19740077978

LASER APPLICATIONS IN NASA PROGRAMS

....

a presentation sponsored by
EIA Laser Subdivision

Tuesday, October 8, 1968

California Room - Fairmont Hotel

San Francisco

Electronic Industries Association

LASER APPLICATIONS IN NASA PROGRAMS
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NOTICE

ELECTRONIC INDUSTRIES ASSOCIATION

2001 EYE STREET, N.W.
WASHINGTON, D. C. 20006

659-2200

The Laser Subdivision of the Electronic Industries Association is happy to present these papers on Laser Applications in NASA programs. They represent an important contribution to the Subdivision's goal of developing better information for its members on the size and potential of laser markets.

We wish to thank the National Aeronautics and Space Administration for their cooperation in arranging the meeting at which they were given.

Malcolm L. Stitch
Assistant General Manager
Korad Department
Union Carbide Corporation
and
Chairman
EIA Laser Subdivision

68-1795

TABLE OF CONTENTS

19740077979

INTRODUCTION AND GENERAL OVERVIEW

Gene A. Vacca
Chief, Instrumentation and Data Processing
NASA Headquarters

The National Aeronautics and Space Administration was established ten years ago by the Space Act of 1958 (coincidentally, the same year the laser was first described) to carry out certain national objectives. Some of the most important of these objectives, are:

1. The expansion of human knowledge of phenomena in the atmosphere and space.
2. The improvement of aeronautical and space vehicles.
3. The development and operation of vehicles capable of carrying instruments, supplies, and living organisms through space.
4. The conduct of long-range studies of benefits to be gained from utilization of space activities.

The physical environment related to those objectives is illustrated in the first slide (RE 68-15206). This picture illustrates the broad arena in which NASA must operate--it goes from the relatively well known terrestrial environment, thru the lesser known earth's atmosphere and into the relatively unknown regions of interplanetary and outer space.

On the next slide (AA 64-1) are illustrated the four major NASA program areas:

At the upper left, is shown the Manned Space Flight Program designed to explore problems associated with travel of man in space. (This program is characterized by Projects Mercury, Gemini and Apollo.)

At the upper right, is shown the Space Science and Applications Program designed to obtain scientific data on the sun, earth, planets and stars, and to develop useful applications of satellites in fields such as meteorology, astronomy, communications and navigation. Typical spacecraft are the Orbiting Solar Observatory, Orbiting Geophysical Observatory, TIROS, Nimbus and SYNCOM.

The Tracking and Data Acquisition Program shown at the lower right, provides the tracking stations and data acquisition facilities around the globe, to support the flight programs.

The Advanced Research and Technology Program, shown at the lower left, is the one with which I am directly associated. Our job is to provide the advances in research and technology required for the nation's aeronautical and space programs. We have the responsibility for advancing the state-of-the-art in the fields of aeronautics, materials, space vehicles, chemical and electric propulsion, electronics, space power systems and biotechnology.

These programs are implemented through a number of major field centers, located as shown in the next slide, (AA 63-22), in various parts of the U.S. There are a total of approximately 30,000 people employed at these centers and the physical facilities include wind tunnels, structural laboratories, environmental chambers, simulators, launching complexes, rocket test stands, test ranges, and data reduction facilities, in addition to offices and utilities. These facilities, built up over the years, are part of our national resources.

NASA activities, ranging from basic scientific research and technological development, to practical application and utilization, are implemented by a large cooperative national triangle composed of government, industry and universities. Approximately 90% of our appropriated funds, are spent for research and development outside NASA--in industry, universities, and other government agencies.

Turning now to the specific topic of our meeting today: Lasers. After the laser was first described by Arthur Schawlow and Charles Townes in 1958 and demonstrated by Maiman in 1960, its unique characteristics (coherence, single frequency, high energy density, etc.) and useful properities, have been recognized and become widely known and are being used in an increasing number of operational and research applications at many NASA facilities. New applications are being investigated at many NASA centers and research into laser improvements, new types of lasers and basic laser physics is also underway. Some of the major technical areas of interest are shown on the next slide (1806). These range from Instrumentation (in test facilities, aircraft, spacecraft), deep space, near earth and earth based Communications, Tracking (and navigation) and Data Processing to Propagation phenomena and basic research related to materials, modulation techniques, molecular and atomic actions, etc.

The other speakers here today from the NASA centers will discuss all the areas listed except Data Processing. There was not sufficient time to cover all areas--and this area was omitted for that reason--not because of any lack of importance. In fact we plan to use lasers to help achieve the large data storage (memory) requirements we foresee and to help solve the problem of handling large volumes of data which are forecast for some of the future space missions--both near earth (e.g. Earth

Resources, MOL and Astronomy) and deep space (future Mariners, Voyagers).

An example of one research effort designed to provide the high capacity memories/data storage which will be required in the future is illustrated, in principle, on the next slide. It utilizes the peculiar properties of certain crystals such as Gadolinium Iron Garnet. When a spot on such a crystal is heated with a laser beam to a temperature above its compensation point (as shown on the left of the figure), and in the presence of an external magnetic field, it becomes magnetized. The spot remains magnetized after cooling and constitutes a stored "bit" which is aligned with the direction of the external field. A number of bits are stored by moving the beam across the face of the crystal. Readout of the stored information (shown on the right) is accomplished by transmitting a beam of polarized light (from a laser or other source) through the magnetized spot in the transparent crystal. As the beam passes through the spot, the Faraday effect causes a rotation of the plane of polarization which may be sensed by a photocell to "read" the stored bit. Storage of a one, or a zero, in binary format is controlled by the direction of the external magnetic field. (Other materials under study are Manganese Bismuth and Potassium Bromide.)

Studies have shown that packing densities of 10^7 to 10^8 bits/sq. in. may be realizable. (For space applications, our goals are to achieve 10^8 bits fast random access and 10^{12} bits bulk storage.)

In order to give you an idea of the extent to which lasers are being used in NASA facilities: A recent quick inventory showed a total of <u>277</u> lasers of all types (gas, solid state, CW, pulsed) and ranging in output, from very small to very large, in use at: ARC, ERC, GSFC, JPL, LaRC, MSFC. It is estimated that approximately $9 million per year is being spent on laser research and development and application efforts in NASA.

Although our prime interest is the useful application of unique laser characteristics, we are also concerned and aware of the hazard associated with lasers and have a safety program in the agency administered by the Director of Occupational Medicine, through the Environmental Health program.

The American Conference of Governmental Industrial Hygientists, "Guide for Uniform Industrial Hygiene Codes or Regulations for Laser Installations," issued 1968, is being used as a guide for laser safety in NASA.

I would now like to introduce the other speakers who will present the papers listed in your program with one change: the paper on Laser Technology will be given last, so the order will be:

1.	Dr. Joseph L. Randall	Laser Communications
2.	Michael S. Shumate	Deep Space Optical Communications
3.	Dr. Henry H. Plotkin	Laser Tracking
4.	Dr. James L. Lawrence	Laser Atmospheric Instrumentation
5.	Benjamin H. Beam	Laser Test Facility Instrumentation
6.	Dr. Paul C. Fletcher	Laser Technology

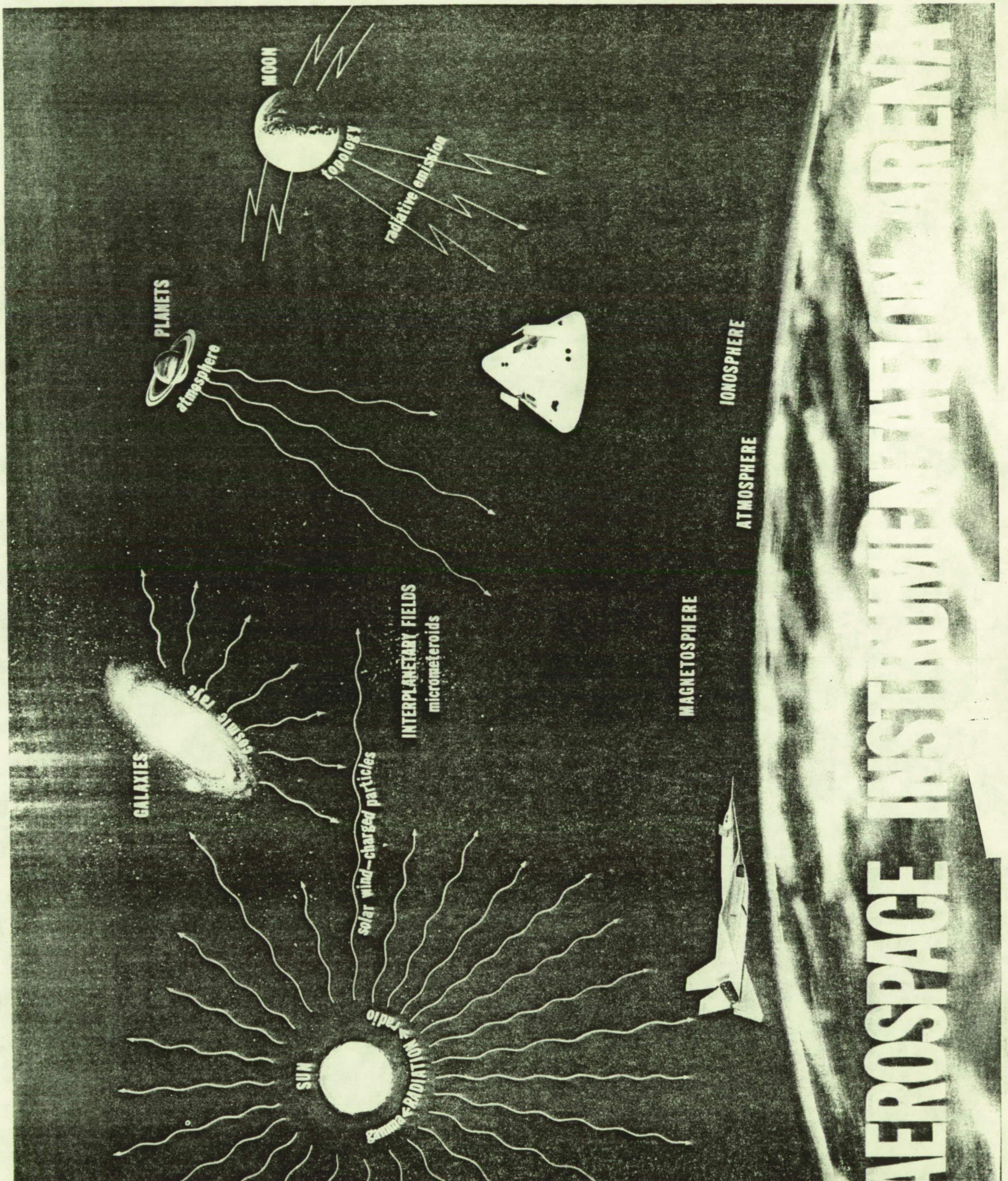

AEROSPACE INSTRUMENTATION ARENA
SUN
gamma RADIATION radio
Solar wind—charged particles
GALAXIES
cosmic rays
INTERPLANETARY FIELDS
micrometeroids
PLANETS
atmosphere
MOON
topology
radiative emission
MAGNETOSPHERE
ATMOSPHERE
IONOSPHERE

Figure 1

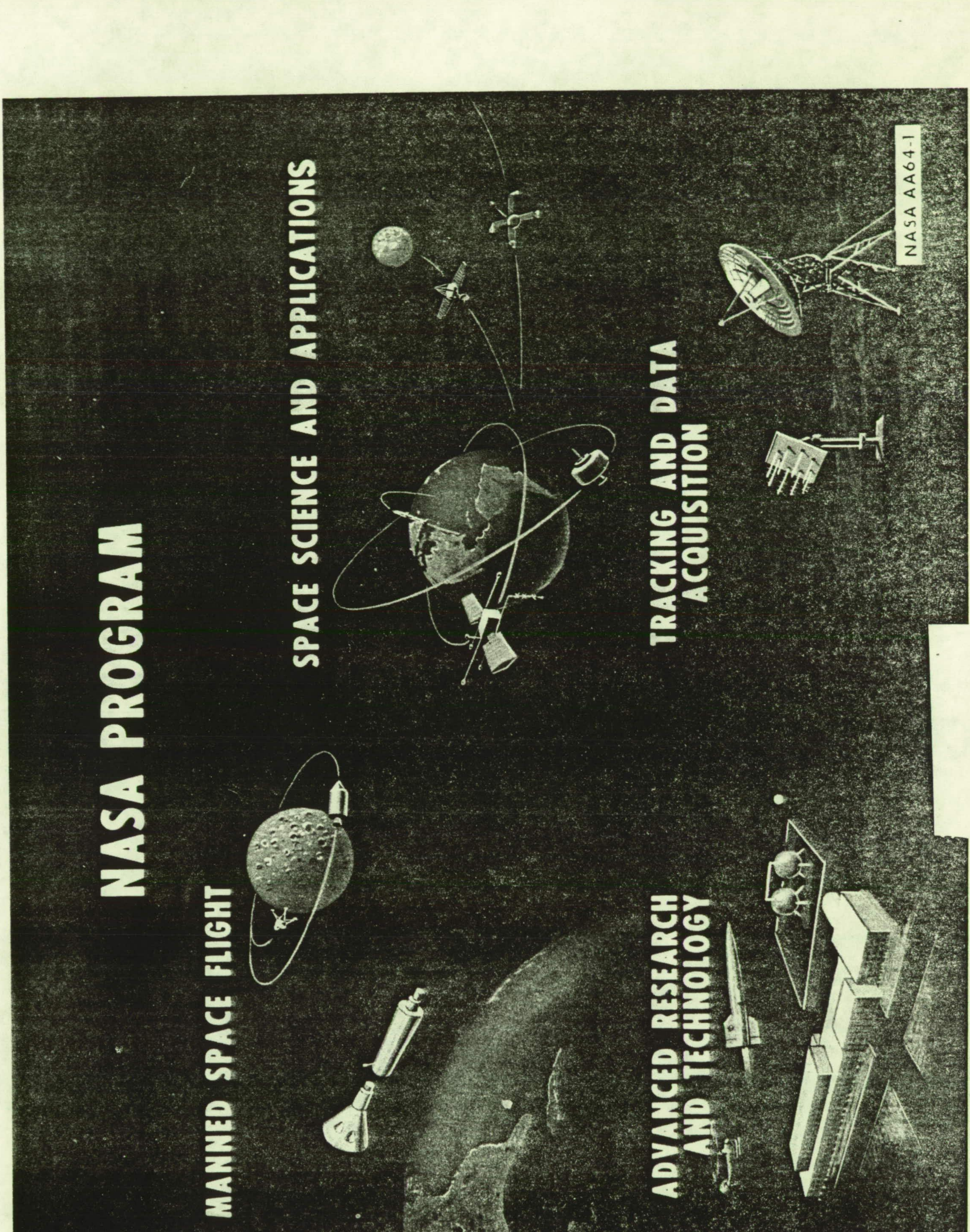

NASA PROGRAM
MANNED SPACE FLIGHT
SPACE SCIENCE AND APPLICATIONS
ADVANCED RESEARCH AND TECHNOLOGY
TRACKING AND DATA ACQUISITION
NASA AA64-1

Figure 2

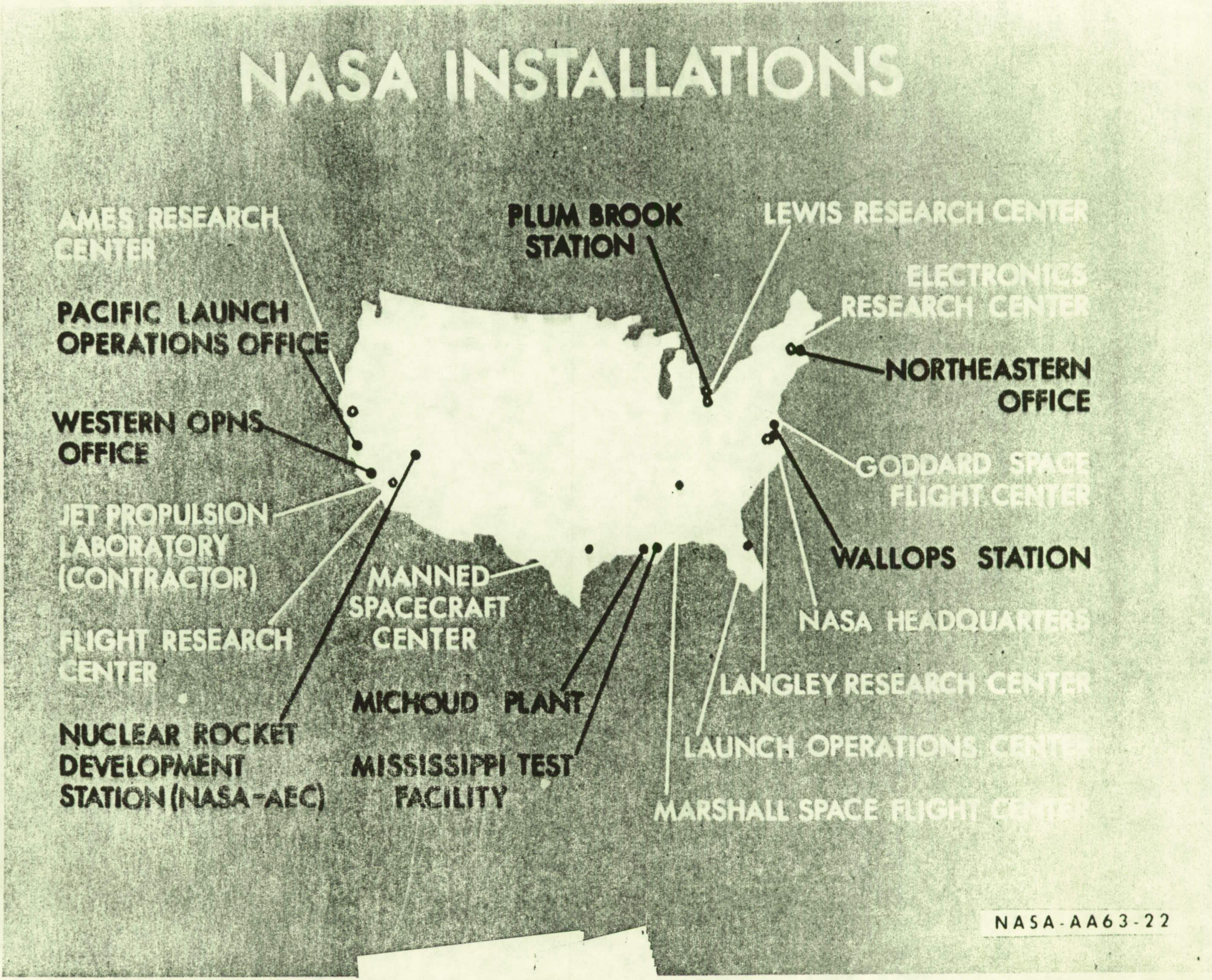

NASA INSTALLATIONS
AMES RESEARCH CENTER
PACIFIC LAUNCH OPERATIONS OFFICE
WESTERN OPNS OFFICE
JET PROPULSION LABORATORY (CONTRACTOR)
FLIGHT RESEARCH CENTER
NUCLEAR ROCKET DEVELOPMENT STATION (NASA-AEC)
PLUM BROOK STATION
MANNED SPACECRAFT CENTER
MICHOUD PLANT
MISSISSIPPI TEST FACILITY
LEWIS RESEARCH CENTER
ELECTRONICS RESEARCH CENTER
NORTHEASTERN OFFICE
GODDARD SPACE FLIGHT CENTER
WALLOPS STATION
NASA HEADQUARTERS
LANGLEY RESEARCH CENTER
LAUNCH OPERATIONS CENTER
MARSHALL SPACE FLIGHT CENTER
NASA-AA63-22

Figure 3

TECHNICAL AREAS

INSTRUMENTATION

DEEP SPACE TRACKING AND COMMUNICATIONS

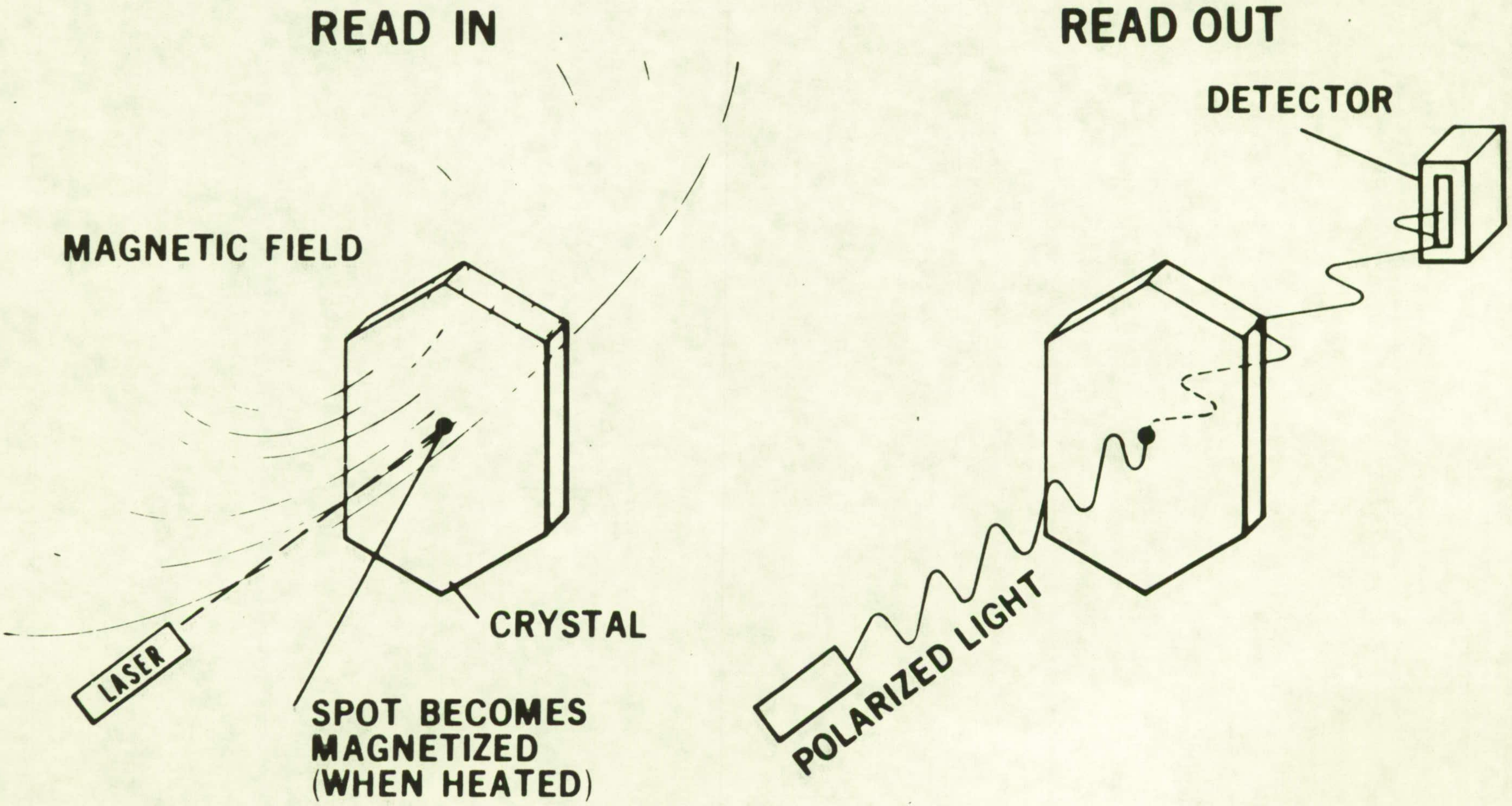
DATA PROCESSING

OPTICAL COMMUNICATIONS AND TRACKING

PROPAGATION PHENOMENA

Figure 4

COMPUTER TECHNOLOGY
OPTICAL MEMORY PRINCIPLE



READ IN

READ OUT

NASA RE 67-409
12-15-66

Figure 5

19740077980

LASER COMMUNICATIONS

Dr. Joseph L. Randall
Marshall Space Flight Center

I Introduction

Since the development of the laser, considerable research and development (R&D) has been performed on electro-optical techniques for optical communication and tracking. Several NASA Centers have been very active in this technology. This discussion deals primarily with the R&D program at the Marshall Space Flight Center with the aim of giving our philosophy of approach and identifying the problems and what might be done to sole them.

Several years ago, it was thought that the most basic problem associated with optical communication was that of pointing narrow laser beams. Accordingly, a theoretical and experimental program was initiated to solve this problem. At that time, it was known that, although the best laser for transmitting information was not yet available the techniques of pointing could be developed with the lasers that were on hand; those lasers being the HeNe laser operating at 6328Å and the Argon laser operating at 4880Å.

Other problems to be attacked included (a) acquisition, (b) atmospheric effects on an optical channel and the modulation format should be used to combat these effects, (c) low electrical efficiency of the lasers and modulators which in turn means a high power consumption of the spacecraft, and (d) maintaining diffraction limited optics in space.

These problems have been systematically approached by NASA and the results of some of these programs are given to indicate the present state of the technology. One appropriate question that can be asked is this:

How close to the theoretically calculated data rates can realistic, practical hardware be made to operate at this time?

Also discussed are some indications of where improvements can be made in devices and components to give a better system performance and some proposed experiments that are needed to give unequivocal proof of the feasibility of optical/infrared communications.

II Recent Advances in Pointing and Tracking Hardware

As was mentioned earlier, NASA initiated hardware development for the precision pointing and tracking of a laser communication system. This work has been performed for MSFC by Perkin-Elmer under Contract NAS8-20115; the program has been in effect for about four years. This work was aimed at the requirements for a deep space optical communication system in which the pointing requirements are the most severe. Of course, there is a difference in an optical communication system and an astronomical optical system. An astronomical telescope must track an astronomical object in order that the desired radiation falls on the film or appropriate sensor without angular motion, whereas the optical communication system must point a very narrow laser beam with information on it in the direction of the receiver. For instance, a one meter telescope or antenna of an optical communication system operating at visible wavelengths will have a beamwidth of only a few tenths of an arc second. At a range of 160 million kilometers this would cover a spot on the earth of only about 160 kilometers. And since the beam must be pointed to within a fraction of the beamwidth to assure hitting the earth receiver, the pointing system must be very accurate and precise. Obviously, if a system operating to these specifications could feasibly be built, systems with less stringent mission requirements could be made also. This then was the philosophy behind the Perkin-Elmer work.

The techniques used have been reported previously at the EIA Aerospace Briefing for Industry in May 1967, but a quick review will be given here to explain more accurately the advances that have been made and the stage of the present equipment.

Figure 1 shows how this technique functions. The basic concept of the two-way optical communication link is for both the ground station and the spacecraft to have a laser beacon and a precise tracking system so that each will track the laser beacon of the other. The optical beamwidths will be arc seconds or less; therefore, the beam must be pointed to a fraction of this beamwidth if it is to communicate with another station. Common optics are used rather than a separate tracking telescope and transmitting telescope because of size reduction and the difficulty of boresighting and maintaining the boresight of two large independent telescopes. Both the ground station and the satellite would have such telescope systems.

After an initial acquisition phase, the received light from the ground station is reflected by the primary/secondary combination onto a coarse tracking sensor which subtends a one-degree field of view. The coarse tracking sensor is a four quadrant photomultiplier with a prism lens combination dividing the image into the four quadrants. The derived error signal is used to move the telescope so that the received light falls through an approximately 2-arc-minute field-of-view hole onto the fine sensor. Because the mass of the telescope is so large, fine tracking is done by a transfer lens. As the image moves off the apex of the beamsplitting prism, the error signals generated are fed to the transfer lens to bring the image back to the apex of the prism. At the same time, this motion of the transfer lens corrects the pointing of the transmitting laser; that is, small motions of the telescope are corrected by the transfer lens, and the transmitted beam with the information always goes back in the direction of the tracked beacon. An optical modulator is used to place information on the transmitted beam. The required point-ahead function of the system is shown implemented by means of a pair of Risley prisms.

Relative and joint rotations of the Risley prisms accomplish two coordinate angular offsets of the transmitted laser beam from the line of sight of the receive channel. A lateral translation of either laser lens would have an identical effect.

An experimental breadboard of the fine tracking and laser repointing system with a 40 cm (16 in.) primary was systematically developed and studied to demonstrate the feasibility of the technique. The results of that study showed the following:

1. The fine guidance tracking detector and transfer lens servosystem operated satisfactorily. The system demonstrated that the transmit laser beam is pointing to an accuracy of 0.1 arc second with respect to the receive channel. This has been achieved with telescope motion which simulates spacecraft motion.

2. Intensity fluctuations of the laser in the far field are no problem.

3. The transmitter beam has been isolated from the tracking detector by using two wavelengths, 6328Å and 4800Å. Isolation of one part in 10^{10} has been achieved.

4. The coarse acquisition system and the Risley prisms subsystem have been developed and are operating satisfactorily.

The transfer lens servosystem will take out motion of the telescope only within reasonable limits; therefore, the spacecraft carrying the telescope and communication system must be stabilized. Studies have shown that the required telescope stabilization should be about ±1/4 arc minute. If the telescope is mounted directly to the spacecraft, the spacecraft must then be stabilized to the same accuracy. If man is present in the spacecraft, distrubance torques must be isolated from the telescope. If the telescope is mounted to the spacecraft through an active gimbaling system, then the spacecraft should be stabilized to ±1/2 degree to perform acquisition. Presently scheduled flight experiments such as the Orbiting Astronomical Observatory (OAO) and the Apollo Telescope Mount (ATM) have more severe requirements.

Figure 2 shows the equipment in the breadboard stage as it was used to demonstrate feasibility. With the feasibility demonstrated, the next phase was the development of a prototype of the system in which all the hardware was combined into a telescope package as might be used in space. Several new additions, however, were incorporated into the new prototype (Figure 3). First, the optical system was made all reflective in the transmit channel for the system to operate with any wavelength from the visible to the infrared. This will allow operation at the 10.6-micron carbon dioxide laser. This was done by changing the "transfer lens" to a "transfer mirror" for image motion compensation. The transfer mirror is suspended by four piezoelectric bimorph beam benders to give the required rotation about two axes. The frequency response of the mirror is about 50 hertz. In this package, dichroic beam splitters are designed to allow the system to operate in either the visible or infrared. Since the Risley prisms use refracting optics, they are now placed in the receive channel which operates at 4880Å. This can be done because it makes no difference which channel they are in.

The second major change in the system is that the entire package is now placed in a four-axes gimbal to simulate spacecraft motion. The two inner gimbals represent the pitch and yaw gimbals that would be used to mount the telescope to a spacecraft. The outer two gimbals will give roll and a rotation about the vertical axis. These two rotations represent the spacecraft motion. Thus with the four-axes gimbal system, a simulated spacecraft motion can be performed and an analysis of the communication system performance can be made while tracking on an earth beacon simulated by a 50-cm collimator. Figure 4 shows this setup. In addition, the simulated earth beacon can be amplitude modulated to simulate atmospheric scintillation on the up going beam. Laboratory experiments to study these problems are now being performed. At the present time, only a visible laser has been installed in the system, but plans call for the addition of a coherent 10.6-micron carbon dioxide laser communication system into the prototype package.

In addition to the hardware development, MSFC also let a contract to IBM to perform a complete computer simulation of the spacecraft optical communication system. In this simulation an ATM spacecraft and attitutde control system was used. For the communication hardware, the Perkin-Elmer system was used. This simulation will allow an analysis and evaluation of the acquisition and pointing of the complete communication system including spacecraft. This program has been written and indicates that satisfactory operation can be achieved hardware. Further studies are now being performed to determine where improvements can be made in overall system performance.

III Data Rates Attainable with Optical Infrared Communications

Assuming that it is possible to point laser beams with the systems discussed previously, it is now appropriate to discuss the data rates that can be achieved with optical and infrared (IR) wavelengths. At the present time it appears that the two best candidates for laser communication are the frequency doubled YAG:Nd laser that operates at 5300Å and the 10.6-micron carbon dioxide laser. Powers of several watts at efficiencies of about one percent should be available in the near future at the 5300Å frequency doubled YAG laser. This represents by far the best laser in the visible wavelength region. The high power and high efficiency of the 10.6-micron CO_2 laser also make it a very promising candidate.

In building a communication system at these two wavelengths, analysis and experimental results dictate that the best approach is to use incoherent detection (or photon counting) in the visible and coherent (or heterodyne) detection at 10.6 microns. This places certain requirements on each of the two systems. For instance, the 10.6-micron system uses a local oscillator laser at the receiver which heterodynes with the transmitter laser. This means that they both must be stable in frequency so that the beat signal can fall in the IF amplifier frequency range. In addition, large doppler frequency shifts must be accounted for. Perhaps the most severe requirement is that a completely automated CO_2 laser in space must be constructed to operate at the proper frequency anytime it is turned on in order that a beat signal with the local oscillator may be achieved during initial acquisition when a search in frequency and space must be made.

Research to solve some of these problems is underway and will be discussed below.

A. 10.6-Micron Coherent Communication System

Two coherent 10.6-micron communication systems have been built. Hughes Aircraft built one that transmits television bandwidths and utilizes a modulator internal to the laser cavity. Honeywell built the other one on contract to NASA-MSFC. That system uses piezoelectric pushers to modulate the laser cavity length, thereby frequency modulating the laser output. Figure 5 shows a block diagram of that system, which is capable of transmitting two voice channels. Evaluation of the system performance has shown that it experimentally operates to within a factor of two of the theoretically calculated performance. Figure 6 shows this graphically. Thus it has been shown that coherent 10.6-micron systems can be designed and built to operate very close to the theoretical limits.

B. Incoherent Visible Communication Systems

Incoherent detection is superior in the visible region for several reasons. First, the atmosphere is very effective at destroying spatial coherence at visible wavelengths. This then places an upper limit on the receiver aperture size in the order of several centimeters for coherent detection if background noise radiation can be eliminated, it is advantageous to use incoherent detection and count photons. In that case, there is no atmospheric limitation on receiver aperture size and the receiver can be made as large as is practical to collect more energy. Analysis has shown that with small receiver fields of view and very narrow spectral bandpass filters, the background radiation can be made small with respect to the signal radiation. Thus one can achieve signal-to-noise ratio time bandwidth products that are equivalent to coherent detection without all the inherent disadvantages of coherent detection. The main disadvantages of the coherent visible system are that the laser efficiency is low and the quantum efficiency of detectors in the visible is low.

Experimental systems have been built to test the feasibility of high data rate incoherent systems. Analog modulation of the intensity is not practical because of the amplitude scintillation by the atmosphere. Pulsed modulation with threshold detection is a much better approach. Several such pulse code modulated (PCM) systems have been built and results of the performance of one built by ITT under contract to NASA are now discussed. Figure 7 shows a block diagram of that system.

The ITT communication system operates at 6328Å and is modulated at a 30 megabit per second rate. It is a binary code PCM system that can operate either in an "on-off" mode or it transmits right- and left-handed circularly polarized light to work the "ones" and "zeroes" of the binary code. This system is unique in that the error rate per bit can be measured. This then allows the comparison of experimentally measured error rates and the theoretically calculated values based on Poisson statistics. The results of one such run, depicted in Figure 8, show that the system is operating very close to the theoretical limit. These results are based on a 50% modulation depth and need to be verified for 100% modulation depth. Many tests of this system over an 8-km range have been performed under varying atmospheric conditions. An interesting result, shown in Figure 9, is the reduction of error rate per bit with increasing receiver aperture diameter. This curve is normalized to constant input power. These results are predicted from theory and indicate the advantage of using a large receiver aperture to aperture average and thus decrease scintillation-induced error rates.

IV Conclusions and Recommendations

From the preceding remarks it can be seen that much has been done in the past several years to develop optical and infrared communication systems. Yet, we still do not have enough information to reach a decision as to what system or technique should be used in the various applications of the laser for space communications. For instance, further R&D is required to determine whether the visible or the infrared should be used. Both wavelength regions have room for considerable improvement. Some of the more obvious areas where improvements could be made are as follows:

a. Laser sources - In both the visible and IR, a more efficient laser would mean less power required as well as reducing the requirement to eliminate the excess heat generated.

b. Modulators - In the IR, modulators now require fairly high power. New techniques are required to reduce these power requirements.

c. Detectors - The quantum efficiency of detectors in the visible has room for significant improvement. IR detectors have quantum efficiencies of about 50% now and significant improvement will be difficult.

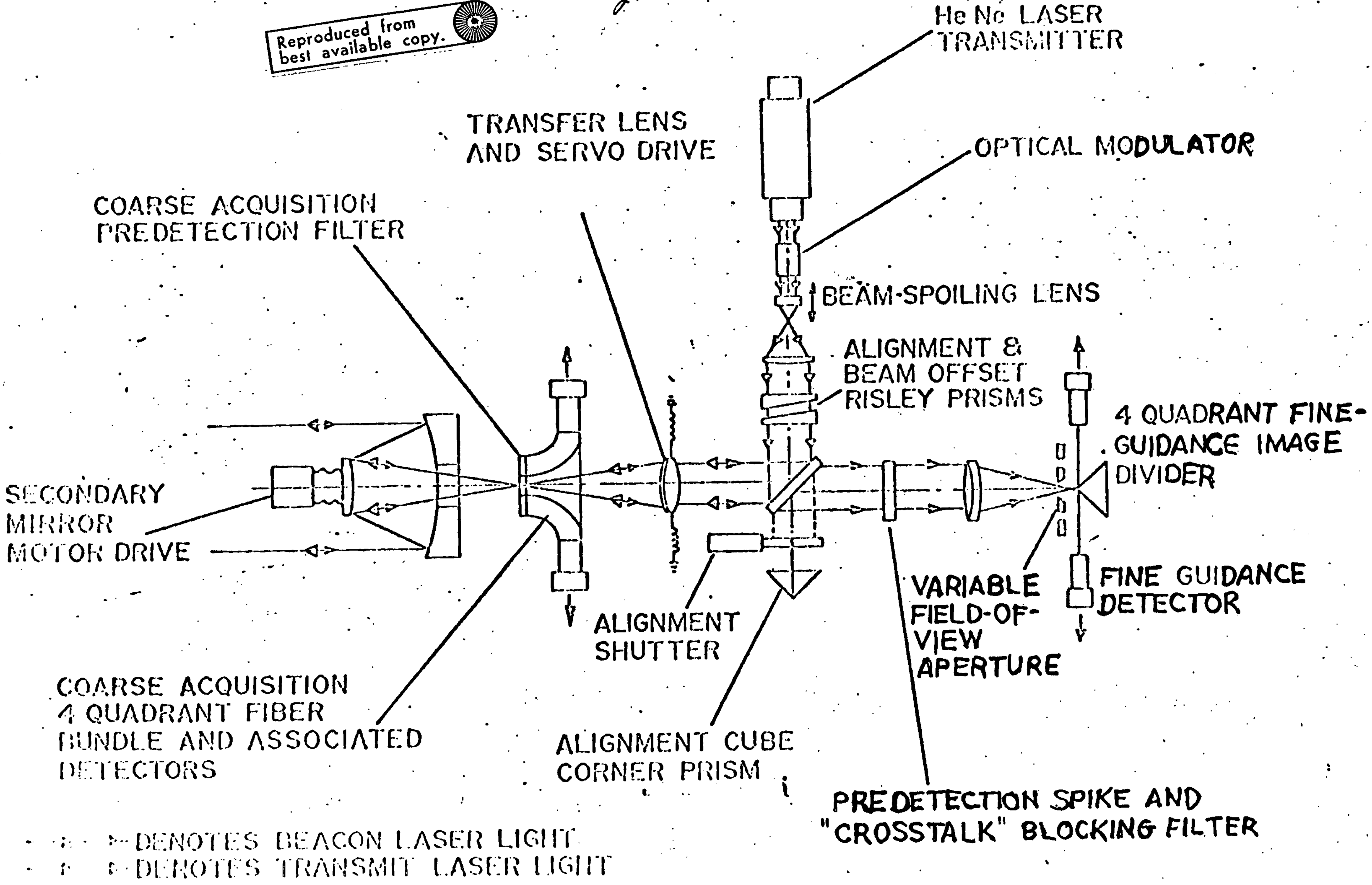
d. Frequency shifters to accommodate Doppler frequency shifts. For coherent detection, some type of practical technique will be required to accommodate Doppler shifts in frequency. It may be that a tunable injection laser can be made to act as a local oscillator such as mixing of a PbSnTe injection laser and a CO_2 laser. This technique as well as others will require research to solve this problem.

e. Determination of the optimum modulation format for both visible and IR wavelengths to combat the degradation of the communication channel by the atmospheric effect.

In addition to solving these problems, there is one other task that must be performed before optical communication will ever get out of the laboratory and into actual use. That task is the successful experiments which simulate mission requirements. Only when this is done will a Program Manager give serious consideration to suing an optical communication system in an actual flight mission.

NASA is now in the planning stage of experiments in space which will be required to demonstrate the feasibility of optical communications and to obtain as much data as possible to allow the final design of communication systems for flight missions.

Figure 1


He Ne LASER TRANSMITTER
OPTICAL MODULATOR
TRANSFER LENS AND SERVO DRIVE
COARSE ACQUISITION PREDETECTION FILTER
BEAM-SPOILING LENS
ALIGNMENT & BEAM OFFSET RISLEY PRISMS
4 QUADRANT FINE-GUIDANCE IMAGE DIVIDER
SECONDARY MIRROR MOTOR DRIVE
FINE GUIDANCE DETECTOR
VARIABLE FIELD-OF-VIEW APERTURE
ALIGNMENT SHUTTER
COARSE ACQUISITION 4 QUADRANT FIBER BUNDLE AND ASSOCIATED DETECTORS
ALIGNMENT CUBE CORNER PRISM
PREDETECTION SPIKE AND "CROSSTALK" BLOCKING FILTER
DENOTES BEACON LASER LIGHT
DENOTES TRANSMIT LASER LIGHT

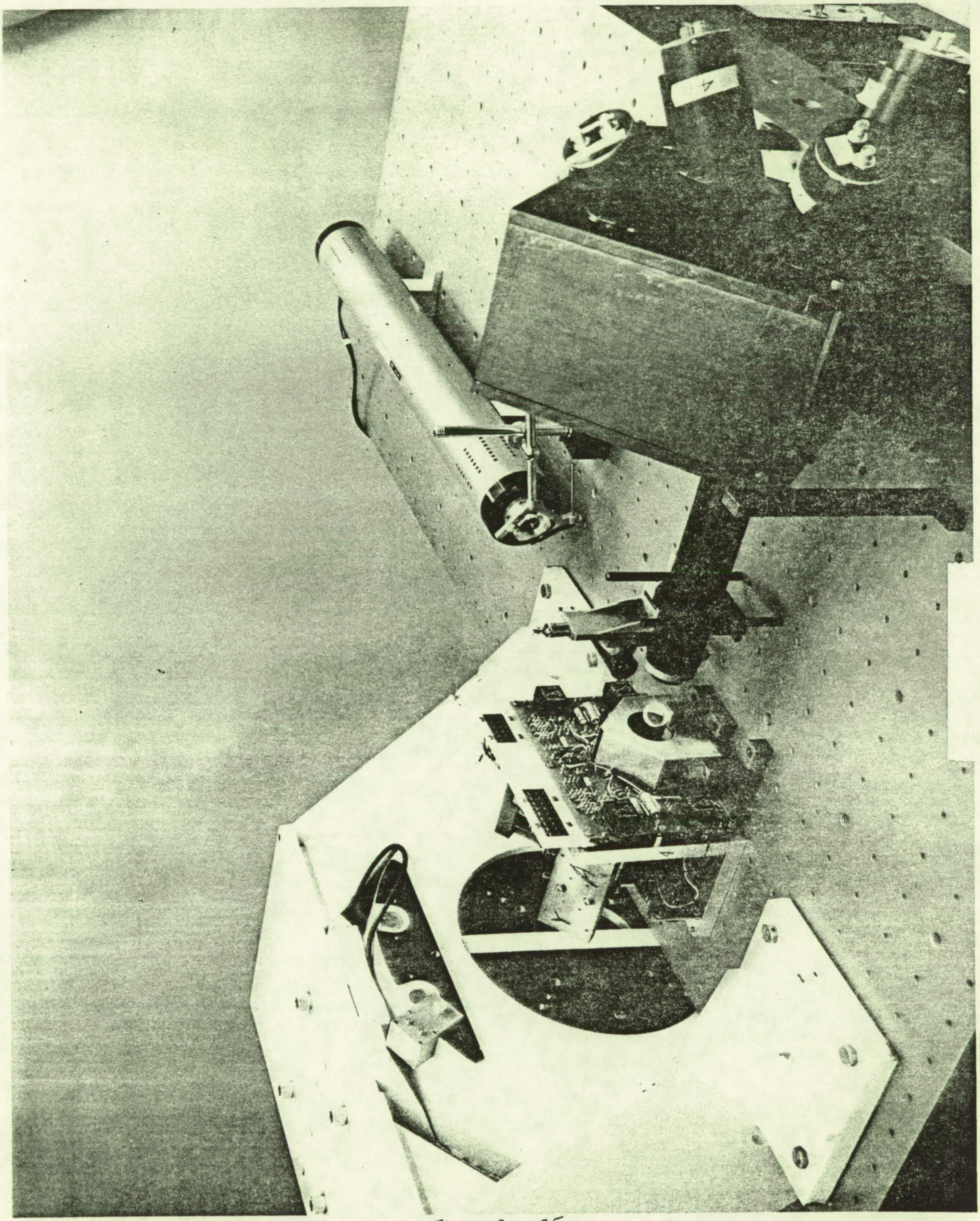
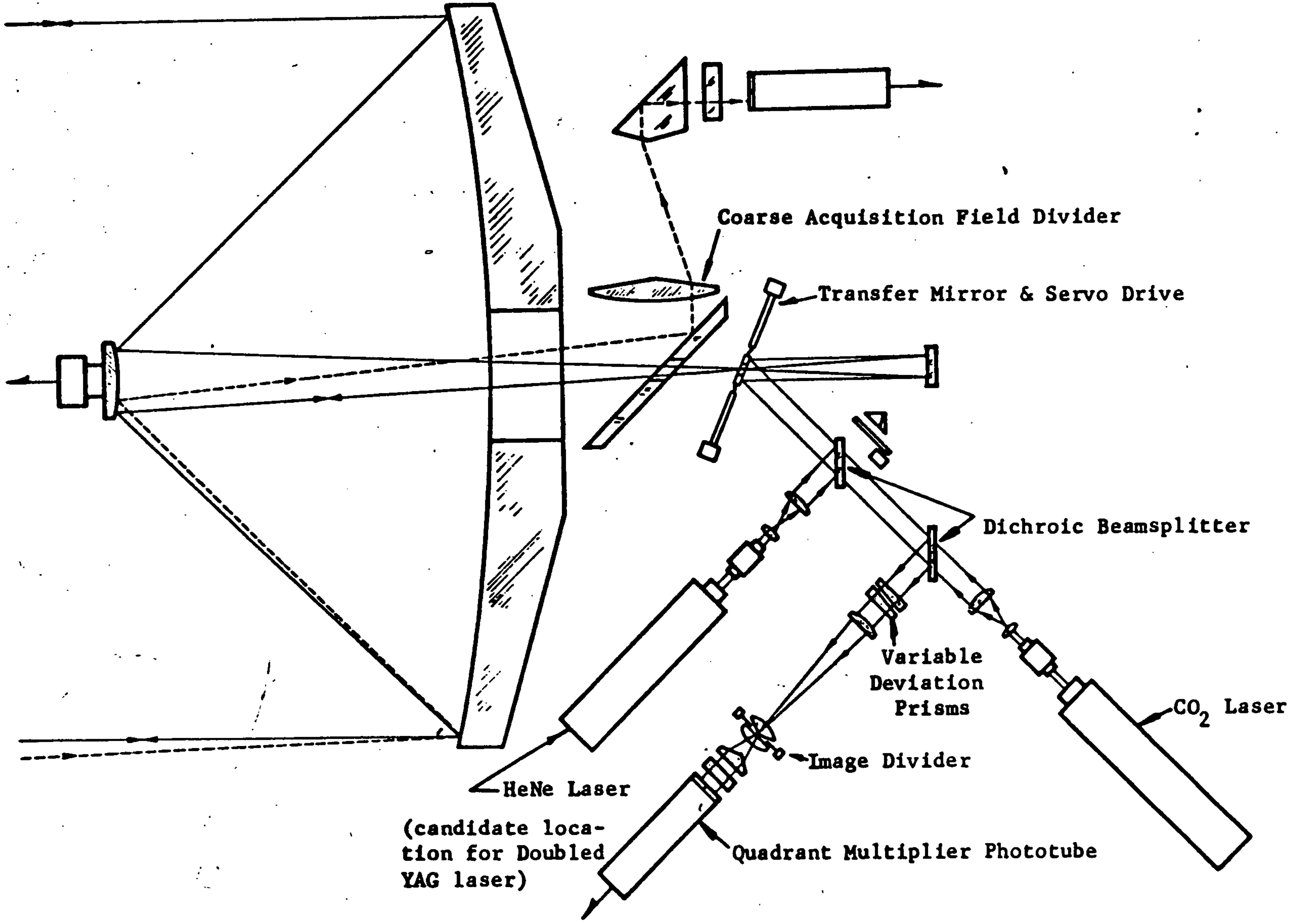
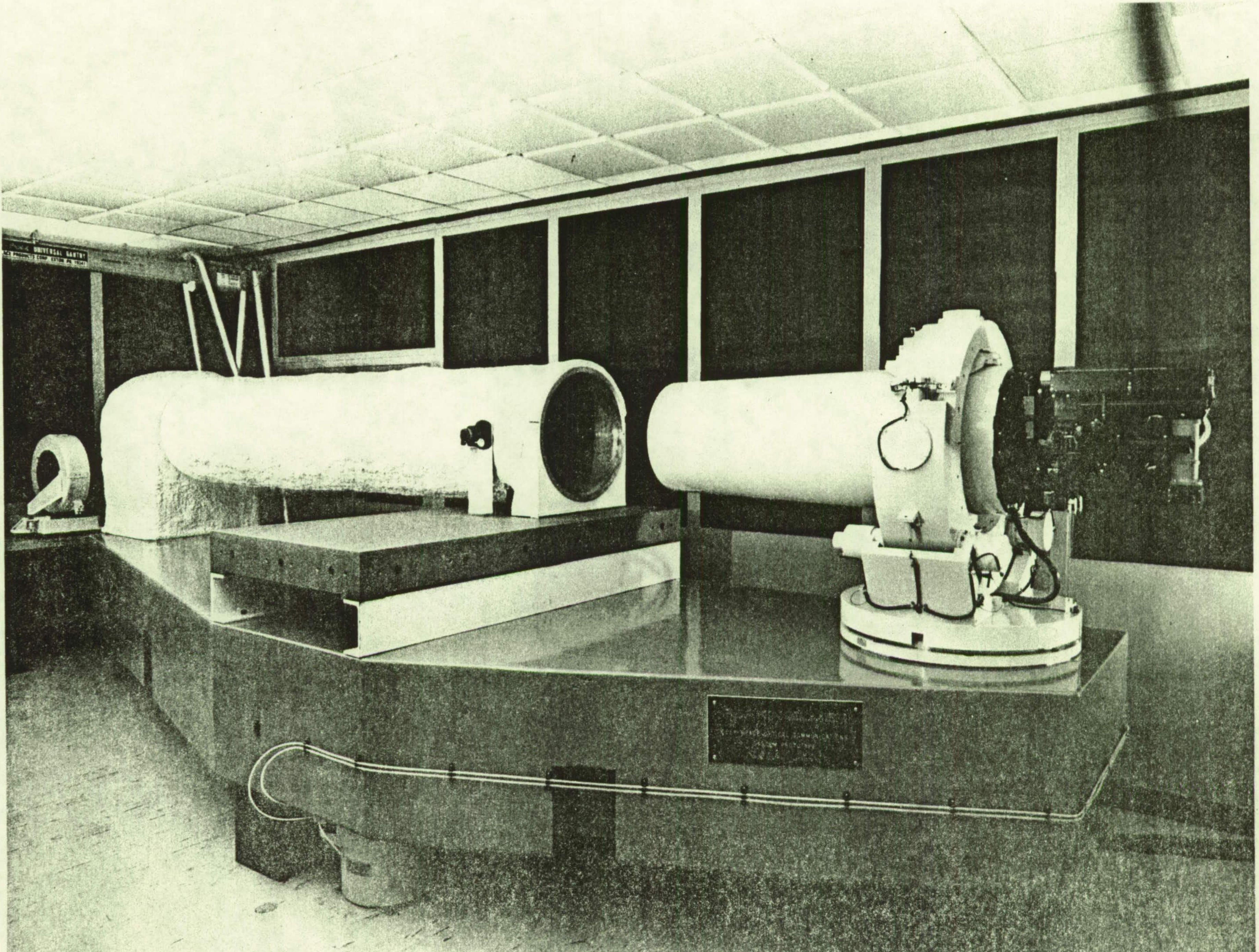


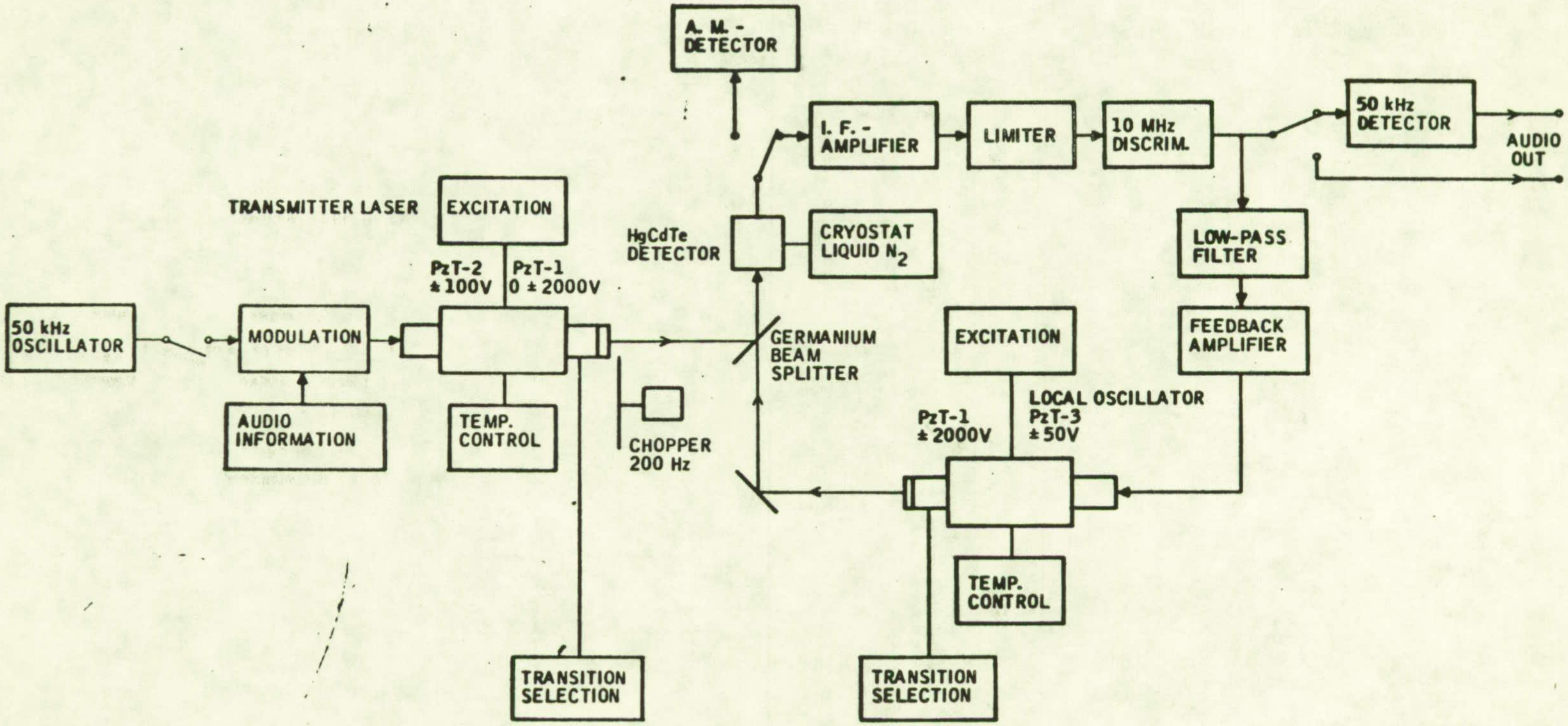
Figure 2



Optical Layout of Laser Telescope

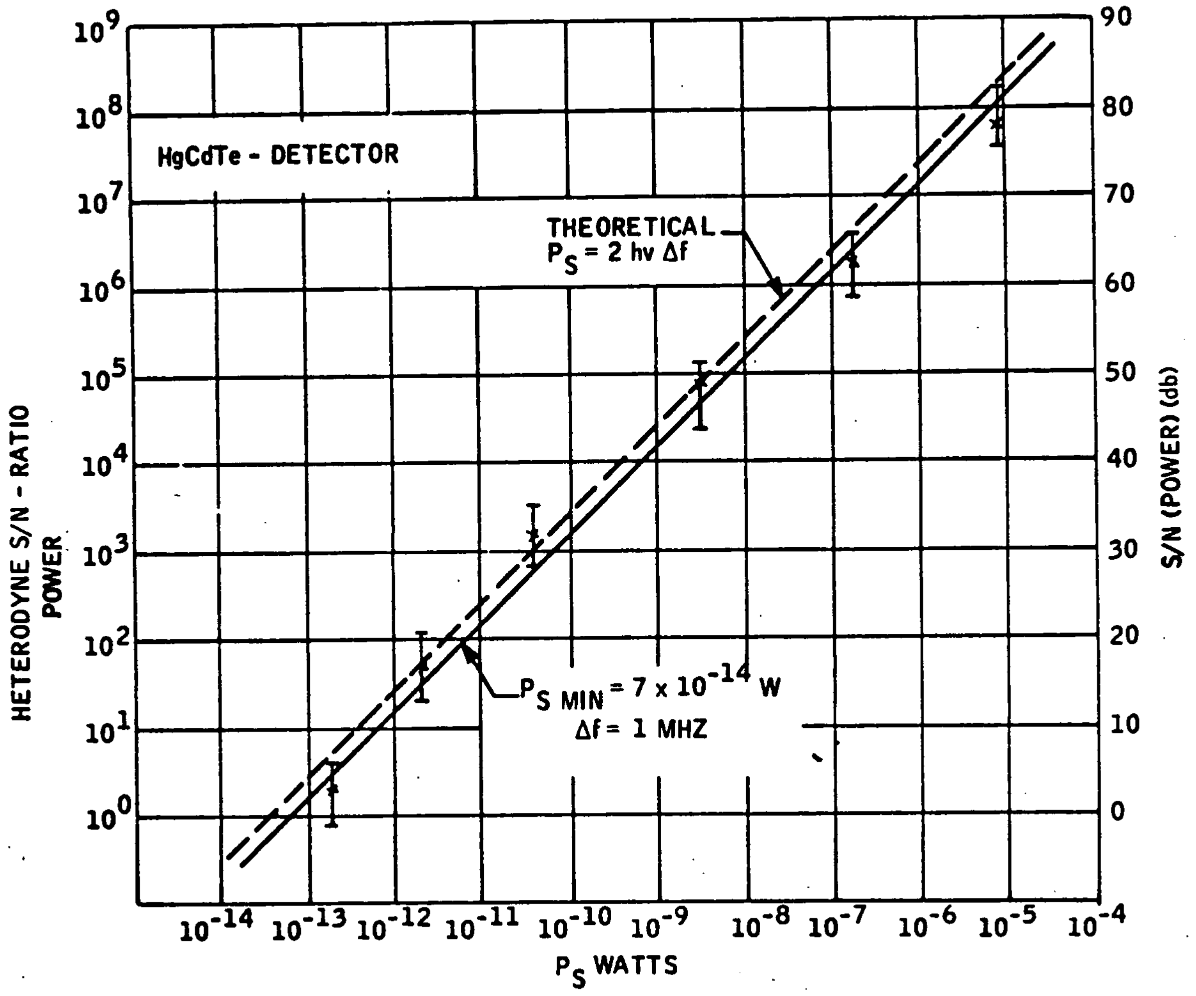
Figure 3


UNIVERSAL GANTRY
PRODUCTS CORP EXTON PA 19341



Two-Ended 10. 6-Micron Optical Communications System

Figure 5



Heterodyne Signal-to-Noise Ratio versus Signal Power

Figure 6

PCM
OPTICAL COMMUNICATION SYSTEM

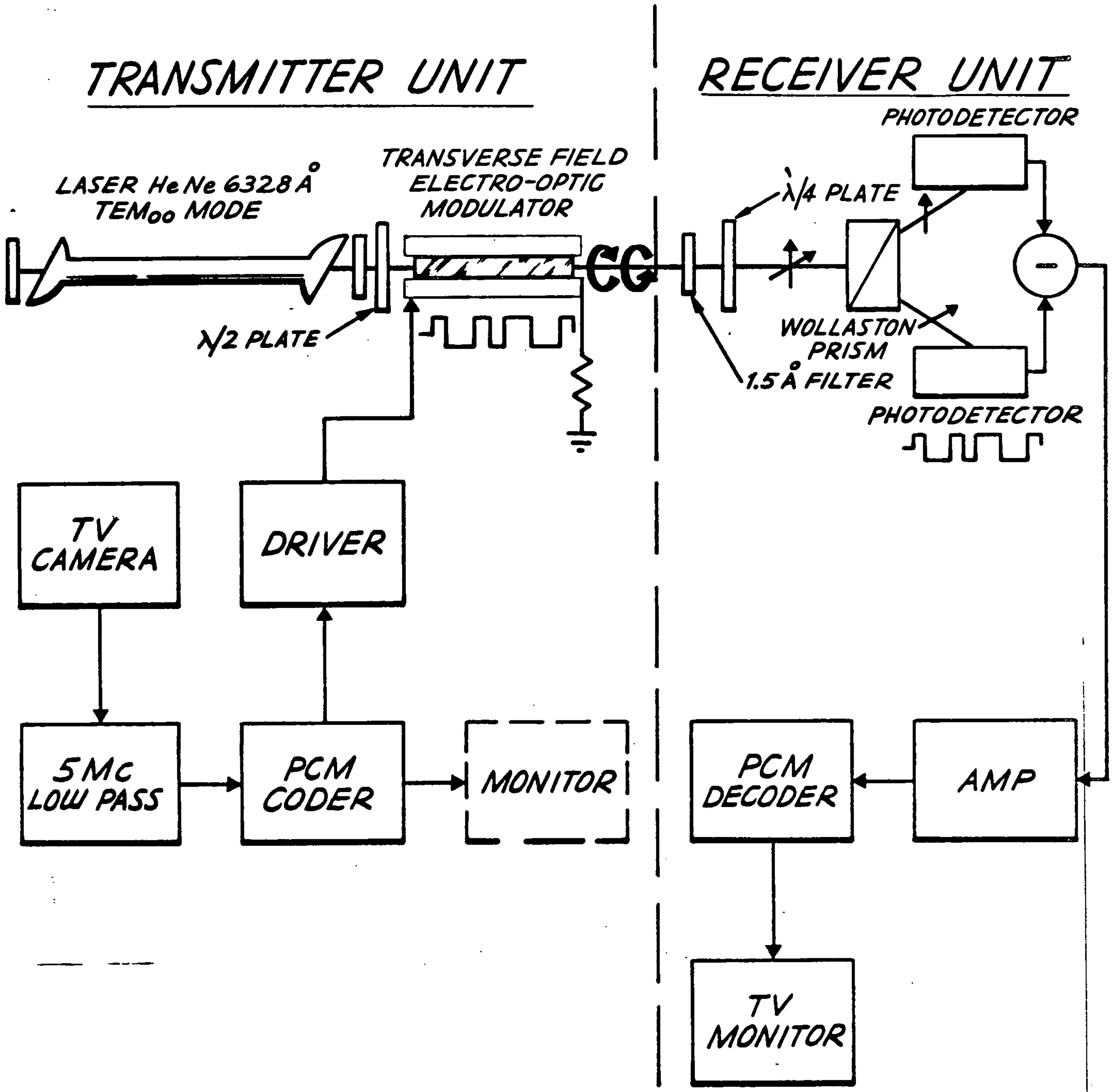
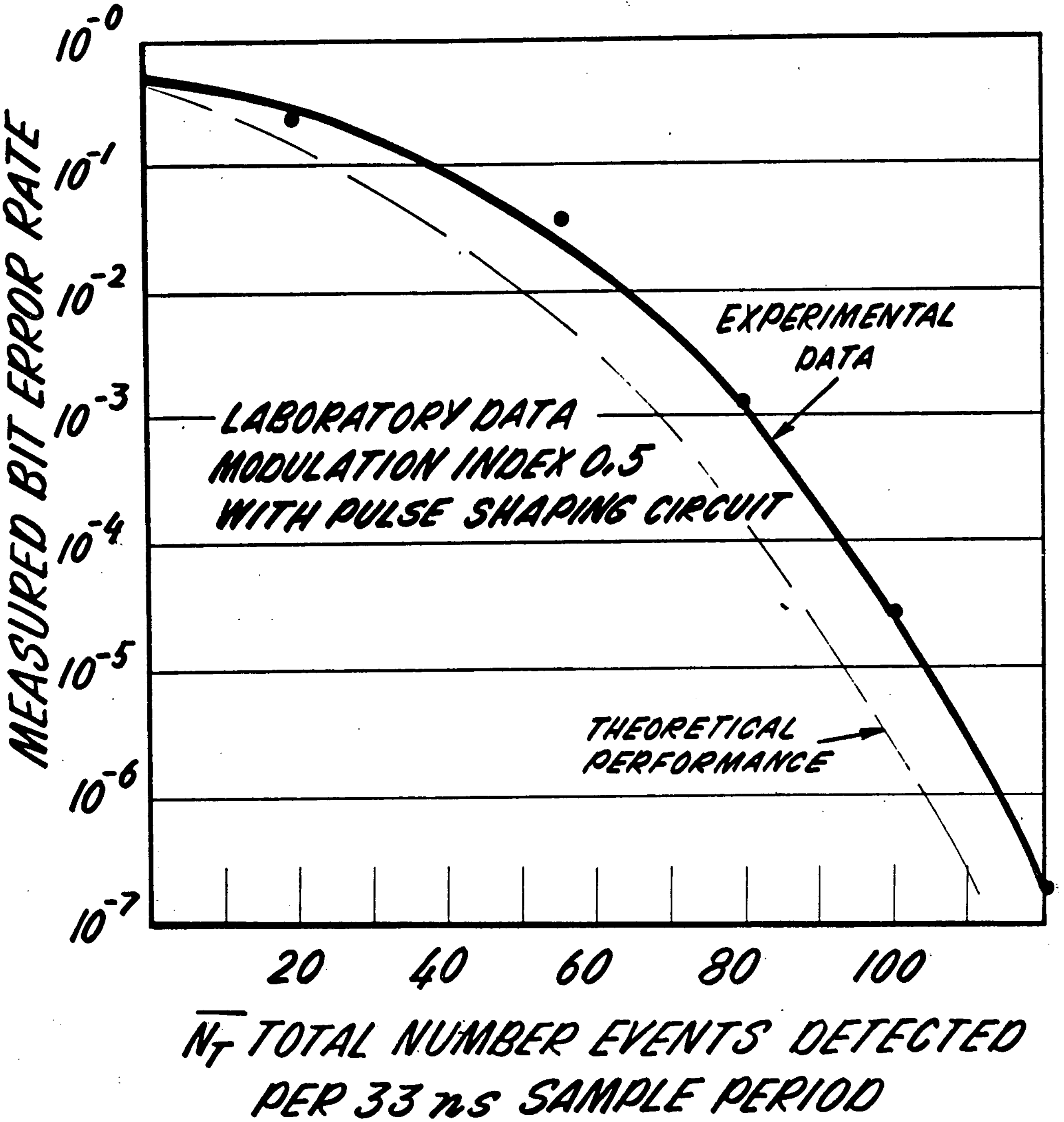


Figure 7

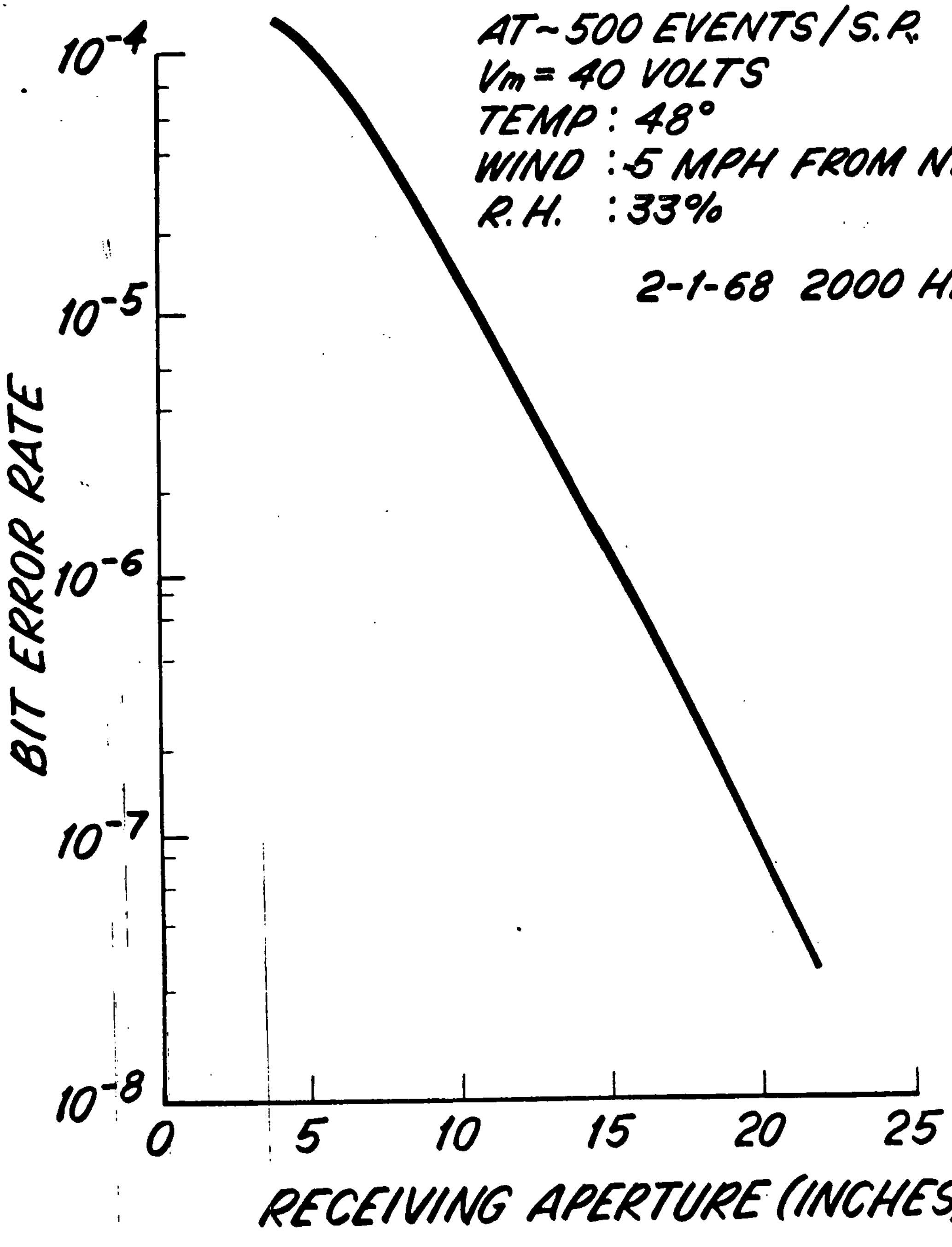
MEASURED SYSTEM PERFORMANCE BINARY DETECTION



(Channel A and Channel B)

Figure 8

BIT ERROR RATE VS RECEIVING APERTURE



SIGNAL LEVEL MAINTAINED
CONSTANT WITH N.D. FILTERS
AT ~ 500 EVENTS/S.P.
V_m = 40 VOLTS
TEMP: 48°
WIND: 5 MPH FROM NE
R.H.: 33%

2-1-68 2000 HRS

ITT AEROSPACE

Figure 9

19740077981

THE POTENTIAL USES OF LASERS FOR OPTICAL DEEP SPACE COMMUNICATION*

M. S. Shumate
Jet Propulsion Laboratory

From the very early days of lasers, their potential for communication was recognized. The property most interesting was single, very high frequency operation. This property can in principle be used to attain two distinct features: very high information bandwidths and very narrow beam angles. The former will be more useful for terrestrial communication, whereas the latter will be advantageous for interplanetary deep space type communication. I will describe the deep space communication problems where lasers would be useful, what limitations are presently envisioned, and what work remains to be accomplished in order to realize an operational optical deep space communication system.

The existing interplanetary communications technique, utilizing two-way S-band at 2300 MHz, has been brought to a very high degree of sophistication; it is a general purpose, all weather type system of very high reliability. It does, however, have a specific limitation: for future interplanetary missions, the information bandwidth economically attainable may not be adequate; furthermore, R. F. spectrum crowding is of a growing concern. By moving to higher operating frequencies, the bandwidth increases, but another serious limitation arises: frequencies significantly higher than S-band are subject to interruption by weather effects.

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* This paper presents one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

There is an interesting analogy to this situation from the history of transportation. The gasoline-powered automobile is in many ways a perfect device for a wide variety of functions. Its physical size, configuration and performance have remained grossly unchanged for 30 years, despite concentrated effort by one of the largest engineering groups in our civilization. It is an essentially perfect, general purpose, all-weather device; it will probably not be replaced for many generations (if ever) and will only change form slightly (e.g., electric rather than gasoline power).

Investigations performed early in this century clearly showed that the airplane was inherently weather-dependent, unreliabile, special-purpose, costly and dangerous. Most of these disadvantages still exist; nonetheless, airplanes have proven to be most useful in applications for which automobiles, trains and steamships are inefficient. The airplane industry has not yet found simple solutions to weather-dependency and reliability; rather they use a variety of partial solutions.

S-band (2300 MHz) is evidentally in the optimum frequency region for most interplanetary communications and tracking requirements. The noise spectral density is minimized in this band, it is virtually independent of weather, and for modest data rates the antenna sizes are reasonable. In principle an S-band system can be built for very high data rates. However, the attendant costs suggest that other approaches be at least investigated; research may result in a more cost effective system in the future. Since the high reliability of the S-band system is indispensable, we must consider using two systems in parallel: a low data rate S-band system for command, two-way precision doppler tracking, engineering telemetry, and failure mode communication; and a high data rate, high frequency system which would be used only when appropriate conditions exist at the earth based receiving station (see figures 1-3). Since outages of the high rate link must be accommodated, it will be necessary to record the data on board the spacecraft, and then dump it upon command from the ground station. This is referred to as "data-dump" type operation. Countermeasures to weather effects such as orbiting relay satellites or receiving station multiplicity should be considered, but are neglected in this discussion on economic grounds. It is, however, conceivable that the advent of an orbiting relay satellite network could have an important effect on the future use of optical frequencies for space communication.

One higher frequency system currently under serious consideration utilizes X-band at 8400 MHz. And, of course we can also consider systems that operate at higher frequencies, yet, such as the 90 GHz-mm band, the 30 THz-near infrared laser band, or the visible laser band.

In order to illustrate that the present laser technology is at a point where the use of a particular laser frequency seems feasible, let us look at the comparison between the planned X-band data dump system and a laser data dump system using a Carbon Dioxide Laser. The mathematical details of the comparison (Ref. 1) cannot be discussed during the time available for this talk, so I will summarize the results in Figure 4. The two systems are designed to perform the following communication task:

Range - 2.3 AU (Typical Mars Encounter)

Data Rate - 10^6 bits/sec

Raw Power Available - 100 watts

Minimum Signal-to-Noise Ratio - 10

The comparison is then performed by calculating the product of the transmitting and receiving antenna diameters, D_tD_r, and then estimating whether the resulting system appears feasible.

At X-band, the choice of earth based receiving antenna diameter is somewhat arbitrary, and is usually limited by economics. At present, D_r = 210 ft., since the new 210 ft. antenna at Goldstone operates very satisfactorily at X-band (Ref. 2). This gives a value of 13.3 ft. for the transmitting aperture, which is quite reasonable in terms of size and weight.

For the CO_2 laser system, the maximum receiving telescope diameter is limited by atmospheric turbulence (or "seeing") effects and is estimated to be 10 ft. The transmitting telescope diameter, 1.53 ft., is again reasonable in terms of size and weight.

Thus, we can conclude that the two systems could have approximately the same weight and power requirements to perform the same job. The only difference is that the technology for the X-band systems exists, today, and the CO_2 laser communications system has a great deal of research and advanced development left to be done.

The basic configuration of a laser communication system has been covered previously by Dr. Randall. Figures 5 and 6 show a laser transmitting and heterodyne receiving system.

We now come to the major point of this whole discussion; what are the problems with laser deep space communication, and what can be done to solve them. (Fig. 7)

The most serious problems, as noted, are probably solvable. Most certainly, enough time and enough money could take care of the first and the second.

The third is a fundamental one--the atmospheric turbulence can seriously affect the reception efficiency of a heterodyne type optical communication receiver. Not only does it limit the diameter of the receiver aperture, it also introduces a noise on the received signal. There are three basic solutions to minimizing or eliminating the atmospheric turbulence effects:

1) operate with a direct detection type receiver (as opposed to a heterodyne type). The difficulty with this approach is that good low noise detectors, which are necessary for this type of detection, do not exist for the infrared part of the spectrum. The story is different in the visible: very good low noise detectors exist (photomultiplier tubes), but there is a lack of efficient, high power lasers, except perhaps for the recent Bell Telephone Labs developed Nd:YAG (doubled). (Ref. 3)

2) provide turbulence countermeasures, such as a multiple aperture, adaptively phased receiving array. Such systems are possible, but very complicated and expensive to fabricate.

3) Use an orbiting relay.

Figure 8 shows the problems with the spacecraft part of the system. It should go without saying, here, that the most serious problems are those of space qualification and reliability of all the spacecraft borne equipment.

The earth receiving station is probably the most highly developed of all the systems discussed, although some difficulties do exist (Fig. 9). The major problem associated with it is the detector, as mentioned previously. It would be very nice to have a room temperature photomultiplier which has a gain of 10^8, negligible dark current, and is sensitive with high quantum efficiency in the infrared at 10 p.m.

There is also a problem of efficiency with the argon laser which will be used as the earth beacon. However, efficiency is of little importance on the earth, and both high power and a desirable wavelength combine to permit the use of an uncooled detector in the spacecraft.

It appears to me that we are fast approaching a point in the evolution of laser system technology that a reasonable evaluation can be made of the total cost and cost effectiveness of development and application of laser systems for the deep space communication data dump function. This would be a very important undertaking for guidance of future laser research and advanced engineering.

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LIST OF FIGURES

TYPICAL DEEP SPACE COMMUNICATION LINK

UP	DOWN
S-BAND	S-BAND
(2.3 GHz)	plus
	S-BAND
	or
	X-BAND (8.4 GHZ)
	or
	MM BAND (90 GHz)
	or
	LASER

Figure 1

S-BAND

NEED	ALL WEATHER COMMUNICATION
USE	COMMAND TRACKING TELEMETRY FAILURE MODE COMMUNICATION
PRESENT LIMITATIONS (1000 LB SPACECRAFT, MARS RANGE)	50 - 100 K BIT/SEC (POWER) (MARINER 69 RATE IS 16.2 K BIT/SEC)

Figure 2

HIGHER FREQUENCY BAND

NEED	HIGHER DATA RATES
USE	DUMP STORED DATA DURING FAIR WEATHER CONDITIONS
PRESENT LIMITATIONS	LACK OF HIGH CAPACITY, HIGH DATA RATE MEMORY LACK OF EFFICIENT HIGH POWER SOURCES LACK OF LARGE APERTURE ANTENNAS ATMOSPHERIC EFFECTS

Figure 3

	λ	Φ	η (OVERALL)	D_r D_t		RCVR. TRANS.
-BAND	3.55 cm	3.1 X 10^{-22}	11%	2.8 X 10^3	=	(210') (13.3')
O_2	10.6 μm	2 X 10^{-20}	1.9%	15.3	=	(10') (1.53')

POWER CONVERSION - 90%
TRANSMITTER - 50
S/C ANTENNA - 65
LINE AND POLARIZATION - 90
GROUND ANTENNA - 41

TRANSMITTER - 12%
S/C TELESCOPE - 72
ATMOSPHERE - 76.5
GROUND TELESCOPE - 72
DETECTOR - 40

Figure 4

LASER TRANSMITTER

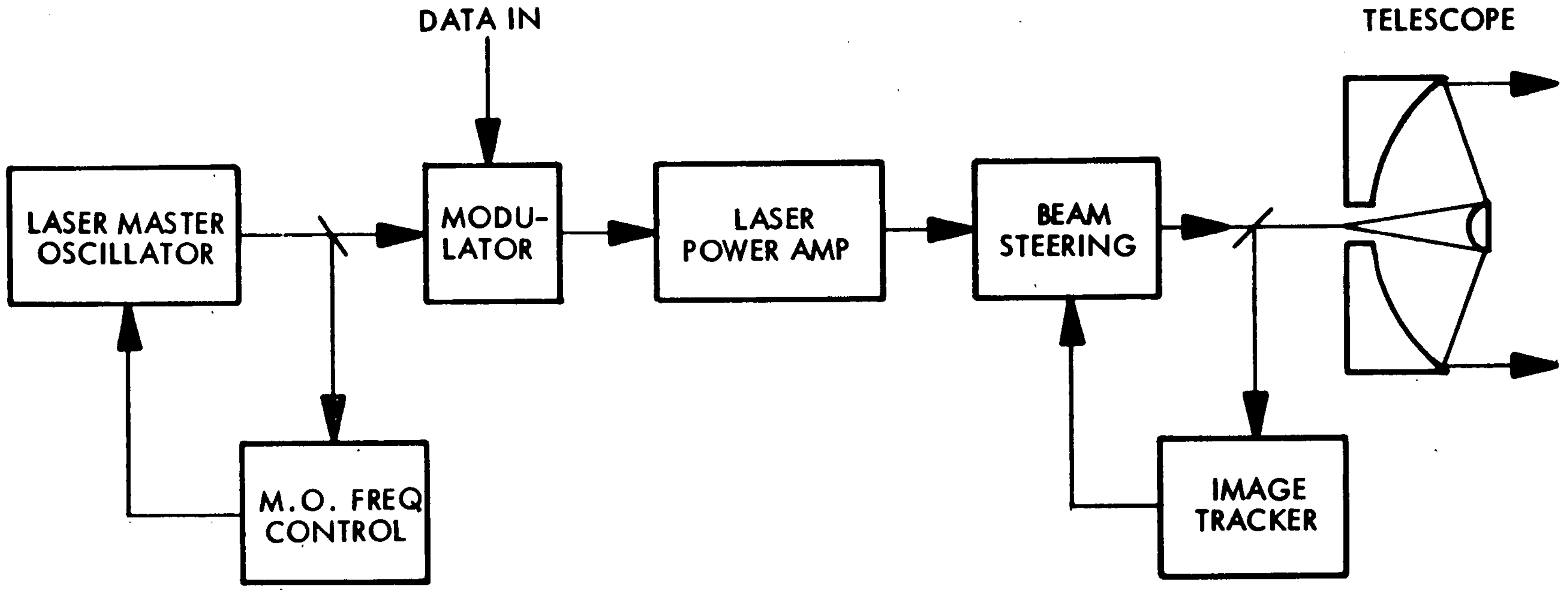

Figure 5

LASER RECEIVER

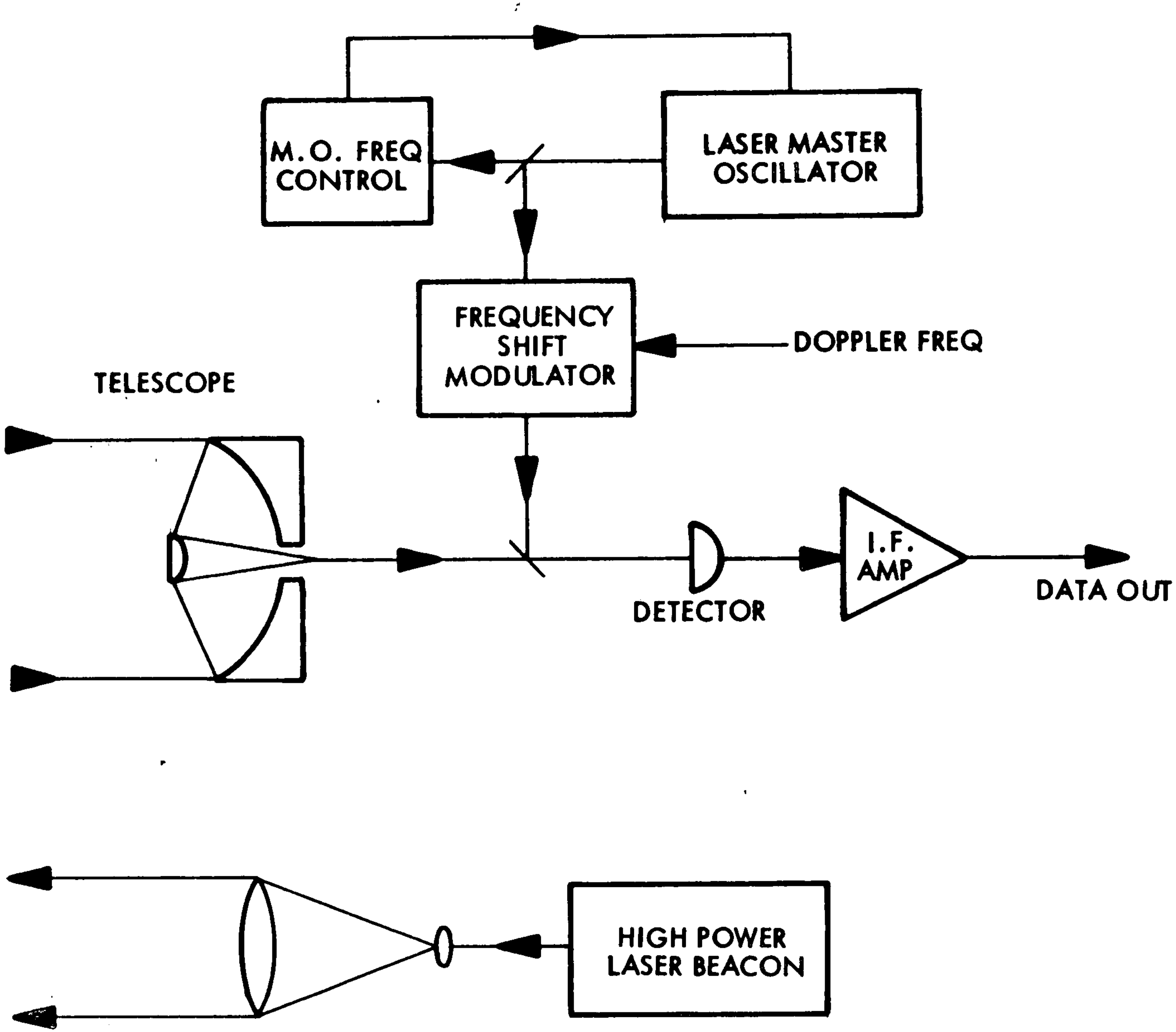

Figure 6

REALLY SERIOUS PROBLEMS:

1. LACK OF A BROAD TECHNOLOGY BASE
2. NEED FOR PROVEN RELIABILITY
3. ATMOSPHERIC TURBULENCE EFFECTS

Figure 7

COMPONENT PROBLEM AREAS

SPACECRAFT BORNE SYSTEM

1. LASER
   - A) HIGH POWER, HIGH EFFICIENCY
   - B) SINGLE MODE, SINGLE FREQUENCY
   - C) LIGHTWEIGHT, RELIABLE, ETC.
2. MODULATORS
   - A) NEED LOW LOSS MATERIALS
   - B) CAPABLE OF 10^6 - 10^8 Hz BANDWIDTH
   - C) LOW OPERATING VOLTAGE, HIGH EFFICIENCY
3. COLLIMATING TELESCOPE
   - A) LIGHTWEIGHT, LARGE DIAMETER
   - B) DIFFRACTION LIMITED PERFORMANCE
   - C) ALL THIS AND LAUNCHABLE, TOO

Figure 8

COMPONENT PROBLEM AREAS

GROUND RECEIVING SYSTEM

1. TELESCOPE
   - A) OPEN LOOP POINTING CAPABILITY OF FEW ARC SEC
   - B) ADAPTIVE MULTIPLE APERTURE CAPABILITY, POSSIBLY
2. DETECTORS
   - A) LOW NOISE PERFORMANCE
   - B) WOULD LIKE INTERNAL MULTIPLICATION
   - C) HIGH OPERATING TEMPERATURE (100° - 300°K)
3. BEACON LASER
   - A) VERY HIGH POWER (≈1000 WATT MINIMUM)
   - B) VISIBLE WAVELENGTH PREFERABLE

Figure 9

LASER TRACKING AND COMMUNICATION WITH SATELLITES

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I Introduction

The potentials of optical communication for space application have been discussed, both pro and con, in many studies (Ref. 1, 2, 3). Translation of these potentials into practice must depend upon successful development of each component and subsystem of a complete space link, plus a considerable body of field experience. From satellite experiments we develop ability to deal with the practical operational problems of this new technology, obtain the necessary knowledge of the channel properties, and gain confidence and maturity in applying optics and lasers to useful projects of immediate interest. This paper will describe some field experiments at Goddard which have tried to keep pace with the component technology and which have begun to indicate to NASA areas in which lasers may play important space roles. The emphasis will be upon systems aspects, applications, such results as we already have, and plans which are to go into effect in the immediate future.

The application of lasers which now seems most firmly established in the space program is that of satellite ranging. We shall review recent results in tracking the retroreflecting satellites now in orbit, discuss the precision being achieved and its significance in geodesy, orbit analysis, and calibration. Prospects for expanding the network of operating stations have become very real. The technique will undoubtedly be applied also to accurate measurement of the moon's motion and to synchronous satellites in a program of measurements for fundamental physics, astronomy, and geo-physics.

The first applications of continuous lasers to satellite experiments have so far involved the use of argon lasers on the ground and detectors in space. They resulted in valuable experience and data on the ability to point laser beams and the effects of the atmosphere. They will be described briefly. The same ground stations will soon be receiving continuous reflection from orbiting spacecraft and measuring radial velocity by doppler frequency shifts. Finally, we will consider the variations required to apply similar techniques with the carbon dioxide laser at 10.6 microns. This will bring us to the difficulties and advantages of heterodyne detection, first on the ground and then on the satellite itself. A set of communication experiments at 10.6 microns between spacecraft and ground is in the preliminary planning phases. These are setting the stage for wide bandwidth laser communication links between near-earth satellites and ultimately to deep space probes.

II Recent Results in Pulsed Laser Ranging to Passive Reflecting Satellites

The techniques and equipment of laser ranging to satellites has been described in detail in a number of references (Ref. 4,5,6,7,8). After a brief review, then, it only remains to relate some of the results of the last year and to comment on the prospects for continued growth in the number of laser tracking stations and in the fields to which such data may be applied.

There are now six satellites in orbit which were supplied with arrays of cube-corner retroreflectors designed for laser ranging. These are the U.S. satellites Beacon Explorers B and C (Explorers 22 and 27), (Fig. 1), GEOS-I and II (Explorers 29 and 36), (Fig. 2), and two French satellites D-1C and D-1D. The reflector arrays are composed of accurately polished fuzed silica cube-corners, which reflect incident radiation back toward its source, with relatively high efficiency. They are fairly inexpensive, lightweight, and passive in nature which, coupled with the real value of the laser tracking results, may explain why there are plans to place more of them in space and why more organizations are becoming interested in turning to lasers.

Even the ground station equipment is relatively modest (Fig. 3). It consists of a laser transmitter and a receiving telescope aligned parallel to each other on a tracking mount. The system at the Goddard Space Flight Center uses a pulsed ruby laser which fires once per second with an energy of 1 to 2 joules and a pulse duration of about 15 nanoseconds. After collimation through a 5 inch telescope, the transmitted beam has a total divergence of 1 milliradiam, and it is this that determines the accuracy with which the instruments must point toward the satellite.

Our tracking accuracy must be within 1 minute of arc in order to illuminate the target. This can be accomplished with a programmed drive based upon a predicted satellite trajectory, aided when possible by an operator viewing through an auxiliary telescope. The satellite range is measured by the time interval between the departure of the transmitted pulse and reception of the echo, with a photomultiplier at the focus of a 16 inch aperture cassegrain telescope.

During the past year, we have improved the resolution of our time-of-flight measurement. Figure 4 shows the state-of-the-art in the form of laser range residuals from a short arc during a typical pass. The plotted points are differences between individual laser observations and the range calculated from an analytic orbit adjusted to a least variance fit. The RMS scatter about this smooth curve is less than one meter.

Such plots allow us to estimate the "precision" of our technique, as distinguished from "accuracy." Aside from calibrating the system against carefully measured distances on the ground, an estimate of possible systematic errors and biases is not so easy to obtain, since we have no suitable available standards. However, several recent tests may help to give us a degree of confidence.

The GEOS-I satellite was also being tracked by other networks during the period when laser measurements were being made. One of these was the network of TRANET radio-frequency doppler stations operated for the Navy. Two days of doppler data on GEOS-I, collected from a worldwide distribution of stations were combined into an orbital solution. This was then compared with laser observations during a pass within that two day period. The differences are plotted in Figure 5. A similar test was carried out using measurements made during those same two days by the worldwide photographic network run for NASA by the Smithsonian Astrophysical Observatory. The differences between laser observations and the orbit derived from those photographic measurements alone, are also plotted in Figure 5. Remember that we are now comparing the laser system against measurements on the same satellite by two completely independent networks, with stations all around the world, none of them near the laser station. Errors in station location, time synchronization, gravitational models, as well as equipment bias will all influence the compariosn. In view of this, the resulting agreement is remarkable.

The Table in Figure 6 summarizes the results of four typical tests of the type described above. For purposes of description the errors were assumed to consist of a constant range bias (or "Zero-set") and a term depending upon range-rate (equivalent to a "timing error"). This would give the residual plot the form of a sloping straight line. The column labelled "random" is the RMS scatter about that straight-line approximation. The zero-set difference with the optical photographic orbit averaged 4.1 meters and with the doppler orbit, the average was 5.9 meters in the other direction. Apparent timing errors averaged around 3.4 milliseconds. By independent analysis of the laser system we feel that the range uncertainty at this stage is about 1 meter.

Another type of laser test which has been performed during the past year is illustrated in Figure 7. For this purpose we moved our station to Wallops Island, where it was in close proximity to an FPQ-6 Radar, an FPS-16 Radar, an Army SECOR (Sequential Correlation of Range) station and a photographic camera. All of these systems could track GEOS-II simultaneously, so that their intercomparison would not suffer from the uncertainties in station location and orbit dynamics which degraded the tests described above. To display our results this time (Fig. 8), we start by fitting a short arc to the laser data for a particular pass, and then plot the difference between that reference are and the ranges observed at the same time from each of the systems being tested. Figure 8 shows the disagreement between 3 of the other instruments and the laser orbit, and Figure 9 summarizes the comparisons for 6 typical passes. Again, the errors are interpreted in terms of a "zero-set" bias and an apparent timing error. The general agreement between the radars and the laser was very gratifying.

III Extension of Pulsed Laser Satellite Tracking

A precision and accuracy of less than one meter, and the prospect of decreasing the uncertainty to a fraction of that, has stimulated interest and participation among many groups. Laser tracking can improve knowledge of satellite orbits, the fine details of the earth's gravitational field, or the position of the tracking station with respect to other stations and the earth's rotation axis. In addition to NASA's first station at Greenbelt, Maryland, a mobile station has been built, and will soon begin a series of intercomparisons like the ones we described. The Smithsonian Astrophysical

Observatory has been operating stations at Mt. Hopkins in Arizona, Mr. Haleakala on the island of Maui and in Athens, Greece. They hope to add to this network with lasers at such places as Brazil, Argentina, and Ethiopia. The French also have been laser tracking at two or three stations and are reported planning to enlarge the number. The data collected over the past two years is already serving to improve world models, station locations, and calibration of other trackers. Other countries which have participated in geodetic programs may be expected to join the laser ranks soon.

We need not restrict pulsed laser tracking only to low altitude reflective satellites such as the six now in orbit. Several synchronous satellites would be excellent for mapping studies, because stations could range simultaneously and eliminate the need for calculating orbits. Since reflector arrays are so easy to add, we expect that some future synchronous communication or meterorology satellites might consider their value.

One other application of pulsed laser ranging which promises to keep us busy for sometime is that of ranging to a retroreflector placed on the surface of the moon (Ref. 9). We hope that one of the early Apollo trips will permit an astronaut to deploy a special array on the lunar surface. Because of the greater distance, all the elements of the tracking system are being drastically improved for this project. The laser pulse must be both more energetic and shorter in duration, limited only by the ability of materials to withstand the extremely high peak powers. The divergence of the transmitted beam must be much less, in order to get the maximum of intensity onto the target. The retroreflector must be of much higher quality than on our satellites, so that the reflected rays do not spread more than necessary. We are planning to use a 60-inch aperture telescope for both transmitter and receiver. In this experiment, the

Goddard Space Flight Center is working with a team of Co-Investigators led by Professor C. O. Alley of the University of Maryland. With frequent measurements of precise range to the lunar reflector over a period of years, we expect to improve our knowledge of the detailed motion of the moon, its libration and precession, its radius and moment of inertia, the earth's rotational rate and wobble, and the position of the tracking station. After 8 to 10 years, we may be able to say something definite about the slow change in the gravitational constant, which is predicted from some cosmological theories. Thus, such an experiment can have great significance in fundamental physics, astronomy, geodesy, map making, and timekeeping.

IV Experiments with Continuous Argon Lasers

Argon laser beams have been transmitted into space from several stations (Fig. 10). The experiments normally require well collimated beams and accurate pointing. When the target is visible, the pointing problem is one of autotracking, similar to that experienced by astronomers, except that satellite rates can be much different from the angular motion of stars. The servo system for a 24-inch diameter telescope at the Goddard Space Flight Center can be controlled by a star tracker and keep the optical axis pointing toward the center of a visible target with an uncertainty of ±0.2 arc seconds. When the target is not visible, we must direct our laser beam or receiver field of view on the basis of computed angular coordinates and the readings of shaft encoders. Now the corresponding aiming accuracy is degraded by structural flexure, bearing eccentricity, non-orthogonality of axes, encoder errors, pier tilt, atmospheric refraction, etc. To these we must add the inaccuracy of the trajectory calculation and uncertainty in time and in the station's position. With great care, the best we can now hope for in absolute or "a priori" pointing accuracy is 3 to 5 arc seconds.

All of this is prelude to a description of some of the space experiments using Argon laser beams, which require an advanced ability to point accurately. The first of these was in response to a suggestion by Professor C. O. Alley and D. G. Currie of the University of Maryland (Ref. 10). The Surveyor VII spacecraft, when it came to rest on the surface of the moon, was able to direct its TV camera back toward the earth and transmit pictures of our planet as seen from that vantage point. In addition to the scientific measurements performed, we were therfore given the opportunity to test the visibility of argon laser beams.

In Figure 11 we see a globe which illustrates the aspect of the earth as seen by Surveyor VII during one of the tests. The sun was illuminating the earth from the right, as indicated by the shaded crescent. Each of the black dots shows the location of one of the stations which participated in the experiment. They consisted of Table Mountain, California (operated by JPL); Kitt Peak, Arizona; Goddard Space Flight Center, near Norwalk, Connecticut; Raytheon, Waltham, Massachusetts; and Lincoln Labs, Lexington, Massachusetts. The position of the Surveyor was carefully pin-pointed with respect to the visible features on the moon's surface, and all the stations attempted to illuminate that spot so as to be seen by the vidicon camera.

Figure 12 is a typical resulting TV picture. In several trails, the beams from Table Mountain and Kitt Peak were observed unambiguously, while none of the eastern stations was ever seen with certainty. This result was repeated several times, but the experiment could not be continued long enough to learn the reason for the differences in performance. They might be traced to power radiated, collimation and aiming techniques, atmospheric conditions, or proximity of the sun illumination to the East Coast.

Even with the limited data obtained from Surveyor VII, a few valuable conclusions can be drawn. Each of the stations detected was transmitting about 1 watt after accounting for telescope losses, with a divergence of several arc seconds, limited essentially by atmospheric seeing. The spots appeared with an approximate equivalent star magnitude of -1, which corresponds roughly to the calculated power density. Thus, we established the feasibility of pointing such narrow beams and checked the transparency of the atmosphere to laser beams. It seems especially remarkable that the 1 watt laser beams appeared as bright stars from the moon, while the diffuse light from major cities was not observed.

The argon transmitter system of Figure 10 is also used for other experiments. The GEOS-II satellite (Fig. 2) was provided with a detector sensitive to one of the strong lines (4880 Angstroms) of the Argon laser. If we could illuminate the satellite as shown in Figure 13, the detector could then measure the intensity of the light reaching it and scintillations introduced by the atmosphere, and transmit the information back via the normal telemetry channel. To aid in distinguishing the laser light from the very large earth background seen within the 80° field of view of the detector, in addition to using a spectral filter, the laser light is chopped at a 13 kHz rate. In the spacecraft, the amplitude of the 13 kHz component is amplified with a logarithmic compression amplifier to give us 3 decades of dynamic range.

In Figure 14, the upper trace is a typical record of the GEOS-II detector output. The receiver aperture had an area of about one square centimeter. The intensity shown corresponds to a received power of about 10^{-11} watts, with sufficient signal-to-noise to permit us to analyze such atmospheric parameters as attenuation, depth of scintillation, and frequency spectrum of scintillations. These can now be related to theories of atmospheric propagation. While publication of such results is in preparation, measurements will continue through the active life of GEOS-II.

The continuous argon laser will also be used to track passive satellites in a manner analogous to pulsed ruby laser tracking. If the transmitted beam is modulated at a high frequency and reflected from the cube-corner array satellites, we can measure a doppler shift in the modulation frequency of the reflected light, giving us a measure of the satellite's radial velocity. The equipment for this task is now being assembled. Future applications of Argon lasers in space can benefit from the experience gained in the experiments we have described. Because of their high power and the ease of detecting the visible wavelengths, they will undoubtedly be used at least as beacons, for space navigation, and for tying down the direction of narrow-beam communication systems.

V Carbon-Dioxide Laser Communication Experiments

The carbon-dioxide laser has properties which are at present so attractive that it is being very actively studies for use in space communication systems. It is the most efficient of the lasers (greater than 20% power conversion to radiation), can be made to operate at high power in a single stable frequency, is rugged, compact, and potentially long-lived. The wavelenght, 10.6 microns, is convenient because of a good atmospheric window and because the mechanical tolerances commensurate with diffraction-limited operation are easier to achieve than at visible wavelengths. Of course, the long wavelength leads to detection problems. The small photon energy means that detectors must be cooled and the signal must compete against thermal radiation in the background and receiving equipment itself.

Fortunately, the coherence of the laser and response characteristics of available detector materials allow us to employ heterodyne mixing techniques. It has been shown in many laboratories that by using local oscillator lasers to beat with a small signal, and by amplifying the resulting intermediate frequency, all extraneous noise can be overcome and our detectability becomes limited only by the photon nature of the signal light itself. Such utilization of the coherent nature of laser radiation gives optical communication its unique character and suggests developments and experiments that must be accomplished before we can safely evaluate its utility in space applications. In particular, we must study the conditions under which the atmosphere does not seriously perturb the phase fronts of the arriving waves so that mixing can be performed efficiently. We shall briefly describe two such experiments.

The first will attempt to receive CO_2 laser radiation which has been reflected from one of the geodetic ballon satellites now in orbit. The plan is shown schematically in Figure 15, and the equipment is shown partially assembled in Figure 16. A single frequency laser, radiating about 20 watts, will be used as transmitter source. Be means of beam splitters, a small fraction of the output is used as local oscillator, while the bulk of the power is transmitted toward the reflecting satellite through a 12-inch telescope. The 10.6 micron reflected radiation is received by the large telescope and focused onto the cryogenic mixer (mercury-doped germanium), where it is superimposed on the local oscillator radiation. The image motion compensator acts to superimpose the signal image on the local oscillator spot to within a fraction of its diffraction limited diameter, so that the phases will match. In this early experiment, information for the image motion compensator will come from a star tracker operating on visible light from the target. Later, angle-error signals must be derived from the CO_2 radiation itself.

Another difficulty arises from the doppler shift in the 10.6 micron radiation because of the motion of the reflecting target. In our experiment, this can amount to over 1 gHz, and will change at rates of several MHz per second as we track the satellite across the sky. Since the doppler shift is actually the beat frequency in our homodyne technique, we must have mixers which respond to such high frequencies, and tracking filters in the IF stage capable of following the rapid changes. All of these components have now been developed and are being tested in the laboratory in preparation for the experiment.

Assuming that this passive satellite experiment has been performed successfully, and that we have demonstrated the ability to receive coherently through the atmosphere with large receiving apertures, the next step must be to launch and test complete active prototype laser communication systems: first from spacecraft to ground, and then between two spacecraft. Only when unanticipated problems are met and solved, and we can put quantitative values on success probabilities, will the technology begin to be applied in operational projects. Such a plan is now being considered very seriously. The experiment we shall be describing is only in a conceptual stage; it may finally take on a very different appearance from the one shown schematically in Figures 17 and 18. It is being proposed as an experiment which can utilize existing state-of-the-art, can be flown and operated on an available spacecraft at the earliest possible time, and yet will provide most of the answers needed by the designers of the next (operational) system.

The ATS-F satellite is planned for launch early in 1972. It will be placed in synchronous orbit and oriented so that a 30-foot microwave antenna is directed down toward ground receiving stations which will perform communication experiments. Its attitude will thus be known to an accuracy of about 0.1 degree. In order to establish an optical link, therefore, the spacecraft laser package will have a single flat mirror whose angles with respect to the spacecraft axes are determined from digital shaft encoders, and which can be slewed by command. The transmitted laser beam will be sent through a fixed 5-inch diameter telescope antenna and then reflected from a flat mirror, so that the optical link may be independent of the other functions of the spacecraft. The same optical system is used as the receiving antenna for radiation from a similar package at the terminal. The received signal is focused on two mixer elements, which are also illuminated by a separate local oscillator laser. One of these mixers produces the video IF signal which is then processed for the communication information, while the other is an angle-error sensor. The latter provides feedback information to a small image motion compensator which is then automatically controlled to keep the signal superimposed with the local oscillator on the mixers. Since the transmitted beam also makes use of the image motion compensator, this also insures that the transmitted beam will be accurately directed toward the other terminal.

In order to isolate the transmitted and received signals at each terminal, we may arrange to operate on different lines of the CO_2 rotational spectrum, so that they will be separated by at least 55 gHz. In each channel, the local oscillator can be offset by 20 MHz. Such details as tuning the laser by piezoelectric transducer mirror mounts, thermal stability, and acquisition techniques cannot be discussed here. They are covered in more detail in Reference 11. It should be noted that the detectors can be made of mercury-cadmium-teluride, which has acceptable properties at temperatures near 100^oK. This could be accomplished on a spacecraft using a radiation cooler mounted on a surface always looking off into cold space.

It is clear that the system proposed for this experiment is only a very early indication of the potential of the CO_2 laser technology for space communication. The expected performance, however, will show an impressive capability for a relatively small package. A completely independent spacecraft optical system would weigh about 30 pounds and use about 30 watts. The antenna of 5-inch diameter would have an equivalent gain of about 100 db. The transmitter laser would radiate 400 milliwatts, with internal cavity modulation, while only 50 milliwatts would be necessary for the local oscillator laser. From synchronous altitude we expect 5 MHz of information bandwidth, with signal-to-noise of 26 db. This assumes that both terminals of the link have identical optical equipment.

We have thus seen that the tracking applications of lasers have at least found limited valuable operations and are expected to be extended considerably. On the basis of that kind of experience and remarkable progress in laser technology, there is every indication that optical communication will also find unique areas in which it is superior in performance and economy to other portions of the spectrum.

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11. N. McAvoy, H. L. Richard, J. H. McElroy, and W. E. Richards, "10.6 Micron Laser Communications System Experiment for ATS-F and ATS-G," NASA/Goddard document X-524-68-206.

Figure Captions

1. Beacon Explorer satellite. The reflector arrays are designed for pulsed laser ranging. The satellite is magnetically oriented so that, in the Northern Hemisphere, the reflector array points generally down toward the earth.
2. The GEOS satellite is gravity-gradient stabilized so that the array of fuzed-silica, cube-corners always faces the earth.
3. Goddard's laser satellite tracking equipment. On the azimuth elevation platform we have, from right to left, a pulsed ruby laser, a 10-inch cassegrain telescope with photomultiplier detector, and an auxiliary telescope for manual control.
4. Residuals of satellite range measured with laser radar from an orbit fitted to the observations. The time interval between independent measurements is one second.
5. Differences between laser range measurements on GEOS-L and orbits derived from two days of photographic data and two days of radio doppler data, respectively. The optical and radio doppler data were collected by independent worldwide networks of stations.
6. Summary of differences between laser range observations and orbits of GEOS-I based upon optical photographic tracking and radio doppler tracking.
7. Co-location experiment at Wallops Island. The laser tracking station operated close to the FPQ-6 Radar (C-Band), both simultaneously tracking the GEOS-II satellite.

8. Comparison between three tracking systems at Wallops Island and the co-located laser tracker, all simultaneously measuring range of GEOS-II. Reference orbit is best fit to laser data.
9. Summary of six passes of GEOS-II which were simultaneously tracked at Wallops Island by the Laser, SECOR, and radars FPS-16 and FOQ-6. Differences listed are averages between a reference orbit fitted only to the laser data for each pass, and observations from each of the other tracking systems.
10. Argon laser beam being transmitted from the Goddard Space Flight Center. In this equipment, the laser is on a stationary platform and the beam is reflected through the hollow shafts of an azimuth-elevation mount.
11. Globe showing the aspect of the earth during one of the Surveyor VII laser tests. The shaded area is the position of the sun-illuminated crescent, and the dots are the positions of laser transmitting stations which participated in the test.
12. Vidicon TV picture of earth from Surveyor VII, showing laser radiation images from Table Mountain, California, and Kitt Peak, Arizona. Eastern U.S. stations indicated in Figure 11 were not observed with certainty.
13. Plan for GEOS-II experiment for studying scintillation produced by the atmosphere on a laser beam transmitted into space from the earth.
14. Typical record of incident laser intensity measured by GEOS-II. In upper trace, the long record is detected radiation when laser is on, the shorter gaps are the result of closing the transmitter shutter. Background signal within filter response is 2×10^{-13} watt, laser signal is about 10^{-11} watt. Vertical marks at bottom of record are one-second time ticks.

15. Functional diagram of 10.6 micron homodyne experiment with passive satellite reflection. The combination of star tracker and image motion compensator insures that the images of received radiation and local oscillator radiation are superimposed on the mixer.

16. Carbon dioxide laser mounted on a 24-inch telescope at Goddard. The laser is 8-feet long, transmits through the "piggy-back" 12-inch antenna, while the large telescope is ued as receiver. Cryogenic mixer and star tracker (not visible) are mounted on underside of telescope housing.

17. The Laser Communication Experiment proposed for the ATS-F spacecraft provides a prototype two-way optical link between a synchronous satellite terminal and ground stations. Design allows extension to link between ATS-F and ATS-G, when the latter is launched one year later.

18. Concept of optical package aboard ATS-F. Coarse beam pointing is provided by flat mirror commanded from the ground, while five adjustments are accomplished by automatic motions of small image motion compensator. Mixer elements for angle-error sensing and information signals are mounted in radiation cooler looking into cold space.

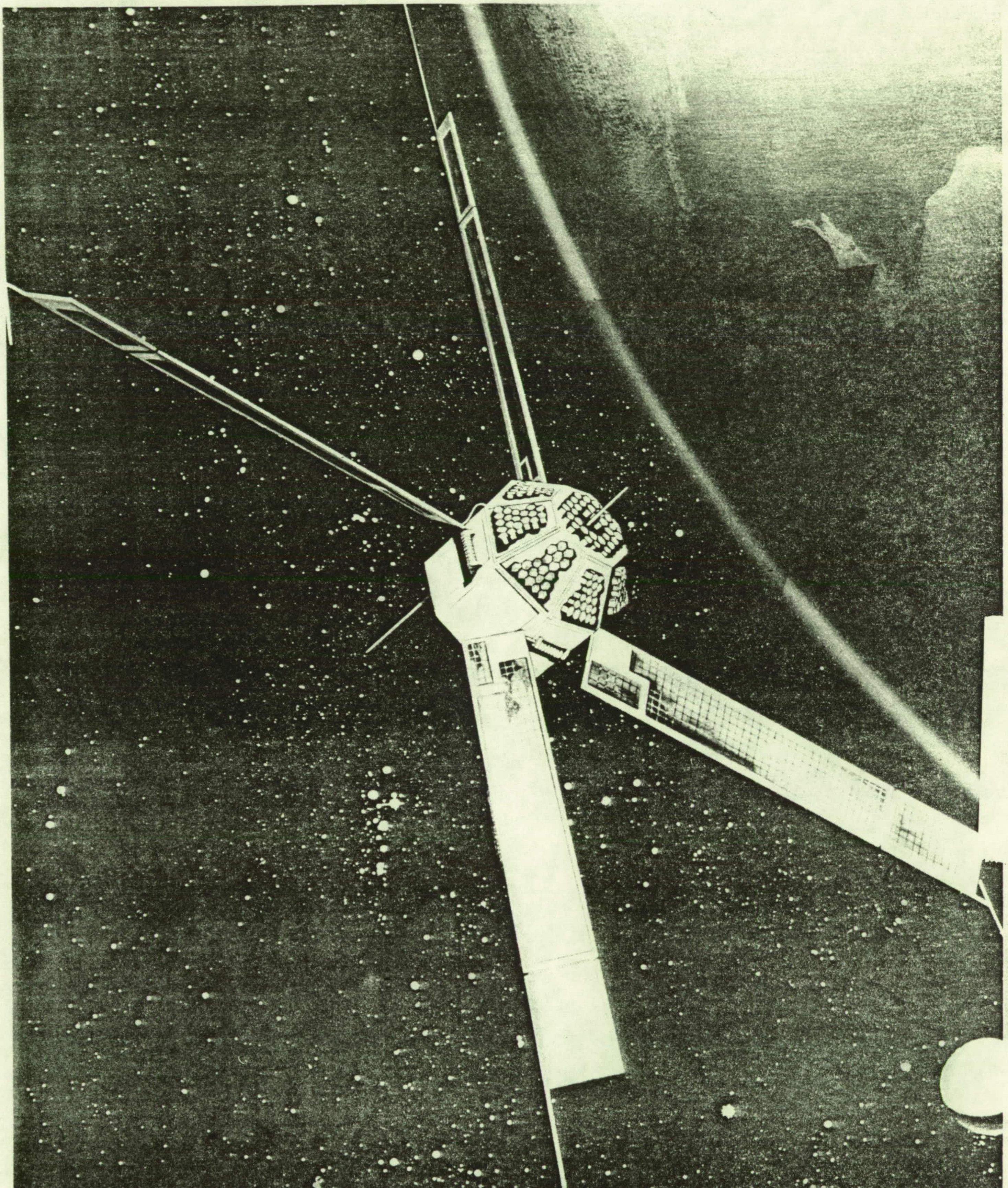


Figure 1

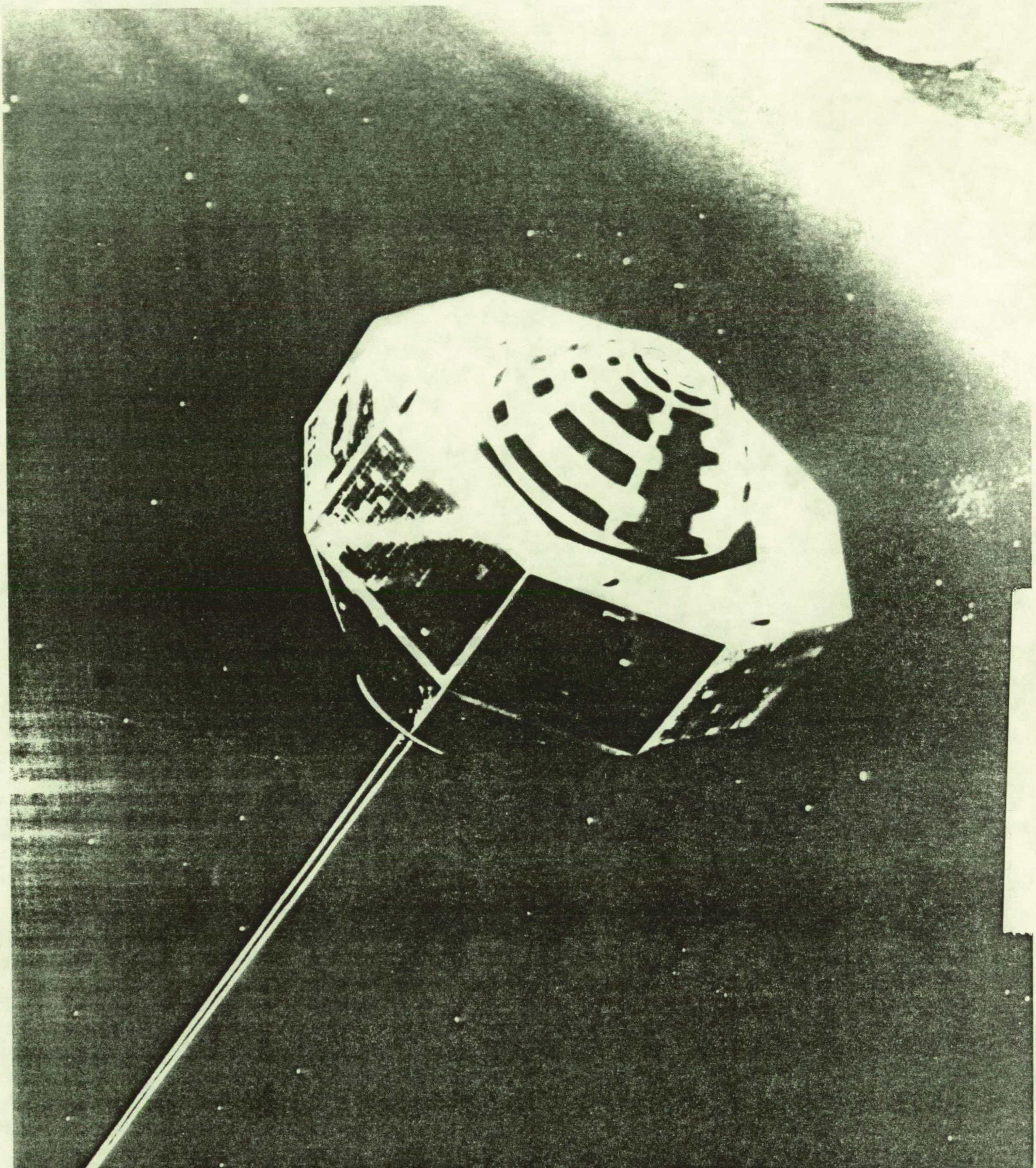


figure 2 69

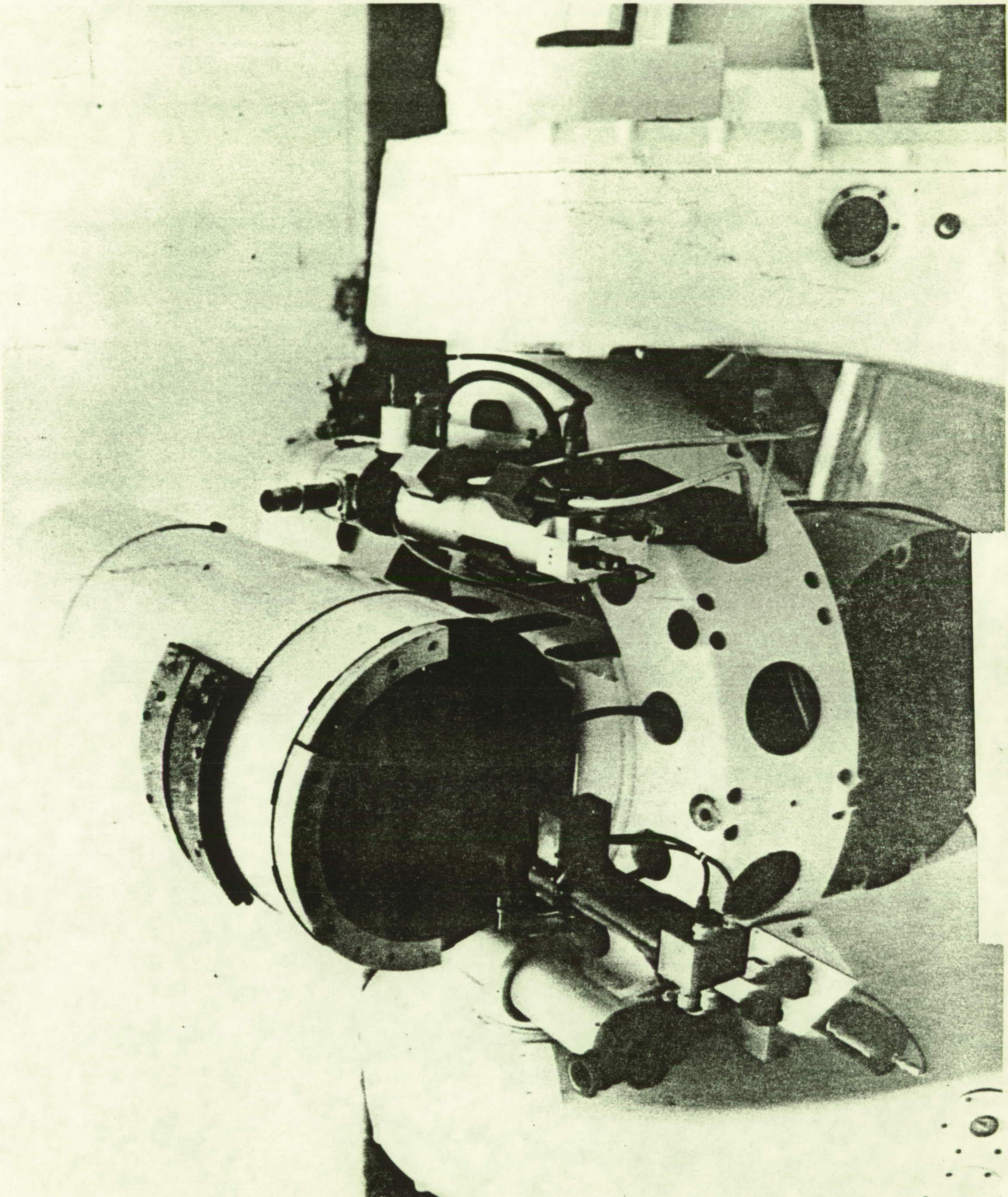


figure 3

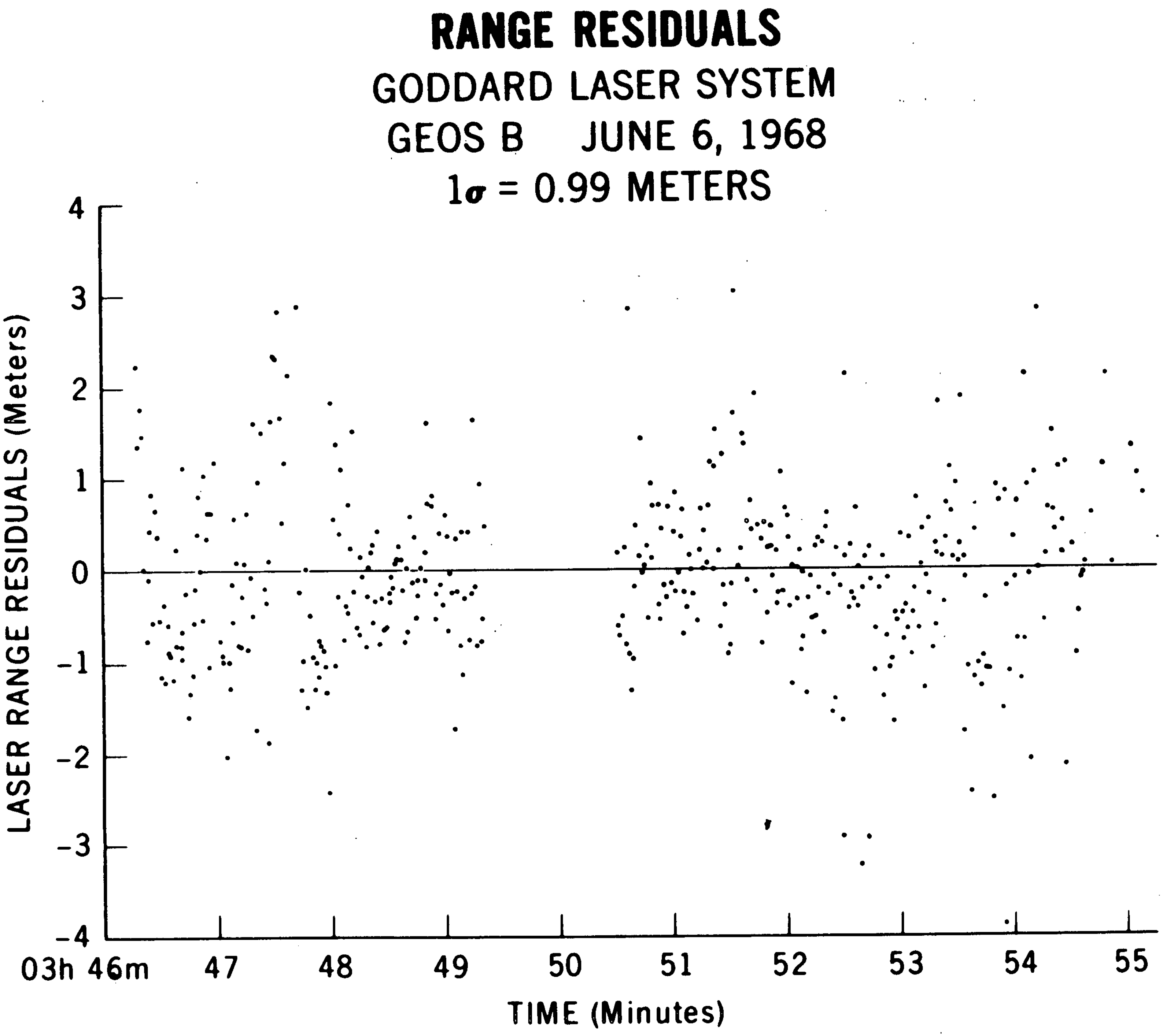

RANGE RESIDUALS
GODDARD LASER SYSTEM
GEOS B JUNE 6, 1968
1σ = 0.99 METERS
LASER RANGE RESIDUALS (Meters)
4
3
2
1
0
−1
−2
−3
−4
03h 46m
47
48
49
50
51
52
53
54
55
TIME (Minutes)

Figure 4

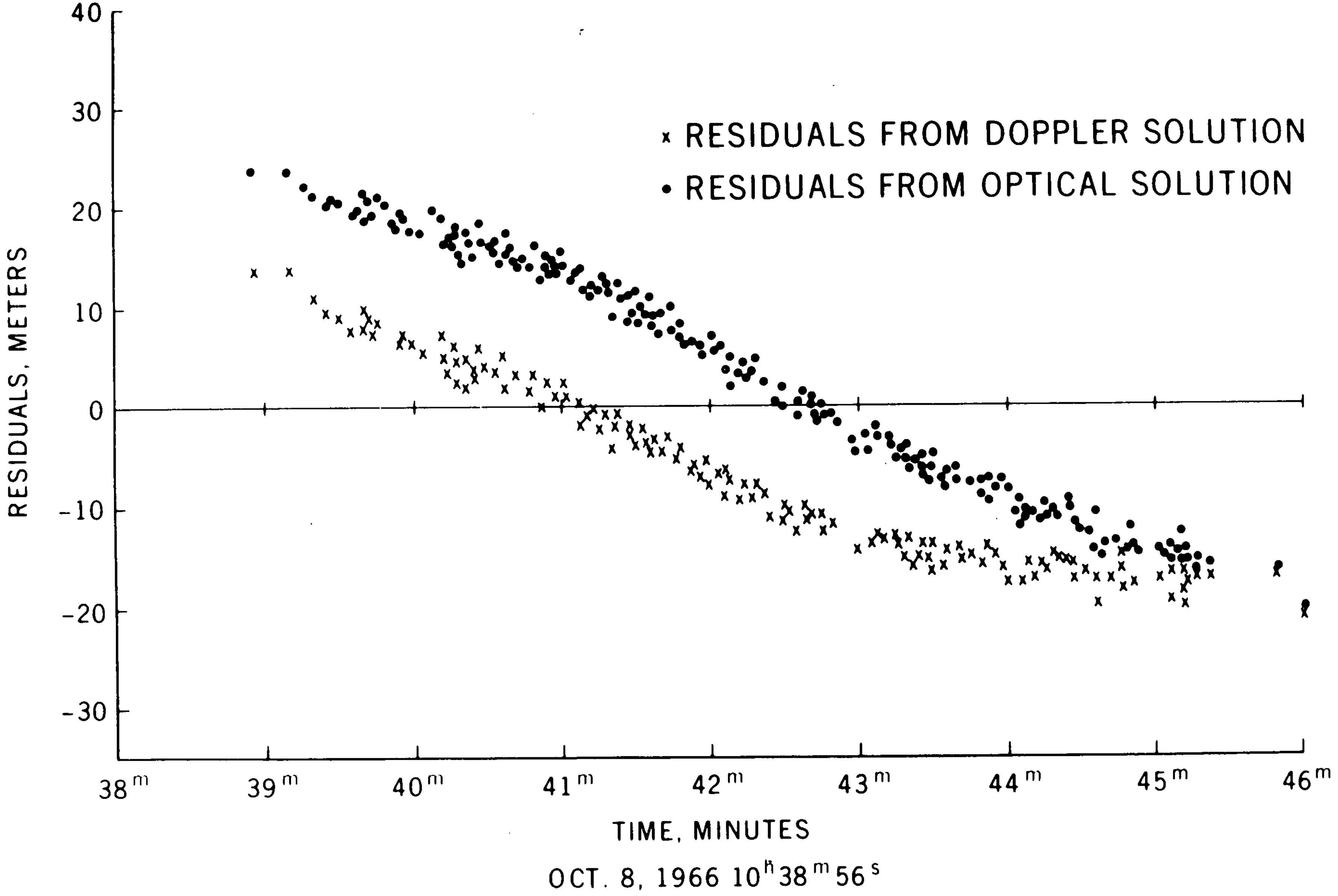

LASER RANGE RESIDUALS

Figure 5

SUMMARY OF LASER RANGE ERROR ESTIMATES

2 DAY ARCS

TYPE OF SOLUTION	PASS		ERROR ESTIMATES		
	YYMMDD	HHMM	ZERO SET (m)	TUNING (ms)	RANDOM (m)
OPTICAL	661005	10 29	3.5	-4.1	1.8
DOPPLER	661005	10 29	-6.0	-1.8	1.8
OPTICAL	661006	10 31	6.9	-3.9	1.7
DOPPLER	661006	10 31	-3.3	-1.5	2.0
OPTICAL	661007	10 35	4.1	-6.4	1.9
DOPPLER	661007	10 35	-6.6	-2.4	1.6
OPTICAL	661008	10 38	2.0	-4.1	1.1
DOPPLER	661008	10 38	-7.9	-3.0	2.1

Figure 6

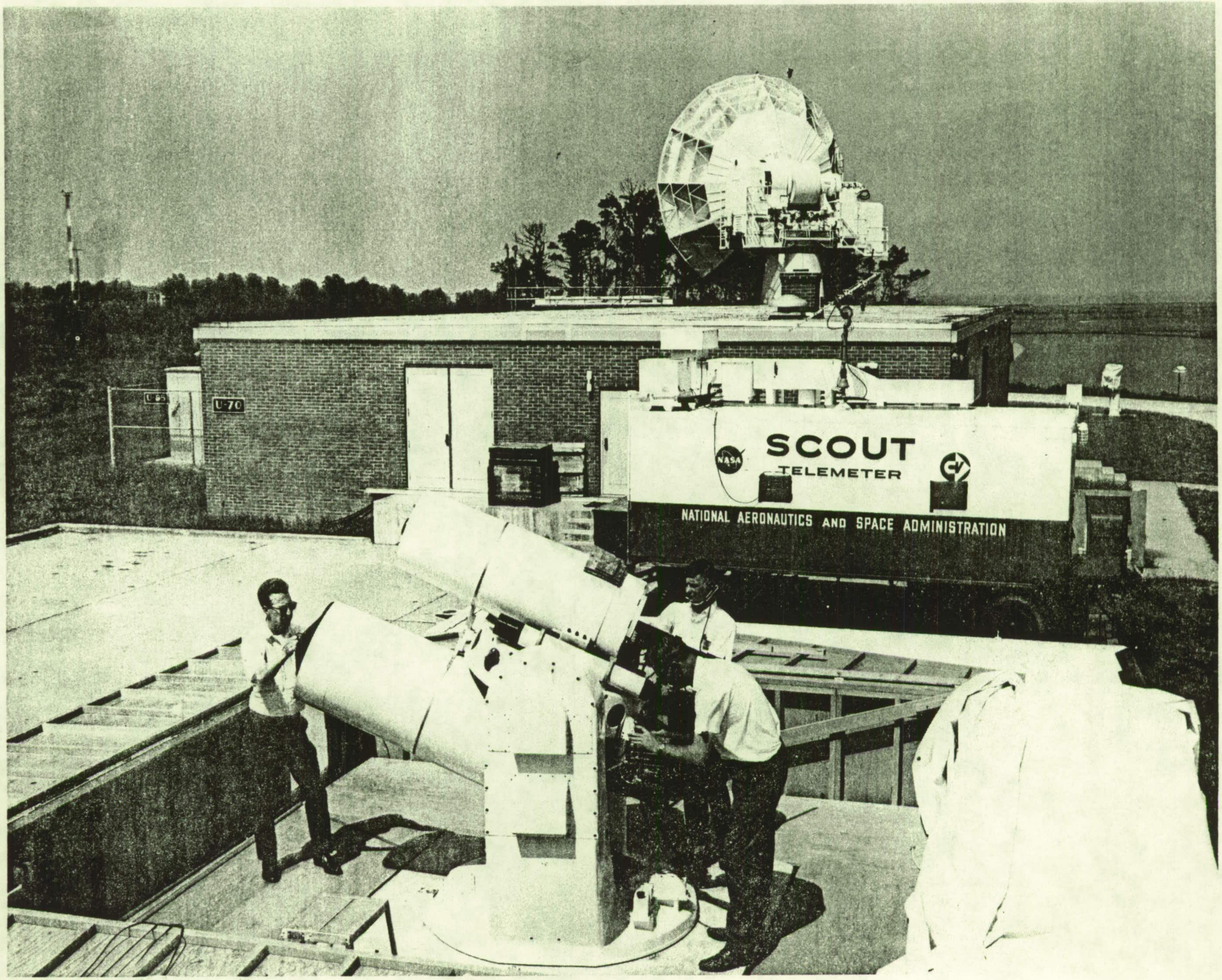

U-65
U-70
SCOUT
TELEMETER
NASA
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Figure 7

APRIL 5, 1968 INTERCOMPARISON TEST #5

GEOS-II ORBIT #1083
RANGE RESIDUALS
LASER REFERENCE ORBIT

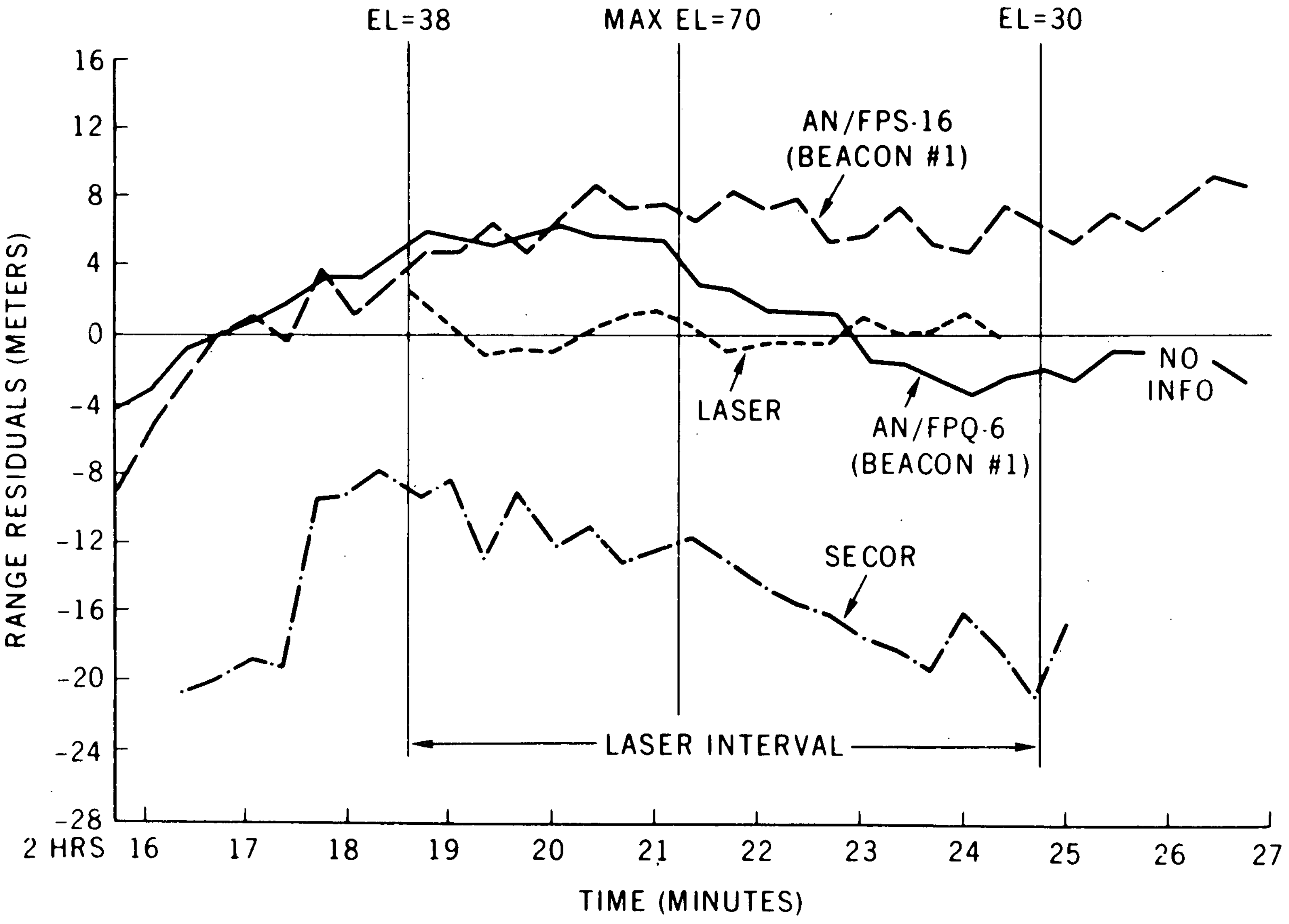


Figure 8

RANGE DATA COMPARISONS

LASER SHORT ARC REFERENCE ORBIT

TEST #	RANGE (METERS)			TIME BIAS (ms)		
	SECOR	AN/FPQ-6	AN/FPS-16	SECOR	FPQ-6	FPS-16
2	-18.6 ± 3.2	-8.9 ± 1.6	-0.1 ± 1.6	-0.58 ± 1.09	-0.80 ± 0.52	0.67 ± 0.52
3	-6.1 ± 5.6	-0.3 ± 2.8	2.6 ± 2.8	-1.38 ± 1.61	-0.02 ± 0.80	-0.04 ± 0.80
5	-13.5 ± 3.2	1.4 ± 1.6	6.6 ± 1.6	-0.94 ± 0.91	-0.11 ± 0.46	-0.01 ± 0.46
9	-9.4 ± 6.3	—	1.2 ± 3.2	-0.35 ± 3.94	—	0.74 ± 2.00
11	—	5.2 ± 1.5	-1.9 ± 1.6	—	0.41 ± 0.46	0.26 ± 0.46
12	—	0.7 ± 1.9	-1.0 ± 1.9	—	0.52 ± 0.86	0.31 ± 0.84
AVERAGE	-11.9 ± 4.7	-0.4 ± 4.6	1.2 ± 2.8	-0.80 ± 0.39	0.32 ± 0.34	0.32 ± 0.30

Figure 9

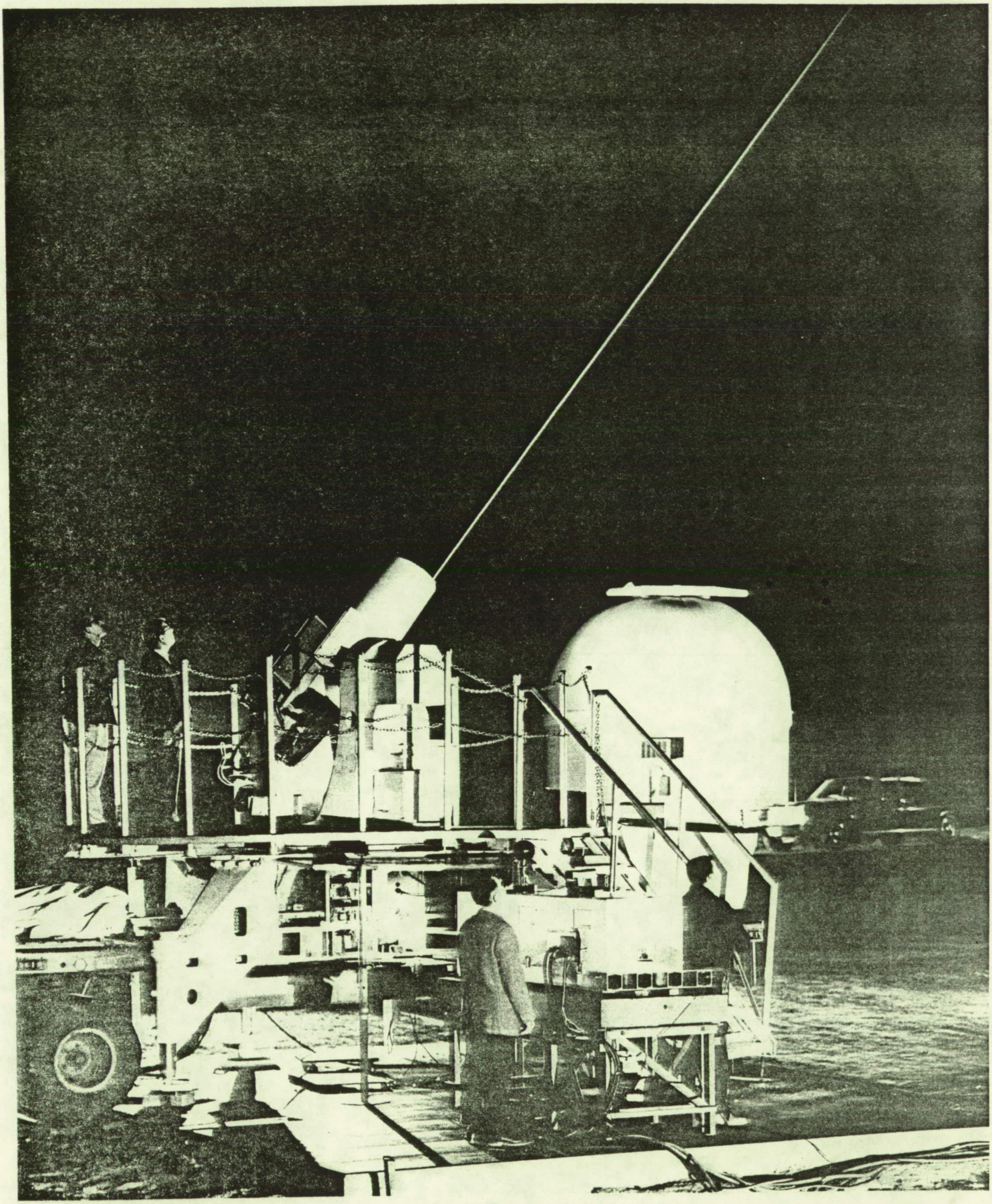


Figure 10

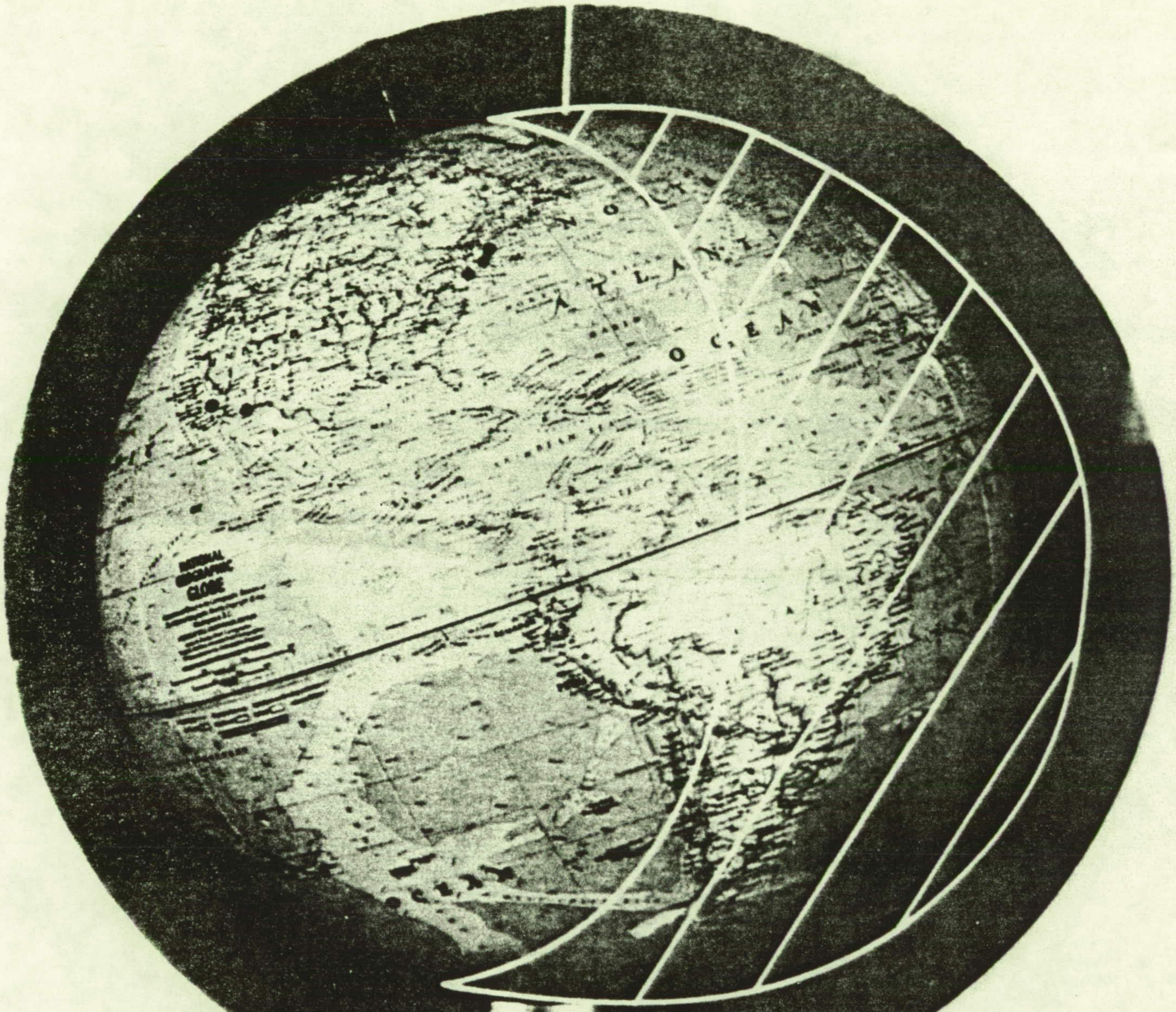


Figure 11

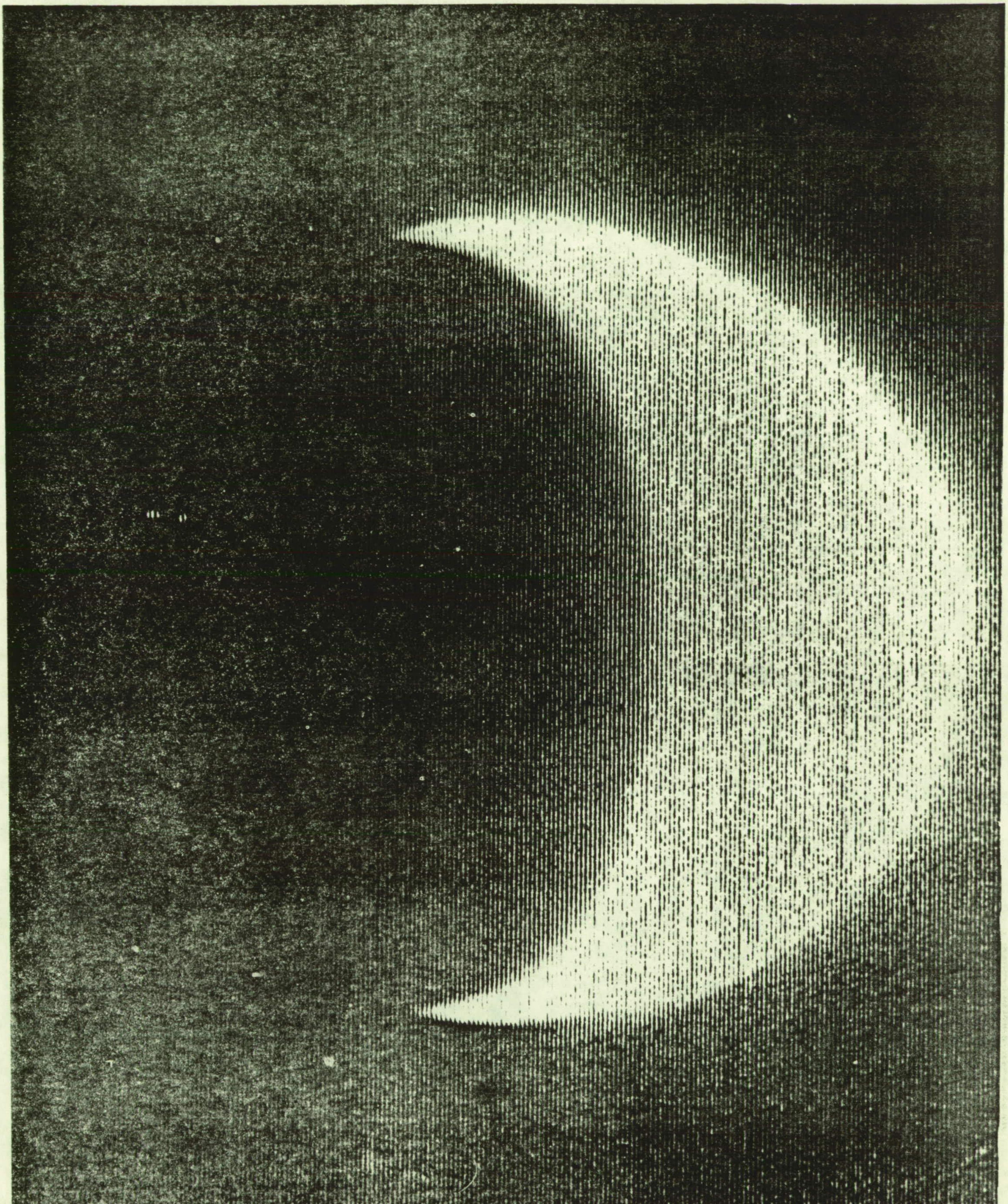
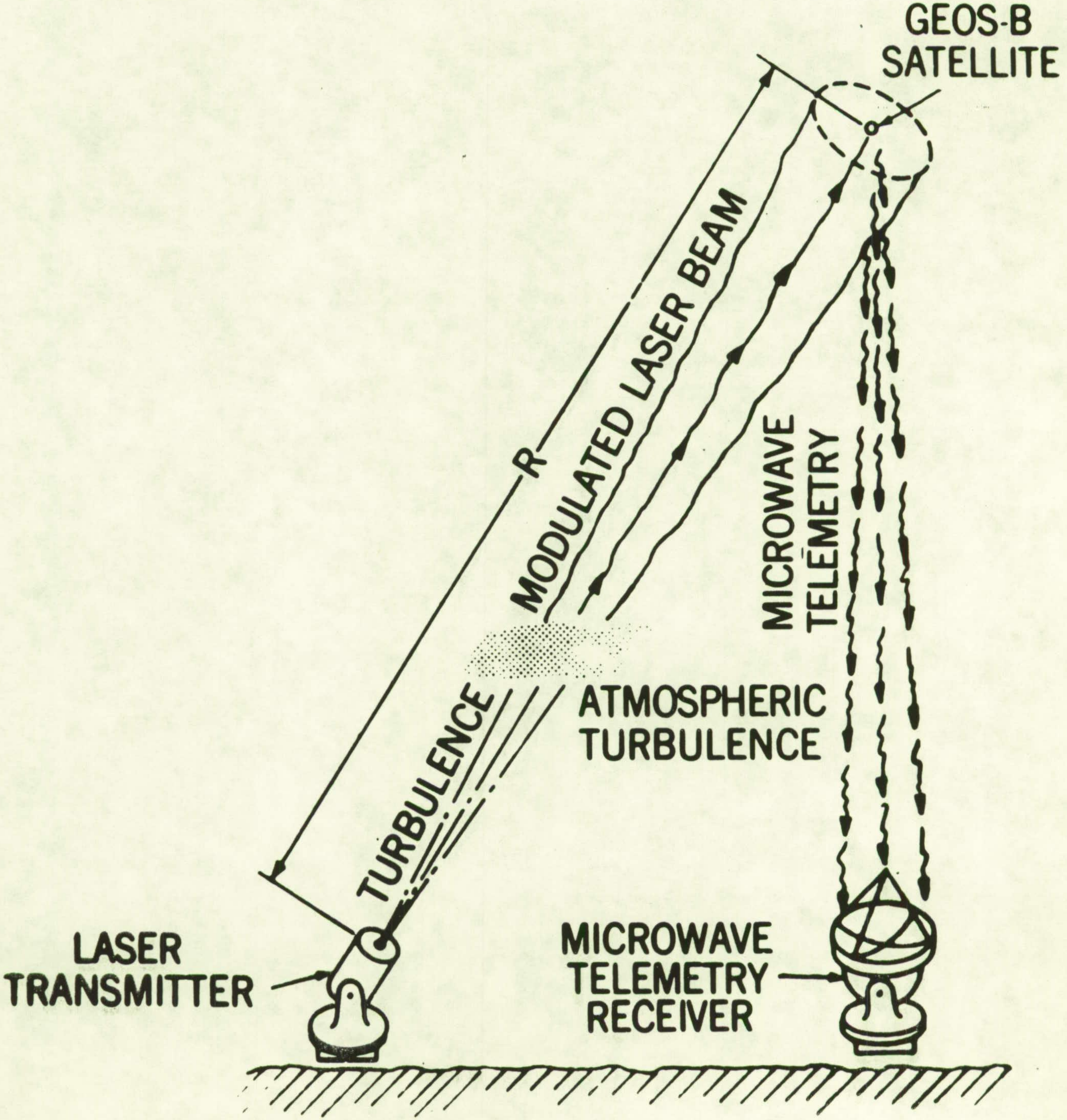


Figure 12



GEOS-B SATELLITE
R
MODULATED LASER BEAM
MICROWAVE TELEMETRY
TURBULENCE
ATMOSPHERIC TURBULENCE
LASER TRANSMITTER
MICROWAVE TELEMETRY RECEIVER

Figure 13

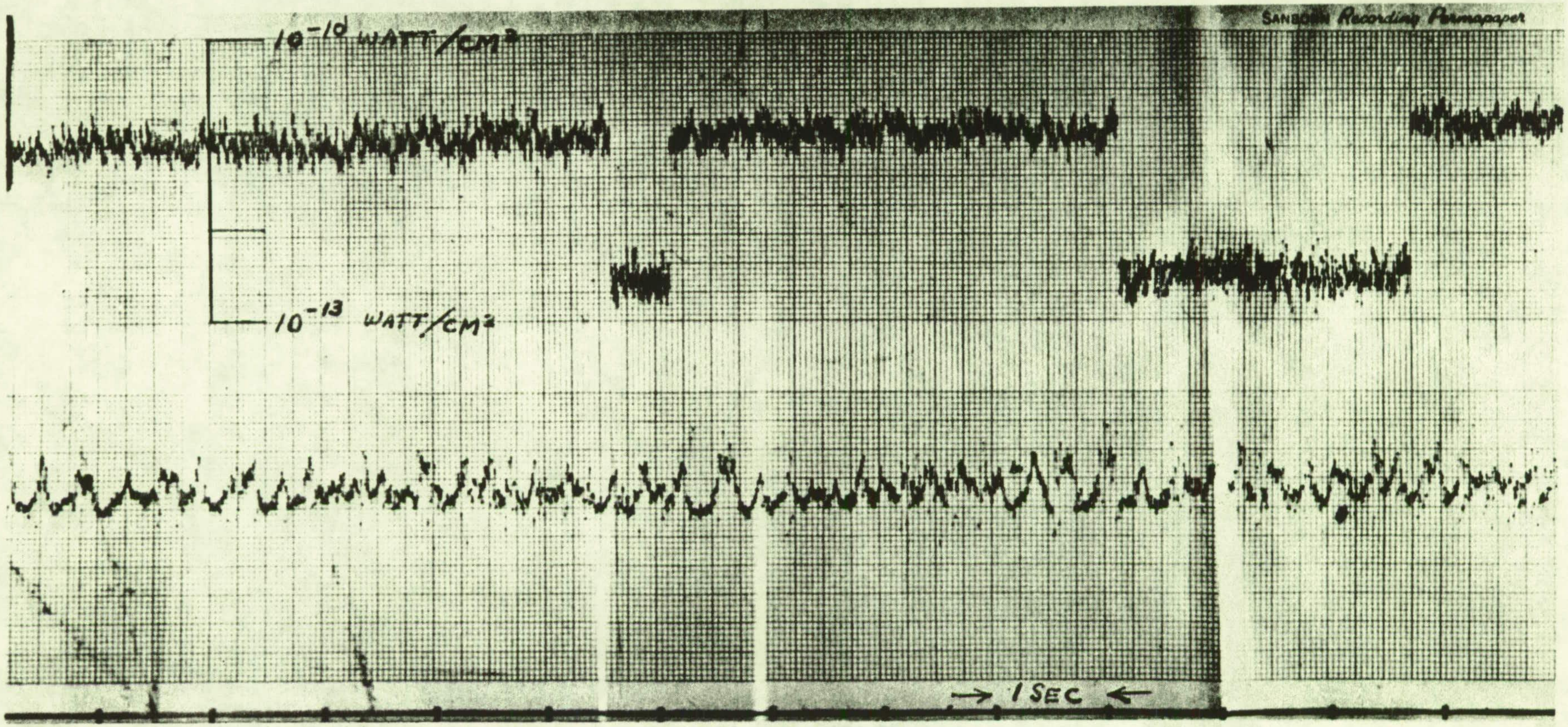

SANBORN Recording Permapaper
10^-10 WATT/CM²
10^-13 WATT/CM²
→ 1 SEC ←

Figure 14

FUNCTIONAL DIAGRAM OF 10.6μ TRANSCEIVER

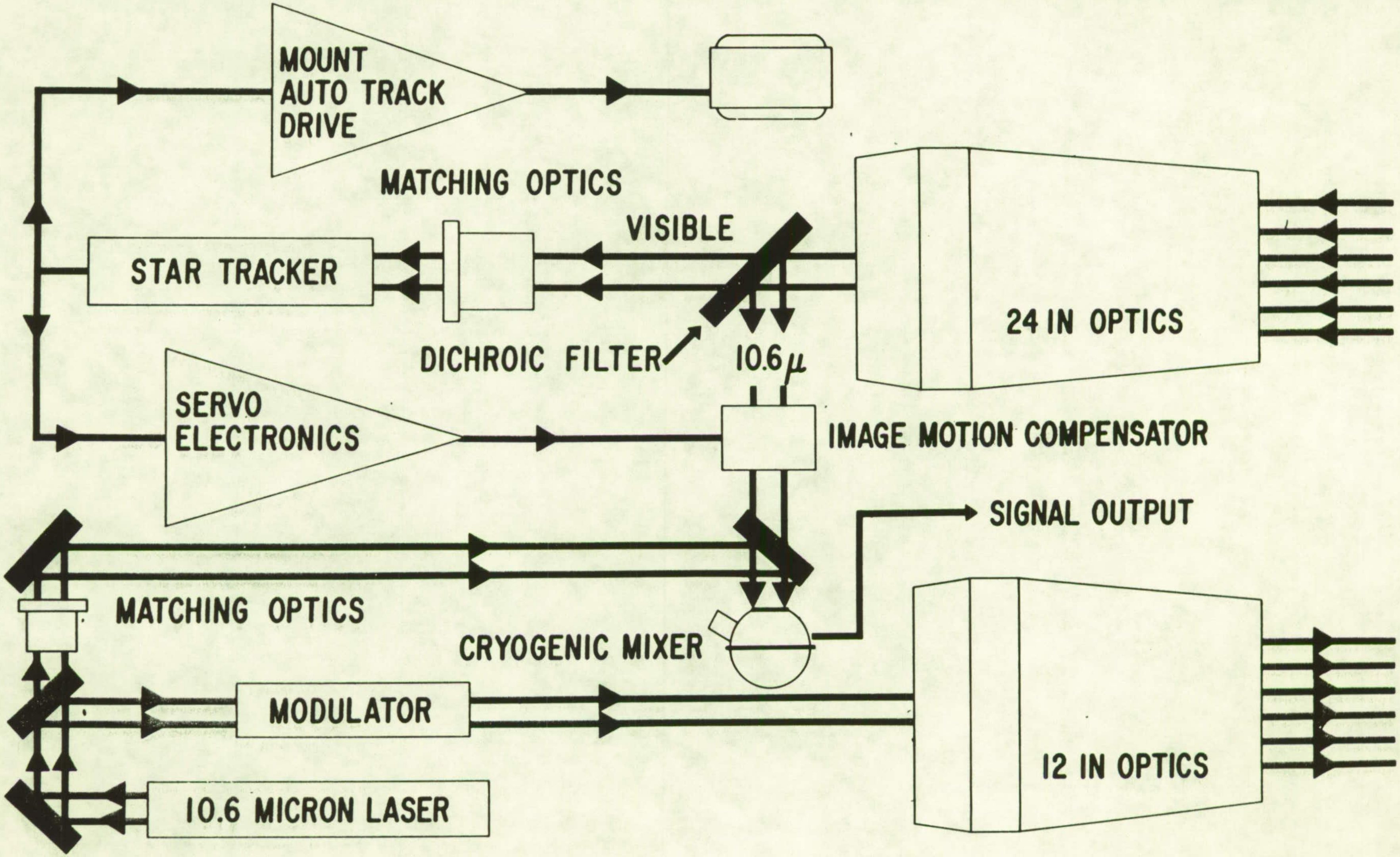


Figure 15

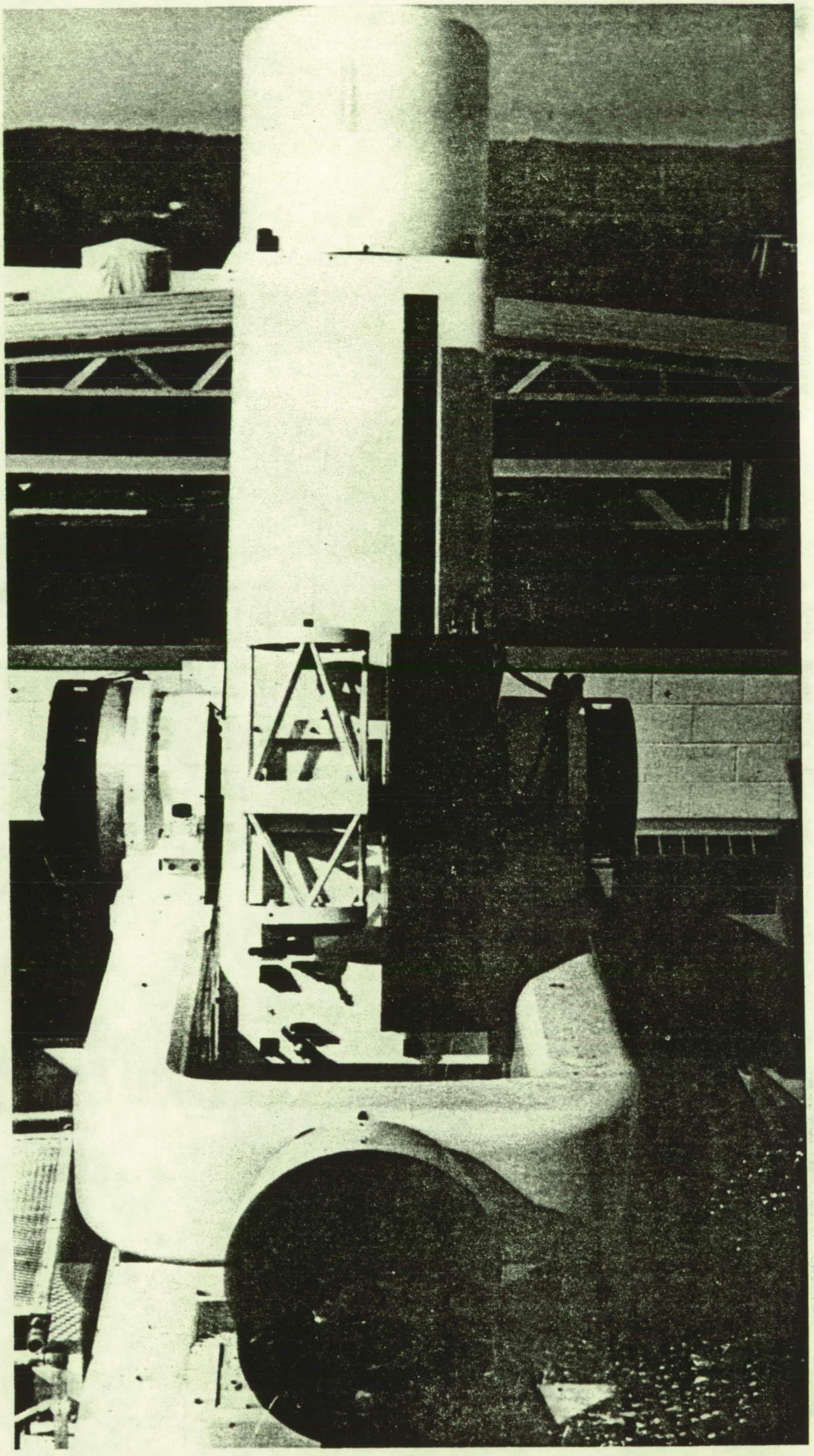


Figure 16

LASER COMMUNICATION LINK GEOMETRY

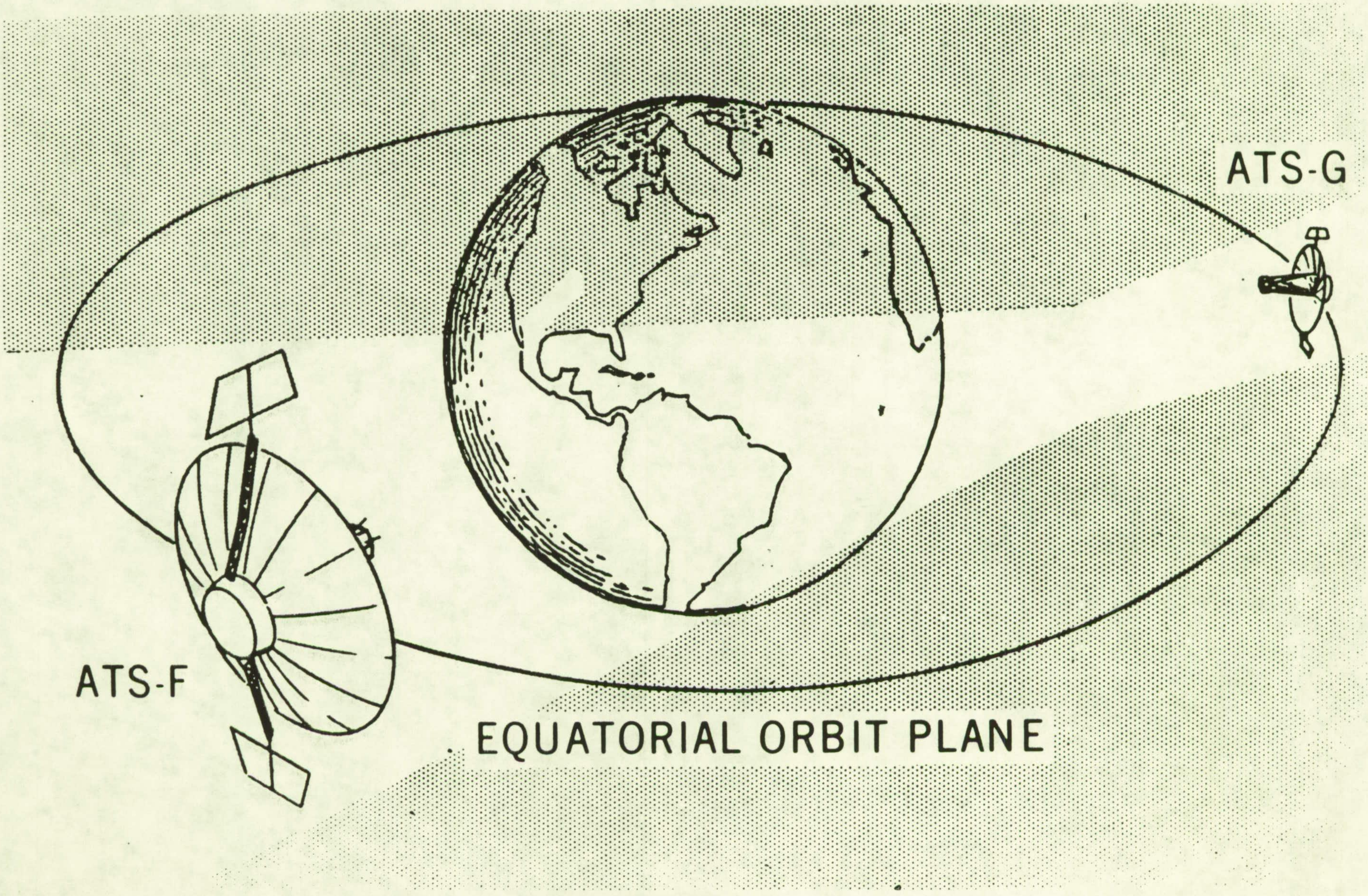


Figure 17

LASER SYSTEM CONCEPTUAL DRAWING

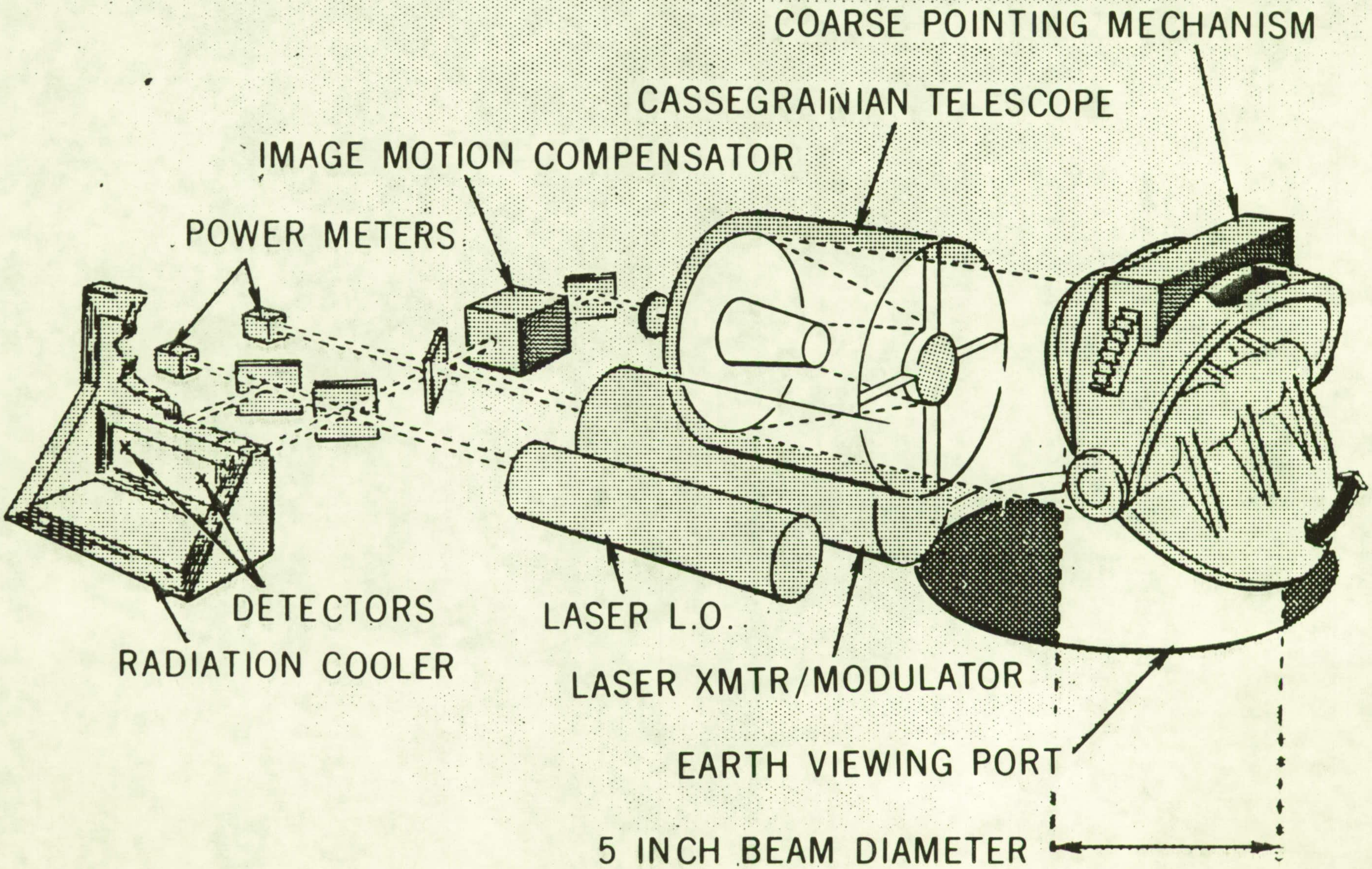


Figure 18

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LASER ATMOSPHERIC INSTRUMENTATION AND MEASUREMENT

Dr. James D. Lawrence
Langley Research Center

Introduction

The development of the high intensity giant pulse laser has placed new emphasis on methods of remotely sensing the properties of the atmosphere. The characteristics of the laser coupled with developments in computer and photodetector technology enable the investigator to significantly extend light scattering methods of observing the atmosphere and, perhaps for the first time place such measurements on a firm theoretical basis. In this paper two NASA laser radar research programs currently in progress will be described, and a number of potential applications of laser radar to problems in meteorology and atmospheric research will be discussed. In addition, the instrumentation developed to probe the atmosphere with lasers will be described as well as our plans for future research.

I Scattering of Laser Radiation in the Atmosphere

In order to establish a basis for the interpretation of laser returns from the atmosphere, we shall briefly present in this section a summary of Mie calculations at laser wavelengths for scattering by a clear atmosphere.

The radiation backscattered by a volume element of the atmosphere located a distance S from laser, expressed as the power incident on a coaxial receiver is given by

$$P(S) = \frac{cEA_R q^2(S)\,\sigma(S)}{2S^2}$$

where E is the transmitted energy, A_R is the area of the receiver, q(S) is the transmissivity of the atmosphere, $\sigma(S)$ is the backscattering volume cross section of a volume element located at S, and c is the velocity of light. In equation (1) the scattering volume is assumed to be a point source which required the beam divergence and pulse width of the laser to be small.

The volume cross section and transmissivity will be interpreted according to a scattering model which assumes the atmosphere to be a mixture of molecules, described by Rayleigh theory, and aerosols, described by rigorous Mie theory.

If the atmospheric absorption is neglected, the transmissivity is given by

$$q(S) = \exp\left[-\int_0^{S'} \beta(S)\, dS\right] \qquad (2)$$

where $\beta(S)$ is the sum of the molecular and aerosol scattering coefficients.

Rayleigh Scattering

The absolute Rayleigh volume cross section for backscatter from the molecular component is

$$\sigma_M = k^4 \bar{\alpha}^2 N(z)\ f \qquad (3)$$

where

k = wave number of incident radiation, $2\pi/\lambda$

$\bar{\alpha}$ = polarizability

N(z) = number density

and

$$f = \frac{3(2 + \Delta)}{6 - 7\,\Delta}$$

where Δ is the depolarization factor. For atmospheric air, G. de Vaucouleurs (1951) has measured $\Delta = 0.031$, and therefore $f = 1.054$.

The scattering coefficient for the molecular component is

$$\beta_M(z) = \int_0^{2\pi} \int_0^{\pi} \tfrac{1}{2}(1 + \cos^2\theta)\ \sigma_M(z)\ \sin\theta\ d\theta\ d\phi \qquad (4)$$

Large Particle Scattering

Assuming that the particulate matter present in the atmosphere may be considered a polydisperse collection of homogeneous spheres of average refraction index η , the volume cross section is given by

$$\sigma_A(z) = \int_{r_1}^{r_2} \frac{i\ (\alpha,\eta,\theta) + i\ (\alpha,\eta,\theta)}{2k^2}\, dn(r,z) \qquad (5)$$

where $i_{1,2}(\alpha,\eta,\theta)$ are the Mie intensity functions for light with electric vector perpendicular and parallel, respectively, to the plane through the direction of propagation of the incident and scattered radiation, r is the radius of the scatterer, $\alpha = 2\pi/\lambda$ is the particle size parameter, dn(r,z) is the number density of particles with radius between r and r + dr at altitude z, and θ is the scattering angle measured between the direction of the incident and scattered radiation.

Similarly, the scattering coefficient for such a collection is given by

$$\beta_A = \int_{r_1}^{r_2}\int_0^{\pi} \frac{\pi\ i_1(\alpha,\eta,\theta) + i_2(\alpha,\eta,\theta)}{k^2}\, \sin\theta\ d\theta\ dn(r,z) \qquad (6)$$

A computer program has been written to evaluate the integral expressions in equations (5) and (6) for an arbitrary choice of aerosol parameters, and we shall compare the results of an atmospheric scattering model calculation with experimental measurements in a section to follow.

II Instrumentation

Three laser radar systems have been constructed to date and have been used to probe the atmosphere.

An airborne system, installed in a T-33 type jet aircraft, consists of a ruby laser transmitter and a refracting telescope receiver whose axes are alined parallel. The laser produces pulses of approximately 0.1-joule energy and of 2--nsec duration with a beam divergence of 1 mrad.

The backscattered laser energy is collected by a receiver which has a field of view of 3 mrad and an effective collecting aperture of 0.1 meter. The optical bandwidth of the receiving system is determined by a temperature-controlled interference filter with a spectral bandwidth of 11.75 Å centered at 6943 Å. The photomultiplier detector used in this system has 16 amplifying stages and a photocathode with an S-20 spectral response. The laser output monitor is calibrated by comparison with a thermopile calorimeter and the spectral response of the receiver was determined using a standard lamp; in consequence, the airborne system can make absolute measurements of the backscattering cross section.

This laser radar system was constructed and flown to explore the feasibility of using laser radar as a clear air turbulence detection device. This system was not successful in detecting atmospheric turbulence; however, it has made excellent absolute measurements of the scattering properties of the atmosphere which will be described in a section to follow.

The first ground-based system designed consists of a ruby laser and and a 60-inch parabolic search light mirror positioned in a steerable mount with their axes parallel. The laser produces a 1- to 2-joule pulse of 20-nsec duration at 6943 Å, and is temperature controlled to prevent detuning into an atmospheric absorption band. A 14-stage photomultiplier detector with S-20 response is positioned near the focal plane. The optical bandwidth of the system is limited to about 700 Å by the combination of a red filter and the S-20 photocathode response. The acceptance angle of the mirror is reduced to approximately 10 mrad by a stop at the focal plane. In view of the wide spectral bandwidth of this system, it can not of course be used to make measurements during the daylight hours. At night, however, the sky background radiance is down from its daylight value by approximately six orders of magnitude and its contribution to the system noise is negligible for altitudes below approximately 30 km. As an indication of the performance of the system during nighttime operation we have listed in table 1 values of the signal to noise ratio for several altitude region.

TABLE 1. - SYSTEM DETECTION CAPABILITY

Altitude (km)	Signal to noise ratio
5	200
10	76
15	37
20	20
26	10

A schematic diagram of a second, more advanced, ground-based system which has been constructed to probe the upper atmosphere is given in Figure 1. This system consists of a 31-inch Newtonian telescope receiver with a ruby laser transmitter. The acceptance angle of the receiver is 1 mrad and the optical bandwidth is limited to 20 Å by an interference filter.

RESULTS

III Observations of the Clear Atmosphere

Typical observations of the clear atmosphere are shown in Figure 2. A composite profile extending to about 22 km has been constructed from three laser shots. The solid curve in the figure is the total return calculated for the U.S. Standard 1962 Atmosphere and an aerosol component based on Rosen's direct sampling measurements. A fast decrease in aerosol number density in the first 2 kilometers is evident; in this region the scattering is predominantly of aerosol origin. The scattering from about 2.5 to 12 kilometers appears to be predominantly of molecular origin; small increases in the absolute cross section, however, are noted throughout and indicate the presence of local concentrations of aerosols. A deviation from molecular scattering appears at about 12 kilometers and increases to about a factor of two at 19 kilometers.

Shown in Figure 3 are the results of a series of simultaneous measurements of the backscattering volume cross section of a clear atmosphere by the airborne and ground systems. The profile measured with the ground-based system has been normalized to the airborne data at 7.2 km. As is evident in the figure the two sets of experimental data agree very well and in addition agree with the model calculation above 2.5 km. Below 2.5 km the measured profile deviates significantly from the calculated profile. This deviation is indicative of the aerosol concentration in the vicinity of a subsidence inversion which existed in the vicinity of 1.8 km.

Observation of Clouds

No systematic observations of cloud systems have been made nor has any attempt been made to fit polydisperse models to our measurements. The observations made to date, however, clearly demonstrate that laser radar constitutes an excellent method for observing cloud systems.

The structure evident in Figure 4(a) is a high cirrus cloud extending from 9 to 12 km; also evident is an altostratus cloud at 5.85 km of thickness 300 m. The return in Figure 4(b) shows a cirrus cloud system centered at approximately 11.85 km. Figure 4(c) shows another cirrus cloud which at the time of observation was stratified into three layers. The base of this system was 11.7 km, while the top was 13.35 km. Figure 4(d) is an example of the return from a dense cirrus cloud similar to that found in figure 4(a) extending from 8.7 km to 11.25 km. In addition, it should be noted that laser radar can detect clouds in their earliest stages of formation.

Observations of Turbulent Regions of the Atmosphere

In a series of experiments conducted over Williamsburg and Wallops Island, Virginia, a T-33 type jet aircraft instrumented with a recording accelerometer was directed into regions of the clear atmosphere where enhanced backscatter of ruby laser radiation was observed by an experimental ground-based pulsed ruby laser radar system. In 33 cases, established over 7 nights of observation, the aircraft encountered light turbulence (vertical acceleration generally in the range 0.10 to 0.25g) in clear air in regions of enhanced backscatter. In addition, the aircraft conducted a general search for turbulence to heights of 12 km above the field station and did not encounter turbulence in regions where no enhancement in backscattered signal was evident.

Figure 5 shows oscilloscope recordings of two such examples in which the aircraft encountered turbulence. A scattering enhancement is clearly evident in Figure 5(a) from 3.3 to 4.05 km; the pilot reported light turbulence (0.1 to 0.2g) in clear air from 3.7 to 4.05 km. In Figure 5(b), an enhancement extending from 2.4 to 3.1 km is evident; the pilot reported light turbulence (0.1 to 0.2g) in clear air in three layered regions extending from 2.5 to 2.8 km. Radiosonde measurements made at Wallops Island, Virginia, (75 miles northeast of Williamsburg) on this evening indicated that a subsidence inversion existed at an altitude of 3.1 km; light turbulence was presented beneath this inversion.

IV Atmospheric Wind Velocity Program

The program which has just been described seeks to explore only one aspect of the laser radar technique. In a second program, which is being conducted at the Marshall Space Flight Center, applications of the CO_2 laser doppler technique to atmospheric measurements are being investigated.

Since the CO_2 laser doppler technique has been successful in making wind tunnel velocity measurements, consideration is being given to extending the development of this type of instrumentation to measurements of atmospheric wind velocity and turbulence. For this type of instrumentation, the S/N power at the output of the receiver for a monochromatic source is

$$S/N = \frac{Q\, P_r\, P_{lo}}{Bhf\ (P_{lo} + P_n + P_{amp})}$$

where Q = detector quantum efficiency

P_r = received signal power

P_{lo} = local oscillator signal power

P_n = equivalent optical noise power

P_{amp} = equivalent noise figure power of post detection amplifier

B = electronic bandwidth

h = Planck's constant

f = transmission frequency

In a coherent detection process, one may increase the local oscillator power to outweigh the effects of the additional noise contributing terms. As a result the S/N equation becomes equal to the product of the detector quantum efficiency and the received signal power and inversely related to the electronic bandwidth, transmission frequency and Planck's constant. The advantages of using a CO_2 laser system for atmospheric studies of this type are:

1. Since the coherent scattering volume increases as the square of the wavelength, the S/N increases as the cube of the wavelength of the incident radiation. The CO_2 laser takes maximum advantage of λ^3 dependence of the signal to noise ratio.

2. The laser is efficient in the use of prime power ($\approx$10%)

3. Alinement is not critical because of long wavelength

4. The CO_2 laser has the highest CW output power available and substantial power increases are predicted in the near future.

Given in Figure 6 is a schematic diagram of a preliminary experiment performed in the atmosphere with a 10 watt single frequency CO_2 laser. Measurements were made of the doppler return for various types of weather conditions ranging from very clear to rainy, and a general correlation has been obtained with the approximate wind velocity prevalent at that time of day. Recently a 25-watt stable single frequency CO_2 laser has been developed to improve these measurements.

V Future Research Program

Our plans for future work at the Langley Research Center may be divided into three areas;

A. Extension of the laser radar technique to include multiple wavelength measurements and Raman scattering

B. Development of instrumentation

C. Investigations of the potential application of laser radar to fundamental problems in upper atmospheric research, meteorology, oceanography, and air pollution

A. Extension of the Laser Radar Measurement Technique

1. Multiple laser wavelength measurements:

The equations developed in section II for the molecular and aerosol scattering components suggest a natural extension of the measurement technique to multiple laser wavelengths. Given in Figure 7 are scattering profiles for three laser wavelengths computed for an aerosol component based on direct sampling measurements and a molecular component based on the U.S. Standard Atmosphere 1962. The curves given in Figure 7 indicate the relative contribution of the aerosol and molecular scattering components at the laser wavelengths 1.06μ, 0.6943μ, and 0.3472μ, and it can be shown that measurements at these wavelengths will completely characterize the atmospheric aerosol.

2. Raman scattering:

If the spectrum of laser radiation scattered by the atmosphere is examined, it will consist of an intense line characterized by the frequency of the incident radiation, and in addition a series of very weak lines produced by inelastic scattering by the various molecular species present in the atmosphere. When an incident photon is inelastically scattered by a molecule, it either gives up energy to the scattering molecule or it takes energy from it. Since the molecule can only give up or absorb energy between stationary states, the inelastically scattered or Raman scattered radiation is characteristic of the scattering molecule. Measurement of the Raman lines associated with laser scattering appears to be a very promising technique for studying the atmosphere. It may be possible to use this technique to measure the transmissivity of the atmosphere, the vertical profile of the constituents of the atmosphere and possibly the temperature profile. It should be noted, however, that the Raman scattered radiation represents a very small fraction of the total scattering and, in consequence, it will be a very difficult measurement to make.

B. Instrumentation

Given in Figure 8 is a schematic diagram of an improved optical radar system which is currently in the design phase. It is anticipated that construction of this system will be completed by the middle of 1969.

The system consists of a steerable 48-inch f/2 Cassegrain telescope receiver which will be trailer mounted. Two laser systems, ruby and neodymium, will be mounted on the receiver with 10:1 collimators. It is anticipated that both of these laser systems will have a pulse repetition rate of approximately 10-15 pulses per minute with a transmitted energy in the range 3-5 joules. In addition a relatively advanced data acquisition system will be incorporated in the optical radar as shown in Figure 8.

C. Planned Investigations of Potential Applications of Laser Radar

1. Meteorology

Laser radar is in many ways similar to conventional weather radar with the added attraction that it is many orders of magnitude more sensitive. It is, in consequence, a very useful tool for meteorological investigations. One important potential application is in the area of weather modification. An important requirement in cloud seeding experiments is a method for determining the possible rain content of a cloud system prior to seeding. It is likely that laser radar can provide an economical and accurate method of determining the cloud systems that can be profitably seeded. A second area in which laser radar may have an important potential application is in the study of turbulence. Preliminary results obtained which were briefly described in a previous section indicate that it may be a promising technique for the study and detection of atmospheric turbulence.

2. Upper atmosphere measurements:

Direct measurements of the atmosphere can be made to altitudes of approximately 30 km by balloon-borne instruments, and above 150 km satellite experiments provide useful data. The region 30-150 km, however, remains accessible only to rocket probes. In view of the fact that it is both difficult and expensive to make systematic measurements with rocket probes, little is known of the latitudinal, seasonal, and diurnal variations in density of the altitude region 30-150 km. Laser radar is a very promising and inexpensive technique for providing systematic measurements of the molecular and particle density of this altitude region.

Air Pollution

Laser radar provides an accurate and convenient method for monitoring pollutants introduced into the atmosphere in industrial areas. An important aspect of the laser radar method of monitoring pollutants is that it provides a remote measurement.

Oceanography

The National Academy of Science has recognized the air-sea interaction as a research area of fundamental importance and has recommended that it be subjected to extensive study. At least, in principle, laser radar can determine the coefficient of eddy transfer in the lower atmosphere by measuring the vertical distribution of salt particles and other aerosols over the ocean. In addition, it can materially aid convective studies over the ocean by providing accurate measurements of the distribution and transmissivity of cloud systems.

At Marshall Space Flight Center further development of the CO_2 laser doppler technique is being considered in the following areas:

1. Perform precise triangulation doppler measurements to compare with anemometer data

2. Develop a three-dimensional ground wind measuring instrument capable of one meter resolution at 500 meters altitude

3. Determine the feasibility of detecting trailing vortices behind aircraft landing or taking off at airports

4. Since the laser doppler technique provides a direct measurement

of turbulence, consideration is being given to the possible development of a CO_2 doppler radar as a clear air turbulence detection system.

VI Future Developments Required

Laser radar systems have excellent potential for a number of important applications with the present state of technology; however, with additional research and development its capabilities can be increased markedly. Fruitful areas for research and development are:

1. Improvement in laser power with increased pulse repetition rate
2. Improved reliability of high-power laser systems
3. Improvement in the efficiency of harmonic generation materials
4. Development to increase quantum efficiency of detectors in visible and infrared
5. Development of interference filters for receiver with small spectral bandwidth and high transmission.

SCHEMATIC DIAGRAM OF LASER RADAR SYSTEM
FOR UPPER ATMOSPHERE MEASUREMENTS

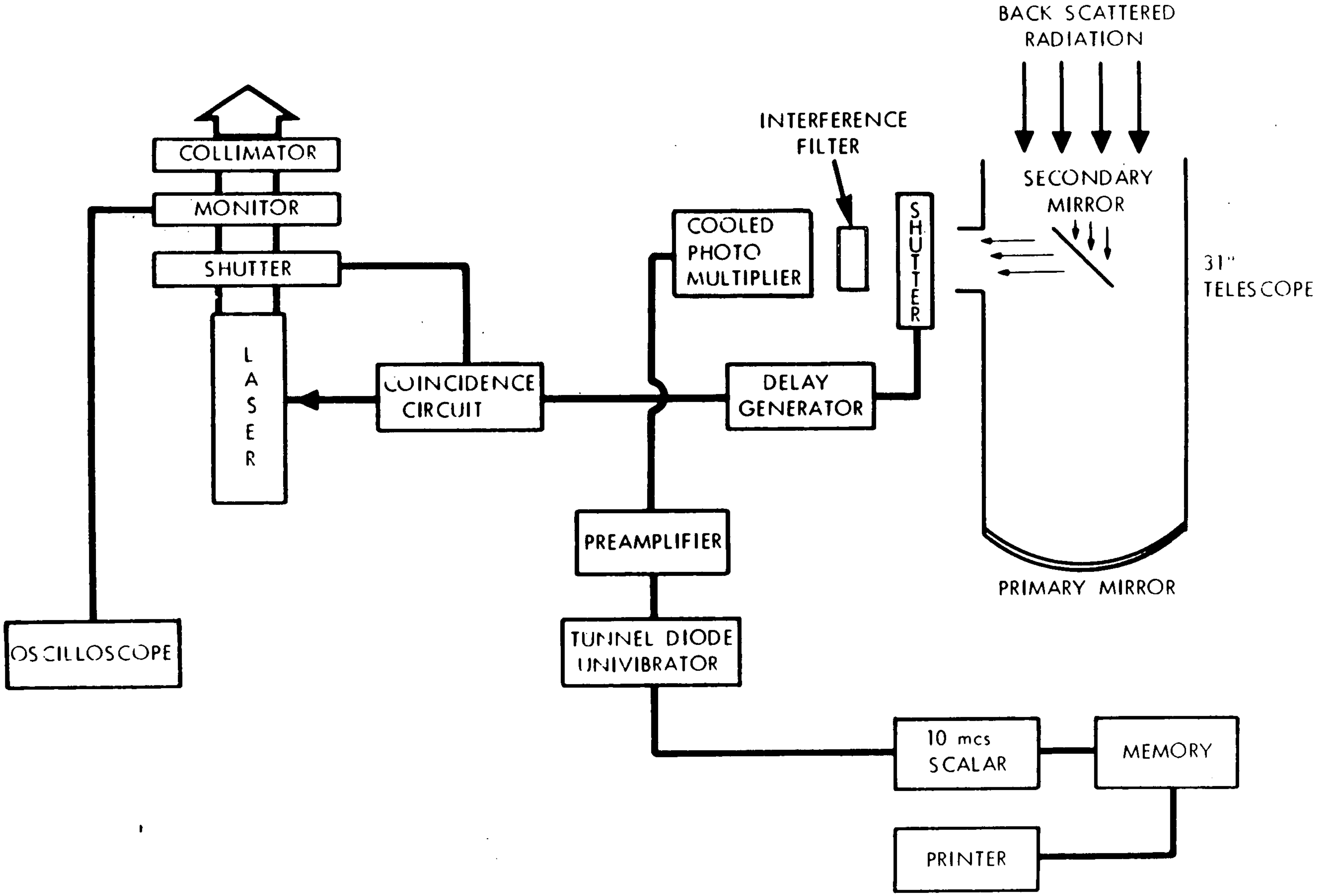

Figure 1

LASER RADAR RETURN FROM THE CLEAR ATMOSPHERE

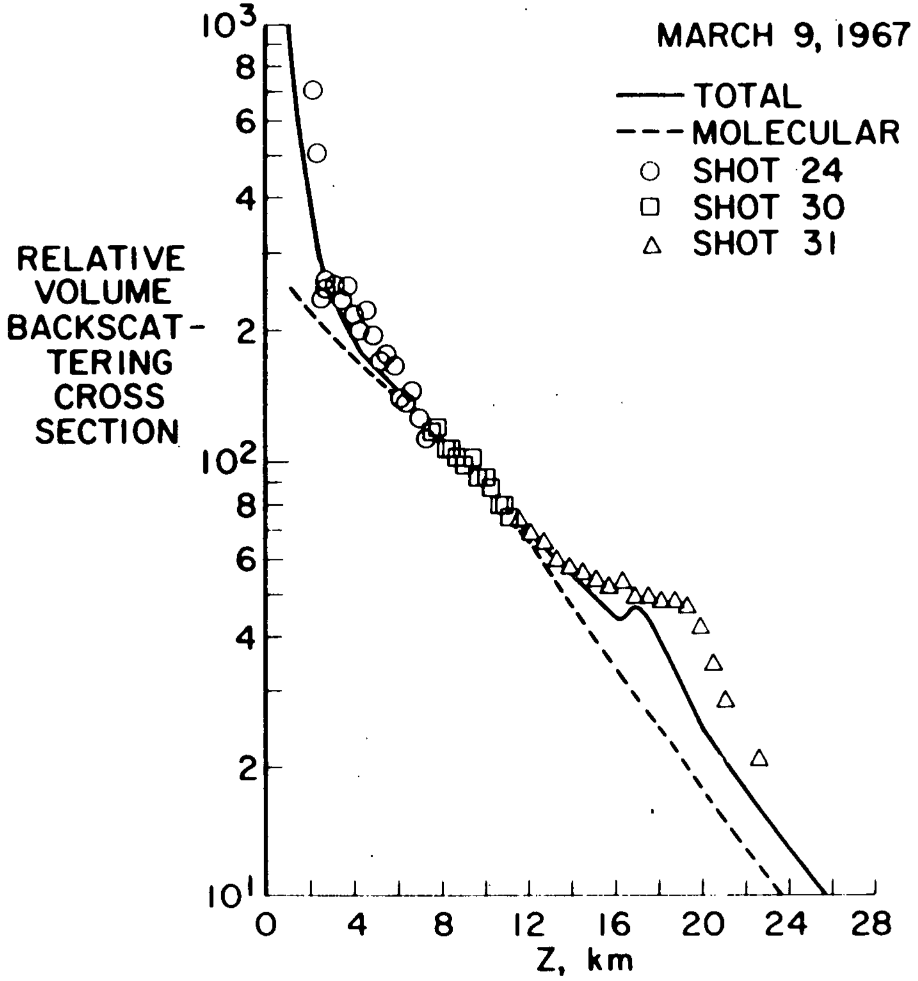

Figure 2

SIMULTANEOUS GROUND-BASED AND AIRBORNE LASER RADAR MEASUREMENTS

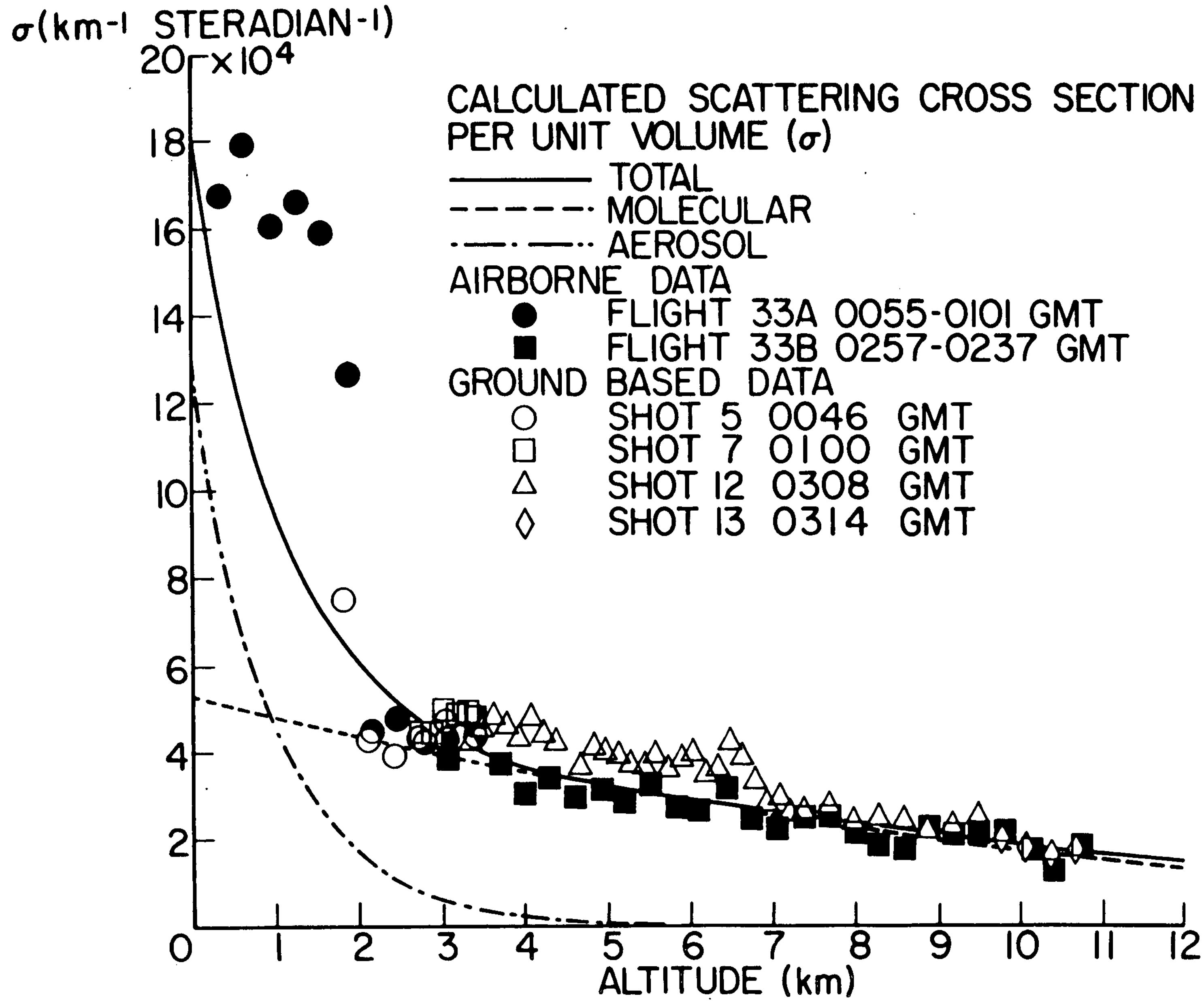

Figure 3

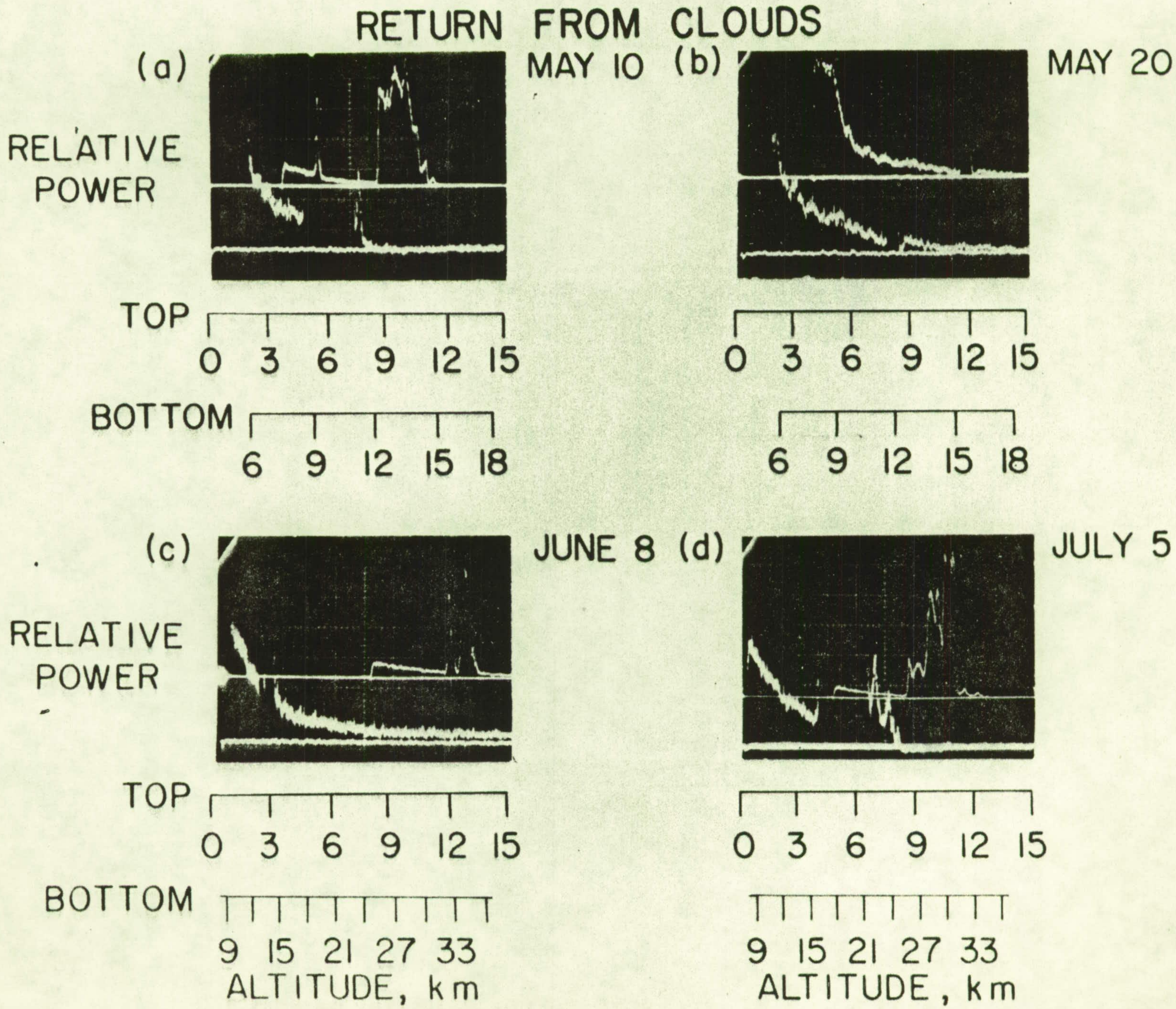
RETURN FROM CLOUDS
(a)
MAY 10
(b)
MAY 20
RELATIVE POWER
TOP
0 3 6 9 12 15
BOTTOM
6 9 12 15 18
0 3 6 9 12 15
6 9 12 15 18
(c)
JUNE 8
(d)
JULY 5
RELATIVE POWER
TOP
0 3 6 9 12 15
BOTTOM
9 15 21 27 33
ALTITUDE, km
0 3 6 9 12 15
9 15 21 27 33
ALTITUDE, km

Figure 4

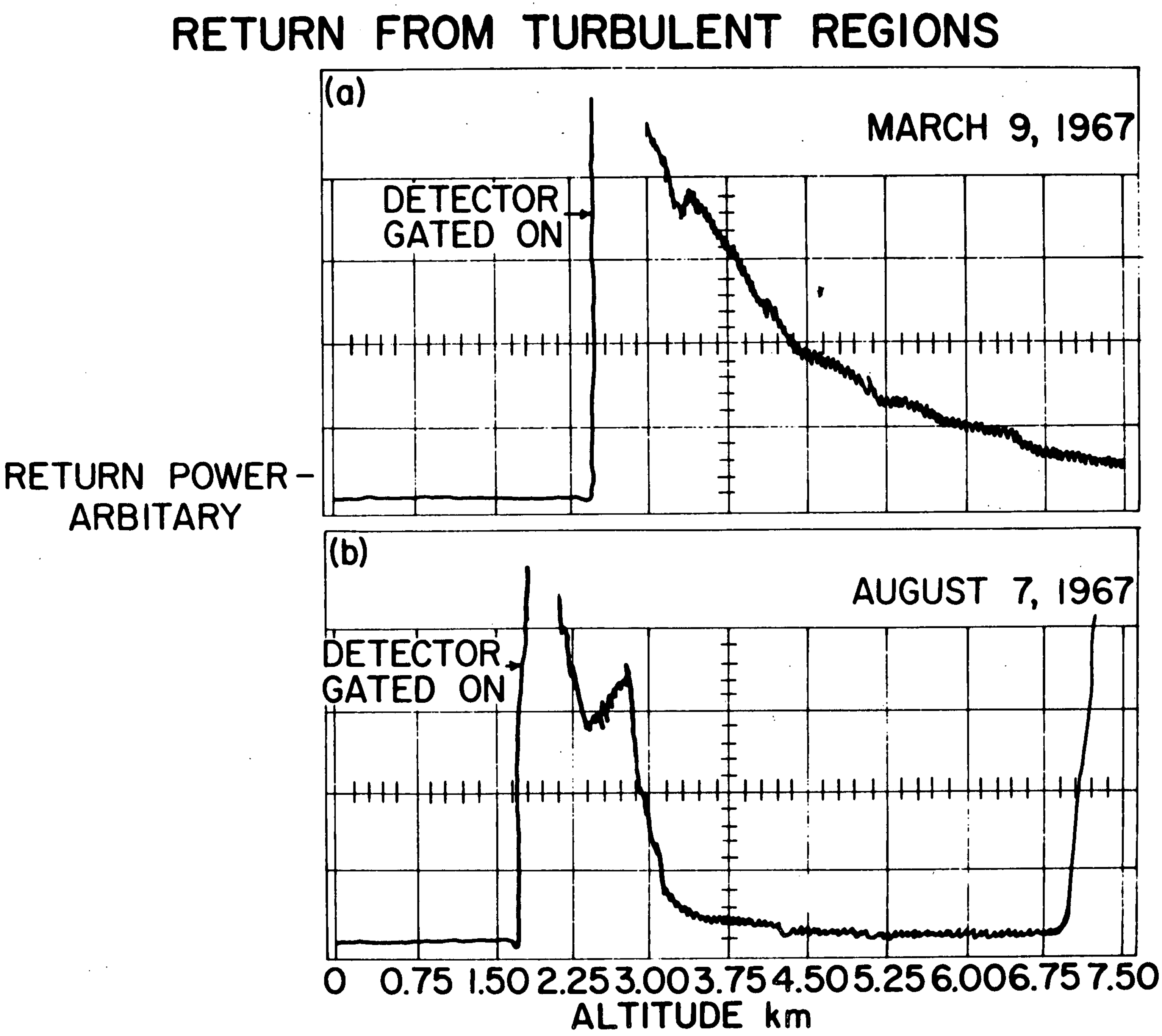
RETURN FROM TURBULENT REGIONS
(a)
MARCH 9, 1967
DETECTOR GATED ON
RETURN POWER - ARBITARY
(b)
AUGUST 7, 1967
DETECTOR GATED ON
0
0.75
1.50
2.25
3.00
3.75
4.50
5.25
6.00
6.75
7.50
ALTITUDE km

Figure 5

LASER DOPPLER TECHNIQUE FOR WIND VELOCITY & TURBULENCE MEASUREMENTS

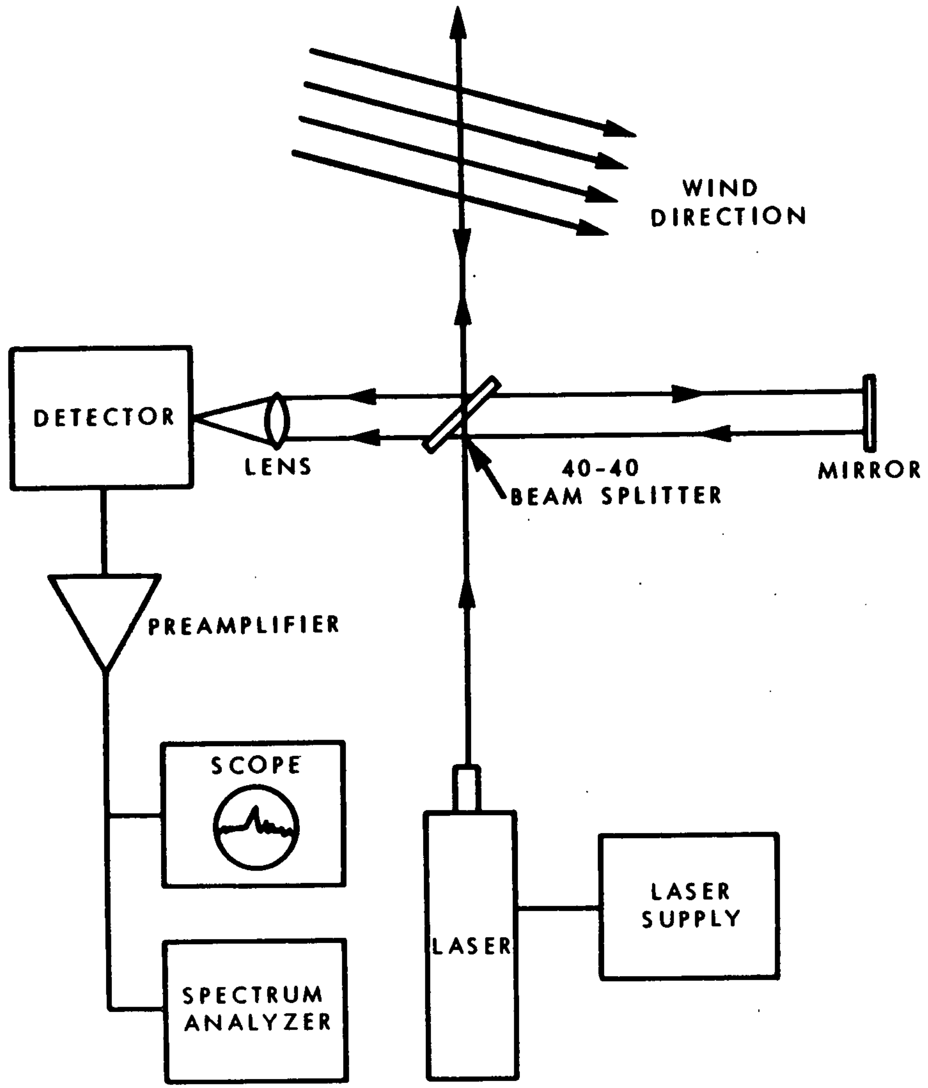

Figure 6

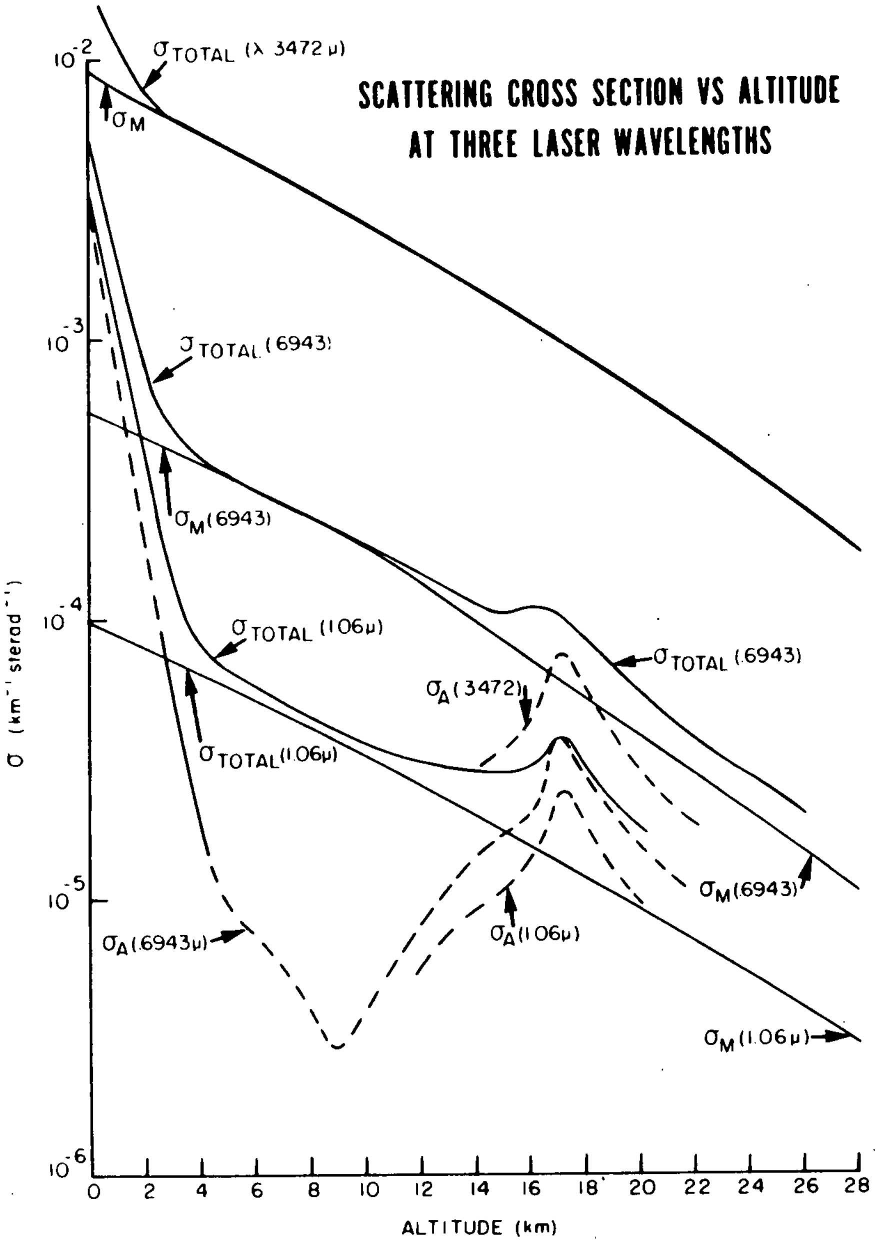
SCATTERING CROSS SECTION VS ALTITUDE AT THREE LASER WAVELENGTHS
σ_{TOTAL} (λ 3472 μ)
σ_M
σ_{TOTAL} (.6943)
σ_M(6943)
σ_{TOTAL} (1.06μ)
σ_{TOTAL}(1.06μ)
σ_{TOTAL} (.6943)
σ_A(3472)
σ_A(.6943μ)
σ_A(1.06μ)
σ_M(6943)
σ_M(1.06μ)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
σ (km⁻¹ sterad⁻¹)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
ALTITUDE (km)

Figure 7

SCHEMATIC DIAGRAM OF LASER RADAR SYSTEM UNDER DEVELOPMENT

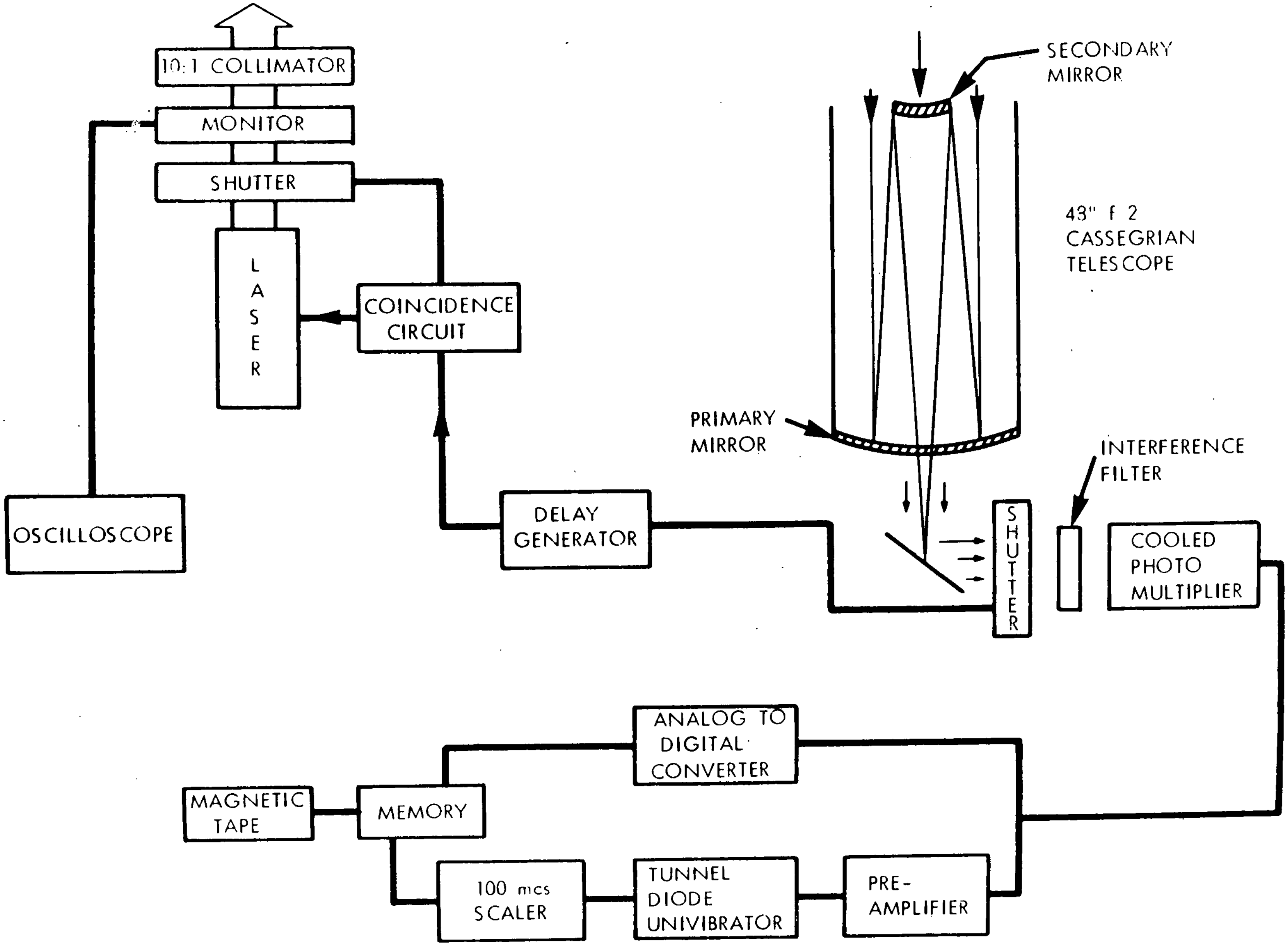

Figure 8

19740077984

LASER TEST FACILITY INSTRUMENTATION

Benjamin H. Beam
Ames Research Center

New applications for lasers are suggesting themselves constantly. In this paper, I will describe a few selected applications in aeronautics and gasdynamics research. Many of the test facilities in NASA are wind tunnels or supersonic nozzles of various types into which scale models of airplanes or missiles are inserted to measure their reaction to air flow. The problem of measuring all the parameters of the gas flow--velocity, density, temperature, pressure, and gas composition--is a recurring one which absorbs a great deal of time and money.

The particular properties of the laser which are considered useful for these instrumentation problems are: first, it can provide a high intensity of light; second, the nature of the light--its spatial coherence--allows the entire light beam to be focused into a very small spot size; and third, the temporal coherence, or frequency monochromaticity, of the laser beam which confines almost the entire output to a single wavelength or a very narrow range of wavelengths. I will give some examples of how these properties are used in aerodynamics test facilities.

An instrument widely used in supersonic aerodynamic research is the schlieren system. In Figure 1 a double-pass schlieren system as used in one of our high speed gasdynamic test facilities is shown schematically. A laser is shown as the source of light which pases through the half-silvered mirror, through the windows of the test section, past the model, is reflected back from the spherical mirror, through the test section again, back to the half-silvered mirror where a portion of the reflected light passes a knife edge and into a camera system. The critical property of the schlieren system is the adjustment of the knife edge to obscure the undeviated light rays but to pass the refracted light rays which focus at a point somewhat removed from the knife edge. By selectively passing the refracted ray, a display of the minute distrubances in the aerodynamic flow patterns around the model is created. It is clear, however, that the light cannot be refocused to a point any smaller than the effective size of the source. It is also clear that as the size, or aperture, of the source is reduced, the intensity of the light will have to be increased to obtain an exposure on film in the same time span. Because of its "spatial coherence," the laser is superior to other light sources to obtain schlieren information with air streams of extremely low density, and to provide very short exposure times. At the top of this photograph, we show a schlieren picture of a blunt-faced cylinder in an air stream at a pressure of 5 x 10^{-4} atmospheres with an exposure time of 1/60 of a second. The air is approaching from the top of the photograph. A shock wave is barely apparent in front of the cylinder. This is not a completely satisfactory photo, but it is about the best we can obtain at present. In order to provide a sensitive schlieren system, many features of the system must be carefully designed. For example, shrouds must be provided around the light path to keep down extraneous air currents; optical elements must be of nearly perfect quality; the mechanical supports must be designed to minimize vibration effects; and the design must minimize thermal distortions.

While the "spatial coherence" of the laser can provide the advantage of shorter exposure time, the extreme temporal coherence of the laser is in fact a nuisance in the schlieren system because of interference produced by reflection from all the optical surfaces in the system. These are evidenced by the faint diagonal lines remaining in the picture after strenuous efforts to eliminate them. The test section windows are normally cocked at a small angle so that spurious reflections from windows will not enter the camera.

Although we feel the schlieren we have obtained using lasers are at least an order of magnitude better than we could obtain using other light sources, we feel that our systems still leave much to be desired. We have low density, short flow duration facilities which cannot now use schlieren techniques because it is not sufficiently sensitive.

No discussion of laser applications to instrumentation problems would be complete without consideration of holography. Ames is working both through in-house research and through support of contract research with other laboratories to develop the application of holography to flow visualization. In Figure 2 we see a two-beam holographic arrangement developed by Dr. Lee Heflinger and Dr. Robert Brookes at TRW Systems. A pulsed ruby laser is used in these experiments to obtain short exposure times. First, the laser beam is split into two parts by a half-silvered beam splitter in the light path. One part, called the reference beam, is passed sequentially through a mirror, a prism inverter and a concave lens used to expand the beam to the full width of the hologram plate. The other half of the laser beam passes through a concave beam expander, to a mirror and to a frosted diffusing screen. The light scattered from the diffusing screen then passes through a lens arrangement, through the test volume, and thence to the hologram plate. We see that a ray traced from the beam splitter through the reference beam path is at the same side of the hologram plate as the same ray through the scene path. The scene ray is in turn split into many rays by the frosted glass. All these rays emerging from the frosted glass derived from the same parent ray arrive at the hologram at essentially the same point and with the same optical delay. The scene to be recorded is placed about midway between these lenses used for focusing and the hologram plate.

Some excellent hologram pictures of sample subjects have been obtained using this arrangement. By means of a large number of improvements in the system (such as painting the back side of the hologram plates before exposure with flat black spray paint to remove reflections from the rear surface, improving coherence of the laser light source by using high quality ruby in the oscillator cavity, improving coherence of the laser light source by using high quality ruby in the oscillator cavity, improving coherence even further by aperturing off all but a selected portion of this ruby, by careful attention to alignment, uniformity of illumination, and path-length-matching throughout the entire system), one can extend the usefulness of the system.

One of the most interesting applications of this technique in our research is in shadowgraph and interferometry. In Figure 3 we have reproduced a shadowgraph and an interferogram of a .22-caliber bullet in flight through air at about 3000 feet per second. The shadowgraph simply shows a shadow at the position of the model and shock wave. It could have been obtained by other methods except that now we focus on different parts of the field. Successive exposures to make pictures at different depth in the hologram plate would permit focusing on details of the scattered material and blast waves. Using a double exposure interferogram technique, everything that is unchanged in two succeeding exposures of the scene, first with no bullet and second with the bullet, emerges as a more or less uniform gray field like an interferometer adjusted for infinite fringe spacing. Any disturbance in the field causing optical delay in the scene beam between succeeding photographs will cause interference lines to appear, from which density can be reconstructed. As with the shadowgraph, we can also focus on flow details. Absolute measurements of density changes can be made by reference to the interferometer fringes in the same manner as with a conventional interferometer. A conventional interferometer used in gasdynamic research is a formidable instrument and the double pulse holographic technique offers many practical advantages. Work is underway at the Graduate Institute of Technology at the University of Arkansas to use a system of two reference beams in a double exposure technique to further improve on interferogram detail. They are also engaged in research to improve response of photographic film used in holography. Many excellent photographs of gasdynamic and fluid dynamic phenomena have been taken using this technique at pressures near atmospheric or slightly below. At very low densities the same problem arises as with the schlieren system, in that there is insufficient change in air density to produce discernible interferometric effects. There are, however, many applications of this technique to flows around projectiles, study of impacts, flows in ducts, and many other applications where depth of field or cancellation of degrading optics is important.

At the Jet Propulsion Laboratory in Pasadena a holocamera, built by the TRW holography group, is being used to study combustion processes in liquid fuel rocket engines. Both shadowgraph and interferograms have been made of rocket exhausts using a Q-switched ruby laser with 50 nano-second exposure times.

At the Langley Research Center holographic interferometry is being used to sutdy structural deformations and structural vibrations of aircraft using a method of time-averaged interferometry. In this method, an example of which is shown in Figure 4, a time exposure hologram is made of a vibrating object. The position of the surface is recorded as a system of light and dark bands at the extremities of its motion toward and away from the plate, and at intermediate intervals of 1/2 wavelength of the light being used. Thus a set of contour lines is recorded showing the deflection of the object. This slide of the various modes in a vibrating membrane was made by Langley researchers, following a method outlined by others, to establish capability. Research is now in progress on applications of the technique to practical structural problems.

Turning from this interesting and potentially very useful subject of holography, to the problem of measuring velocity in supersonic streams using doppler-shifted laser light, we see in Figure 5 a schematic arrangement of such a velocity measuring apparatus. The nozzle shown is a small, variable-throat nozzle in which variations in the throat opening cause changes of the Mach number and volocity of the supersonic stream. An Argon-ion laser is focused at a point within this stream. Light scattered from small particles in the flowing stream will enter the collector lens at two different slit apertures--one upstream and one downstream from the scattering point. These two beams will be mixed by the mirror arrangement and focused on the photomultiplier tube. Doppler shift of the forward-scattered beam increases the frequency of the light, whereas doppler shift of the backward-scattered beam decreases the light frequency. Mixing these two beams at the photomultiplier tube face results in a beat frequency which is related to velocity.

The next application of this instrument technique we intend to explore is the measurement of velocity in a combustion facility in which the high temperature of the gas stream precludes use of probes for local measurements in the stream, and in which there will be enough particulate matter in the stream to provide adequate light scattering.

Marshall Space Flight Center has been working with this method of measuring velocity for some time and now, with support from Raytheon, the doppler-shift technique is being applied to measurement of the local turbulent velocity vector in rocket exhausts and supersonic nozzles. This is accomplished by using three photomultiplier detectors, each at a different scattering angle, to provide data for resolving the three vector components of velocity. The system is useful for measuring mean velocity with an accuracy equal to or better than that obtained with conventional gas velocity measuring instruments, and is also capable of measuring trubulence level to determine the same parameters as those from hot-wire anemometers.

A somewhat different technique for measuring gas velocity in high temperature gas and plasma streams is in use at the Jet Propulsion Laboratory. A giant pulse laser is focused in a gas flow by a lens, producing a gas breakdown in the small region of the focal point of the beam. Light produced by the breakdown serves as a tracer for the flow velocity measurement using a drum camera to record the motion. Motion of the plasma droplet is also detected using an electrostatic probe a fixed distance (5mm) downstream from the focal point. Tests with this equipment in an Argon plasma jet at gas velocities up to 1700 meters per second have been made within an estimated experimental error of 3%.

Deflections or vibrations of a structure during testing or operation can be measured using a laser technique developed for Ames by Sylvania. This system utilizes a continuous-wave laser, amplitude-modulated at at microwave frequency, reflected from the surface under test.

The monochromatic properties of the laser have been utilized in other ways, one of which is in spectroscopic applications. The great number of different materials being used for lasers provide a number of spectrally pure lines extending from Argon-ion in the blue to CO_2 in the infrared at 10.6 microns and beyond. In the particular example to be described we consider the hydrogen-carbon absorption band around 3.1 to 3.4 microns shown in Figure 7. The wavelength corresponding to the fundamental stretching vibration of the hydrogen-carbon atoms in methane is at the point Q occurring at about 3.31 microns. Around this fundamental wavelength there is a structure of fine absorption lines representing quantized vibration-rotation levels where a light beam transmitted through a methane sample would be strongly absorbed. Absorption of similar strength would occur in a wide range of hydrocarbons. In the methane spectrum shown, the 7th peak in the p branch centered at 3.3922 microns is very near, and thus absorbs strongly, the Helium-Neon laser emission line at 3.3913 microns. Using this fortuitous coincidence, we have developed at Ames a prototype of a "hydrocarbon gas detector," which is shown in schematic, functional form in Figure 8. A Helium-Neon laser beam at 3.39 microns is incident on a mirrored tuning-fork chopper which alternately allows the light to be transmitted to the corner mirror which returns it to the detector; and, for the other half cycle, reflects the light from the tuning-fork chopper blade directly to the detector. After the instrument is balanced by adjusting the light intensity from the long path and the short path to the same value, any differences in absorption through the long path, due to the presence of absorbing gas, will cause an instrument deflection.

Measurements have been made of absorption coefficients of various hydrocarbons at 3.39 microns as shown in Figure 9. All the hydrocarbons on which tests were conducted showed appreciable absorption. A comparison with other data shows that the absorption coefficients obtained in this way are considerably different from those inferred from data taken at lower spectroscopic resolution. This is not surprising in view of the extreme narrowness of the vibration-rotation lines and the laser lines, and the spacing between the lines. For example, spectroscopic data at low resolution shows that ethane absorbed more strongly than methane while the reverse is shown by our data. One application of this instrument technique which is being considered now is detection of low concentrations of combustible hydrocarbon vapors such as jet fuels and gasoline as a warning of fire and explosion hazard.

Many other uses of the laser in NASA include such applications as interferometric arrangements to measure electron densities in extremely high temperature plasmas in shock tubes, and high intensity point sources of light for certain ultraviolet spectroscopic applications. In this discussion it has not been possible to cover more than a few examples, but I hope that these I have selected have served to illustrate some of the scope and vitality of the applications of lasers to test facility instrumentation.

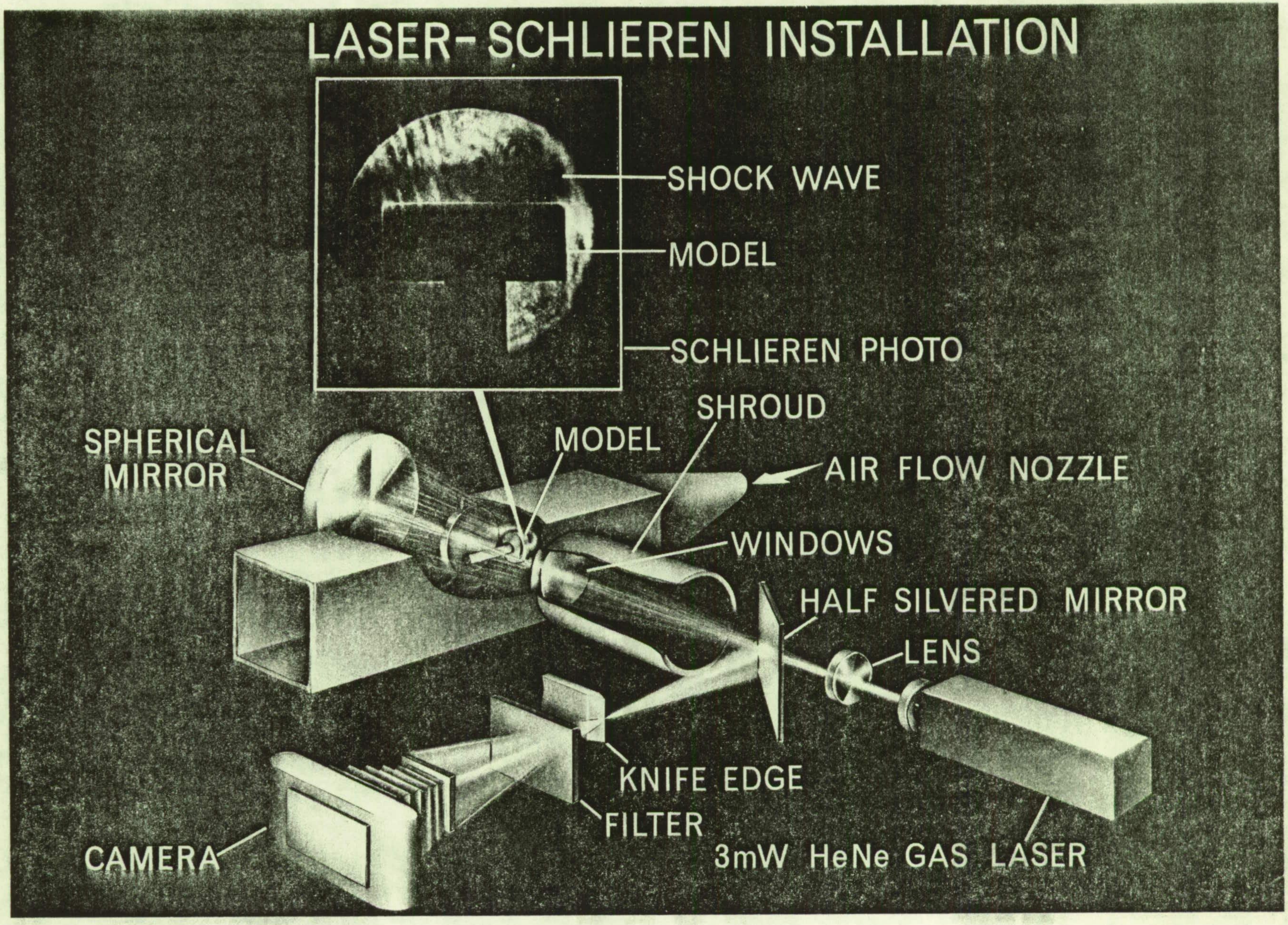

Figure 1

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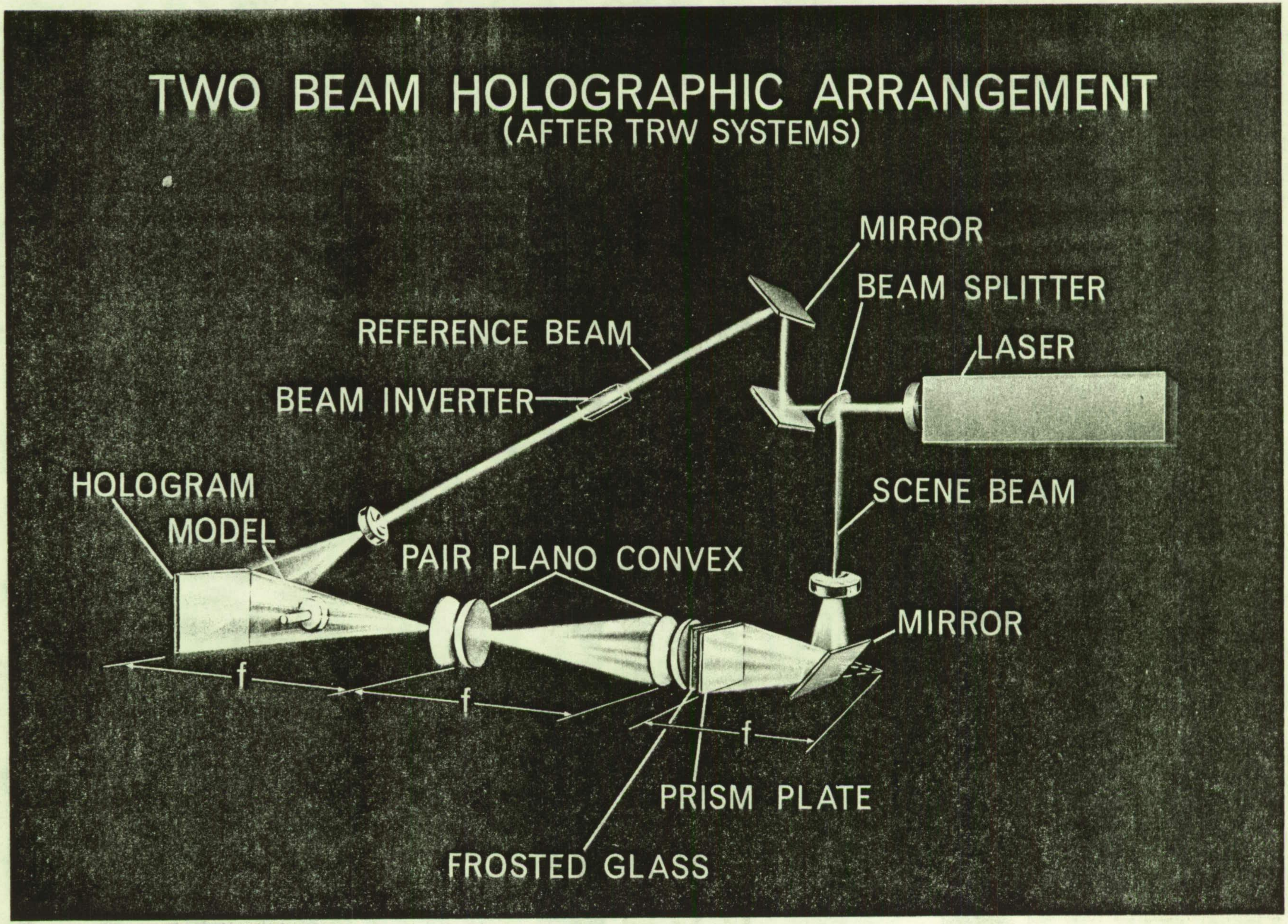
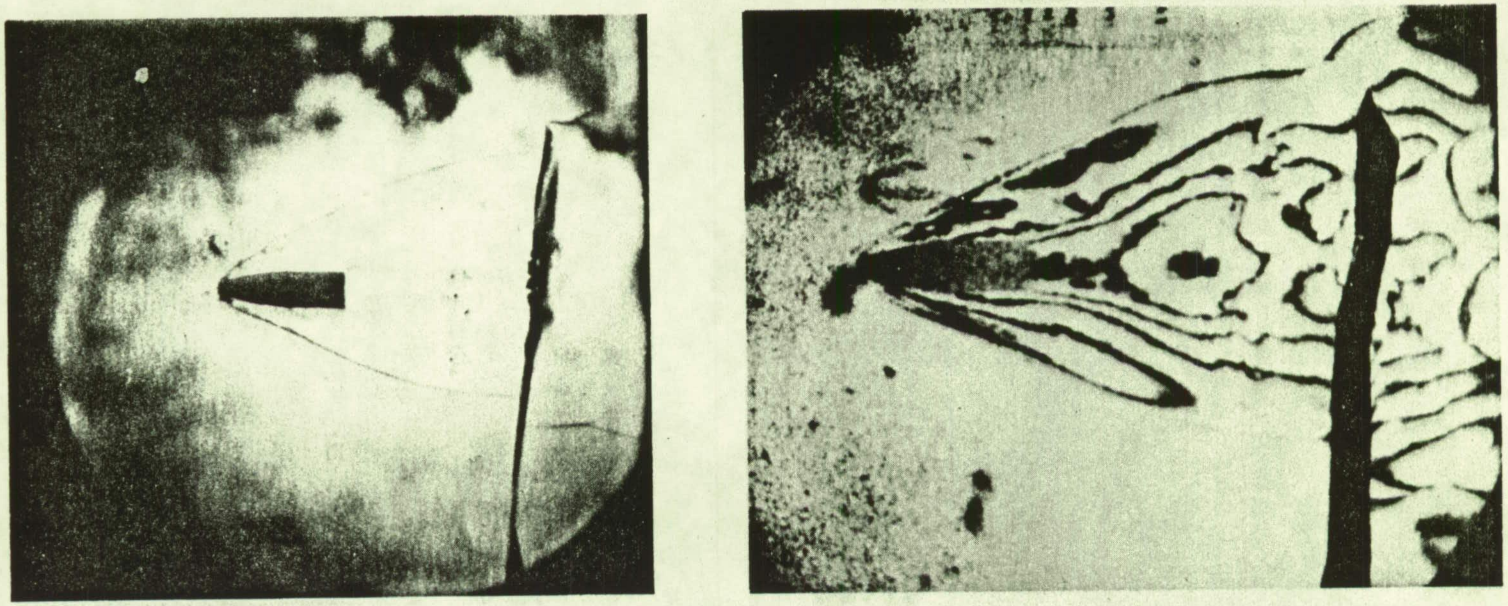


TWO BEAM HOLOGRAPHIC ARRANGEMENT
(AFTER TRW SYSTEMS)

Figure 2

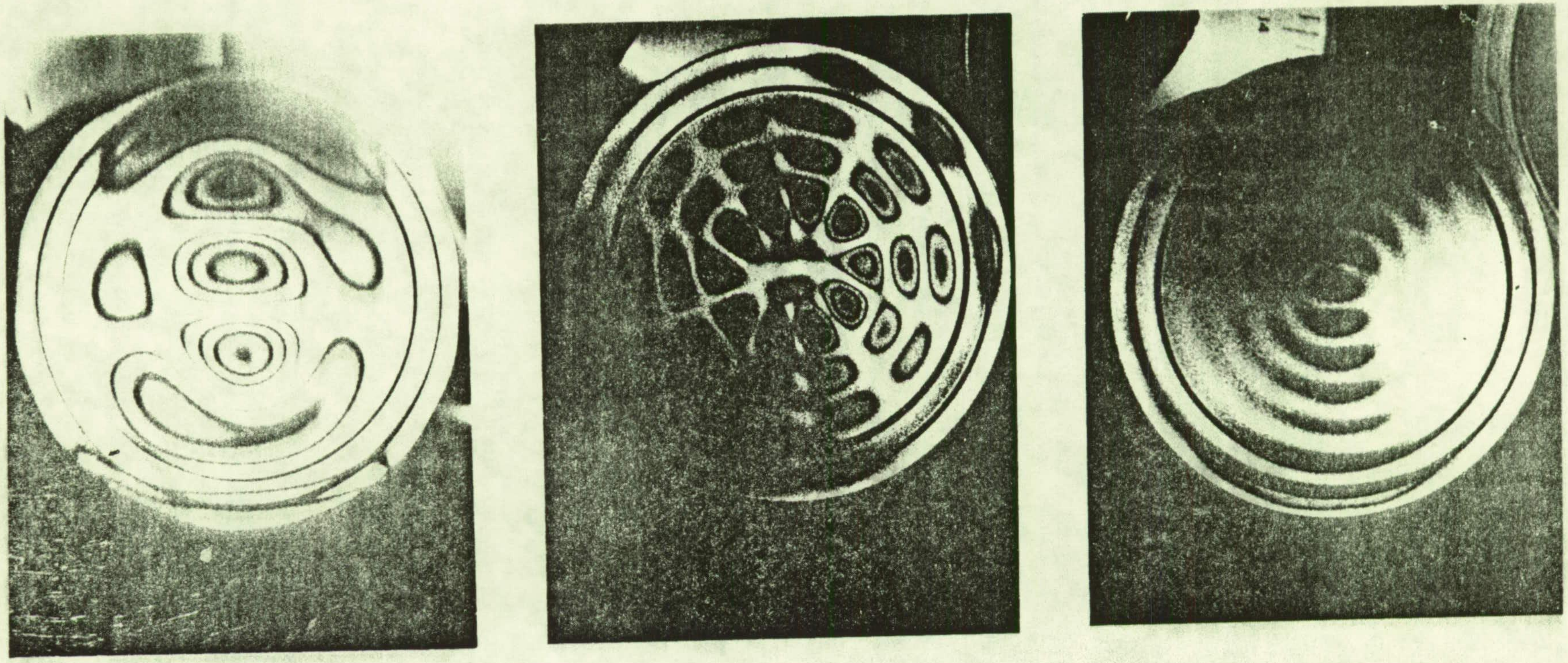
TYPICAL COPIES FROM HOLOGRAMS OF PROJECTILES



SINGLE PULSE SHADOWGRAPH

DOUBLE PULSE INTERFEROGRAM

Figure 3



2420 Hz

6110 Hz

6730 Hz

Interferograms of resonating 35mm film can

Figure 4

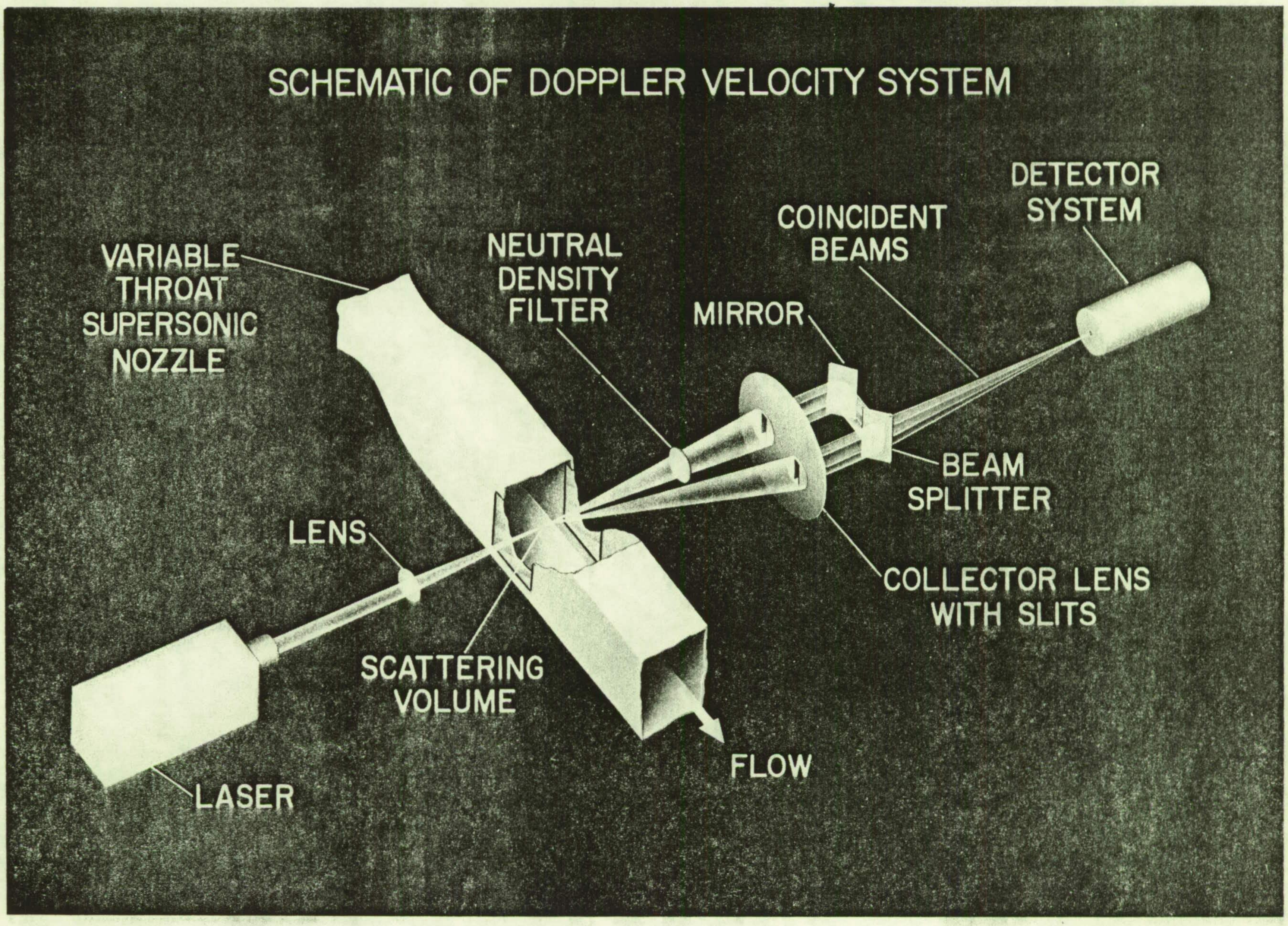

SCHEMATIC OF DOPPLER VELOCITY SYSTEM
VARIABLE THROAT SUPERSONIC NOZZLE
NEUTRAL DENSITY FILTER
MIRROR
COINCIDENT BEAMS
DETECTOR SYSTEM
BEAM SPLITTER
COLLECTOR LENS WITH SLITS
LENS
SCATTERING VOLUME
LASER
FLOW

Figure 5

COMPARISONS BETWEEN LASER-DOPPLER AND PITOT-PRESSURE MEASUREMENTS

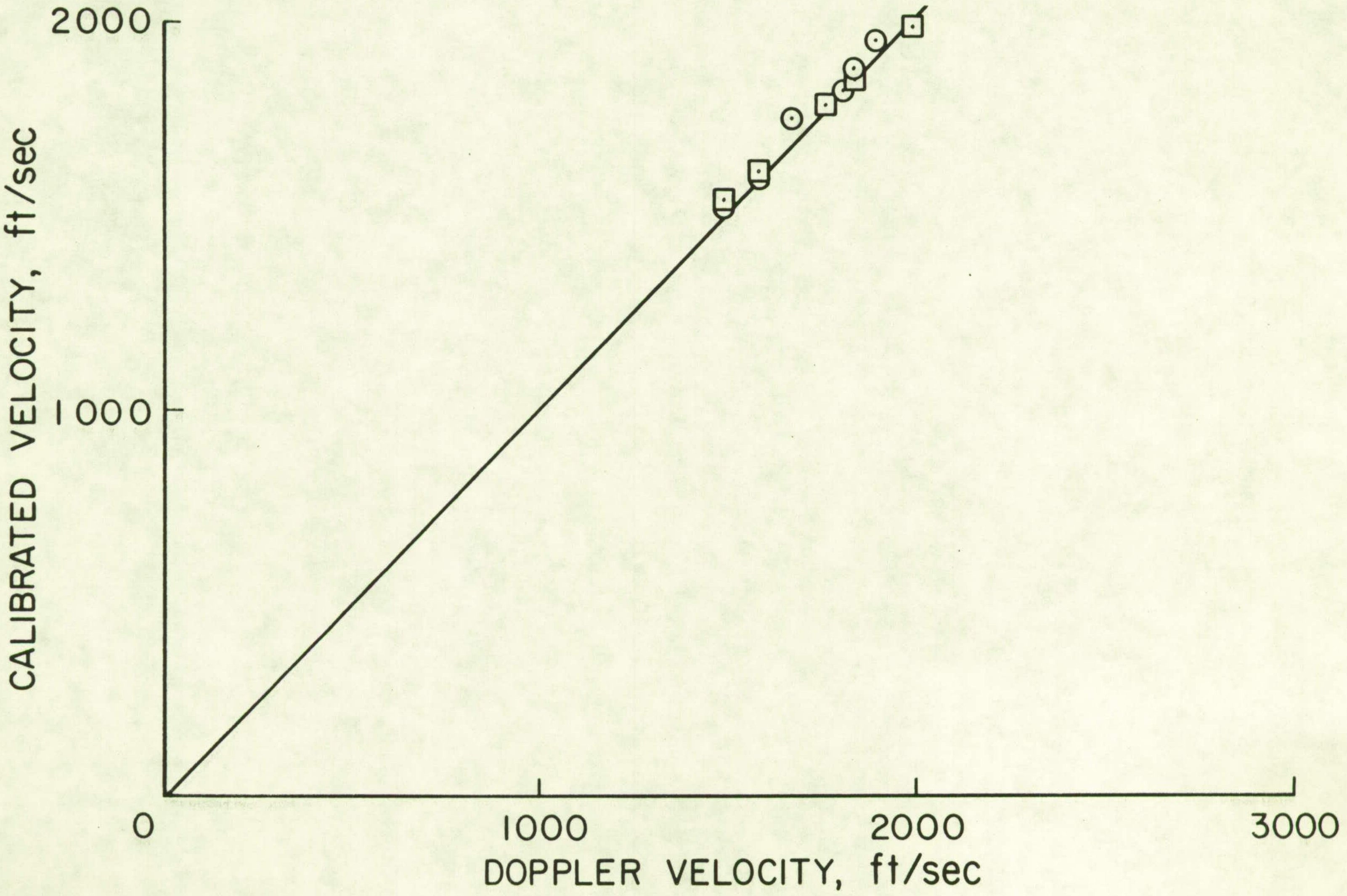


Figure 6

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

THE ν_2 FUNDAMENTAL OF METHANE IN HIGH RESOLUTION

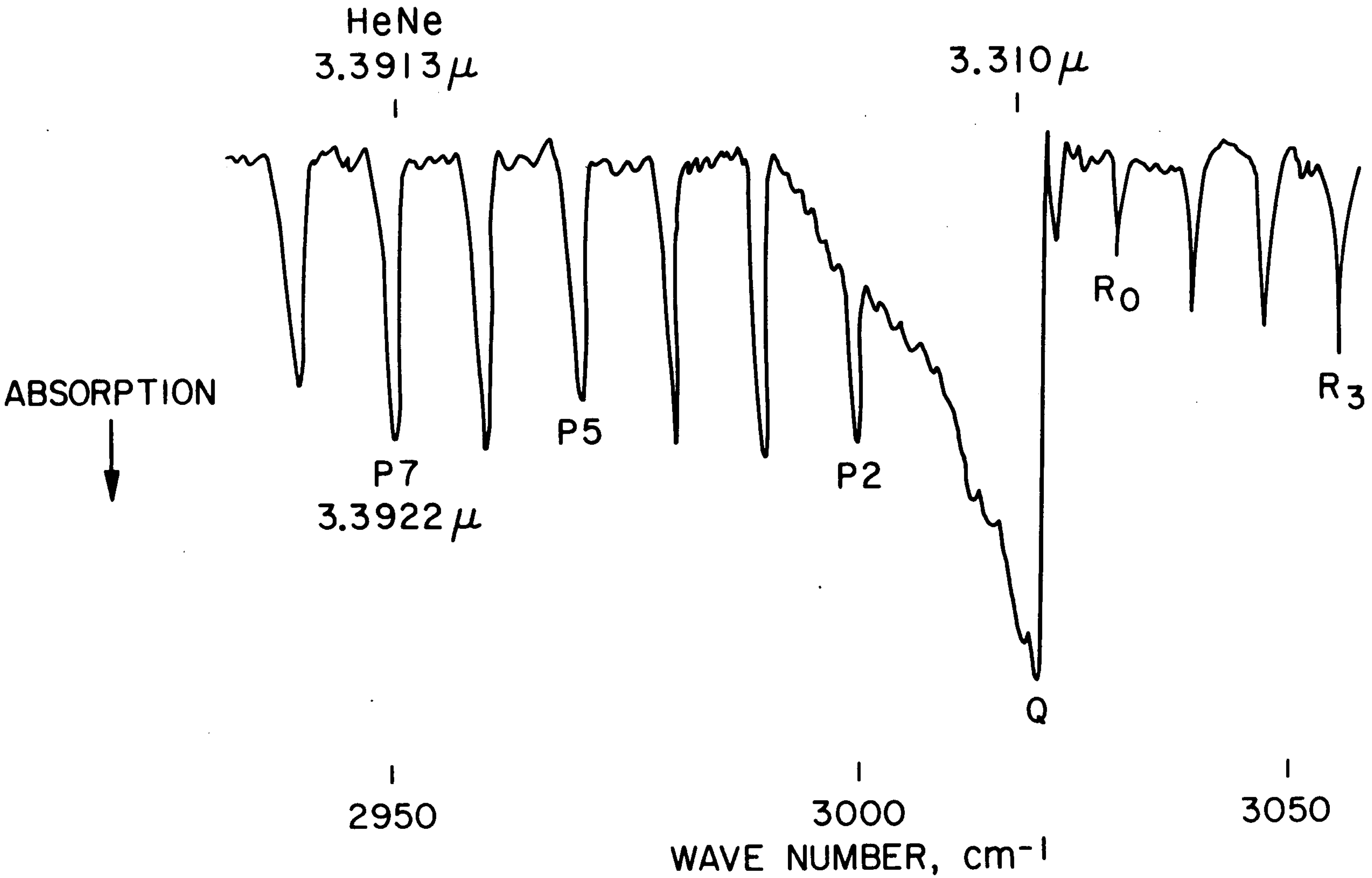


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Figure 7

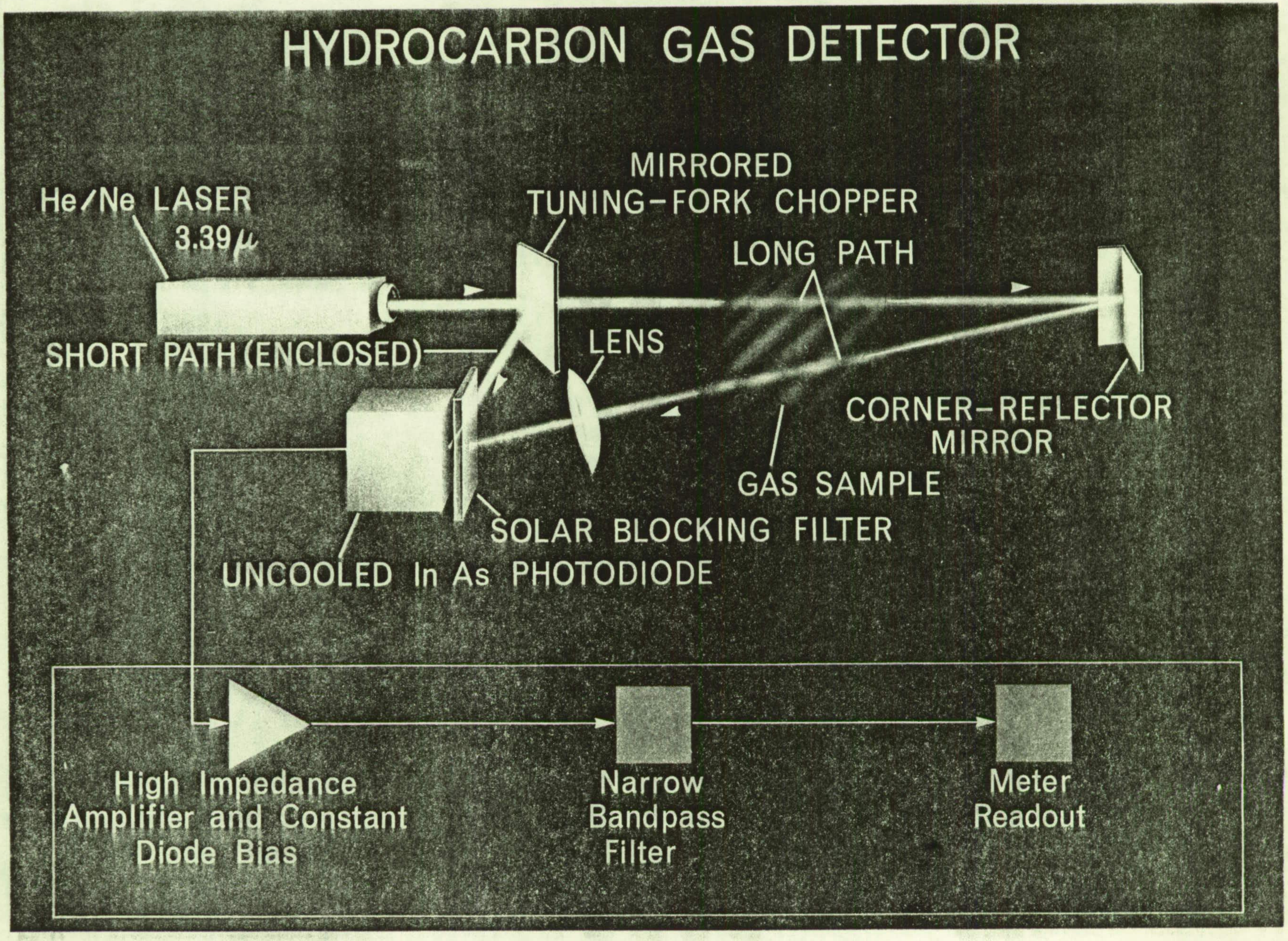
HYDROCARBON GAS DETECTOR
MIRRORED
TUNING-FORK CHOPPER
He/Ne LASER
3.39μ
LONG PATH
SHORT PATH (ENCLOSED)
LENS
CORNER-REFLECTOR
MIRROR
GAS SAMPLE
SOLAR BLOCKING FILTER
UNCOOLED In As PHOTODIODE
High Impedance
Amplifier and Constant
Diode Bias
Narrow
Bandpass
Filter
Meter
Readout

Figure 8

ABSORPTION COEFFICIENT OF VARIOUS HYDROCARBONS AT 3.39 μ

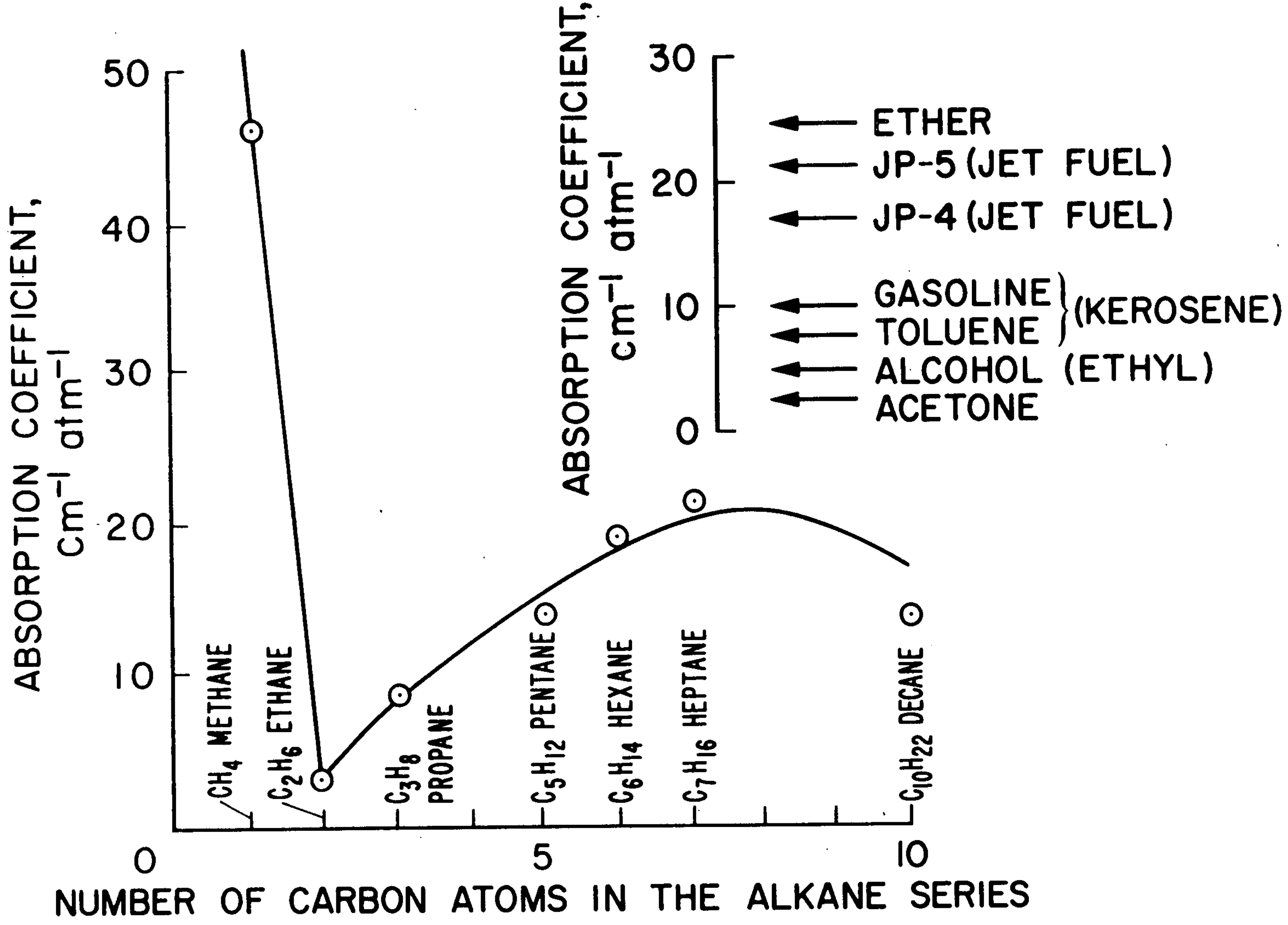

Figure 9

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19740077985

LASER TECHNOLOGY

Dr. Paul C. Fletcher
Electronics Research Center

I Introduction

It is the purpose of this talk to gaze into our crystal ball and try to determine what innovations might occur in the next few years in the field of lasers and laser applications which will be useful to NASA.

We will proceed then according to the outline shown in the first Figure 1. The talk will be divided into two sections: the first section devoted to improvement of known lasers and the second half, the development of new types of lasers and the implications for applications.

We will first determine which lasers one must be concerned with by examining the applications in which lasers have been used in the past. A condensed list of these applications is shown in the second Figure 2 together with the types of lasers which are most often used in those applications. We will not at this time discuss the details of each of these applications, but recommend to those interested in more details, various survey articles such as the Bibliography of Laser Applications by Martin Stickley of AFCRL (Air Force Cambridge Research Laboratory). You have already heard today a more detailed discussion of several of these applications. Many others are only used in an ancillary way for NASA purposes, but nevertheless, are important for the development of new technology. Taking a look at the list of applications and their lasers, we see that there are essentially seven types of lasers which one has to be concerned with for the majority of applications. As NASA is interested in almost all of these lasers and applications, we will discuss the state of the art of each of them and try to designate the problem areas or the areas most likely to be investigated for improvement in the next few years.

IIA The Ruby Laser

Since the ruby laser has been with us the longest of any laser, it is probable that the smallest amount of improvement will be shown in its performance in the next few years. The next Figure 3 reviews some of the existing characteristics of the ruby laser as we have it today. Much effort has been expended in trying to increase the repetition rate, the average power output and the maximum power output. It is not probable that great strides will be made in these areas in the coming years. The one area where one might expect an improvement is in the single mode operation. Again the pressures of high speed holography and optical data processing will push for very long coherence lengths so that one can use the high power, and the coherence length of the ruby laser to do long distance and wide depth of field holography.

IIB The Helium-Neon Laser

The next Figure 4 reviews the state of the art of the helium neon laser. This laser is so well known that it will not pay me to spend much time in detailing what these properties are, but go directly to some of the well-known deficiencies. The major problems are the low peak power, less than optimum stability, poor efficiency and the loss of power in going to single mode operation. We must then at this point make a crystal-ball estimate as to which of these parameters stands the greatest chance of improvement. It seems highly improbably that either the efficiency or the power output per unit length of the laser will be changed substantially, without some fundamental changes in the basic laser operation. It does seem probable, however, that new schemes for

for stabilizing lasers both by more rigid and stable structures and by more sensitive feedback schemes for stabilizing will be developed. It would be my expectation that the stability will be improved by several orders of magnitude, within the next couple of years by these techniques and will probably come as a result of a need for time and wavelength standards using lasers. It also seems probable that the pressures coming from the holographic and data processing applications will probably bring about higher single mode power from the helium neon laser.

Because of the pressures to get laser systems operational, it is highly probable that the helium neon laser will be one of the most useful tools that we have for all applications, either for interim use until the other lasers become better developed or because there is initial need for monitoring a precise optical equipment in the laser systems. For this reason, a program to build a helium neon laser which will withstand the launch environment and field environment is underway by NASA. Furthermore, the helium neon laser is presently being planned in several applications until better lasers can be made operational.

IIC Pulsed Neodymium Laser

Because of the ease of making large pieces of glass compared with making large rubies, there has been much work done towards making large high power neodymium lasers. The state of the art has been well developed and is shown in the next Figure 5. Similar to the ruby laser, there is a great effort towards making high peak power neodymium lasers as well as high average power. The disadvantage of the neodymium laser, of course, is that it operates at 1.06 microns, a wavelength at which detectors and photomultipliers are not as sensitive as in the more visible wavelength region. For this reason, we would expect for many applications to see in the next few years an attempt to double the pulsed neodymium laser for applications such as tracking, range finding, and even holography and data processing. From the doubling of CW neodymium YAG systems, we might expect in the future as much as 90-100% efficiency in the doubling process, which would enable one to use the double neodymium system in those systems now requiring high power and sensitive detection.

IID CW Neodymium Lasers

Although the neodymium YAG system has been with us for several years, it is still undergoing advanced development in many areas. We find the power and the efficiency (Figure 6) continuing to increase so that we would expect, in the next few years, outputs between 200-500 watts, single transverse mode power out at about an 80% efficiency and the single supermode or single transverse and longitudinal mode of about 65% efficiency. We also find that the neodymium is still being put into new hosts which have low thresholds and therefore are more efficient. We will expect to see future overall eficiencies in the neodymium YAG laser from 10-12% multi-mode or perhaps 5-8% in the single mode. We are also finding that the YAG laser is increasing in its lifetime as its pump sources increase their lifetime. Present pump lamps such as Tungsten have lifetimes less than 500 hours, krypton lamps are known to go to 5000 hours, and it is expected to find in the not too distant future sub lasing diodes or even lasing diodes to pump the YAG laser which might have lifetimes greater than 10,000 hours. For this reason, it seems that the YAG laser will be a strong candidate for some of the NASA long range missions both in communications, tracking, range finding, etc. From recent data of the Bell Laboratory we know that one can get approximately 100% conversion efficiency from the neodymium wavelength to the double neodymium at

.53 microns. One might expect then to see the development of a laser showing both the doubling and mode locking for efficient generation of visible pulses.

IID The Carbon Dioxide Laser (Figure 7)

Because of its high power output and efficiency the CO_2 laser has been a prime candidate for most space missions. Some of the problems which have been plaguing the CO_2 laser in the past have been its limited lifetime, its longer wavelength, and its limited stability. On the other hand, these problems have now by and large been solved and the CO_2 laser is now ready to be used in the field. We may expect then to see also this laser being space qualified for several applications. We may expect the peak power to increase from 50 kilowatt up to the megawatt region. We may expect to see the CO_2 laser used in conjunction with several new nonlinear techniques for generation of the far infrared or submillimeter wavelengths. With the new frequency controlling techniques, we may expect to see literally hundreds of different spectral lines of the CO_2 laser being used for multiple applications. Furthermore, with new techniques for frequency stabilization similar to those used in the helium neon, we might expect the stability of the CO_2 laser to be improved by several orders of magnitude.

IIE The CW Ion Lasers (Argon and Krypton)

The characteristics of the argon laser are shown in Figure 8. Because of the low efficiency of these lasers, it is doubtful that they will be used in very many space applications; however, they have been considered as an important contender as ground beacons and for many of the display applications because of their multiple wavelength outputs and their higher power capabilities. At present, these lasers are unstable and noisy, they are inefficient and difficult to operate, they have a limited lifetime and in general have been undesirable to use for many applications, except that the lasers with the largest amount of power in the visible wavelength region. However, recent developments indicate that the instability problems will soon be understood and corrected. The argon lasers then will be single moded and will be able to be used for holographic and data processing applications, and will be used for selected chemical processes. It is expected that in the not too distant future the other lasers will be equally as powerful as the argon laser has been, rendering many more wavelengths available. Also, there is a great amount of work going in to prolonging the lifetime of the argon lasers. It is expected that one might get 2000-5000-hour life in the ion lasers in the next couple of years.

Since these noble gas lasers represent the largest amount of continuous wave power in many of the optical regions, they probably will be used for many years to come and for this reason they will be commercially sold and further field tested and developed. However, gazing into my crystal ball again, I predict that there will be other lasers coming up in the future which will be easier to operate and which will have equally as much power but more versatility than these lasers.

IIF Semiconductor Lasers

Figure 9 reviews characteristics of one type of semiconductor lasers. It will be noticed that the advantage of these lasers is that they can be compositionally tuned from the 14 micron wavelength to the .3 micron wavelength continuously. They have further advantages in that they are lightweight and they have a reasonably large average power output. This is particularly true when techniques of arraying are considered. They have the disadvantage that they do not operate in a CW fashion. In fact, I am told there are no continuous wave semiconductor lasers which operate at room temperature. For many applications this is not a disadvantage as long as it can be pulsed fast. However, for many other applications, one would like to have continuous operation and the lasers are then not useful. An additional problem is that the efficiency and the best use of these lasers occurs at cryogenic temperatures or at least cooled temperatures. The difficulties involved in cooling sometimes are enough to discourage applications-oriented people from using solid state lasers. However, I predict that these will be used in a very large precentage of the applications that NASA will get involved in, when they become operationally useful.

III New Systems Using Old Lasers

In discussing the improvements that will occur in the foregoing lasers, we have discussed briefly also their effects on existing systems. We may expect that almost all laser applications will be more competitive and more commonly accepted as the lasers themselves become more operational. A second effect of the improvement of these lasers that we shall see in the next couple of years will be the feasibility of other systems heretofore deemed unfeasible which now become feasible. It is beyond the scope of this talk to discuss all of these applications, but I might mention one at this time. In the applications of lasers to power transmission one has seen proposals to transmit power by means of the laser beam in times past. However, because of the inefficiencies of the laser, the overall inefficiencies of systems using lasers for power transmission, one has not really considered this power transmission seriously. However, now that lasers such as the CO_2 lasers have efficiencies above 25%, one may consider the use of the laser to transmit power from the ground, say to a spacecraft. Indeed, if one had a 10 kilowatt beam which was limited in beam diameter by the atmosphere, say to 10 microradians, then a near orbit satellite at 200 miles could receive all of that 10 kilowatts by use of a 10-foot dish. Since this power need not be focused accurately in order to convert it to electrical power, one could use light-weight materials such as inflatable balloons as a mirror material, perhaps even going to larger diameters for larger orbits. If then one were able to convert the 10.6 micron radiation to electrical energy with better than 1% efficiency, one would than have 100-watt electrical source in the satellite. This now becomes more interesting since it is difficult to get 100-watt sources over long periods of time in the space vehicle. There are problems, of course, in near orbit since the satellite is only visible to one ground station for a few minutes at a time. However, one could think of more than one ground station since the cost of the lasers is minimal. The cost of the associated tracking station is not minimal, however, so that existing tracking stations using microwave tracking data would probably have to be used. If one wished to go further out, say to a synchro-satellite at 22,000 miles, one might consider enlarging the dish from 1-feet to say 100-feet and then one would catch only 1% of the beam. Thus, instead of 100 watt, one would have 1 watt in the synchro-satellite. However, even one watt might be useful in the case that the satellite needed auxiliary power. Thus, an increase in the output of lasers from 100 watts to 10 kilowatts has made an application which previously looked unfeasible to one which might look more promising. In this particular application, we have chosen a 1% conversion efficiency for the 10.6 micron radiation. We have had estimates from power engineers which indicate that this is a pessimistic number. However, in our particular application, if we had only 100 watts to begin with on the ground, the synchro-satellite would only be receiving 10 milowatts which has not been deemed useful in times past, but certainly one watt becomes much more interesting to the space power people. In a similar manner, one must re-evaluate continuously all of the systems in which the laser could be potentially used to see if the new capabilities of the lasers do not change the application from infeasible to feasible.

IV New Laser Techniques

We now go on to the second half of this talk which is a discussion of more recent developments in the laser field and their possible implications for applications. We will first discuss the developments in the lasers themselves and some of the characteristics of these new developments, after which we will gaze into our crystal ball and see what these characteristics might do for those systems which have already been proposed, and in this we will only mention a few that come to mind, and then we will really stick our necks out and try to propose entirely new systems for which there are no parallels in existing applications.

IVA The Mode Locked Lasers

This technique was developed approximately two years ago and has been worked on by a limited number of people since that time. We will not talk about plain mode locking, but only that mode locking which causes laser pulses to be extremely short, that is in the picosecond ranges. Although the picosecond pulses undoubtedly have been here since mode locked lasers started, it wasn't until quite recently that one realized that they really were as short as 10^{-12} second. Again, I will refer you to the literature for the full development of the mode-locking technique, but just speculate briefly as to what the characteristics of these might be.

Almost any laser can be mode-locked so that the pulses of very short duration can be made. Presently, the ruby, HeNe and neodymium lasers have all been mode locked. The characteristics of a mode lock depend upon the amplifying medium discussed above. It is characteristic that the broader the bandwidth of the amplifier, in this case, the broader the linewidth of the material used as an amplifier, then the shorter the pulses might be. One has to realize that when one is talking about pulses with durations of 3×10^{-12} seconds, that one is talking about a pulse which is spatially only 1/100 of a centimeter or 1/100 of a millimeter in length. It turns out that these lengths are convenient to measure the pulse width in time, if one converts the pulse width to distance and measures distance. This was first achieved by the people at Bell Labs, and of course, repeated by many in the country, using dye cells. One simply reflects a laser beam off a mirror inside a dye cell and where the beam overlaps itself, it is coherent over the period of time going to the mirror and back, then one will have positions where the E fields are twice as much and since the fluorescence is a quadratic effect, the radiation is four times as much where they overlap as it is where they do not. This produces a bright spot which was imaged on a photographic plate. Quite recently, the people at ERC developed a technique of viewing these without using the dye cell, or not using a separate dye cell, but using the dyes that are intrinsically in the photographic emulsion. We overlap the two Nd beams on the emulsion. Since the 10.6 micron radiation does not activate the film, only the doubled frequencies are detected and the pulse widths appear as bright spots in the emulsion. For interest, we also were able to beat two beams in the emulsion and see the fringe effects of the two beams as they impinged with slightly separate incident angles. Of course, it was always expected that if one had coherent light sources of 5 x 10^{14} cycles per second, that one could operate in times close to the reciprocal of that frequency, namely in 10^{-13} seconds. So this is just a natural consequence of the fact that you have a high frequency source in the laser. We are only just now beginning to take full advantage of this characteristic of lasers and open a new picosecond era.

IVB Parametric Lasers

A second innovation in the last few months in the laser field is that of parametric oscillation. When one has a medium which can be impressed with high intensity radiation and which has a strong non-linear coefficient, one can use this medium for parametric processes, i.e., the generation of other frequencies. The people at Stanford and the people at Bell Labs both have seen these parametric effects. The interesting part about these oscillators is that the frequencies which are involved can be changed by temperature and by electric field. This implies that these oscillators can be tuned, and indeed, we find that we have the ability to tune over wide regions, 2,000 Angstroms, using this technique. The variable frequencies which have been obtained have covered the entire visible region using different pumps and non-linear materials. At present, the troubles with this technique are that the power levels have been quite low, in the order of one milowatt. This is good for such applications as spectroscopy, local oscillators, etc., but perhaps not good for major systems or production. With the development of higher power CW lasers spoken of above, it is expected that the efficiency of these non-linear effects will increase orders of magnitude, and we will have then much higher powers available which are tuneable over the entire visible and infrared regions.

IVC The Dye Lasers

The third development occuring within the last few months is the so-called dye lasers. Although liquid lasers have been here for some time, the actual development of high-powered, room-temperature liquid lasers has had a new stimulus in the dye lasers. Almost any dye and many other chemicals not used for dyes can be used to get stimulated emission. The wavelength region of these stimulated emissions varies from the ultraviolet into the infrared. The powers available are up in the magawatt re regions in the pulse regime. Here again, one difficulty with these lasers is that they do not operate well in a continuous mode. Furthermore, they are still found to be quite inefficient. They have still the advantage, however, of being tuned, and in some senses, this is a disadvantage since almost any parameter you might choose will succeed in tuning them; the concentartion, temperature, electric fields, optical pumping pathlength, the choice of a solvent, the pumping energy, etc. These are a disadvantage, since many of these things will change during the operation in the field or under adverse conditions such as high temperature or radiation environments. For more details for the history and operation of such a laser, I refer you to an article in a recent Laser Focus, September 1968, by Kagan, Farmer, and Hoof.

IVD New Molecular Lasers

It is unfortunate that we have only one molecular laser with efficiencies in the 25-35% region. One reason for this is that there are very few molecules that you can irradiate or electrically discharge which will not decompose to some other specie. Hence, an inversion population is not the only criterion but a viable pumping scheme is a necessary second criterion. It seems that there probably are few if any new systems which may be pumped with electrical discharge because the electric discharge creates electrons of sufficient energy to break the chemical bond. One may then try to find additives which slow down electrons, or alternatively, one may pump one laser with another laser such as a CO_2 laser. The energy of the photons is sufficiently low that the chemical bonds do not get destroyed and the specie is left untouched. One such scheme was proposed by Russians in the last electronics conference in Miami. There are many other candidates for such a scheme. The desirability of accomplishing this, of course, is that one would like to have the same efficiency as CO_2 but available at many other wavelengths.

V Old Systems Using New Lasers

We now examine the implications of these proceeding techniques on the applications shown in the Figure 1. Taking first the very short pulses, we can go down several of the applications. The first one, of course, is communications. If you have pulses with 10^{-12} second half-widths, then if you filled all time with these, i.e., 100% duty cycle, and you can modulate each pulse independently, it is obvious that you can transmit 10^{12} bits per second. This is, of course, greater than almost any communications system now in existence or even envisioned in the next ten years. Many of the techniques of modulation, demodulation, and of maximum sensitivity must be developed to take full advantage of this high bit rate. The second advantage in communications of dividing all time up into these short intervals is that one essentially eliminates background noise since any source that you can think of other than a very short pulse such as a laser does not have a sufficient number of photons to be significant. Thus one has done away with the necessity for such techniques as heterodyning, since the advantage of heterodyning is simply to increase the signal over the background noise. This is also true for lower bit rates but using the very short time intervals. One has to go, however, to photon counting at a very fast rate. These are techniques now being examined which show great promise, if it is not 10^{-12} seconds at least close to it. With such bit rates one can now talk about computer-to-computer, real-time data transmission: one can talk about transmission of high resolution, photographs; one can talk about real-time TV of reasonably good resolution; one can talk about high density communication links such as TV, telephone, etc. which will be here in the next 10-20 years. In the field of illumination, one can now talk about high speed holography, simple high-speed photography, high enough speed so one can essentially stop phenomena in the microwave region, such as ferromagnetic resonance, avalanche phenomena in semiconductors, and almost all other solid state microwave phenomena, heretofore too fast to be observed photographically. In the field of tracking, one now has the ability to measure range to the accuracy of the pulse width or some fraction thereof, a tenth of a millimeter, assuming that all other electronics and the transmission medium of the system permits this kind of accuracy.

The parametric lasers can be used anywhere a spectrograph has been used heretofore either for comparison, monitoring of wavelengths, or monitoring of chemical species. One gets a very high resolution inexpensive, spectrograph simply using a parametric laser. Similarly, the dye lasers can be used for applications in the field where one needs tunability or flexibility in wavelengths as well as high optical power. One immediately thinks of things like remote sensing of chemicals, for air pollution, earth resources, etc. New molecular lasers can be used for any application in the commercial field where efficiencies are important and wavelength flexibility is needed.

VI New Systems Using New Lasers

We now go to the furtherest of our crystal-ball guesses as to what new applications might be coming out of these lasers, and I will just hit on some that come quickly to mind. First, with the pico-second pulses, if one can for instance get bursts of energy commensurate with this time, then one can cause a tremendous transfer of momentum; and if this indeed is the case, than one can think of impressing the laser beam onto a surface, blasting off a small amount of material which would then give an impulse to the main base and we would have then essentially an optical propulsion system. One, of course, must do this fast enough to get a sufficient impulse and we are not sure what the time constant of blast-off of materials is, but at least there is a possibility that this might be an efficient process. A second application one thinks of might be the many nonlinear processes now being studies in the laboratory. When we talk about 10^{12} watt pulses, that is, a one-joule pulse over a period of 10^{-12} seconds, then one is in a position to make many of the nonlinear processes heretofore extremely inefficient become more efficient, since they depend upon higher electric fields of the incident optical radiation. Thus, it is possible that detectors using this scheme for up-conversion might be possible. One might expect that with the complete tunability of the laser that many of the biophysical processes will be more understood and in some sense controlled using lasers at a specific wavelength. One that has been suggested is that of genetic engineering, that is, hitting the genes with the particular wavelength in such a manner that you can control the characteristics of subsequent generations. Also, there is a possibility that such things as tumors might be selectively damaged or controlled by a particular wavelength. And finally as we get higher powers at higher and higher frequencies into the ultraviolet and further, one can talk about coherent sources commensurate with crystal lattices (now we are talking about x-rays): we can talk about generation, calibration of x-ray techniques similar to the calibration which happened or is happening right now in the optical industry. Indeed we may expect to see in the next 10 or 20 years a resurgence of the x-ray technology similar to that which has happened to the optical industry in the past decade.

OUTLINE

I. INTRODUCTION - LIST OF APPLICATIONS AND LASERS USED

II. STATE OF THE ART OF EIGHT LASERS - NEED FOR DEVELOPMENTS

   A. Ruby
   B. HeNe
   C. Nd Pulsed
   D. Nd CW
   E. CO_2
   F. Argon and Krypton
   G. GaAs

III. NEW SYSTEMS USING OLD LASERS

IV. NEW LASER TECHNIQUES

   A. Mode Locking
   B. Parametric Lasers
   C. Dye Lasers
   D. New Molecular Lasers

V. OLD SYSTEMS USING NEW LASERS

VI. NEW SYSTEMS USING NEW LASERS

LASER APPLICATIONS

	CURRENT TASKS	TYPE OF LASER
1.	ATMOSPHERIC PROBING	R, N, C
2.	UNDERSEA PROBING	D, A
3.	PHOTOGRAPHY, ILLUMINATION	R, A
4.	MEDICAL	R, A, C
5.	SIGNAL PROC. HOLOGRAPHY	R, A, H
6.	RADAR TRACKING, RANGING	R, N
7.	INDUSTRIAL (CUT, DRILL, WELD)	R, N, C
8.	PRINTING AND DISPLAY	H, A
9.	ELECTRO-OPTICAL COMM.	H, A, N, C
10.	STANDARDS (LENGTH, TIME, ROTATION)	H, C, O
11.	CHEMICAL-MONITORING, SYNTHESIS	R
12.	SCIENTIFIC	ALL
13.	POWER TRANSMISSION	N, D, C
14.	ALIGNMENT	H

CODE	
R	Ruby
N	Nd
G	GaAs
C	CO_2
H	HeNe
A	Argon
D	Doubled Nd
O	Other

RUBY LASER $\lambda = 6943$ A

		BEAM DIVERGENCE	PERCENT EFFICIENCY
MAXIMUM ENERGY OUTPUT	100-120 joules 2J/CC	1 MILLIRADIAN	0.2
MAX. SINGLE MODE OUTPUT	Several joules with Amplif.	DIFFR. LIMTD.	0.05
MAX. CW OPERATION	0.01 Watt		0.01
MAX. PULSE REP RATE	30 pps		
MAX. Q SWITCHED POWER	10^9 Watts		

HeNe LASER λ = 6328 A

		BEAM DIVERGENCE	PERCENT EFFICIENCY
MAXIMUM POWER OUTPUT			
5.5 Meters	1000 mw	3 TIMES DIFFRACTION LIMITED	0.2
2.0 Meters	200 mw		0.1
1.7 Meters	50 mw		0.025
MAX. SINGLE MODE OUTPUT			
2.0 Meters	20 mw	DIFFR. LTD.	0.01
FREQUENCY STABILITY			
Free Running	10 MHz		
Stabilized	10 KHz		

ELECTRICALLY PUMPED
BEING SPACE QUALIFIED - MIL SPEC - FIELD TESTED
HIGH QUALITY - LOW PRICE 5 mw - 1000 HRS

Nd LASER, PULSED

		BEAM DIVERGENCE	PERCENT EFFICIENCY
PEAK POWER OUTPUT	2J/CC		6.0
MAX. SINGLE MODE OUTPUT	0.2 J		1.5
Single Transverse	Hundreds of Joules with Amplification		
MAX. Q SWITCHED POWER	$6 \cdot 10^{10}$ Watts		

Nd LASER CW

	POWER OUTPUT	BEAM DIVERGENCE	PERCENT EFFICIENCY
MULTIMODE	50 - 100 W (200 - 500)	> 1 MILLIRAD	3.0 10.0 - 12.0
SINGLE TRANSVERSE MODE LOCKED	25 - 50 W (150 - 400)	DIFFR. LTD.	1.0 - 2.0 8.0 - 10.0
SINGLE TRANSVERSE AND SINGLE LONGITUDINAL	1 - 5 W (20 - 40)	DIFFR. LTD.	
SINGLE TRANSVERSE WITH SUPER MODING	20 - 40 W (130 - 325)		1.0 6.0 - 8.0

FREQUENCY STABILITY UNKNOWN
DOUBLING 20% (>50%)

TUNGSTEN IODINE 500 HRS, KRYPTON 5000 HRS
SUB-LASING DIODE (10,000 HRS)

CO_2 LASER 10.6μ

		BEAM DIVERGENCE	PERCENT EFFICIENCY
MAXIMUM POWER OUTPUT	10 KW (AS YET UNLIMITED)	3 TIMES DIFFR. LTD.	33.0
MAXIMUM SINGLE MODE OUTPUT	10% MAX. PWR.	DIFFR. LTD.	3.0
FREQUENCY STABILITY			
FREE RUNNING	10 kc		
STABILIZED	PZT CRYSTAL SUPER INVAR CAVITY - ETC.		

LASER COMM. SYSTEM - SYLVANIA, HONEYWELL

BEGIN SPACE QUALIFICATION - 2000 HR. LIFE

MECH Q SWITCHING 50 KW + PEAK POWER - REFLECTIVELY Q SWITCHED BY ABSORBING GASES, PEAK POWER 100 WATT TO KW AT 1-100 KHz - HUNDREDS OF LINES IN 9 - 11.

ARGON LASER

		BEAM DIVERGENCE	PERCENT EFFICIENCY
MAX. POWER OUTPUT			
3 METER	50 KW PINCH DISCH 102 WATTS (RAYTHEON)		0.2
SINGLE MODE TEM_{00}	5 WATTS IN AR 7 WATTS IN KR	DIFFR. LTD.	
MAX. POWER SINGLE AXIAL MODE, PASSIVE (ETALON IN CAVITY)	1 WATT		
FREQUENCY STABILITY			
FREE RUNNING	50 MHz (SPERRY)		
SINGLE MODED	0.3 MHz		

LIFE 1000 HRS. AT 5 WATTS (RAYTHEON)

GaAs LASER

		TEMPERATURE
PEAK PULSED POWER	100 WATTS/DIODE	300 °K
CONTINUOUS POWER OUTPUT	1/3 WATT	77 °K
PEAK ARRAY POWER	1000 WATTS	77 °K
AVERAGE POWER	$3W/CM^2$	77 °K
FREQUENCY STABILITY SINGLE MODED AND TEMP STABILIZED	0.1 KHz	

LIFE - IN EXCESS OF 1000 HRS.

EFFICIENCIES - COOLED, UP TO 50 PERCENT.AT ROOM TEMPERATURE, A FEW PERCENT.

COMPOSITIONALLY TUNABLE FROM 0.325μ to