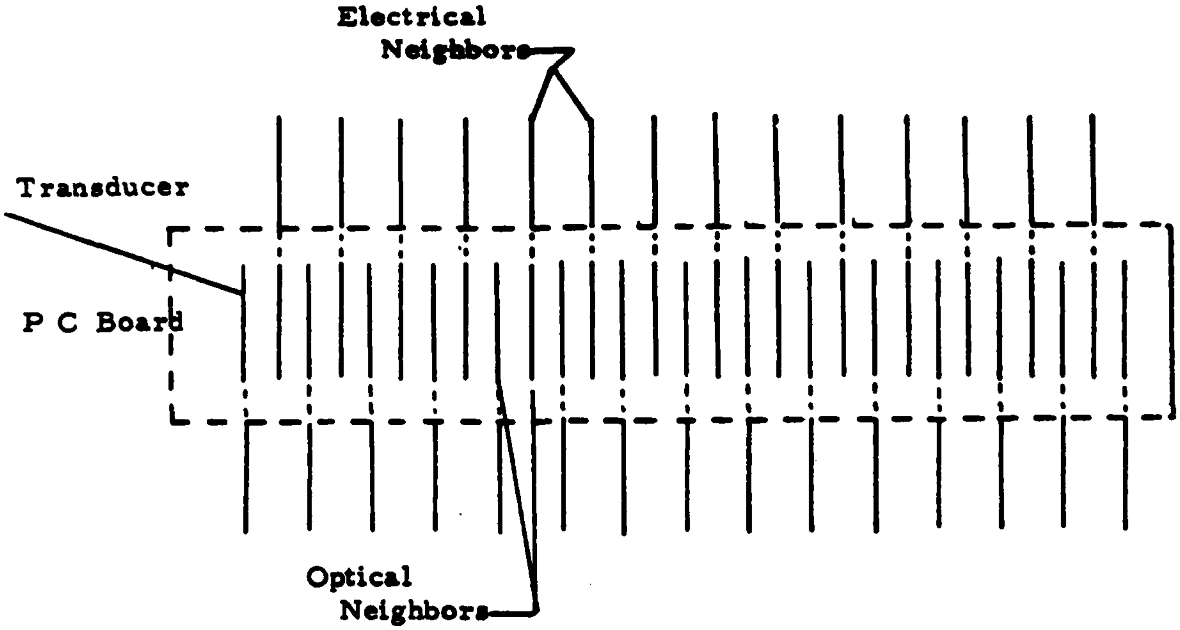
The old page composer and RF electronics were then removed from the system and the new page composer was installed. The entire optical path was then aligned for optimum hologram formation. This alignment provided the necessary Bragg angle illumination for the new AOPC.

After the AOPC was installed, an effort was made to level the page composer, i.e., equalize the light output of all channels. Potentiometers were available in the RF drive system to adjust the gain of each channel separately. Unfortunately, when we attempted to adjust the individual gains with these potentiometers, they tended to come off the PC card. Since most channels were approximately equalized, we chose to accept the existence of 5 relatively weak channels and did not level the new page composer.

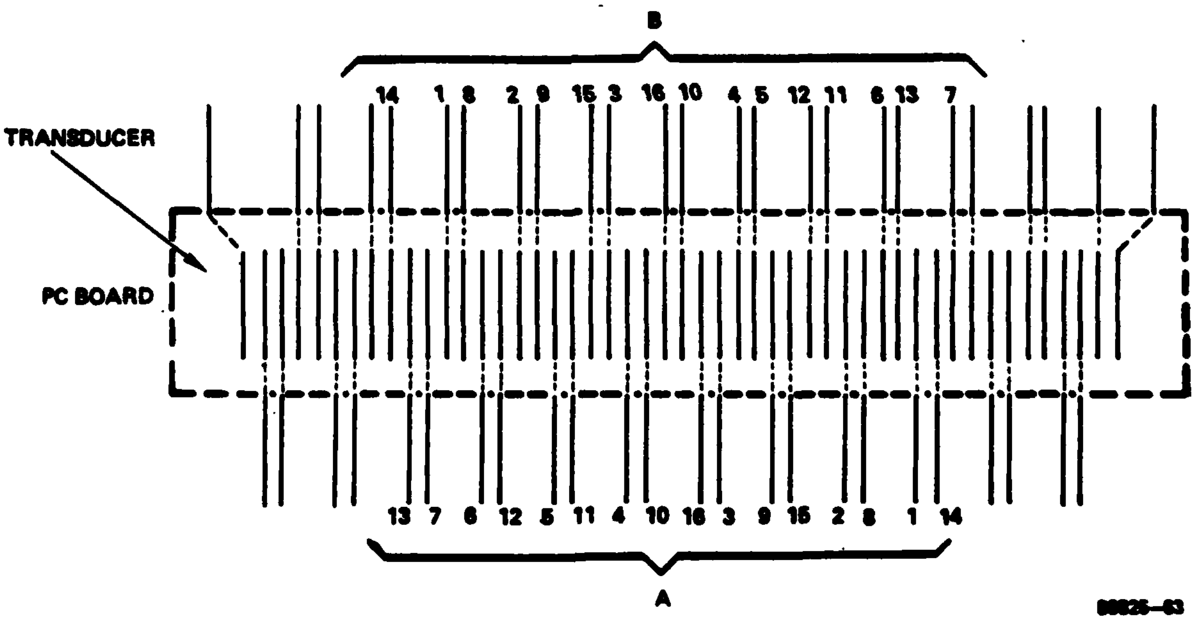
One other problem was observed. Three channels were present only intermittently due to poor electrical connections. Time and cost constraints prevented us from locating and repairing the connections. We noted the intermittent channels to determine the effect on bit error rate and tried to ensure that at least 31 of the 32 channels operated for each recording. The intermittent connections are not fundamental issues and are correctable for future systems with additional testing and repair.

The RF phase assignments for the new page composer were different than for the previous page composer due to differences in the transducer connection pattern. The pattern for the previous page composer is shown in Figure 4.4.4.1-1a. For the previous configuration, "optical neighbors" (channels with adjacent transducers) were not "electrical neighbors" (channels with adjacent microstrips). To minimize electrical crosstalk, phase assignments were made so that electrical neighbors were always in phase quadrature. This, however, forced some optical neighbors to be driven by the same phase, which increased the level of optical crosstalk. The transducer connections for the new page composer are shown in Figure 4.4.4.1-1b. In this case, optical neighbors may also be electrical neighbors, but it is possible to assign the phases such that both optical and electrical neighbors are driven in phase quadrature. This is the minimum crosstalk phase assignment and was used for the Phase IV experiments.

Standard recordings were made and readout using the new page composer. The average bit error rate was about 3.0×10^{-5}. In general, the weak channels had an error rate around 8×10^{-5}. The channels with intermittent connections had error rates greater than 1×10^{-4}. The remaining strong channels had an average error rate of about 1.5×10^{-5}. This shows that with a fully equallized page composer



A. Phase II Configuration



B. Phase III - IV Configuration

Figure 4.4.4.1-1 Wideband Recorder AOPC Transducer Configuration.

and no poor connections, the system raw error rate for a 32 channel page composer can be held below 2×10^{-5}.

The difference in the 32 channel BER and the 128 channel BER using the old page composer was about a factor of 2.1. Applying this same factor to the new page composer yields a potential system BER of about 4×10^{-5} for a 128 channel page composer built to the design parameters of the Phase III page composer.

4.4.4.2 Crosstalk Measurements

System crosstalk measurements were made with the old page composer reduced to 32 channel operation and with the new page composer. The system was set for a recording, and the data bits were brought through the readout optics to the fiber array. The resulting analog data pattern for any channel was then detected and displayed on an oscilloscope. The height of individual bits in the scan was then measured as a function of the RF phases which were turned on. The crosstalk figure in dB is $20 \log (\sqrt{1 + \Delta x} - 1)$, where Δx is half the total observed variation in bit height normalized to the mean height of the particular bit.

The channels of the old page composer can be characterized as channels which are electrical but not optical neighbors and channels which are optical but not electrical neighbors. It is possible to isolate the effects of electrical neighbors by turning off the RF drives which are in phase quadrature with the measured channel. However, since optical neighbors may be driven with the same phase as the measured channel, they can not be definitely isolated. Crosstalk measurements were made with electrical neighbors off and with electrical neighbors on. The crosstalk due to electrical neighbors was -30.4 dB. The crosstalk due to optical neighbors was -33.8 dB. This confirms the previous experiments which demonstrated that electrical crosstalk was the stronger effect. The crosstalk due to for electrical and optical neighbors was -29.6 dB.

The channels of the new page composer can be categorized as electrical but not optical neighbors, optical but not electrical neighbors, and both optical and electrical neighbors. The phase randomization scheme was arranged so that both electrical and optical neighbors are driven in phase quadrature. For this reason, it was not possible to isolate the effect of electrical or optical neighbors operating alone. The crosstalk figure for the new page composer was measured to be -35.8 dB which is 6.2 dB better than the old page composer. This 6 dB decrease in crosstalk resulted in the improvement in BER reported above.

4.5 Recording Material Response

The recording medium used for the Phase II and Phase III WBR experiments was Kodak Type SO-141 film. This was selected during Phase III evaluations as the baseline material for future WBR work;

unfortunately, when we placed an order for the Kodak SO-141 film, we were told it is no longer available. Discussions with Kodak personnel recommended the selection of Kodak SO-332 film as a viable alternative. According to Kodak engineers, the Kodak SO-332 has the same emulsion as Kodak SO-141, but the coating procedure has been changed to reduce scatter noise. Therefore, the sensitometric properties and frequency response of the two films should be identical and the signal-to-noise ratio should be better for the Kodak SO-332. Based on this information, Kodak SO-332 was selected as the WBR Phase IV film.

The first recordings on the new film identified a potential problem. There was a significant decrease in diffraction efficiency for the high frequency data channels. After all other possibilities were eliminated, we considered the recording material as the potential cause.

The spatial frequency response is a quantitative measure of the modulation as a function of spatial frequency. The spatial frequency response was indirectly determined by measuring the diffraction efficiency of grating holograms recorded over a range of spatial frequencies while holding all other parameters constant. The maximum diffraction efficiency measured for a grating at a particular spatial frequency, normalized by the theoretical maximum value of diffraction efficiency, is defined as the holographic response at that frequency.

To compare the frequency response of Kodak SO-332 to that of Kodak SO-141 using recording parameters similar to those used in the WBR system, a static holographic recorder was set up. Plane wave gratings were recorded on these films at a reference to signal beam ratio, K, of 4 to match WBR parameters. At each frequency an exposure series was made and the resulting diffraction efficiency was plotted as a function of exposure. Figure 4.5-1 shows the maximum diffraction efficiency as a function of spatial frequency for SO-332 and SO-141. Note that over the frequency range (300 cy/mm to 600 cy/mm), the Kodak SO-141 has a flat frequency response whereas the Kodak SO-332 shows a sharp decrease at about 500 cy/mm. This matches the fall in readout intensity of the high frequency data bits.

For the work in Phase IV, the poor high frequency response of the film was not a critical problem. The purpose of Phase IV recordings was to compare the properties of the new 32 channel AOPC to those of the old AOPC. For this reason, we were primarily interested in the channels which were in the center of the frequency range where the falloff in frequency response was not yet apparent. However, it does pose problems for future WBR systems.

The channel-to-channel resolution is set by the number of spatial frequency cycles (fringes) recorded in the hologram. To provide

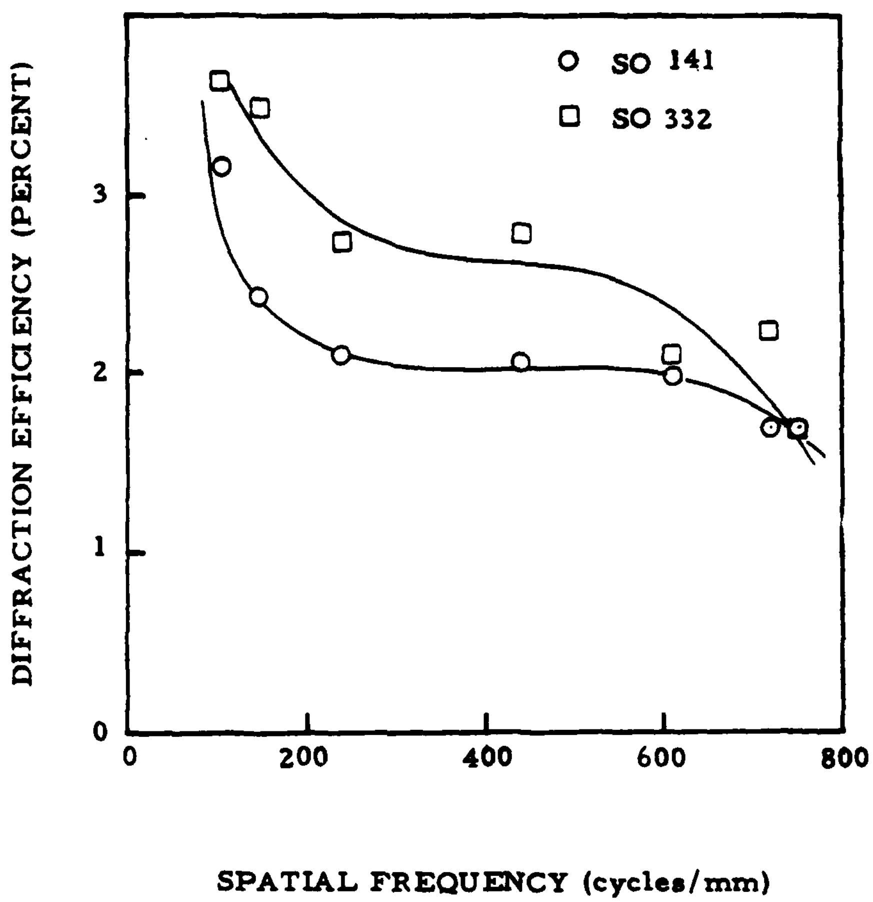


Figure 4.5-1 Diffraction Efficiency as a Function of Spatial Frequency at K = 4 for SO 141 and SO 332.

"double Rayleigh" resolution of 128 channels requires a minimum spatial bandwidth of 256 cycles/hologram. The Phase II system, recording 1 mm holograms in a spatial frequency band of 313 to 623 cycles/mm, provides slightly better than double Rayleigh resolution of its 128 channels. To maintain double Rayleigh resolution while shifting the spatial frequency band down by 20% to 250 to 562 cycles/mm will require an increasing hologram length by 20%, an option which reduces the packing density of the system but should maintain the BER. The alternative is to record at 250 to 562 cycles/mm while maintaining the hologram length at 1 mm and accepting the loss in channel-to-channel resolution and hence BER. One third possibility would be to bias the light intensity of the AOPC to compensate for the film frequency response. This reduces the K-ratio of the high frequency channels and therefore increases the noise level during readout. For future WBR systems, a careful tradeoff of these parameters will have to be made to determine the optimum solution.

4.6 Summary and Conclusions

The Phase IV experimental measurements have evaluated some of the recommendations of the Phase III analysis and have evaluated the operation of the system with the new AOPC. The key results are summarized in the following paragraphs.

4.6.1 Coding Study

The (63, 51) and (127, 113) BCH double error correcting codes were proven to reach their full random error correcting potential at high interleave depths. Preliminary circuit designs completed during Phase IV indicated that the (127, 113) code would require half the number of LSI chips as the (63, 51) code. For the system raw BER of 4×10^{-5} demonstrated during Phase IV, the corrected BER using the (127, 113) code would be 8.4×10^{-10}. For applications where this is sufficient, we recommend use of the (127, 113) BCH double error correcting code full scan interleaved.

4.6.2 Apodization

Phase III analysis indicated that a readout apodization to the $1/e^2$ levels would suppress side-lobe formation; this sidelobe suppression would improve optical crosstalk at the fiber plane and BER. We found that BER was minimized for an intensity apodization of $1/e$ levels rather than $1/e^2$ levels. This still allows some reduction in hologram size while maintaining system BER. The extent of the packing density increases has not been determined.

4.6.3 New AOPC

The AOPC designed to have reduced electrical crosstalk and fabricated during Phase III was installed in the breadboard. Some weak channels which could not be fully equallized and 3 poor electrical connections were noted. Despite these issues, the measured BER was approximately half the rates achieved with the old page composer operating with 32 channels. With full equalization and no bad connections, a factor of 3 improvement from the old page composer is predicted. This implies a system BER for a 128 channel page composer on the order of 4×10^{-5}.

Crosstalk measurements on both the old and new page composer showed a 6 dB reduction in electrical crosstalk. This supports the lower BER we measured.

4.6.4 System Simplification

The overall light efficiency of the WBR EDM was improved by combining the operations of the Main AOM and the beam splitter AOM into one device. System optical efficiency was improved by a factor of 5, requiring only 425 mW of raw laser power to record acceptable quality holograms. The efficiency is now limited by the diffraction efficiency of the beam splitter AOM. The maximum efficiency of this device is limited to 30%; however, higher efficiency AOM's are possible. Therefore, a further improvement in optical efficiency is possible for future systems. The system effect of the improvement in optical efficiency is that the 9 W Coherent Radiation CR-12 laser can be replaced with a 500 mW laser which is cheaper and requires less facilities support.

4.6.5 Film Evaluation

Kodak SO-332 is the recording medium recommended by Kodak to replace the Kodak SO-141 which is no longer available. We measured the frequency response of SO-332 and found a strong MTF falloff at about 500 cycles/mm. Kodak has agreed to look into this issue; however, it is probable that no improvements will be made. To compensate for this, future systems must either record with less than double Rayleigh resolution or increase hologram length by about 20%. This tradeoff between BER and packing density has to be made with a particular system requirements in mind.

SECTION V

TECHNOLOGY FORECAST

5.0 TECHNOLOGY FORECAST

The most important conclusion to be drawn from the successes achieved by the Phase III and IV programs is that the technical risk in building a 1.0 gigabit/second recorder/reproducer has been essentially eliminated. In addition, the gains achieved in such areas as packing density and optical power requirements have opened new horizons for the application of holographic digital data storage. Specifically, it is now possible to make parameter tradeoffs and design choices which will tailor a system to provide exceptional performance in one or several key areas, such as packing density, access time, or bit error rate.

In the first part of this paragraph, we will first describe the major parameters which define a high-speed optical data storage system, and which must be well defined before a prototype production phase is begun. This will be directed toward acquainting a potential user with the information he must provide to minimize the cost and risk of an initial system specification activity.

The next subsection will describe by way of design example, the Phase III parameters recommended for a 900 Mb/s recording and playback system and their relationship to the tradeoffs detailed previously.

Finally, to show the versatility of the optical data storage and retrieval approach developed under the WBR program, and to provide further examples of the kind of tradeoffs that can be made, we will briefly outline some systems loosely based on the WBR but directed toward special requirements.

5.1 Key Tradeoff Areas

A significant side-effect of the reduction in technical risk (and a natural consequence of any system's progression from concept to breadboard to deployable hardware) is the increased importance of coordinating user requirements with the system specification and design activities. Such coordination can greatly decrease both cost and schedule requirements of the production phase of an operational system. This paragraph will provide a list of the critical design parameters which must be specified or limited prior to the final system design activity, and discuss some of the trade-off decisions associated with them.

1. Total User Data Rate.

   The achievement of recording rates near 1.0 gigabit/second is the primary reason for the development of a Holographic Wideband Recorder System. The user data rate is ultimately translated into the system operation rate by the addition of the overhead data associated with both error correction encoding and housekeeping (e.g., synchronization signals). Once a system rate is chosen at the beginning of the design activity, small changes of the order of 10 percent either way can usually be accomodated at any later stage. Larger changes are another matter; essentially every system component is affected, from logic gates to film transport servo design. Other rate-dependent parameters are AOM rise times, scanner speed and servo design, and photodetector bandwidths. An additional factor is that in many of these areas, speed reductions are achieved more easily than speed increases. These considerations should serve to emphasize the importance of early and precise (or at the least, worst-case) definition of total user data rate requirements.

2. Continuous Record Capability.

The maximum length of a stream of incoming data and the period which will separate it from the next stream are parameters which strongly affect the film transport design activity. When packing density (and consequently raw BER) variability is included in the system design, film velocity may also be varied, changing the length of recording time possible with a given length of film.

In situations where film velocity is fixed changes in record time requirements translate directly into changes in system film capacity requirements. Additional trade-offs may arise when the structure of the data is known, making a multiple transport system with handover a viable option. The processing facilities to support the system's film output are also affected by the continuous recording requirement.

3. Recording Duty Cycle.

This refers to the percentage of time (e.g., number of hours per day) that the system must record data. Areas of concern here include: the logistics of supplying the required raw film to the recorder, and archiving those portions which are to be retained for an extended period; the processing configuration required to support the recording system; and the decision to design the system around either a single recorder-reader unit or separate independent units for each function (or some combination.

4. Data Access Time.

In some situations, recording the incoming data may be the major priority, with readout access to the data not required until some convenient time (e.g., hours) later.

More typically, however, access time is also of importance. In this case, the specific access time requirements must be combined with knowledge of the data format ("mission profile") to determine an operational routine and film processing configuration which can support those requirements. The classic example is that no (currently foreseeable) system can begin readout--especially at slowed-down rates - of the first half of a data unit while the second half is still being recorded. Knowledge of the mission profile, however, especially as regards any gaps that may occur in the recorded data stream, can be used in certain system configurations (notably the dual-transport system to be described below) to provide relatively quick access to selected data blocks.

5. Readout Rates.

As with the recording rate, the readout rate has a direct impact on many areas of the system. The dynamic range and servo systems of the scanner and film transport, as well as the photodetector bandwidth and circuit design, are directly coupled to readout rate. Experimental performance data obtained from the

Phase II system, as well as most of the relevant investigations of Phase III, have indicated that operation of the readout system over a dynamic range of 10 or 20 to 1 is feasible, with the full record rate being the top readout speed. Further data time expansion (100-fold or more) toward computer-compatible readout rates may be possible in a Holographic Wideband Recorder system, especially in the context of a read-only unit designed for that specific purpose; thus, early definition of readout rate requirements may permit significant extensions of the system's current capabilities.

6. <u>Bit-Error-Rate Requirements.</u>

The fidelity of the playback process can vary greatly in importance with the particular application; real-time video data can tolerate a fairly high error rate, for example, while some computer-interfaced process control or high-resolution imagery data may be of use only when substantially error free. Specification of a required system BER is primarily related to, and must be traded off against, packing density. Thus, the BER maximum must be known in order to make firm choices of hologram size and resolution parameters. Equally important is the error-correcting code choice; such codes can be shown to always improve the BER/packing density trade-off in low BER systems, and the code choice must precede much of the system electronic design.

7. Volume Packing Density Requirements.

We have mentioned the fundamental relationship between volume packing density (VPD) and BER. Packing density also impacts other system parameters, such as film velocity and hence, the record time/film capacity trade-off. This is further illustrated by the fundamental equation for the recording rate, R, in terms of the film's velocity (V), width (W), and packing density (H):

$$R = VWH.$$

Since both V and W are limited by the mechanical capabilities of the film transport (and W also by the scan lens capacity), high data rate systems will depend primarily on the ability to operate at high packing densities. The VPD/BER relationship also offers the possibility of a system with user-selectable data priorities: high VPD and moderate BER on some data blocks, lower VPD and very low BER on others.

8. Archival Storage.

One of the positive factors associated with the use of photographic film is the ability to provide long-term (i.e., years) archival storage of the recorded data. Yet in some system applications, a "quick look" at the newly recorded data may take precedence over processing for archival storage. These options need to be considered early in a system configuration definition procedure, because of the potential cost (or cost savings) associated with the processing system. One possibility worthy of investigation is the use of a two-step procedure: one quick turn-around processing for ready access to newly recorded data, and a later (after readout) processing for converting the film to archival quality. The BER penalty to be paid for such a system, as well as the required processing facilities, would be the main areas of investigation.

9. Environmental Requirements.

The environment in which the system is to operate can affect the design in several areas, primarily those of electronics and mechanical support structures. The most important areas are those of temperature and humidity. Others include physical vibrations and accelerations, electromagnetic noise, and atmospheric particulates.

10. Space Constraints.

The volume into which the system must fit, including any floor-space or height restrictions, can conceivably affect the optical and mechanical design tasks, and should therefore be specified as early as possible. The Phase II system occupied a 4 x 8 foot bench, with a separate free-standing electronics control rack. Some economies in space are anticipated for any deliverable system, however, we should remember that available space can often be translated into maintainability and serviceability, which may be a cost-effective trade-off to make in some situations.

11. Facilities Availability.

Another important item to be coordinated between the user and the system designer is the system's facilities requirements. This primarily refers to electrical power and water, with some subsidiary areas such as compressed air, air conditioning, water heating, and compressed argon also of some importance. Again, considerable reduction in these requirements from their Phase II levels is anticipated (excluding the film processor requirements). If a separate read-only unit is constructed, for example, its use of a relatively low-power, air-cooled laser would require greatly reduced amounts of both electrical power and water, as compared to the Phase II recorder/reader.

The above list is not necessarily exhaustive, but should provide an adequate starting point for system definition prior to the final design phase of a prototype system. The actual values achieved by the Phase II system in many of the areas discussed, as well as some of the preliminary trade-off decisions associated with a particular set of system requirements, are discussed in the following paragraph.

5.2 Baseline Phase III Design Parameters

As we have noted in previous paragraphs, the concepts and techniques used in Holographic Wideband Recorder systems will permit recorder and reader designs responsive to a rather wide variety of requirements in the high-rate data storage and retrieval area. The Phase III study program had the goal of both proving feasibility and initiating the system synthesis process for a recorder/reader system with a specific set of requirements. The specification of these requirements was not as complete as the previous paragraph indicates is desirable at the beginning of the design phase of a fully operational and deliverable unit. Nevertheless, enough system requirements were available to make a system design based on a straightforward extension of the Phase II hardware appear to be the most effective solution. We now list the baseline system parameters and requirements on which the Phase III study was based. To permit easy reference to the trade-off considerations associated with each parameter as described in the previous Paragraph, we will formulate the list in parallel to the one given there; Table 5.2 is the result.

Some additional insight into these system requirements may be gained by comparing them to the actual performance values of the Phase II system, and discussing how the major changes were investigated by the Phase III study.

5.2.1 Comparison of Phase III Goals to Phase II Performance

5.2.1.1 Total User Data Rate

Increasing the total user data rate from the 600 Mb/s Phase II value to 900 Mb/s for Phase III can be done in several ways. The trade-off process starts from the fundamental equation

$$R = VWH,$$

where the data rate (R), film width (W) and velocity (V), and area packing

Table 5.2 Baseline Phase III Design Parameters

1.	Total User Data Rate	900 Mb/s
2.	Continuous Record Capability	20 Minutes
3.	Recording Duty Cycle	$\leq$ 900 Minutes/Day
4.	Data Access Time	$\leq$ 90 Minutes
5.	Readout Rates	Full Rate, Half Speed, and One Tenth Speed
6.	BER Requirements	$\leq 10^{-6}$ with 10^{-7} as a Goal
7.	Volume Packing Density	Not Specified (But as High as Possible)
8.	Archival Storage	5 Years
9.	Space Constraints	Not Specified
10.	Facilities Availability	Not Specified

density (H) are the parameters to be specified. Clearly the increase in R will have to be matched by a net increase on the right side of the equation. The transport velocity in Phase II (4.0 m/s) is already high, and not a good source of possible rate increases. The other two parameters, however, were thoroughly treated during the Phase III study. Section 3.2.1 of this report describes the lens design effort undertaken to permit about a factor of two increase in scan (and hence film) width, while packing density increases of about the same magnitude have been investigated experimentally and are reported on in Section 3.2.6. The overall gains which are reported in those sections greatly exceed those which are required to extend the data rate from 600 Mb/s to 900 Mb/s. This presents a range of options to the system designer and/or user, including:

- Maintaining the 900 Mb/s data rate, and reducing the transport velocity to 1.56 m/s;
- Maintaining the 900 Mb/s rate, maintaining (or only slightly reducing) the transport velocity, and substantially reducing the packing density for a major decrease in bit error rate;
- Maintaining both transport velocity and packing density and increasing the recording rate to 1.5 Gb/s or more.

These options merely define the range of the parameters; systems with values between those mentioned are equally viable.

Most of the other areas investigated during Phase III were also affected by the increased data rate requirement. In Section 3.2.3, we report on the development and testing of a page composer which can support the 900 Mb/s data recording rate, and Section 3.2.4 details the parameters of the high-speed, high-sensitivity photodetectors with which the data can also be played back at that rate.

5.2.1.2 Continuous Record Capability

As an exploratory development model, the Phase II system was not required to provide recording capability beyond about 19 seconds. The 20 minute requirement for Phase III, therefore, called for major changes, primarily to the film transport. As we have discussed above, increases in the film width and data packing density were sought and achieved, and the feasibility of a 3000-foot capacity film transport was assessed by vendor survey. The preliminary indications, received prior to the termination of funding in this area, were that such a transport was feasible. With the increased packing density and wider film format, a 3060 foot reel would provide approximately 5.4×10^{11} bits of user data storage, for a record time at 900 Mb/s of 10.0 minutes. Thus, a total of 6120 feet of film, possibly on two 3060 foot segments in a dual-transport configuration, would provide the system's required 20-minute record time.

As a part of the System Engineering effort during Phase III, several system configurations which could provide the required recording time were defined, and their advantages and disadvantages were tabulated. Key considerations here were the availability of the recording medium, the impact on the system of splices, and the effect of the film length on the data access time. Table 5.2.1.2 summarizes the configurations considered.

5.2.1.3 Recording Duty Cycle

Since Phase II had no duty cycle requirement, the 900 minute/day Phase III value had no standard against which to compare it. The system engineering considerations associated with recording duty cycle are delineated in Item 3 of Paragraph 3.2 8.1. Here we simply note that the increased packing density and resulting decreased film velocity in the nominal system configuration will result, for any system duty cycle, in approximately a two-fold reduction in both the amount of film accumulated per day and the processing capacity required to handle that film.

5.2.1.4 Data Access Time

Again there is no Phase II standard. The primary areas in which the Phase III study was directed to this requirement were: the Film/Processor task, which detailed the impact of processor throughput rate on data access time, as well as describing the results of a survey of available processing units and their capabilities; and the System Engineering task, which considered the system implications of various access time requirements.

TABLE 5.2.1.2

Potential Record System Configurations to Support

20-Minute Recording Requirements

Transport System	Advantages	Disadvantages
Single Transport, 6120-Foot Capacity, Unspliced Film	Single-Film Supports Entire Mission	6120-Foot Lengths not Currently Available. Longer Data Access Time.
Single Transport, 6120-Foot Capacity, Spliced Film	Single-Film Supports Entire Mission.	Longer Data Access Time. Splice Handling Options: Lose Data At Splice; Buffer (40 Mb); Format Splice to Fall in Known Data Gap.
Dual Transport, 3060-Foot Capacity Each Side, Unspliced Film.	3060-Foot Lengths Available Quicker Data Access Time.	Multiple Transport Complexity (Switching Electronics, Opto-Mechanical Design, etc.) More Spools/Mission

Interrelated within any potential system are the data access time, the recording configuration (i.e., number and length of film segments per mission), the recording duty cycle, and the system film processing capability. Typically, incoming data will be divided into blocks, which in many cases will be independent of each other. This suggests the possibility of assigning priorities to certain blocks to which rapid access is required; these could then be removed from the main film spool and given priority handling and processing. Data block length, processor throughput speeds and other handling requirements create a minimum access time in the vicinity of 10 to 15 minutes (for conventional films). A typical access time to data blocks as long as 120 seconds could probably be brought down to the 20 to 30 minute range.

5.2.1.5 Readout Rates

The readout rates for Phase III underwent the same increase from the Phase II values that have been discussed above for the record rate. The film transport considerations associated with recording rates and packing density trade-offs therefore apply equally to the readout rates. The Phase III activity which was most strongly affected by the increased readout rate was the photodetection task. Summarized in Section 3.2.4, this task involved the survey, selection, and signal-to-noise analysis of photodetectors which require many times less light than the Phase II PIN detectors (for the same SNR); thus the light budget detailed later in this section requires a much smaller (possibly even air-cooled) laser for the readout process.

5.2.1.6 Bit Error Rate and Packing Density

The Phase III system requirements on these parameters are not specific, stating simply that they must be at least as good as those of Phase II (1×10^{-6} BER and 0.45×10^{6} b/cm^2 average packing density), and as much better as possible. To investigate how much better might be possible, the System Evaluation task, summarized in Section 3.2.6, performed experiments using the Phase II hardware to: 1) determine the packing density/BER relationship; 2) characterize the errors to which the system is subject; and 3) use the preceding results to determine the most effective error-correcting code and interleave scheme for the system. Another System Evaluation activity involved the investigation of the transporting and handling properties of thin-base film, with a view toward minimizing the volume occupied by a given quantity of data.

5.2.1.7 Summary of Phase III Changes

The following tables give the system performance parameters for the Phase II and Phase III systems. Some of the Phase III values given are the basic specifications listed above; others have been calculated, either from the basic trade-off considerations or by extrapolation from the Phase II values.

TABLE 5. 2. 1. 7-1

WBR System Performance - Recorder

	Phase II	Phase III Recommendation
Total User Data Rate	600 Mb/s	900 Mb/s
Channel Data Rate	6 Mb/s	10 Mb/s
Number of Channels	128	128
Film Velocity	4.0 m/s	1.56 m/s
Recording Medium		
Type	SO-141	SO-141
Dimensions	35mm x 250 ft x 4.0 mil	70mm x 3060 ft x 2.5 mil
Packing Density (Peak)	0.8×10^6 b/cm^2	1.5×10^6 b/cm^2
Hologram Exposure	2.0 mW x 80 ns	4.0 mW x 50 ns
Continuous Record Time	19 s	≥ 20 min
Storage Capacity/Reel	1.1×10^{10} b	5.4×10^{11} b

TABLE 5.2.1.7-2

WBR System Performance - Reader

	Phase II	Phase III Recommendation
Total User Data Rate (Max)	600 Mb/s	900 Mb/s
Channel Data Rate	6 Mb/s	10 Mb/s
Film Velocity	4.0 m/s	1.56 m/s
Phase Lock Accuracy	±10%	± 1%
Photodetector Input Requirement	100 nW	5 nW
Photodetector Type	PIN	Avalanche
Signal-to-Noise Ratio	18 dB	20 dB
Error Rate	10^{-6}	10^{-7}

5.3 Viable System Modifications

We have seen that optical holographic recording is well suited to the requirements of the Phase III system, providing adequate operational margin in each area of performance. The Phase III system requirements, however, are by no means indicative of the limits of this technology. By reworking the tradeoffs from different perspectives, we can easily envision the application of holographic recorders to a variety of system needs.

The basic parameters which participate in the tradeoff process are as follows.

W	Film Width
B	Bit Error Rate
R	Data Rate
L	Film Length
I	Latency Time
V	Film Velocity
E	Processor Speed
S	Film Slew Velocity
O	Processor Delay Time
N	Total Recording Time
H	Packing Density
A	Average Access Time

These parameters are then related according to the equations

$$R = VWH$$

$$L = VN$$

$$A = L/2S$$
$$I = O + L/E,$$

and by the approximately inverse relationship between BER (B) and packing density (H). These relationships clearly delineate the tradeoffs which we must make if we wish to configure systems for low BER, high data rate, fast access, etc.

During the course of the WBR program, several related studies, proposal efforts, and design exercises have been completed which drew heavily on the WBR technologies. The results of these exercises serve as examples of the kinds of systems which can be produced with optical holographic techniques. This section will describe several of these systems.

5.3.1 A Large Capacity System

An important potential application of a WBR-like system is a large capacity archival data base. In one such conceptual design, the requirement was for a system which could record data at 400 Mb/s, store up to 10^{15} bits in an archival mass memory, and support a system bit error rate of 10^{-9}. Note that the low speed (compared to WBR III) makes tighter packing densities easier, while the low BER makes looser packing more desirable.

The approach taken to this system was a straightforward modification of the WBR system. By using 70 mm film in 3000 ft. lengths, a capacity of 5×10^{11} bits per reel is achieved, requiring 2000 reels for the 10^{15} bit memory. At WBR packing densities, the film velocity required to support the 400 Mb/s recording rate is 0.7 m/s, and results in a 20 minute record time per reel. Using a high speed film processing system would provide access to each newly recorded reel in 40 minutes or less (with more rapid access possible if a real-time recording material is developed for use in a system of this type). A high slew rate film transport could provide an average access time to data within a reel of 45 seconds or less. The entire recorder and film archive system, including the 10^{15} bit memory, could be configured to fit in an area of about 600 square feet, and access in the archive to data on any reel could be achieved within about 5 minutes. The parameters characterizing this archive system are summarized in Table 5.3.1.

5.3.2 Data Distribution System

Let us next consider the application of the WBR technology to a 50 Mb/s data distribution system. This could be a system intended for remote, slow speed recording and playback of the data from the archive in the previous paragraph, or a separate development with its own recording and readout parameter specifications. We will assume for simplicity that the data formats are to be compatible with those in the archive. In that event, a typical scenario would be 1) transmission of the data from the archive, 2) remote recording of the data, and 3) playback of the data on a

TABLE 5.3.1

Key Parameters for a 400 Mb/s Archive System

Total Capacity	10^{15} bits
Film Length	3000 Ft.
Reel Capacity	0.5×10^{12} bits
Number Of Reels	2000
Record Time Per Reel	20 Min.
Access Time To Data After Recording	40 Min.
Average Access Time To Data Within A Reel	45 Sec.
Average Access Time To An Archived Reel	5 Min.
Bit Error Rate	10^{-9}
Storage Material Cost Per Bit	5×10^{-8}¢

conso... r instrument design for fast access to data within a small segment of the master archive. Thus the first tradeoff encountered is the size of the unit record received by the distribution system and its effects on the processing and access times achievable. Using packing densities similar to those of the WBR system, this tradeoff can be summarized by the data in Table 5. 3. 2. If access time to data within the unit record is controlled primarily by operator convenience, then 5 seconds is probably the longest comfortable time allowable.

In that case, the table shows that, assuming a 10 m/s maximum search mode slew rate for the transport, a capacity of 5×10^{10} bits is achievable with data being available 20 minutes after transmission for higher (or lower) data rates; the table may be modified by increasing (or decreasing) the film velocity and decreasing (or increasing) the record time. Extension of this kind of distribution system to higher data rates would be easily done, because of its base in the established WBR technology. If storage capacity requirements remained unchanged, there are no system penalties for data rates at least as high as 200 Mb/s.

Like the previous system, this Data Distribution system would be packaged to occupy a relatively small amount of office space. If the processing requirement (which may soon be removed by developments in real-time storage media) is excluded, the system and operator's console would require less than 100 square feet of floor space.

TABLE 5.3.2

Tradeoff Parameters For A 50 Mb/s

WBR-Based Data Distribution System

Capacity (10^{10} bits)	Record Time (min.)	Film Velocity (ips)	Film Length (ft.)	Access Time To Data After Recording (min.)	Access Time To Data Within a Reel (sec.)
x 1	3.3	4.3	60	12.5	1
2	6.7	4.3	120	14.0	2
5	16.7	4.3	300	20.0	5
10	33.3	4.3	600	27.5	10

5.3.3 Local Mass Store System

Now we consider modifying the WBR system design toward a local mass store system. This is similar to the data distribution system with the following exceptions: it must be smaller in size and power requirements; it must operate at lower, perhaps computer compatible, data rates; it must be reproduced numerous times for installation at locations remote from the main data base; it probably will require both local copying of data files and the ability to read replicated copies of important data files; and operator access to data in the files must be 2 seconds or less.

To address this problem with the wideband technologies, several changes are needed from the previous systems. As a baseline, we will assume: use of a real-time storage medium to eliminate processing cost and complexity; 16 mm film width and a 32-channel AOPC, to reduce the scan lens cost and complexity; and 100 ft. maximum film length to provide the 2 second access time within a given data record. With these assumptions, we can derive most of the other system parameters. These are listed in Table 5.3.3, where we have assumed a total data rate for both recording and playback of 20 Mb/s. The advantages of this system derive from its volume packing density, providing a large amount of on-line data and a minimal total memory volume. The main risk in this system is the requirement to use a newly-developed real-time storage

TABLE 5.3.3

Design Parameters For A WBR-Based Local Mass Store System

Film Width (mm)	16
Film Length (ft.)	100
Capacity Per Cassette (bits)	3.3×10^9
Film Speed (cm/s)	14
Number of Channels	32
Total Data Rate (Mb/s)	20
Channel Rate (Mb/s)	0.625
Access Time To Data Within A Record (s)	2
Access Time To A New Record (min.)	1
Record Time Per Reel (min.)	3.6
Number of Reels For 100 Gb Capacity	30
Volume of 100 Gb Memory ($ft.^3$)	0.5

medium, successful testing of which (under a parallel program) has only recently begun. Nevertheless this system is steadily increasing in viability, and provides a good example of the variety of systems now supportable using WBR technology.

5.4 Areas for Technology Development

In the preceding sections we have described various systems for optical data storage and retrieval, most of which were based on currently developed technology, or which require only relatively straightforward advances in some areas to meet their requirements. We have also described many of the tradeoffs that must be made in the design of a wide-band recording system when we are constrained by the current state of the various required technical arts. It is therefore appropriate at this point to provide some discussion of the technology "breakthroughs" which, if attained, would significantly extend the range of capabilities of WBR-type data storage and retrieval systems.

5.4.1 Laser Efficiency

The recording systems described in this report have all been based on the use of Argon Ion(514.5 nm wavelength) lasers as the illumination source. These are typically available in two power ranges: one group at around 5 to 20 mW, which require about 1 kw of input power and are air-cooled; and another group in the 1 to 10 watt range which draw 7 to 50 kw of input and require water cooling. For some system scenarios, where small, relatively low-speed, read-only systems are needed, helium-neon lasers are also viable. These lasers (632.8 nm wavelength) have output powers between 0.5 and 50 mW, require from 35 to 450 watts of input power, and are air-cooled.

From the smallest He-Ne to the largest Argon Ion, the sizes range from about 0.5 to 30 cubic feet, and the weights from 1 to 1000 pounds. Increased efficiency lasers would provide significant reductions in system cost, power consumption, facilities requirements, and size. For example, a promising candidate laser which is reportedly under development, is a frequency-doubled YAG device (532 nm wavelength) with 200 mW optical output and requiring only 250 watts of input power; this is also said to be an air-cooled unit with at least 10,000 hours of operational tube life. A careful reading of the WBR Phase III final report (summarized above in Section III) shows that this device, if commercially available, would be a potential solution to the entire WBR optical input requirement for recording and readout.

Another promising area for development of improved light sources is that of injection laser diodes. These devices, operating in the visible and near IR ranges, are improving rapidly. They are primarily suited to use in direct spot recording systems at the present time, but future developments may change that situation. Furthermore, even in a peripheral mode, use of such devices in the WBR system would offer substantial simplification, as for example in the potential replacement of the marker laser of the WBR Phase II brass board.

5.4.2 Scanning Lens Design and Production

Some of the advantageous features of optical data storage and retrieval systems stem from the ability to distribute data across a wide storage medium; others arise from the ability to provide high packing densities. Both of these abilities require sophisticated, wide-field, low F-number lens designs, which increase the cost of the systems of which they are a part. Through supervised subcontracts, Harris has achieved several applicable lens designs of this type. Additional design efforts, with particular attention to minimization of fabrication and materials cost, could have very healthy effects on WBR-like systems. These effects would include the reduction of overall cost, an increase in system flexibility, and potentially an increase in overall data packing density.

An alternative technology development would be in the area of additional sophisticated scanning systems. An example of this is the acoustic travelling-wave lens system, for which Harris has been a pioneer.

5.4.3 Storage Medium Transporting

For systems which must provide both large capacity unit records and short access time within a record, the ability to transport the storage medium rapidly past the read or write head is crucial. Even with the high packing densities of which optical systems are inherently capable, film and tape speeds are pushing against the current boundaries of transport technology. One area in which Harris has contributed to this technology is the development of a series of successful air-bearing platens, which provide non-contact positioning of the storage medium at the read/write station. Additional developments which are needed from the vendors of sophisticated transport mechanisms are: high-speed (i.e., up to 100 ips and beyond) search modes with good surface preservation; effective lateral tracking methods for thin-base media up to 70 mm wide; and high quality servo capabilities over speeds ranging from 0.5 to 5 meters per second. Modular design and computer control capabilities would also contribute to overall system flexibilities.

5.4.4 Real Time Storage Media

The advantages of combining optical storage techniques with a real time storage medium (i.e., one which requires no off-line processing procedures) should be self-evident. They include the elimination of the facilities and chemical requirements of a film processor, radically decreased access times to data after recording, and the potential for read-after write error checking. Although no such medium is currently available to meet all the requirements of high-density information storage, a number of organizations are working in this area, and

Harris is maintaining contact with many of them. In addition, a current program at Harris, sponsored by RADC, is directed to the study of several of these candidate materials. Currently, the completed tests indicate that the materials now available are still marginal with respect to use in a WBR system; however, the most promising materials had not been tested at this writing.

The required sensitometric properties for a successful digital recording medium include: sensitivity to exposures of less than 1 mJ/cm^2; a response which is peaked in the red (633 nm) or green (515 nm) regions of the spectrum; high contrast; and controllable contrast or sensitivity losses (reciprocity failure) for shorttime, high intensity exposures. Structurally, high resolving power and low statistical noise figures are the relevant requirements. From a systems engineering point of view, a qualified digital recording medium is characterized by: non-destructive data recovery, long archival lifetime, environmental integrity under extreme conditions, dimensional stability, reasonably long shelf life, commercial availability, simple and repeatable processing, and exceptional quality control. These criteria are satisfied by few current recording media; nevertheless, they often represent the minimum requirements for optical data storage systems.

Producing a real time recording material which can meet all the stringent requirements listed above, and adapting the material and the WBR system to each other, will be a difficult undertaking. However, the expanded scope and applicability of high-density, high-speed optical data storage and retrieval systems which would be the result of such a development would provide a very adequate reward for such an effort.

5.5 Overview and Recommendations

The technical risk in designing, building, and delivering a fully operational prototype recorder/reproducer system based on the use of silver halide film for rates up to 1.0 gigabit/second has been essentially eliminated with the experimental and analytical data now available from the Phase III and IV programs. The implementation of a film transport subsystem for continuous recording intervals of 10 to 20 minutes is a remaining engineering challenge; we recommend that such a capability be added to the WBR Exploratory Development Model (EDM) in the near future. A more thorough study of laser illumination sources with improved energy efficiencies and more compact packaging could lead to a more reliable and serviceable future system; we recommend such a study. Additional design and analysis effort on the scanning lenses for 70 mm and 125 mm film widths could result in cost reductions for these lenses, potentially greater data packing density, and/or increased system design flexibilities; we recommend such a study.

The incorporation of a real-time, on-line processed, non-silver halide recording material into the WBR system is a key challenge yet to be faced. In the event that one or more of the candidate materials now being evaluated for RADC at Harris on Contract F-30602-78-C-0304 are judged to have the potential to replace silver halide film, a logical next step would be to modify the existing WBR EDM to incorporate a film transport and processing subsystem for the best candidate. A set of record and readout experiments with the modified WBR EDM would then be required to collect data that characterizes the system performance with this material. An evaluation of these data would provide the needed information to assess the potential performance of a prototype WBR system operated with this material. We recommend such a program when the best candidate non-silver halide real-time material has been identified.

With the design and tradeoff data now available from Phase III and Phase IV, we can generate specific design data and related cost data for a large variety of wideband recording applications. The identification of users with requirements aligned with the WBR system capabilities is a key remaining challenge.

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