

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

NASA CR-152551

STUDY REPORT ON LASER STORAGE AND RETRIEVAL OF IMAGE DATA

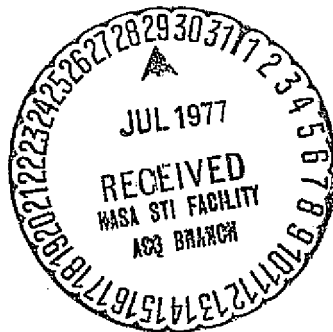
(NASA-CR-152551) STUDY REPORT ON LASER
STORAGE AND RETRIEVAL OF IMAGE DATA (Becker
(Carl H.)) 228 p HC A11/MF A01 CSCL 20E

N77-27380

Unclas
G3/36 40305

NASA Contract: NAS5-22977
Goddard Space Flight Center
Greenbelt, Maryland 20771

Dr. Carl H. Becker



June 7, 1976
21316 Glen Place # 5
Cupertino, California

STUDY REPORT ON LASER STORAGE
AND RETRIEVAL OF IMAGE DATA

NASA Contract: NAS5-22977
Goddard Space Flight Center
Greenbelt, Maryland 20771

Dr. Carl H. Becker

June 7, 1976
21316 Glen Place # 5
Cupertino, California

TABLE OF CONTENTS

page #

LIST OF ILLUSTRATIONS

LIST OF TABLES

ABSTRACT

PREFACE

INTRODUCTION

1.	Subject of study	1
2.	Scope of study	5
3.	Previous state of the art	6
4.	Expected advancement in the state of the art	9
5.	Summary of effort	10
6.	Conclusions	11
7.	New technology	12
I.	THE CONCEPTS OF DIGITAL LASER MASS STORAGE AND RETRIEVAL	13
1.1	Principles	14
1.2	Theory of diffraction	29
1.3	Laser	45
1.4	Optical modes of laser beam intensity distribution	47
1.5	Laser beam focusing, resolution & power concentration	51
1.6	Laser beam expansion	55
1.7	Optics & thermodynamics of digital laser mass storage	57
1.8	Signal modulation techniques for digital laser mass storage	66
	a) Principles	66
	b) External signal modulation of a laser beam	69
	c) Internal signal modulation of a laser beam	72
	d) Signal modulation techniques for parallel or serial digital laser storage	75
	e) Pulse-code-modulation for digital laser mass storage & retrieval	76
1.9	Optimum digital laser storage format	79
	a) Review of the previous state of the art of laser mass storage & retrieval	79
	b) Analysis of the previous state of the art of laser mass storage & retrieval	80
	c) Review of photographic & magnetic digital data storage	82

d)	Optimum format for non-photographic & non-magnetic digital laser mass storage & retrieval	83
(1)	Polar coordinate systems invariance	83
(2)	Frequency response invariance	85
(3)	Image formation invariance	86
(4)	Scanning invariance	87
e)	Expected principal characteristics of optimum storage format	89
f)	Dual density laser disc storage & retrieval	90
g)	Expected future extension of non-photographic & non-magnetic laser mass storage & retrieval	92
1.10	Two-dimensional flat-field laser scanning	94
1.11	Distinction between "writing" & "reading" operations	97
a)	Laser "writing" & "reading" operations	97
b)	Respective laser power requirements for writing	97
c)	Respective laser power requirements for reading	97
d)	Respective cost requirements for writing	98
e)	Respective cost requirements for reading	98
f)	Cost requirements for disc drive	98
1.12	Operational systems requirements for digital laser disc "writing" & "reading" at stationary NASA installations	99
1.13	Cost trade-off between "write" & "read" functions	104
1.14	System requirements for mass storage & retrieval of laser images & laser image data	106
1.15	Sectorizing & computer input conversion	108
1.16	Electronic data processing of image data	111
a)	geometric corrections	111
b)	conformal mapping	112
c)	radiometric corrections	112
d)	radiometric enhancement	112
e)	multispectral image data separation	113
f)	digital gamma correction	113
g)	search & selection	113
h)	digital information extraction	113
i)	mosaicking	114
j)	error detection & correction	114
k)	computer output image data	114

II LIMITS OF DIGITAL LASER MASS STORAGE AND RETRIEVAL 115

2.1	Diffraction-limits	116
2.2	Maximum packing density with non-photographic & non-magnetic digital laser mass storage & retrieval	117

2.3	Uncertainty of digital laser mass storage & retrieval	119
2.4	Maximum data transfer rates for laser "write" & "read" operations	121
a)	Principles	121
b)	Modulation transfer function of digital laser mass storage & retrieval	123
c)	Maximum data transfer rates $f(\omega)$ for laser "write" & "read" operations	128
III	EXPERIMENTAL FOUNDATION OF DIGITAL LASER MASS STORAGE	129
IV	PROBLEMS TO BE SOLVED TO DEMONSTRATE FEASIBILITY OF DIGITAL LASER MASS STORAGE & RETRIEVAL	139
4.1	Laser disc	140
4.2	Laser disc production	140
4.3	Automatic laser focusing	141
4.4	Accessing with laser disc	141
4.5	Interchange between writing & reading stations	142
4.6	Frequency response	142
4.7	Archival storage	142
V	BACKGROUND FOR SUBSEQUENT IMPLEMENTATION OF DIGITAL LASER MASS STORAGE AND RETRIEVAL	144
5.1	Laser disc	145
5.2	Laser disc drive	150
5.3	Automatic positioning of laser focus	153
5.4	Laser beam signal modulation	161
5.5	Laser beam tracking	163
5.6	Mirror galvanometer for laser beam tracking	168
5.7	Laser beam accessing	170
5.8	Laser beam interferometer for laser beam accessing controls	176
5.9	Laser beam interferometer (H+P)	178
5.10	Large scale electronic circuits (LSI)	184
5.11	Error detection & correction with digital laser mass storage & retrieval	186
5.12	Laser storage control	191
VI	IMPLEMENTATION OF THE CONCEPTS OF DIGITAL LASER MASS STORAGE AND RETRIEVAL	193
6.1	Physical structure of feasibility system	194
6.2	Laser disc	194
6.3	Feasibility test unit	197
6.4	Automatic laser focusing	198
6.5	Primary digital laser disc storage & instantaneous retrieval	199
6.6	Secondary digital laser disc retrieval	200
VII	PROPOSED SPECIFICATIONS FOR A DIGITAL LASER MASS STORAGE & RETRIEVAL FEASIBILITY SYSTEM	204
	REFERENCES	207

LIST OF ILLUSTRATIONS

<u>Figure #</u>	<u>Title</u>	<u>Page #</u>
1-01	Electron Microscope Photograph	15
1-02	Vacuum Thin Metal Film Production	16
1-03	Spiral Triple Tracks for Digital Laser Storage	20
1-04	6-Bit Unit Laser Storage Cell	22
1-05	Optical Controls for Primary Laser "Writing" and Instantaneous Laser "Reading"	24
1-06	Optical Controls for Secondary Laser Reading	25
1-07	Linear Actuator	27
1-1	Surface of Integration	30
1-2	Point-Source Illumination of a Plane	33
1-3	Construction of the Green's Function for a Plane Screen	35
1-4	Fraunhofer Arrangement for Diffraction Observations	42
1-5	Rayleigh's Criterion	44
1-6	Amplitude Distribution of the Fundamental Beam	49
1-7	Astronomical Telescope	56
1-8	Frequency Dependence of Digital Laser Storage	65
1-9	Flat-Field Laser Scanning	96
3-1	Plane Polar Coordinates	84
3-01	Diffraction-limited Destruction	131
3-02	Experimental Set-up	132
3-03	Laser Print	135
3-04	Laser Printer	136
3-05	Laser Microprinter	137

4-1	Coherent Transfer Function for Diffraction-limited System with Circular Aperture	127
4-2	Primary Digital Laser Storage & Instantaneous Retrieval	100
4-3	Secondary Digital Laser Reading	102
4-4	Computer Input Conversion	103
4-6	Mass Storage System for Laser Image Data and Laser Images	107
5-1	Laser Focus Positioning Servo Mechanism	166
5-2	Galvo Tracking Control Electronics	169
5-3	Michelson Interferometer	177
5-5	Block Diagram of Storage System Employing Error Correcting Code	~~188~~
~~5-4~~	~~Block Diagram of Storage System~~	~~187~~
6-01	Embodiments of Feasibility System	195
6-02	Top Plate of Feasibility System	196
6-03	Secondary Laser Reading, Servo Controls	202
7-6	Laser Interferometer Controls	179
7-7	Laser Transducer System	180
7-8	Pneumatic Laser Focusing	154
7-9	Computer Input Conversion	109

LIST OF TABLES

<u>Table #</u>	<u>Title</u>	<u>Page #</u>
I	Required NASA Performance Characteristics	4
II	The First Maxima & Minima of the Function $y = \left(\frac{2J_1(x)}{x} \right)^2$	40
III	$\sin cx$, $\sin c^2 x$, and $\exp(-\pi x^2)$	54
IV	Linear Electro-optic (Pockel's) Coefficients	71
V	Laser Disc Storage Space Estimate	93
VII	Characteristics of Digital Laser Disc Drive	152
VIII	Reynolds Equation Formulations	159
IX	Expected Performance Characteristics of Laser Disc System	174
X	H&P Components for Laser Interferometer	182
XI	Computer Input Conversion	110

ABSTRACT

This study report comprises the theoretical foundation for a future system of real-time non-photographic and non-magnetic digital laser storage and retrieval of image data. The study encompasses the entire background for its subsequent experimental implementation, as well as guidelines for expected performance of a feasibility ~~study~~ ^{system}. The new system utilizes diffraction-limited laser focusing upon thin metal films, melting elementary "holes" in the metal films in laser focus. The metal films are encapsulated in rotating flexible mylar discs which act as the permanent storage carriers. Equal sized holes encompass two-dimensional digital ensembles of information bits which are time-sequentially (bit by bit) stored and retrieved. The bits possess the smallest possible size, defined by the Rayleigh criterion of coherent physical optics.

Space and time invariant reflective read-out of laser discs with a small laser, provides access to the stored digital information. At a diffraction-limited bit size of one (1) micrometer in diameter, the packing densities of a laser disc storage system are of the order of 10^{10} bits per ~~cm~~ ^{unit} density disc. The projected total capacity of the system is 10^{14} bits (100 Terabits).

By eliminating photographic and magnetic data processing, which characterize the previous state of the art, photographic grain, diffusion and gamma-distortion do not exist. Similarly, magnetic domain structures, magnetic gaps and $(\frac{d\phi}{dt})$ magnetic read-out are absent with a digital laser disc system.

PREFACE

This study report on laser storage and retrieval of image data is based upon NASA Contract NAS5-22977 for Goddard Space Flight Center, Greenbelt, Maryland. The principal objective of this study is to provide the theoretical foundation for a future system of real-time non-photographic and non-magnetic digital laser storage and retrieval of image data. The study also encompasses the entire background for its subsequent experimental implementation, as well as the guidelines for future design and the expected performance of a feasibility ^{system} ~~study~~.

In accordance with these objectives, the study report comprises the following main subjects:

Physical optics and quantum optics of digital laser storage and retrieval of image data, in conjunction with optics and thermodynamics of laser ^{periodic} irradiation upon thin metal films.

Theory of optical diffraction, yielding the basic requirements for focusing a laser beam to the smallest possible event, i. e. to achieve maximum resolution and power concentration in time sequential laser focus. Creation of diffraction-limited "holes" (bits) takes place by melting the thin metal films in laser focus.

Digital laser writing and reflective reading by means of integrating the differential equation of heat conductivity in solids for ^{strong} periodic temperature fluctuations created in laser focus.

Optimum format for non-photographic and non-magnetic digital laser storage and retrieval comprising fast rotating flexible mylar discs, which

carry the thin metal films in permanently sealed, laminated form. Laser storage and retrieval occurs by means of flat-field laser scanning.

Pneumatic focusing to maintain constant focal distance of the writing and reading microscope objective.

Space-time invariance during laser writing and reading, so that the permanently stored digital information is an "entirety" which is unchanged during laser storage and retrieval.

Maximum packing density with digital laser storage and retrieval deter-^(MPD)
mined by the diffraction-limits of the system, yielding extraordinary improvements over the state of the art of photographic and magnetic storage.

Digital laser writing characteristics comprising pulse-code-modulation (PCM) to control the laser beam intensity as a function of the incoming image data to be stored.

Automatic laser beam tracking and accessing, provided by means of a linear translator, carrying the writing and reading objectives. Laser tracking utilizes triple track (ACB) servo controls. Laser reading of the side tracks (A, B) controls the tracking servo mechanisms, while laser reading of the central track (C) provides reflective laser read-out. Laser accessing may encompass a laser interferometer to control the position of laser focus in units of ^{a quarter}~~half~~-wavelength.

Modulation transfer function (MTF) of digital laser storage and retrieval of image data, determined by the diffraction-limited laser focusing system.

There exists a final passband in the frequency domain, within which all

frequency components are stored and retrieved up to the optical resolution of the system, without amplitude or phase distortion. The system does not possess any of the frequency limitations nor non-linearities of photographic and magnetic storage devices.

Expected over-all performance characteristics for a digital laser disc storage and retrieval system, determined by the smallest bit size in the order of one (1) micrometer in diameter. The conditions are determined for a laser reading station at the lowest possible cost.

Acknowledgements:

Mr. Albert G. Ferris

Mr. John Y. Sos

INTRODUCTION

INTRODUCTION

1. Subject of study.

This study report presents the new technology of non-photographic and non-magnetic digital laser storage and retrieval of image data. During the course of recording images transmitted from a satellite, it became evident that the state of the art was not compatible to the requirements of satisfactorily storing and retrieving the image data received. As an immediate consequence, human readable two-dimensional images became less important for data analysis and were replaced by strictly digital image data. Essentially, these data were stored on magnetic tapes, which were computer readable only. The information content of these tapes were 6-bit or 8-bit "words", thus coordinating to each picture element grey scales of 2^6 or 2^8 steps, i. e. 64 or 256 shades, respectively. Parallel to this development, the number of picture elements per unit area were increased rapidly, as did the image storage rate per second. Hence, human readable real images became less important, while its computer readable digital form became dominant.

With this refinement of image storage and retrieval it became apparent that a new technology, with increasing emphasis on digital storage of images, had to be established. It appeared necessary to replace photographic and magnetic storage processes entirely, thus eliminating: photographic development, non-linear gamma, diffusion, etc., as well as magnetic domains, magnetic heads, non-linearities and $\frac{d\phi}{dt}$ frequency dependence, respectively.

In 1963, it was discovered ⁽⁰¹⁾ that the laser ⁽⁰²⁾ could be used as a real-time image recording tool. In 1966 it was conceived ⁽⁰³⁾, that the

laser was applicable to digital data storage in general. Hence, it appeared possible to eliminate the classic photographic and magnetic data processes by a new technology of laser recording, storage and retrieval.

First, photographic and magnetic storage media were replaced by thin metal films having none of their drawbacks. Simultaneously, lasers were developed which made the new writing and reading processes diffraction-limited. The most important steps in this direction were the establishments of the Argon II ionic laser (Bridges, 1963⁽⁰⁴⁾) and the Helium-Neon laser (Javan, 1964⁽⁰⁵⁾). Simultaneously, laser beam modulation techniques became applicable in the form of external electro-optical modulation, (Pockell's cell, 1889⁽⁰⁶⁾) and internal acoustical modulation (Geusig⁽⁰⁷⁾).

With the establishment of laser recording, storage and retrieval systems, fundamental operational parameters could be met:

The elementary bit size became diffraction-limited, i. e. its diameter (d) was equal to the smallest possible size (Airy disc), determined by the relation⁽⁰⁸⁾

$$d = 1.22\lambda \frac{f}{D}$$

where (1.22) is the first root of a Bessel function, (λ) is the laser wavelength, (f) is the focal length of the laser focusing objective, and (D) is its effective aperture.

On the basis of the diffraction-limits, the laser power in laser focus was proportional to the square of the ratio of $(D/d)^2$, thus permitting the incident laser power to increase by several million times. This phenomenon was contradictory to classical optics, which taught that the image intensity of a light source can by no means be higher than the intensity of the original light source.

During the course of the development of a laser recording, storage and retrieval system it became evident that digital laser storage and retrieval required a time-sequential bit-by-bit process. Different photographic approaches failed, because space-time invariance could not be conserved and the laser power per bit had to be simultaneously applied to the total number of bits per frame.

With the introduction of the TM satellites, the problems of recording, storage and retrieval of image data ^{will} become more and more critical. As is shown in the following Table I, presented by Mr. John Y. Sos, of NASA, Goddard Space Flight Center, Greenbelt, Md., (09) required performance characteristics increased by orders of magnitude in each of the operational parameters. With these aspects in mind, NASA awarded Contract NAS5-22977 to the author, to establish the theoretical foundation for digital laser storage and retrieval of image data.

TABLE I

REQUIRED NASA PERFORMANCE CHARACTERISTICS

Present (77, 78)

Future (81)

Thematic Mapper

MSS 6×10^{10} bits/dayTM 10^{12} bits/day

RBV

MSS

15 M bits/sec

120 M bits/sec

7 spectral bands

6,800 x 6,800 pixels/frame
(10,000 x 10,000 pixels/frame)

6 bits/pixel + 1

8 bits/pixel + 1

2. Scope of study.

The scope of this study comprises the theoretical foundation for a future system of real-time non-photographic and non-magnetic digital laser storage and retrieval. The study also encompasses the entire background for its subsequent experimental implementation.

3. Previous state of the art.

The previous state of the art is characterized by photographic and magnetic data processing, extending to analog, as well as digital data.

(a) Photographic image data processing:

Photographic image data processing is essentially determined by the chemistry of the photographic emulsion and its development process. The unexposed photographic film consists of a photosensitive colloidal halide with a grain structure. When exposed by light, a latent image is created in the colloid, which has to be developed to the final image. Primarily, the latent image comprises a quantum process. However, the final image results from photo-chemical processes. It yields the actual picture elements in the typical grain structure of the photographic emulsion. After fixation, the grains comprise the photographic image.

The photographic process encompasses a non-linear gamma, which separately incorporates negative and positive. Theoretically, a correct gamma product (equal to one) of the negative and positive H-D curves, should yield a linear density curve. In fact, however, a gamma product of one is only obtainable in a narrow region, and is a very critical function of photographic grain structure and development process. Thus, the digital characteristics of a photographic image data process can barely be met due to the non-linearities of the process.

A more important factor making photographic data processes not applicable to digital storage and retrieval of image data, is the structure of the developed photographic image elements. (10) It determines the photographic resolution and the writing energy in conjunction with the non-linear photographic diffusion and non-reciprocity effects of the emulsion. The most

important drawback here is that the principle of bit by bit storage is fundamentally jeopardized: A single bit cannot be created photographically without being effected by its neighboring bits.

Last but not least, the photographic process is not a real-time process, due to the photographic development involved. The necessity of this process also violates the law of space-time invariance, since the photographic emulsion is subject to structural changes between exposure and development.

Application of a laser to photographic writing and reading does not change these adverse conditions, because the photographic process is not diffraction-limited.

Considering the extreme requirements for future digital storage and retrieval of image data (see reference 09), it becomes obvious, that photographic image data processing is not applicable.

(b) Magnetic tape data processing:

It represents the adaptation of the original magnetophon system for very high fidelity magnetic sound recording. (11) In its digital form, magnetic tape data processing utilizes parallel multiple track recording of 6-bit or 8-bit codes on 7 or 9 track tape formats of half-inch (1.27 cm) width. The maximum achievable linear resolution is 2,461 bits/cm (6,250 bits/inch), assuming special digital magnetic tapes and heads. There is no possibility of improving this performance any further. Considering also that magnetic tape systems do not provide direct access storage, magnetic tape systems appear inapplicable to digital storage and retrieval of image data.

(c) Magnetic disc storage.

Presently, this comprises the most widely used direct access storage device. (12- 16) Its most advanced form is the IBM 3350 Direct Access Storage. (17) This system has a linear resolution of 2,460 bits/cm (6,250 bits/inch) at a rate of 9.584 M bits/second. Because of reference 09, it is not directly applicable to future satellite application. However, certain aspects of the IBM 3350 are applicable to digital laser storage and retrieval of image data. This refers particularly to disc drive, direct access, data removability and hydrodynamic air-bearings. Hence, further reference will be given in pertinent sections of this study.

4. Expected advancement in the state of the art.

The expected advancement in the state of the art of non-photographic and non-magnetic digital laser storage and retrieval of image data may be summarized as follows:

As presented by the author at the LASER 75 Conference, Munich, W. Germany, June, 1975⁽¹⁸⁾, the new technology is expected to provide digital laser storage at 10^{10} bits per disc. A bandwidth of 120 M bits/sec. will be provided, utilizing frequency division and dual density storage, so that each metal disc stores 60 M bits/sec. The total capacity of the digital laser disc system should be 10^{14} bits (100 Terabits), comprising 10,000 discs.

5. Summary of effort.

The total effort of this study comprises the establishment of the following operational parameters for non-photographic and non-magnetic digital laser disc storage and retrieval of image data:

- I. The concepts of digital laser mass storage and retrieval.
- II. Limits of digital laser mass storage and retrieval.
- III. Experimental foundation of digital laser mass storage.
- IV. Problems to be solved to demonstrate feasibility of digital laser mass storage and retrieval.
- V. Background for subsequent implementation of digital laser mass storage and retrieval.
- VI. Implementation of the concepts of digital laser mass storage and retrieval.
- VII. Proposed specifications for a digital laser mass storage and retrieval feasibility system.

6. Conclusions.

The conclusions of this study are: Non-photographic and non-magnetic digital laser storage and retrieval has the definite potential to digitally store image data transmitted from a TM satellite.⁽⁰⁹⁾ After a feasibility system has been successfully accomplished, based upon the guidelines presented by this study, the expected performance characteristics of the system will be:

Daily storage capacity: 10^{12} bits/day

Number of pixels per frame: 10,000 x 10,000

Bit word: 8 bit + 1 parity bit

Linear bit density: 10,000 bits/cm (25,000 bits/inch)

Areal bit density: 10^{10} bits/disc

Total storage capacity per system: 10^{14} bits (100 Terabits)

Grey scale: $2^8 = 256$

7. New technology.

No new technology was discovered during the course of this contract.

I

THE CONCEPTS OF DIGITAL
LASER MASS STORAGE AND RETRIEVAL

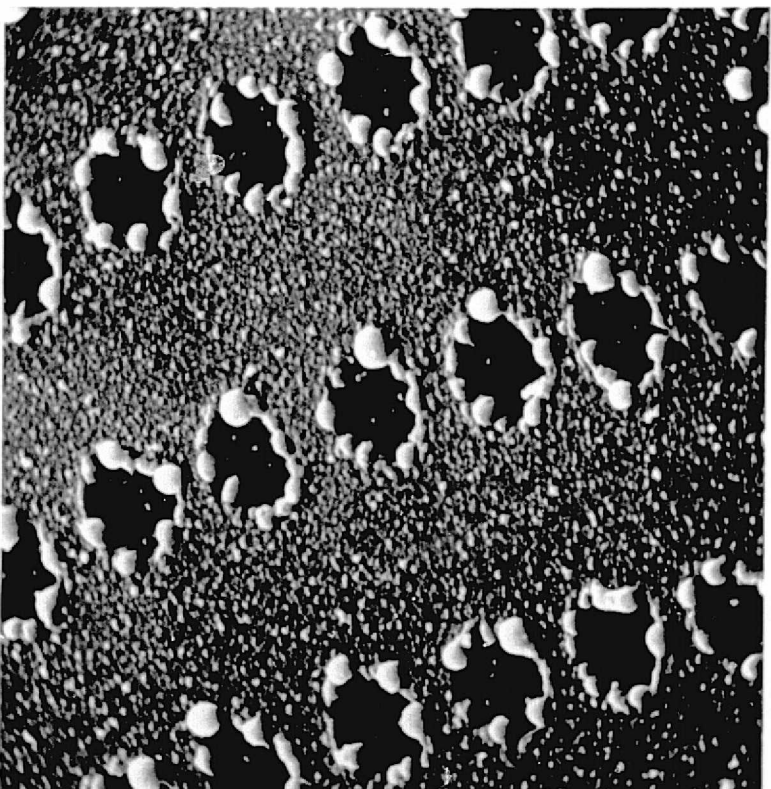
1.1 Principles

Digital laser mass storage comprises the creation of diffraction-limited "holes" (bits) in thin metal films, which are hermetically encapsulated between flexible mylar discs. Digital laser mass storage utilizes diffraction-limited laser focusing to the thin metal films, yielding laser-melting of the thin film materials (indium, tin), to form the circular holes. The laser melting process comprises deformation of the thin metal film to build submicroscopic globuls of the metal which encompass the external structure of the holes. See, electron microscope photographs from reference 404 for laser holes in indium and tin thin metal films of one (1) and three (3) micrometers in diameter, respectively (Figure 1-01). Hole creation results from transverse pondero-motoric forces, excited between the mylar sheets by means of strong laser irradiation. The hole forming process of digital laser storage is determined by its thermodynamics. Essentially these are characterized by the physics of thermal conductivity in solid materials, in conjunction with strong periodic laser irradiation in laser focus.

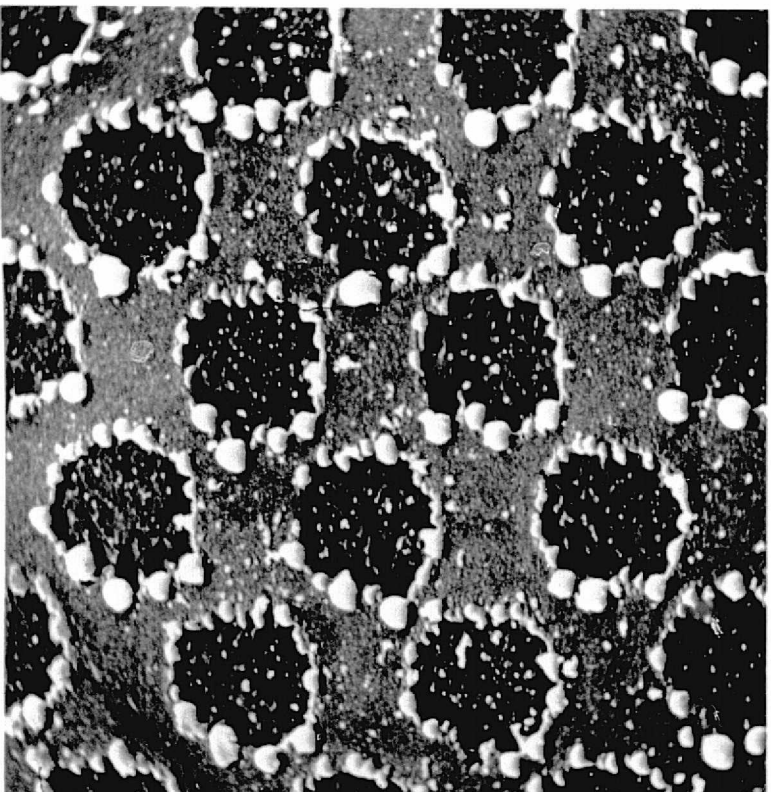
The digital laser mass storage format encompasses rotating mylar discs. Laser storage and retrieval takes place by means of laser-focusing through the mylar substrates, so that the thin metal films are permanently protected against external damage or dust depositions.

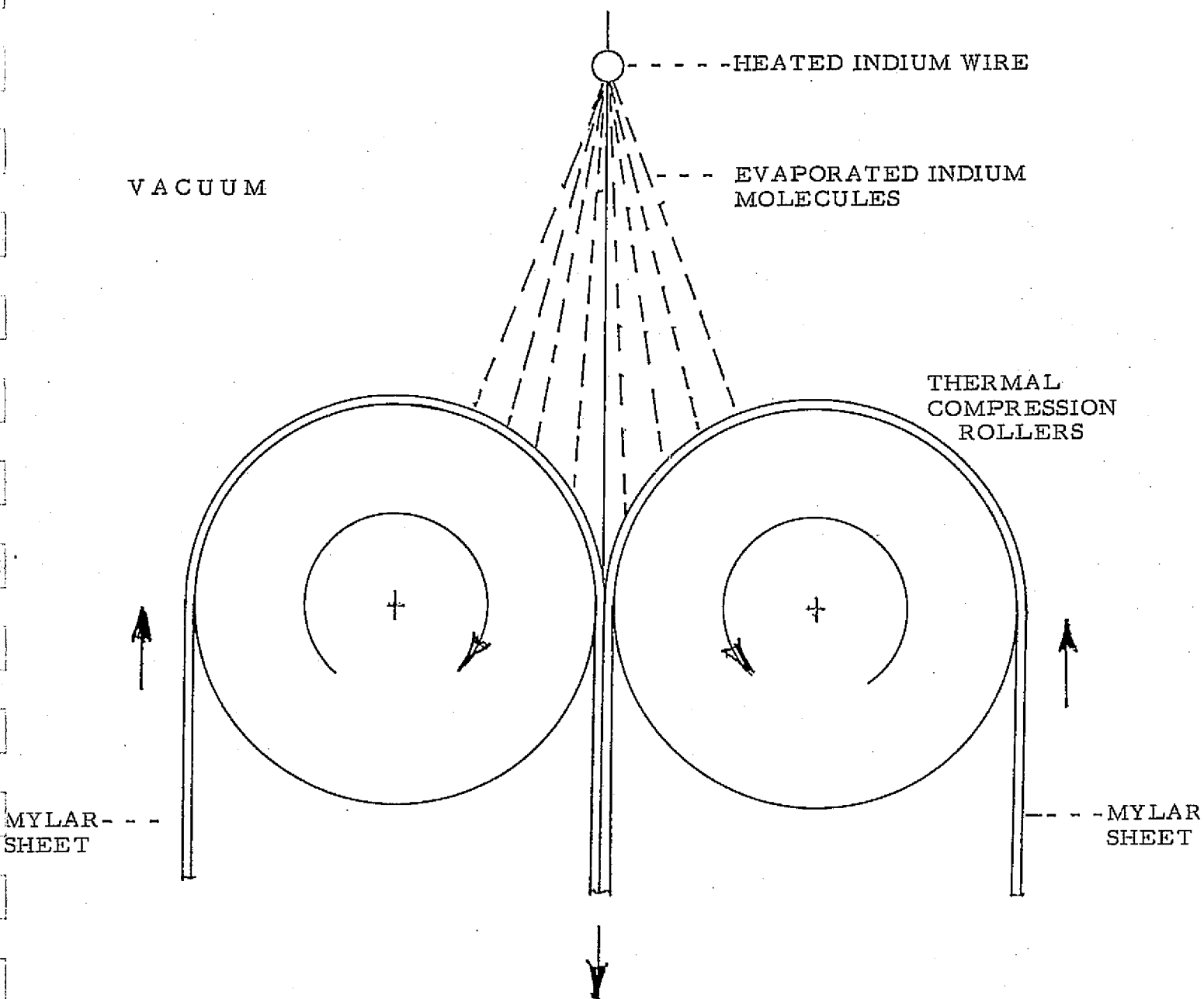
Laser disc production takes place in the vacuum, by means of thermal evaporation of an indium wire, utilizing an appropriate vacuum chamber. For this purpose, two transparent mylar sheets of (15 inch) width are inserted in the chamber, utilizing a constant transport mechanism. See, Figure 1-02. Constant transport velocity is provided by phase-lock servo controls. During motion of the sheets, the evaporated indium molecules are equally coating the two inside surfaces of the mylar sheets. In order

INDIUM



TIN





TWIN MYLAR SHEET WITH
ENCAPSULATED THIN METAL FILM

VACUUM THIN METAL FILM PRODUCTION

(Schematics)

Fig. 1-02

to produce covalent bonding between the two thin metal films, certain pressures and temperatures are applied to the transport mechanism, so that one thin metal film is created in the vacuum between the two mylar sheets. Final sealing of the sides of the mylar sheets in the vacuum with a CO₂ laser results in a completely encapsulated and protected laser storage medium. Any dust particles or scratches applied to the mylar surfaces are entirely invisible to the writing and reading laser beam, because the mylar surfaces are "out of focus" by a margin of the order of

$$\left(\frac{6 \text{ millimeter}}{1 \text{ micrometer}} \right)^2 = \frac{36 \times 10^{-6}}{1 \times 10^{-12}} \cong 36 \times 10^6$$

Cutting of the long metallized mylar sheets takes place outside of the vacuum, providing circular (disc) or quadratic (plate) laser storage media. After cutting, the discs or plates are sealed again by means of a CO₂ laser. Measuring of the optical RTA characteristics of the complete discs or plates occurs by means of a laser densitometer.

Diffraction-limited laser focusing obeys the Fraunhofer approximation: Assuming a circular aperture of diameter (D) and introducing a Fourier Bessel transform one obtains the intensity distribution within laser focus from the Rayleigh-Sommerfeld theory of diffraction. The resulting diffraction pattern has its intensity maximum at the center (Airy disc) with a diameter (d) equal to:

$$d = 1.22 \lambda f/D ,$$

where 1.22 is the first root of the Bessel function, λ is the laser wavelength, f is the focal length of the focusing objective, and f/D represents its effective f-number. The elementary hole diameter (d) is of the order of one (1) micrometer. The depth of focus of the system is defined as the

z-component of the diffraction ellipsoid of focus:

$$\Delta z = 2\lambda(f/D)^2 .$$

On this basis, digital laser mass storage utilizes diffraction-limited laser focusing in order to achieve maximum optical resolution. Independent of these considerations, the process also provides laser focusing, in order to obtain the highest concentration of energy at the smallest possible area of the metallic storage medium. The square of the reduction in laser beam diameter during focusing, compared to that at the entrance aperture (D) of the focusing objective, yields a proportional increase in laser power density. This extraordinary power concentration is utilized with digital laser mass storage to create megawatts of laser power within laser focus, while the incident laser power transmitted from the laser is only of the order of a tenth of a watt.

Digital laser mass storage provides two-dimensional ensembles of diffraction-limited holes in the "flat-field" of focus. In order to make this possible, the incident reading and writing laser beam should be parallel, so that it can be deflected over the field of focus within the diffraction limits. The resulting deflection (ρ) of laser focus is determined by the geometrical relation

$$\rho = f \cdot \tan \theta ,$$

where f is the focal length of the focusing objective and θ is the angle of deflection.

The laser energy (u) to create a hole is determined by the product of incident pulsed laser power (W) in laser focus and the laser pulse duration (τ):

$$u = W \cdot \tau .$$

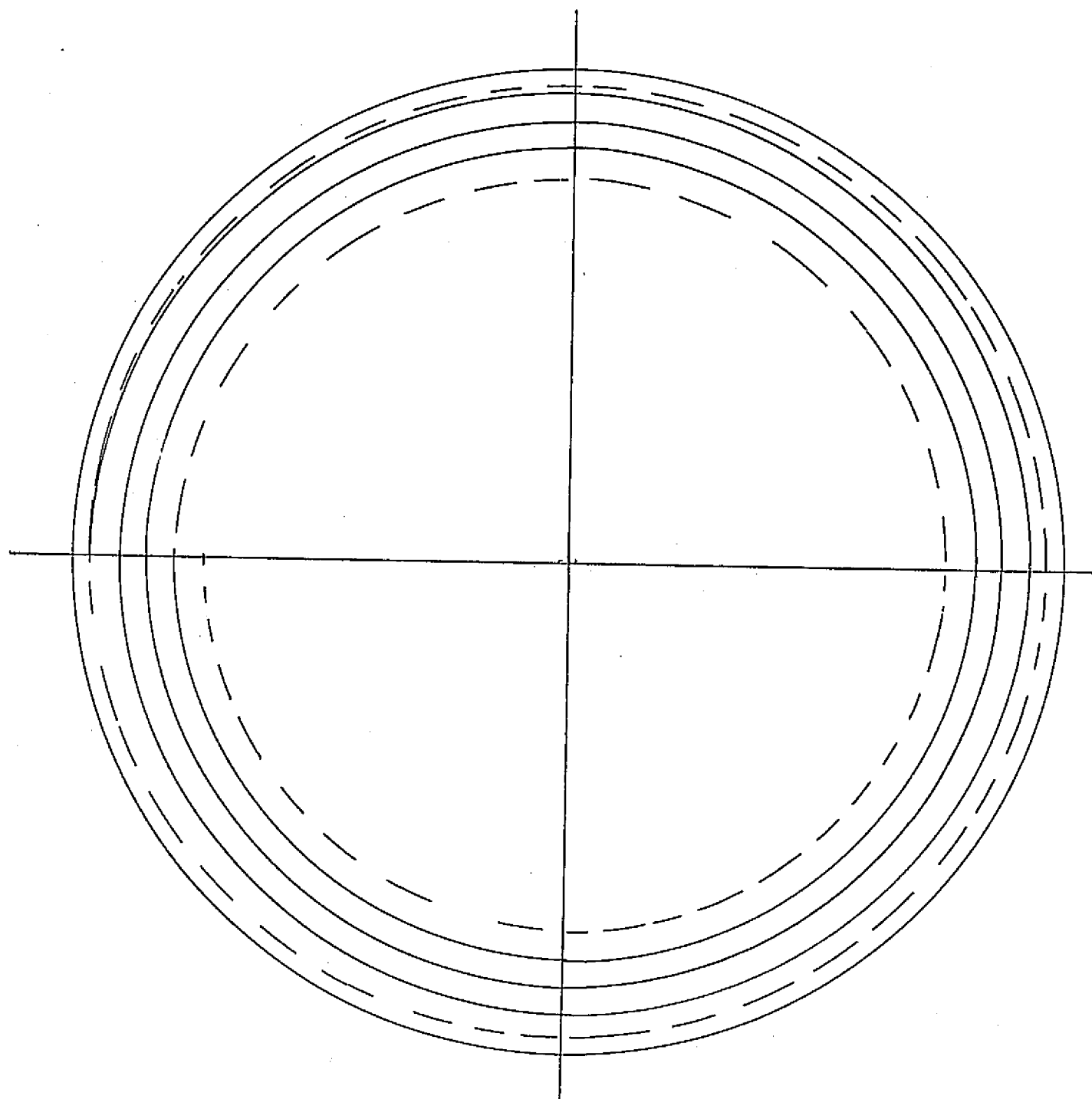
The storing laser is an Argon II ionic laser with the order of one (1) Watt C. W. laser power. Digital signal modulation of the laser occurs by means of internal modulation of the laser cavity, characterized as mode-locking. Frequency bandwidth (f_{ω}) is determined by the laser cavity length (L), and is defined as:

$$f_{\omega} = \frac{c}{2L}$$

where (c) is the velocity of light. Mode-locking requires exact cavity lengths, as defined by the equation above. For example, a practical modulation frequency is 60 MHz. If a frequency modulation deviating from the mode-locking frequency is required, external laser beam modulation is ~~required~~ ^{NECESSARY}, utilizing a linear electro-optical light modulation (Pockel's cell), constructed from four ADP or KD*P crystals in series. External laser beam modulation utilizes low-impedance driver electronics. Signal modulation form is pulse-code-modulation (PCM).

Diffraction-limited laser focusing in conjunction with digital laser mass storage and retrieval requires a reflective microscope objective of high numerical Aperture and short focal length (ZEISS EPIPLAN L. D. 40X, N.A. = 0.60, f = 4.1 millimeter). Laser focusing is automatically provided by pneumatic means.

Digital laser disc storage and retrieval takes place in a spiral form, beginning with the outer track of laser disc. See Figure 1-03. This format is very similar to that of laser video discs (Philips, Thomson C.F.R.). Laser disc has an outer diameter of the order of 38.1 cm (15 inches), with the laser storage area extending from 35.6 cm (14 inches) to 30.5 cm (12 inches). For digital laser storage, laser disc is rotating at phase-lock



SPIRAL TRIPLE TRACKS FOR DIGITAL LASER DISC STORAGE
(Schematics)

Figure 1-03

servo controlled constant angular velocity of 3,600 RPM.

Positioning of laser focus during laser scanning takes place by means of a mechanical linear translator, the velocity and position of which are servo controlled. Modern linear translators (Lansing) provide a resolution per drive unit of 0.25 micrometer [one (1) microinch]. Translation occurs continuously at a pitch of 2.53 micrometer per disc revolution. Pre-recorded laser serialization of the disc provides necessary space-time synchronization, including any required sectorizing of the disc.

Digital laser disc storage and retrieval format is in compliance with the 6-bit unit storage cell of the system (See, Figure 1-04). It encompasses three (3) elementary tracks (ACB) with two (2) bits per track. Dimensions of the unit cell are determined by three interrelated parameters:

hole-diameter

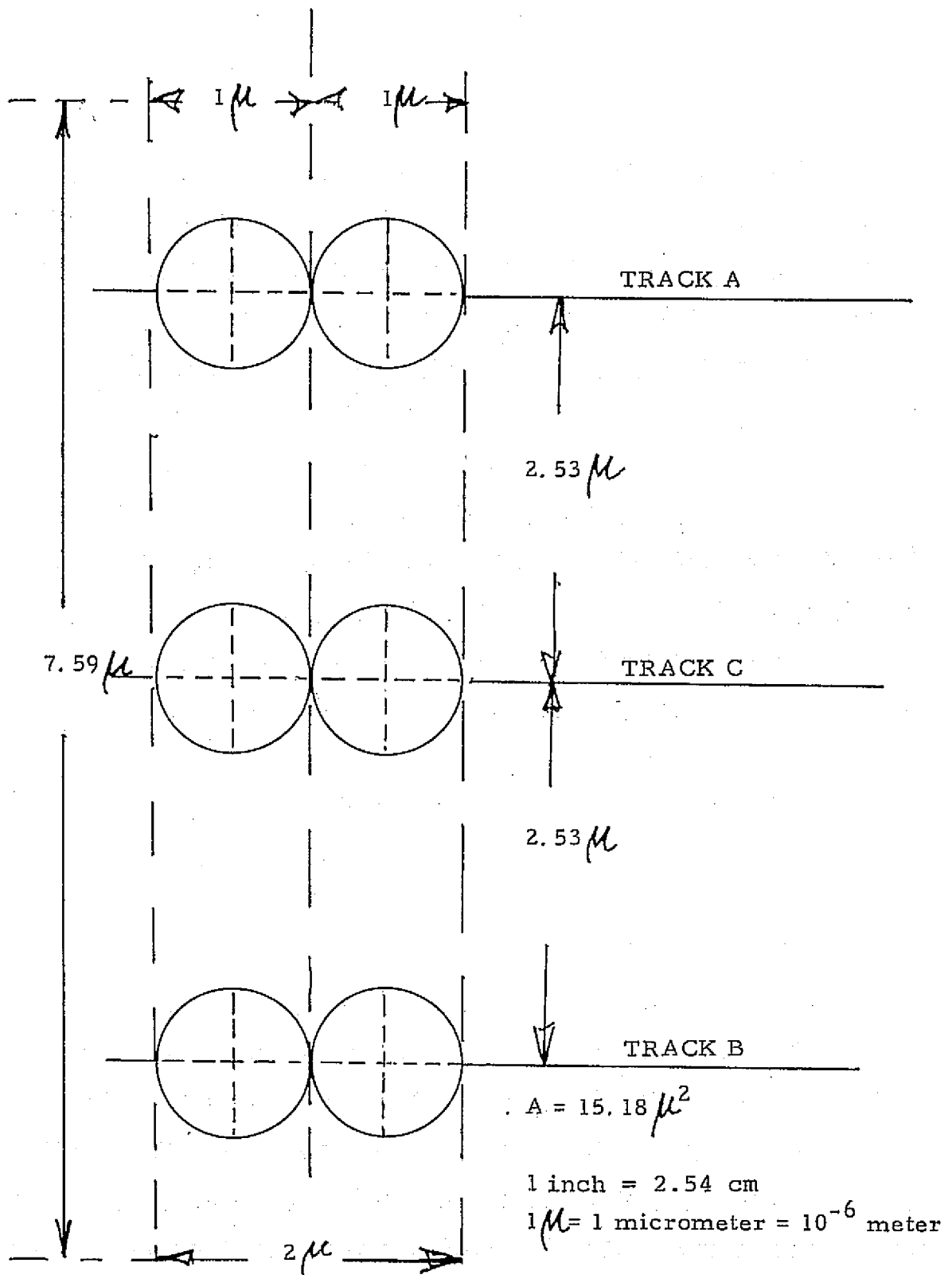
hole-spacing

track-spacing

Hole(bit)-diameter is equal to the diffraction-limits (d) of typically one (1) micrometer. Hole(bit)-spacing is equal to the Rayleigh criterion (d). Track spacing is equal to an integer number of quarter wavelengths ($\lambda/4$) of a laser beam interferometer ($\lambda = 0.6328$ micrometer), in case of interferometric positioning controls of laser focus at the thin metal film of laser disc. Typical track spacing equals 16×0.1572 micrometer, or 2.53 micrometer.

On the basis of the dimensions of the unit storage cell, 10,000 spiral tracks are provided per laser disc. Each track per revolution contains of the order of 10^4 bits, yielding a linear storage density of 10,000 bits/cm (25,000 bits/inch). The resulting aerial bit density (I_d) is

$$I_d = 0.393 \times 10^8 \text{ bits/cm}^2$$

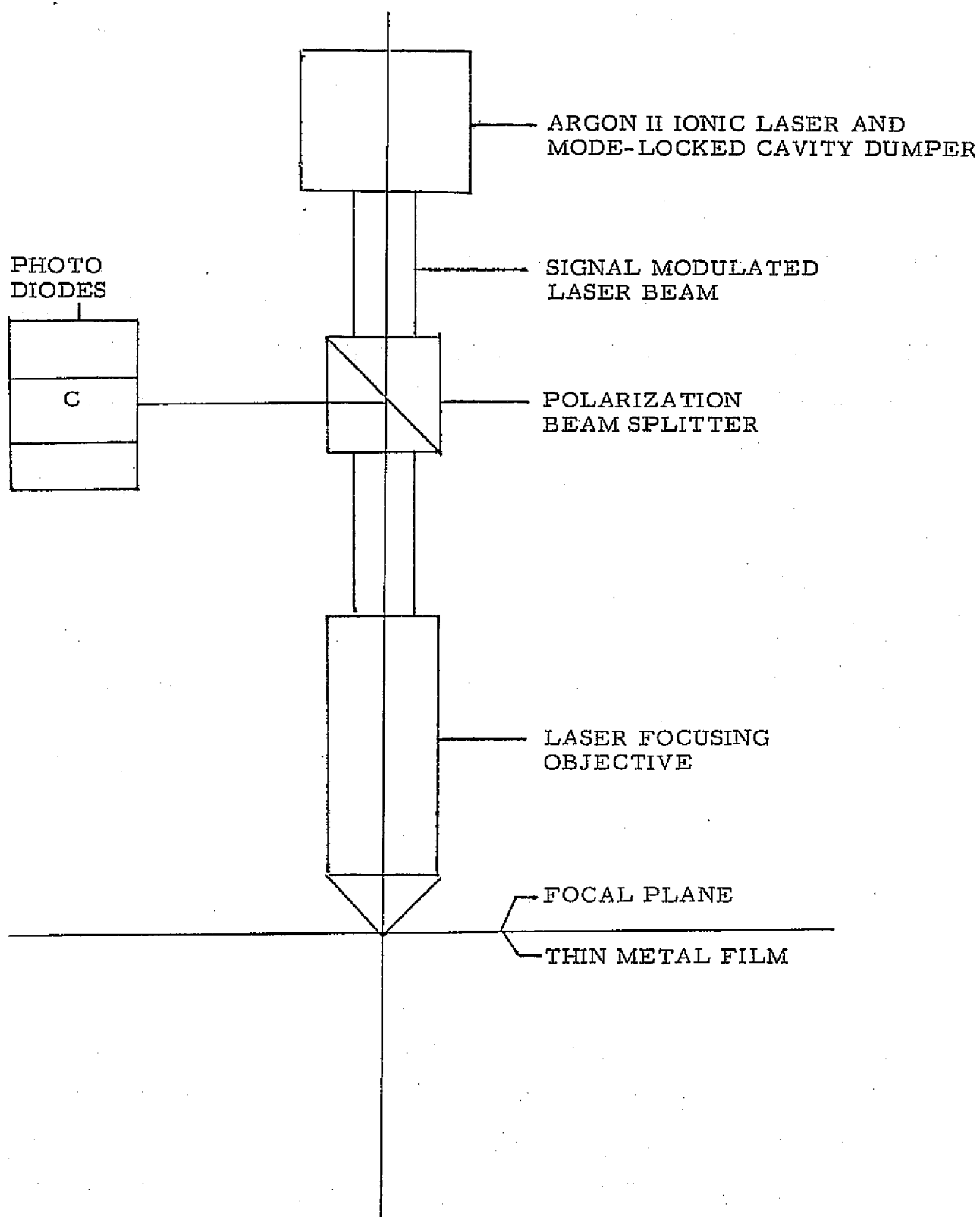


6-BIT UNIT LASER STORAGE CELL

Figure 1-04

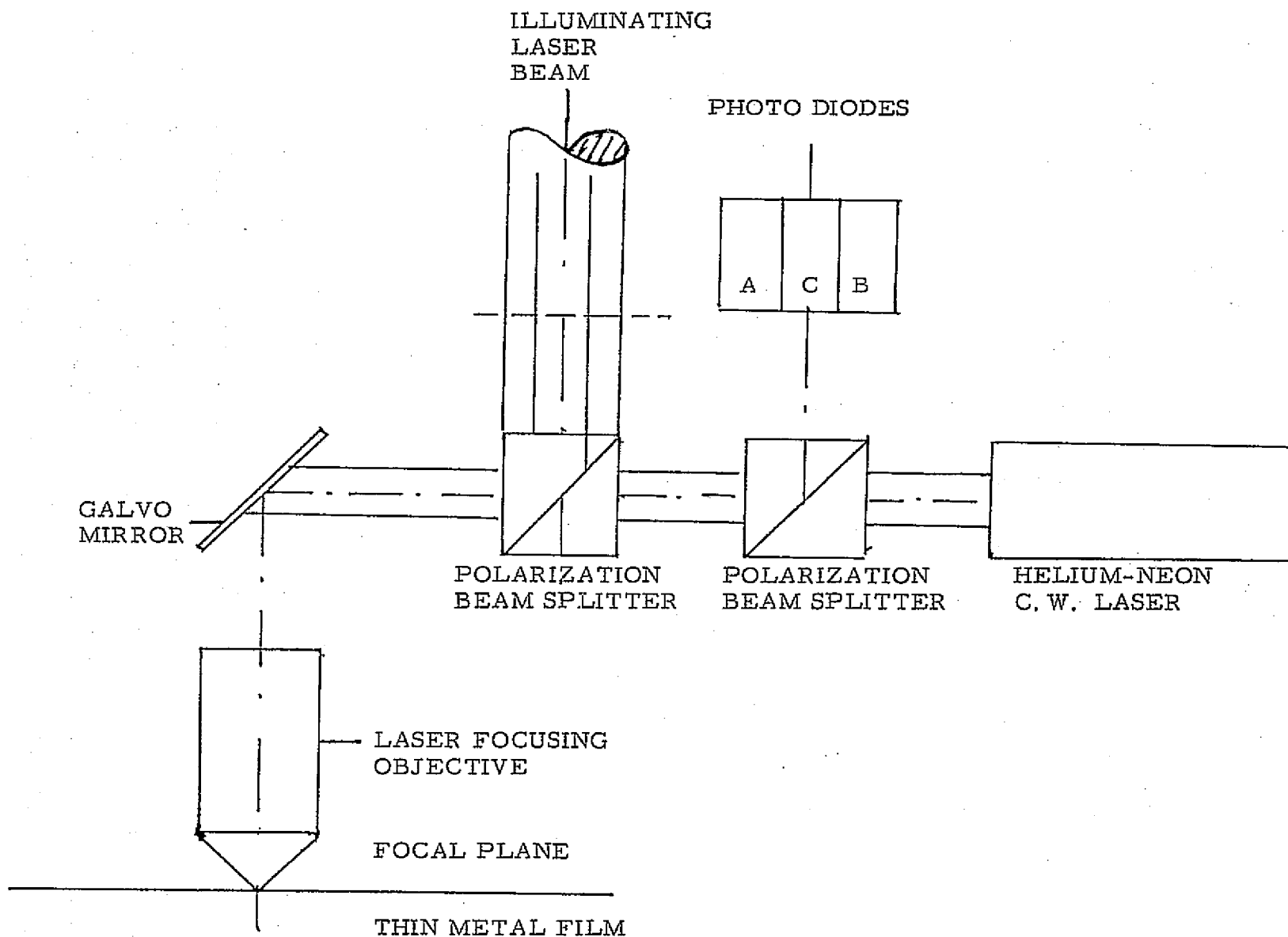
Instantaneous laser reading during primary digital laser storage (read while write) is provided by means of imaging the thin metal film of the disc to an enlarged real image. Imaging takes place through the laser focusing objective. Separation between incident (writing) laser radiation and instantaneously reflected (reading) laser radiation is provided by a polarization beam/splitter inserted between focusing objective and laser. See Figure I-05. The laser image is projected upon a flat screen (macroscopic projection) which comprizes an optical slit at its center. Behind the screen three photodiodes are located, characterized as ACB photo detectors. The center photo-diode (C) provides laser reading, while photo-diodes (A,B) are utilized for servo control of the secondary laser reading process. See Figure 1-06. Diodes (A,B) provide $K(A-B)$ and $K(A+B)$ electromagnetic outputs for automatic laser tracking. K is an appropriate gain factor. In principle, secondary laser reading is a spiral triple track operation, where the center track provides primary or secondary laser reading, while the adjacent side tracks activate the tracking servo controls. Track locations are determined by the 6-bit unit memory cell of the laser disc. Hence, after each disc revolution, the previous spiral center-track acts as one of the servo control tracks, while one of the former side tracks acts as a read-out track. Track spacing is constant at 2.53 micrometer. Servo tracking encompasses classical automatic velocity and position controls.

Secondary laser reading of the digitally stored information is provided by means of "vertical" laser illumination of the storage area occupying the field of view of the laser focusing objective. See Figure 1-06. It utilizes a small Helium neon laser and appropriate collimation optics. It comprizes similar means which are classically applied with vertical illumination in conjunction with a reflective microscope. Thus, compared to instantaneous



OPTICAL CONTROLS FOR PRIMARY LASER "WRITING"
AND INSTANTANEOUS LASER "READING"

Figure 1-05



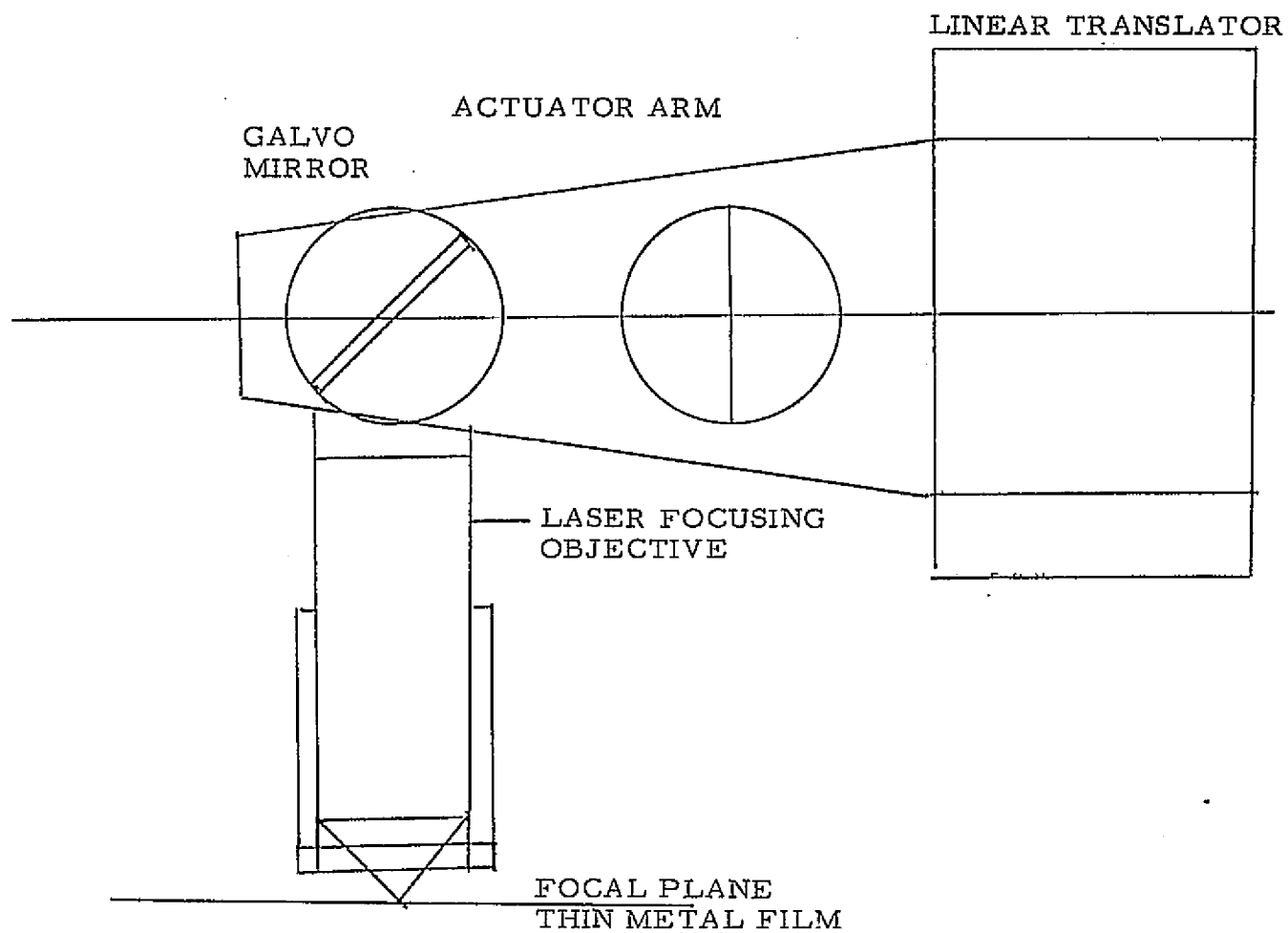
OPTICAL CONTROLS FOR SECONDARY LASER READING

Figure 1-06

digital laser reading, secondary laser reading utilizes the auxiliary illumination from a small laser to provide projection of the laser storage area to the projection screen, which carries the ACB photo-diodes behind a real slit.

One of the fundamental concepts of digital laser mass storage and retrieval is the achievement of space-time invariance. It may be formulated as the principle to read appropriately stored digital information at any appropriate laser disc reading station. In engineering terms space-time invariance characterizes the fact that a fully recorded laser disc encompasses an invariant "entirety." On this basis, secondary laser reading automatically compensates tracking deviations in regard to the central and azimuthal position of laser disc during disc rotation. These position variations are automatically eliminated, due to servo-controls by means of a laser tracking galvanometer located at the top of the laser focusing objective. See, Figure 1-07. In order to make automatic tracking possible, certain initial serialization of laser disc has to be provided, before actual digital laser storage and retrieval can occur. For example, a once around hole pattern has to be initialized in conjunction with certain sectorizing at constant angular disc velocity. In addition, electronic track counting and memorizing of the individual tracks is required in respect to the initialized zero track mark. All serialization takes place by means of electronic laser storage controls, prior to laser writing and reading. Laser storage controls also provide appropriate velocity and position controls during laser disc storage and retrieval.

Secondary laser disc reading encompasses a process which is coined Computer Input Conversion. It provides the adjustment of the original laser storage rate to that of the subsequent electronic data processor (CPV).



LINEAR ACTUATOR

Figure 1-07

For example, assuming that the primary laser disc storage occurs at 60 Mbits/second, while the electronic data processor operates at 7.5 Mbits/second, the integer computer input conversion ratio would be 8:1. Due to the fact that laser read-out is independent of laser reading rates below the original laser writing rates, data input conversion to lower frequencies does not effect the secondary laser reading process.

The new concept of digital laser mass storage and retrieval opens the possibility to obtain the magic mass storage capacity of 10^{14} bits. Based upon 10^{10} bits per single density laser disc, 10^{14} bits encompass 10^4 discs. In units of conventional Terabits (10^{12} bits), this means 100 laser discs provide one (1) Terabit of digital laser mass storage capacity.

1.2 Theory of diffraction.

The theory of diffraction⁽¹⁰⁵⁻¹⁰⁹⁾ comprises the foundation of non-photographic and non-magnetic digital laser storage and retrieval. The theory is based upon the Huygens-Fresnel principle, combining Huygen's concept of superposition of waves with the principle of optical interference.

The basic idea of the Huygens-Fresnel theory is that a light disturbance at a point (P) arises from the superposition of secondary waves that proceed from a surface (S) situated between this point and the light source. (See Fig. 1-1) This idea was put on a sounder mathematical basis by G. Kirchhoff, who showed that the Huygens-Fresnel principle may be regarded as an appropriate form of an integral theorem, established earlier by H. von Helmholtz.

Considering a monochromatic scalar light wave

$$u(x, y, z, t) = U(x, y, z) e^{-i\omega t}$$

propagating in the vacuum, one obtains the scalar wave equation:

$$\nabla^2 u - \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2} = 0$$

The complex disturbance (U) must obey the time-independence equation (Helmholtz equation)

$$\nabla^2 U + K^2 U = 0$$

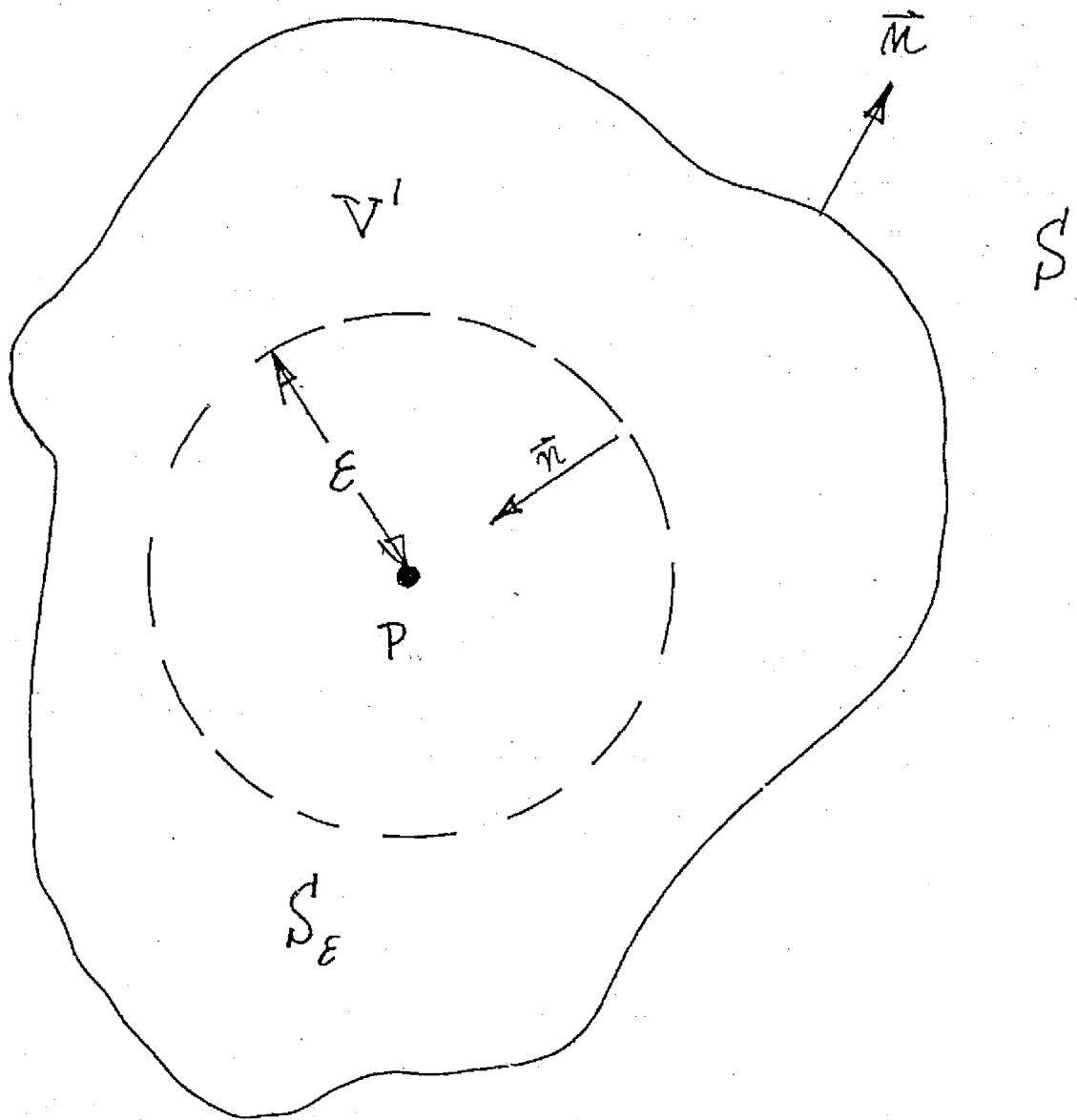
where

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

represents the Laplacian operator, and

$$K = \frac{\omega}{c} = \frac{2\pi}{\lambda}$$

(ω) is the angular frequency of the wave, equal to 2π times the frequency (ν).



SURFACE OF INTEGRATION

(reference 107)

Figure 1-1

(c) is the velocity of light in the vacuum, and (λ) is its wavelength.

Calculation of the complex disturbance (U) at an observation point in space utilizes Green's theorem, which is one of the three integral theorems of mathematical physics:

$$\begin{aligned} \text{Gauss's theorem: } & \int \text{div } \vec{A} d\tau = \int A_n d\sigma \\ \text{Stokes's theorem: } & \int \text{curl}_n \vec{A} d\sigma = \oint A_s ds \\ \text{Green's theorem: } & \int (U \nabla^2 V - V \nabla^2 U) d\tau = \\ & \int (U \frac{\partial V}{\partial n} - V \frac{\partial U}{\partial n}) d\sigma \end{aligned}$$

Note: Green's theorem is the result of applying Gauss's theorem to a vector $\Psi \text{ grad } \varphi$.

Let the point of observation (P) being located within a closed surface (S), as shown in Fig. 1-1. Applying Green's theorem and selecting as a Green's function (G) a unit-amplitude spherical wave expanding about the point (P), then the value of (G) at an arbitrary point (P_1) is given as:

$$G(P_1) = \frac{\exp(iKr_{01})}{r_{01}}$$

where (r_{01}) is the length of the vector ($\vec{r}_{01}$) pointed from (P_0) to (P_1).

Within the volume (V), the disturbance (G) satisfies a Helmholtz equation

$$\nabla^2 G + k^2 G = 0$$

Substituting the two Helmholtz equations on the left side of Green's theorem, one obtains

$$\iiint_V (G \nabla^2 U - U \nabla^2 G) dV = - \iiint_V (G U k^2 - U G k^2) dV = 0$$

After some mathematical operations, one finally arrives at the integral theorem of Helmholtz and Kirchhoff:

$$U(P_0) = \frac{1}{4\pi} \iint_S \left\{ \frac{\partial U}{\partial n} \left[\frac{\exp(iKr_{01})}{r_{01}} \right] - U \frac{\partial}{\partial n} \left[\frac{\exp(iKr_{01})}{r_{01}} \right] \right\} ds$$

Simplifying the expression for $U(P_0)$ by means of noting that the distance ($\vec{r}_{01}$) from the aperture to the point of observation comprises many wavelengths, and assuming a plane aperture screen, (See Fig. 1-2), then one obtains the Fresnel-Kirchhoff diffraction formula:

$$U(P_0) = \frac{A}{i\lambda} \iint_{\Sigma} \frac{\exp[iK(r_{21} + r_{01})]}{r_{21} r_{01}} \left[\frac{\cos(\vec{M}_1, \vec{r}_{01}) - \cos(\vec{M}_1, \vec{r}_{21})}{2} \right] ds$$

The experimental inconsistencies with the Fresnel-Kirchhoff formulation of optical diffraction led Arnold Sommerfeld to a more rigorous solution of the diffraction problem. Following are A. Sommerfeld's deviations, utilizing his original notations:⁽¹⁰⁵⁾

One obtains Green's function (G), by means of starting with Green's theorem in the form:

$$\int (u \Delta v - v \Delta u) d\tau = \int \left(u \frac{\partial v}{\partial n} - v \frac{\partial u}{\partial n} \right) d\sigma$$

where (Δ) is the Laplace operator and (u) is the function

$$u = \frac{1}{r} e^{iKr}$$

of the spherical wave, and (v) is the desired solution of the equation

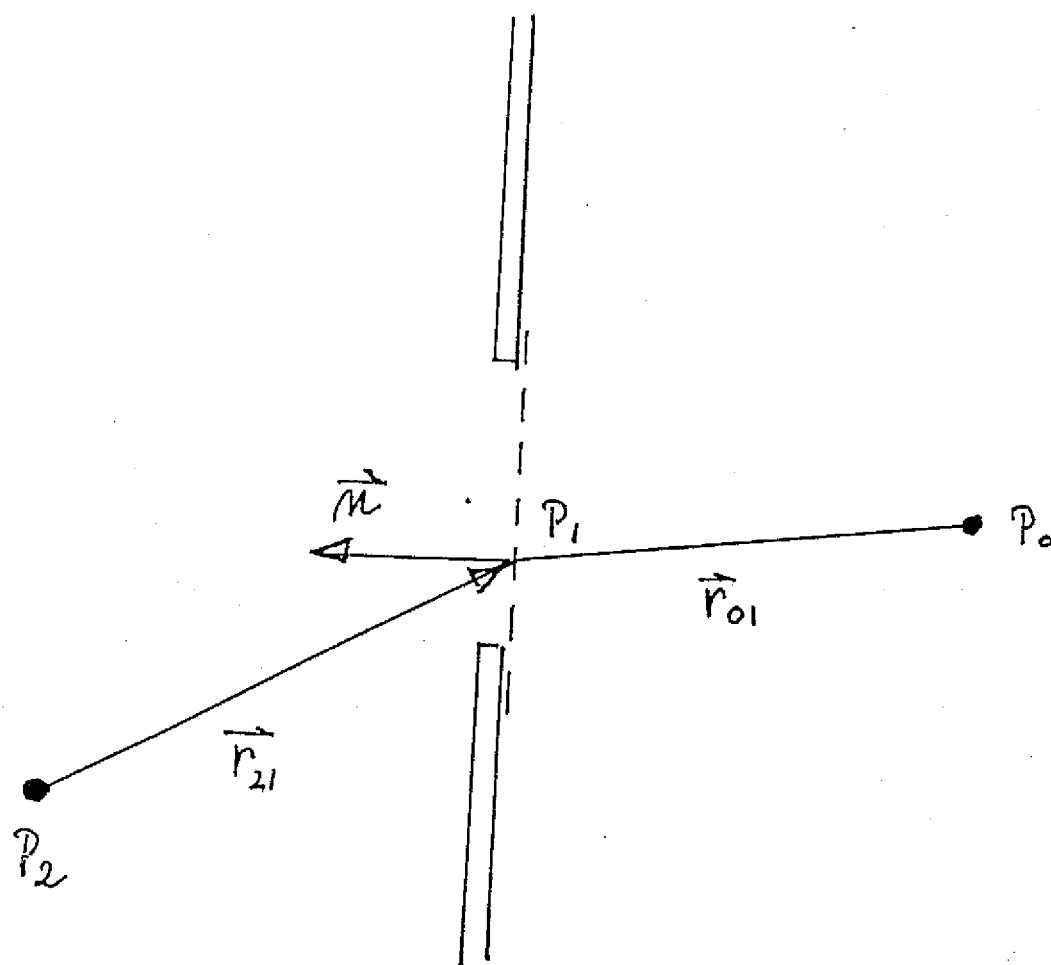
$$\Delta v + k^2 v = 0$$

one writes:

$$(a) \quad \Delta G + k^2 G = 0 \quad \text{in } \tau$$

$$(b) \quad G = 0 \quad \text{on } \sigma$$

$$(c) \quad G \rightarrow u \quad \text{as } r \rightarrow 0$$



POINT-SOURCE ILLUMINATION OF A PLANE

(reference 107)

Figure 1-2

$$(d) \quad r \left(\frac{\partial G}{\partial n} - iK G \right) \rightarrow 0 \quad \text{as } M \rightarrow \infty$$

(r) is the distance from the point (P) and (d) is the so-called radiation condition. Equation (c) states that, like (u), (G) shall have a singularity only at the point (P) and shall be continuous everywhere else in the exterior.

(G) differs from (u) because of the additional condition (b). As a result of this condition, the term containing $\frac{\partial v}{\partial n}$ in equation:

$$4\pi v_p = \int_{\sigma} \left(\frac{\partial v}{\partial n} \cdot \frac{e^{iKr}}{r} - v \frac{\partial}{\partial n} \cdot \frac{e^{iKr}}{r} \right) d\sigma$$

disappears and then one obtains:

$$4\pi v_p = - \int_{\sigma} v \frac{\partial G}{\partial n} d\sigma$$

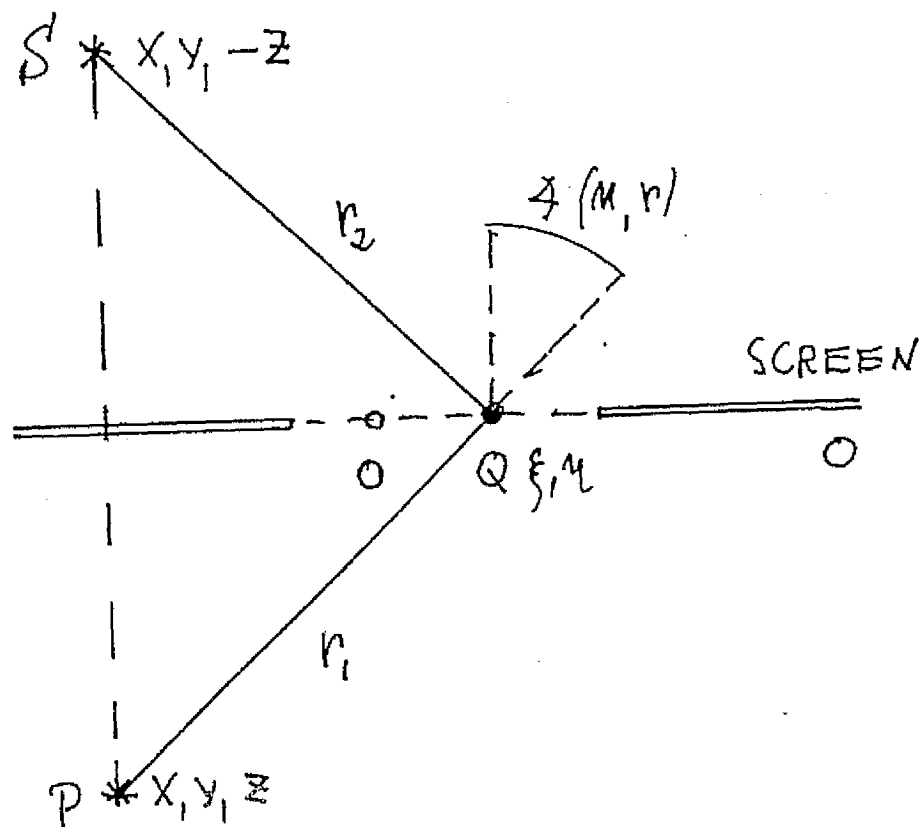
Now we prescribe the boundary values of (v) itself. It is reasonable to assume that

$$(a) \quad v = 0 \quad \text{on } \vec{\sigma}$$

$$(b) \quad v = A \exp \frac{iKr'}{r'} \quad \text{on } \sigma$$

Furthermore, according to the theory of Green's function, the boundary values (a, b) above are actually assumed to be the function (v_p) as computed when the point (P) is placed on the screen or in the aperture.

Assuming sufficiently small wavelengths, and restricting to the special case of a plane screen (see Fig. 1-3), one applies the method of images: One constructs the mirror image (S) of the point (P) with respect to the screen ($Z=0$). After certain mathematical calculations, one arrives first at another formulation of Huygen's principle:



CONSTRUCTION OF THE GREEN'S FUNCTION FOR A PLANE SCREEN

(reference 105)

Figure 1-3

$$i\lambda v_p = \int \frac{e^{iKr}}{r} \cos(\theta, r) v d\sigma$$

It says that a "light wave falling on the aperture (σ) propagates as if every element ($d\sigma$) emitted a spherical wave, the amplitude and phase of which are given by that of the incident wave (v). " The factor $\cos(\theta, r)$ corresponds to Lambert's cosine law of surface brightness ($I(\alpha, \beta)$):

$$I(\alpha, \beta) = I_0 \cdot \cos \Theta$$

If one substitutes for (v) the value given above, where (v) corresponds to the illumination by a point source,

$$v = A \frac{e^{iKr'}}{r'}; \quad \frac{\partial v}{\partial m} = A \frac{\partial}{\partial m} \cdot \frac{e^{iKr'}}{r'},$$

one obtains the Rayleigh - Sommerfeld integral of diffraction:

$$i\lambda v_p = A \int e^{iK(r+r')} \frac{\cos(\theta, r')}{rr'} d\sigma$$

Principal application of the Rayleigh-Sommerfeld diffraction integral encompasses the diffraction phenomena by certain apertures (circular, square, rectangular, etc.). These phenomena determine the diffraction-limits of any optical instrument, no matter how large or small the size of the aperture may be. Depending on the degree of approximation, one determines two basic diffraction characteristics of first or second order, respectively:

- A. Fraunhofer diffraction (first order)
- B. Fresnel diffraction (second order)

Digital laser storage and retrieval is entirely controlled by the physics of Fraunhofer diffraction, i. e. quadratic terms are eliminated in the evaluation of the diffraction patterns.

Considering the most applicable Fraunhofer diffraction pattern of a circular aperture, one first has to restrict the Rayleigh-Sommerfeld integral, by means of putting the obliquity factor $\left[\frac{\cos(\mu, r')}{r r'} \right]$ in front of the integral, obtaining

$$i \lambda v_p = \frac{A}{R R'} \cos(\mu, R) \int e^{i k(r+r')} d\xi d\eta$$

(R) and (R') are the respective values of (r) and (r') at (O) , i. e. the origin of our new integration variables (ξ, η) . After some mathematical manipulations, we obtain the Rayleigh-Sommerfeld diffraction integral in the form:

$$i \lambda v_p = \frac{A}{R R'} \cos(\mu, R) e^{i k(R+R')} \int e^{-i k \phi} d\xi d\eta \quad (14)$$

where we introduce the abbreviation:

$$\phi = (\alpha - \alpha_0) \xi + (\beta - \beta_0) \eta - \left(\frac{1}{R} + \frac{1}{R'} \right) \frac{\xi^2 + \eta^2}{2} + \frac{(\alpha \xi + \beta \eta)^2}{2R} + \frac{(\alpha_0 \xi + \beta_0 \eta)^2}{2R'}$$

with the direction cosines (α, β) of the diffracted ray $(O \rightarrow P)$ with respect to the (ξ) and (η) axis.

For Fraunhofer diffraction

$$R \rightarrow \infty ; R' \rightarrow \infty$$

only the linear terms in (ϕ) remain, i. e. we deal only with a superposition of plane waves.

Assuming circular apertures only, we introduce polar coordinates to replace the rectangular coordinates (ξ, η) and (a, b) :

$$\begin{aligned} \xi &= r \cos \varphi ; & a &= s \cos \psi \\ \eta &= r \sin \varphi ; & b &= s \sin \psi \end{aligned}$$

(r) is the distance from the center of the circular aperture; (s) is the sine of the deflection angle between the diffracted ray and the perpendicularly incident ray. Denoting the radius of the aperture by (a), a symbol which should not be interpreted by (a) above, we obtain instead of (14):

$$N = C K \int_0^a r dr \int_{-\pi}^{+\pi} e^{-i K r s \cos(\varphi - \psi)} d\varphi \quad (7)$$

where (C) is a complex constant which is proportional to the amplitude of the incident light and is independent of the angle between the central ray and the direction of observation.

The (φ) integral cannot be evaluated by elementary methods, but comprises a Bessel function (J_0):

$$\begin{aligned} J_0(s) &= 1 - \frac{1}{(1!)^2} \left(\frac{s}{2}\right)^2 + \frac{1}{(2!)^2} \left(\frac{s}{2}\right)^4 - \dots \quad (8) \\ &= \frac{1}{2\pi} \int_{-\pi}^{+\pi} e^{\pm i s \cos \varphi} d\varphi \\ J_1(s) &= \frac{s}{2} \left(1 - \frac{1}{1!2!} \left(\frac{s}{2}\right)^2 + \frac{1}{2!3!} \left(\frac{s}{2}\right)^4 - \dots\right) \\ &= -\frac{d}{ds} J_0(s) \end{aligned}$$

and the differential equation

$$\frac{d}{ds} \left(s \cdot \frac{dJ_0}{ds} \right) + s J_0 = 0$$

from which the following relation is obtained:

$$\int_0^s s' J_0(s') ds' = s J_1(s)$$

Applying the asymptomatic representations for large (ρ)

$$J_0(\rho) = \sqrt{\frac{2}{\pi \rho}} \cos\left(\rho - \frac{\pi}{4}\right); J_1(\rho) = \sqrt{\frac{2}{\pi \rho}} \sin\left(\rho - \frac{\pi}{4}\right)$$

we obtain

$$U(\rho) = V = G \frac{2\pi a}{s} J_1(ksa)$$

where

$$V = \pi a^2 G K$$

The intensity $|U|^2$ of the diffracted light is given as: ⁽¹⁰⁶⁾

$$I = |V|^2 = \left[\frac{2J_1(ka w)}{ka w} \right]^2 I_0 \quad (14)$$

where

$$I_0 = C^2 D^2 = \frac{ED}{\lambda^2}$$

Equation (14) is the Airy formula.

$$Y = \left(\frac{2J(x)}{x} \right)^2$$

is presented in Table II from reference 106, page 397, characterizing the Fraunhofer diffraction pattern for a circular aperture radius (a).

The first zero of the diffraction pattern is at

$$S_1 = 1.22 \frac{\lambda}{D}$$

where ($D = 2a$) is the diameter of the circular aperture.

From geometrical optics we introduce

$$\frac{D}{2} = f. \sin u$$

TABLE II

THE FIRST MAXIMA AND MINIMA OF THE FUNCTION

$$y = \left(\frac{2J_1(x)}{x} \right)^2$$

x	$\left(\frac{2J_1(x)}{x} \right)^2$	
0	1	MAX.
1.220 $\tilde{\pi} = 3.833$	0	MIN.
1.635 $\tilde{\pi} = 5.136$	0.0175	MAX.
2.233 $\tilde{\pi} = 7.016$	0	MIN.
2.679 $\tilde{\pi} = 8.417$	0.0042	MAX.
3.238 $\tilde{\pi} = 10.174$	0	MIN.
3.699 $\tilde{\pi} = 11.620$	0.0016	MAX.

where (f) is the focal length of an objective which focuses the diffraction pattern. (2 u) is the angle of opening of the focusing ray cone of the objective. This finally yields for the first zero diffraction pattern the diameter (d)

$$d = 1.22 \lambda \frac{f}{D} \quad (1)$$

which in terms of the f-number (f#) of the focusing objective is expressed as:

$$d = 1.22 \lambda f \# \quad (2)$$

(λ) is the wavelength of the focused light.

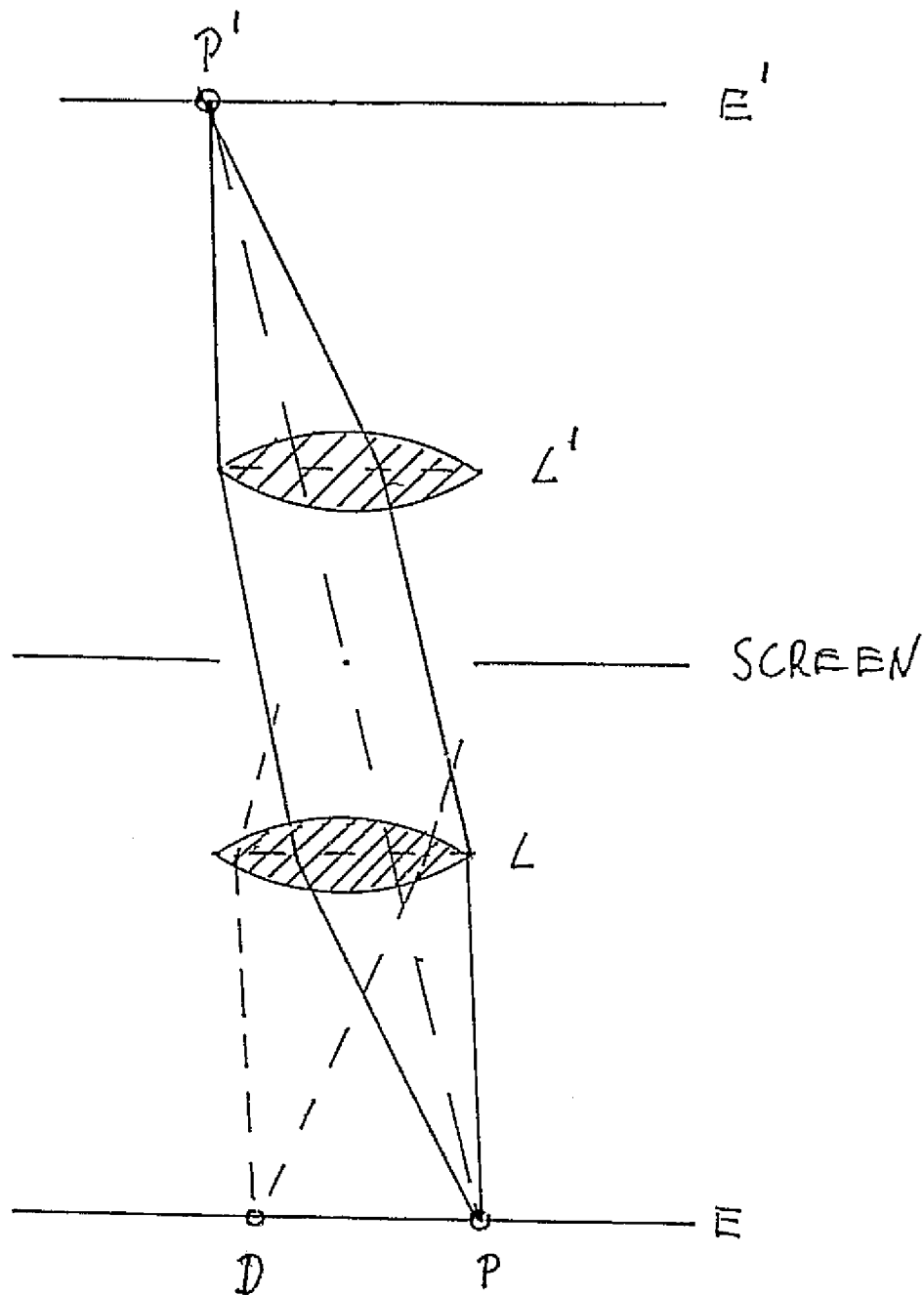
The physical meaning of these relations is that a parallel and coherent light beam entering a distortion free objective of effective aperture (D) and focal length (f) is focused at the focal plane of this objective with a diameter (d) of equations (1) and (2). Any inclination (Θ) of the incident parallel light beam against the optical axis of the objective yields a deflection (ρ) of the focal point within the focal plane, defined as ⁽¹⁰⁸⁾

$$\rho = f \cdot \tan \Theta$$

where (f) is the effective focal length of the objective. See Fig. 1-4.

The geometrical reason for this characteristic behaviour of a focused parallel coherent light beam is the fact that all optical path lengths (of rays parallel to the principal ray) from a plane perpendicular to the principal ray to the focal point are equal.

Summarizing the most important results of diffraction-limited focusing of a parallel coherent light beam, one obtains the following relations:



FRAUNHOFER ARRANGEMENT FOR DIFFRACTION OBSERVATIONS

(reference 105)

Figure 1-4

Minimum spot size:

$$d = 1.22\lambda \text{ f \#}$$

f-number:

$$\text{f \#} = \frac{f}{D}$$

Numerical aperture:

$$\text{N. A} = \frac{1}{2 \text{ f \#}}$$

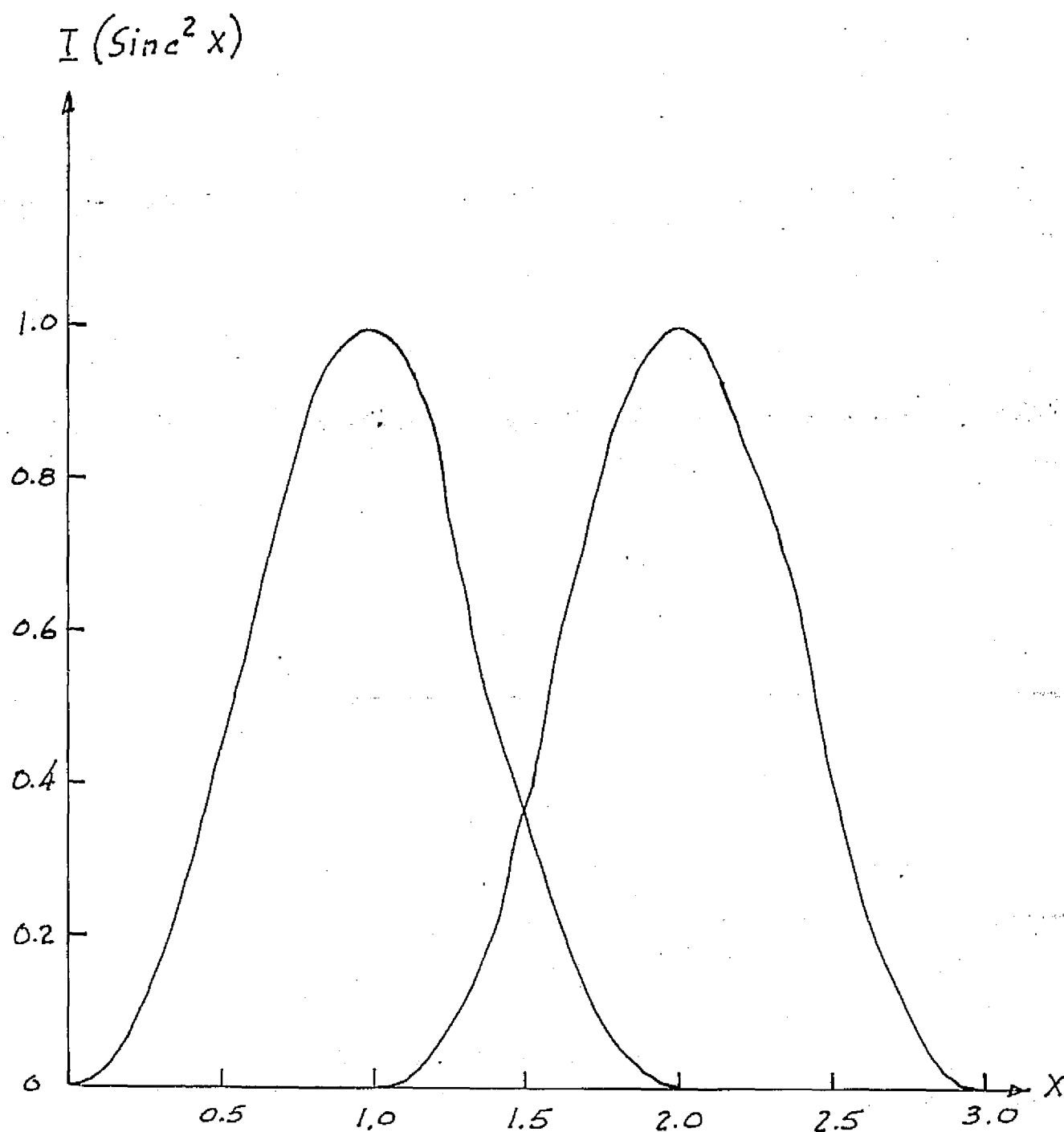
Resolution:

$$(d^{-1}) = \frac{1}{1.22\lambda \text{ f \#}}$$

Depth of focus:

$$\Delta z = 2\lambda \left(\frac{f}{D}\right)^2$$

Note: The resolution (d^{-1}) follows from the Rayleigh criterion. (109) See Fig. 1-5. The depth of focus represents the z - component of the first order diffraction ellipsoid of focus.



RAYLEIGH'S CRITERION

(Reference 106)

FIGURE 1-5

1.3 Laser

At the present state of laser technology,^(04, 05, 110, 111) the most appropriate lasers for non-photographic and non-magnetic digital laser storage and retrieval are:

Argon II ionic laser

Helium-Neon gas laser

In principle, a laser is a light amplifier by means of stimulated emission of radiation.⁽⁰²⁾ Optical gain is achieved by utilizing media with three or more energy levels. A laser oscillator is constructed by utilizing the laser gain medium inside of a Fabry-Perot optical cavity. Optical regenerative gain occurs for light traveling along the cavity axis. The cavity length (L) is typically 10^{13} to 10^6 times larger than the laser wavelength, and typically more than one axial or longitudinal cavity resonance will fall within the laser gain profile. Oscillation occurs at those cavity resonances lying within the inhomogeneous width of the laser transition for which the laser gain exceeds the cavity losses.

The Helium-Neon gas laser⁽⁰⁵⁾ is a collision laser. Its laser medium is a glow discharge in a Helium-Neon mixture. The principal wavelength applicable to digital laser storage and retrieval is at 0.6328 micrometer. The maximum commercially available output power is 100 m watt. The lowest commercially produced output power is 100 μ watt

The Argon II ionic laser⁽⁰⁴⁾ has an ion laser medium which is typically a low-pressure (less than 1 Torr), small capillary arc (1 to 10 millimeter in diameter), with current densities ranging from 100 to more than 10,000 A (the latter figure refers to pulsed operation). This is two to four orders of magnitude larger than the densities required by the Helium-Neon laser.

The output power continues to increase with increasing current density. It is limited by discharge technology. In the ion laser, the upper laser levels (the 4 p ionic states) are populated by electron collision.

1.4 Optical Modes of laser beam intensity distribution.

The intensity distribution of a laser beam is characterized by certain optical modes. ⁽¹¹¹⁾ Because of the deviations from plane parallel light waves which originally encompass the theory of diffraction, a detailed analysis of these modes is required in order to determine the intensity profile of a laser beam. Note, that the preceding theory of diffraction was entirely based upon coherent plane monochromatic light waves of parallel rays, evenly and completely "filling" the apertures of the focusing objective.

Following reference 112, we apply the Helmholtz scalar wave equation to a laser beam. One obtains

$$\nabla^2 u + K^2 u = 0 \quad (9)$$

where

$$K = \frac{2\pi}{\lambda}$$

is the wave propagation constant and (λ) is the laser wavelength.

Assuming the laser beam is traveling in the z -direction, one writes:

$$U = \psi(x, y, z) \exp(-iKz) \quad (10)$$

where (ψ) is a slowly varying complex function which represents the differences between a laser beam and a coherent plane light phase. Thus, (ψ) characterizes a non-uniform intensity distribution of the laser beam expansion with distance of propagation, and the curvature of the laser wave front. By inserting (10) into (9) one obtains:

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} - 2iK \frac{\partial \psi}{\partial z} = 0 \quad (11)$$

Assuming now a solution to (11) which has the characteristics of a Gaussian function $\exp (-\gamma x^2)$, one postulates:

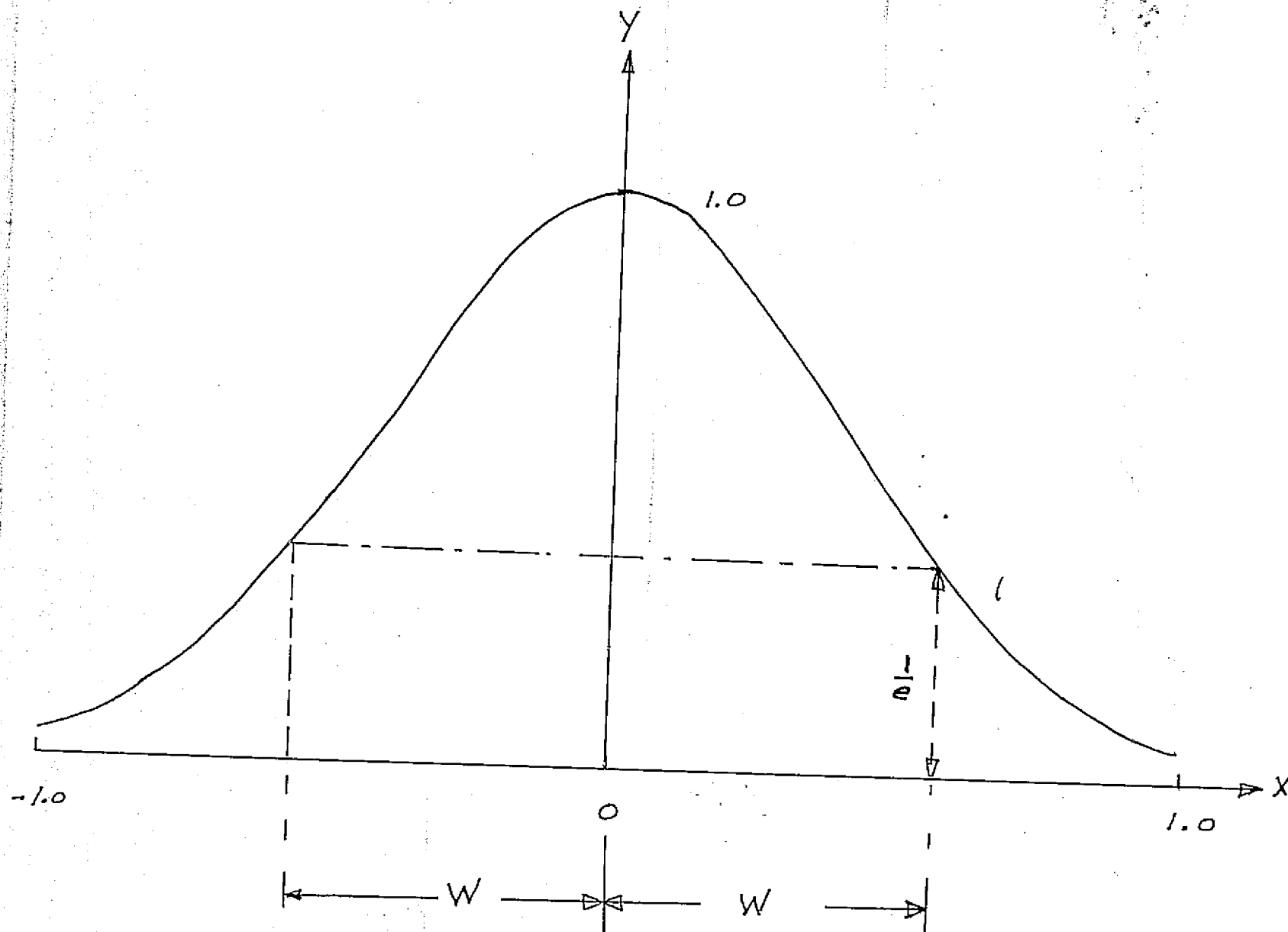
$$\psi = \exp \left\{ -i \left(P + \frac{k}{2q} r^2 \right) \right\} \quad (12)$$

where

$$r^2 = x^2 + y^2 \quad (13)$$

The parameter $P(z)$ represents a complex phase shift which is associated with the propagation of the laser beam, and $q(z)$ is a complex beam parameter which describes the Gaussian variation in beam intensity with distance (r) from the optical axis, as well as the curvature of the phase front, which is spherical near the axis.

A coherent light beam with a Gaussian intensity profile comprises a fundamental mode, as compared to higher order modes. The amplitude distribution of the fundamental mode is presented in the following Fig. 1-6 ⁽¹¹²⁾. The half width (w) of the Gaussian profile is the distance (r) at which the amplitude is $1/e$ times that on the axis. The parameter ($2w$) is called the beam diameter of a Gaussian laser beam.



AMPLITUDE DISTRIBUTION OF THE FUNDAMENTAL BEAM

Figure 1-6

LEGEND

$$y = f(x)$$

1.0	0
0.969	0.10
0.881	0.20
0.754	0.30
0.605	0.40
0.456	0.50
0.3679	0.56
0.323	0.60
0.215	0.70
0.134	0.80
0.078	0.90
0.043	1.0

GAUSSIAN DISTRIBUTION $\exp(-\eta^2 x^2)$ OF FUNDAMENTAL BEAM

(reference 112)

Figure 1-6

1.5 Laser beam focusing, resolution and power concentration.

The foundation of non-photographic and non-magnetic digital laser storage and retrieval of image data is the principle of creating diffraction-limited "holes" in thin metal films. Each hole comprises one (1) bit. In order to create a bit, a laser beam is focused at the laser storage medium within diffraction-limits. One pulse of the laser beam creates one bit.

In comparing the theory of diffraction and laser beam focusing, one recognizes that the basic prerequisite of the theory of optical diffraction is not immediately fulfilled with the incidence of a laser beam: The theory of diffraction was based upon the incidence of a monochromatic coherent plane light wave, assuming that the circular aperture of a focusing objective was completely and homogeneously "filled" with the incident light beam. For laser-focusing, one has to incorporate the effect of the Gaussian laser intensity profile.

Application of the Gaussian intensity distribution of laser beams to non-photographic and non-magnetic digital laser storage and retrieval requires a theoretical foundation, which is quite different from earlier theories (Kogelnik and co-workers, 1964).⁽¹¹²⁾

The essential tool for a modern analysis are Fourier optics and Fourier transforms.⁽¹¹³⁾ As derived earlier, diffraction - limited focusing of a plane parallel coherent light beam yields the focal Fraunhofer diffraction pattern of light intensity in focus, characterized by the $\sin^2 x$ function:

$$\sin^2 x = \left(\frac{\sin \pi x}{\pi x} \right)^2$$

This function is tabulated in reference Bracewell⁽¹¹³⁾. It yields a

diffraction-limited elementary spot size (d) of

$$d = 1.22 \lambda \frac{f}{D}$$

For a laser beam of Gaussian intensity distribution, one recognizes that a focusing single thin lens comprises a Fourier transform of the incident Gaussian function:

$$\exp \left(-\pi x^2 \right)$$

This Fourier transform is again a Gaussian function, so that the intensity distribution of the focused Gaussian laser beam is also a Gaussian function. The significance of the intensity distribution in laser focus is a scaling factor which is proportional to the square ratio of the width (w) of the incident laser beam and its width (w_0) in laser focus. It is determined by the lens law of geometrical optics.

$$\frac{1}{a} + \frac{1}{b} = \frac{1}{f}$$

where (a) is the object distance, (b) is the image distance, and (f) is the effective focal length of the lens. Substituting (a) and (b) by the curvatures of (R_1) and (R_2), the incident and exident laser beam, one obtains correspondingly:

$$\frac{1}{R_1} - \frac{1}{R_2} = \frac{1}{f}$$

On this basis, we obtain the scale factor of the Gaussian focal point to be proportional to

$$\left(\frac{w}{w_0} \right)^2$$

Assuming for example, the focusing objective to be a ZEISS EPILAN L. D. 40 x (N. A = 0.60, $f = 4.1$ millimeter, $f \# = 0.833$) with a diffraction-limited spot diameter of

$$d = 0.56 \text{ micrometer}$$

and a width (w) equal to the effective aperture size (4.7 millimeter) of the focusing objective, one obtains

$$\left(\frac{w}{w_0}\right)^2 = 70 \times 10^6$$

For comparison, the $\sin^2 x$ function and the $\exp(-x^2)$ are normalized to one (1) and presented in the following Table III, the numerical values of which are graphically shown in Fig. 1-6 . See reference Bracewell. (113)

Introducing these parameters in the focusing process with a ZEISS EPIPLAN L.D and assuming that one "fills" the aperture at 3.3 millimeter, one obtains for a spot diameter of one (1) micrometer

$$\left(\frac{W}{W_0}\right)^2 = \left(\frac{3.3 \times 10^3}{1.0 \times 10^{-6}}\right)^2 \approx 10 \times 10^6$$

TABLE III

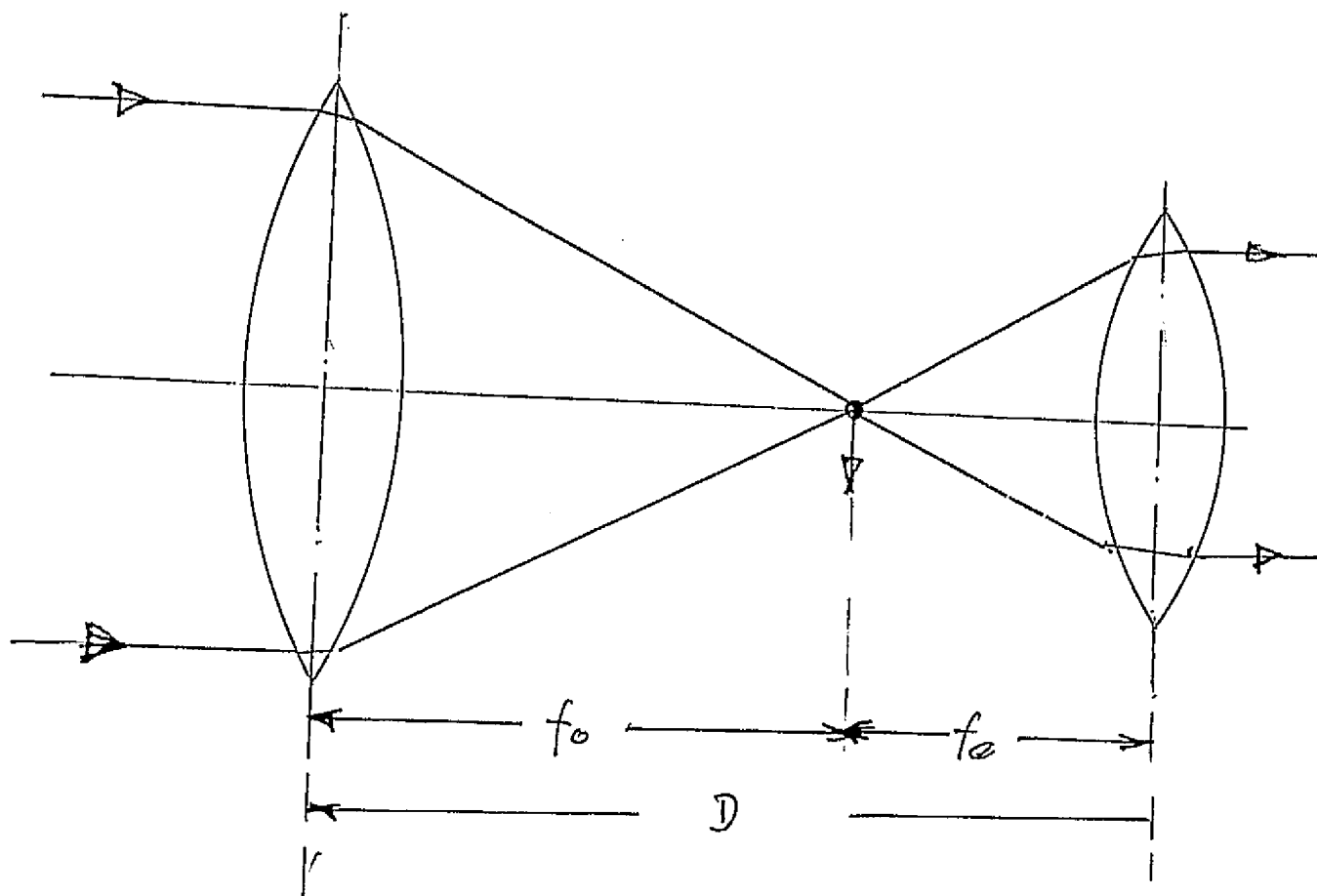
 $\sin x$, $\sin^2 x$, and $\exp(-x^2)$

x	$\sin^2 x$	$\exp(-x^2)$
0	1.000	1.000
0.10	0.968	0.969
0.20	0.875	0.882
0.30	0.737	0.754
0.40	0.573	0.605
0.50	0.405	0.456
0.56	0.312	0.368
0.60	0.254	0.323
0.70	0.135	0.215
0.80	0.055	0.134
0.90	0.012	0.078
1.0	0.000	0.043

1.6 Laser beam expansion.

In order to match the laser beam diameter transmitted from the laser with the effective aperture diameter of the laser focusing objective, a beam expander is required. The most common approach to producing a laser beam expander is the construction of an astronomical telescope.⁽¹¹⁴⁾ This type of telescope is composed of two positive, i. e. converging objectives, which are spaced so that the two back focal points are coinciding. (See Fig. 1-7).

The focal lengths of the beam expanding objectives are so selected, that their ratio is proportional to the filling factor of the beam expander. For restriction of stray-light, the common focal area is surrounded by a pin hole.



ASTRONOMICAL TELESCOPE

(reference 114)

Figure 1-7

1.7 Optics and thermodynamics of digital laser mass storage.

Digital laser storage in thin metal films is determined by two physics phenomena: The optics of thin metal films and the laser bit creation process. Both principles combined yield the optical characteristics of the metallic storage media when irradiated by an incident ^{periodic} strong laser beam.

The optical properties of the thin metal films are characterized by two parameters:⁽¹¹⁷⁾ the index of refraction (n) and the extinction coefficient (K) of the media. The refractive index is defined as the ratio of the phase velocity of light in the vacuum, to the phase velocity of light in the thin metal film. All operational parameters are incorporated in the equation of propagation of electromagnetic light waves passing through the absorbing thin metal film.

Describing the absorbed light wave by its electric field intensity (E), one obtains:

$$\vec{E} = \vec{E}_0 \cdot e^{-2Kx/\lambda_0} \cdot e^{-2\pi i (nx/\lambda_0 - \nu t)}$$

where ($\vec{E}_0$) is the amplitude of the light wave, measured at the point ($x = 0$) in the storage medium. ($\vec{E}$) is the instantaneous value of the electric field intensity at a distance (x) from the point ($x = 0$) and at some time (t), (ν) is the frequency of the incident light (laser beam) and (λ_0) is the wavelength of the light in the vacuum.

The two parameters (n) and (K) are combined in the form of a complex index of refraction (N) of the thin metal film, defined as:

$$N = n - i K$$

where (i) is the square root of (-1).

The operational parameters of the laser beam passing through the thin metal film are determined by Fresnel's equations. ⁽¹¹⁸⁾ They describe the reflectivity (R), transmissivity (T) and absorptivity (A) of the propagation process. At the first approximation, we assume that the incident laser beam enters the absorbing metal film from the vacuum (air) of refractive index (n_o). The complex refractive index (N_1) of the thin metal film is denoted as:

$$N_1 = n_1 - i K_1$$

Then, from Fresnel's equations one obtains the intensity of reflectance (R) at normal incidence:

$$R = \frac{(n_o - n_1)^2 + K_1^2}{(n_o + n_1)^2 + K_1^2}$$

For a thin metal film made of indium, one obtains with ($n_o = 1$) and $K = 2.0805$, at a laser wavelength (λ) of 0.5 micrometer

$$\begin{aligned} \text{or} \quad R &= 0.52 \\ R &= 52\% \end{aligned}$$

The intensity of transmittance (T) at normal incidence may be calculated from a more complicated deviation, based upon Fresnel's equations. One has to consider the incident medium (mylar) with index (n_o), the true thickness (n_1) of the thin metal film with index (N_1), and obtains (See reference 117, page 6-120):

$$T = \frac{16n_o n_2 (n_1^2 + K_1^2)}{b_1 e^{\gamma} + b_2 e^{-\gamma} + b_3 \cos \gamma + b_4 \sin \gamma}$$

where

$$b_1 = [(n_o + n_1)^2 + K_1^2] [(n_1 + n_2)^2 + (K_1 + K_2)^2]$$

$$b_2 = [(n_o - n_1)^2 + K_1^2] [(n_1 - n_2)^2 + (K_1 - K_2)^2]$$

$$b_3 = 2 \left\{ \left[n_o^2 - (n_1^2 + K_1^2) \right] \left[(n_1^2 + K_1^2) - (n_2^2 + K_2^2) \right] - 4n_o K_1 (n_1 K_2 - n_2 K_1) \right\}$$

$$b_4 = 4 \left\{ \left[n_o^2 - (n_1^2 + K_1^2) \right] \left[(n_1 K_2 - n_2 K_1) \right] + \frac{n_o K_1}{\lambda_o} \left[(n_1^2 + K_1^2) - (n_2^2 + K_2^2) \right] \right\}$$

$$\sigma = \frac{4 \parallel K_1 h_1}{\lambda_o} ; \nu = \frac{4 \parallel n_1 h_1}{\lambda_o}$$

Introducing the parameter values for indium from reference 117:

$$\begin{array}{ll} n_o = 1 & K_1 = 2.0805 \\ n_1 = 1.0190 & K_2 = 0 \\ n_2 = 1 & \lambda = 0.5 \text{ micrometer} \end{array}$$

$$h^1 = 800 \text{ Angstrom}$$

= optical thickness of thin metal film

One obtains the transmissivity (T) of the thin metal indium film

$$T = 3.73\%$$

Introducing from above:

$$R = 52\%$$

$$T = 3.73\%$$

one obtains: $A = 44.27\%$ because of $R + T + A = 1$

On the basis of these considerations, we have determined what optical parameters occur at the first linear approximation, i. e. if a laser beam

of very low intensity is passing through the thin metal film. Now we have to determine what occurs when a strong laser beam passes through the metal film, i. e. what takes place if the intensity of the passing laser beam is so strong that it changes the optical parameters.

The mathematical solution to this problem is the theory of heat conduction in solids. (119-120) Application of this theory is based upon the perturbation which is created in the thin film by means of a temperature gradient, originated in laser focus.

$$\vec{f} = -K \text{grad} v$$

(1)

where ($\vec{f}$) is the heat energy flux vector, (v) is the temperature and (K) is the thermal conductivity of the thin metal film.

For a homogeneous, isotropic solid metal film, whose thermal conductivity is independent of the temperature, the thermodynamics of heat conduction are described by the second order partial differential equation:

$$\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} - \frac{1}{\kappa} \frac{\partial v}{\partial t} = 0$$

(2)

where

$$\kappa = \frac{K}{\rho c}$$

(v) is the temperature variable, (ρ) is the density, and (c) is the specific heat of the thin metal film. (κ) is called the temperature conductivity (Sommerfeld) or diffusivity (Kelvin).

Integration of (2) requires certain boundary conditions which are characterized as the conduction of heat in a solid, when its surface temperature is a periodic function of the time. The same mathematical problem arises in conjunction with the fluctuations in the temperature of the earth's

crust, due to periodic heating by the sun.

Assuming a one-dimensional heat flow in the x - direction, equation

(2) reduces to:

$$\frac{\partial^2 v}{\partial x^2} - \frac{1}{\kappa} \frac{\partial v}{\partial t} = 0 \quad (3)$$

we postulate a solution of (4) of the type

$$v = u e^{i(\omega t - \varepsilon)} \quad (4)$$

where (u) is a function of (x) only, and (i) is equal to the square

root $\sqrt{-1}$. This solution will have a period ($\frac{2\pi}{\omega}$), where (ω) is the angular frequency of the periodic perturbation, equal to 2π times its frequency (ν).

Substituting (4) into (3), we obtain:

$$\frac{d^2 u}{dx^2} = \frac{i\omega}{\kappa} u \quad (5)$$

The solution of (5) which is finite as

has the form:

$$u = A \cdot e^{-x \sqrt{(i\omega/\kappa)}} = A \cdot e^{-x(1+i)\sqrt{\omega/2\kappa}}$$

Thus, the solution of (4) of period ($\frac{2\pi}{\omega}$) is:

$$v = A \cdot e^{-\vec{k}x} \cos \left\{ \omega t - \varepsilon - \vec{k}x \right\} \quad (6)$$

where

$$\vec{k} = \left(\frac{\omega}{2\kappa} \right)^{\frac{1}{2}} \quad (7)$$

is the propagation vector of the heat wave with wavelength (λ):

$$\lambda = \frac{2\pi}{\vec{k}} = \left(\frac{4\pi\kappa}{\omega} \right)^{\frac{1}{2}} \quad (8)$$

where (ν) is the frequency ($\frac{\omega}{2\pi}$); At $x=0$ one obtains:

$$v = A e^{-kx} \cos (\omega t - kx - \varepsilon)$$

The important consequences of these deviations are the following (See reference 120.)

(i) The amplitude of the temperature oscillations diminishes like

$$e^{-\vec{K}x} = e^{-x\sqrt{\omega/2\vec{K}}} = e^{-2\pi x/\lambda} \quad (10)$$

and falls off more rapidly for large (ω) . If the surface temperature is given by a Fourier series, the higher harmonics disappear most rapidly, as we move into the solid. At a distance of one wavelength the amplitude is reduced by a factor of

$$\exp \left[-2\pi \right] = 0.0019$$

so that the heat waves are very strongly attenuated.

(i i) There is a progressive phase lag in the phase of the temperature wave:

$$\vec{K}x = x(\omega/2\vec{K})^{\frac{1}{2}} \quad (11)$$

This lag increases with ω .

(i i i) The temperature fluctuations, i. e. the positions of maxima and minima of temperature, are propagated with the velocity

$$(2\vec{K}\omega)^{\frac{1}{2}} \quad (12)$$

Direct application of the preceding considerations to the thermodynamics of digital laser storage leads to the following conclusions:

The flux of heat ($\vec{F}$) created in laser focus at the surface of the thin metal film is defined as:

$$\vec{F} = -\vec{K} \left[\frac{\partial T}{\partial x} \right]_{x=0} = 2^{\frac{1}{2}} \vec{K} K A \cos \left(\omega t - \varepsilon + \frac{1}{4}\pi \right) \quad (13)$$

Thus, the steady temperature ($\bar{v}$) in the thin metal film, which is strongly heated in laser focus at the surface ($x = 0$) by the periodic flux

$$F_0 \cos(\omega t - \varepsilon)$$

from the incident laser beam, is equal to:

$$v = \frac{F_0}{K \vec{k} \sqrt{2}} \cos(\omega t - \vec{k}x - \varepsilon - \frac{1}{4}\pi) \quad (14)$$

with the parameter

$$\begin{aligned} K &= \text{thermal conductivity} \\ \vec{k} &= \text{heat wave vector} \end{aligned}$$

Assuming indium to be the material of the thin metal film, and assuming an angular frequency (ω) of the periodic temperature perturbation, equal to

$$\omega = 2\pi \times 20 \times 10^6 \text{ (sec}^{-1}\text{)}$$

one obtains:

$$K = 87 \left(\frac{\text{Watt}}{\text{cm}^{\circ} \text{K}} \right)$$

$$K = 0.51 \left(\frac{\text{cm}^2}{\text{sec}} \right)$$

$$\vec{k} = \left(\frac{\omega}{2K} \right)^{\frac{1}{2}}$$

$$\vec{k} = \left[\frac{2\pi \times 20 \times 10^6 \text{ (sec}^{-1}\text{)}}{2 \times 0.51 \text{ (cm}^2/\text{sec)}} \right]^{\frac{1}{2}}$$

$$\vec{k} = \left[123 \times 10^6 \text{ (cm}^{-2}\text{)} \right]^{\frac{1}{2}}$$

$$\vec{k} = 11 \times 10^3 \text{ (cm}^{-1}\text{)}$$

Hence, one obtains

$$|f_o| = \alpha \times K \sqrt{2}$$

and with

$$\alpha = T_{\text{melting}} = 430^\circ \text{ K}$$

$$|f_o| = 430^\circ \text{ K} \times 0.87 \left(\frac{\text{Watt}}{\text{cm}^2 \text{ K}} \right) \times 11 \times 10^3 (\text{cm}^{-1}) \sqrt{2}$$

$$|f_o| = 5.8 \times 10^6 \frac{\text{Watt}}{\text{cm}^2}$$

For a laser focus diameter (d) of

$$d = 1.22 \times 0.5 \times 10^{-4} \text{ cm}$$

$$d \approx 1 \text{ (micrometer)}$$

and assuming the laser power to be concentrated by means of $\left(\frac{w}{w_o} \right)^2$

one obtains

$$|f_o| = 5.8 \times 10^6 \times 1 \times 10^{-8} (\text{Watt})$$

$$|f_o| = 58 (\text{milliwatts})$$

The important result of the preceding calculations is the frequency dependence of digital laser storage and retrieval, to be proportional to the square root of the angular recording frequency. See Fig. 1-8.

LASER POWER (WATT)

FREQUENCY DEPENDENCE OF DIGITAL LASER STORAGE

1.0 10

9

8

7

6

5

4

3

2.5

2

1.5

0.1 10

9

8

7

6

5

4

3

2.5

2

1.5

0.01 1

1

1.5

2

2.5

3

4

5

6

7

8

9

10

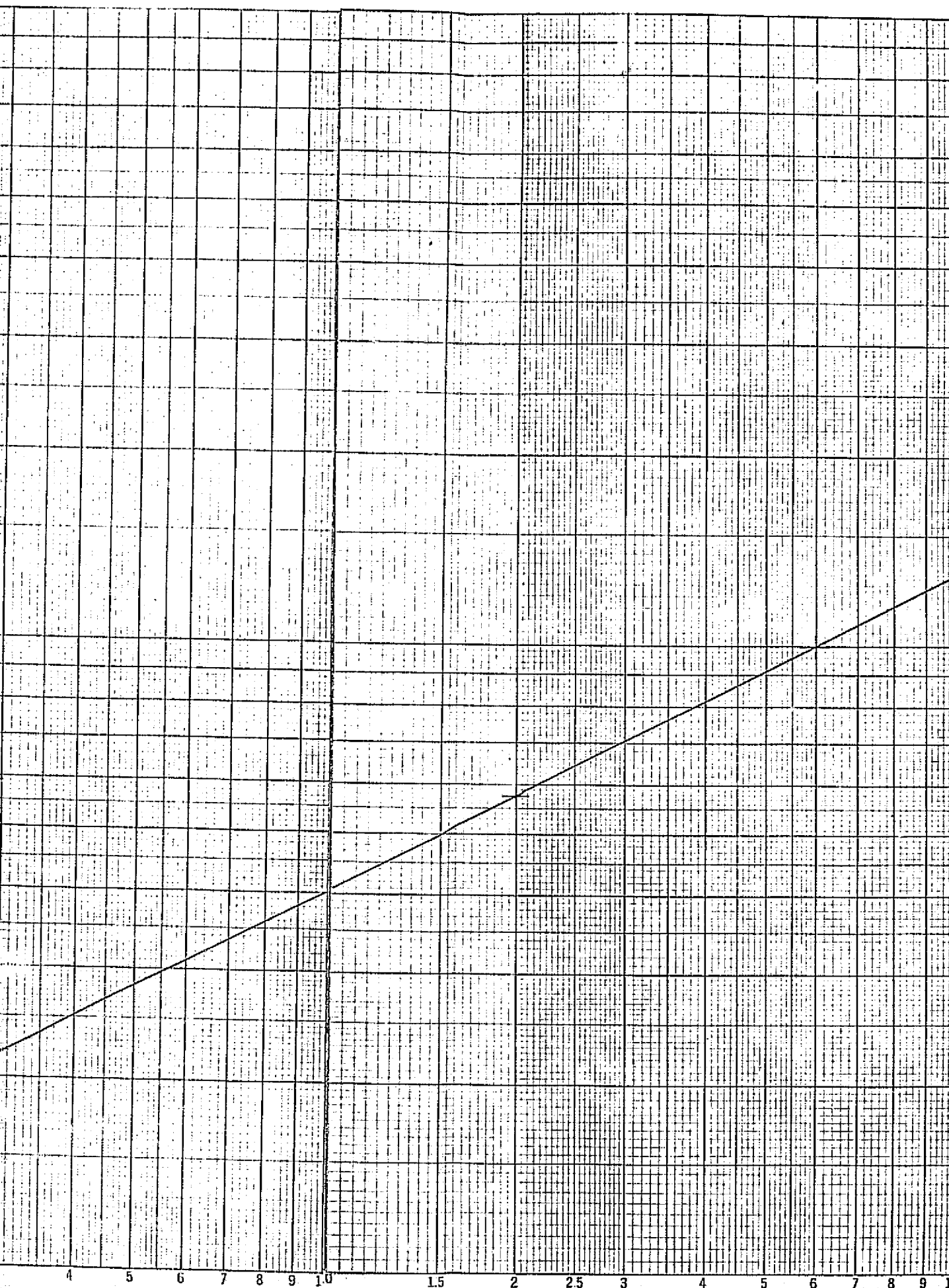
1.5

2

2.5

3

FOLDOUT FRAME



FOLDOUT FRAME

FREQUENCY (MHz)



1.8 Signal modulation techniques for digital laser mass storage.

a) Principles

The principles of non-photographic and non-magnetic digital laser storage and retrieval of image data have been presented by the author at the LASER 75 Conference, Munich, W. Germany, June, 1975. ⁽¹⁸⁾ These principles may be summarized as follows:

Assume an encoded binary image signal is received; transmitted from a satellite for example. During reception, the incoming signal is split into two identical information channels: one channel is entering a non-magnetic digital laser storage system, while the other channel is connected to a non-photographic laser image recording system. Both systems simultaneously record the transmitted original image information. As a result, the digital laser storage system stores the image on a thin metal film in an encoded binary form; Each "word" corresponds to a 6-bit or 8-bit linear density grey value comprising a 2^6 or 2^8 bit permanent binary storage for example. On the other hand, instantaneously viewable transparencies are simultaneously created on another thin metal film, resulting in non-photographic two-dimensional laser image recordings, each picture element encompassing a linear density grey scale.

After completion of the simultaneous laser storing and recording process, two corresponding image representations result simultaneously: An encoded image on a flexible disc with encapsulated thin metal films, plus a two-dimensional transparency of the original image. Both processes take place in synchronous real time. Hence, they comprise two different

versions of one and the same original image.

The signal modulation techniques of both processes are determined by their principal image storage techniques: Generally speaking, non-magnetic binary laser image storage utilizes pulse-code-modulation (PCM), while non-photographic two-dimensional laser image recording requires pulse-duration-modulation (PDM).⁽¹²⁷⁾ In terms of the laser storage and recording events within the thin metal films, binary laser image storage creates a "hole" and a "no-hole" in the metal film of equal size and distance, while two-dimensional laser image recording produces "holes" of varying sizes in the film, depending on the linear density grey level of each picture element.

Considering digital laser image storage and retrieval exclusively, signal modulation comprises pulse-code-modulation (PCM) of the storing laser beam of such a sequence in time and space, that the created holes (bits) are separated by the Rayleigh criterion. The extent to which the adjacent code elements (ones and zeroes) are separated, depends on the velocity of the storing thin metal film, as well as the wave form of the code elements.

Of course, the overall transient response of the system is to be commensurate in time with the Rayleigh criterion in space. Phenomenologically, this means that the code elements (bits) represent a continuous wave form.

Optimum band width is achieved when noise and interference of the digital laser storage process is at a certain minimum. Because precise timing is involved in identifying the signal elements, a clock

has to be recorded simultaneously with the actual laser storing process.

The rate of digital laser storage is determined by the error rate involved with the storage process. In principle, it is a function of the certainty to create a hole. Without data compression, (PCM), pulse-code-modulation in conjunction with binary laser image storage, requires that the continuous image is first sampled in the spatial domain to produce $N \times N$ array of discrete samples which are then quantized in brightness by using 2^K grey levels. Then the total number (B) of bits per image frame to be stored is given by: ^(124, 126)

$$B = N^2 K$$

b) External signal modulation of a laser beam.

External signal modulation of a laser beam utilizes the linear electro-optical effect (Pockel's cell). (201) Applied electric fields control the intensity of an incident laser beam by means of the relation:

$$\Delta a_i = r_{ij} E_j$$

where (Δa_i) are the increments of the coefficient of the index ellipsoid, (E_j) are the components of the applied electric field intensity, and (r_{ij}) are the linear electro-optical coefficients. The values of all electro-optical coefficients depend on the elastic boundary conditions. If the subscripts (T) and (S) denote respectively the conditions of zero stress (free crystal) and zero strain (clamped crystal), one finds:

$$r_{ij}^T = r_{ij}^S + q_{ik} \epsilon_{jk} = r_{ij}^S + p_{ik}^E d_{jk}$$

Here

$$\epsilon_{jk} = \left(\frac{\partial T_k}{\partial E_j} \right)_S$$

and

$$d_{jk} = \left(\frac{\partial S_k}{\partial E_j} \right)_T$$

are the customary piezoelectric coefficients. Note that the order of subscripts in the electro-optic tensor is the reverse of the customary order of subscripts in piezoelectric coefficients, where (i) indicates the electric and (j) the elastic variable.

Optical path differences of an incident laser beam result from the (Δa_i) of equation

$$\Delta a_i = r_{ij} E_j$$

Linear electro-optic (Pockel's) coefficients ($r_{ij} \times 10^{-12} \text{ m/V}$) are presented in the following Table IV for a selection of materials, quoted from reference 201. The most often applied materials are ADP and KD*P, arranged in low-impedance modes of four crystals in series per electro-optical modulator.

TABLE IV

Materials	r_{41}	r_{63}	r_{33}	r_{13}	r_{42}
KH_2PO_4 (KDP)	+ 8.7	- 10.3			
KD_2PO_4 (KD*P)	+ 8.8	- 26.4			
$\text{NH}_4\text{H}_2\text{PO}_4$ (ADP)	+ 24.5	- 8.5			
Li Ta O_3			30	7.0	23.5
Ba Ti O_3			28	8.0	840
K (Ta, Nb) O_3 (KTN)					14,000

Linear Electro-Optic (Pockel's) Coefficients

c) Internal signal modulation of a laser beam.

Internal laser beam signal modulation comprises cavity modulation within the laser itself. ⁽²⁰²⁾ These techniques are also called mode-locking, ⁽²⁰³⁾ mechanical Q-switching, ultrasonic Q-switching and time variable reflectance.

Mode-locking is characterized as the pulsing of a single transverse, multi-axial laser mode by introducing an intracavity loss or phase modulator which is driven at a frequency equal to the frequency separation ($\Delta\nu$) between axial modes:

$$\Delta\nu = \frac{c}{2L}$$

For a large number (N) of lock modes the oscillator has an oscillation envelope which is a pulse train with period (T), pulse width (τ) and peak power (W), which is (N) times the average power.

$$T = \frac{2L}{c} \quad ; \quad \tau = \frac{\pi}{N}$$

For example, for a laser oscillator with cavity length (L)

$$L = 30 \text{ (cm)}$$
$$N = 20$$

one obtains:

$$T = 2 \times 10^{-9} \text{ (seconds)}$$
$$\tau = 10^{-10} \text{ (seconds)}$$

Mode locked pulse widths of 500 p sec., 200 p sec., and 50 p sec. have been respectively obtained from a Helium-Neon laser, an Argon II ionic laser and a Neodymium YAG laser. The most important applications of these mode-locked lasers are in high data rate optical PCM systems.

Q-switching and cavity dumping are provided at lower repetition rates, i.e. below 30 MHz. In cavity operation, the laser oscillator stores

energy in the optical cavity during the interpulse period, when the output mirror transmission is zero. For the case in which maximum peak output power is required, the transmission is switched to 100% (for a time interval $\gg \frac{2L}{c}$), at a time when the optical cavity has a maximum stored energy. As a result, all the stored energy of the laser cavity is dumped and the output is a narrow pulse whose peak power is equal to the maximum internal circulating power. Restoration of the minimum transmission to zero permits a repetition of the cycle. The technique of laser cavity dumping was first proposed by Vuylsteke⁽²⁰⁴⁾

Ultrasonic control of Q-switching comprises a Fabry-Perot optical cavity with one mirror tilted away from parallelism with the other. A quartz ultrasonic cell is placed between the tilted mirror and the laser rod. Shortly after initiation of optical pumping, the cell is shock excited, generating an acoustic wave-front which moves through the quartz crystal. For an instant a condition prevails in which the light being refracted by the acoustic waves, emerges from the cell at the angle normal to the non parallel mirror. This completes the optical path and allows stimulating radiation to reflect back to the laser rod. Refracted light striking the non parallel mirror other than normal is simply reflected out of the cavity.

The intercavity modulator is comprised of a V-shaped, three-mirror laser cavity in one arm of which is located an acousto-optical modulator. Radiation in the cavity converges to a waist near the center of curvature of the end mirror. The modulator is located at this center of curvature. Part of the optical power in the cavity is diffracted by

acoustic waves propagating in the modulator, to form a beam of radiation that is extracted from the cavity. Because the diffracted optical power is proportional to the radio-frequency power in the signal applied to the modulator, amplitude modulated pulses of coherent radiation are diffracted from the cavity, when amplitude-modulated pulses of radio-frequency waves are applied to the acousto-optical modulator.

Based upon Maydan,⁽²⁰⁵⁾ ultra-sonic cavity dumping is utilized by Spectra Physics, to pulse Helium-Neon laser and Argon II ionic laser.

For giant laser pulses, time variable reflectance (TVR) utilizes a laser rod, two end reflectors, a calcite prism, and a Pockel's cell. The prism, cell and end mirror provide a unit, constituting the variable reflectance in the sense that the effect of the prism is a function of the voltage of the cell.

d) Signal modulation techniques for parallel or serial digital laser storage.

Time sequential permanent digital laser storage and retrieval of image data may take place in parallel or serial form. (206-208) For example, at the present state of the art, parallel digital storage is applied to magnetic tape storage and retrieval, (209) while serial digital storage is applied to magnetic discs. The main reason for these two different approaches is the requirement for direct access.

In principle, parallel digital data storage possesses a linear time-sequential format related to the length of the tape. Thus, direct access is practically excluded from parallel digital data storage. Quite differently, serial digital data storage provides direct access to any word of data stored within a storage unit. Such a unit may be a semiconductor memory, a magnetic core memory, or a magnetic disc.

Based upon these considerations, it is best to select serial time-sequential signal modulation as the appropriate means for permanent digital laser storage and retrieval. Such a choice yields certain difficulties which would not exist with parallel signal modulation. The main disadvantage is the necessity for feedback control between input and output. This requirement creates certain instabilities and uncertainties. They are discussed in detail in reference 210, pages ^{201 - 255} ~~201 - 255~~.

The final decision for selecting serial versus parallel digital laser storage and retrieval results from the requirement of compatibility with digital computer disc storage and retrieval.

e) Pulse-code-modulation (PCM) for digital laser mass storage and retrieval.

With the selection of serial signal modulation techniques, we have to specify the modulation characteristics for non-photographic and non-magnetic digital laser storage and retrieval of image data. Because of the requirement for computer disc compatibility, frequency-code-modulation (FCM) is not applicable; neither is pulse-amplitude-modulation (PAM) applicable. Instead, a specific pulse modulation is required, which may be selected from the following alternatives:⁽²¹¹⁾

- pulse-code-modulation (PCM)
- pulse-interval-modulation (PIM)
- pulse-gated binary-modulation (PGBM)
- pulse-position-modulation (PPM)

PCM is characterized as the transmission of one bit per pulse, comprising a "1" or a "0" output. PCM systems using binary code elements require extra band width for a given information capacity, but in return they are more tolerant of interference.

Band width is conserved by using many quantum steps per code element, but only at the expense of increased susceptibility to interference. According to Shannon's central theorem (reference 212, pages 72-124), a method of coding exists, whereby (C) binary digits per second may be transmitted with arbitrarily small frequency of error, where (C) is given by

$$C = B \log_2 \left(1 + \frac{S}{N} \right)$$

where (B) is the signal band width, (S) is the signal power, and (N) is the mean resistance noise power. The equation states that no higher rate can be transmitted.

Assuming

$$\frac{S}{N} = q^2 - 1$$

where (q) are the possible values of quantization, one obtains instead of above:

$$C = 2B \log_2 q$$

where the right hand side is the channel capacity.

In order to make PCM efficient, a local clock has to be transmitted, to keep the same time as a distant standard clock. One possible procedure to accomplish this task is to set aside a code element or pulse within the frame and to transmit this pulse only every other frame. Apparently, the most promising solution to this problem is to provide one master oscillator for the entire system.

Pulse-interval-modulation is a process in which one pulse conveys information representing many bits in an ordinary binary system. The normal interpulse time interval is divided into M-discrete time slots. One and only one pulse is sent in the time interval of M slots. The number of bits transmitted per pulse is therefore $\log_2 M$.

Pulse-gated binary-modulation is similar to cw. binary PCM, in that one bit per pulse is transmitted by a "1" or "0" output. The difference is that in PGBM, the laser operates at a low duty cycle in which the pulse width is only a small fraction of the interpulse spacing. A significant feature of PGBM is the fixed pulse spacing, which is compatible with the inherently regular-spaced pulse output of a mode-locked laser.

Pulse-position-modulation, compared to PCM, conserves signal power. However, in situations where band width is at a premium, it is less

desirable than PCM.

Conclusion: Digital laser storage and retrieval of image data utilizes PCM as the most effective laser modulation means. Pulse shape and pulse width are determined by the Rayleigh criterion, so that each pulse in space and time corresponds to one bit.

In principle, non-photographic and non-magnetic binary laser storage and retrieval of image data comprises two operations: sampling and quantization. The sampling rate in samples per second is governed by the picture size and the resolution requirements in space and time. The number of quantizing levels, is determined by the spatial-temporal contrast.

Experimentation shows that the number of discrete voltage levels, required to reduce impairment due to quantizing distortion, is between 64 and 256 levels, or between 6-bits and 8-bits words. ⁽²¹³⁾

Taking the upper figure, we find that the digital channel capacity, required to transmit a simply coded PCM signal is at most $8 \times 2 \times 10^6$ bits/sec = 16 M bits per square degree of picture.

1.9 Optimum digital laser storage format.

a) Review of the previous state of the art of laser mass storage and retrieval.

Such a review is characterized as the UNICON Computer Mass Memory.

(See reference 03.)

It comprises a rotating drum system which carries removable data-strips of rhodium thin metal films. It operates on the principle of evaporating binary information elements in the metal films, yielding diffraction-limited, permanent "holes" in the metal.

The UNICON was the first laser memory system ever constructed. It is presently in operation at the NASA Ames Research Center, Moffet Field, California.

b) Analysis of the previous state of the art of laser mass storage and retrieval.

This analysis essentially comprises the analysis of the UNICON. However, the following other mass memories were also presented at the first session on "Technology and System of Ultra High Capacity Storage" at the Fall Joint Computer Conference, San Francisco, Calif. Nov. 1966. IBM: Photo-Digital Mass Storage System--utilizing silver halid photographic film and an electron beam; General Electric: electron beam random access large capacity memory system; Eastman Kodak: Photographic digital recording system--utilizing images of a small diffraction grating.

Without discussing the further development of the other systems, the following analysis concentrates entirely on the UNICON, which was the only laser storage and retrieval system presented at the AFIPS conference in the fall of 1966. The most important aspect of this analysis is the fact that the UNICON substantiated for the first time the basic concept of non-photographic and non-magnetic digital laser storage and retrieval. It produced diffraction-limited "holes" in thin metal films, acting as the digital laser storage elements. This concept was created by the author in 1963. (01)

The main problem involved in the substantiation of this concept to a laser mass memory system was the conservation of space-time invariance during laser mass storage and retrieval.

A more realistic formulation of space-time invariance is the requirement for removing the stored information from the laser storage unit to any reading station, without destroying the space-time invariance. In other

words, the reproduced digital information content should be exactly identical to the information of the original laser storage process.

Independent of these basic considerations, another drawback of the UNICON was the utilization of an unprotected and physically open metallic storage medium. Thus, the medium attracted dust particles resulting in uncorrectable errors.

The UNICON's most dramatic violation of the space-time invariance principle was the utilization of "data-strips" and a drum. These drawbacks yielded unsatisfactory "writing" and "reading"; particularly after removal of the recorded information from the drum.

c) Review of photographic and magnetic digital data storage.

Concentration here is on the IBM 3340, 3350 direct access magnetic disc storage system. (301-304) While important characteristics of these systems will be discussed in following chapters, this chapter will only quote the performance characteristics of the IBM systems, based upon the references above:

<u>Parameters</u>	<u>IBM 3340</u>	<u>IBM 3350</u>
Storage capacity	34, 944, 768 bytes or 69, 889, 536 bytes	200-317 million bytes per drive
Data rate	885, 000 bytes per second	1198 thousand bytes/second
Access time	average of 25 milliseconds	average of 25 milliseconds
Linear bit density	5600 bits/inch	6250 bit/inch
Rotational angular velocity	3000 rpm	3600 rpm

d) Optimum format for non-photographic and non-magnetic digital laser mass storage and retrieval.

Possible information carriers for non-photographic and non-magnetic digital laser storage of image data are: thin metal films, fiches, microfiches, ultra-microfiches and discs. Selection of the most appropriate carrier and its optimum storage format follows.

In accordance with the present , most advanced direct access magnetic storage and retrieval systems, it is conceived that the flexible rotating metallized disc comprises the optimum format for digital laser storage and retrieval. The main reason for this conclusion: under proper conditions, this configuration conserves space-time invariance. In the following it is shown that appropriate laser disc storage permits laser reading of the laser stored digital information at any suitable reading station--without destroying the space-time invariance.

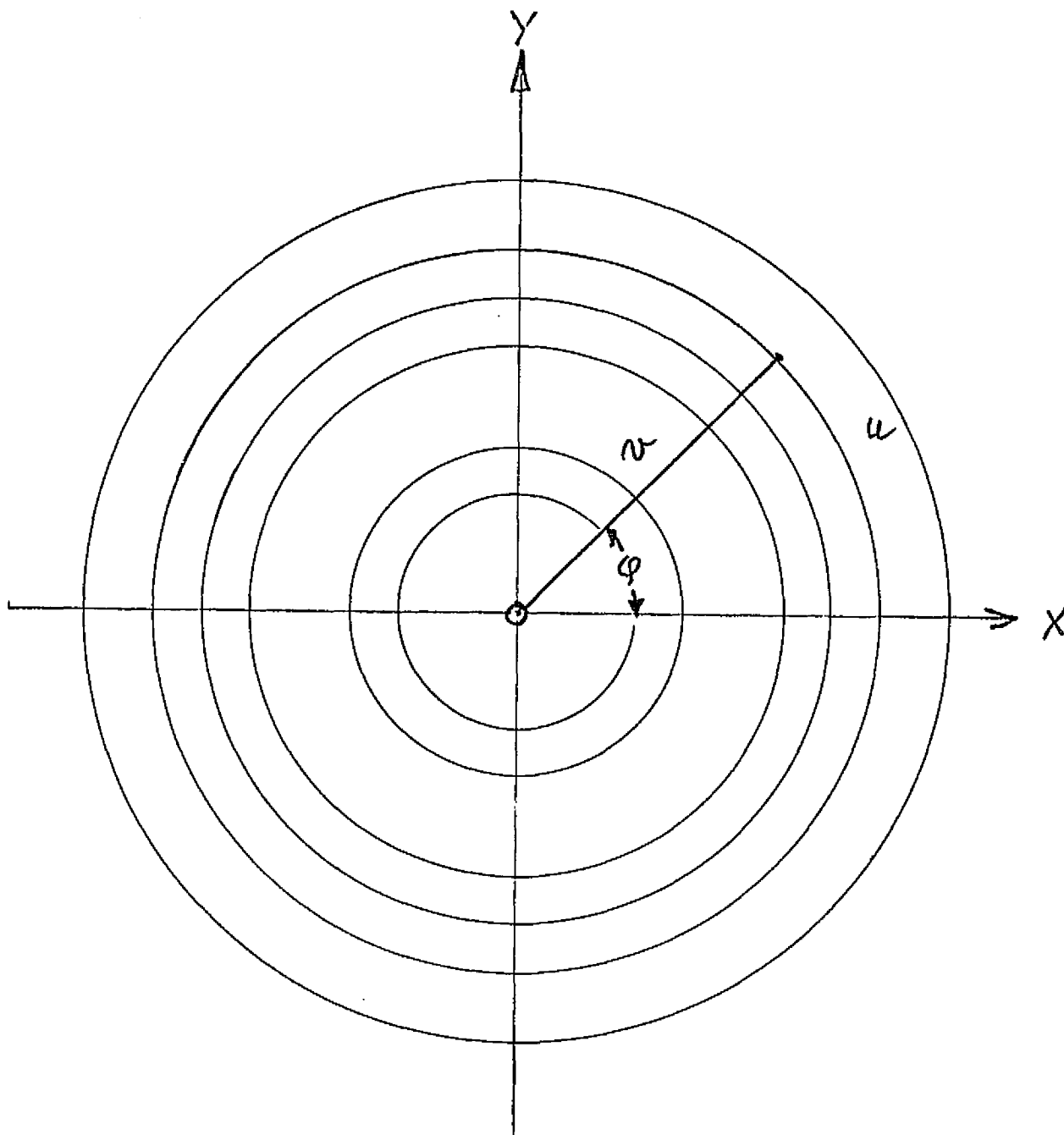
The theoretical foundation for the laser disc concept goes back to the mathematics of polar coordinate systems, ⁽³⁰⁶⁾ the theory of frequency response of a system defined as the steady-state response to a sinnsodial input signal, ⁽³⁰⁵⁾ as well as the theory of image formation ⁽³⁰⁷⁾ and scanning. ⁽²¹¹⁾

(1) Polar coordinate systems invariance:

As shown in Fig. ¹⁻⁰³ ~~Fig. 1-03~~, digital laser disc storage ^{occurs} in polar form ⁽³⁰⁶⁾ ~~It~~ may be ^{approximated} ~~represented~~ as a series of concentric and discrete circles. The information elements are equally distributed along the circles, comprising their coordinates (u, v) of concentric u-circles and radial V-straight lines. ^{See, Fig. 3-1.}

One obtains:

$$u = iv = \ln (x + iy)$$



concentric (u) circles and radial (v) straight lines

$$x = e^u \cos v$$

$$y = e^u \sin v$$

PLANE POLAR COORDINATES

(reference 306)

Figure 3-1

Q-2

$$u = \ln \sqrt{x^2 + y^2} ; \quad x = e^u \cos v ; \quad -\infty < u < +\infty ;$$

$$v = \arctg \frac{y}{x} ; \quad y = e^u \sin v ; \quad 0 \leq v \leq 2\pi ;$$

In rectangular coordinates of the points x, y one writes instead with polar coordinates r, Θ of a point P :

$$x = r \cos \Theta$$

$$\Theta = \tan^{-1} y/x$$

$$y = r \sin \Theta$$

$$r = \sqrt{x^2 + y^2}$$

In reality, digital laser storage and retrieval occurs in sections of an Archimedes spiral of pitch (Δ), defined as

$$r = a \Theta$$

where (a) is the outer circle of the disc storage area. For the unit cell of digital laser storage and retrieval.

$$\Delta = 2.53 \text{ micrometer}$$

(2) Frequency response invariance.

The invariant frequency response of a system ⁽³⁰⁵⁾ is defined as the steady-state response of the system to a sinusoidal input signal. The advantage of the frequency response invariance is that the transfer function describing the sinusoidal steady-state behavior of the system can be obtained by re-

placing the Laplace variable (S) with (i ω) in the system transfer function T (S) . The transfer function representing the sinnsoidal steady-state behavior of the system is then a function of the complex variable (i ω) and is itself a complex function T (i ω) which possesses a magnitude and phase angle. The frequency response method allows consideration of the amplitude and phase of a system, which yields a polar plot in the graphical presentation of the frequency response.

(3) Image formation invariance.

When a function of two independent variables is reproduced elsewhere as another function of two variables, then we speak of image transformation.⁽³⁰⁷⁾

For example, a television system presents--on a two dimensional display-- an image which is fully described by the intensity distribution of illumination B (x, y). This presentation is equivalent to what, in the time domain, would be time invariance. Then the image distribution B is obtained from the object distribution A by convolution with the point image distribution I; i. e.

$$\begin{aligned} B &= I * A \\ &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A(x^1, y^1) I(x - x^1, y - y^1) dx^1 dy^1 \end{aligned}$$

The invariant imaging process is specified by the function I (x, y). Since

$$B = I * A$$

it follows by the two-dimensional convolution theorem that

$$\overline{B} = \overline{I} \overline{A}$$

where bars indicate two-dimensional Fourier transforms.

(4) Scanning invariance.

From the point of view of ideal scanning, the scanning⁽¹²³⁾ elements (picture elements or bits) are arranged in band-limited space-time frequency space, scanned with a spot of infinitesimal width which can be represented by a delta function. This means that the spectrum of the sampled signal is a scaled version of the spectrum of the original $G(u, v, f)$ repeated at intervals $1/X$, $1/Y$ and $1/T$ throughout the frequency space u, v, f , the scaling factor $1/XYT$ being equal to the sampling density. The main source of spatial band limitation is the spot size. The video signal may be in time-discrete form, as when the scanned samples are read into a computer or converted to PCM. The videotransmission bandwidth is directly proportional to the space-time sampling density.

Going back to the polar coordinate presentation of the laser disc storage processes, it is assumed that it possesses initialized index marks along the u -radial, v -straight line. Then the stored digital image data are presented along the various ~~circles~~ ^{spiral tracks}, beginning with the outer ~~track~~ ^{track}. It is further assumed, that digital laser storage and retrieval occurs within the diffraction-limits, utilizing ZEISS L.D. EPIPLAN 40x reflective microscope objective (N.A. = 0.60; $f = 4.1$ millimeter). The disc is rotating at a constant angular velocity of 3600 rpm. Pneumatic focusing is provided over the stroke area of the disc of one (1) inch. The objective is mounted on an appropriate ~~moving coil actuator~~ ^{linear translator} so that laser-focus positioning takes place in equal incremental steps across the (u) radial straight line, in conjunction with a second objective axially positioned with the first one.

Assuming that the angular velocity of the disc is constant and phase-locked to the ~~translator~~ ^{translator}, each time the index mark reaches zero position, ~~an incremental step of the translator moves~~ ^{the linear translator has moved} the laser-focus to

spiral track.

the next ~~stage~~ Assuming further, that laser disc storage occurs on the basis of a unit storage cell with one (1) micrometer

bit diameter and 2.53 micrometer track spacing, and assuming that

spiral track
the outer ~~radius~~ of the laser disc is 14 inches in diameter, while the *spiral track* inner ~~radius~~ is 12 inches, i. e. one (1) inch stroke of the ~~actuator~~ *translator*, then

we will have a linear bit density (I d) of

$$I d = \frac{2 \pi \times 6 \times 2.54 \text{ cm}}{1 \text{ micrometer}} \left(\frac{\text{bits}}{\text{circumference}} \right)$$

$$I d = 95.7 \times 10^4 \left(\frac{\text{bits}}{\text{circumference}} \right)$$

approximately

$$I d \approx 10^6 \left(\frac{\text{bits}}{\text{circumference}} \right)$$

With a track spacing of 2.53 micrometer, we have 10,040 tracks per disc, which yields a single density storage capacity of (I) 0.96×10^{10} bits per disc surface, or approximately:

$$I = 10^{10} \left(\frac{\text{bits}}{\text{disc surface}} \right)$$

For dual density laser disc storage, the total bit capacity is twice that amount, except for frequency division of twice the modulation frequency, where storage capacity is still 10^{10} bits/disc.

e) Expected principal characteristics of optimum storage format.

These are based on the earlier specifications of a diffraction-limited bit size of one (1) micrometer in diameter, and the associated unit laser storage cell of the system.

The digital laser storage unit is one (1) laser disc. It possesses either single density storage of 10^{10} bits per laser disc, or dual density storage of 2×10^{10} bits per disc. Hence, the capacity of a conventional Terabit mass memory of 10^{12} bits is provided by one hundred (100) laser discs. Enclosed in mylar envelopes, these discs encompass a small cubicle. The inherent engineering problem of inserting a disc into the cubicle, and removing it, must still be solved.

For single density laser disc storage the bandwidth is 60 M bits/second, while for dual density operation, it is 120 M bits/second by means of frequency division. Hence, the storage time per disc for digital image data is 1.67×10^2 seconds/disc, or approximately 3 minutes/disc.

f) Dual density digital laser disc storage and retrieval.

This is provided by means of vacuum lamination and evaporation of three transparent mylar discs with four layers of thin metal films. (308-309)
~~During sputtering~~ ^{For example}, the discs are rotating under constant evaporation, so that no accidental error can occur in the thin metal films. After the required film thickness is reached, (half the final thickness), the discs are pressed together in the vacuum, possibly with an RF heating effect. The effect results just above the melting temperature of the metal, so that intimate covalent bonding occurs. Subsequently, the seams are sealed in the vacuum--by means of an infrared laser beam for example--making the discs hermetically sealed.

Laser storage and retrieval takes place through the mylar substrates, yielding error-free and safely protected laser disc storage. Particles, or scratches of the disc surfaces are "invisible" to the laser beam because the focal depth (ΔZ) of the writing and reading laser beam is equal to

$$\Delta Z = 2\lambda \left(\frac{f}{D} \right)^2$$

where (λ) is the laser wavelength, and (f/D) is the f-number of the objective. Hence, (ΔZ) is of the order of a few micrometer, a negligible amount compared to the mylar thickness of the order of 2 to 3 mils, (50 to 75 micrometer).

A schematic presentation of dual density laser disc storage and retrieval is shown in Fig. 7-8 ^{on page 154}. Two identical "writing" and "reading" reflective microscope objectives of high numerical aperture, and small focal length, (ZEISS EPIPLAN 40 x; N. A. = 0.60; f = 4.1 millimeter) are mounted on the moving coil actuator of the system. Each objective is focused to its respective thin metal film.

The incident "writing" and "reading" laser beams originate from an optical beam splitter, which splits the single incident beam in two. Laser focusing is automatically provided, as described in ~~Section V, page 153~~ ^{Section V, page 153}. Laser "writing" and "reading" takes place in a ~~circular~~ ^{spiral} form, thus yielding ~~"spiral"~~ ^{"spiral"} laser storage and retrieval.

In order to extend the bandwidth of digital laser disc storage and retrieval from 60 M bits/second to 120 M bits/second, dual density laser storage and retrieval appears to be appropriate in conjunction with frequency division. ⁽²¹²⁾ Frequency division is the process of propagating two or more information bearing signals over a common path, by using a different frequency band for the transmission of each signal.

Frequency multiplexing provides the means for dividing a band of relatively high frequencies into a number of narrower bands, each of which serves as a channel.

g) Expected future extension of non-photographic and non-magnetic laser mass storage and retrieval.

In order to satisfy the target needs of the National Aeronautics and Space Administration (09) digital laser storage and retrieval should ultimate encompass a 100 Terabit (10^{14} bits) permanent laser mass memory. Along this line, it should also incorporate a virtual mass memory of the same bit capacity. (310)

The basic unit of a 100 Terabit permanent laser mass memory is a digital laser disc of the 10^{10} bits/disc, of either single or dual density storage format. The main problem with the memory is the storage and retrieval of the discs. Phenomenologically, it comprises a cubicle storage principle. In other words, a certain number of discs are arranged in "blocks". See Table V . Assuming, for example, the storage space for one disc would be the thickness of the disc (of the order of 75 micrometer) plus that of a soft envelope (of the same order of additional thickness), then one has to add the thickness of the individual disc manipulator (of the order of 2.35 millimeter), yielding a total per unit disc storage thickness of 2.5 millimeter.

For a block of 100 discs, one should obtain a block thickness of 250 millimeter, equal to 25 centimeter, (0.25 meter). This block should comprise 10^{12} bits. Hence, a 100 Terabit (10^{14} bit) laser disc mass memory should comprise a total thickness of 25 meter.

TABLE V

LASER DISC STORAGE SPACE ESTIMATE

1 laser disc	= 10^{10} bits/disc
1 block laser discs	= 100 laser discs = 10^{12} bits
100 blocks laser discs	= 10,000 laser discs = 10^{14} bits

1.10 Two-dimensional flat-field laser scanning.

Two-dimensional flat-field laser scanning is based upon A. Sommerfeld's theory of diffraction of light from a binary star. ⁽¹⁰⁵⁾ Sommerfeld determined theoretically that a coherent parallel beam of light can be focused within the flat focal plane of an objective. In his analysis, he considered the Rayleighs criterion is fulfilled during the focusing process, and determined the diffraction-limited resolving power of the focusing objective as:

$$\frac{1}{\int \sin \alpha} = \frac{D}{\lambda}$$

The condition for diffraction-limited flat-field deflection of focus is mathematically presented in the form (see reference 108, page 170):

$$\varphi = f \cdot \tan \Theta$$

where

φ = beam deflection

f = focal length

Θ = deflection angle

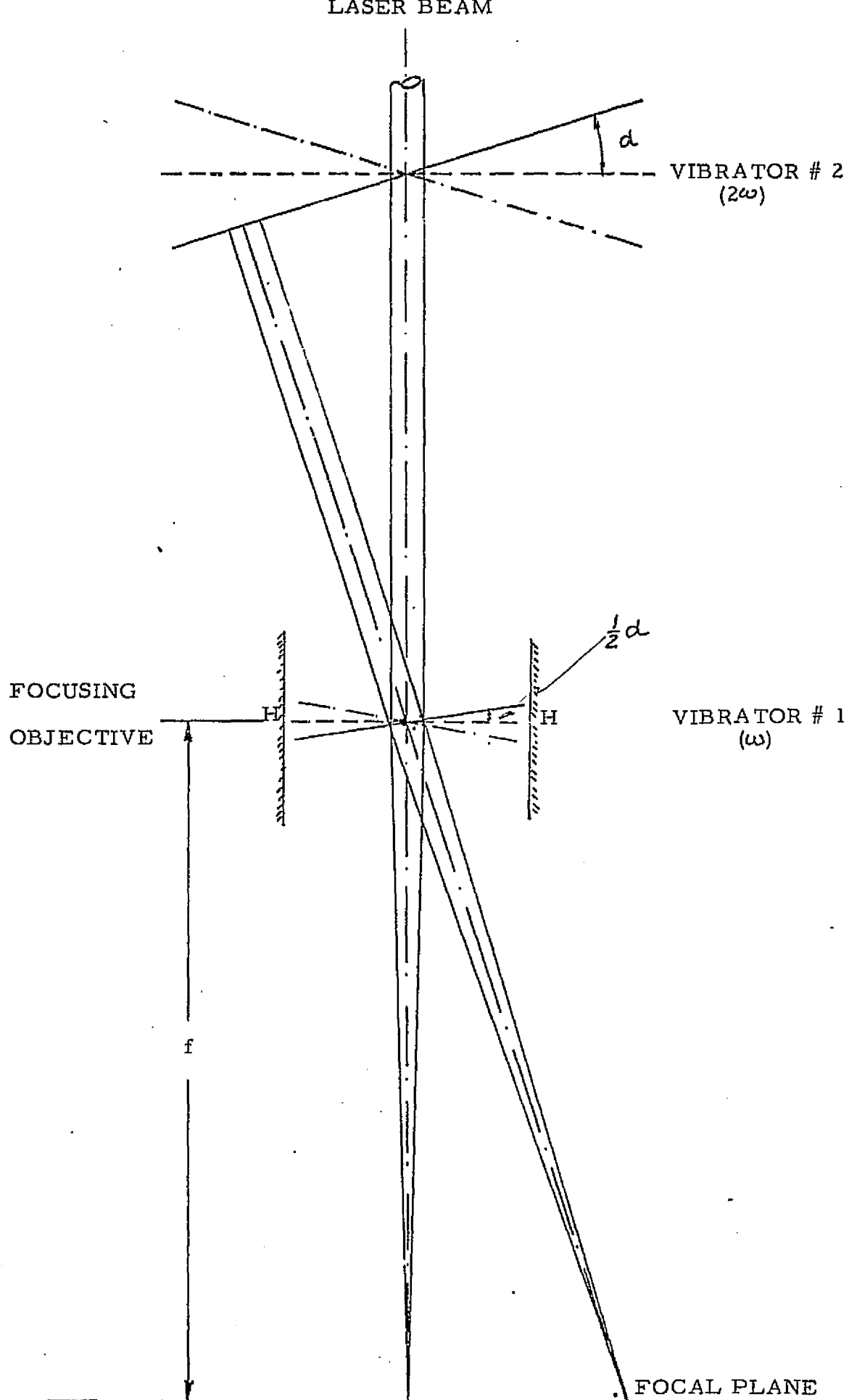
This relationship is valid only if the deflected incident light beam is coherent and parallel.

Replacing the parallel light beams from a binary star by a parallel laser beam, one obtains the condition for flat-field laser scanning. Experimental evaluation shows that the limits for flat-field laser deflection are essentially determined by the "filling" of the focusing objective; its distortion-free angle of deflection; and the focal length of the objective.

For small focal lengths and deflections (narrow fields), microscope objectives of high numerical aperture are most appropriate for flat-field

laser beam deflection and focusing. In that case, the objectives remain in a fixed position, while the storage media are rotating at constant speed. The obtainable flat laser scanning field is 1.7 millimeter wide, utilizing a ZEISS EPIPLAN 40x reflective microscope objective of N. A. = 0.60 and $f = 4.1$ millimeter.

For large focal lengths and wide-field deflections, special twin-mirror deflecting systems are required for flat-field laser beam focusing and deflection. ⁽¹⁸⁾ Such a system is schematically presented in the following Fig. 1-9, and may be described as follows: An incident laser beam of appropriate diameter does not directly enter the focusing objective, but through a galvanometer mirror #1, positioned at the top of the objective, with its axis of vibration passing through the entrance aperture of the objective. Beam deflection from mirror #1 goes to galvanometer mirror #2, which is phaselocked to mirror #1 at a 2:1 angular velocity ratio. Thus, beam reflections from mirror #2 are entering the objective exactly at the center of its entrance pupil, independent of mirror reflections #1 and #2. Hence, the twin mirror system "steers" the incident laser beam automatically through the center of the focusing objective.



FLAT FIELD LASER SCANNING Figure 1-9

1.11 Distinction between "writing" and "reading" operations.

(a) Laser "writing" and "reading" operations.

The main distinction between "writing" and "reading" operations with non-photographic and non-magnetic digital laser storage and retrieval comprises laser power requirements and signal modulation.

The writing power requirements are determined by the thermodynamics of laser bit creation. The reading power requirements are a function of the signal to noise ratio of the laser reading process, which is essentially determined by the R, T, A characteristics of the thin metal film storage media.

The signal modulation characteristics of the writing process are basically determined by the internal cavity modulation of the Argon II ionic laser, or the electro-optical characteristics of the Pockel's cell as well as the performance of integrated circuits (IC) for digital control of the optical transmission of the modulator. The reading characteristics are strictly a d. c. operation of enough laser intensity to adjust the reading output to the desired signal to noise ratio.

(b) Respective laser power requirements for writing.

The writing power requirements extend from 50 m Watt (minimum) to 1 Watt (maximum). This power range can be easily obtained with Argon II ionic lasers, while Helium-Neon lasers are limited to 100 m Watt, except for internal cavity modulation, where pulsed operation increases the laser power output as a function of reciprocal modulation frequency.

(c) Respective laser power requirements for reading.

They are of the order of 1 to 3 m Watt, depending on bit size and bit rate. This can be accomplished best by a small Helium-Neon laser, as it is general usage today with video laser disc readers (Philips, Thomson-CSF).

(d) Respective cost requirements for "writing".

These are essentially the costs for the writing laser (approximately \$10,000), electro-optical modulator (approximately \$2500), and the integrated circuits for electro-optical modulation (approximately \$1,000). For internal laser beam modulation, approximately \$2,500 more are required for the cavity dumper. One has to add also the costs for optical components, such as beam expander, beam splitters, polarizers, accessing optics and servo controls, focusing objective, etc., (totaling approximately \$5,000).

(e) Respective cost requirements for "reading".

These comprise the reading laser (approximately \$150-300) as well as optical components for beam expander, tracking and accessing optics and servo controls, beam splitter, polarizer, focusing objective, vertical laser illuminator, etc. (totaling approximately \$5,000). In addition, the cost of a laser interferometer, of the order of \$10,000 per reading unit, should be considered.

(f) Cost requirements for disc drive.

These are identical for "writing" and "reading". They encompass the actual disc drive and the controller. Exact price determination can be obtained from the main manufacturers (IBM, Control Data, Memorex, Cal-Comp, Hewlett-Packard, etc.). The costs for the disc drive should also include the formatter between incoming signals and the digital laser disc storage system.

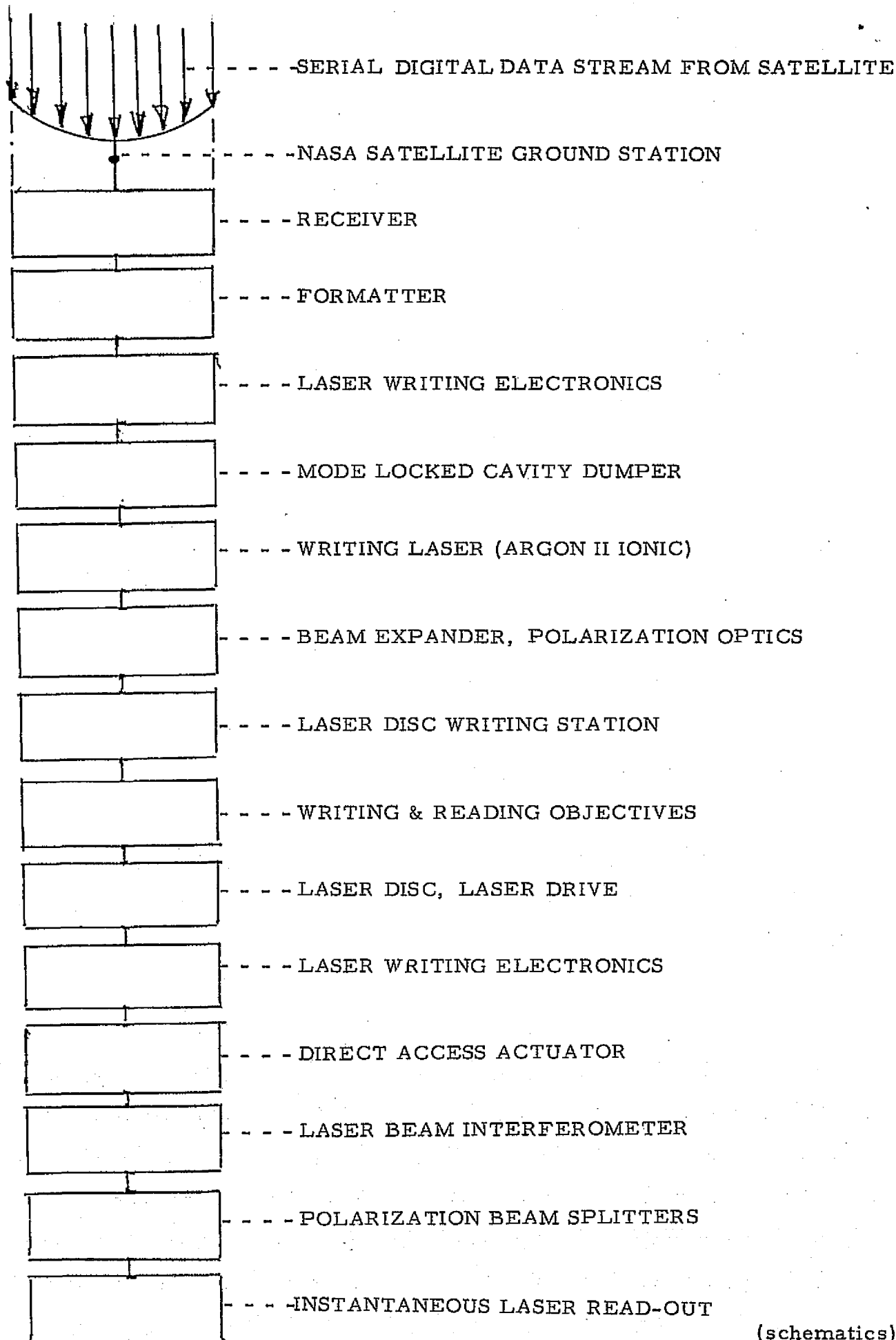
1.12 Operational systems requirements for digital laser disc "writing" and "reading" at stationary NASA installations.

These comprise three principal phases:

- (a) Primary digital laser disc writing and instantaneous laser disc reading at 60 M bits/second or 120 M bits/second;
- (b) secondary digital laser disc reading at 60 M bits/second or 120 M bits/second;
- (c) Computer Input Conversion at 6. 3:1 (6:1) or 12. 5:1 (12:1) frequency conversion ratios.

As schematically presented in Fig. 4-2 , phase (a) encompasses the reception of a serial digital image data stream at a satellite ground station. It is followed by entering laser-writing electronics, which signal modulate the mode-locker of the writing laser (Argon II ionic). Subsequently, the intensity modulated laser beam enters the beam expander, polarizer and beam splitters, followed by the laser disc writing station. There, under laser storage control, the two laser writing and reading microscope objectives store the incoming information on laser discs in a single density, or dual density ~~circular~~ ^{spiral} mode at 60 M bits/second or 120 M bits/second. Laser-writing electronics control actuator and laser beam interferometer, so that ~~circular~~ ^{spiral} tracks are continuously recorded on the laser disc. Simultaneously, instantaneous laser-read-out is provided by another beam splitter which energizes the instantaneous read-while-write electronics. The continuous read-out voltages are sectorized and energize a CRT monitoring system.

After completion of phase (a), secondary digital laser disc read-out--phase (b)--takes place at 60 M bits/second, or 120 M bits/second. As

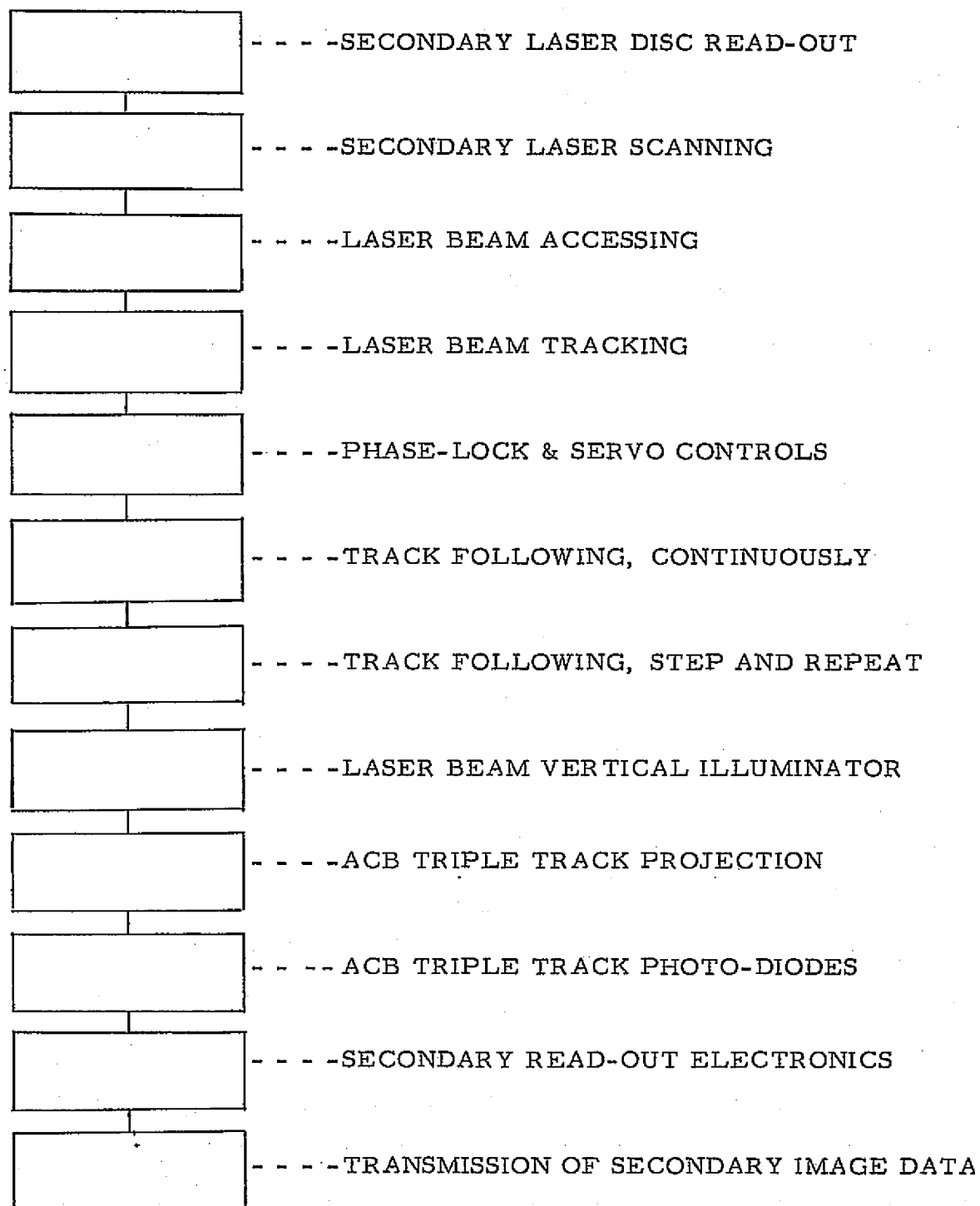


PRIMARY DIGITAL LASER STORAGE & INSTANTANEOUS RETRIEVAL

(schematics)
Figure 4-2

schematically presented in Fig. 4-3 , secondary laser disc read-out occurs by means of laser scanning of the primary laser storage, or any other primarily recorded laser disc. Laser beam accessing and tracking is provided by phase-lock and servo-controls, which follow the stored information tracks, either continuously or in a step-and-repeat fashion. A laser beam vertical illuminator is inserted in the optics system, illuminating the ACB triple tracks under observation and yielding the enlarged projection image of the ACB tracks at the macroscopic photo-detector slit within the screen of the read-out projection system. Because of the 1:1 transmission ratio of phases (a) and (b), the reproduced image data can be simultaneously transmitted; for example: via microwave links.

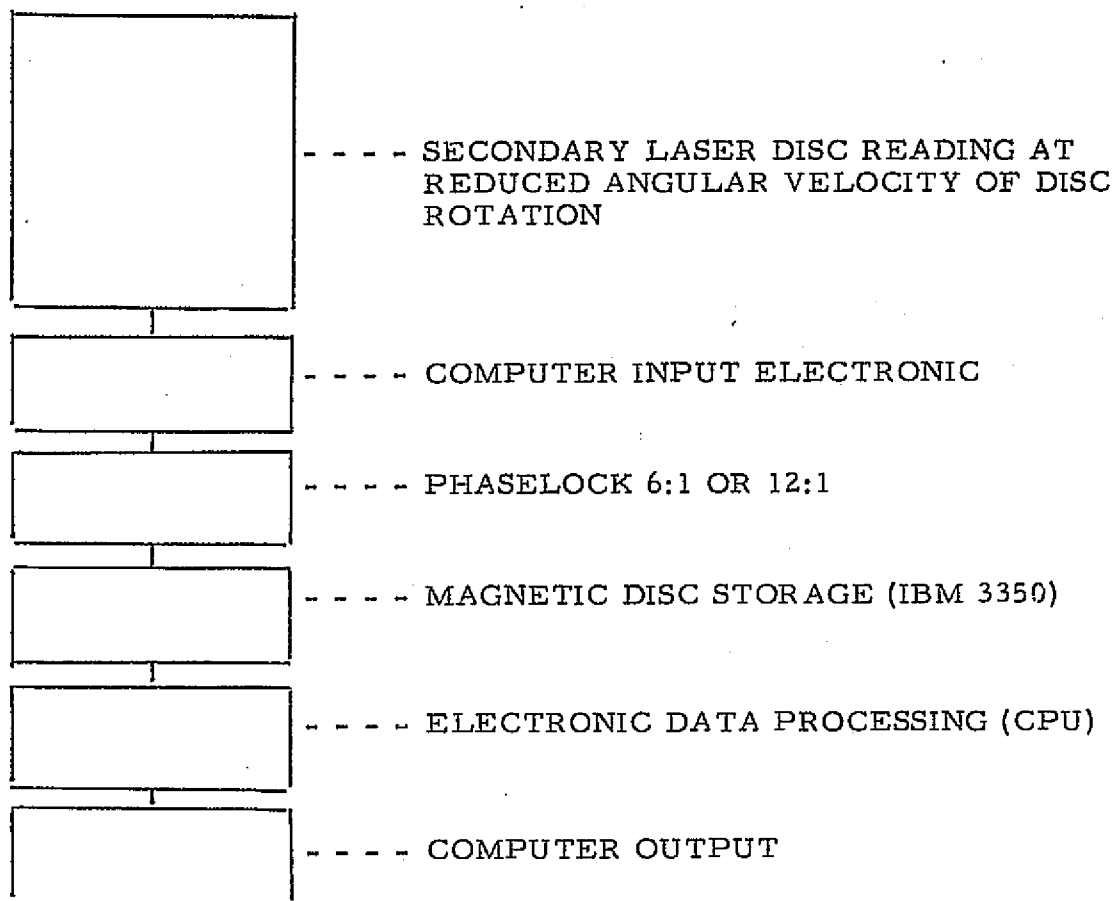
Phase (c) is determined by the necessity of matching the secondary laser disc reading process to computer input. For this purpose, ^{for example, at} secondary laser disc read-out takes place, ~~at 6,000 rpm (600 or 1,200 rpm)~~ ^{8:1} reduced angular disc velocity, compared to the 3,600 rpm original angular velocity of the laser disc drive. See Fig. 4-4 . At the reduced reading rate, the read-out voltage energizes the magnetic disc storage unit ~~of the magnetic disc storage unit~~ (IBM 3350), followed by special electronic data processing of the image data. The processed image data are then available as the computer output.



SECONDARY DIGITAL LASER READING

(schematics)

Figure 4-3



COMPUTER INPUT CONVERSION

(schematics)

Figure 4-4

1.13 COST TRADE OFF BETWEEN "WRITE" AND "READ" FUNCTIONS.

Economic aspects indicate that "read" operations should be provided at the lowest cost possible. In order to satisfy this requirement, certain techniques should be applied which are presently utilized in conjunction with laser video discs (Philips, Thomson-CFR).

The most striking significance of laser video disc systems is the fact that the place of laser video recording is completely separated from the laser reading stations. The laser video recording process involves the primary exposure of a photoresist (deposited on the master disc) by means of a writing laser beam. After exposure, the photoresist is photographically developed and electroplated. Subsequently, laser video discs are pressed from the master, very similar to the pressing of grammophon discs. Hence, the laser reading process of the video disc takes place at the customer's terminal--at minimum possible cost and effort.

On the basis of these considerations, laser writing and reading of the digital image data (transmitted from a satellite) should be separated. In other words, at the laser writing stations all efforts should be concentrated on producing a high-quality, real-time primary disc record of the transmitted image information. At the laser reading station, which may be physically separated and remote from the laser writing station, secondary laser read-out of the stored image data should take place.

In order to make secondary laser reading most economical, the electronic data processor for the secondarily reproduced image data should be a mini computer, ⁽⁵⁵²⁾ in connection with a cartridge disc subsystem and a virtual memory. Appropriate computer input conversion of secondary laser reading to mini computer provides optimum image data exploration of digital data transmitted from a satellite.

feasibility system

After completion of a ~~prototype~~ *based upon* for digital laser storage and retrieval, ~~of image data, subject of~~ this Study Report, a subsequent development effort should be established, to create an inexpensive laser-read and display system. The principle of computer input conversion described in this Study Report should provide the means for such an economical system, particularly when low-cost play-back methods for video-discs were to be applied. It should require appropriate phase-lock electronics, to adjust the laser reader to the mini-computer. This should also yield an economical laser COM system, based upon the principles of laser-printing and laser-microprinting.

For large scale applications in nation-wide and global operations, more sophisticated "read" principles should be developed, which would concentrate on specific electronic data processes, for example, for satellite exploration and prospecting. Similar to present electronic data processes for geophysical exploration, highly sophisticated stop and repeat methods may be applied to the CPU, to provide exploitation of the laser storage and retrieval data, processed from image data transmitted from a satellite, based upon the principles established in this Study Report.

1.14 System requirements for mass data storage and retrieval of
laser images and laser image data.

These may be extrapolated to the expected state of the art in 1980 and 1981. See reference 09. In principle, it is assumed that the system for mass data storage and retrieval of laser images and laser image data is non-photographic and non-magnetic. In other words, magnetic storage and retrieval would be restricted to computer data processing.

As presented in ~~the preceding~~ ^{the preceding 1.12} paragraph ~~1.12~~, mass storage and retrieval of laser images and laser image data encompass a three-phase process. See Figure 4-6.

DIGITAL IMAGE DATA INPUT
TRANSMITTED FROM A SATELLITE

DIGITAL LASER STORAGE, RETRIEVAL
AND COMPUTER INPUT CONVERSION
OF IMAGE DATA

ELECTRONIC DATA PROCESSING
OF IMAGE DATA

DIGITAL IMAGE GENERATION,
LASER PRINTING AND
LASER MICROPRINTING OF IMAGE DATA

MASS STORAGE SYSTEM FOR
LASER IMAGE DATA AND LASER IMAGES

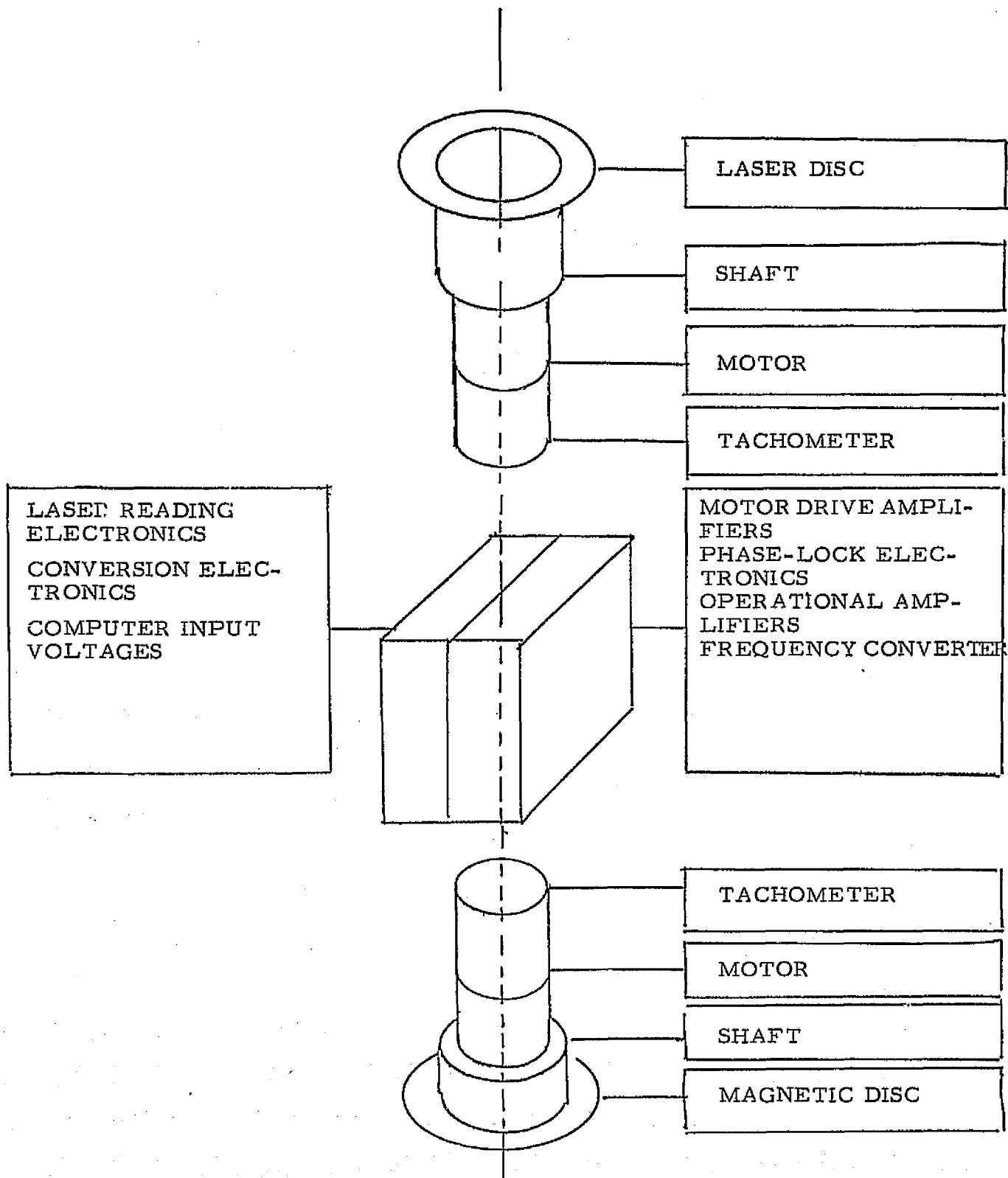
Figure 4-6

1.15 Sectorizing and computer input conversion.

Subsequent electronic data processing of the stored digital image data requires sectorizing of the image data, because laser image storage capacity and rates are far beyond that of a computer. The laser reading rates should be reduced so that the original data rates of 60 Mbits/second, or 120 Mbits/second are adjusted to the operational rates of the computer, typically 9.6 Mbits/second. Due to the fact that secondary laser reading is unaffected by reduced angular velocity of the laser disc, the angular velocity of disc rotation can be reduced in integer ratios of ~~6:1, 12:1, etc.,~~ ^{8:1} for example. The computer input conversion process is determined by the respective operational parameters of digital laser storage and retrieval, and the following electronic data processor. They encompass:

- format
- rates of operation
- linear storage density
- storage capacity per disc
- total storage capacity per system

Computer Input Conversion is schematically presented in Figures 7-9. The related conversion parameters are shown in Table XI, *for example.*



COMPUTER INPUT CONVERSION

Figure 7-9

TABLE XI

COMPUTER INPUT CONVERSION

PARAMETER	PRIMARY READING DIGITAL LASER DISC	IBM 370/3350	CONVERSION FACTOR	HP-3000 CX	CONVERSION FACTOR
Format	Digital laser disc (1)	Magnetic discs (4)		Magnetic discs	
Rate of operation	60 M bits/disc (single density)	9.584 M bits/sec	6.3:1	7.5 M bits/ sec	8:1
	120 M bits/disc (dual density)	9.584 M bits/sec	12.5:1	7.5 M bits/ sec	16:1
Linear storage density	10,000 bits/cm (25,000 bits/inch)	2,500 bits/cm (6,250 bits/inch)	4:1	1,843 bits/ cm (4,680 bits/ inch)	5.43:1
Storage capacity per disc drive	10^{10} bits/disc drive	1.6×10^9 bits/disc drive	6.3:1	14.746 Mbits/ disc drive	6.78:1
Real-time daily storage capacity	10^{12} bits/day				
Total storage capacity per system	10^{14} bits				
Angular velocity of disc rotation	3,600 RPM	3,600 RPM	600 RPM 300 RPM	3,600 RPM	450 RPM 225 RPM

1.16 . ELECTRONIC DATA PROCESSING OF IMAGE DATA.

Computer input image data, resulting from the digital laser storage, retrieval and conversion process, first enter the magnetic disc main storage system of the electronic data processing unit (CPU). Main storage provides the system with directly addressable fast-access storage of data. Both data and programs must be loaded into main storage, before they can be processed. Main storage may be volatile or non-volatile. The system transmits information between main storage and CPU, or channel, in units of eight bits or multiples of eight bits, at a time. Each eight-bit unit of information comprises a "byte", the basic building blocks of all formats. For purposes of error detection and correction, one or more check bits are transmitted with each byte, or with a group of bytes. The check bits are generated automatically by the CPU system. Various parameters which are subject to electronic data processing by the CPU, are outlined in the following paragraphs. See references 401-403.

a) Geometric corrections.

Ground control points on the earth are utilized to correct the distorted geometry of the earth, transmitted from the satellite. Typical reference points are airports, highway intersections, land-water interfaces, geological structures, etc. Electronic data processing compares the transmitted geometry with that of the ground control points and corrects

the data. For this purpose, a network of grid points is mapped into the input image, in conjunction with an interpolation grid of the output image. After determining the position of an output picture element on the input image, the intensity value of the output element is calculated.

b) Conformal mapping.

Spacecraft roll, pitch, and you are not presented with sufficient accuracy by the satellite attitude determination system. The related parameter errors are calculated by the CPU, yielding a conformal mapping process, by means of bilinear interpolation and cubic convolution methods.

c) Radiometric corrections.

CPU provides radiometric corrections by means of table-look-up operations in which a value output by a given detector is used to extract the correct value from the correction table. A unique table is required for each of the radiation detectors.

d) Radiometric enhancement

Due to the fact that digital sensor data have a wider dynamic range than two-dimensional images can provide, radiometric enhancement is applied by the CPU, yielding image information which otherwise could not be observed.

e) Multispectral image data separation.

Each spectral band of the image data transmitted from the satellite is radiometrically adjusted and geometrically corrected with the CPU and recorded on computer compatible magnetic tapes, which are subsequently supplied to the digital image generation and laser microprinting system.

f) Digital gamma correction.

Considering the expected $2^8 = 256$ linear density scale of digital laser storage and retrieval of image data, digital gamma correction should be provided by the CPU. This process is of ultimate importance for satellite exploration, because it expands or compresses digital information on the earth, which can not be detected by linear image data transmission.

g) Search and selection.

Concentrating on special areas of the images transmitted from the satellite, a search and selection process may be provided by the CPU, equivalent to an enlargement process. Precautions are necessary so that this process does not yield "empty" enlargement of the image area.

h) Digital information extraction.

In order to determine certain characteristics of image areas, digital information extraction can be provided by the CPU, a

feature which is of particular importance for satellite exploration.

i) Mosaicking.

Computer techniques have been developed to digitally combine two or more image areas, a process which is called "mosaicking". The purpose of mosaicking is to allow larger sub-areas of the earth to be investigated, i.e. geological faults, hydrologic structures, etc.

j) Error detection and correction.

For a quantitative evaluation of electronic data processing by the CPU, it is necessary to detect possible transmission errors and provide for their correction. In regard to correctable errors, error detection and correction is an inherent part of the CPU.

k) Computer output image data.

The results of electronic data processing by the CPU are applied to Digital Image Generation, where two-dimensional *real* images are created by means of special laser microprinters.

II

LIMITS OF DIGITAL LASER MASS STORAGE AND RETRIEVAL

2.1 Diffraction-Limits

In principle, the theoretical limits of digital laser mass storage and retrieval are the diffraction-limits. They determine the smallest possible bit size (d), as well as the maximum digital areal packing density (I_d):

$$d = 1.22 \lambda f/D \text{ (micrometer)}$$

$$I_d = 0.395 \times 10^8 \text{ bits/cm}^2.$$

The determining factors for the diffraction-limits are physical optics and the laser, in conjunction with laser wavelength (λ). The certainty of creating and detecting a bit is determined by quantum mechanics. It is of the order of 10^{-11} , providing that no detectable errors are produced during the disc manufacturing process. These errors are actually determined by the dust particle content of the clean room around the vacuum deposition chamber. Preliminary washing of the mylar surfaces reduces dust particles further to a minimum, a technique which is successfully applied in conjunction with the surface coating of dielectric optics (Varian).

The practical diffraction-limits of digital laser storage and retrieval are essentially determined by the storage format. In order to conserve space-time invariance, laser disc provides the optimum solution. As a result of the limited storage space per disc unit, the process to interchange laser discs between writing and reading stations determines ^{the} actual laser mass storage ^{capacity.} Hence, practical solutions should be found for storing and handling laser discs. In this respect, particular emphasis should be given to preserve the archival characteristics of digital laser disc mass storage and retrieval, and to operate them in the form of active archives.

2.2 Maximum packing density (MPD) with non-photographic and non-magnetic digital laser mass storage and retrieval.

As a result of the preceding analysis, maximum packing density (MPD) with non-photographic and non-magnetic digital laser storage and retrieval can be determined as follows: In principle, MPD is defined by means of a 6-bit unit storage cell. As presented in Fig. ~~Fig. 1-04~~¹⁻⁰⁴, such a cell encompasses 6 bits of information, arranged along triple ACB tracks. The center track (C) comprises the laser reading information, while the side tracks (A, B,) are utilized as servo-tracks. Of course, during the laser reading process, the next elementary scanning makes track (C) function as servo-track (A), while, for example, servo-track (B) acts as the laser reading track, etc.

The dimensions of the 6-bit unit storage cell are primarily determined by the diffraction-limits of the system. They define the bit size of one (1) micrometer in diameter. According to Rayleigh's theorem, the nearest bit is exactly one micrometer apart (from center to center), so that a "bit" and a "no-bit" occupy a space of two micrometers along the track.

Track spacing is determined by minimum track separation, so that during (ACB) triple servoing, no interference between neighboring tracks can occur. The other factor, which influences track to track spacing, is given by the laser interferometer which ^{MAY} control position-_Aing of laser focus. Because it is operating on integer multiples of quarter wavelengths incremental steps, at a laser wavelength of $\lambda = 0.6328$ micrometer (red Helium-Neon line) with $\frac{\lambda}{4} = 0.158$ micrometer, it is conceivable to select a track spacing of $8 \times \frac{\lambda}{2}$ or

$16 \times \frac{\lambda}{4}$ as the interferometrically controlled track spacing, equal to 2.53 micrometer.

On this basis, maximum packing density of digital laser storage and retrieval results from the effective area (A) of one bit

$$A = 1 \mu \times 2.53 \mu = 2.53 \mu^2$$

which yields with $A = [\text{MPD}]^{-1}$

$$\text{MPD} \approx 0.4 \times 10^{12} \text{ bits/meter}^2$$

2.3 Uncertainty of digital laser mass storage and retrieval.

The errors of diffraction-limited laser focusing follow from the uncertainty principle of quantum mechanics:⁽¹²¹⁾ The precision of positioning a "hole" (bit) is limited by the fact that it is a diffraction-limited spot of finite extension. From the dimensions (d) of the spot one can deduce the limit of precision, which is equal to the diffraction limits above:

$$\Delta X = d = 1.22 \lambda \left(\frac{f}{D} \right)$$

where 1.22 is the first root of a Bessel function, (λ) is the laser wavelength, and (f/D) is the effective f-number of the focusing objective. Because (ΔX) determines the certainty of one photon of energy ($h\nu$), the precision of positioning the hole is increased by the number of photons participating in the formation of the hole.

According to the laws of statistics,⁽¹²²⁾ the effective error (ϵ) is $\sqrt{N}$ times smaller than the uncertainty (ΔX) above, where (N) is the number of photons participating in the formation of the spot.

Assuming, for example, that the power (W) to create one hole (bit) is

$$W = 50 \text{ m Watt}$$

and the time (τ) to create one hole (bit) is

$$\tau = \frac{1}{30 \times 10^6 \text{ bits/second}}$$

$$\tau = 3.3 \times 10^{-8} \text{ (seconds)}$$

then the energy (u) per hole (bits) is

$$u = 50 \times 10^{-3} \text{ (Watts)} \times 3.3 \times 10^{-8} \text{ (seconds)}$$

$$u = 165 \times 10^{-11} \text{ joule}$$

This quantity is equal to the number (N) of photons participating in the hole (bit) creating process, each photon energy being equal to $\hbar\omega$, where ($\hbar$) is Plancks constant divided by 2π and (ω) is the angular frequency of the hole (bit) creating laser wavelength (λ), approximately equal to 0.5×10^{-6} meter. With

$$\frac{\omega}{2\pi} \lambda = c = 3 \times 10^8 \text{ (meter/second)}$$

where (c) is the velocity of light in the vacuum, one obtains

$$\frac{\omega}{2\pi} = \frac{3 \times 10^8 \text{ (meter/second)}}{0.5 \times 10^{-6} \text{ (meter)}}$$

or

$$\hbar\omega = 39.7 \times 10^{-20} \text{ (joule)}$$

Finally, one obtains

$$N = \frac{u}{\hbar\omega} = \frac{165 \times 10^{11} \text{ (joule)}}{39.7 \times 10^{-20} \text{ (joule)}}$$

$$N = 0.42 \times 10^{10}$$

and

$$\sqrt{N} = 0.65 \times 10^5$$

Hence, the hole (bit) positioning error (ϵ) is

$$\epsilon = \frac{1.22 \times 0.5 \times 10^{-6} \left(\frac{f}{D} \right)}{\sqrt{N}}$$

Assuming

$$\frac{f}{D} = 1$$

one obtains:

$$\epsilon = \frac{0.61 \times 10^{-6}}{0.65 \times 10^5}$$

$$\boxed{\epsilon \approx 1 \times 10^{-11}}$$

2.4 Maximum data transfer rates for laser "Write" and "Read" operation.

a) Principles

The data process of non-photographic and non-magnetic digital laser storage and retrieval of image data may be described as follows:

Incoming digital image data, transmitted from an ERTS satellite for example, enter the electronic controller of the system. This device converts the data to a 6-bit or 8-bit serial data stream. Each 6-bit or 8-bit "word" represents a picture element (pixel) of the original image, comprising a 6-bit or 8-bit grey scale of 64 or 256 shades of grey. The output from the controller also incorporates a parity bit for each word. In this form, digital information is applied to the electro-optical signal modulator of the system, which digitally controls the intensity of the writing laser beam. After appropriate beam expansion, the signal-modulated laser beam is then focused to the thin metal film laser storage medium of the laser disc. The disc is rotating at 3600 rpm in phaselock with the clock of the system, which is also provided by the controller. The digital laser storage process is serial, thus providing time-sequential elementary bits in the form of diffraction-limited equal sized "holes" in the thin metal films of the laser disc. Each hole represents one (1) bit.

The data transfer between the incoming digital signal and the laser storage process is generally determined by the theory of optical imaging. More precisely, it is determined by the optical focusing of the digital laser beam intensity upon the laser storage medium. On this basis, the theory of digital laser information transfer should be specified as follows:

- (1) The input image is a series of pulses from a parallel laser beam which is digitally intensity-modulated.
- (2) Each laser pulse is time-sequentially focused to the storage medium creating equal sized holes (bits) of distinct spacing in the storage medium.
- (3) The hole sequence is referred to as a spatial frequency (f_o), measured in cycles per millimeter. Assuming a circular aperture of the focusing objective, the size of each hole is equal to its diffraction-limited diameter:

$$d = 1.22 \lambda f \#$$

where 1.22 is the zero order Bessel function, (λ) is the laser wavelength and ($f \#$) is the effective f-number of the focusing objective.

For equal spacing of the holes, one obtains the spatial frequency (f_o) to be equal to the optical resolution

$$(d^{-1}) = f_o$$

$$(d^{-1}) = (1.22 \lambda f \#)^{-1}$$

b) Modulation transfer function (MTF) of digital laser mass storage and retrieval.

Following a presentation in reference 407, the interrelation between the optical events in the object space (x, y, z) and events in the image space (x^1, y^1, z^1) comprise a linear transformation, accomplished by the optical focusing system. Introducing the fundamental concept of coherent light imaging, each point in the object plane is weighted by a generalized quantity $Q(x, y)$ representing for example, the radiant flux density $W(x, y)$. Each point in image space is then weighted by a quantity $T(x^1, y^1)$ which is related to the object space weighting quantity by a transfer parameter ($\mathcal{R}$). Thus, one obtains:

$$T(x^1, y^1) = \mathcal{R} Q(x, y) \quad (9-2)$$

Assuming that the coherent imaging (focusing) process of the system has negligible aberrations and optical distortions, and that the imaging (focusing) objective has an effective circular aperture (D), then the flux density $W_c(p^1)$ of an electromagnetic wave in the image (focal) point is

$$W_c(p^1) = W_{co} \left[2 J_1(u) \right]^2 / u^2 \quad (9-30)$$

(W_{co}) incorporates the appropriate constants and represents the maximum flux density in the image (focus) formed by the diffraction-limited optical system. The flux density in the image (focus), for a general distribution $W_o(x, y)$ in the object, can be found by

$$W_i(x^1, y^1) = W_r(x^1, y^1) * W_o(x^1, y^1) \quad (9-31)$$

From there one finally finds for the coherence of the system

$$W_i(x^1, y^1) = \vec{V}_i(x^1, y^1) \vec{U}_i^* (x^1, y^1) \quad (9-32)$$

Because the first zero of the Bessel function $J_1(u)$ occurs when the argument (u) is equal to $1.22 \sqrt{\lambda} f/D = 3.832$, the central disc (focus) has a diameter (d) determined by

$$d = 1.22 \lambda f/D$$

One obtains again the conditions for the diffraction limits of the system.

The image distribution function $W_i(x^1, y^1)$ has a Fourier transform which is the two-dimensional frequency function

$$\vec{H}_i(K_x^1, K_y^1) = \iint_{-\infty}^{+\infty} W_i(x^1, y^1) \exp \left[-2\pi i (K_x^1 x^1 + K_y^1 y^1) \right] dx^1 dy^1 \quad (9-33)$$

The expression for $H_i(fx, fy)$ can be reached also by first finding the transform individually of the functions on the right of equation (9-31) and then forming their product. In this sequence, the operation of $W_r(x^1, y^1)$ amounts to taking the transform of the object response function and obtaining the frequency response function of the optical system:

$$\vec{\mathcal{R}}(fx^1, fy^1) = \int_{-\infty}^{+\infty} W_r(x^1, y^1) \exp \left[-2\pi i (K_x^1 x^1 + K_y^1 y^1) \right] dx^1 dy^1 \quad (9-34)$$

The frequency response $\mathcal{R}(K_x^1, K_y^1)$ is called the optical transfer (response) function. Its magnitude (R) is known as the modulation transfer function (MTF) of the system. Similarly, the frequency function $\vec{H}_o(fx, fy)$ is the Fourier transform of the object distribution $W_o(x, y)$. Then

$$\vec{H}_i(K_x^1, K_y^1) = \vec{H}_o(K_x^1, K_y^1) \vec{\mathcal{R}}(K_x^1, K_y^1) \quad (9-35)$$

Note that the preceding analysis refers to an optical system which is linear and space-invariant.

A somewhat different and more rigorous approach to arriving at the modulation transfer function is presented in reference 408. In the following, these deviations are presented with certain modifications, tailored to the specifics of digital laser storage and retrieval.

A linear imaging (focusing) system is said to be space-invariant (also termed planatic), if its impulse response $\vec{h}(x_2, y_2; \xi, \eta)$ depends only on the distances $(x_2 - \xi)$ and $(y_2 - \eta)$. For such a system we can write:

$$\vec{h}(x_2, y_2; \xi, \eta) = \vec{h}(x_2 - \xi, y_2 - \eta) \quad (2-22)$$

Thus, an imaging (focusing) system is space-invariant if the image (focus) of a point-source object changes only in location, not in functional form, as the point source explores the object field.

For an invariant system the super-position integral takes the particularly simple form

$$\vec{g}_2(x_2, y_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \vec{g}_1(\xi, \eta) \vec{h}(x_2 - \xi, y_2 - \eta) d\xi d\eta \quad (2-23)$$

where $\vec{g}_1(x_1, y_1)$ represents the input system and $\vec{g}_2(x_2, y_2)$ represents the output system.

Equation (2-23) is the two-dimensional convolution of the object function with the impulse response of the system. In shorthand notation, one writes instead of (2-23)

$$\vec{g}_2 = \vec{g}_1 * \vec{h}$$

where an asterik between any two functions is the symbol indicating that those functions are to be convolved.

The convolution relation (2-23) takes on a particularly simple form after Fourier transformation: Transforming both sides of (2-23) and invoking the convolution theorem, the spectra $\vec{G}_2(fx, fy)$ and $\vec{G}_1(fx, fy)$ of the system output and input are seen to be related by the simple equation:

$$\vec{G}_2(fx, fy) = \vec{H}(fx, fy) \vec{G}_1(fx, fy) \quad (2-24)$$

where $\vec{H}$ is the Fourier transform of the impulse response

$$\vec{H}(fx, fy) = \iint_{-\infty}^{+\infty} h(\xi, \eta) \exp[-i 2\pi (f_x \xi + f_y \eta)] d\xi d\eta \quad (2-25)$$

comprising the coherent modulation transfer function (MTF) of the system.

One recognizes that the frequency analysis of optical imaging systems is determined by Fourier optics, a concept created earlier by Ernst Abbe⁽⁴⁰⁹⁾ and Lord Rayleigh⁽⁴¹⁰⁾. Carrying the previous analysis still further, one describes the intensity in the image (focus) plane of the laser beam during the imaging process: ⁽⁴⁰⁸⁾

$$I_i(x_i, y_i) = \langle \vec{U}_i(x_i, y_i; t) \vec{U}_i^*(x_i, y_i; t) \rangle \quad (6-7)$$

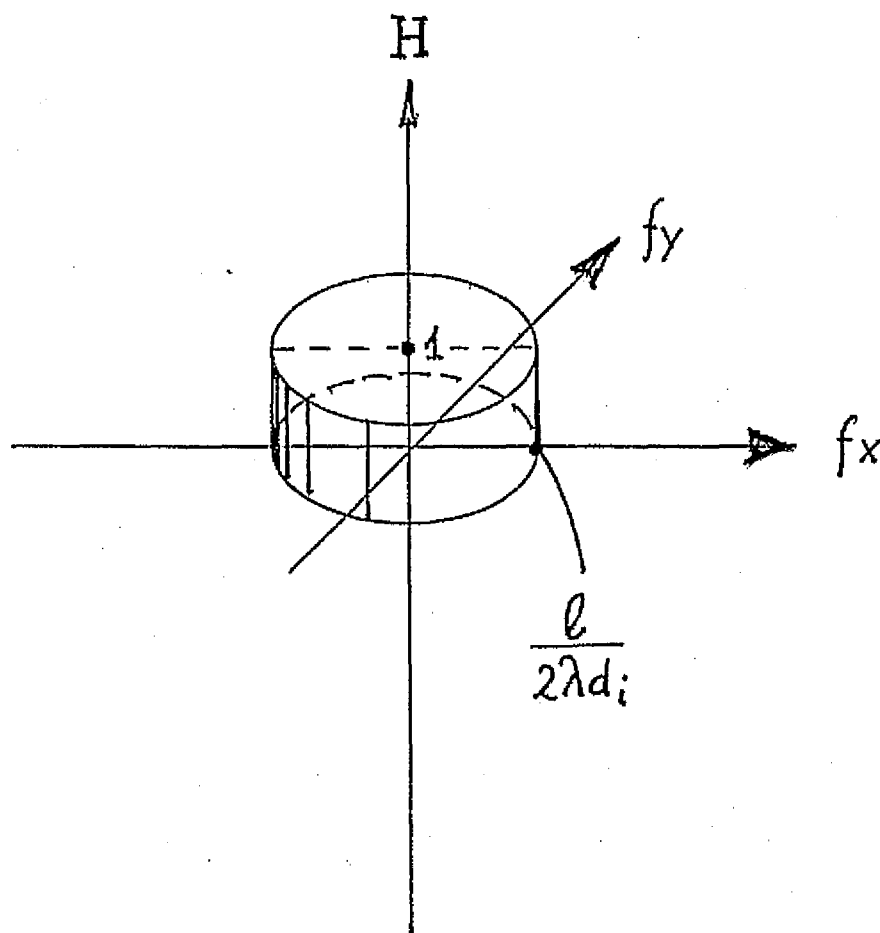
After some mathematical manipulations, and recalling that we are dealing with a coherent modulation transfer function $\vec{H}(fx, fy)$ for a diffraction-limited system, we arrive at:

$$\vec{H}(fx, fy) = P(-\lambda d f_x, -\lambda d f_y) \quad (6-18)$$

where $P(x, y)$ is the optical pupil function:⁽¹⁰⁶⁾

$$P(x, y) = \begin{cases} 1 & \text{inside the objective aperture} \\ 0 & \text{outside the objective aperture} \end{cases}$$

Since the pupil function $P(x, y)$ is always either unity or zero, the same holds for the modulation transfer function. This implies that there exists a finite pass band in the frequency domain within which the diffraction-limited imaging (focusing) system passes all frequency components without amplitude or phase distortion. See Figure 4-1.



COHERENT TRANSFER FUNCTION FOR
DIFFRACTION LIMITED SYSTEM WITH
CIRCULAR APERTURE

(Reference 408)

Figure 4-1

c) Maximum data transfer rates $f(\omega)$ for laser "write" and "read" operations.

The numerical values for the coherent modulation function of digital laser storage and retrieval are presented in Figure 4 - 1. Essentially, they comprise the resolution of the system. The maximum data transfer rates $f(\omega)$ of digital laser storage and retrieval follow from the phenomenological equation:

$$f(\omega) = \frac{V_{\text{scan}}}{d}$$

where (V_{scan}) is the scanning velocity of the laser disc at the inner circumference of the laser storage area and (d) is the effective bit diameter.

III

EXPERIMENTAL FOUNDATION OF
DIGITAL LASER MASS STORAGE

The R+D activities to create digital laser mass storage and retrieval were originated by the author and his coworkers. They took place at the Research Laboratory of Precision Instrument Company.

The basic concept of diffraction-limited "hole" creation in laser focus of solid state materials was created in October, 1963. It was published first in "Quantum Electronics of Optical Phonons II", Zeitschrift für Physik, Vol. 179, pp. 439-360 (1964). This paper showed the first diffraction-limited destruction of an alpha-quartz laser cavity. See, Figure 3-01, originated from Figure 10 of the paper. Destruction was produced by ultraviolet laser oscillations at 2541.83 Å in the confocal alpha-quartz cavity. This phenomenon was indicated as the manifestation of ultraviolet light diffraction by optical phonons in alpha quartz. See, Xerox attached.*

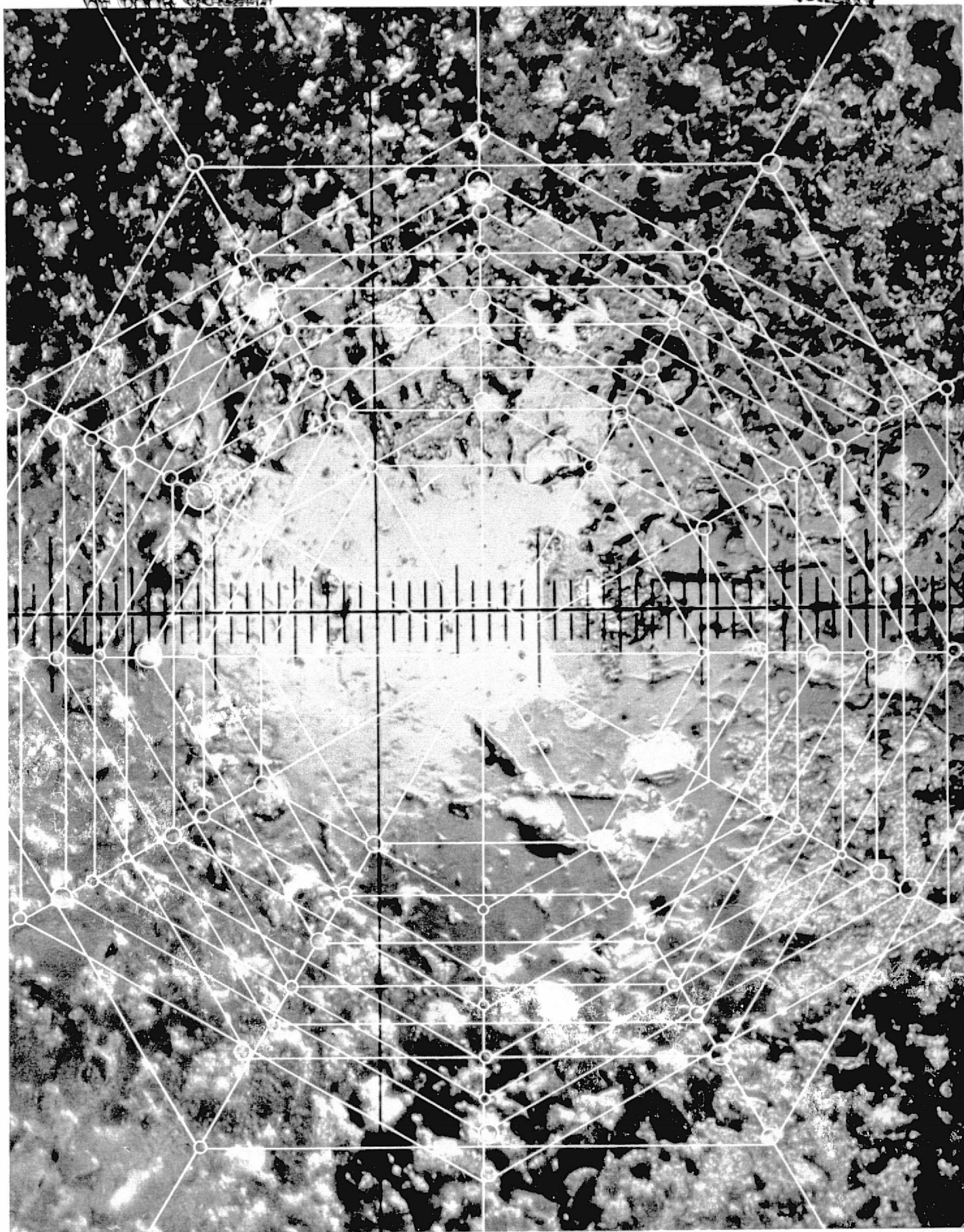
Application of diffraction-limited destruction of a solid state material toward digital laser mass storage and retrieval was first experimentally demonstrated on 14 October 1964. See, photograph Figure 3-02. A Helium-Neon Laser of 50 mWatt was utilized to create diffraction-limited "holes" in a highly absorbing thin film, mounted on a micromanipulator. Instantaneous laser read-out was detected by a photomultiplier behind the film and observed with a Tektronix oscilloscope. Signal modulation took place with a rotating disc, possessing a morse-code hole pattern of the word "UNIDENSITY".

The first public presentation of the new concept occurred at a Session of the 13th Annual Meeting of the German Television Society (Fernseh-Technische Gesellschaft) in Berlin on 17 September, 1965. See Xerox* attached, as well as an English translation of the paper. The presentation of 1965

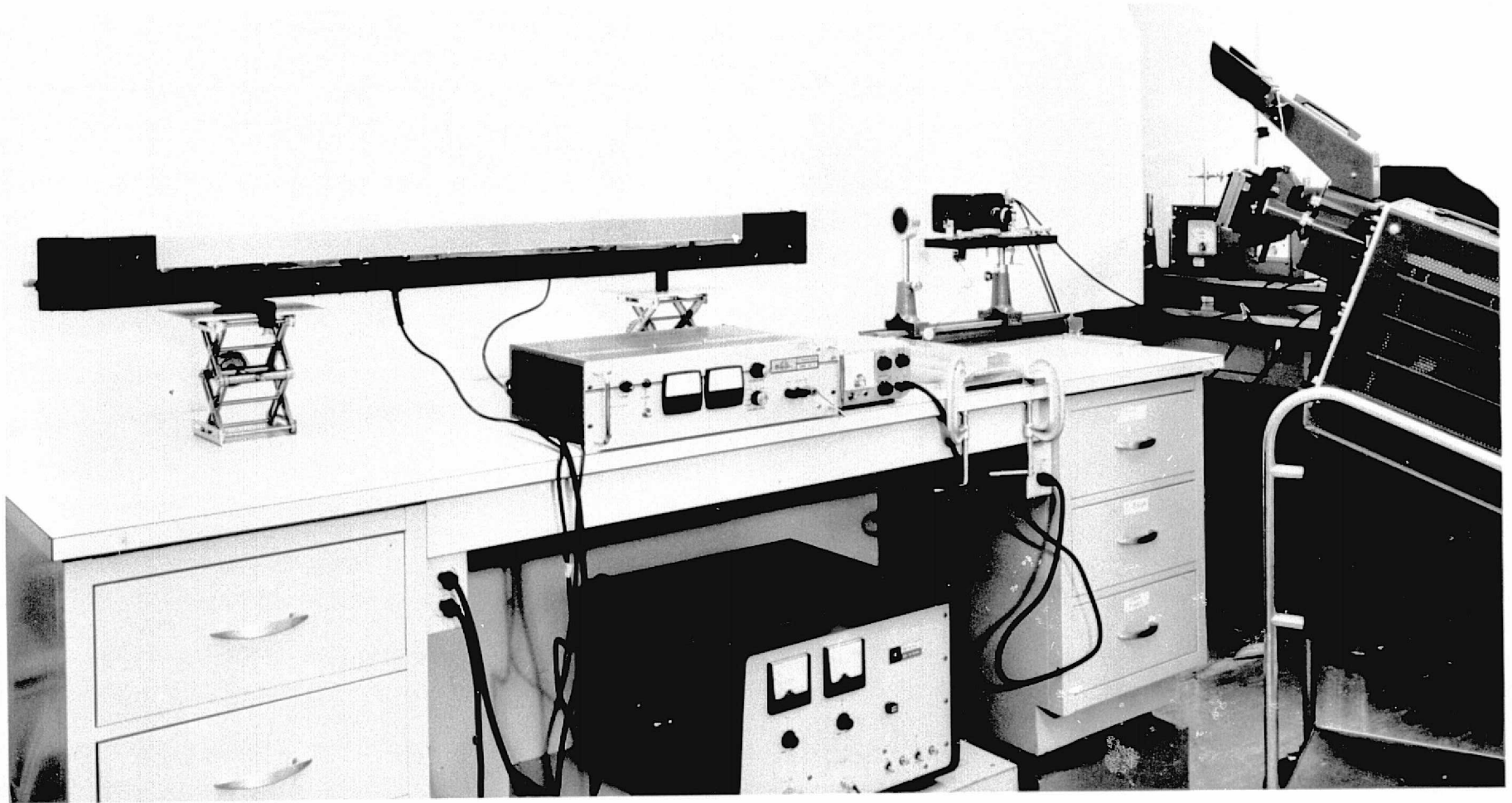
*All Xerox copies of this Section are attached under separate cover.

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY



ORIGINAL PAGE IS
OF POOR QUALITY



indicated the basic conditions of coherent light recording, that

- (a) information density and bandwidth are determined by Heisenberg's uncertainty relation of quantum mechanics,
- (b) laser recorded information comprises a two-dimensional sequence of elementary diffraction images, by means of moving the laser focus in a two-dimensional scanning process,
- (c) coherent light recording comprises Fraunhofer diffraction images,
- (d) diffraction-limited laser power density concentration occurs proportional to $(\lambda/D)^{-2}$,
- (e) optical resolution (Δx) of diffraction-limited laser focusing takes place at

$$\Delta x = 1.22 \lambda (f/D) .$$

The first presentation of the UNICON Laser mass memory took place at the Fall Joint Computer Conference, San Francisco, California, November, 1966, and was published in the Proceedings AFIFS Conference, Vol. 29, pp. 711-716, 1966, entitled "UNICON Computer mass memory system." The paper indicated for the first time the significance to create diffraction-limited "holes" with a laser as the permanent digital elements for laser mass memories. See, Xerox attached*, as well as Xerox of pp. 50-51 of the FICC 1966 program.

The first laser video recording was produced in May 1967, utilizing a rotating drum and helical laser scanning, as well as stop-scanning. These efforts had been presented at the IEEE 9th Annual Symposium on Electron, Ion and Laser Beam Technology, Berkeley, 9-11 May, 1967, pp. 333-343. See, Xerox attached.* The most significant contribution of this paper is the identity between digital data input and output of an experimental UNICON computer mass memory. However, the still remaining problem of space-time invariance between separated laser writing and reading stations was bypassed,

because the thin metal film was not removed from the demonstrator. It took nine years later, until now, that digital laser disc storage and retrieval provides a solution to space-time invariance for physically separated laser writing and reading stations.

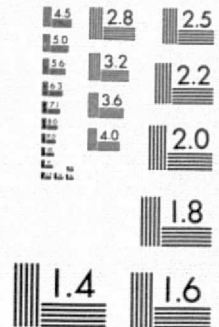
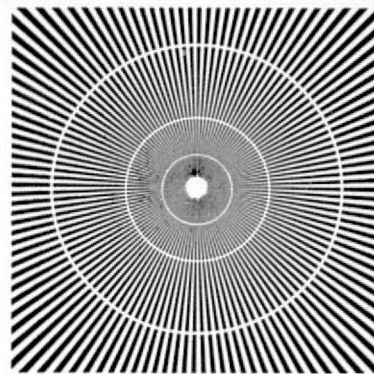
The principles of coherent light systems, in general, were reviewed at the 1972 National Conference of the National Microfilm Association, New York City, Proc. NMA 21, III, pp. 78-95 (1972). See Xerox attached.*

First newspaper and facsimile Laser Printing took place on February 9, 1973. See Palo Alto Times, Friday, February 9, 1973, page 32. See also the following Test Laser Prints. See, Figure 3-03. The prints had been produced with an experimental laser printer, shown in Figure 3-04.

Laser microprinting was first commercially applied in June 1974, comprising a prototype laser microprinter delivered to CANON Inc., Tokyo, Japan. See, Figure 3-05. This event was first published at the SPIE Conference on Laser Recording, San Diego, California, August 21-22, 1974, Proc. Vol. 53, pp. 141-147 (1974). See Xerox attached.* The successfully accomplished acceptance test by CANON, Inc. indicated the experimental substantiation of laser storage and retrieval with one (1) micrometer laser storage elements at one (1) micrometer spacing. It was essentially based upon operational characteristics of mechanical-optical linear translation of the system, and its related servo mechanism. See the linear translator at the right of Figure 3-05, constructed from an older model translator (Lansing).

A recent presentation on the subject matter took place at the Third Conference on the Laser, held by the New York Academy of Sciences, New York City, April 1975, published in the Annals of the New York Academy of Sciences, Volume 267, January 1967, pp. 460-468, entitled "Nonphotographic Image

ORIGINAL PAGE IS
OF POOR QUALITY

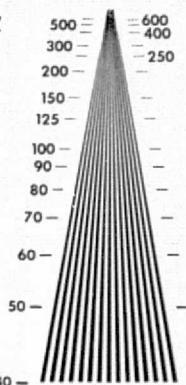


NMA MICROFONT QJKLPYZ
6BSI2GH5D4X7U3W8V9E
PQR45DE9UV670FG8STHIJNOWXABYZ
3KLM12C IJKN0FGH8STU67ABN5CDEZ123VWNPXYQRLM

ABCDEFGHIJKLMN0PQRS
TUVWXYZ 0123456789
'-[]%?@YH ASA 0CR-A

ABCDEFGHIJKLMN0PQRSTU
VWXYZabcdefghijklmnopqrstuvwxyz
1234567890PICA

ABCDEFGHIJKLMN0PQRSTU
VWXYZabcdefghijklmnopqrstuvwxyz
1234567890 Elite



ABCDEFGHIJKLMN0PQRSTU
VWXYZabcdefghijklmnopqrstuvwxyz
1234567890 Spartan Medium 6 pt

ABCDEFGHIJKLMN0PQRSTU
VWXYZabcdefghijklmnopqrstuvwxyz
1234567890 Spartan Medium 4 pt

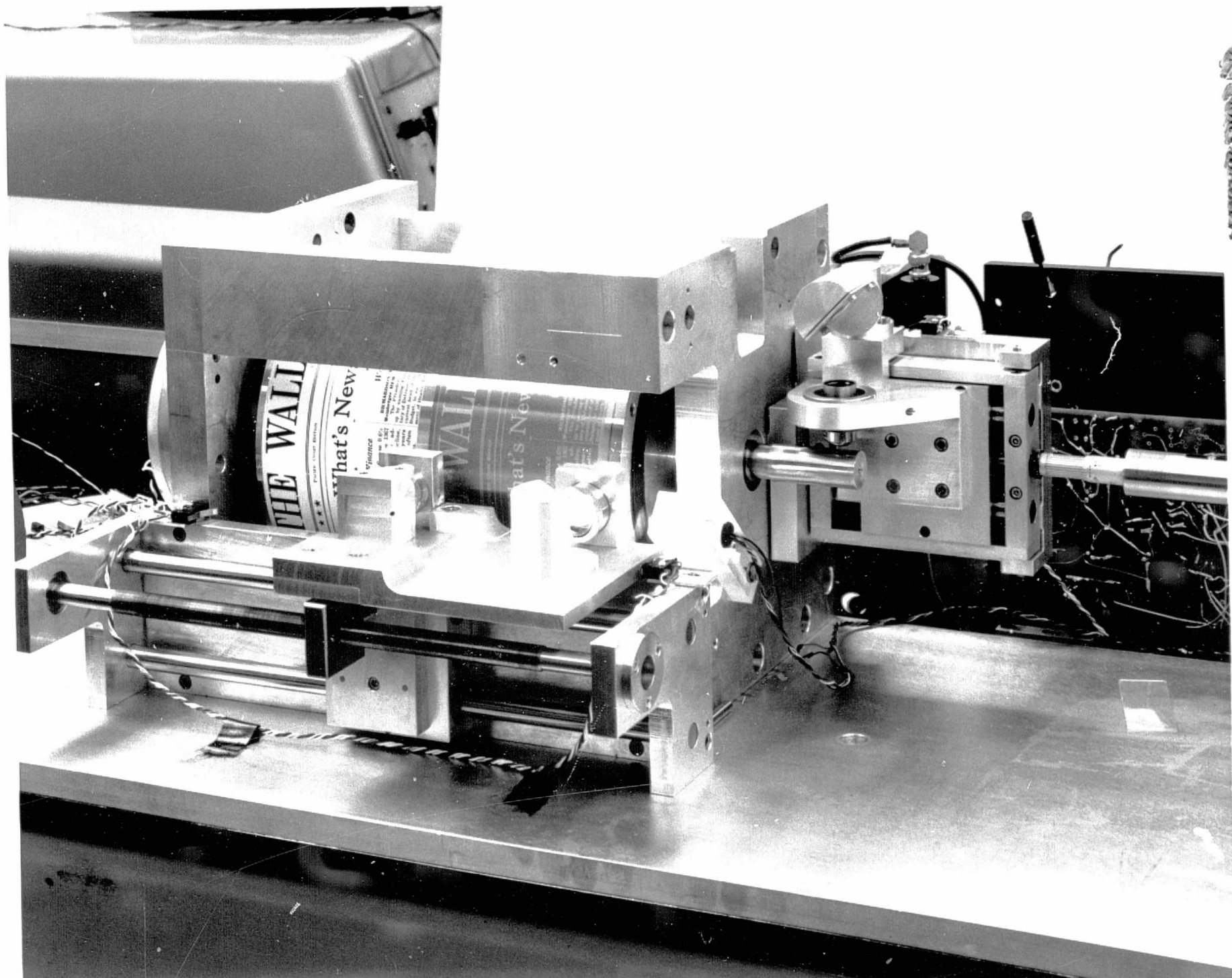
ABCDEFGHIJKLMN0PQRSTU
VWXYZabcdefghijklmnopqrstuvwxyz
1234567890 Spartan Medium 8 pt

ABCDEFGHIJKLMN0PQRSTU
VWXYZabcdefghijklmnopqrstuvwxyz
1234567890 Spartan Medium 10 pt

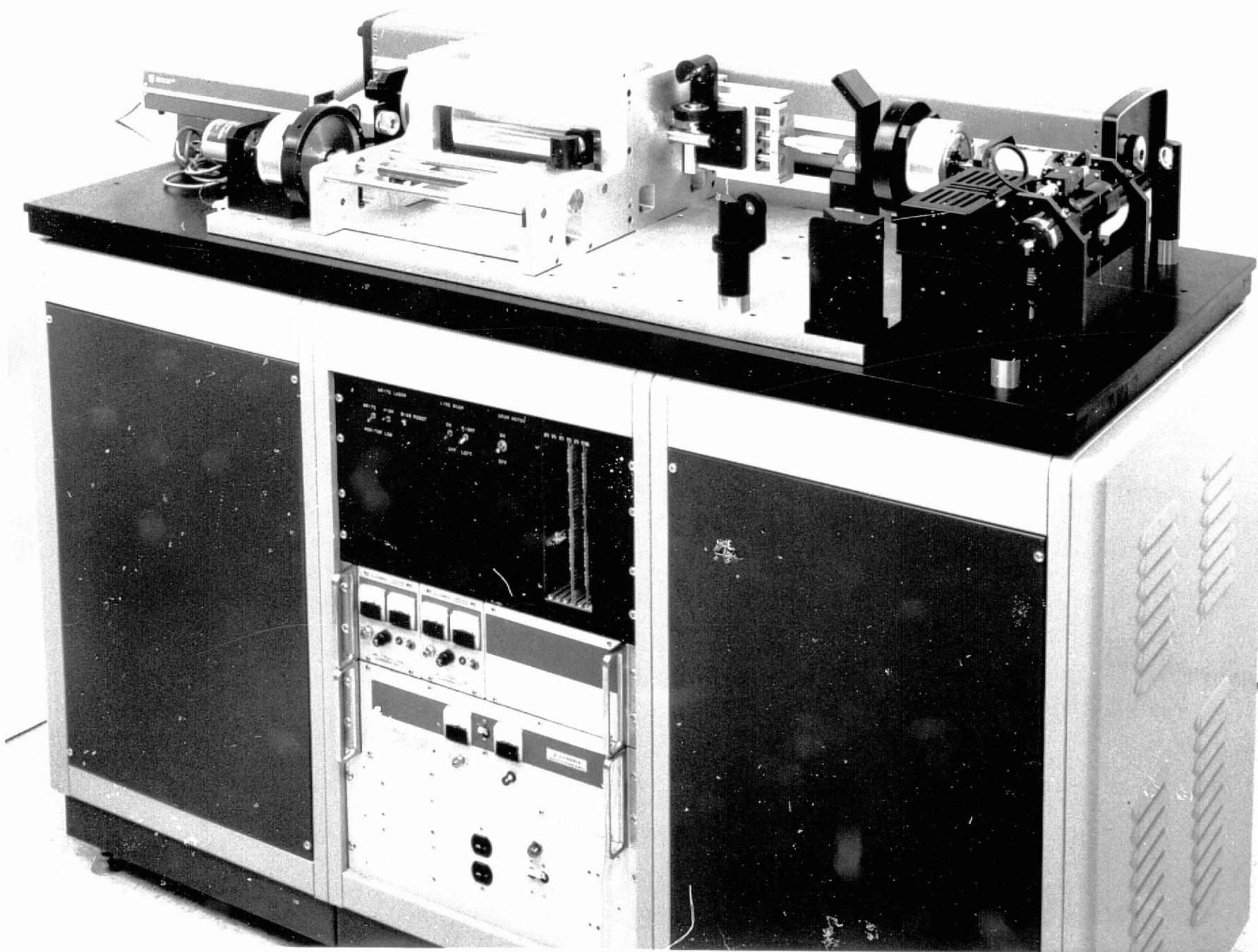
ABCDEFGHIJKLMN0PQRSTU
VWXYZabcdefghijklmnopqrstuvwxyz
1234567890 Spartan Medium 12 pt

FACS

This chart p
and printed
Co. — Copyri
Electronics E



ORIGINAL PAGE IS
OF POOR QUALITY



Recording and Retrieval." See Xerox attached.*

The most recent presentation on "Nonphotographic Image Recording and Retrieval" took place at the LASER 75 Conference, Munich, West Germany, June 24-27, 1975. It utilized laser slides, made from thin metal films, including one interferometric color laser slide, showing a laser diffraction pattern, originally produced in 1967 and published first in the 1967 Annual Report of Precision Instrument Company. See Xerox attached.*

IV

PROBLEMS TO BE SOLVED TO
DEMONSTRATE FEASIBILITY OF
DIGITAL LASER MASS STORAGE AND RETRIEVAL

4.1 Laser Disc

Experimental evidence should be established to demonstrate that flexible laser disc provides the appropriate means for digital laser mass storage and retrieval. Different from present high resolution magnetic disk systems, laser discs are so flexible that they may automatically stay in laser focus within one (1) micrometer. In other words digital laser disc storage and retrieval has to be experimentally substantiated. The necessity for flexibility stems from various requirements: Thickness of the substrate, so that laser focusing can take place through the mylar; smoothness to follow automatic focusing and to allow covalent bonding of the thin metal films; continuity of bonding of the laser storage medium; assurance to keep disc excentricity within half a millimeter, probably made possible by solid metallic disc centers, etc.

4.2 Laser Disc Production

After the main physical characteristics of laser disc are experimentally substantiated, the actual disc production process should be investigated. The main problem in this respect is to produce an error free metal thin film, hermetically sealed between two mylar disc layers, and to control accurately thickness and optical characteristics (R,T,A) of the thin film. Large size metallic coatings are widely produced for Aluminum coating of capacitor foils, but they possess only one layer of thin metal and no covalent bonding. Present dielectric vacuum coating equipment produces surface coatings, however generally of relatively small sizes. Formerly used RF-sputtering techniques are to be replaced by much simpler vacuum evaporation methods for indium and tin. The main goal of laser disc production is to overcome the previous state of the art of "strips". This is necessary not only in order to provide

error free metallic coatings, but also to guarantee space-time invariance of the discs.

4.3 Automatic Laser Focusing

The present state of the art of ~~laser focusing~~ ^{disc drives} utilizes pneumatic controls and electromagnetic controls. Airfoil techniques are presently used only in connection with magnetic disk drives. Hence, the appropriate means should be experimentally established for automatic laser focusing. Essentially, a large background of theoretical data should be converted into realities, thus providing continuous laser beam focusing at constant disk velocity within one (1) micrometer. In addition, means should be determined to adjust for different angular velocities of the disc, as required for computer input conversion. In other words, automatic laser focusing should be provided at 3,600 RPM or 450 RPM, for example, in connection with a 8:1 conversion ratio.

4.4 Accessing with Laser Disc

Continuous accessing with laser disc follows straightforward from present laser video disc techniques. In principle, the same holds for stop-scan single line accessing, as well as for slow-motion scanning. The main problem, however, needs further investigation, how to numerically control continuous and incremental laser beam accessing. Presently existing interferometric controls are too expensive, too slow and much too accurate. It is the belief of the author, that combined strictly mechanical and optical accessing means can be developed in conjunction with advanced electronic calculators, which represent an accurate and economical solution to laser disc accessing. In principle, correct velocity and laser focus positions should be automatically controlled and conserved.

4.5 Interchange between writing and reading Stations

This operational parameter of digital laser disc storage and retrieval comprises a fundamental problem. Theoretically, it is easily solved by stating that laser writing and reading are to be space-time invariant within the accuracy of less than one (1) micrometer square. In practice, however, very advanced servo engineering is required in order to obtain this accuracy. Essentially, angular velocity of laser disc drive, laser beam accessing and laser beam tracking should be combined to a uniform operation, so that space-time invariance will be experimentally achieved. In particular it is required that each digital pixel (computer word) is stored and retrieved accurately and at the correct position within the entirety of the two-dimensional bit distribution of the disc. As a result, digital laser disc should be retrieved at any other laser-reading station which is commensurate with the original laser-writing station.

4.6 Frequency Response

The frequency limits of digital laser mass storage and retrieval are determined by the Modulation Transfer Function (MTF) of the system. Correct operation assumed, the MTF is equal to one (1) over the entire range of the frequency bandwidth. In other words, for example, a 60 MHz bandwidth is correctly stored and retrieved with a digital laser mass storage and retrieval system from zero (0) frequency up to 60 MHz. As described above, the reasons for this extraordinary characteristic are the diffraction-limits of the system.

4.7 Archival Storage

Due to the permanency of laser disc storage and retrieval archival storage

is unlimited. The remaining problem is the handling of the discs, i.e. the protective packing of the discs, their insertion within the archive and their subsequent random retrieval. However, these problems become predominant only after the feasibility of the system is experimentally proven. The main goal of archival laser disc storage is the experimental substantiation of an ultimate storage capacity of 10^{14} bits., i.e. 100 Terabits per unit system. For this purpose, a feasibility ~~study~~^{system} should prove experimentally, that a certain number of laser discs can be produced, filled with digital information at high rates (60 Mbits/second), as well as stored and retrieved at random over a period of time. During this process, sophisticated error detection and correction means should be applied to verify the accuracy of operation.

V

BACKGROUND FOR SUBSEQUENT IMPLEMENTATION
OF DIGITAL LASER MASS STORAGE AND RETRIEVAL

5.1 Laser disc.

Application of vacuum evaporation of thin metal films ⁽⁵⁰¹⁾ and covalent bonding ⁽⁵⁰²⁾ yield dual density flexible laser discs in a modern vacuum sputtering process. ⁽⁵⁰³⁾ After inserting three transparent mylar discs of 14 inches (35.6 cm) in diameter in a specially constructed vacuum chamber, a sputtergun device creates indium metallic thin films on the appropriate surfaces, *for example*.

Deposition of thin metal films by means of vacuum evaporation consists of several distinguishable steps:

1. Transition of a condensed phase into a gaseous state.
2. Vapor traversing the space between the evaporation source and the substrates at reduced gas pressure.
3. Condensation of the metallic vapor upon arrival on the substrates.

The theory of vacuum evaporation includes the thermodynamics of phase transitions from which the equilibrium vapor pressure of the materials can be derived. It also comprises the kinetic theory of gases which provides the atomistics processes of evaporation. Thermodynamics, characterize the condensed and the gaseous states of materials by functions which depend on the macroscopic variables of pressure, temperature, volume and mass. Of particular significance is the thermodynamic equilibrium, where the amounts of evaporating and condensing materials are equal at all times, as long as the equilibrium is maintained.

According to the second law of thermodynamics, the conversion efficiency of thermal energy is limited because a fraction of it must serve to increase the entropy of the system and is not available for the production of mechanical energy. Basically, the thermodynamics of vacuum evaporation are determined by the Clausius-Clapeyron equation: (504)

$$\frac{dp}{dT} = \frac{L}{T \Delta V}$$

where (dp) is the change in equilibrium pressure, resulting from a small temperature change (dT); (L) is the latent heat of vaporization; (T) is the absolute temperature, and (ΔV) is the change of volume when a molecule is transferred from a solid or liquid phase to the gas.

The directionality of the vacuum evaporation process is determined by the cosine law of emission, which is equivalent to Lambert's law in geometrical optics. According to the cosine law, emission of material from a small evaporating area does not occur uniformly in all directions, but favors directions approximately normal to the vapor emitting surface where $\cos \Theta$ has its maximum values. The amount of material which condenses on an opposing surface also depends on the position of the receiving surface with regard to the emission source. In other words, the material contained in an evaporant beam of solid angle ($d\omega$) covers an area which increases with distance as well as with the angle of incidence (Θ). The element (dA) of the receiving surface which corresponds to ($d\omega$) is (501)

$$dA = r^2 d\omega / \cos \Theta$$

where (r) is the radius vector from the emitting surface element to the receiving surface.

Vacuum evaporation of indium, preferably utilizes Molybdenum boats.

Melting of indium occurs at 156° C. A modern sputtergun (S-gun source)⁽⁵⁰⁵⁾ "consists of a water cooled cathode (target material), a water cooled anode and an annular permanent magnet assembly in a configuration similar to that of an inverted magnetron. Electrons emitted by the cathode are trapped by the influence of the magnetic field and are forced to travel in long helical paths. As they travel along the magnetic field lines, the electrons make elastic or ionizing collisions with argon gas atoms. As in conventional sputtering devices, the positive ions bombard the cathode target material, sputtering away atoms from its surface. The S-gun source is available in a complete modular assembly, ready to install in a vacuum chamber equipped with standard 19 inch (48.3 cm) fixture for sequential multilayer depositions." (Quoted from reference 505.)

Metallic bonding of the laser disc is characterized as covalent bonding. It results from the sharing of electrons between two or more atoms to achieve a stable electron energy configuration. It is a strong bond. The spins of the two electrons in the bond are anti-parallel, thus creating quantum-mechanical exchange interaction. Applying thermal heat to the covalent bonding process, the contact area of the two thin metal films is extended over the entire metallized surface (thermo compression).⁽⁵⁰³⁾

Application of vacuum evaporation to dual density laser discs yields the following manufacturing procedures, *for example*.

Certain manipulations within the vacuum chamber first create two indium coated mylar discs which are then "joined" together under pressure, by means of RF heating of the bonded metal surface up to 158° C. In a secondary process, the backside of the first bonded mylar disc and the frontside of the third mylar disc are also indium coated and subsequently joined together by RF heating under pressure. Thus the twin indium layer triple mylar disc is completed. After completion, the disc is sealed by means of laser melting, completely encapsulating the indium laser storage medium. According to a recommendation by Vance Hoffman, manager, Varian Vacuum Division, Coating Applications Laboratory, Palo Alto, Calif. (506) pre-cleaning of the mylar discs is provided by washing the discs in a cleanroom. This method is presently used to pre-clean the surfaces of plastic lenses before coating.

The optical characteristics of the dual density laser discs are determined by the optics of thin films. They are essentially determined by the reflectivity (R), transmissivity (T) and absorptivity (A) of each composite indium thin film.

The optical thickness of each composite indium layer is of the order of 800 Å. Control and monitoring of the growth of the thin metal film may be provided by several means. A most appropriate method is the utilization of crystal quartz to determine the growth of the thin metal film in the vacuum. (501) The crystal-oscillator monitor utilizes the piezo-electric properties of α -quartz. A thin crystal wafer is metallurgically contacted on its two surfaces and made part of an piezo-oscillator circuit. The resonance frequencies (f_0) for thickness-shear-piezo-oscillations of an AT crystal cut are:

$$f_0 = \frac{N}{d_q}$$

where (d_q) is the wafer thickness and

$$N = 1.67 \times 10^6 \text{ Hz mm}$$

Measurement of the frequency variation (Δf_0) with increasing wafer thickness (Δd_q) yields the thickness of metallization within the vacuum chamber.

Final determination of the R, T, A values of the dual density laser disc is provided outside of the vacuum chamber, after completion of the evaporation process, utilizing a laser densitometer.

5.2 Laser disc drive.

Operation and construction of the laser disc drive for digital laser storage and retrieval of image data are based upon the principles of magnetic disc drives--IBM 3340/3350 ⁽³⁰⁴⁾ The basic differences of the laser disc drive are the replacement of the magnetic discs, the finess of laser beam tracking and direct accessing, as well as ^{possible} laser beam interferometric servo controls.

Following first the principles of IBM 3340/3350 magnetic disc drive, data removability is applied with laser disc drives. That is, a laser disc, once written, may be removed and subsequently read on any laser disc drive. Radial alignment of laser head (objective) and track is accomplished within a fraction of the track width, typically $\pm 20\%$. This radial alignment tolerance must include static tolerances, associated with laser-focus alignment differences between drives, as well as dynamic tolerances, such as spindle-bearing runout, disc-axial runout, carriage bearing runout, thermal effects, vibrations and tolerances of the tracking and accessing position servo system. In addition, pneumatic laser focus positioning has to be accurately controlled within the depth of laser focus. All radial alignment tolerances ~~are~~ ^{may be} interferometrically measured and controlled in integer multiples of a quarter of the reading laser wavelength of 6328 A, i. e. 0.1582 micrometer.

The laser disc is flexible, flying on conventional hydrodynamic air-bearings during recording and reading operations. Thus, disc contact by the writing and reading microscope objectives is eliminated at all times. Servo controlled air pressure of the air-bearings is provided by a sealed disc drive. Two writing and reading objectives are provided at fixed distances of their laser foci, utilizing dual density digital laser storage and retrieval. They are also applied to yield the two constant

air-foils of servo-controlled air-spacing. Characteristics of a digital laser disc drive unit are presented in the following Table.

Digital laser disc storage and retrieval of image data utilize ACB triple servo-controls, by means of permanently storing ~~tracks~~ ^{spiral} tracks possibly under laser interferometric control in integer multiples of $\lambda/4$ laser wavelengths of 0.6328 A. Pneumatic laser focusing provides for continuous laser focus during writing and reading. ACB triple servo-controls utilize a center track (C) for laser reading, while its neighboring recording tracks (A, B) are simultaneously projected toward a slit in front of the triple photodetector system.

^{linear translator}
A ~~moving-coil linear actuator~~ provides direct data accessing during laser writing and reading. Automatic laser tracking utilizes an electrodynamic mirror galvanometer per objective.

Data integrity with digital laser disc drive is warranted by the design and manufacturing principles of the laser discs, thus avoiding one of the most troublesome problems of magnetic disc drives. Because of the ^{manufacturing} ~~planetary~~ ^{process} of the discs during the thin film metallization ~~process~~ in the vacuum, the indium laser storage medium is free of erroneous "holes" in the medium. Due to the encapsulation of the thin indium metal films, any damage to the storage medium is eliminated. Dust deposition at the disc surface is "invisible" to the writing or reading laser beam, because they are "out of focus". The ^{theoretically} ~~only~~ possible errors of the system are those resulting from the quantum-mechanical uncertainty of the elementary bit-creation process. It is of the order of 10^{-11} for one (1) micrometer bit diameter.

TABLE VII

CHARACTERISTICS OF DIGITAL LASER DISC DRIVE UNIT

Laser disc capacity	10^{10} bits/disc
Objective per disc surface	1
Objectives per disc	2
Bit diameter	1 micrometer
6-bit unit memory cell area	15.18 micrometer square
Radial track separation	2.53 micrometer
Stroke length for direct accessing	2.54 cm
Linear bit density	10,000 bits/cm
Number of data tracks per disc	10,000 tracks/disc
Average direct access time	25 m second
Data rate (single density storage)	60 M bits/second
Data rate (dual density storage)	120 M bits/second
Angular disc velocity, laser writing	3,600 rpm

5.3 Automatic positioning of laser focus.

This is required to maintain laser focusing at the surface of the thin metal films. Laser focusing should comply with the focal depth of the focusing objective which is proportional to the square of the f-number of the "writing" and "reading" objective, while stored bit diameter is directly proportional to the f-number of the focusing objective. For example, the ZEISS EPIPLAN 40x, at full aperture filling, has a focal depth (Δz) of

$$\Delta z = 2\lambda \left(\frac{f}{D}\right)^2$$
$$\Delta z = 1.4 \text{ micrometer}$$

in order to utilize the full numerical aperture of the objective. The corresponding diffraction-limited bit size (d) is

$$d = 0.56 \text{ micrometer}$$

Taking a bit diameter of one (1) micrometer, one should reduce the filling of the writing and reading objective to an f-number of the order of 0.7, yielding a focal depth (Δz) of approximately

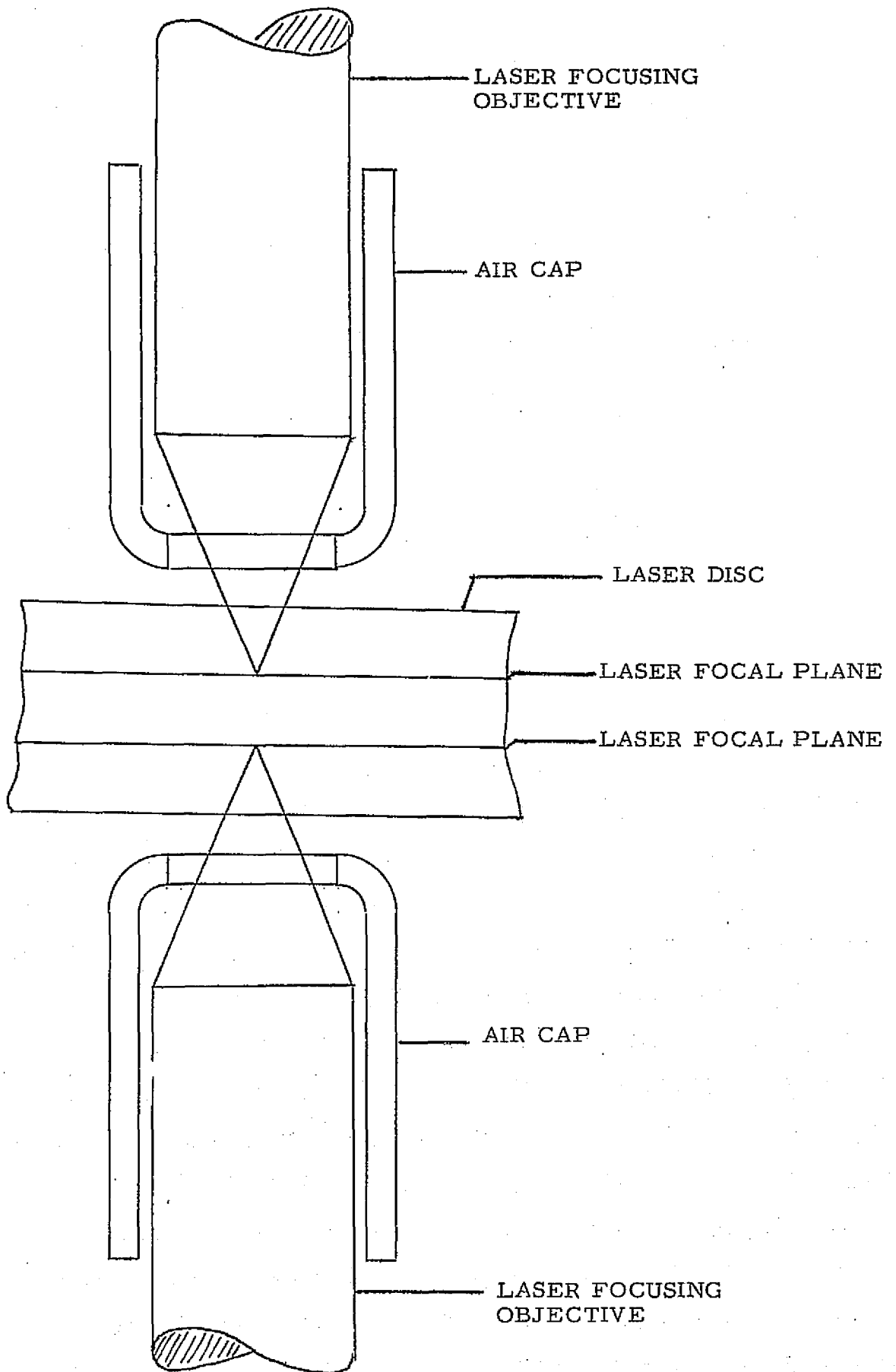
$$\Delta z \approx 5 \text{ micrometer}$$

Automatic positioning of laser focus is conceivable if based upon two principles:

- pneumatic laser focusing
- electro static laser focusing

Presently, electro static laser focusing is applied only in one system: Philips. ⁽⁵⁰⁸⁾Hence, pneumatic positioning appears to be the appropriate means for laser focusing. See Fig. 7-8.

Pneumatic positioning is determined by fluid mechanics. ⁽⁵⁰⁹⁾More specifically, it comprises the liquid flow at low Reynold's numbers. The equation of motion of the fluid is determined by the Navier-Stokes equations for incompressible viscous flow:



PNEUMATIC LASER FOCUSING

Figure 7-8

momentum equation:
$$\frac{D\vec{q}}{Dt} + \frac{1}{\rho} \text{grad } p = \nu \nabla^2 \vec{q}$$

continuity equation:
$$\text{div } \vec{q} = 0$$

where D/Dt expresses the time variation relative to a given fluid particle; (p) is the state pressure; $(\vec{q})$ is the velocity vector; (μ) is the viscosity; $\nu = \frac{\mu}{\rho}$ is the kinematic viscosity. The Reynold's number (Re) is defined as

$$Re = \frac{\ell U}{\nu}$$

where (ℓ) is a characteristic length of the object, (U) is a velocity, and $(\nu) = \frac{\mu}{\rho}$ is the kinematic viscosity with $(\mu) = \text{viscosity}$ and $(\rho) = \text{density}$.

The first pneumatic positioning of magnetic heads was applied in 1956 in conjunction with the IBM RAMAG disc storage system. ⁽⁵¹⁰⁾ The spacing of the heads from the discs was maintained by an air bearing obtained from minute air jets in an annular manifold surrounding the magnetic elements. Since the 0.001 inch head spacing was held despite the axial runout in the disc, there was never physical contact between the heads and the magnetic coating. The use of compressed air in the magnetic heads, and the access positioning detents required a small compressor, operating constantly and supplying air to a surge tank, or, if necessary, by-passing it to the atmosphere. Approximately 0.6 cubic feet per minute, at a pressure of 50 pounds per square inch, were used per access.

Subsequent to RAMAG, a flexible disc magnetic recorder was described by R. T. Pearson. ⁽⁵¹¹⁾ His paper analyzed the maintenance of a small and constant separation between a recording head and its associated

medium, utilizing a read-write head supported hydrodynamically at a constant separation of 200 micro-inches from a drum or disc surface. A recording head was shaped to produce an air-bearing effect, and positioned at a point close to the periphery of the disc. The disc was drawn into close proximity (1mil) of the recording head gap, and assumed a stable standing-wave shape. In a second experiment, the standing wave shape of the disc was controlled by introducing a single air-bearing surface on the side of the disc opposite a recording head. A further experiment proved to be of key importance to the final device concept: A mylar disc was rotated in proximity to a smooth backplate and was observed to conform stably to the surface. The disc was rotated and initially observed to vibrate as before, but as the backplate was moved axially toward the plane of rotation, the disc was attracted toward the plate where it operated at a stable equilibrium separation.

The principle of a flexible-disc recorder became evident, indicating that the operating model was still, in reality, a fixed separation device. It appeared, however, that if the read-write heads could be incorporated into the backplate, and the disc made to operate in the same stable manner--except at a separation from the backplate in the order of 1 mil--an extremely promising storage device would result.

A new model was constructed with an adjustable valve, allowing control of the rate at which air could enter beneath the disc, and resulting in the capability of controlling the disc-to-backplate separation. Analysis of the disc operation yielded the following: In the non-operating condition, the flexible disc is limp and rests against the backplate. When the drive shaft is rotated, the disc tends to straighten out under the action of centrifugal force and lift away from the backplate. At the same time, a

circumferential velocity is impaired, by viscous friction to the fluid in the space between the disc and backplate. This circumferential velocity gives rise to a centrifugal force on the fluid and a resulting outward radial velocity. These fluid velocities vary with radius and generate a pressure field in the separation gap that varies radially. The pressure forces differ from the pressure forces acting on the open, or atmospheric side of the disc. The flexible disc deflects to equalize these pressure fields, and in so doing, counter centrifugal and curvature forces are caused to act on the disc material. The equilibrium operating condition exists as a balance of the pressure forces generated by the fluid flow, together with the normal components of the centrifugal and curvature forces in the disc.

The flow analysis was derived from the Navier-Stokes equations and the continuity equation with the following simplifying assumptions: steady flow, incompressible fluid, axial symmetry, laminar flow, very low Reynold's number referred to gap width and angular velocity, and separation (s) small compared with radius (r).

Application of fluid mechanics to foil bearings, in conjunction with magnetic tapes, requires the application of the theory of lubrication.

This theory is based on Reynold's equation: ⁽⁵⁰⁹⁾

$$\frac{1}{6\mu} \left[\frac{\partial}{\partial x} \left(h^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left(h^3 \frac{\partial p}{\partial y} \right) \right] = - \left(U \frac{\partial h}{\partial x} + V \frac{\partial h}{\partial y} \right) + h \left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} \right) + 2W$$

where (h) is the distance between the walls of the foil, (μ) is the viscosity of the liquid, (U) and (V) are the velocities of the upper plate, $\frac{\partial p}{\partial x}$ is the pressure gradient constant, and (W) is a normal

velocity component in the Z-direction. Formulation of Reynold's equation by various authors are presented in the following Table VIII.

Publications in conjunction with self-acting foil bearings and magnetic tape are summarized as follows: The first paper on the subject was presented by E.J. Barlow, ⁽⁵¹²⁻⁵¹³⁾ followed by A. Echel & M. Wildman, ⁽⁵¹⁴⁾ L. Licht, ⁽⁵¹⁵⁾ A. Eshel, ⁽⁵¹⁶⁾ T.B. Barnum & H.G. Elrod, ⁽⁵¹⁷⁾ and W.E. Langlois, ⁽⁵¹⁸⁾ I. Pelech & A. Shapiro, ⁽⁵¹⁹⁾ C.J. Brown & J. T. Ma. ⁽⁵²⁰⁾

Recently, a number of papers have been published by IBM on magnetic disc systems. See IBM Journal of Research & Development, Nov. 1974. ⁽⁵²¹⁻⁵²⁸⁾

A somewhat different approach to pneumatic focus servo was published by D. Cronin, et al. ⁽⁵²⁹⁾

Based on the present state of the art of pneumatic head positioning with discs and tapes, the following analysis outlines laser focus positioning in conjunction with non-photographic and non-magnetic digital laser storage and retrieval. Of course, this analysis should be considered only as a guide to construction of a future experimental ~~prototype~~ ^{feasibility} system.

In principle, the air foil between each of the two objectives and the disc is assumed to extend within the range of 2 to 25 micrometer, assuming the dual mylar disc is composed of 3 transparent mylar discs of 25.4 micrometer (1 mil) each. The working distance of a ZEISS EPIPLAN LD 40x focusing objective in respect to its protective cap is 2.3 millimeter at a focal length of 4.1 millimeter. In order to match

TABLE VIII

Fluegge (62):

$$\frac{1}{6\mu} \left[\frac{\partial}{\partial x} \left(h^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left(h^3 \frac{\partial p}{\partial y} \right) \right] =$$

$$- \left(U \frac{\partial h}{\partial x} + V \frac{\partial h}{\partial y} \right) + h \left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} \right) + 2W$$

Barlow (67):

$$\frac{\partial}{\partial x} \left(h^3 p \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial s} \left(h^3 p \frac{\partial p}{\partial s} \right) = 6\mu U \frac{\partial}{\partial s} (ph)$$

Barnum (69):

$$12\mu \frac{\partial}{\partial t} (ph) \pm 6\mu U \frac{\partial}{\partial x} (ph) = \frac{\partial}{\partial x} ph^3 \frac{\partial p}{\partial x}$$

Eshel (69):

$$\frac{\partial}{\partial s} \left(h^3 \frac{\partial p}{\partial s} \right) = 6\mu U \frac{\partial h}{\partial s} + 12\mu \frac{\partial h}{\partial t}$$

Eshel & Wildman (68)

$$\frac{\partial}{\partial s} \left(h^3 p \frac{\partial p}{\partial s} \right) = 6\mu \frac{\partial (Uph)}{\partial s} + 12\mu \frac{\partial (ph)}{\partial t}$$

optical and air-foil parameters, it is assumed that a pneumatic cap is attached to the objective in such a way, that air gap and focal distance can be independently adjusted. The whole arrangement occurs in duplicate in conjunction with the focusing objective at the other side of the disc. With the separate arrangement of optical laser focusing and pneumatic focus positioning, each parameter can be optimized independently.

5.4 Laser beam signal modulation.

This is based upon Spectra Physics model 165 Argon II ionic laser. (530)
The following analysis concentrates on a constant bandwidth of 60 M bits/second, corresponding to single density digital laser storage and retrieval at 60 M bits/second, in conjunction with frequency divided dual density laser storage and retrieval of 120 M bits/second.

Signal modulation of the writing laser beam is provided by mode-locking, (531-33)
instead of acousto-optical output coupling. In principle, mode-locking is an intracavity amplitude modulation at the Fabry-Perot resonant frequency of $c/2L$, where (c) is the velocity of light and (L) is the cavity length.

"Each side band interacts with an adjacent mode. Two independent oscillators in a non-linear medium will tend to synchronize each other. As each mode has a fixed phase relationship with its side-bands, there will be a general locking of all modes in a definite phase and amplitude relationship. In the time domain, the Fourier transform of this frequency spectrum is a series of short pulses propagating at a repetition rate of $2L/c$. To minimize losses in the cavity, the mode-locker and the intracavity wavelength selection prism are combined in the same unit. An ultrasonic transducer bonded to the prism is RF excited at $c/4L$ and produces a standing wave inside the quartz prism. The index of refraction is thus modulated at $c/2L$ and produces the desired loss amplitude modulation.

The cavity dumper is an acousto-optic deflector operating in the Bragg regime. When a light beam is incident on a crystal at the Bragg angle (Θ_B), defined by

$$\sin \Theta_B = \frac{\lambda_s}{2\lambda_p}$$

Then the diffracted light is all in the first order which is also the Bragg angle. The deflected beam is Doppler shifted by the traveling sound wave and its frequency is given by:

$$\omega_D = \omega_L + \omega_S$$

If the light beam is in the reverse direction, the frequency is downshifted by the same amount." (Freely quoted from reference 533.)

Performance data of a mode locker for Spectra Physics Argon II ionic laser 164/165 are presented in reference 530. Adjustment of the laser frequency to the required 60 MHz is accomplished by adjusting the cavity length (L) to the mode lock frequency:

$$\frac{c}{2L} = 60 \text{ MHz}$$

The corresponding $c/2L$ Bragg modulation frequency of 60 MHz is provided by the modulation electronics (Harris).

Should laser writing not be possible at a constant fixed rate, the internal laser modulation principle may be replaced by external laser beam modulation. For this purpose, a special Pockel's cell should be designed, incorporating a special digital driver amplifier. The Pockel's cell should be made out of four (4) KD*P crystals in series. The driver amplifier should be of low impedance, matched to the increased impedance of the Pockel's cell which is proportional to the modulation frequency.

Note that it is much more advantageous to utilize a fixed frequency of 60 M bits/second and internal laser beam modulation, as described above.

5.5 Laser beam tracking.

Laser beam tracking with non-photographic and non-magnetic digital laser storage and retrieval takes place with servo-controlled mirror galvanometers mounted atop of the entrance aperture of the writing and reading microscope objectives. The track following function of the system maintains the position of laser focus exactly over the center of a given track with minimum displacement error in the presence of any possible disturbances. Simultaneously, the tracking servo furnishes a clock signal, synchronized with the disc rotation and the writing channel so that all tracks will contain the same number of bits in case of spindle velocity variations. The tracking servo also provides index marks and rotational position information for the data channel.

Since the scanning laser beam has to follow the recording tracks with an accuracy of the order of 20% of the track width, mechanical guidance systems are inadequate for laser beam tracking. Instead, the tracking information can be retrieved only by optical means. The most practical tracking control is provided by an electro-dynamic mirror galvanometer, the circular diameter of which is commensurate with the effective circular aperture diameter of the writing and reading microscope objective.

Tracking with laser disc drive occurs in two operations: During primary laser writing and instantaneous laser reading, original tracks

are incrementally laid down ^{possibly} by laser interferometric controls. Track spacing is 2.53 micrometer, equal to $16 \times \lambda / 4$ of the laser interferometer wavelength (λ), i. e. $\lambda / 4 = 0.1582$ micrometer. During secondary laser reading, tracks are followed by galvanometer control. Basic positioning of laser focus is accomplished by ~~the~~ ^{possible} interferometric controls and occurs in steps of $16 \times \lambda / 4$ of the laser interferometer wavelength. ~~However,~~ ^{In} order to stay on the ~~channel~~ ^{spiral} tracks, reading laser focus follows the primarily recorded tracks, by means of ACB triple servo-controls. For this purpose, a vertical laser illuminator is inserted in the optics system, the field of view of which illuminates the tracks so that the reflected laser light is imaged through the reading objectives to a projection screen. Behind a slit in the screen, triple photo-diodes (ACB) are located, where (C) reads the information of the central track (C), while (A, B) read the (A, B) control tracks. Output of photo-diodes (A, B) activate the servo-amplifiers by means of $K(A-B)$ and $K(A+B)$ error signals, where (K) comprises a gain parameter. A closed loop in servo-controls is established by means of galvanometer reading of laser focus. The positioning error is mainly a result of disc drive eccentricity during secondary reading.

The servo control mechanism for laser tracking adheres to the following principles: Designating the output of the auxiliary photo detectors by (A) and (B), respectively, one obtains a compensation feedback control system. More specifically, one obtains a position signal, defined as $K(B-A)$, where (K) is the gain parameter adjusted to make

$$K(A + B) = \text{constant}$$

Hence,

A = portion of servo signal due to track (A)

B = portion of servo signal due to track (B)

K = gain parameter

A related block diagram of the track following servo is presented in Fig. 5-1, using Laplace transform operational notation. Servo operation is characterized as pulse-position encoding in which a synchronization character is coincidentally recorded on both (A) and (B) tracks, comprising simple logic gating of the (A) and (B) gate signals. $K_c(S)$ comprises the compensator in the network that equalizes the performance deficiency. The transfer function of the compensator is designated as:

$$G(S) = E_{out}(S)/E_{in}(S)$$

The performance of the control system may be determined in terms of the time-domain performance measures. The performance specifications are defined in terms of the desirable location of the poles and zeros of the closed-loop system transfer function $T(S)$. Thus the location of the s-plane poles and zeros of $T(S)$ may be specified.

Typically, one is interested in controlling the system with a control signal $u(t)$, which is a function of several measurable state variables. (535-36)

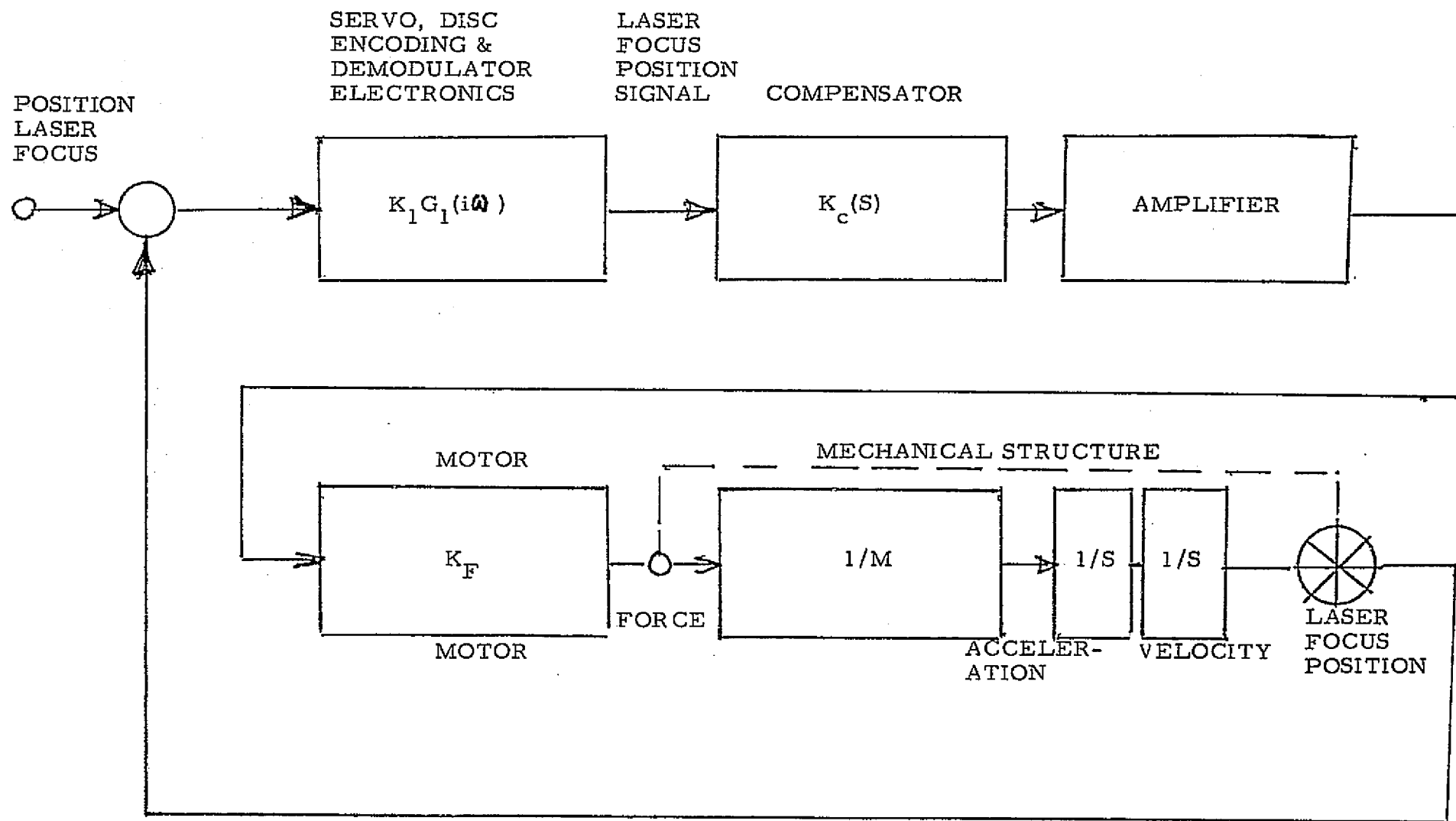
The open loop transfer function (G) is given by:

$$G = \frac{K_c(S) K_1 K_A K_t}{S^2 M}$$

where

$K_c(S)$ = compensation

K_1 = servo demodulator electronics



LASER FOCUS POSITIONING SERVO MECHANISM

(References 536 & 14)

Figure 5-1

K_A = power amplifier

K_F = mirror galvanometer

S = Laplace variable

$$= \frac{d}{dt}$$

M = effective galvanometer mass

Without the compensator $K_c(S)$, (G) describes a classical second order type positioning servo.

In order to secure removability of the laser discs for data read-out purposes, the laser tracking characteristics secure complete invariance of data during read-out. This is accomplished by the tracking servo which stays on the track even at eccentricities of the reproducing disc up to one (1) millimeter. The safety margin for eccentricity control is 0.5 millimeter with a ZEISS EPIPLAN 40x microscope objective.

5.6 Mirror galvanometer for laser beam tracking.

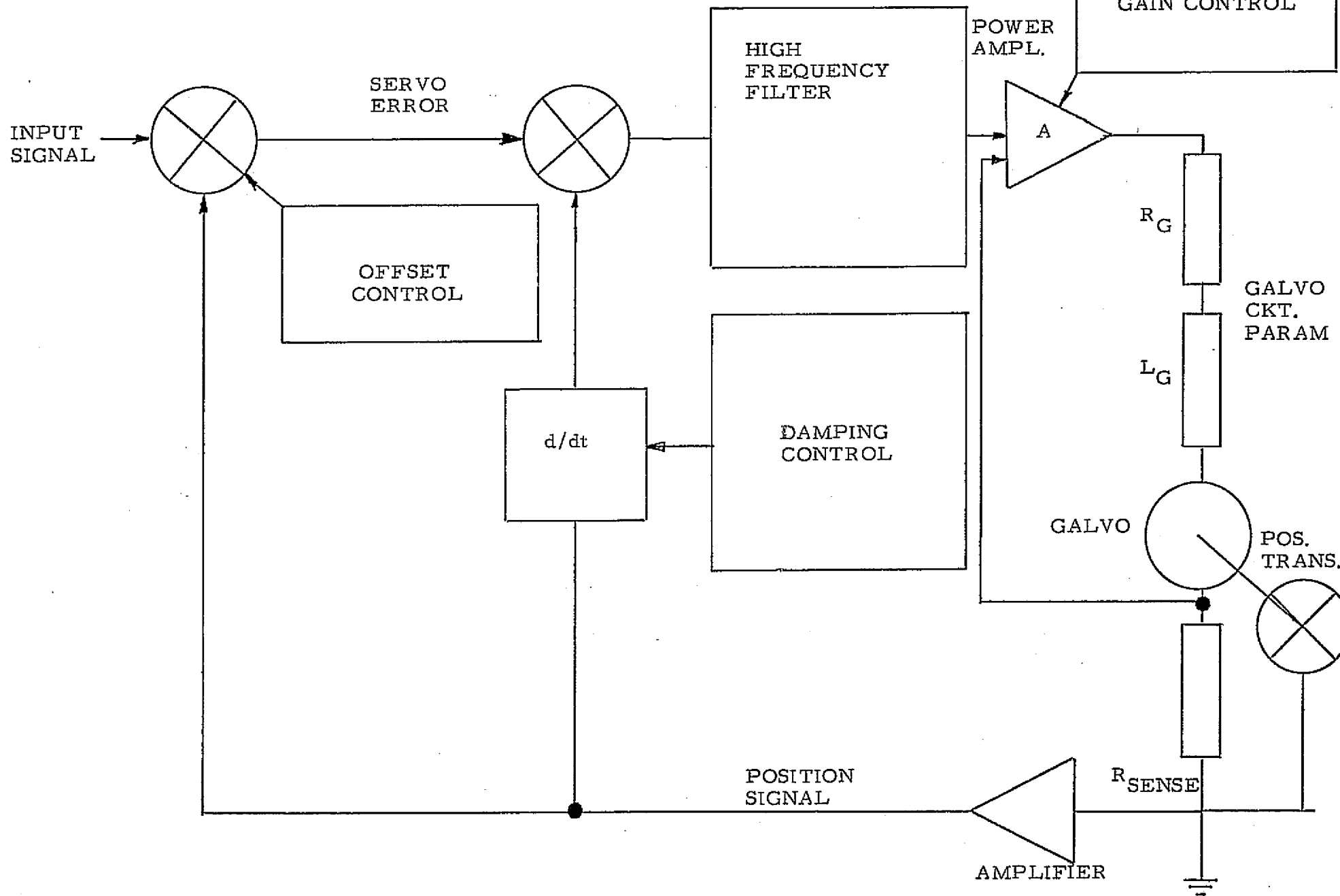
An electrodynamic mirror galvanometer for laser beam tracking should be specially developed. Presently, an optical mirror scanner is available--produced by General Scanning, Inc. (537-538) However, it is a moving-iron galvanometer, instead of an electrodynamic system. The mirror size should be of the order of 3.2 millimeter in diameter. The resonance frequency should be of the order of 1,000 Hertz. Electromagnetic non-linearities should be completely eliminated.

The associated electronics of the system utilize position control loops, as described in reference 537. A block diagram of the system is shown in Fig. 5-2, based on this reference. The outer loop governs the error signal between the reference input command and the actual mirror position. The inner loop is provided for aperiodic damping of the transient response and to secure a smooth rolloff of the frequency response. The galvanometer position detector and the drive coils are connected as shown in the block diagram.

Particular emphasis in the design of the mirror galvanometer for laser beam tracking should concentrate on the linearity of laser beam deflection. Such a requirement can be fulfilled exclusively with electrodynamic systems. This point of view was intensively applied in motion picture sound recording. The requirement of linearity of deflection is even more mandatory with digital laser storage and retrieval.

GALVO TRACKING CONTROL ELECTRONICS

(Reference 537)
Figure 5-2



5.7 Laser beam accessing.

As already indicated earlier, laser beam tracking provides only a very narrow servo control over three tracks. Hence, it is incapable of controlling track variations over distances of many tracks, as is required for laser beam accessing. On this basis, it is necessary to provide a separate servo system for laser beam accessing, with particular emphasis on direct access to any of the tracks of a laser disc.

While the laser tracking mechanism utilizes a galvanometer controlled electro-optical and electro-dynamical tracking system, laser beam direct accessing requires a ~~moving coil electro-mechanical actuator~~ ^{linear translator, possibly} in conjunction with a laser interferometer.

The objective of the servo for laser beam direct accessing is to achieve minimum moving time between any three tracks, on the disc, in addition to achieving optimum tracking accuracy in following any specific track triplet. The control circuits of the direct accessing servo are therefore much different from those of the track-following servo. In other words, the tracking servo is a positioning servo, while the direct accessing servo encompasses a velocity servo and a positioning servo.

The moving coil actuator consists of a ~~moving coil linear actuator~~ ^{linear translator}, possibly a simulated load (objectives) to an optical laser interferometer transducer, a laser and a lens assembly. The linear actuator, the simulated load and the laser interferometer are connected by a common hardened shaft (non-magnetic stainless steel) mounted in linear bearings. The load glides horizontally on hardened guide rails, with three roller bearings to minimize friction. The range of travel is one (1) inch and the load

is moved in steps of one laser track separation. Since the center of mass of the assembly is near the centerline of the shaft, the driving force acts on the center of mass of the total system. This prevents an induced moment, which would tend to cause oscillations in the system.

The servo mechanism moves the load (objectives) and the transducer until each photo diodes are aligned to a quarter of a wavelength of ~~the~~ a laser interferometer. Since the two photo diodes then see the same level of "grey", the push-pull system is nulled, and the system reaches the desired state.

possible
The laser interferometer provides a velocity feedback signal for the actuator control system. The control electronics generate the control signals to the actuator and provide negative feedback proportional to position and velocity errors.

A mathematical analysis of the actuator just described is presented in reference 520, C.J. Brown & J. T. Ma, IBM Journal of Research & Development, Sept, 1968, pages 372-379.

possibly a

The optical position transducer is ~~the~~^a laser interferometer, counting quarter-wavelength intensity variations of a Helium-Neon gaseous laser, operating at 0.6328 micrometer. The servo mechanism moves the writing and reading microscope objectives until each phototransistor is aligned to an integer multiple which equals the individual track spacing. For example, eight half-wavelengths of $\lambda = 6328 \text{ \AA}$ correspond to one track spacing of 2.53 micrometer. Since the two phototransistors see the same level of grey, perfect balancing of the photo-electric push-pull system provides the null of each track accessing.

may

Laser interferometric control of laser beam direct accessing also provide^a a velocity feedback signal to the actuator control system. The control electronics generate the control signals to the actuator and provide negative feedback proportional to position and velocity errors. Since the complete assembly (including ~~the~~^a laser interferometer) is rigid and the force applied passes through its center of mass, the assembly can be treated as a mass particel with one degree of freedom. The applied force is assumed to be linearly proportional to the electric current in the moving coil.

After some mathematical calculations (see reference 520), utilizing the impulse response method and assuming space-time invariance, one obtains an impulse response $g(f)$ output $X(t)$:

$$X(t) = \int_0^t g(t - \xi) e^{j\omega \xi} d\xi \quad (1)$$

When we apply a step voltage to the ~~osc~~ and measure the control signal output, this signal corresponds to the impulse response of the system.

We can compute the switching times for optimal control on the basis of the function of $g(f)$. We differentiate both sides of (1) successively with respect to time, substitute

$$e(t) = E \left\{ 1 - 2 [U(t-t_1) - U(t-t_2)] \right\} \quad (2)$$

and obtain

$$g(t) \cong \frac{1}{a} v(t) + \frac{b}{a^2} \int_0^t v(\tau) d\tau \quad (3)$$

Completion of this analysis requires introduction of the dynamic characteristics of ~~the~~ ^a laser beam interferometer which is subject to the following paragraph 5.8

Combining laser beam tracking and direct accessing with a phase-locked disc drive and a laser, yields direct access with digital laser disc storage and retrieval. The main characteristic of this system is, that it utilizes removable flexible discs with encapsulated thin metal films, acting as the non-photographic and non-magnetic digital laser storage medium. The time-sequential laser storage format is 9 bits per word (8 image data bits + 1 parity bit.) The basic storage element is a unit storage cell with one (1) micrometer diffraction-limited "hole" (bit) diameter.

The expected performance characteristics of the laser disc system are presented in the following Table, in comparison to equivalent performance data of the IBM 370/3350 digital storage system. In accordance with the requirements of the National Aeronautics & Space Administration, (09) the specifications for digital laser storage of image data extend far beyond the operational characteristics of the IBM 370/3350.

TABLE IX

Parameter	Digital laser disc system	IBM 370/3350
Storage capacity	10^{10} bits/disc	1,600 to 2,536 million bits per disc drive
Data rate single density	60 M bits/second	9.58 M bits/second
Data rate dual density	120 M bits/second	9.58 M bits/second

EXPECTED PERFORMANCE CHARACTERISTICS
OF LASER DISC SYSTEM

However, if one reduces the retrieval rate of the laser disc system to the rate of magnetic data processing with the IBM 370/3350, both systems become compatible. The essential reason for obtaining this result, is the main retrieval characteristic of the laser disc system, to be operative at much lower rates than those of the original real-time laser storage and retrieval process. In other words, the digital content of laser disc storage is unaffected by reducing the scanning rate in a secondary laser retrieval process. Comparing the data presented in the Table, one recognizes that the laser retrieval rate should be reduced by a factor of the order of six (6) or twelve (12), depending on the laser storage rate of 60 M bits/second or 120 M bits/second, respectively, *considering IBM 370/3350 as the following CPU.*

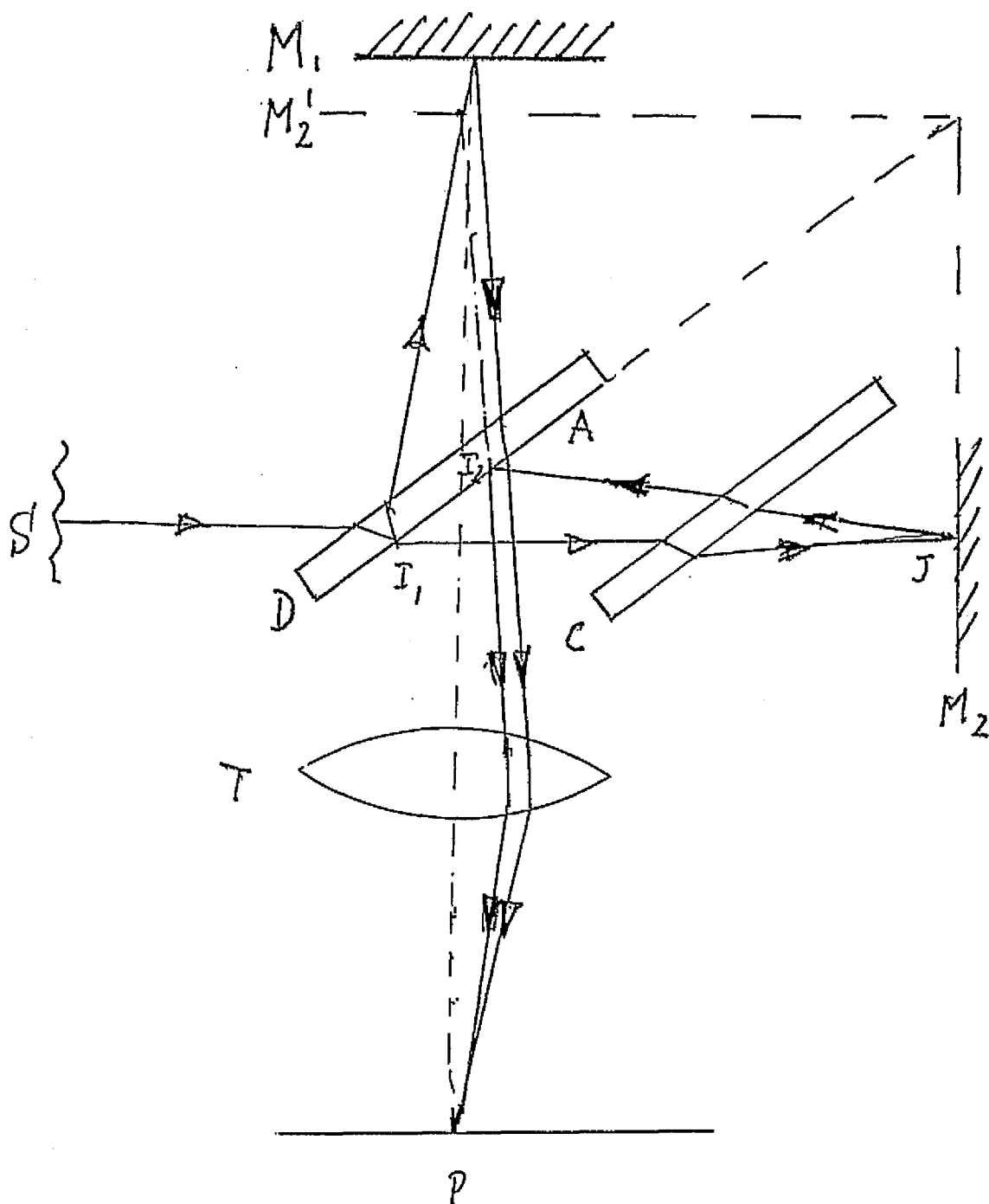
possible

5.8 Laser beam interferometer for laser beam accessing controls.

Laser beam interferometry is based upon the principles of the Michelson interferometer⁽⁵³⁹⁾ (see Fig. 5-3): "Light from an extended source (S) is divided at the semi-reflecting surface (A) of a plane parallel glass plate (D) into two beams at right angles. These are reflected at plane mirrors (M_1 , M_2) and return to (D), where they are recombined to enter the observing telescope (T). (M_2) is fixed, while (M_1) is mounted on a carriage and can be moved towards or away from (D) by means of a micrometer screw". (Quoted from reference 539.)

Introduction of a laser as the coherent monochromatic light source to a Michelson interferometer, and adding modern digital electronics, yields a laser beam interferometer. It provides laser beam positioning and accessing controls of ultimate accuracy.⁽⁵⁴⁰⁻⁵⁴⁶⁾ The principles of a laser beam interferometer are shown in Fig. 7-6, 7-7, ^{from} reference 546, ^A in conjunction with photodetector and electronic counter. Michelson's original mirror arrangement is replaced by a cube-corner polarization reflector, reflecting the laser beam parallel to its angle of incidence, regardless of the retro-reflector alignment accuracy. The photodetector converts the light intensity variations into voltage pulses which are processed by electronic counters to give the amount of positional variations.

Laser beam interferometers measure linear positional variations in integer multiples of quarter wavelengths of the laser beam. Utilizing a Helium-Neon laser with a red wavelength (λ) of 0.6328 micrometer, for example, the interferometric measuring unit of a quarter wavelength is 0.1582 micrometer. Thus, interferometric track positioning with digital laser storage and retrieval of 2.53 micrometer incorporates exactly 8 x half-wavelengths, or 16xquarter wavelengths of 6328 Å.



MICHELSON INTERFEROMETER

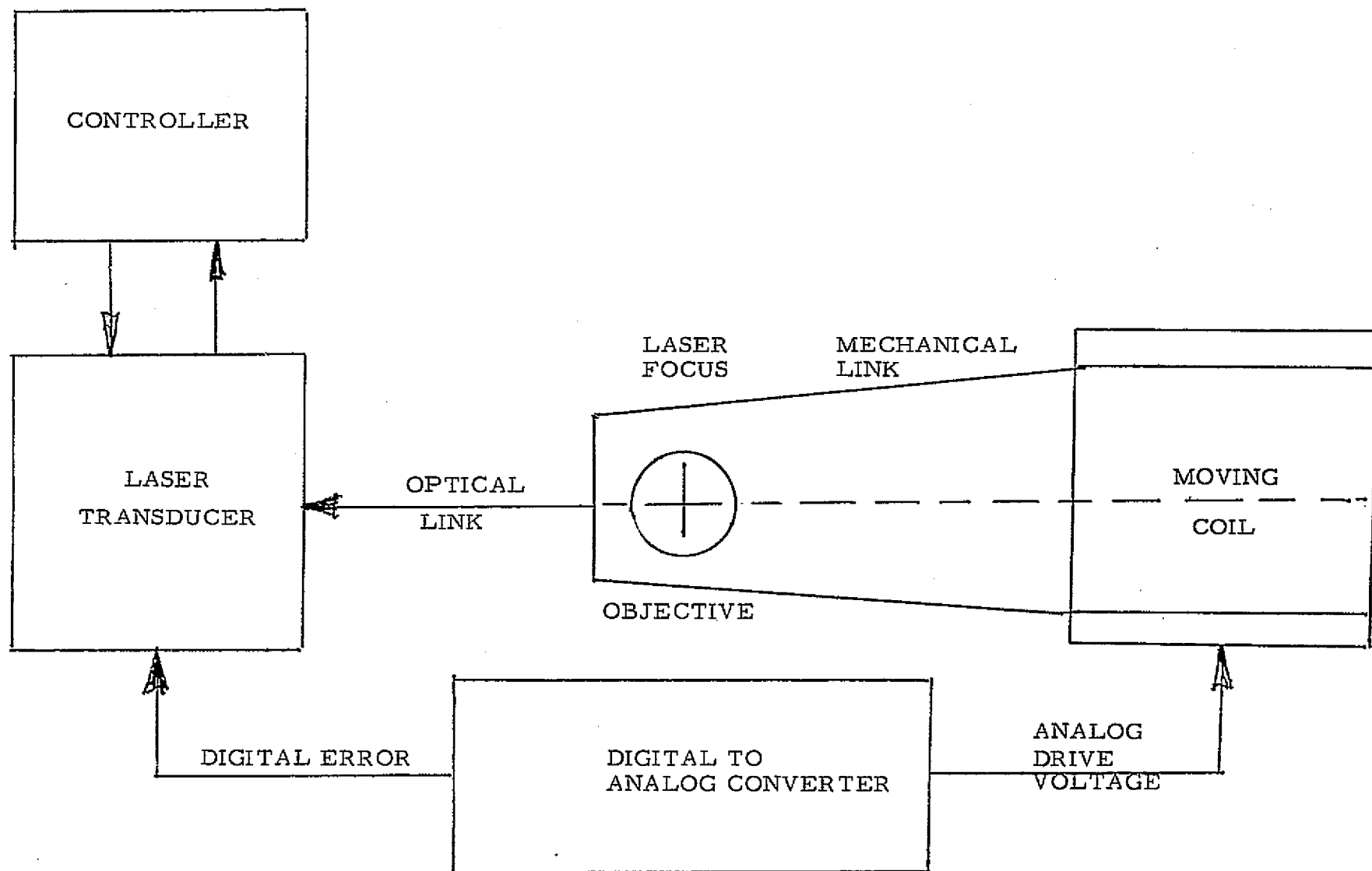
(Schematics)
 (Reference 106)
 Figure 5-3

5.9 Laser beam interferometer (H + P).

The following analysis is based upon Hewlett-Packard #5501 A ⁽⁵⁴⁶⁾
Laser Transducer System", replacing "object" by "laser focus".

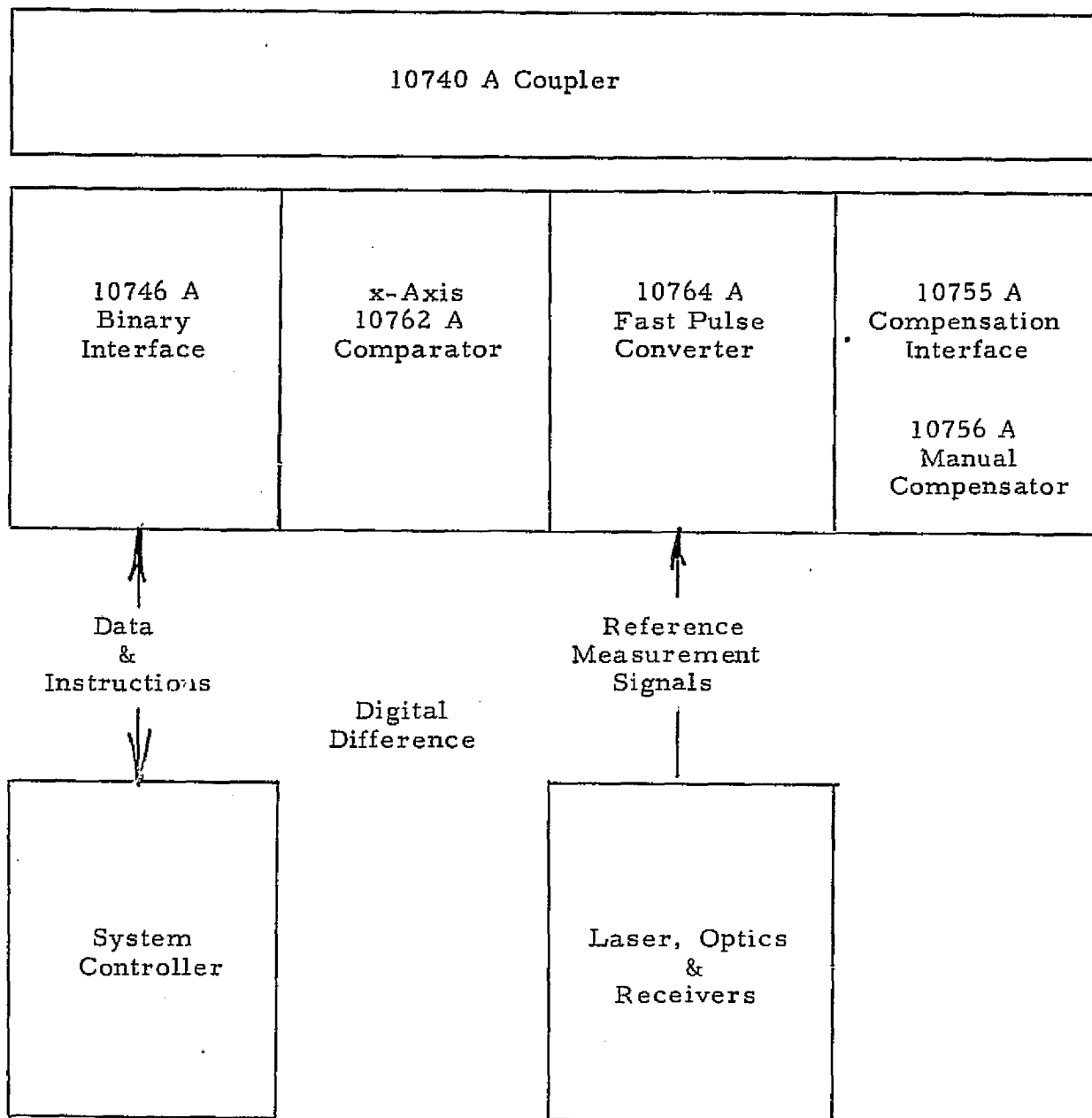
Control of laser beam tracking and direct accessing ^{maybe} ~~is~~ accomplished by means of a laser beam interferometer which comprises a Hewlett-Packard 5501 A Laser Transducer. It encompasses real-time position feedback control in a closed loop system. In conjunction with a binary interface, the system controller sends a digital representation of the determined position of laser-focus to the laser transducer interface electronics. The laser transducer system then measures the position of laser focus and controls the moving coil actuator. Control action is completed, when the system controller is notified that laser-focus arrives at the destination. See, Fig. 7-6.

Schematics of the laser transducer system are presented in Fig. 7-7. They encompass one H & P 10746 A Binary Interface, one H & P 10762 A Comparator, one H & P 10764 A Fast Pulse Converter, and an H & P 10740 A Coupler. The heart of the comparator is a 28-bit up/down counter which accumulates the displacement pulses from the H & P 10764 A Fast Pulse Converter and a 28-bit parallel subtractor with a null decoder for the upper 24 bits. This subtractor unit receives and stores a 28-bit digital representation of the destination of laser-focus under control from the system controller via the H & P 10746 A Binary Interface. Also received and



LASER INTERFEROMETER CONTROLS

(Reference 546)
Figure 7-6



LASER TRANSDUCER SYSTEM

(schematics)
(Reference 546)
Figure 7-7

stored is a 4-bit tolerance code representing the degree of precision required. As soon as the laser-focus destination address is programmed, the comparator immediately begins to calculate the difference between the contents of the 28-bit counter and the contents of the laser-focus destination register. This difference appears at the input of the null decoders.

As laser-focus under control begins motion, its displacement is sensed by the H & P 5501 A Laser Transducer System, and the 28-bit counter on the H & P 10762 A Comparator is changed in a direction which brings it closer to the value stored in the 28-bit destination register. This then causes the 28-bit Digital Difference Output to the servo-system to decrease in value as the laser-focus under control moves closer to destination.

Interferometric positioning of laser-focus takes place in incremental steps of $16 \times \lambda/4$ of the laser interferometer, i.e. 16×0.1582 micrometer per step, in order to achieve track spacing of 2.53 micrometer. H & P components to accomplish laser interferometric positioning of laser focus are presented in the following table.

Note, that the preceding analysis shall be only a guideline to laser interferometric control of the position of laser-focus. On one hand, the H & P laser interferometer is much more selective than required; the integer control step of

TABLE X

H & P COMPONENTS FOR LASER INTERFEROMETER

5501 A	LASER TRANSDUCER
10780 A	RECEIVER
10701 A	50% BEAM SPLITTER
10702 A	LINEAR INTERFEROMETER
10703 A	RETROREFLECTOR
10740 A	COUPLER
10746 A	BINARY INTERFACE
10762 A	COMPARATOR
10764 A	FAST PULSE CONVERTER
10755 A	COMPENSATION INTERFACE
10756 A	MANUAL COMPENSATOR

laser focus are 16 times a quarter wavelength of the laser. On the other hand, access time of the H & P interferometer is much too slow, particularly for the controls of track to track laser focus positioning.

5. 10 Large scale electronic circuits (LSI).

Large scale electronic circuits for digital laser storage, retrieval and conversion of image data encompass the following functions: (548-550)

- laser signal modulation;
- laser focusing;
- laser storage;
- ^{possible} laser interferometer controls;
- primary laser writing and instantaneous reading;
- secondary laser reading and ACB servo controls;
- conversion electronics;

Laser signal modulation controls the Bragg ultrasonic cavity dumper of the writing Argon II ionic laser, providing traveling sound waves within the laser cavity.

Laser focusing is provided by the pneumatic servo controls which maintain constant airfoils between the writing and reading laser focusing objectives.

Laser storage utilizes the digital signal output, transmitted from the satellite and converts it to the driving stage of the mode-locked writing laser. This stage also includes the phase-lock electronics for laser disc drive and systems clock. The signal modulated writing laser beam enters the laser disc scanning system at a rate of 60 M bits/sec. (single density laser storage) or 120 M bits/sec. (dual density laser storage). The 120 M bits/sec. signal is frequency divided 2:1, so that the effective laser storage rate per metallic storage surface is still 60 M bits/sec. Writing laser power is adjusted by means of a polarization analyzer, inserted in the laser beam, so that an elementary bit size of one (1) micrometer in diameter results. Note that the product of laser power (w) and laser pulse duration (τ) yields the laser energy per bit (u) of

the order of 10^{-9} joule (10^{-16} erg).

Possible

Laser interferometer (LSI) electronics provide binary interface, comparator, fast pulse-converter, compensation interface, systems control and laser receivers.

Primary laser writing and instantaneous reading comprises LSI electronics for demodulation, modulation, encoding and detection.

Secondary laser reading and ACB servo controls utilize LSI electronics to read and control laser reading, servo tracking and direct accessing.

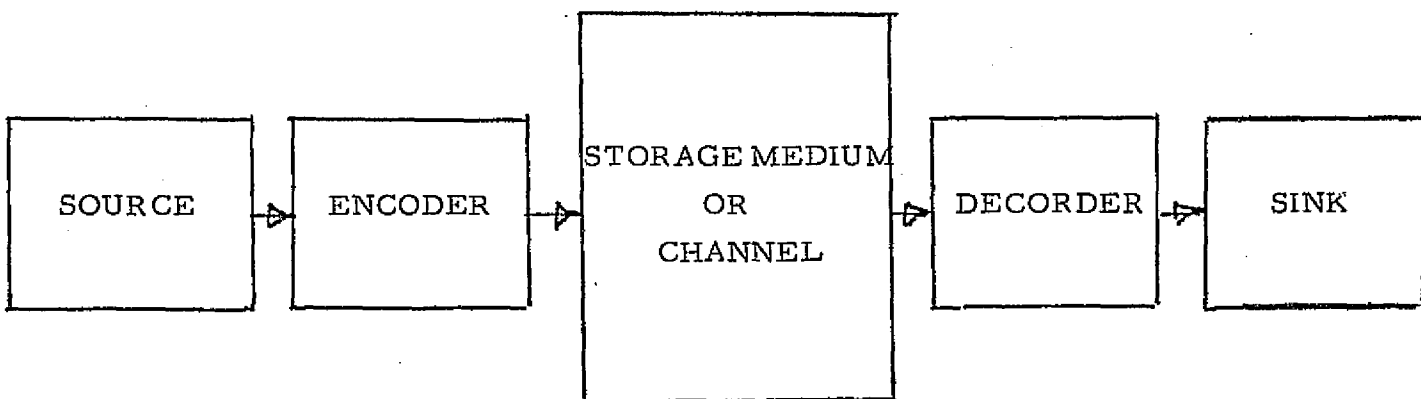
Conversion electronics with particular emphasis on systems clocking and phase-lock ~~changing~~ ^{provide} computer input conversion. They are essentially determined by the operational parameters of the subsequent electronic data processor.

5.11 Error detection and correction with digital laser mass storage and retrieval.

In reference 547 a model is described (see Fig. 5-4) of an information storage system, assuming the storage medium to be a communication channel. The source information is usually composed of binary or decimal digits or alphabetic information in some form. The encoder transforms these messages into signals acceptable to the channel. These signals enter the channel and are perturbed by noise. The output enters the decoder, which makes a decision concerning which message was sent and delivers this message to the sink. The communication engineering problem is principally to design the encoder and decoder.

A system that employs error-correcting codes is described in Fig. 5-5. "The converters in this system translate symbols of one alphabet to symbols of another. The modulator accepts at its input a single channel symbol and produces at its output the corresponding channel waveform, i. e., a pulse which is always associated with that symbol. The demodulator performs the inverse operation of the modulator; it attempts to associate a channel symbol with the noise-corrupted received waveform. The encoder and decoder implement the channel symbol error-correcting code which is employed"(freely quoted from reference 547).

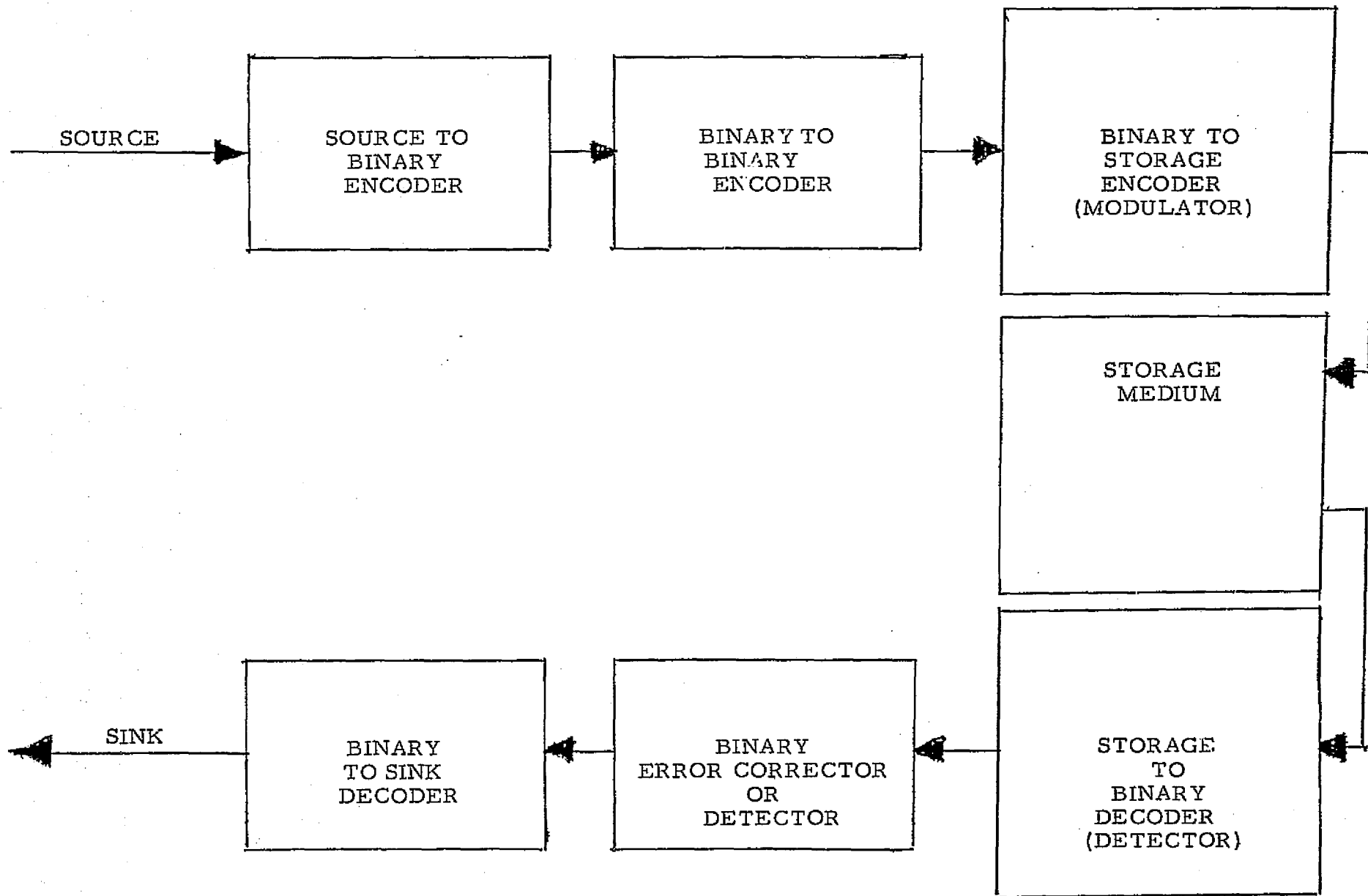
In principle, error detection and correction with digital laser storage and retrieval requires a coding and decoding process, i. e. expressing a given quantity in binary form, and vice versa. Code converters are combinational or sequential circuits, translating one code form into the other.



BLOCK DIAGRAM OF STORAGE SYSTEM

(Reference 547)

Figure 5-4



BLOCK DIAGRAM OF STORAGE SYSTEM EMPLOYING
ERROR CORRECTING CODE

(Reference 547)
Figure 5-5

The codes⁽⁵⁴⁸⁾ that allow for error detection and correction enable a computer to determine whether a character which was coded and transmitted is received correctly and, if there is an error, to correct it. A basic code to consider is the Binary-Coded-Decimal, or BCD code. It utilizes the binary number system to specify the decimal numbers 0 to 9. One recognizes that each decimal digit requires its 4-bit binary coded equivalent. Other codes are octal coding and hexadecimal coding.

Codes for error detection and correction⁽⁵⁴⁸⁾ are characterized as odd parity and even parity codes. For the odd parity check an additional bit is chosen so that the sum of all 1's in the transmitted word, including the check bit, is odd. In even parity, the added parity will make the total number of 1's an even amount. When a code word is received it is checked for parity (even or odd being previously chosen) and is accepted as correct if it passes the test.

Odd parity in codes is more commonly used than even parity, since the latter would not recognize a fault condition in which all zeros are transmitted.

Block parity codes are utilized to detect and correct errors more ef-

ficiently. (548)

The message to be transmitted is arranged in an array of (n) rows and (m) columns. An odd parity bit is added to each row, and an even parity bit to each column. Finally, the parity bits are also checked at the intersection of the parity row and column $(H=V)$.

This code detects all single errors and provides an indication of their location through the intersection of the horizontal check bit, H_{h1} and the vertical check bit V_{n1} where the subscripts (h) and (v) refer to the row and column, respectively, in which the error has occurred.

Another error detection and correction code are the distance-3 codes. (548)

The commonly used of these codes is the Hamming code, capable of detecting and correcting one error in a word. The code is constructed by incorporating several check bits (C) with the information bits (I) . The check bits within the composite word occupy positions $1, 2, 4, \dots, 2^i$, as shown below:

Position	7	6	5	4	3	2	1
Bit	I_7	I_6	I_5	I_4	I_3	C_2	C_1

Error detection and correction with IBM Integrated Storage Control (302) utilizes parity checking. When a byte (8 bits) is formed, the parity bit is set to either 1 or 0 to maintain an odd number of 1-bits within the byte (that is, odd parity). Each byte of data to be written is checked for correct parity as it is received. As data is transferred from the channel to disc storage (write operation), the disc storage control removes the parity bit associated with each byte. It then computes the error correction code bytes, which are written after each recorded area. The correction code bytes, coded to represent the data in the recorded area, are used for both error detection and correction.

5.12 Laser storage control.

General principles of electronic storage control (507) are applied to control digital laser storage and retrieval of image data. However, in consideration of the preceding paragraph on computer input conversion, important variations to the general principles of storage control are required. Essentially, laser storage control extends into two parts:

- Primary storage control of the real-time digital laser storage and retrieval process;
- Secondary storage control of the computer associated secondary laser read-out process;

Primary storage control comprises Channel Interface with the incoming digital image data stream which is transmitted from the satellite. It provides track layout on the disc, synchronization, actuator control and counting for real-time laser writing and reading, servo-controls for laser focus positioning and tracking, as well as microprogramming.

Secondary storage control incorporates the means of adjusting secondary read-out of the laser disc system to the read-in requirements of the data processing computer system. It comprises:

- (a) Channel Interface, communicating with secondary digital laser read-out channel, operating at the computer input conversion ratio of ~~8:1~~ ^{for example,} ~~8:1~~ ^{8:1}. It also incorporates system's synchronization, clocking, stop-and-repeat operations, etc.
- (b) Device Interface, talking with one of the modules attached to storage control, linking secondary laser read-out to the ultimately important electronic data massaging process by the computer.
- (c) Data Processing Unit, processing the incoming digital signals from secondary laser read-out at computer input conversion rates. It also incorporates general registers, serializer/deserializer, error detection and

error correction, arithmetic units, etc.

(d) Microprogramming Control Unit, encompassing a sequence of micro-instructions, ie. single steps which control all three preceding storage units.

VI
IMPLEMENTATION OF THE CONCEPTS OF
DIGITAL LASER MASS STORAGE AND RETRIEVAL

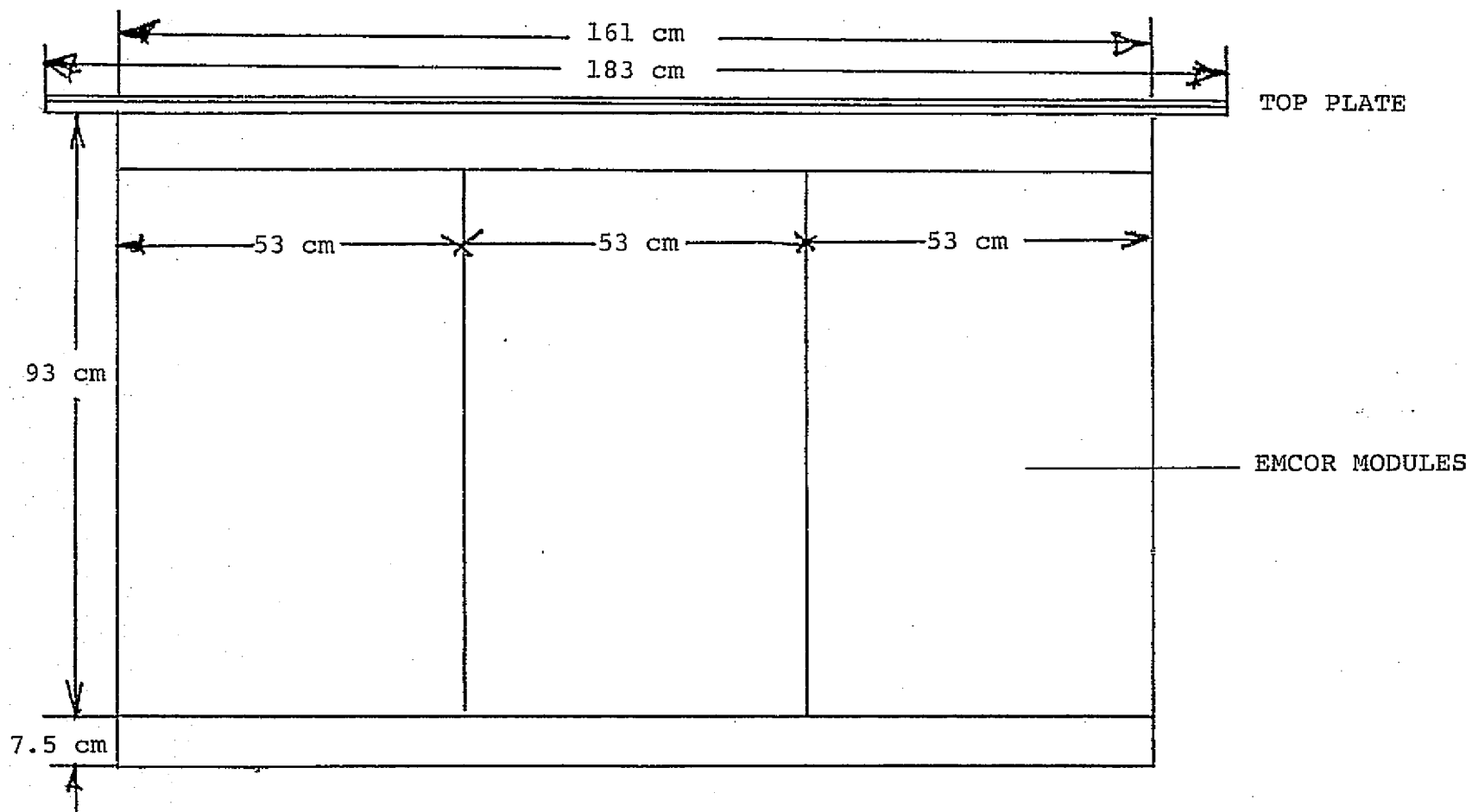
6.1 Physical Structure of feasibility system

The feasibility system to implement the concepts of digital laser mass storage and retrieval encompasses an embodiment which is constructed on the basis of a standard enclosure of three joined EMCOR modules (ESQ SFR-115A) and an optical table. See Figure 6-01 and 6-02.

6.2 Laser Disc

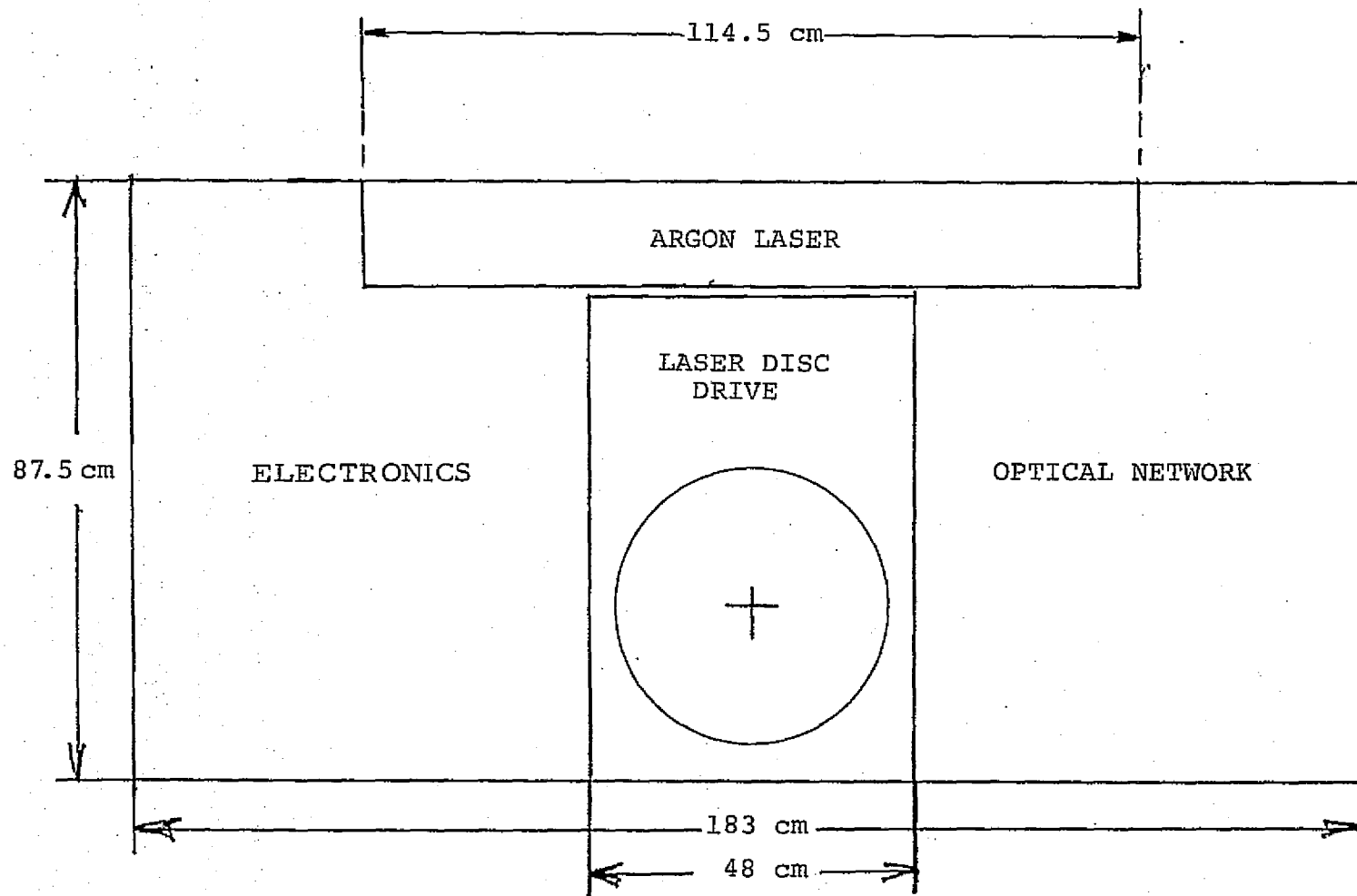
For simplicity, only single-density laser disc storage and retrieval are foreseen for the feasibility ~~study~~ ^{System}. Thus, the laser disc comprises only one thin metal film storage medium, vacuum encapsulated between two mylar discs. Creation of these laser discs represents the state of the art at Varian Associates, Palo Alto, California, except that no satisfactory clean room facilities are presently available at Varian. This means that the theoretically predicted error rate of 10^{-11} for digital laser mass storage and retrieval is reduced, due to dust particles migrating in the vacuum chamber. Laser disc storage with the feasibility model takes place in an uninterrupted, time-sequential spiral form, thus creating serial diffraction-limited "holes" (bits) in the thin metal film of laser disc. Hole size is one micrometer in diameter in regard to digital laser storage and retrieval. Hole-separation is in accordance with the Rayleigh criterion. Track separation of the spiral tracks is 2.53 micrometer.

The optical characteristics (R, T, A) of the produced laser discs are determined by a laser densitometer. The appropriate values for R, T, A follow from the optics of thin metal films.



EMBODYMENTS OF FEASIBILITY SYSTEM

Figure 6-01



TOP PLATE OF FEASIBILITY SYSTEM

Figure 6-02

6.3 Feasibility Test Unit

The feasibility test unit comprises a top plate, schematically presented in Figure 6-02. The storing laser is mounted in the rear center of the plate. It is an internally signal-modulated Argon II ionic laser with mode-locked cavity dumper (Spectra Physics 165-366). The signal modulated laser beam passes first a polarizer rotator (Spectra-Physics 310-21), followed by a beam expander (Spectra-Physics 310-21) and a 90° beam reflector (Spectra-Physics 576-23). Subsequently, the laser beam enters a polarization beam splitter (Spectra-Physics 513-24), in order to separate the incident laser beam from laser radiation which is reflected back from the thin metal film of laser disc. For the purpose of instantaneous laser reading, the reflected laser radiation is guided through the polarization beam splitter toward ACB photo-diodes (Texas Instruments), which are positioned behind a slit in a photodetector screen. Automatic laser focusing takes place with a microscope objective (ZEISS EPIPLAN L.D. 40x, N.A. = 0.60; f = 4.1 millimeter). Simultaneously, another optical system is provided at the top plate of A-unit, utilizing a small Helium-Neon laser (Spectra-Physics 132) and a second polarization beam splitter (Spectra-Physics 513-24), inserted between the first beam splitter and the objective. The second optical system produces vertical laser illumination of the field of view of the objective, after passing specially designed collimation optics. Reflections from the laser beam illumination of the thin metal film of laser disc are guided back to the ACB photo-diodes, utilizing the primary polarization beam splitter. The specially designed laser disc drive comprises a subsystem, encompassing the rotating disc and a mechanical linear translator, which

carries the two writing and reading microscope objectives. In order to simplify the feasibility tests, only one objective is optically activated, while both objectives together provide pneumatic laser focusing by means of their attached, specially designed air-foil caps. Hence, only single density laser storage and retrieval is provided with the feasibility test unit. The linear translator comprises a specially designed servo-controlled driver stage, utilizing a printed circuit motor (PMI U9-M2), a 5,000 line encoder (Baldwyn) and a flywheel for stabilization purposes. Laser disc drive comprises a hollow shaft printed circuit motor (PMI U12 M2) and a hollow shaft encoder (Baldwyn). Linear motion of the translator is phase locked to the laser disc drive, so that uninterrupted time sequential spiral laser disc storage and retrieval takes place, in accordance with the projected unit storage cell of the system. Track separation is 2.53 micrometer. Automatic tracking is provided by means of a mirror galvanometer (General Scanning G-100PD), mounted at the top of the laser writing and reading objective. Galvanometer motion is controlled by servo electronics (General Scanning, A-600).

6.4 Automatic laser focusing

Intensive investigation is to be provided ^{for} ~~the~~ the feasibility ^{system} ~~to~~ to determine optimum conditions for automatic laser focusing. The initial approach should concentrate on pneumatic focusing, by means of creating an airfoil between rotating laser disc and the laser writing objective. For symmetry reasons two airfoils are ^{to be} ~~are~~ created, utilizing a second dummy objective. It is conceived that independent optical and

pneumatic focusing can be achieved within an accuracy of one (1) micrometer.

Pneumatic focusing should be alternatively possible at 3,600 RPM (primary laser storage) and 450 RPM (secondary laser retrieval at reduced angular velocity of rotation, for the purpose of computer input conversion).

6.5 Primary digital laser disc storage and instantaneous retrieval

After passing laser disc storage control, the digital information input enters primary laser disc storage. Beginning with the outer periphery of the disc storage area, spiral tracks are laid down at 3,600 rpm with constant track spacing of 2.53 micrometer. To store a 10,000 x 10,000 pixel image, 10,000 tracks are created at 10^6 bits per disc revolution. Instantaneous retrieval of the stored information is provided by means of separating the incident writing laser radiation from the laser radiation reflected back from the thin metal film of the laser disc, utilizing a polarization beam splitter. The reflected laser radiation is imaged to the center C-photo-diode behind a photo detector slit, utilizing the writing and reading microscope objective. Output of the center photo-diode is supplied to a CRT display and control subsystem. Correct accessing of the feasibility ~~model~~ ^{system} is determined by instantaneous laser reading.

Primary digital laser disc storage and instantaneous retrieval is provided by the mode-locked Argon II-ionic laser (Spectra-Physics 165/366). Laser accessing basically utilizes a high resolution translator (Lansing 20-129), which will be modified to incorporate velocity

and position servo controls. In order to provide continuous accessing (for primary laser storage), stop-scan (for secondary reading) and group-selection (for laser storage and retrieval), an electronic controller, calculator and counter should be provided to select the appropriate track positioning. It should be also investigated, if laser-interferometric track positioning is possible, in a much simpler form than presently used at the H-B laser interferometer-calculator. If this should be ~~possible~~ ^{accomplished}, laser accessing would be fully digitized. Testing of laser beam accessing encompasses the determination of obtainable packing density, in conjunction with primary digital laser disc storage. It utilizes instantaneous laser reading in connection with electronic counting and calculation. Another testing procedure during this phase of the feasibility ~~study~~ ^{tests} incorporates the experimental determination of the obtainable modulation transfer function (MTF) of primary digital laser storage and retrieval. Ultimately, the inherent error rates on primary digital laser disc should be experimentally determined *and corrected.*

6.6 Secondary digital laser disc retrieval

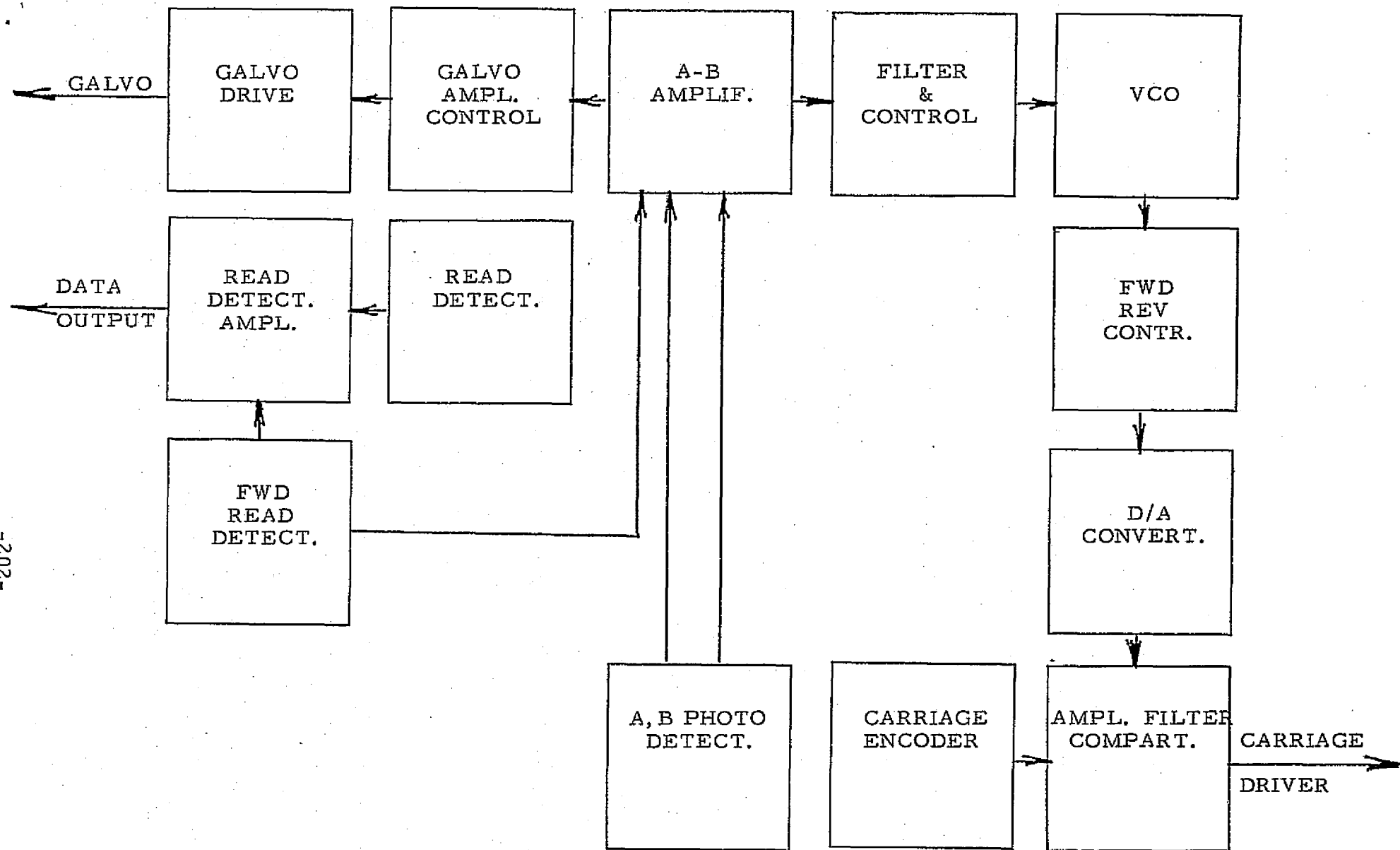
Secondary laser disc retrieval is applied, by means of re-scanning the laser disc ^{first} at a rotational angular disc velocity of 3,600 RPM. Secondary laser read-out results from vertical laser illumination of the field of view of the reading microscope objective, utilizing a small Helium-Neon laser applied for vertical laser illumination. During a secondary laser read-out, automatic tracking is provided by galvano-

metric controls. For this purpose, the mirror galvanometer at the top of the laser writing and reading objective is servo controlled via ~~the~~ ACB photo-diodes, utilizing a feed-back servo amplifier. Because of the space-time invariance of the system, only eccentricities of disc playback are to be compensated by the tracking servo-controls. They occur at 3,600 rpm angular disc velocity.

Essentially, secondary laser disc retrieval comprises a triple-track scanning process during spiral laser scanning. The center (C) tracks always provide laser reading, while the side tracks energize the laser tracking servo controls. The principles of these servo controls are presented in Figure 1-06, and may be outlined as follows:

Mirror galvanometer tracking control for secondary digital laser retrieval keeps the reflected track image to coincide with a fixed-positioned reference system, utilizing feedback servo electronics and a diffraction-limited projection system. Projection of the spiral recording tracks takes place in such a way that the center recording track (C) and its two (2) adjacent servo tracks (A,B) are projected to the ACB photo-diodes. These are fixed mounted behind a real slit in the projection screen. Vertical laser illumination from a small auxiliary Helium Neon laser illuminates the field of view of the writing and reading microscope objective. Appropriate collimation optics between laser and objective provide for laser illumination.

The servo controls involved with secondary laser reading are schematically presented in Figure 6-03. The electronic output of the A, B photo detectors is entering the (A - B) servo amplifier. Its output is split into the galvo amplifier control and the carriage motor control, respectively. Galvo amplifier control energizes the galvo drive in a feedback



SECONDARY LASER READING, SERVO CONTROLS

Figure 6-03

loop system. Carriage motor control passes filter and servo controls, which activate a voltage control oscillator (VCO), creating the reference signal to a D/A converter. This output goes to the carriage driver which controls the speed of the linear translator in relation to the speed of the spiral track recording. The carriage encoder grating is energizing a comparator which finally controls the carriage motor.

The controls just described encompass a classical combination of velocity and position servo controls. Appropriate adjustment of the gain controls keeps track-reading fluctuations automatically within $\pm 10\%$ of the track width.

Feasibility testing of secondary read-out determines first the digital laser reading errors, and provides for electronic error correction. As a result, the deviation from the theoretical minimum error of 10^{-11} shall be experimentally determined. For optimum results, secondary laser reading errors should not be larger than the errors primarily originated from dust particles immigrating into the vacuum chamber of the laser disc production facilities.

Secondary laser reading takes place first at a 1:1 angular velocity ratio for laser writing and reading. For final testing of the feasibility ~~system~~ ^{system}, the angular velocity of disc rotation should be reduced to an amount which is commensurate with the frequency bandwidth of the following electronic data processor (CPU). Assuming a mini-computer is applied for final testing, an 8:1 computer input conversion ratio appears to be appropriate. In order to make this possible, automatic laser focusing should be adjusted to the disc angular velocity reduction from 3,600 RPM to 450 RPM.

VII

PROPOSED SPECIFICATIONS FOR A DIGITAL LASER MASS STORAGE AND RETRIEVAL FEASIBILITY SYSTEM

The advancement of digital laser mass storage and retrieval requires an experimental feasibility system for its implementation. The theoretical foundation for such a system is thoroughly established in the preceding Sections of this Study Report.

The proposed feasibility system encompasses the following major experimental steps:

- (1) Create a limited number of, for example, 100 single density laser discs, by means of vacuum ~~evaporation~~ ^{evaporation} of thin metal films (indium) and simultaneous covalent vacuum bonding of two (2) mylar sheets. Thus, sheets of twin mylar substrates are produced, in which the thin metal films are hermetically encapsulated in the vacuum. Experimental laser discs result by means of adding a metallic hub in the disc center, followed by cutting circular discs out of the sheets and sealing of the rims with the CO_2 laser.
- (2) Determine the optical characteristics (R,T,A) of the produced laser discs, by means of a laser densitometer.
- (3) Create a laser disc drive, alternatively operating at 3,600 RPM or 450 RPM, utilizing velocity and position phase-lock servo controls.
- (4) Provide automatic laser focusing.
- (5) Provide primary digital laser storage and instantaneous laser reading with the produced disc drive, utilizing Mode-lock internal cavity modulated Argon II-ionic laser and a mechanical-optical linear translator for laser accessing. Accessing is servo controlled, incorporating an electronic calculator and a digital controller, in conjunction with an electronic counter, possibly utilizing a laser-interferometer.
- (6) Determine the obtainable packing density of primary digital laser disc storage.

- (7) The achieved modulation transfer function (MTF) of primary digital laser storage and retrieval should be 60 Mbits/second.
- (8) Determine inherent error rates at primary digital laser disc storage.
- (9) Extend operation to secondary digital laser disc retrieval, by means of adding appropriate laser reading optics, galvanometer tracking, vertical laser illumination, ACB velocity and position servo controls, etc., *possibly utilizing a laser interferometer*
- (10) Determine digital laser reading errors and provide for electronic error correction.
- (11) Adjust for Computer Input Conversion, by means of reducing angular velocity of disc rotation from 3,600 RPM to 450 RPM.
- (12) Adjust automatic laser focusing to the 8:1 reduced angular disc velocity.
- (13) Determine the overall performance characteristics of the feasibility model.

REFERENCES

Section 8. REFERENCES

- 01 Becker, C.H. "Quantum Electronics of Optical Phonons II "
Zeitschrift f. Physik, 179, 439-460 (1964)
- 02 Maiman, T.H. "Laser Action in Ruby"
British Communications Electronics, Vol. 7, p. 674 (1960)

Maiman, T.H. "Stimulated optical radiation in ruby masers"
Nature, Vol. 187, pp. 493-494, August (1960)
- 03 Becker, C.H. "UNICON Computer Mass Memory System"
Fall Joint Computer Conference, San Francisco, Cal. (1966)
AFIPS Conference Proceedings, Vol. 29, pp. 711-716 (1966)
- 04 Bridges, W.B. "Laser oscillations in single ionized argon in the
visible spectrum"
Appl. Physics Letters, Vol. 4, pp. 128-130 (1964)
- 05 Javan, A. et al. "Population inversion and continuous optical maser
oscillation in a gas discharge containing a helium-neon mixture"
Phys. Rev. Letters, Vol. 6, pp. 106-110 (1961)
- 06 Pockels, F. Annalen d. Physik, III, 37, pp. 145-172, 269-305 (1889)
- 07 Geusig, J.E. et al, "A repetitive Q-switched, continuously pumped
YALG:Nd laser"
Appl. Phys. Letters, Vol. 6, pp. 175-177 (1965)
- 08 Lord Rayleigh, "On the passage of waves through apertures in
plane screens and allied problems"
Phil. Mag. 43, p. 259 (1897), Scientific Papers, Vol. IV, p. 283 (1899)
- 09 Sos, John Y., personal communication, NASA Goddard Space Flight
Center, Greenbelt, Md., March 18, 1976
- 10 Anwyl, Robert, D. "Storage Materials for laser recording"
Proc. Soc. Photo-Optical Instrumentation Engineers, Vol. 53, pp. 15-21
(1974)
- 11 Braunmuehl, H. T. & Weber, H., "Verfahren zur magnetischen
Schallaufzeichnung"
DRP. 743 411 (7. 28. 1940)
- 12 Lenneman, E. "Aerodynamic Aspects of Disk Files"
IBM Journal Res. & Development, Nov., pp. 480-488, (1974)
- 13 Mulvany, R.P. "Engineering design of a disk storage facility with
data modules"
IBM Journal Res. & Develop., Nov. pp. 489-505 (1974)
- 14 Oswald, R.K. "Design of a disc file head-positioning servo"
IBM Journal Res. & Develop., Nov. pp. 506-512 (1974)
- 15 Stahl, K. J., et al. "Dynamic response of self-acting foil bearings"
IBM Journal Res. & Develop. Nov. pp. 513-520 (1974)

- 16 Tseng, R. C. & Talke, F. E. "Transition from boundary lubrication to hydrodynamic lubrication in slider bearings"
IBM Journal Res. & Develop., Nov., pp. 534-540 (1974)
- 17 IBM, "Introduction to IBM 3350 Digital Access Storage"
IBM Systems, GA 26-1638-0
- 18 Becker, C. H. "Non-photographic Digital Laser Storage"
LASER 75, Opto-Elektronik Conference, Munich, W. Germany
June 24-27, (1975)
- 101 Planck, Max "Ueber eine Verbesserung der Wien'schen Spectralgleichung"
Verh. d. Deutschen Phys. Ges. 2, pp. 202-204 (1900)

Planck, Max, "Zur Theorie des Gesetzes der Energieverteilung im Normalspektrum"
Verh. d. Deutschen Phys. Ges., 2, pp. 237-245 (1900)

Planck, Max "Ueber das Gesetz der Energieverteilung im Normalspektrum"
Ann. d. Physik, (4) 4, pp. 553-563 (1901)
- 102 Einstein, Albert
Annalen der Physik, 17, 891 (1905)
- 103 Einstein, Albert "Ueber die Quanten Theorie der Strahlung"
Physikalische Zeitschrift, 18, 121 (1917)
- 104 Maitland, A. & Dunn, M. H. "Laser Physics"
North Holland (1969) pp. 93-107
- 105 Sommerfeld, Arnold "Optik"
Vorlesungen ueber Theoretische Physik, Vol. IV, pp. 179-352
Dietrich, (1951)
- 106 Born, Max & Wolf, Emil "Principles of Optics"
Pergamon pp. 370-591 (1974)
- 107 Goodman, Joseph "Fourier Optics"
pp. 30-77, McGraw-Hill (1968)
- 108 Shulman, Arnold "Optical Data Processing"
Wiley (1970) pp. 156-209
- 109 Lord Rayleigh "On the Character of the Complete Radiation at a Given Temperature"
Phil. Mag. (5) 27, pp. 460-~~469~~ 469 (1889)
- 110 Barnes, Frank "Laser Theory"
IEEE Press (1972) pp. 339-416
- 111 Kaminow, Fran P. & Sigman, Anthony, E. "Laser Devices and Applications"
IEEE Press (1972)
"Laser Modes and Mode-Control"
Part V pp. 171-248
- 112 Kogelnik, H. & Li, T. "Laser Beams and Resonators"
Proc. IEEE, 54, 1312-1329 (1966)

- 113 Bracewell, Ron "The Fourier Transform and its Applications"
McGraw-Hill pp. 51-68, 98-122 (1965)
- 114 Smith, Warren J. "Modern Optical Engineering"
McGraw-Hill (1966) pp. 209-212
- 115 Sikorski, M. E. "Correlations of the Coefficient of Adhesion with Various Physical and Mechanical Properties of Metals"
Journal Basic Engineering Transactions ASME 85, -D, pp. 279-285 (1963)
- 116 Berry, Robert, et al. "Thin Film Technology"
Van Nostrand (1968) pp. 559-632
- 117 Hass, Georg "Optical Properties of Metals"
American Institute of Physics Handbook, pp. 6-118 to 6-160 (1972)
- 118 von Hippel, A. "Dielectrics and Waves"
Wiley (1954) pp. 50-55
- 119 Kittel, Charles "Thermal Physics"
Wiley (1969) pp. 309-337
- 120 Carslaw, H. S. & Jaeger, J. C. "Conduction of Heat in Solids"
Oxford (1973) pp. 4-91
- 121 Messiah, Albert, "Quantum Mechanics" Volume I
North Holland (1961) pp. 129-161
- 122 Madelung, Erwin "Die Mathematischen Hilfsmittel des Physikers"
Springer pp. 339-350 (1964)
- 123 Pearson, D. E. "Transmission and Display of Pictorial Information"
Wiley (1970) pp. 1-30; 51-90; 124-198
- 124 Andrews, H. C. "Computer Techniques in Image Processing"
Academic Press (1970) pp. 31-54

Andrews, H. C. "Digital Image Restoration: a Survey"
Computer, May, pp. 36-45 (1974)
- 125 Rosenfeld, A. "Picture Processing by Computer"
Academic Press (1969) pp. 1-19
- 126 Wintz, P. A. "Transform Picture Coding"
Proc. IEEE, 60, pp. 809-820 (1972)
- 127 Becker, C. H. "The Principles of Coherent Light Data Systems"
Proc. 25th Annual Conference, National Microfilm Assoc., New York
pp. III-78 to III-95 (1972)
- 201 Cook, W. R. & Jaffe, H. "Magneto-Electro-, and Elasto-Optic Constants"
pp. 6-230 to 6-241, American Institute of Physics Handbook
McGraw-Hill (1972)
- 202 Geusig, J. E. et al. "Coherent Optical Sources for Communications"
Proc. IEEE, 58, pp. 1419-1439 (1970)

- 203 Smith, P. W. "Mode-locking of Lasers"
Proc. IEEE, 58, pp. 1342-1357 (1970)

Smith, P. W. "Mode Selection in Lasers"
Proc. IEEE, 60, pp. 422-440 (1972)
- 204 Vuylsteke, A. A. "Theory of Laser Regeneration Switching"
Journal Appl. Phys. 34, pp. 1615-1622 (1963)
- 205 Maydan, Dan, et al. "Recording and Display Method and Apparatus"
U. S. Patent 3, 720,784 (1973)
- 206 Dickey, L. W. "Computer Concepts Hardware and Software"
Prentics Hall (1974) pp. 11-144
- 207 Barna, A. & Porat, D. I. "Integrated Circuits In Digital Electronics"
Wiley (1973) pp. 361-423
- 208 Nashelsky, L. "Introduction to Digital Computer Technology"
Wiley (1972) pp. 519-565
- 209 Sebestyen, L. E. "Digital Magnetic Tape Recording for Computer Applications"
Chapman & Hall (1973) pp. 1-15
- 210 Ryne, V. T. "Fundamentals of Digital Systems Design"
Prentice Hall (1973) pp. ~~201-255~~ 201 - 255
- 211 MonteRoss, "Laser Applications"
Vol. I (1971), Vol. II (1974) pp. 239-293
- 212 Black, H. S. "Modulation Theory"
van Nostrand (1953) pp. 59-70
- 213 Peavy, Bernard & Sos, John Y. "Image Recording Requirements
for Earth Observation Applications in the Next Decade"
Proc. Soc. Photo-Optical Instrumentation Engineers, 53, pp. 106-115
(1974)
- 301 IBM "Introduction to IBM Direct Access Storage"
GA 26-1638-0
- 302 IBM "Reference Manual for IBM Integrated Storage Control"
Ga 26-1620-2
- 303 IBM "Reference-Manual for IBM 3340/3344 Disc Storage"
Ga 26-1619-4
- 304 IBM System/370, "Principles of Operation"
GA 22-7000-4
- 305 Dorf, R. C. "Modern Control Systems"
pp. 21-71, 73-146, Addison Wesley (1974)

- 306 Madelung, E. "Die Mathematischen Hilfsmittel des Physikers"
Springer, pp. 150-166, 212-245 (1964)
- 307 Bracewell, R. "The Fourier Transform and its Applications"
MacGraw Hill (1965) pp. 291-293
- 308 Chopra, K. L. "Thin Film Phenomena"
MacGraw-Hill (1969) pp. 137-265
- 309 Maissel, L. I. & Gland, R. "Handbook of Thin Film Technology"
Mc Graw-Hill (1970) pp. 1-341-130
- 310 Chu, Yaohan "Computer Organization and Microprogramming"
Prentice Hall (1972) pp. 256-328
- 401 Bernstein, R. & Ferneyhough, D. "Digital Image Processing"
Photogrammetric Engineering and Remote Sensing, 41, pp. 1465-1476 (1975)
- 402 Bernstein, R. "Digital Image Processing of Earth Observation
Sensor Data"
IBM Journal Res. & Develop., January, pp. 40-57 (1976)
- 403 Bernstein, R. "All-Digital Precision Processing of ERTS Images"
IBM Final Report to NASA, Contract NAS5-21716, April 1975
NASA Goddard Space Flight Center, Greenbelt, Md.
- 404 Becker, C. H. "Laser Microprinter"
Proc. Soc. Photo-Optical Instrumentation Engineers, 53, pp. 141-148
(1974)
- 405 Born, Max & Wolf, Emil "Principles of Optics"
Pergamon pp. 256-367 (1974)
- 406 Mande, M. "Modern Television Systems"
Prentice Hall (1974) pp. 417-440
- 407 Williams, C. S. & Becklund, O. A. "Optics"
Wiley, pp. 196-230 (1972)
- 408 Goodman, J. "Fourier Optics"
McGraw-Hill, pp. 4-22, 101-140 (1968)
- 409 Abbe, Ernst,
Archiv. Mikroskopische Anal., 9, p. 413 (1873)
- 410 Lord Rayleigh, "On the Theory of Optical Images"
Phil. Mag. (5) 42, p. 167 (1896)
- 501 Glang, Reinhard "Vacuum Evaporation"
Handbook of Thin Film Technology, Edit. Maissel & Glang, p. I-3 to
I-130, McGraw-Hill (1970)
- 502 Kittel, Charles, "Solid State Physics"
Wiley pp. 99-106 (1966)
- 503 Berry, R. W., Hall, P. M., Harris, M. T. "Thin Film Technology"
pp. 559-632, van Nostrand (1968)

- 504 Kittel, Charles "Thermal Physics"
Chapter 20, Vapor Pressure Equation, pp. 325-337 Wiley (1969)
- 505 Varian, Vacuum Division, Palo Alto, Calif.
"S-Gun Thin Film Source"
- 506 Hoffman, Vance, Varian-Vacuum Division, Palo Alto, Calif.
personal communication, April (1976)
- 507 Flores, Iran "Peripheral Devices"
Prentice Hall (1973) pp. 298-391
- 508 Philips Technical Review, Vol. 33 No. 7, pp. 178-193 (1973)
- 509 "Handbook of Engineering Mechanics"
Ed. Fluegge, Part 7, Fluid Mechanics pp. 68-3 to 72-24
- 510 Lesser, M. L. & Haanstra "The Random Access Memory Accounting
Machine"
IBM Journal, Jan. pp. 62-75 (1957)
- 511 Pearson, R. T "The Development of the Flexible-Disc Magnetic Re-
corder"
Proc. IRE pp. 164-174 (1961)
- 512 Barlow, E. J. "Deviation of Governing Equations for Self-Acting
Foil Bearing"
Transactions ASME, Journal of Lubrication, pp. 334-340 (1967)
- 513 Barlow, E. J. "Self-Acting Foil Bearings of Infinite Width"
Transactions of the ASME, Journal of Lubrication Technology
pp. 341-345 (1967)
- 514 Eschel, A. & Wildman, M. "Dynamic Behaviour of a Foil in the
Presence of a Lubricating Film"
Transactions of the ASME, Journal of Applied Mechanics, pp. 242-
247 (1968)
- 515 Licht, L. "An Experimental Study of Elastohydrodynamic Lubrication
Technology"
pp. 199-220 (1968)
- 516 Eshel, A. "The Propagation of Disturbances in the Infinitely Wide
Foil Bearing"
Transactions of the ASME, Journal of Lubrication Technology
pp. 120-125 (1969)
- 517 Barnum, T. B. & Elrod, H. G. "A Theoretical Study of the Dynamic
Behavior of Foil Bearings"
Transactions of the ASME, Journal of Lubrication Technology
pp. 133-142 (1971)
- 518 Langlois, W. E. "Static Determinancy in the Theory of Finite Width
Foil Bearings"
Journal of Applied Mechanics pp. 51-54 (1974)

- 519 Pelech, Ivan & Shapiro Asher, H. "Flexible disc Rotating on a Gas Film Next to a Wall"
Transactions of the ASME, Journal of Applied Mechanics, pp. 577-584 (1964)
- 520 Brown, C.J. & Ma, J. T. "Time-Optimal Control of a Moving-Coil Linear Actuator"
IBM Journal Res. & Develop. pp. 372-379 (1968)
- 521-
- 526 IBM Journal Res. & Develop. November (1974)
- 527 IBM Reference Manual for IBM 3340/3344 Disc Storage GA 26-1619-4
- 528 IBM Reference Manual for IBM Integrated Storage Control, GA 26-1620-2
- 529 Cronin, D. et al. "Design and Testing of a Pneumatic Focus Servo for a High-Speed Microdensitometer"
Optical Engineering, pp. 366-371 (1975)
- 530 Spectra-Physics, Model 165 Ion Laser
- 531 Smith, P.W. "Mode Selection in Lasers"
Proc. IEEE, Vol. 60, pp. 422-440 (1972)
- 532 Smith, P.W. "Mode-locking in Lasers"
Proc. IEEE, Vol. 58, pp. 1342-1357
- 533 Spectra Physics, Model 166/366 Combo
- 534 Spectra Physics, Polarization Components 502, 515, Beamsplitters
- 535 Dorf, R. C. "Modern Control Systems"
pp. 195-280, Addison Wesley (1974)
- 536 Thaler & Brown "Servo-Mechanisms Analysis"
McGraw Hill, pp. 124-133 (1953)
- 537 General Scanning, Inc. "G-100 PD Optical Scanner"
- 538 Grenda, P. & Brosens, P. "Closing the Loop in Galvo Systems"
Electro-Optical Systems Design Magazine, pp. 31-34 (1974)

Brosens, P. & Grenda, E. "Applications of Galvanometers to Laser Scanning"
Society of Photo-Optical Instrumentation Engineers, August 19-23, San Diego, Cal. (1974), pp. 54 - 59
- 539 Michelson, A. A. Phil. Mag. (5) 13, 236 (1882)

Born, M. & Wolf, E. "Principles of Optics"
pp. 300-302 (1974)
- 540 Dukes, John N. & Gordon, Gary B. "A Two-Hundred-Foot Yardstick with Graduations every Microinch"
Hewlett-Packard Journal, Aug., pp. 2-8 (1970)

- 541 Baldwin, R. R. et al, "Remote Laser Interferometry"
Hewlett-Packard Journal, December pp. 14-19 (1971)
- 542 Herreman, G. O. "Laser/Calculator System Improves Encoder Plate
Measurements"
Hewlett-Packard Journal, June, pp. 16-18 (1973)
- 543 Baldwin, R. R. et al, "A Laser Interferometer that Measures
Straightness of Travel"
Hewlett-Packard Journal, January, pp. 10-19 (1974)
- 544 Rude, A. & Ward, M. J. "Laser Transducer System for High-Accuracy
Machine Positioning"
February, pp. 2-6 (1976)
- 545 Olson, W. E. & Smith, R. B. "Electronics for the Laser Transducer"
February, pp. 7-18 (1976)
- 546 Hewlett-Packard "System Description for 5501A Laser Transducer"
June 15 (1975)
- 547 Peterson, W. W. & Weldon, E. J. "Error Correcting Codes"
MIT press (1972) pp. 1-18
- 548 Barna, A. & Porat, D. I. "Integrated Circuits in Digital Electronics"
Wiley, pp. 264-342 (1973)
- 549 Motorola "Semiconductor Data Library"
Vol. I - VII (1974)
- 550 Peatman, John B. "The Design of Digital Systems"
McGraw Hill, pp. 180-189 (1972)
- 551 Kilburn, T. et al, "One-Level Storage System"
IRE Transactions on E. C. April, pp. 223-235 (1962)
- 552 Hewlett-Packard "HP 3000 cx Mini Data Centers and Subsystem Data"
(1976)
- 553 Becker, C. H. "Non-photographic Image Recording and Retrieval"
3rd Conference on the Laser, Annales of the New York Academy
of Sciences, Vol. 267, pp. 460-468 (1976)
- 554 Becker, C. H. "Technik der hohäerenten Lichtaufzeichnung"
Internationale Electronische Rundschau, Berlin No. 2, (1966) pp. 83-84
- 555 Polger, John E. & Schulman, Arnold R. "Advantages of Color Laser
Recorder for producing Landsat Large Format Images"
Optical Engineering, 15, pp. 115-118 (1976)
- 556 Hannah, Merle & Harris, William "Laser Color Recording Directly
on Nine-inch color film"
Optical Engineering, 15, pp. 119-123 (1976)
- 557 Claussen, H. C. "Mikroskope"
Handbuch der Physik, Vol. XXIX, Optische Instrumente pp. 380-385 (1960)