RADC-TR-77-153
Executive Summary
April 1977

# WIDEBAND HOLOGRAPHIC DIGITAL RECORDING AND REPRODUCTION

Harris Corporation/ESD



Sponsored by
Defense Advanced Research Projects Agency (DoD)
ARPA Order No. 2322





ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

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(6) WIDEBAND HOLOGRAPHIC DIGITAL RECORDING AND REPRODUCTION.


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Techniques were investigated to apply the concept of holography to the problems of wideband digital recording and reproduction. The feasibility of recording at rates up to 2 Gb/s and playback at both full-record and reduced speeds was theoretically and experimentally considered. The program was a multi-phased effort including the design, development and experimental evaluation of two Exploratory Development Models (EDMs): the Phase I EDM demonstrated recording at 400 Mb/s and playback at 40 Mb/s, and was used to guide design trade-offs for Phase II; the Phase II EDM demonstrated recording at 600 Mb/s playback at

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full-record and 0 to 1 time expanded rates with bit-error-rates better than $10^{-6}$. Both full-system operational testing and parametric evaluation on a component basis were performed.

This report describes design and performance data at both the system and the subsystem levels for the Phase II hardware. Also a part of this program was the development of conceptual designs for potential multi-gigabit recorders. These designs are presented, along with system and subsystem level trade-offs between the various concepts, and recommendations for subsequent development. Overall, this program has made available a new, high-speed, high-capacity information storage approach offering significant advantages over more conventional recording techniques.

Block 7.

Andrew M. Bardos, George S. Moore, Richard H. Nelson, Lynda M. Ralston, Michael W. Shareck, Curt A. Shuman, Ron J. Straayer, Tom E. Wisnewski

# INTRODUCTION

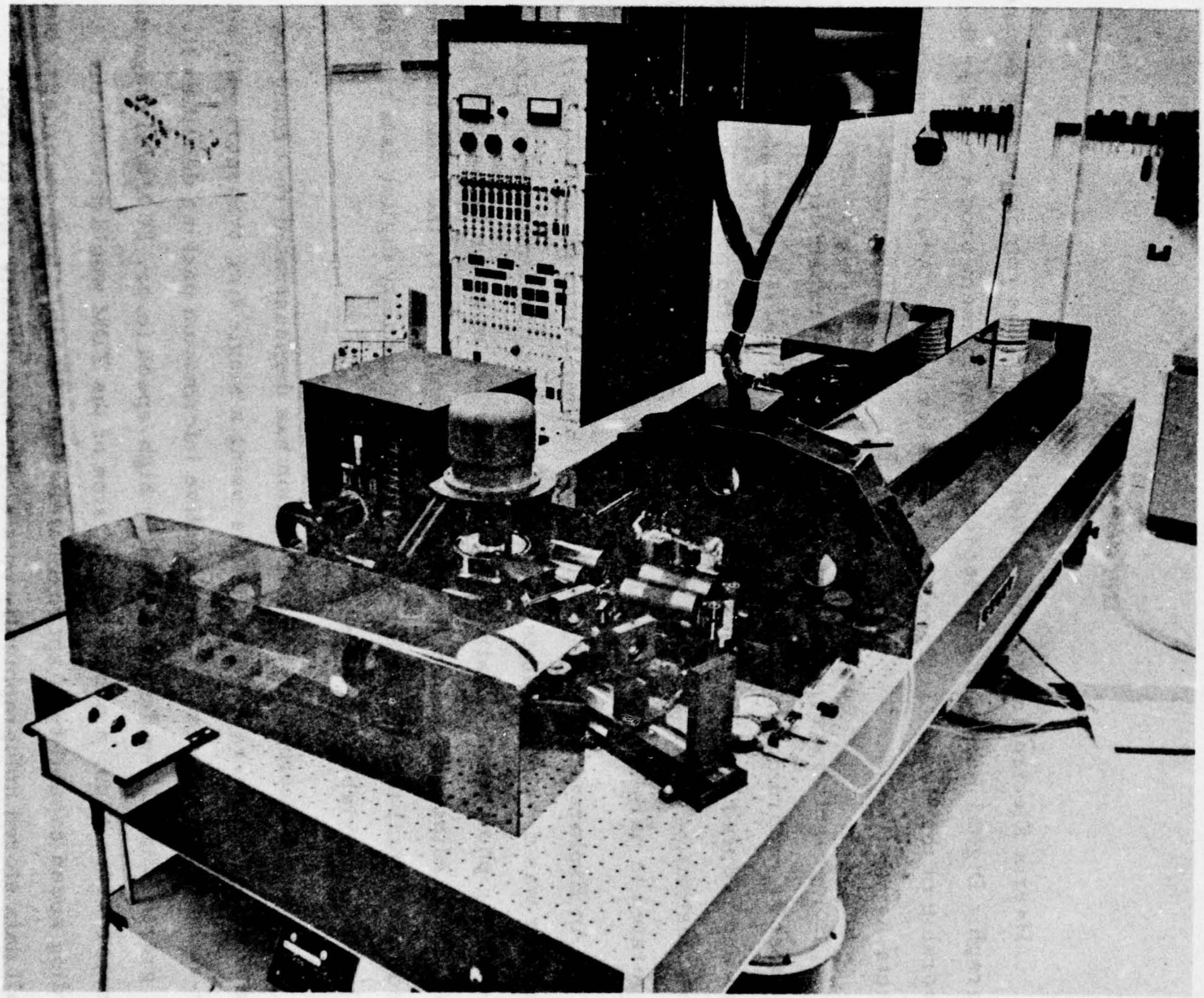
Harris Electronic Systems Division (HESD) has completed a Wideband Holographic Digital Recorder and Reproducer development program under the sponsorship of the Rome Air Development Center and the Advanced Research Projects Agency.

Holographic recording techniques provide the capability of high-rate, high-capacity recording on single reels with low error-rate readout at both full-record and reduced speeds. These features eliminate the problems associated with reconstituting bit-to-bit time integrity when multiple-unit recorder systems are operated in parallel to obtain high data-rate capability.

An Exploratory Development Model (EDM) holographic recorder/reproducer was developed and tested under this recently completed program. The following photograph illustrates the EDM as set up in the laboratory at Harris ESD. Although not intended to be a finished product, the EDM has demonstrated that optical techniques for high-rate, high capacity digital data recording and playback are viable and sound.

Harris Electronic Systems Division has demonstrated recording and playback at user-data-rates of 600 Mb/s using a single film transport with bit-error-rates better than $1x10^{-6}$, at effective information packing densities five times greater than those demonstrated by high-speed (e.g., 80 Mb/s) magnetic tape recorders. Thus, a production version of the EDM would provide the recording speed capability of approximately eight 80 Mb/s tape recorders, but with all data stored holographically on a single high-density reel of film.

# WIDEBAND RECORDER/REPRODUCER
# EDM



Playback of the recorded data is readily achieved without the need for phase-locked multiple transports. Furthermore, it has been demonstrated that playback may be conducted at a broad range cf playback speeds (e.g., from full speed to a twenty-fold time expansion), and may be repeated a large number of times (e.g., 400) from the same film with little degradation of data integrity.

In addition, continuing technology investigations, design studies and experimental work at Harris have provided realistic performance objectives for the present development of a 1 Gigibit Recorder/Reader, and the near term development of multi-gigabit systems based on the same technological approach.

The following table summarizes the demonstrated system performance of the completed EDM, and the performance of an upgraded system presently under development at Harris ESD.

| System Parameter | Performance Demonstrated By EDM | Performance Objectives of Upgraded System |
|---|---|---|
| User I/O Data Rate | 600 MBPS | 900 MBPS |
| Number of Channels | 128 | 128 |
| Channel Data Rate | 6 MBPS | 10 MBPS |
| Recording Medium | 35mm, SO-141 | 70mm, SO-141 |
| Film Velocity | 4 meters/sec | 3 meters/sec |
| Packing Density | $0.8 \times 10^6$ bits/cm$^2$ | $1.5 \times 10^6$ bits/cm$^2$ |
| Error Rate | $10^{-6}$ | $10^{-6}$ |

With these demonstrations and the multigigabit technology investigations and design studies both completed and continuing, Harris Corporation is now in a position to responsibly reply to requests for wideband digital recording and reproduction systems capable of user data rates up to 2 Gb/s.

The following pages present a brief overview and functional description of the 600 Mb/s recorder/reproducer system developed and demonstrated under this recently completed program. A short summary follows dealing with the present and on-going wideband recorder development programs at Harris' Electronic Systems Division.

A detailed and thorough description of the various technologies advanced under the completed development program addressed in this Executive Summary is included in the Final Technical Report for Contract No. F30602-73-C-0155, WIDEBAND HOLOGRAPHIC DIGITAL RECORDING AND REPRODUCTION, dated November 1976, prepared for the Rome Air Development Center, Griffiss Air Force Base, New York 13441.

## SYSTEM OVERVIEW

The implementation of the Wideband Holographic Recorder/Reproducer System is a significant extension of fundamental laser line-scanning technology. Two particular improvements in the fundamental techniques make possible the high-rate, high-capacity data recording and retrieval achieved.

First, the scanner is augmented with a multi-channel, acousto-optical modulator specifically developed by Harris for this application. With this optical-modulator, the high-rate digital data to be recorded is demultiplexed into several lower-rate data channels, which are clocked into the optical system in parallel. In this manner, the high-speed requirements of the system are placed on the input electronics, thereby correspondingly reducing the dynamic requirements of the various opto-mechanisms (e. g., light modulators, deflectors and film drive) of the system.

Second, holographic techniques are employed to improve the data recovery performance of the system during playback. By simultaneously recording a linear array of data bits (i. e., one bit from each of the input channels) into a one-dimensional Fourier transform hologram, the readout performance (extremely low bit-error-rate) during high-speed data recovery is significantly enhanced. The spatial invariance property and relatively large dimension (in one direction) of the hologram significantly relaxes the degree of accuracy necessary to sequentially address and read out the data with a scanning laser beam. A measure of redundancy, with associated immunity to recording medium imperfections (such as film scratches and emulsion defects) is also provided by the holographic structure of the recorded data.

In addition, since data from each input channel is recorded and subsequently reconstructed simultaneously, "skew" between readout channels is eliminated - an advantage over high-density, longitudinal magnetic tape recording and playback. A further comparison of Laser and Magnetic Recorders is summarized in the following table:

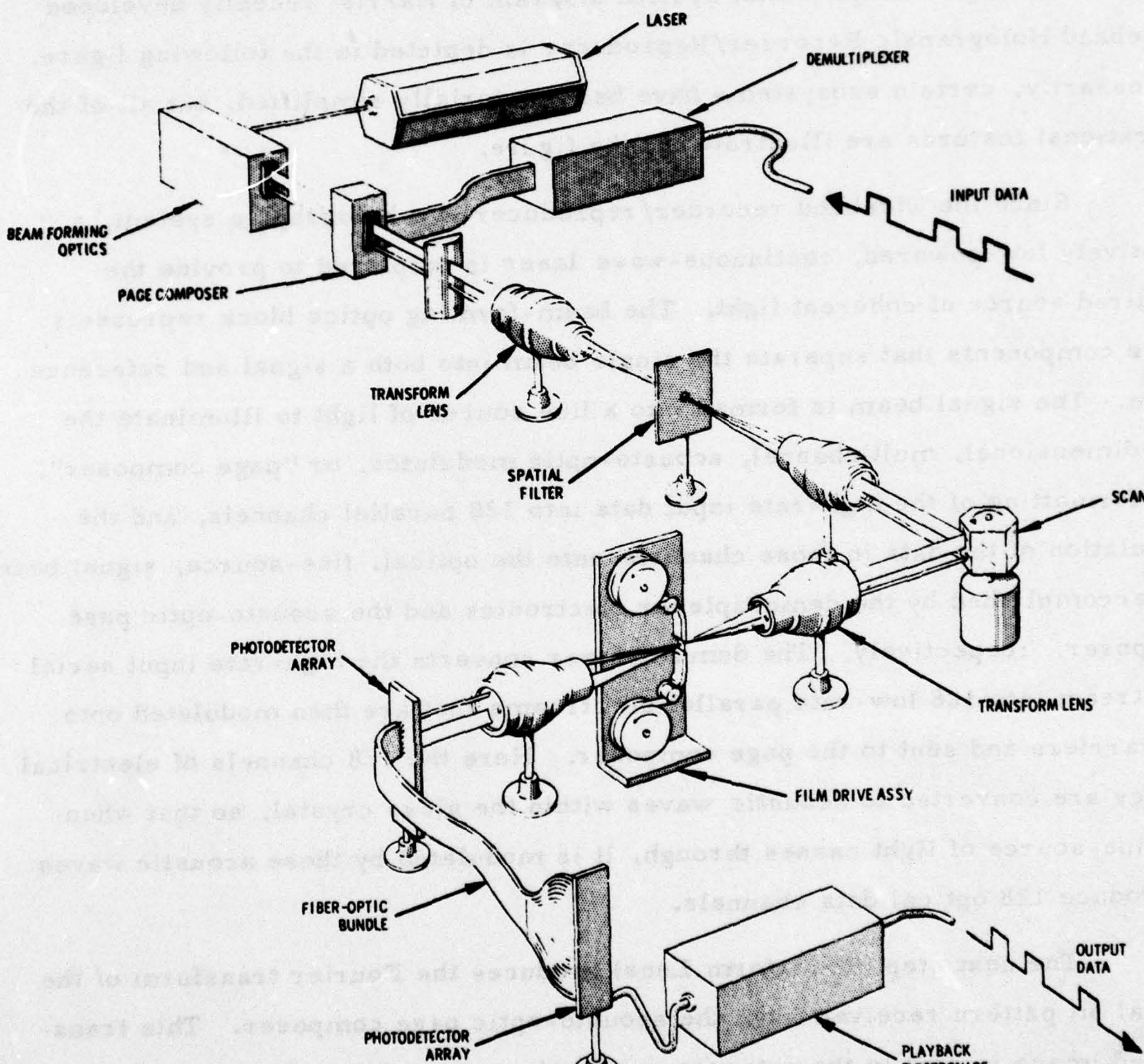
| Design Parameter | Laser Recording | | Magnetic Recording |
|---|---|---|---|
| User I/O Data Rate | 900Mb/s | 300MBPS | 80 MBPS |
| Number of Data Channels | 128 | 128 | 24 |
| Linear Packing Density | 8.3Mb/in | 7.7 Mb/in | 0.59 Mb/in |
| Film or Tape Width | 70mm | 70mm | 1 inch (25.4mm) |
| Packing Density | 3.02Mb/in$^2$ | 2.79Mb/in$^2$ | 0.59 Mb/in$^2$ |
| Film or Tape Speed | 108 IPS | 39 IPS | 135 IPS |
| Recording Media Reel | 20 in 10,800 ft of 2.5 mil | 18 in $\left\{\begin{matrix}\text{5,000 ft}\\ \text{0f 4 mil}\end{matrix}\right.$ | 15 in $\left\{\begin{matrix}\text{10,800 ft}\\ \text{of 1 mil}\end{matrix}\right.$ |
| Record Time (Approx.) | 20 min. | 25 min. | 16 min. |
| Total Data Capacity | 1080 Gb | 450 Gb | 76.8 Gb |

## SYSTEM FUNCTIONAL DESCRIPTION

A simplified functional system diagram of Harris' recently developed Wideband Holographic Recorder/Reproducer is depicted in the following figure. Necessarily, certain subsystems have been pictorially simplified, but all of the operational features are illustrated in the figure.

Since the wideband recorder/reproducer is a holographic system, a relatively low-powered, continuous-wave laser is employed to provide the required source of coherent light. The beam-forming optics block represents those components that separate the single beam into both a signal and reference beam. The signal beam is formed into a line source of light to illuminate the one-dimensional, multichannel, acousto-optic modulator, or "page composer". The formatting of the high-rate input data into 128 parallel channels, and the modulation of the data in those channels onto the optical, line-source, signal beam are accomplished by the demultiplexer electronics and the acousto-optic page composer, respectively. The demultiplexer converts the high-rate input serial bit stream into 128 low-rate parallel bit streams that are then modulated onto RF carriers and sent to the page composer. Here the 128 channels of electrical energy are converted to acoustic waves within the glass crystal, so that when the line-source of light passes through, it is modulated by these acoustic waves to produce 128 optical data channels.

The next step (Transform Lens) produces the Fourier transform of the optical bit pattern received from the acousto-optic page composer. This transformed image is sent to the autoscan spinner/scanner where it is laterally scanned and imaged to the film plane to be recorded on the moving film. As the film is transported through the film plane, the transformed beam scans laterally across it, recording rows of holograms.

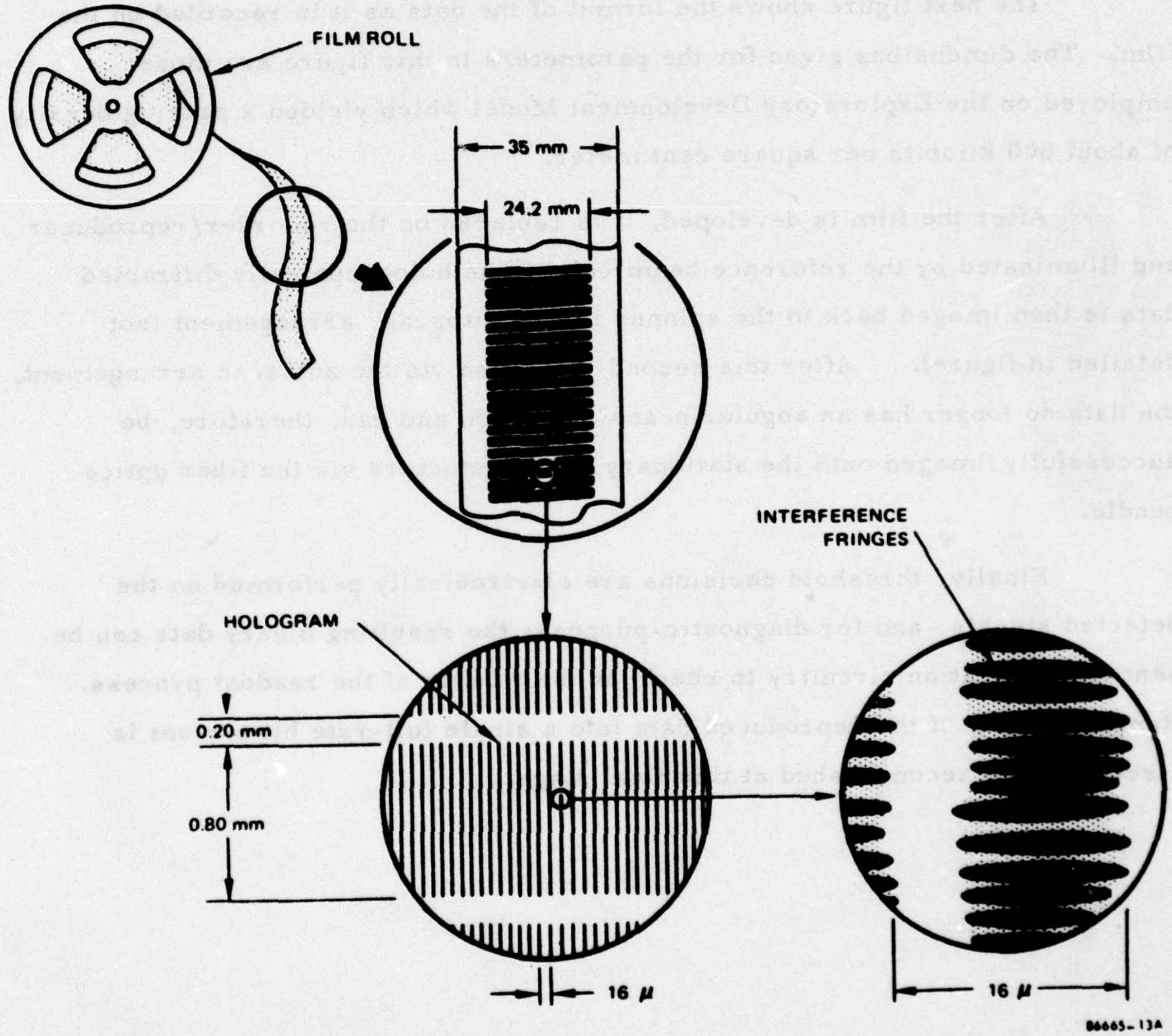



**SIMPLIFIED FUNCTIONAL SYSTEM DIAGRAM**

The next figure shows the format of the data as it is recorded on the film. The dimensions given for the parameters in this figure are those employed on the Exploratory Development Model which yielded a packing density of about 800 kilobits per square centimeter.

After the film is developed, it is replaced on the recorder/reproducer and illuminated by the reference beam only. The holographically diffracted data is then imaged back to the spinner in an "autoscan" arrangement (not detailed in figure). After this second reflection via the autoscan arrangement, the data no longer has an angular scanning motion and can, therefore, be successfully imaged onto the stationary photo-detectors via the fiber optics bundle.

Finally, threshold decisions are electronically performed on the detected signals, and for diagnostic-purposes the resulting binary data can be sent to verification circuitry to check on the fidelity of the readout process. Remultiplexing of the reproduced data into a single full-rate bit stream is electronically accomplished at this final stage.




RECORDING FORMAT

# SUMMARY

The development, implementation and experimental evaluation of the Wideband Recorder Exploratory Development Model has proven the viability of high-speed digital data storage and playback using holographic techniques and photographic film. This development program has made available a new, high-speed, high-capacity information storage approach offering significant operational advantages over more conventional recording approaches (e.g., magnetic-tape recording) for some applications.

Additionally, a significant part of this development program was the consideration of the potential for higher rate recording and reproduction systems (i.e., up to 5Gb/s user rates). To achieve this, Harris has synthesized advanced system concepts and component specifications for rates up to 2 Gb/s. It is noteworthy that these systems are based upon a common technology base which was addressed as part of this and related programs. Within this technology base, Harris has assessed the state of the art and has identified the critical areas for further development.

From these investigations, Harris has concluded that the system approach developed under this program is currently best for most systems that are required to support user data rates up to 2 Gb/s.

Present on-going programs at Harris now include the development of a 900 Mb/s (user rate) wideband holographic recorder/reproducer further extending this already proven system approach through the use of a wider film format to effectively increase the total record time for a given film reel-length.

APPENDIX A

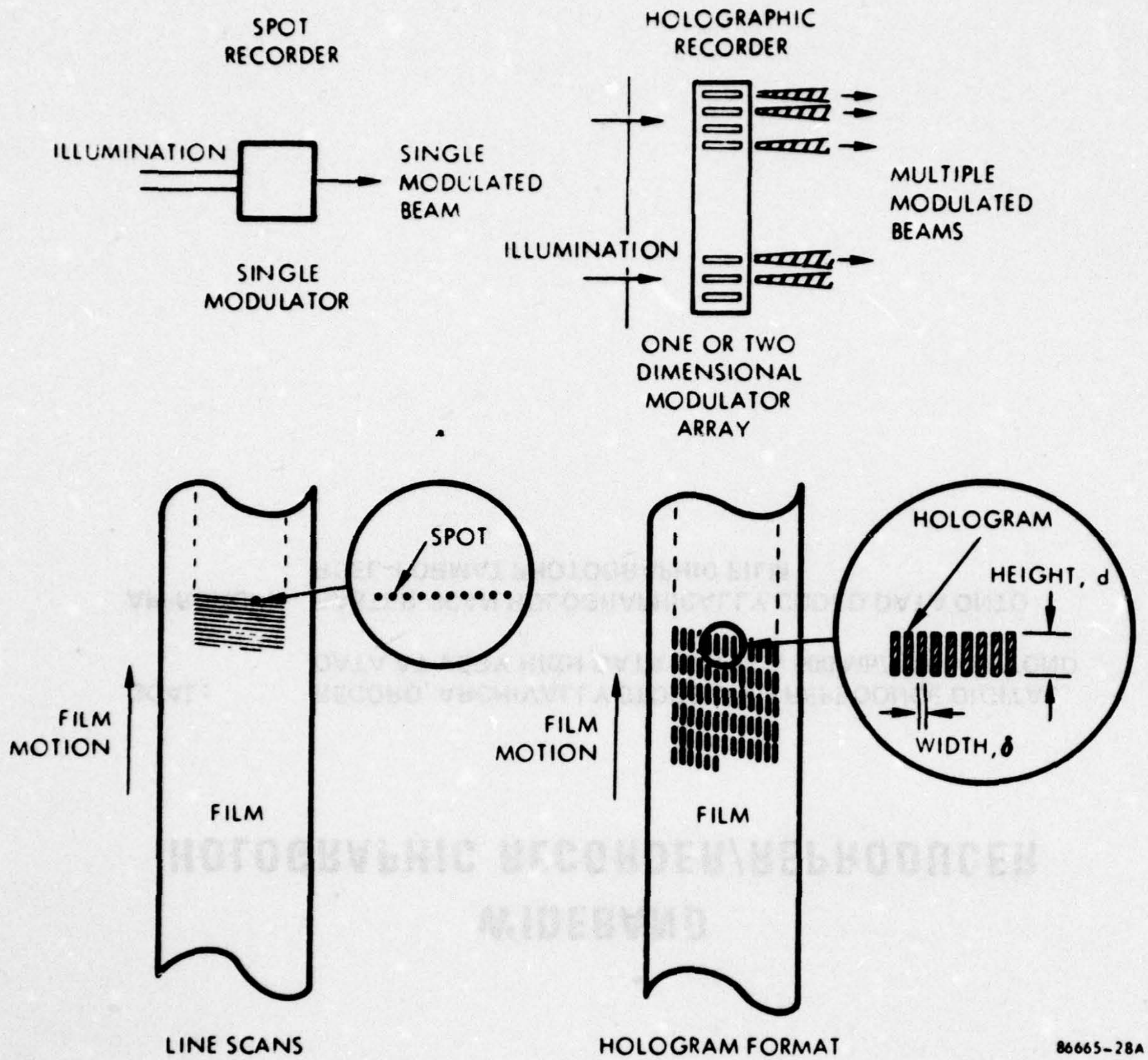
WIDEBAND HOLOGRAPHIC DIGITAL RECORDER

VIEWGRAPH PRESENTATION

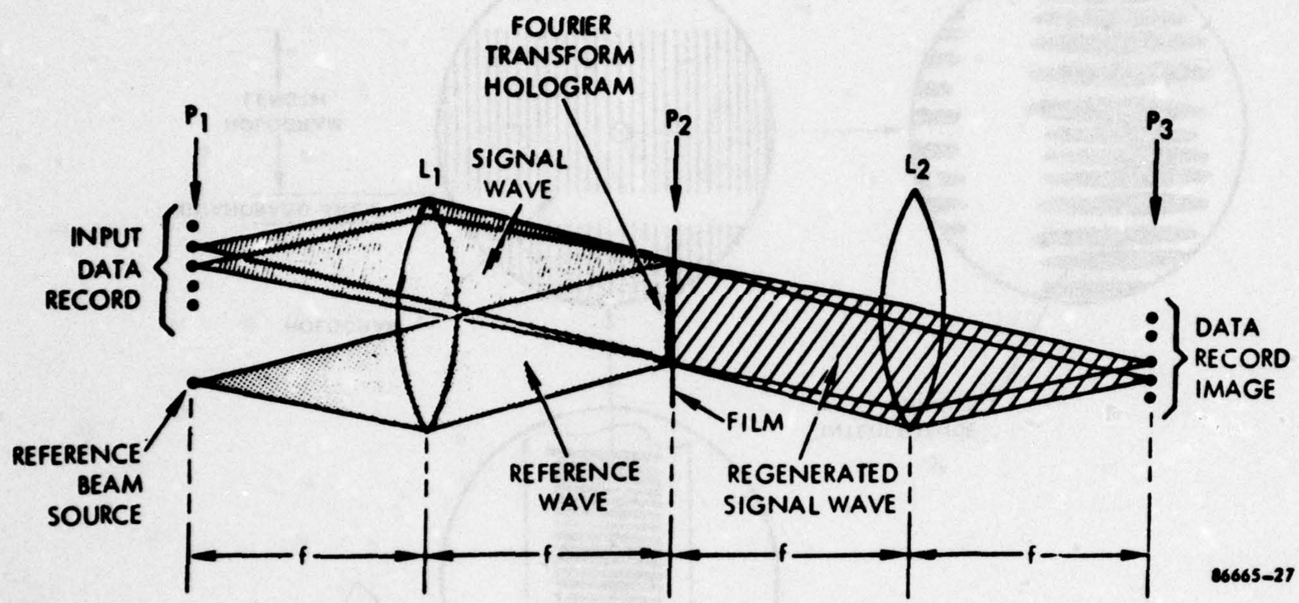
# WIDEBAND
# HOLOGRAPHIC RECORDER/REPRODUCER

**GOAL:** RECORD, ARCHIVALLY STORE, AND REPRODUCE DIGITAL DATA AT VERY HIGH DATA RATES – 500 Mb/s AND BEYOND

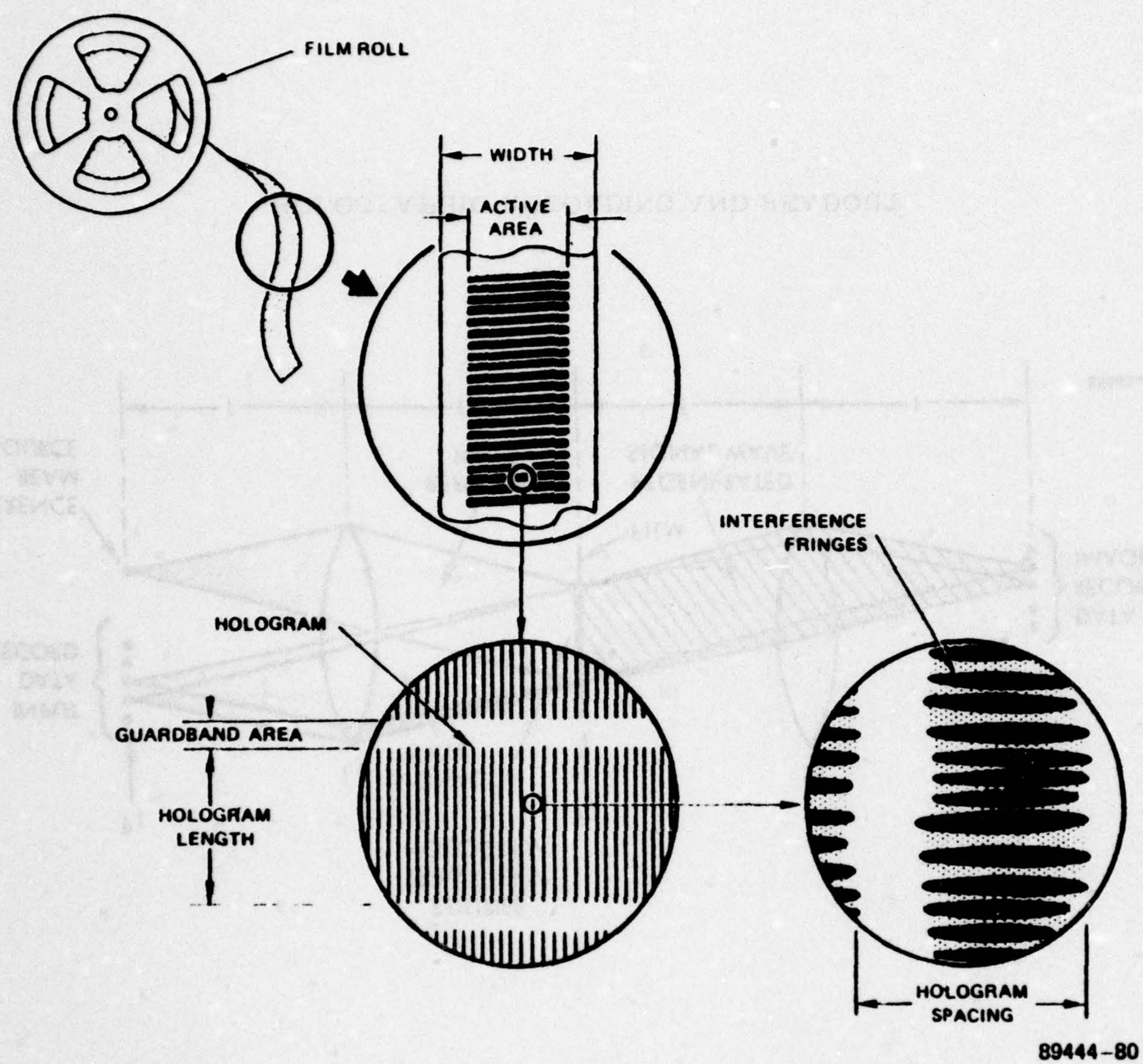
**APPROACH:** RASTER-SCAN HOLOGRAPHICALLY CODED DATA ONTO REEL-FORMAT PHOTOGRAPHIC FILM




COMPARISON OF HOLOGRAPHIC AND SPOT RECORDING FORMATS

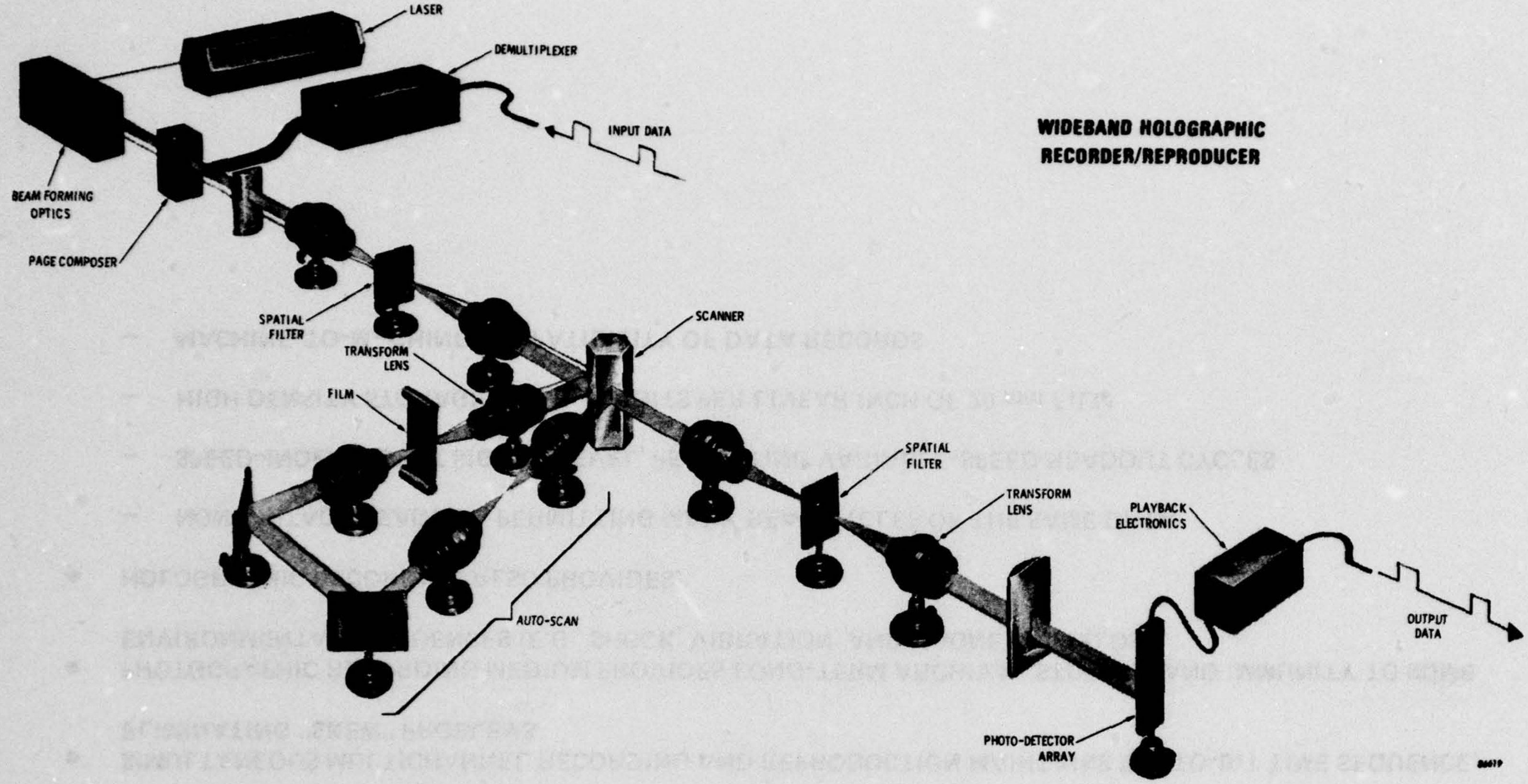



HOLOGRAPHIC RECORDING AND READOUT




HOLOGRAPHIC STORAGE FORMAT

**WIDEBAND HOLOGRAPHIC RECORDER/REPRODUCER**



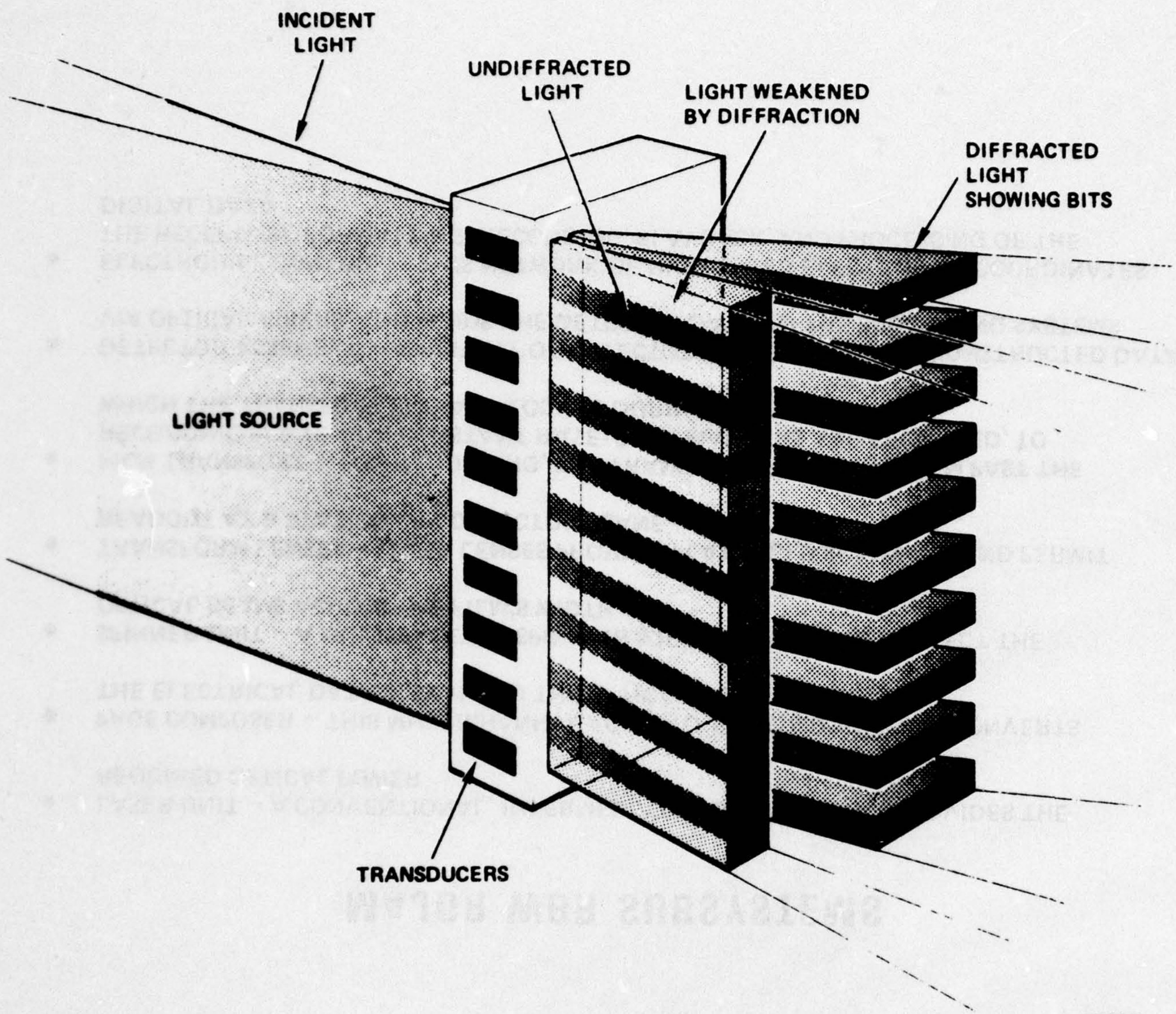
# KEY SYSTEM FEATURES

- MULTICHANNEL FORMATTING OF DATA REDUCES ELECTROMECHANICAL SPEED REQUIREMENTS
- RASTER-SCANNING PERMITS WIDE RECORDING MATERIAL, REDUCING TRANSPORT SPEED REQUIREMENTS
- HOLOGRAPHIC STORAGE PROVIDES DISTRIBUTED CODING, MINIMIZING BIT "DROPOUT"
- HOLOGRAPHIC SHIFT INVARIANCE REDUCES READOUT TRACKING ACCURACY REQUIREMENTS
- SIMULTANEOUS MULTICHANNEL RECORDING AND REPRODUCTION MAINTAINS BIT-TO-BIT TIME SEQUENCE, ELIMINATING "SKEW" PROBLEMS
- PHOTOGRAPHIC RECORDING MEDIUM PROVIDES LONG-TERM ARCHIVAL STORAGE AND IMMUNITY TO SOME ENVIRONMENTAL INFLUENCES (E.G., SHOCK, VIBRATION, AND MAGNETIC FIELDS)
- HOLOGRAPHIC RECORDING ALSO PROVIDES:
  - NONCONTACT READOUT, PERMITTING MANY READ CYCLES OF THE SAME DATA
  - SPEED-INDEPENDENT SIGNAL LEVEL, PERMITTING VARIABLE-SPEED READOUT CYCLES
  - HIGH DENSITY STORAGE, OVER 10 MBITS PER LINEAR INCH OF 70 mm FILM
  - MACHINE-TO-MACHINE COMPATIBILITY OF DATA RECORDS

# MAJOR WBR SUBSYSTEMS

- LASER UNIT – A CONVENTIONAL, INTERMEDIATE-POWER CW UNIT PROVIDES THE REQUIRED OPTICAL POWER
- PAGE COMPOSER – THIS MULTICHANNEL ACOUSTO-OPTIC MODULATOR CONVERTS THE ELECTRICAL DATA SIGNALS TO THE OPTICAL DOMAIN
- SPINNER UNIT – A MULTIFACETED SPINNING MIRROR IS USED TO DEFLECT THE OPTICAL BEAMS ACROSS THE FILM'S WIDTH
- TRANSFORM LENSES – THESE LENSES PROVIDE FLAT-FIELD SCANNING, AND PERMIT READOUT AT A STATIONARY DETECTOR PLANE
- FILM TRANSPORT – FOR RECORDING, THE TRANSPORT MOVES THE FILM PAST THE RECORDING PLANE AT A CONSTANT RATE; EDGE MARKERS ARE RECORDED, TO WHICH THE TRANSPORT IS PHASE-LOCKED DURING READOUT
- DETECTOR ASSEMBLY – AN ARRAY OF DETECTORS RECEIVES THE RECONSTRUCTED DATA VIA OPTICAL FIBERS, AND SENDS THE DETECTED DATA TO THE PROCESSING SYSTEMS
- ELECTRONICS CONTROL – THIS NETWORK OF HIGH-SPEED ELECTRONICS COORDINATES THE RECEPTION, FORMATTING, RECORDING, PLAYBACK, AND PROCESSING OF THE DIGITAL DATA

# ACOUSTO-OPTIC PAGE COMPOSER

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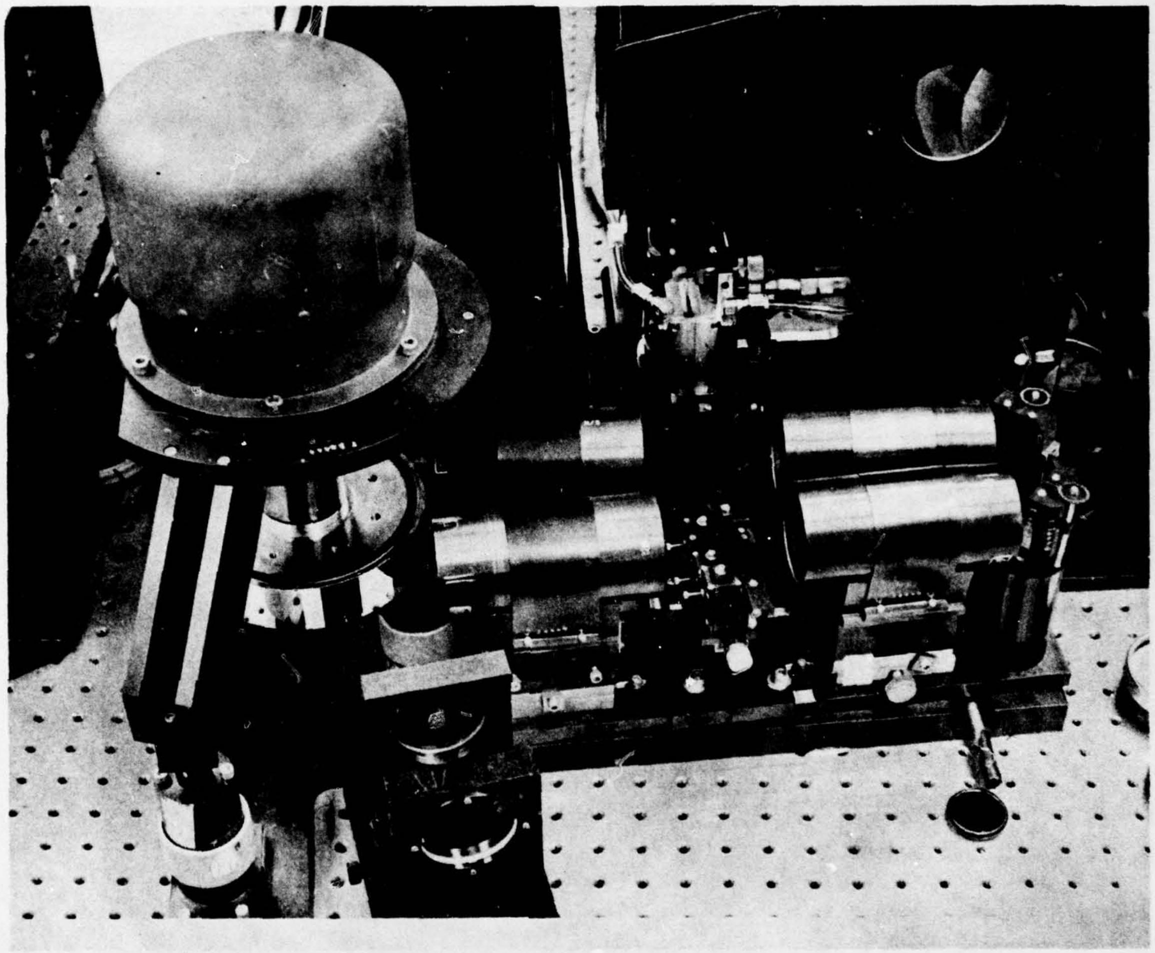
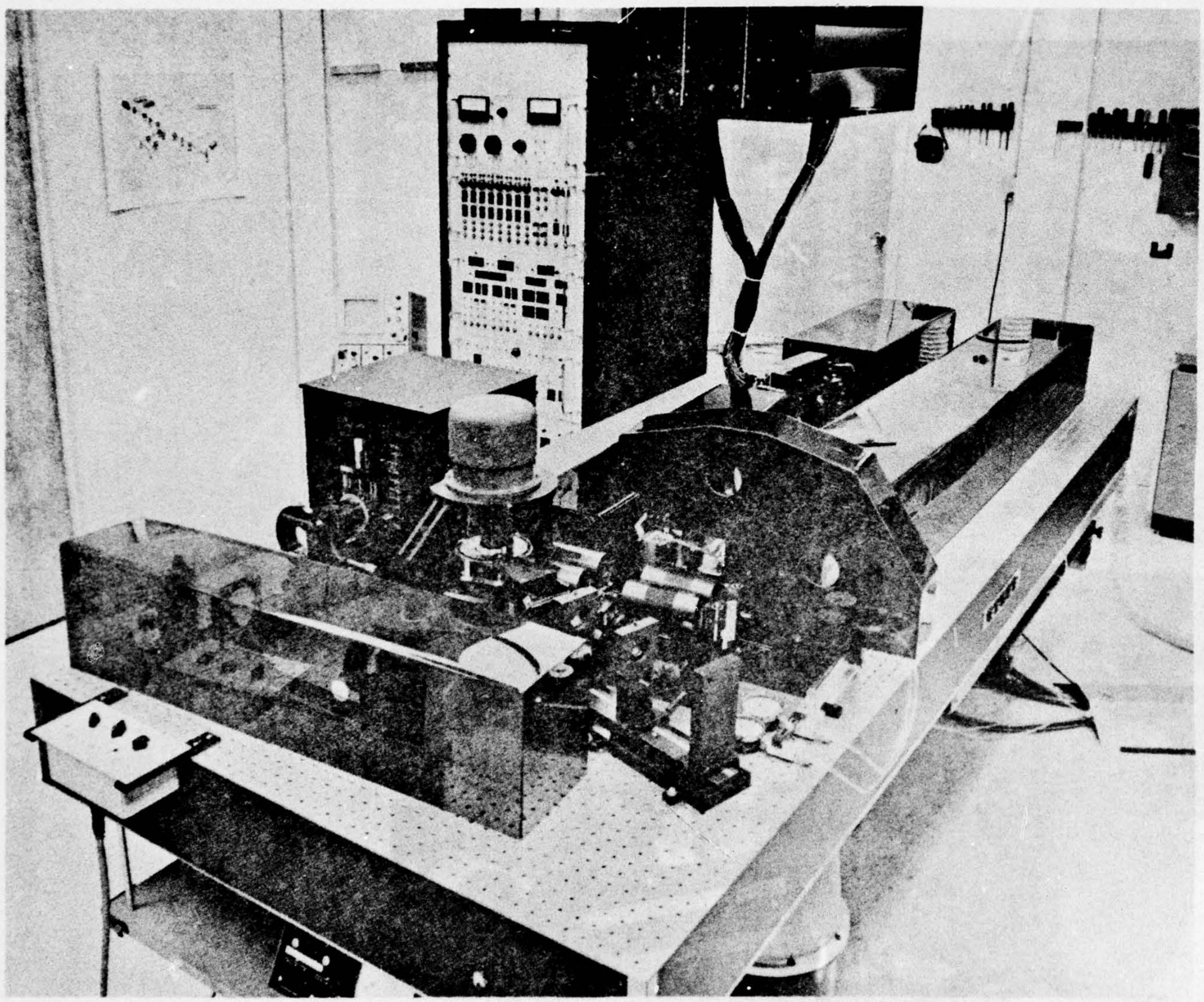


# WIDEBAND RECORDER/REPRODUCER
# EDM



# WBR SYSTEM PERFORMANCE – RECORDER

| | PHASE II | PHASE III GOAL |
|---|---|---|
| TOTAL DATA RATE | 750 Mb/s | 1200 Mb/s |
| CHANNEL DATA RATE | 6 Mb/s | 10 Mb/s |
| NUMBER OF CHANNELS | 128 | 128 |
| FILM VELOCITY | 4.0 m/SEC | 3.1 m/SEC |
| RECORDING MEDIUM | | |
| TYPE | SO-141 | SO-141 |
| DIMENSIONS | 35 mm X 250 FT X 4.0 mil | 70 mm X 3000 FT X 2.5 mil |
| PACKING DENSITY | $0.8 \times 10^6$ BITS/cm$^2$ | $1.5 \times 10^6$ BITS/cm$^2$ |
| HOLOGRAM EXPOSURE | 2.0 mW X 80 nSEC | 4.0 mW X 50 nSEC |
| CONTINUOUS RECORD TIME | 19 SEC | $\geq$ 20 MIN |
| STORAGE CAPACITY/REEL | $1.1 \times 10^{10}$ BITS | $5.0 \times 10^{11}$ BITS |

# WBR SYSTEM PERFORMANCE — READER

| | PHASE II | PHASE III GOAL |
|---|---|---|
| TOTAL DATA RATE | 750 Mb/s | 1200 Mb/s |
| CHANNEL DATA RATE | 6 Mb/s | 10 Mb/s |
| FILM VELOCITY | 4.0 m/SEC | 3.1 m/SEC |
| 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 | $10^{-6}$ | $10^{-7}$ |

# WBR SYSTEM SUMMARY

- PERFORMANCE ACHIEVED:
  - 600 Mb/s USER DATA RATE, RECORD AND PLAYBACK
  - BIT ERROR RATE $\leq 10^{-6}$
  - MULTIPLE AND VARIABLE-SPEED PLAYBACK
- ALSO INVESTIGATED:
  - TECHNOLOGY REQUIRED FOR EXTENSION TO 2 Gb/s RATES
- CURRENT GOALS:
  - 900 Mb/s USER DATA RATE, RECORD
  - FULL AND FRACTIONAL RATE PLAYBACK
  - BIT ERROR RATE $< 10^{-6}$
  - 20-MINUTE CONTINUOUS RECORD TIME

# SOME IMPORTANT DESIGN PARAMETERS FOR FUTURE WBR SYSTEMS

- TOTAL USER DATA RATE
- RECORD TIME (CONTINUOUS)
- RECORD TIME (PER DAY)
- ACCESS TIME (TURNAROUND)
- READOUT RATE(S)
- MAXIMUM BER
- ARCHIVAL STORAGE REQUIREMENT
- VOLUME PACKING DENSITY REQUIREMENTS
- ENVIRONMENTAL REQUIREMENTS
- SPACE CONSTRAINTS
- FACILITIES CONSTRAINTS

## METRIC SYSTEM

### BASE UNITS:

| Quantity | Unit | SI Symbol | Formula |
|---|---|---|---|
| length | metre | m | ... |
| mass | kilogram | kg | ... |
| time | second | s | ... |
| electric current | ampere | A | ... |
| thermodynamic temperature | kelvin | K | ... |
| amount of substance | mole | mol | ... |
| luminous intensity | candela | cd | ... |

### SUPPLEMENTARY UNITS:

| | | | |
|---|---|---|---|
| plane angle | radian | rad | ... |
| solid angle | steradian | sr | ... |

### DERIVED UNITS:

| | | | |
|---|---|---|---|
| Acceleration | metre per second squared | ... | m/s |
| activity (of a radioactive source) | disintegration per second | ... | (disintegration)/s |
| angular acceleration | radian per second squared | ... | rad/s |
| angular velocity | radian per second | ... | rad/s |
| area | square metre | ... | m |
| density | kilogram per cubic metre | ... | kg/m |
| electric capacitance | farad | F | A·s/V |
| electrical conductance | siemens | S | A/V |
| electric field strength | volt per metre | ... | V/m |
| electric inductance | henry | H | V·s/A |
| electric potential difference | volt | V | W/A |
| electric resistance | ohm | | V/A |
| electromotive force | volt | V | W/A |
| energy | joule | J | N·m |
| entropy | joule per kelvin | ... | J/K |
| *force* | newton | N | kg·m/s |
| frequency | hertz | Hz | (cycle)/s |
| illuminance | lux | lx | lm/m |
| luminance | candela per square metre | | cd/m |
| luminous flux | lumen | lm | cd·sr |
| magnetic field strength | ampere per metre | ... | A/m |
| magnetic flux | weber | Wb | V·s |
| magnetic flux density | tesla | T | Wb/m |
| magnetomotive force | ampere | A | ... |
| power | watt | W | J/s |
| pressure | pascal | Pa | N/m |
| quantity of electricity | coulomb | C | A·s |
| quantity of heat | joule | J | N·m |
| radiant intensity | watt per steradian | ... | W/sr |
| specific heat | joule per kilogram-kelvin | ... | J/kg·K |
| stress | pascal | Pa | N/m |
| thermal conductivity | watt per metre-kelvin | ... | W/m·K |
| velocity | metre per second | ... | m/s |
| viscosity, dynamic | pascal-second | ... | Pa·s |
| viscosity, kinematic | square metre per second | ... | m/s |
| voltage | volt | V | W/A |
| volume | cubic metre | ... | m |
| wavenumber | reciprocal metre | ... | (wave)/m |
| work | joule | J | N·m |

### SI PREFIXES:

| Multiplication Factors | Prefix | SI Symbol |
|---|---|---|
| 1 000 000 000 000 = $10^{12}$ | tera | T |
| 1 000 000 000 = $10^{9}$ | giga | G |
| 1 000 000 = $10^{6}$ | mega | M |
| 1 000 = $10^{3}$ | kilo | k |
| 100 = $10^{2}$ | hecto* | h |
| 10 = $10^{1}$ | deka* | da |
| 0.1 = $10^{-1}$ | deci* | d |
| 0.01 = $10^{-2}$ | centi* | c |
| 0.001 = $10^{-3}$ | milli | m |
| 0.000 001 = $10^{-6}$ | micro | µ |
| 0.000 000 001 = $10^{-9}$ | nano | n |
| 0.000 000 000 001 = $10^{-12}$ | pico | p |
| 0.000 000 000 000 001 = $10^{-15}$ | femto | f |
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RADC plans and conducts research, exploratory and advanced development programs in command, control, and communications ($C^3$) activities, and in the $C^3$ areas of information sciences and intelligence. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.

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