

PHASE A STUDY
OPTICAL TECHNOLOGY
APOLLO EXTENSION SYSTEM (OTES)

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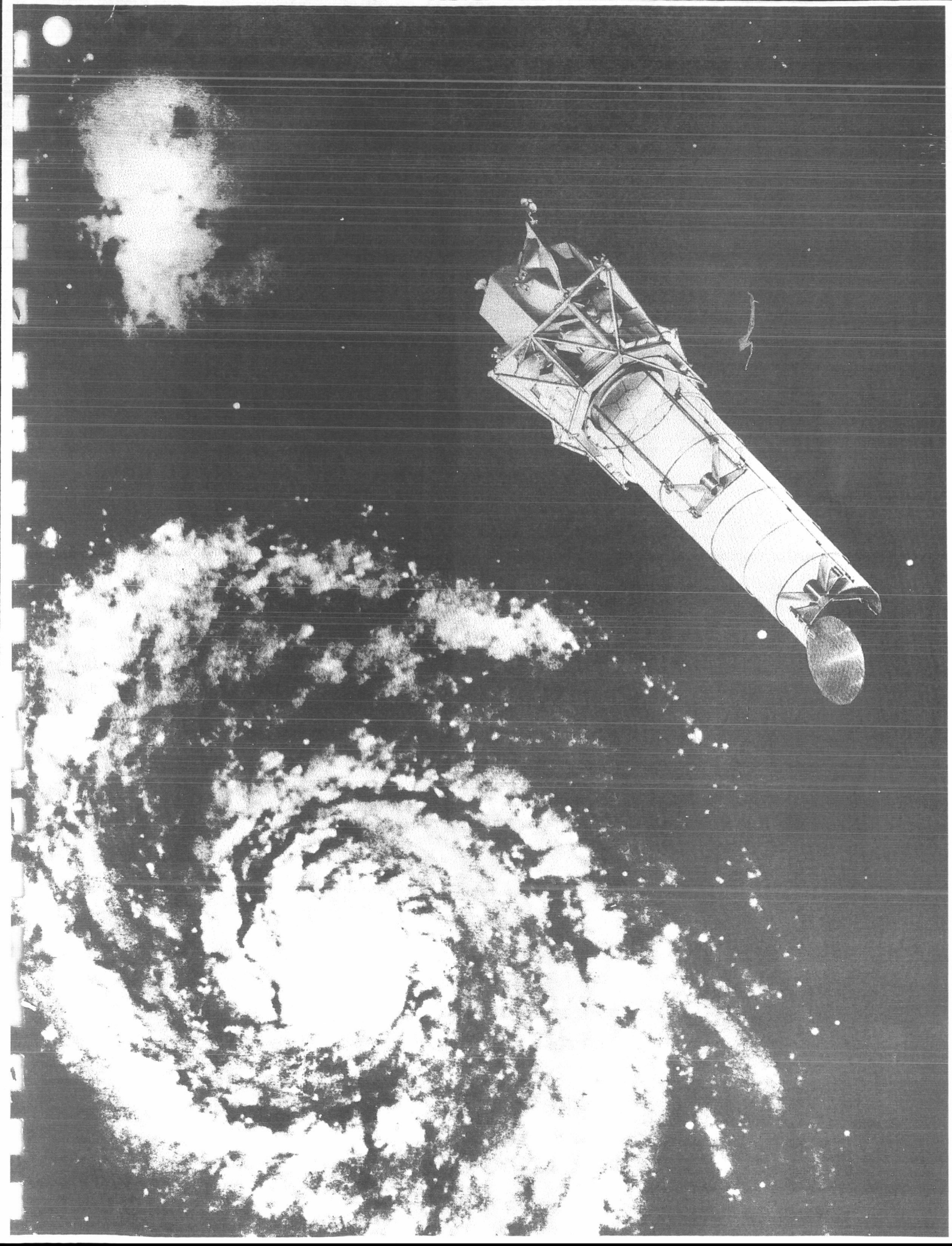


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CHAPTER 1 - SUMMARY

In order to proceed with the simple formulation of an objective for a technology oriented program in space optics, it is necessary to step well back from the details of the program. There are two basic questions which must be answered by NASA management:

Where is the U. S. going in space?

What prospective national goals require new space optics?

If the answer to the first question includes the concept of the "exploration of space", then the answer to the second question must include the two areas of space astronomy and planetary probes. And, it is in these two areas that the major source of the proposed optical technology experiments in space are found. If the reader agrees to the twin concepts of "exploration" and "new space optical technology" presented above, then the justification for an optical technology flight program is established.

Space astronomy and planetary probes represent two fundamental tools required for the exploration of space. The development of these tools requires new space optical technology in order to satisfy the future mission needs of NASA. Space astronomy requires the new optics associated with resolution performance not obtainable on earth in both angle (large diffraction-limited optical systems) and wavelength (ultraviolet and infrared). Planetary probes require new high data rate laser communication systems in order to conduct successful experiments in the vicinity of the planets. Thus, by understanding the nature of the future NASA missions requiring new space optics, the objectives of the OTES can be clearly formulated.

The objective of the OTES is the performance of scientific and engineering space experiments which advance space optical technology in support of future NASA missions.

The proposed experiments and the integrated experiment system fall in broad, yet systematically related, categories:

- Optical Technology (diffraction-limited performance of large apertures and fractional arc-second guidance)
- Optical Communication and Tracking (with deep-space emphasis)
- Effects of Aerospace Environment (on optical technology and laser communication problems)

Forty-four experiments, including applications, have been identified and approximately thirty optical technology experiments were studied in detail. Five different system concepts were evolved and examined for feasibility within the restraints and guidelines of the specification.

PRINCIPAL PROGRAM CONCLUSIONS OF THE PHASE A STUDY

SPACE OPTICAL EXPERIMENTS

As a consequence of three years of study of space optical experiments, Perkin-Elmer in consort with NASA specialists have arrived at the following position:

1. There are worthwhile flight optical experiments.
2. Apollo vehicles can be justified for a manned space optical laboratory.
3. 2-Meter and 3-Meter aperture telescopes and the optical experiments with spacecraft are technically feasible.

The first principal conclusion is supported by the experiments presented in Chapter 2. Specifically, after approximately two years of study and in the current study, NAS8-20255, one year of effort through Contract NAS8-11408 (Determination of Optical Technology Experiments for a Satellite), the list of prospective space experiments has grown in some areas and has been reduced in other areas. Perkin-Elmer recommends the following space experiments in optical systems to NASA:

OTES EXPERIMENTS

- | | |
|------------------------------------|--|
| 1. 2-METER ACTIVE OPTICS | 17. (DELETED) |
| 2. SUPER COLD TELESCOPE | 18. (DELETED) |
| 3. ASTRONAUT UTILIZATION TESTS | 19. 1/10 ARC-SECOND TRACKING |
| 4. FIGURE MEASUREMENT/SCATTERPLATE | 20. POINT AHEAD |
| 5. FIGURE MEASUREMENT LASER | 21. ACQUISITION |
| 6. MIRROR COATING | 22. EARTHSHINE/ACQUISITION-TRACK TESTS |
| 7. THIN MIRROR | 23. LASER COMMUNICATION |
| 8. ACTIVE THERMAL CONTROL | 24. RLOS |
| 9. 1/100 ARC-SECOND POINTING | 25. TRACKING TRANSFER |
| 10. OFF-AXIS MEASUREMENTS | 26. SUSPENSION SYSTEM |
| 11. RADIATION/PMT TESTS | 27. CALIBRATION LOOP |
| 12. FIGURE/TEMPERATURE | 28. SCINTILLATION |
| 13. ALIGNMENT/TEMPERATURE TESTS | 29. ABSORPTION |
| 14. FIGURE/ EARTHSHINE TESTS | 30. HETERODYNING (EARTH) |
| 15. RADIATION/OPTICAL TESTS | 31. HETERODYNING (SPACE) |
| 16. (DELETED) | 32. POLARIZATION |
| 34. OPTICAL SCATTERING ENVIRONMENT | 33. CLEAR AIR TURBULENCE |

We believe that these are important space optical technology experiments that can best be conducted from a space vehicle. Some of the proposed experiments can only be conducted from a space vehicle. From the broad program point of view, it is the Perkin-Elmer recommendation that two flights be conducted: one for the laser communication experiments and a second flight for the large optics experiments utilizing a 2-meter aperture telescope which could function at a low orbit (260 mile).

JUSTIFICATION FOR FLIGHT EXPERIMENTS

There is no argument with the concept that optical systems will contribute significantly to the exploration of space. The underlying philosophy of the OTES Program is that space optical technology* will be advanced to a position of timeliness by the conduct of scientific and engineering experiments aboard an Earth-orbiting vehicle. The thoroughly engineered optical spacecraft test bed with complete instrumentation will not only advance optical technology, but is economically sound. Future optical missions, whether space observatories with giant telescopes or deep-space probes with laser communication links, are orders of magnitude more expensive than the proposed optical experiments.

The justification for the OTES Program concept stated as simply as possible is: THE CONDUCT OF SELECTED OPTICAL EXPERIMENTS ABOARD A SPACECRAFT IS THE TIMELY AND ECONOMIC METHOD OF DEVELOPING SPACE OPTICS.

The technical data that the 2-meter OTES flight would provide is summarized below:

2-METER OTES JUSTIFICATION

PROVIDE NASA WITH DATA FOR NATIONAL SPACE OBSERVATORY

- ORBITAL ALTITUDE DECISION DATA
 - DAYLIGHT ASTRONOMY
 - POINTING DISTURBANCES
 - THERMAL BALANCE
- MANNED SPACE ASTRONOMY TECHNIQUES
 - ERECTION
 - ALIGNMENT
 - MODIFICATION
 - MAINTENANCE
- PRIMARY MIRROR EVALUATION
 - ACTIVE OPTICS
 - SEGMENTED TESTS
 - DEFORMABLE TESTS
 - THERMAL TESTS
- MATERIALS
 - QUARTZ
 - SILICON
 - CERVIT
 - BERYLLIUM
- POINTING DEVELOPMENT
 - TRANSFER LENS
 - FREE FLOAT
 - FLEXURE GIMBALS
 - CLUSTER - AUTONOMOUS MODES

* "...preeminence in aeronautics and space in the future certainly demand a continuous evolvement of new technology. The consequences of not having done our homework prior to undertaking a system development to meet an explicit requirement are overruns in cost and time. These costs and resources are often so high that the means must be found to evolve new technology in advance of requirements." R.I. Bisplinghoff at the Air Force Association Meeting, March 15, 1967.

OTES PROGRAM PLANS

In the implementation of the technology oriented program in space optics, the spectrum of flight possibilities varies from the concept of conducting a myriad of small individual flight experiments on orbiting vehicles of opportunity to the concept of designing a special flight vehicle tailored exclusively to the optical technology experiments and conducting all of the experiments aboard a single flight vehicle. In the OTES Phase A study, these possibilities were reviewed and the recommendation of Perkin-Elmer and Lockheed is that the laser communication experiments be conducted independent from the flight system for the large optics experiments. The payload for the laser experiments must be at a 22,000 mile orbit while there is considerable benefit from conducting the large optics experiments at altitudes below 500 miles as noted on the previous page.

The program concept of the 2-meter OTES is based on five key elements:

2-METER OTES PLAN

1. CLUSTER- 260-MILE ORBIT
2. FIT INTO ATM GIMBALS & LM RACK
3. CONDUCT OPTICAL ENGINEERING EXPERIMENTS
4. USE RESIDUAL HARDWARE 2-METER APERTURE TELESCOPE FOR ASTRONOMY
5. PROVIDE THE TECHNOLOGY FOR THE 3-METER (and LARGER) TELESCOPES OF THE FUTURE

In order to gather the data required for the laser communication area, a synchronous orbit payload is required to conduct the communication and propagation experiments. The program concept of a 0.5 meter laser/telescope flight is based on five key elements:

LASER EXPERIMENTS PLAN

1. 500 POUND LASER/TELESCOPE-SYNCHRONOUS ORBIT,
2. FITS INTO ATM GIMBALS & LM RACK.
3. CONDUCT LASER PROPAGATION EXPERIMENTS UP GOING AS WELLAS DOWN GOING ON AT LEAST 2 WAVELENGTHS.
4. USE RESIDUAL HARDWARE FOR TELEMETRY OF SCIENTIFIC OR ENGINEERING DATA FROM THE SPACECRAFT.
5. PROVIDE THE TECHNOLOGY DATA FOR DEEP-SPACE LASER COMMUNICATIONS.

Thus, data to be developed from the Laser Communication Satellite Experiments (LCSE) will be the measurements of the propagation and tracking performance of the system. In addition, the LCSE will verify the operation of key sub-systems and components by telemetry of diagnostic data. The key parameters to be measured at the ground receiver telescope at the OTTOS* site are:

- Measurement of laser propagation data through the entire atmosphere in the form of received signal power and operating SNR. The average signal-to-noise ratio is approximately 30 db for daytime operation at 60 degree zenith angle based on radiated power outputs of 3 milliwatts from a spaceborne helium-neon laser.
- Measurement of 10^6 and 10^7 bit/second data and measurement of probability of bit error rates (fade statistics).
- Measurement of 0.1 arc second laser beam pointing by the laser telescope to the earth receiver station.
- Evaluation of received video data, i.e., TV picture to establish realistic fade margin requirements for quantum limited photon communication channels.

SPACE OPTICAL TECHNOLOGY PLAN FOR NASA

One of the most difficult problem areas in the current OTES study was the broad question of recommendation to MSFC and OART of an optical technology plan with appropriate flight experiments at suitable times. The plethora of concepts had to be sifted and sorted to search for that recommendation which would represent a good buy for NASA. The recommendation would have to stand the test of acid scrutiny in the area of satisfying the future needs of NASA in the most economic manner. The interdependence of the two proposed flights and the data that they would bring to the prospective national goals of the U.S.A., are inherent in the Perkin-Elmer recommended NASA SPACE OPTICAL TECHNOLOGY PLAN. See Figure 1.

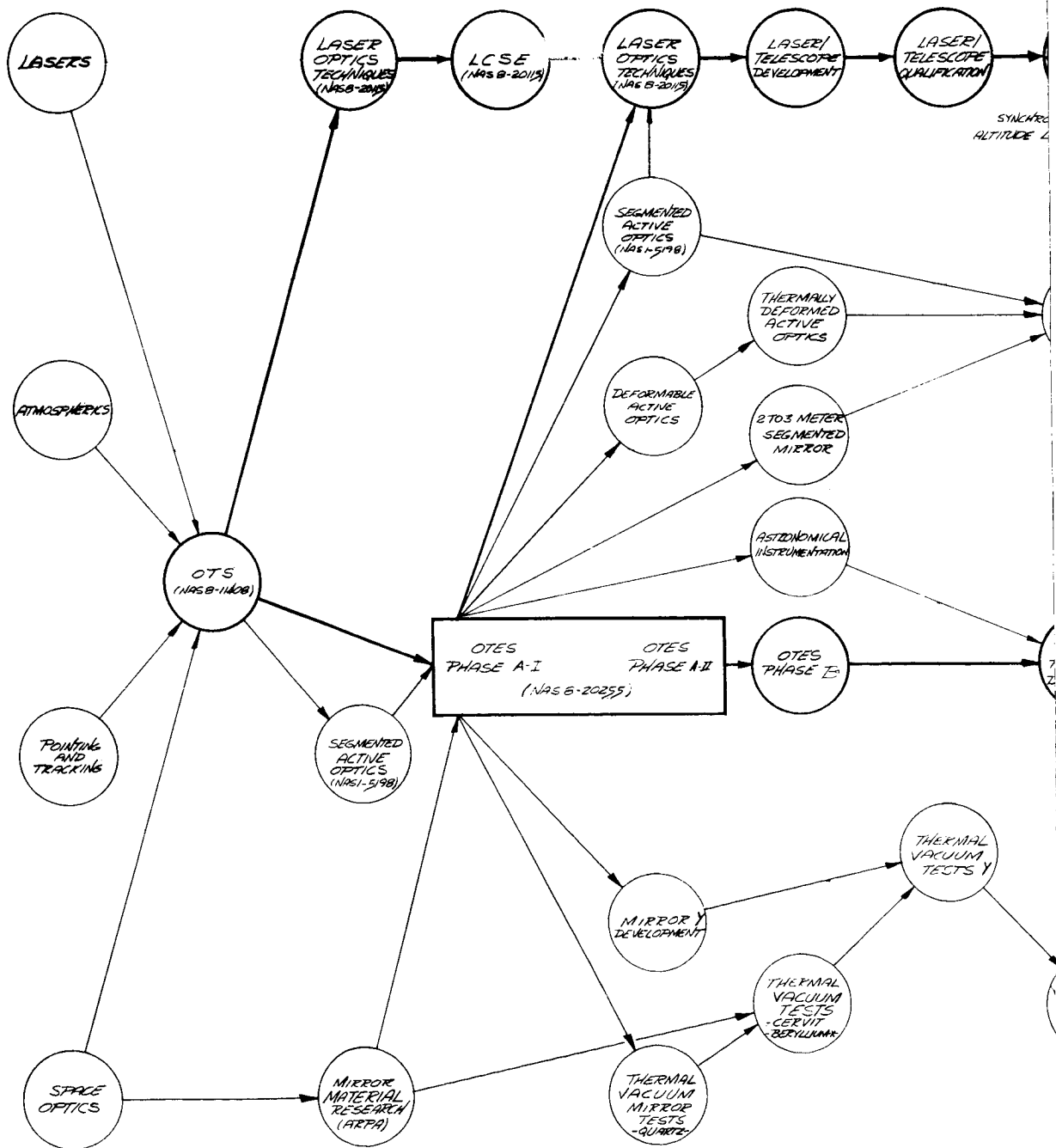
The KEY FEATURES of the Plan are:

1. Two flight experiments.
 - Laser Satellite Experiment launched to synchronous orbit in 1971 for the development of laser propagation data. (Figure 8, page 15).
 - 2 Meter OTES Telescope launched into low orbit in 1973 as part of the AAP Cluster. This instrument would be designed to conduct experiments in large optical technology and act as a test bed before committing significant funds to the development of a 3 Meter Telescope. (Frontispiece.)

* Optical Technology Test and Operations Site (See Chapter 5).

I-6

63	64	65	66	67	68	69
FOUNDATION OPTICAL TECHNOLOGY R & D	INITIAL SYSTEMS STUDY	LABORATORY DEVELOPMENT AND EXPERIMENTS	SPECIFIC SPACE EXPERIMENT STUDIES	EQUIPMENT DEVELOPMENT AND GROUND TESTS		



OPTICS TECHNOLOGY PLAN

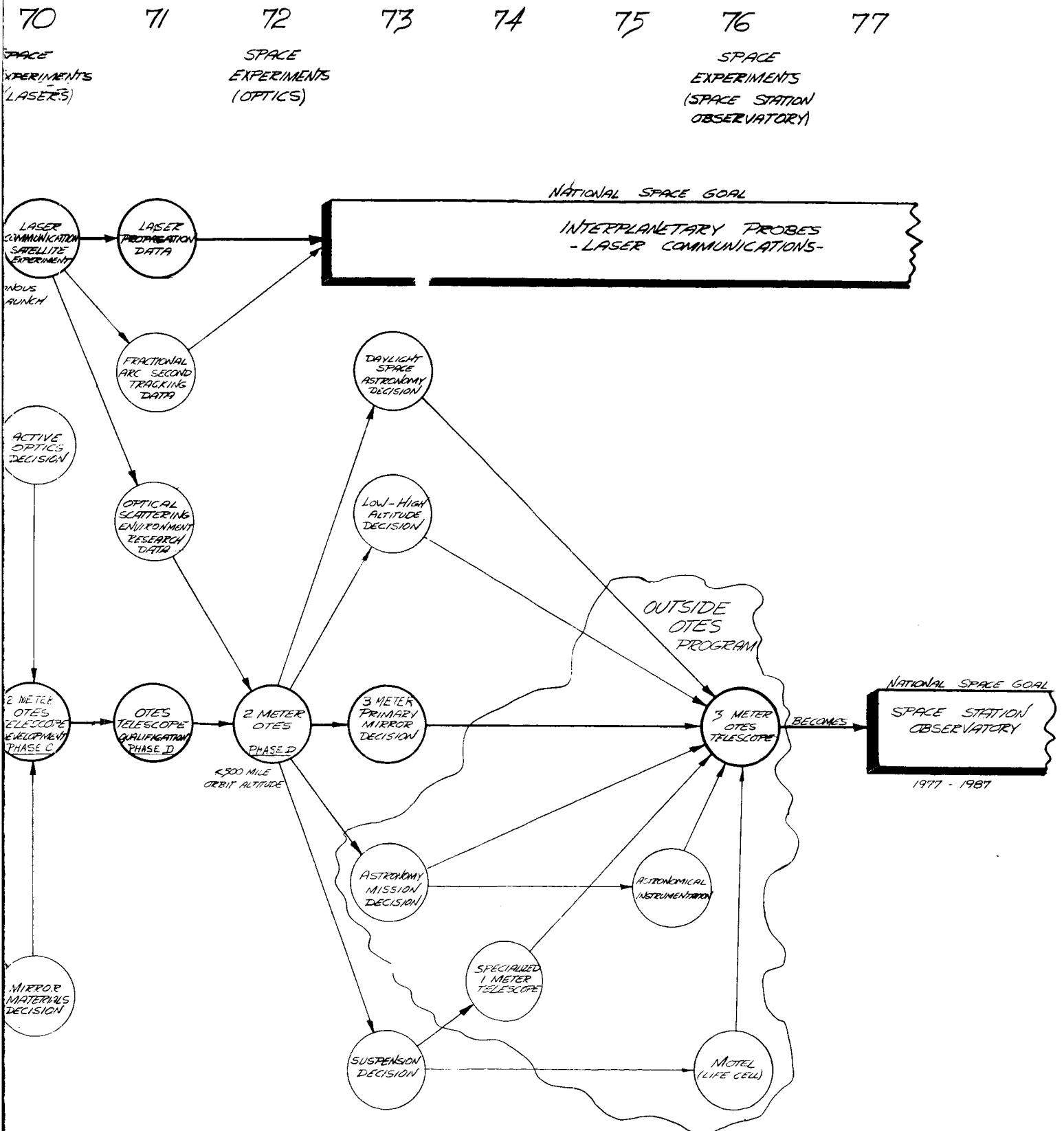


Figure 1

The EQUIPMENT BUDGET RECOMMENDATIONS to Implement This Plan are:

Supporting Technology (1968-1972)-----	\$8 million
Laser Satellite Experiments at synchronous altitude in 1971-----	7.5 million
2 Meter OTES Telescope as part of AAP Cluster at a low altitude in 1973-----	42 million
Total	\$57.5 million

The BASIC ADVANTAGES AND/OR DISADVANTAGES TO NASA are:

- Timely technology development.
- Conduct appropriate space experiments to develop the necessary data to provide answers to key questions:
 1. Up and Down going laser propagation data.
 2. Daylight astronomy feasibility.
 3. Low-High orbit for space observatory.
 4. Optimum primary mirror for space observatory.
 5. Optimum suspension technique for future telescopes.

PRINCIPAL TECHNICAL CONCLUSIONS OF OTES PHASE A

As a consequence of the efforts of the Perkin-Elmer/Lockheed OTES Team during the Phase A of the OTES Program, there have been important computations and concepts developed to precipitate advances in the space optical technology areas:

Large Optics Technology Area 1) An experiment system temperature of -80°C can be achieved passively for a 3-meter aperture telescope mirror at synchronous orbit and almost -80°C for a 2-meter aperture telescope in a 260 mile orbit. 2) Active Optics is an excellent area for space experiments in large optics.

Thermal

The temperature at which the expansion coefficient of fused quartz goes through zero is -80°C . Therefore, the effects of thermal gradients in the mirror which would tend to deform the figure of the mirror are minimized. The calculations which have been performed indicate that variation about the -80°C point of $\pm 4.5^{\circ}\text{C}$ would cause thermoelastic deformations of 1/50 wave, while the corresponding spacecraft calculations indicate that the mirror would have thermal gradients of less than 1°C . Thus, there is overlap between what the optical system needs and what the spacecraft can supply.

In addition to the theoretical thermal calculations, Perkin-Elmer has made the measurements of the figure deformation of a large space mirror of fused quartz to support the contention that precise thermal engineering of the space telescope is mandatory. Figure 2 shows an instrumented 32 inch eggcrate

quartz mirror prior to its insertion into thermal vacuum test facility designed to measure the departure of a mirror surface in the presence of thermal gradients.

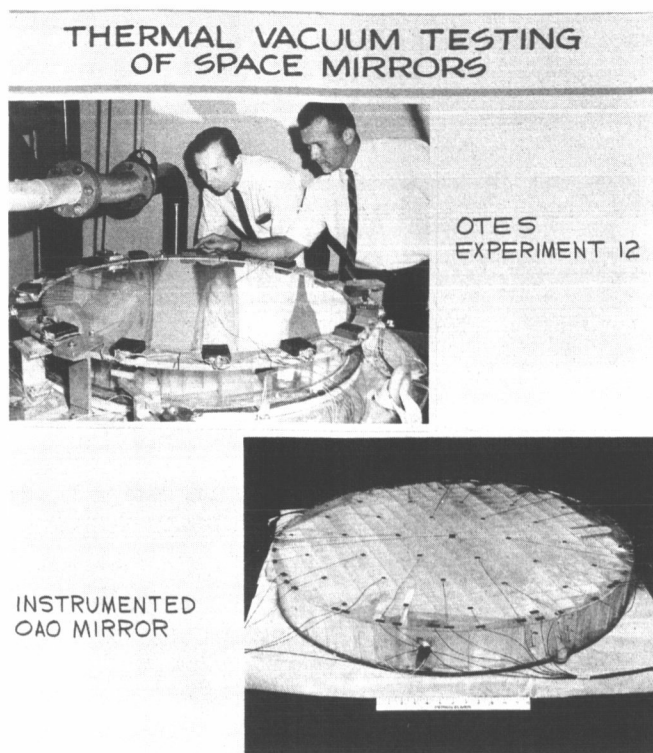


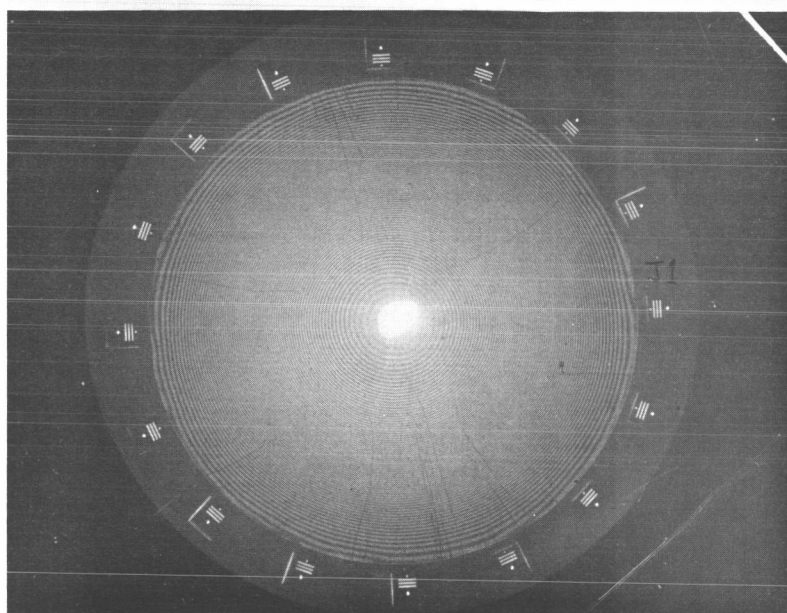
Figure 2

Scatterplate interferograms were made of this mirror while in thermal equilibrium and while the mirror was subjected to heat at the mounting points (Figure 3). Reduction of the interferometric data showed that a $+6^{\circ}\text{C}$ rise at the mounting points gave rise to a change in mirror figure of $\lambda/33$ at 20°C . This deformation can be scaled proportional to the coefficient of expansion ($\alpha \approx 4 \times 10^{-7}$ at 20°C and $\approx 0.5 \times 10^{-7}$ at -75°C); thus, the measured thermal deformation of this quartz mirror would have been less than $\lambda/200$ at the -80°C temperature.

Experiment No. 2, the Super Cold Telescope, has a temperature of -80°C specified for it. This temperature is optimum only for fused quartz #7940. The mirror segments number 1, 2, 6 and 7, and the spacer rods as shown in the Frontispiece are made of this material. The -80°C temperature is not optimum for those mirror segments made of Cervit (number 5), silicon (number 3), Ultra Low Expansion (U.L.E.) quartz #7971 (number 6) or beryllium (number 4). The optimum temperature for each of these materials is readily apparent by reference to the curves of allowable temperature tolerance as a function of temperature. Figure 4 shows the peaking of the tolerance at -80°C while other curves* indicate different optimum temperatures for each material (i.e., $+100^{\circ}\text{C}$, -180°C , -160°C , -269° respectively for the materials listed above). The justification for the -80°C temperature specification for Experiment No. 2 is that this temperature provides the maximum amount of technology data consistent with the need to provide the greatest degree of technological advance and reliability for the proposed 2-meter OTES flight.

* See Figures 48, 49, and 50 starting on page I-100

THERMAL VACUUM TESTING OF SPACE MIRRORS



QUIESCENT

Mounting
Point

HEATED

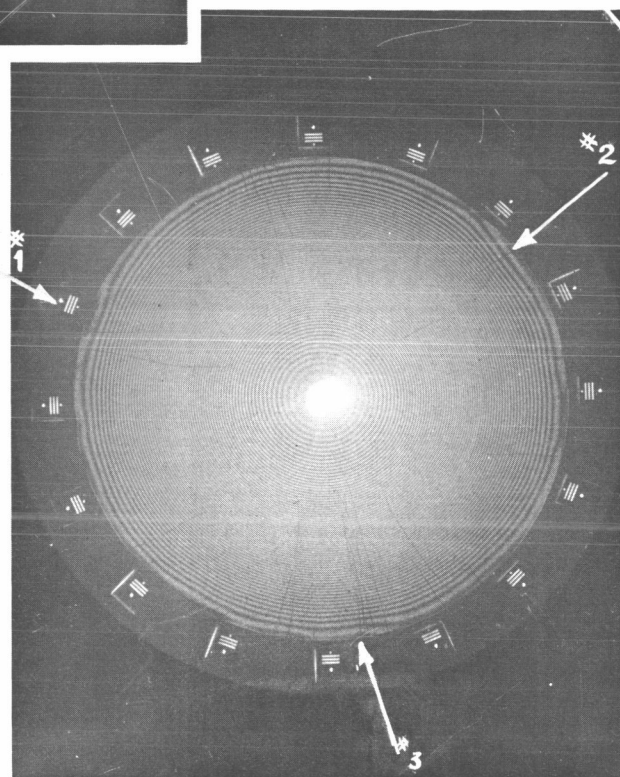


Figure 3.

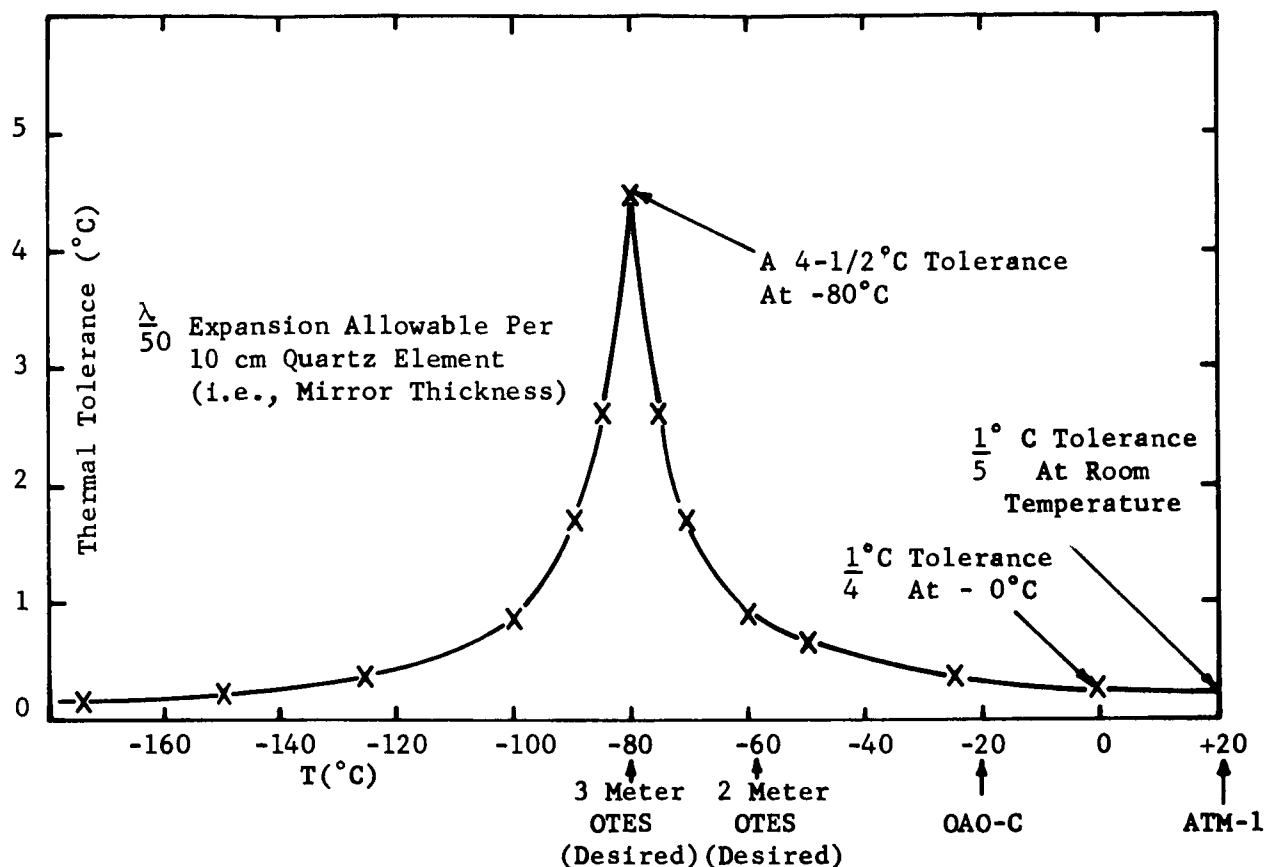


Figure 4. Quartz Mirror Thermal Tolerance

Active Optics

The Segmented Active Optics technique for the achievement of large diffraction-limited mirrors is of paramount importance to the future of large orbiting space telescopes. During the course of the OTES Study, Perkin-Elmer completed the laboratory demonstration of the Segmented Active Optics for NASA under sponsorship of Langley Research Center. The demonstration proved conclusively that a large mirror can be fabricated in sections and by the application of laser interferometry and precise servos, these sections can be positioned to the necessary precision to produce the equivalent surface of a single one piece mirror. The 20 inch, three segment mirror is shown in Figure 5 while the corresponding figure error measurement scans illustrate the power of this technique. The average figure error for the composite mirror measures at $\lambda/40$ while the corresponding figure of the segments individually measures at $\lambda/30$ average. Not only does the technique permit operation at the performance level of the individual segments, but the technique permits small - but not negligible - performance improvements since the control system positions the segments to their optimum location.

The segmented active optics technique is capable of providing a $\lambda/50$ rms mirror of 3-meter or larger aperture in a space telescope. The deformable active optics mirror work has started at Perkin-Elmer, but there are no results to report as of this date.

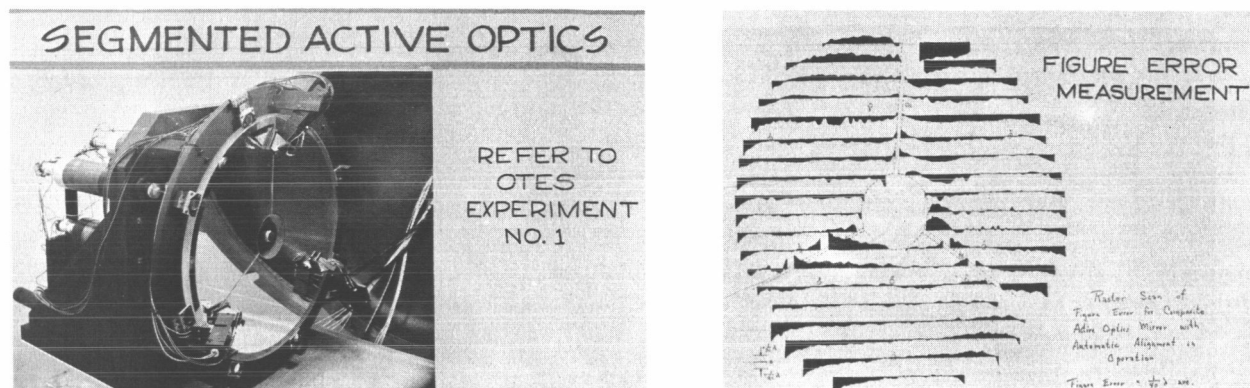


Figure 5. Segmented Active Optics

Optical Communication Area - The optical communication system calculations of the OTS Study (NAS8-11408) and the Laser Optics Techniques experiments (NAS8-20115) have been reexamined, reconfirmed, and expanded.

During the present study, link calculations were made on 5300 Å lasers, helium-neon lasers, coherent and incoherent carbon dioxide molecular lasers, and sun-pumped YAG lasers for the space transmitter. These calculations confirm the high data rate capacity of deep-space optical communications system which establish laser communications as an important telemetry tool for deep-space probes.

There were ten outstanding advances during the last three years of the study in the laser communication field:

December 1964: The Phase I Report of the OTS was released. In this report, a complete down link communication system was conceptually synthesized which had the capacity of 1 million bits/second at an error rate of 0.001 per bit for a range of 100 million miles. Each important element of the laser/optical communication system was characterized by its key performance requirements and the techniques required to achieve the required parameters were identified. (Perkin-Elmer NAS8-11408).

April 1965: High quantum efficiency detectors through the use of total internal reflection were developed. (NASA-AMES Research Center.)

June 1965: High power and high efficiency CO₂ lasers were developed. (Bell Telephone Laboratories).

September 1965: Measurements were completed on the variations of intensity in the far field beam of a diffraction-limited single mode helium-neon laser. Fluctuations of intensity of less than 1 percent were observed. Consequently, beam intensities in the far field could be predicated on photometric calculations without applying excessive safety margins for centroid of illumination wander. (Perkin-Elmer NAS8-20115.)

December 1965: High power argon lasers were developed. These lasers replaced in principle the arrays of gallium arsenide lasers required for the ground beacon. (Raytheon, RCA, Hughes and Perkin-Elmer.)

March 1966: 10" isolation between two laser wavelengths in a common laser transmitter/receiver telescope was demonstrated in the laboratory. (Perkin-Elmer NAS8-20115.)

June 1966: 1/10 arc second laser beam pointing was demonstrated in the laboratory. The transfer lens used in the demonstration is shown in Figure 6 with the laser telescope in Figure 7. Figure 8 shows the complete laser/telescope designed to conduct the laser communication experiments from a satellite.

August 1966: The technical announcement of a very narrow band high transmission Fabry-Perot tunable filter appeared in Applied Optics. (National Standards Laboratory SCIRO, Australia.)

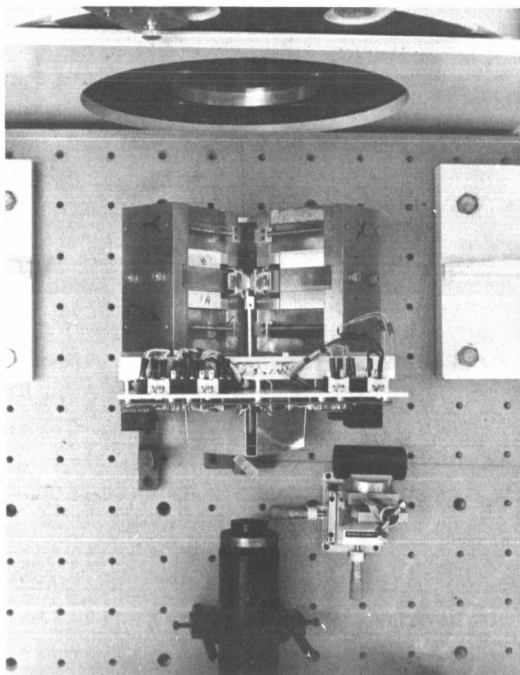


Figure 6. Transfer Lens

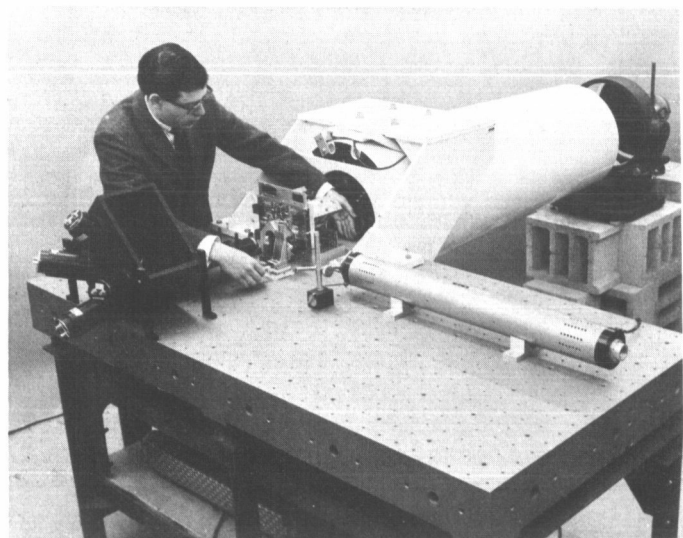


Figure 7. Laser Telescope



Figure 8.

October 1966: Point ahead of a laser beam demonstrated in the laboratory using Risley prism servo systems. The Risley prism point ahead assembly used in the demonstration is shown in Figure 9 and the physical arrangement of the apparatus behind the telescope appears in Figure 10. (Perkin-Elmer NAS8-20115.)

November 1966: Announcement released of high power CW 5300Å laser with high efficiency. (Bell Telephone Laboratory.)

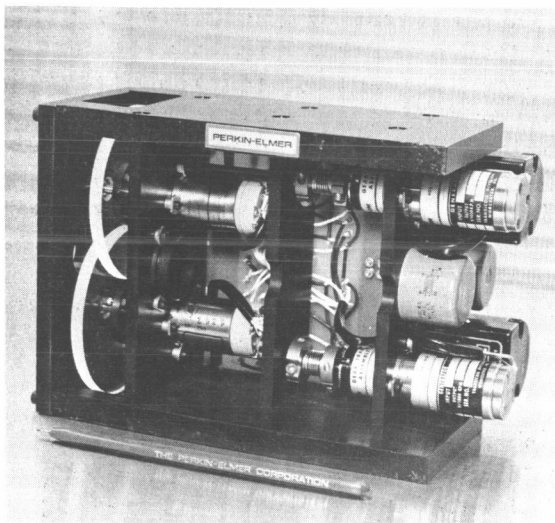


Figure 9.

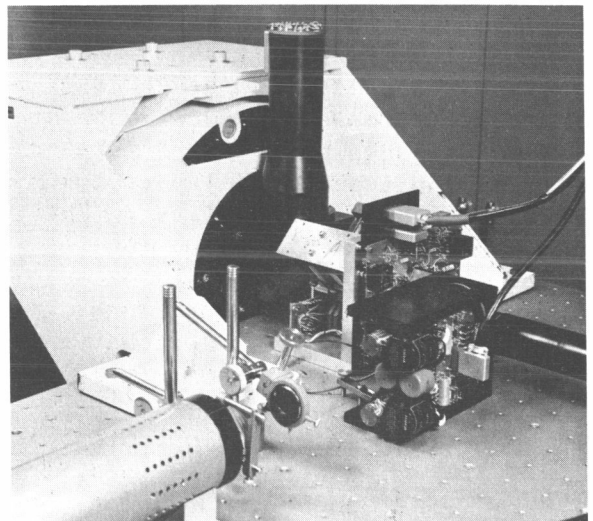


Figure 10.

The importance of each of these advances to the ultimate development of operational deep-space laser communications system is significant because four of the ten advances have been "reduce to practice" techniques (which are necessary for a laser communicator). Six of the ten advances improve the efficiency of the communication link itself by new and improved components. For example, the quantum efficiency of detectors has improved from 5 percent to 25 percent through the use of new dormer photomultipliers (which depend upon the principles of additional reflection). The shorter wavelengths, that is, going from 6328Å to 5300Å also assists in bringing up the quantum efficiency of the detectors. This is identical in effect, to improving the power output of the laser aboard a spacecraft in the communication link. Further, the new 5300Å lasers have power efficiencies in the vicinity of 1 percent as compared to the efficiency of helium-neon lasers with 0.1 percent. These same green lasers (5300Å) also have the capacity for higher outputs: values as high as 20 watts are technically feasible as compared to 0.2 watts of the helium-neon lasers. The new Fabry-Perot filters have transmissions in the range of 50 percent as compared with the Lyot filters with transmission efficiencies of 0.15 percent.

Without pursuing in depth the details of communication link signal/noise calculations, it can be seen that the factor of 5 improvement in quantum efficiency, the factor of 100 potential increase in power output, the factor of 3 increase in transmission efficiency of the predetection filter; if, all multiplied together, provide potential improvement factors of over 1000 (30 db).

The net result of these improvement factors is to reduce the telescope diameter and the weight of the laser communicator by appreciable factors and to introduce conservative safety margins. Thus, the Laser Communication System Experiment unit which was evaluated in 1966 as a half scale prototype for a deep space communicator (See Figure 8) is now adequate in size to function as a full scale communicator by substitution of lasers (i.e., 5300Å instead of 6328Å).

The rapid progress of the last three years in the laser art and science will continue, hopefully, and the experiments described in this report will be applicable to the future laser systems. As the laser communication efficiencies increase, there will be an ever increasing desire to apply these techniques to projects which could take advantage of them. However, the missing link in the application of laser communication techniques to interplanetary probes will be the propagation data on the laser beam for the two cases of up-going beams and down-going beams.

The last five illustrations, with the attendant supporting data, present convincing arguments that the state of the art of a deep-space laser communication system has graduated from an experimental level to a practicable level.

- Pointing Technology Area - The OTES mission plan as presently contemplated, provides the most complete space experiments set needed to develop the 1/100 arc second pointing technology for future NASA missions.

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The large orbiting telescope systems which are being considered for future NASA missions are absolutely dependent upon precise pointing as well as diffraction limited optical systems. The modulation transfer function of the entire optical system - a precise measure of performance - degrades extremely rapidly if the motion of the image begins to approach the dimensions of the resolution element. In practical terms, the pointing system performance of a space telescope in angular measure - fractions of an arc second - must be significantly less than the resolution capability of the same telescope. Thus, Stratoscope II which is a 36 inch aperture diffraction-limited telescope has an angular resolution of 1/6 arc seconds (visible wavelengths) and yet the pointing system had to be 1/60 arc second. For the case where the telescope is being used to propagate a laser beam, communicator applications, these conditions are not as severe. For that type of operation, pointing system performance approximately equal to the beam divergence is adequate. Thus, the LCSE with its 0.4 arc second beam requires a pointing system in the vicinity of 0.1 arc seconds.

Because of the interest in 3-meter space telescopes for future NASA missions, the pointing precision experiments of the OTES (Experiment No. 9) are planned for 1/100 arc second down to 1/200 arc second. This latter number corresponds to 1/10 the diffraction limit angle of the 3-meter instrument.

The work completed in the Phase A Study by Perkin-Elmer in the evolution of pointing group of experiments (Experiment No. 9) points out the feasibility of conducting appropriate flight experiments to evaluate each of the four candidate techniques:

- Transfer Lens Experiments
- Flexure Gimbal Body Point Experiments
- Free Float Body Point Experiments
- Image Plane Equipment Motion Compensation Experiments

in each of the two orbited modes of operation.

- Connected to the cluster (with its man and large air drag induced disturbances)
- Autonomous (without man and with correspondingly lower amounts of orbital disturbances due to man, earth anomalies, magnetic field and air drag)

in each of the two background light conditions.

- Daylight
- Night.

The recommended plan is to orbit the 2-meter OTES at a < 500 mile altitude and compare this data with the LCSE data obtained at 20000 mile altitude.

PERKIN-ELMER

Each of these pointing experiment combinations can be obtained to yield most valuable data by the presently configured OTES. Each of the instrument modules shown behind the telescope has its own autonomous guidance requirements and equipment. The concept details of the devices are included in this report in Chapter 3.

Manned Astronomy Area - Due to the long trouble free life requirement and due to the need to provide equipment flexibility in the instrument section of a large space telescope, it is an inescapable conclusion that the future large optical space observatories will be maintainable by an astronaut in space. There are three OTES experiments directed at the utilization of man in the tending of future large orbital telescopes.

Experiment No. 3, the astronaut utilization experiment, is basically designed to learn how to support the large orbiting telescope system by having the astronaut perform two monumental task series:

1. Removing and replacing one of the mirror segments in the segmented optics group of the primary mirror.
2. Removing and replacing the scientific and engineering equipment modules located behind the primary mirror.

In the first series, the experiment would be conducted after the conduct of Experiment No. 1, the Primary Mirror Group. Based on data obtained from that experiment, it could be established which of the primary mirror segments has the poorest figure in the space environment, and that specific mirror segment would be replaced by a spare mirror segment which was carried aloft at the time of launch. The removal and replacement of one of the equipment modules behind the primary mirror is more complex than the initial mirror removal experiment because these units have electrical interfaces with the spacecraft and telescope as well as the close tolerances between optical and mechanical equipment.

Experiment No. 4, Scatterplate Photographs of the Primary Mirror, is too complex an operation to execute without the assistance of a specially trained astronaut. The performance of this task in the optical laboratory requires a high degree of optical know-how and dexterity. There is considerable question as to the likelihood of success of this experiment in the initial attempt. However, an important factor working for the success of this experiment is that the location at which the astronaut will conduct the experiment is at the very front of the telescope. This area is clear and unencumbered with other equipment.

Experiment No. 6, Mirror Coating in Space, requires the services of the astronaut to assist in the experiment. The mirror that is removed from the primary in Experiment No. 3 can be transferred to the mirror recoating tank by the astronaut. The astronaut would get it properly placed in the equipment, and after the recoating operations are completed, the mirror could be returned to the main telescope.

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It is important that the reader recognize that for a space telescope to be serviced in flight, the instrument must be designed with this intent from the very beginning. Thus, the present state of the OTES conceptual design is such that the primary mirror, secondary mirror, figure sensor, scientific instruments and all functioning mechanisms are arranged so that access is provided to the astronaut from outside the telescope. Also, all mechanisms and functional units are modularized so that they may be replaced with the minimum of astronaut participation in EVA.

Effects of Aerospace Environment Area - Both Perkin-Elmer and Lockheed have studied the launch environment of the Saturn IB and V systems and the effect it would have on the optical system. From this study evolved the need to provide an extendible telescope structure in order to accommodate either 2- or 3-meter aperture telescopes. The maintainability of large-aperture space telescopes of the future will be enhanced by the experiments which involve the space skills of the astronauts. The release of exhaust products from the astronaut life support systems and from the optical laboratory life cells has been analyzed as well as the light-scattering effects on space telescopes, from the molecular gas, aerosols, and particle debris.

During the OTES Phase A Program, there have been 15 optical technology milestones:

OPTICAL TECHNOLOGY MILESTONES OF PHASE A

Space Optics

1. Super cold telescope concept (-80°C temperature achieved passively)
 $\pm 4.5^{\circ}\text{C}$ gradient tolerance predicted for -80°C
 $< 1^{\circ}\text{C}$ gradient for 3-meter mirror anticipated at -80°C
2. Diffraction pattern for 3-meter segmented optics computed and verified experimentally.
3. Active segmented optics demonstrated

Precise Pointing

4. $1/10$ arc second laser tracking demonstration (Figure 11)
5. Body point plus all reflective transfer lens concept developed
6. Free float technique demonstrated (Figure 12)

PRECISION POINTING WORK

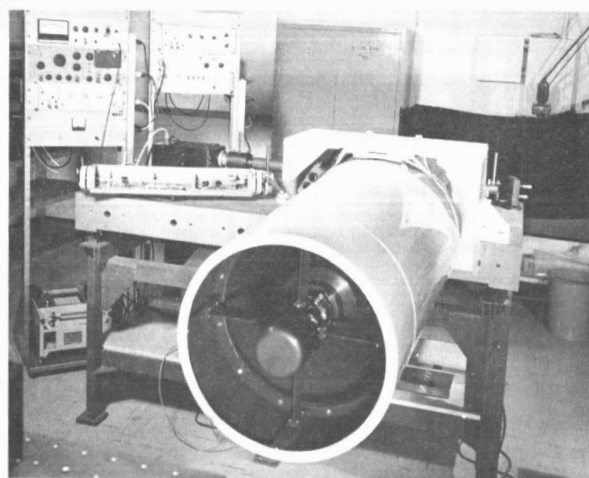
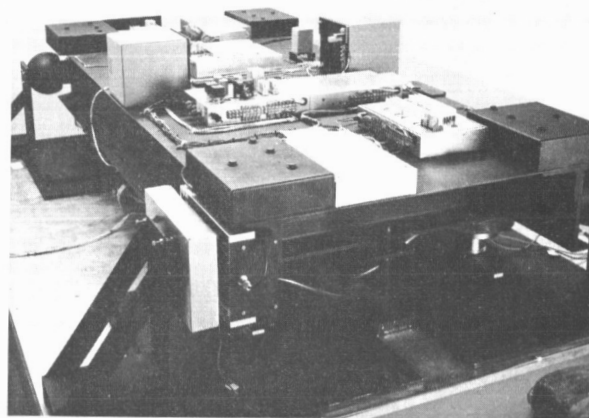
 $\frac{1}{10}$ sec OPTICAL POINTING of LASER BEAM

Figure 11. Laser Beam Pointing

 $\frac{1}{100}$ sec. TELESCOPE POINTING *

* SUPPORTED BY NASA THROUGH PRINCETON UNIVERSITY

Figure 12. Free Float Pointing

Laser Communications

7. 10^{11} beam isolation measured
8. Laser beam wander (intensity fluctuation measured) $< 1\%$
9. 10^6 bits/second @ 10^8 miles computations completed for candidate lasers:

	5300Å	6328Å	10.6 micron coherent
Laser power output (watts)	3	0.140	20
Mirror diameter (meters)	0.5	1	1.5
Margin	3.6	1	1

10. Up-going beam spread @ 4880Å computed to be < 0.5 arc-seconds

Spacecraft

11. 22,767 n. mi. required orbit for communication experiments; 260 mile orbit most suited for optical experiments.

12. Thermal concept (coatings plus super insulation) evolved
13. Life Cell concept for the 3-meter telescope developed (MOTEL)
14. Compatibility with ATM Gimbals, Cluster and Apollo Flight Hardware established
15. 2-Meter telescoping tube concept developed as shown in Figure 13

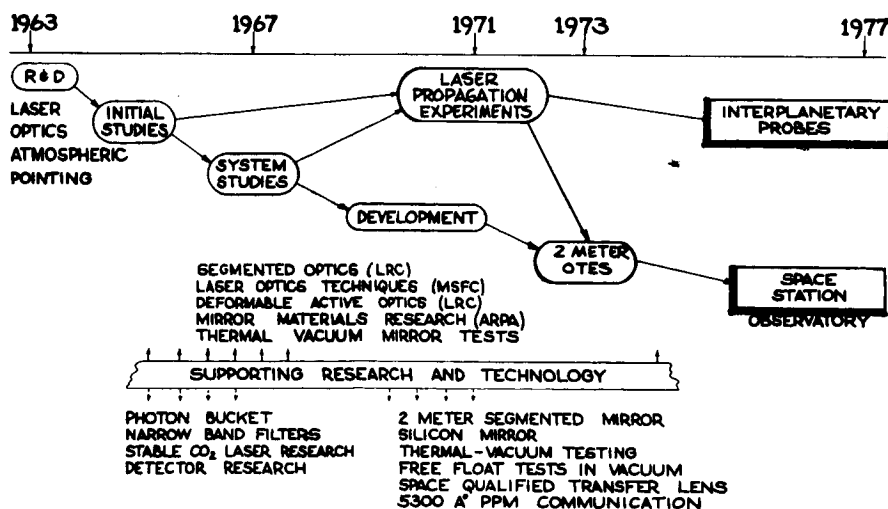
MISSION AREAS RECOMMENDATION

While Perkin-Elmer has studied the prospective relationship between short wave-length astronomy (i.e., gamma ray and X-ray) and the OTES Program, we have found that the instrumentation for this area is quite unique and bears little resemblance to the optical instrumentation needed for the OTES. In a similar manner, the broad general areas of planetology and meteorology are important in their own right, but have little in common with the impetus of the OTES. It is the Perkin-Elmer recommendation that the areas of optical technology in space which could benefit most from the conduct of space experiments utilizing Saturn launch vehicles are: large space optics, laser communications, astronaut experiments and atmospheric measurements.

SUPPORTING RESEARCH AND TECHNOLOGY RECOMMENDATIONS

The NASA Space Optics Technology Plan in Figure 1 shows the interrelations between the current OTES Study, the two flight experiment systems and the goals or missions. The supporting research and technology areas (SRT) that are presently funded are listed above the SRT bar while the Perkin-Elmer recommended new areas for SRT are shown below the bar:

NASA SPACE OPTICS TECHNOLOGY PLAN



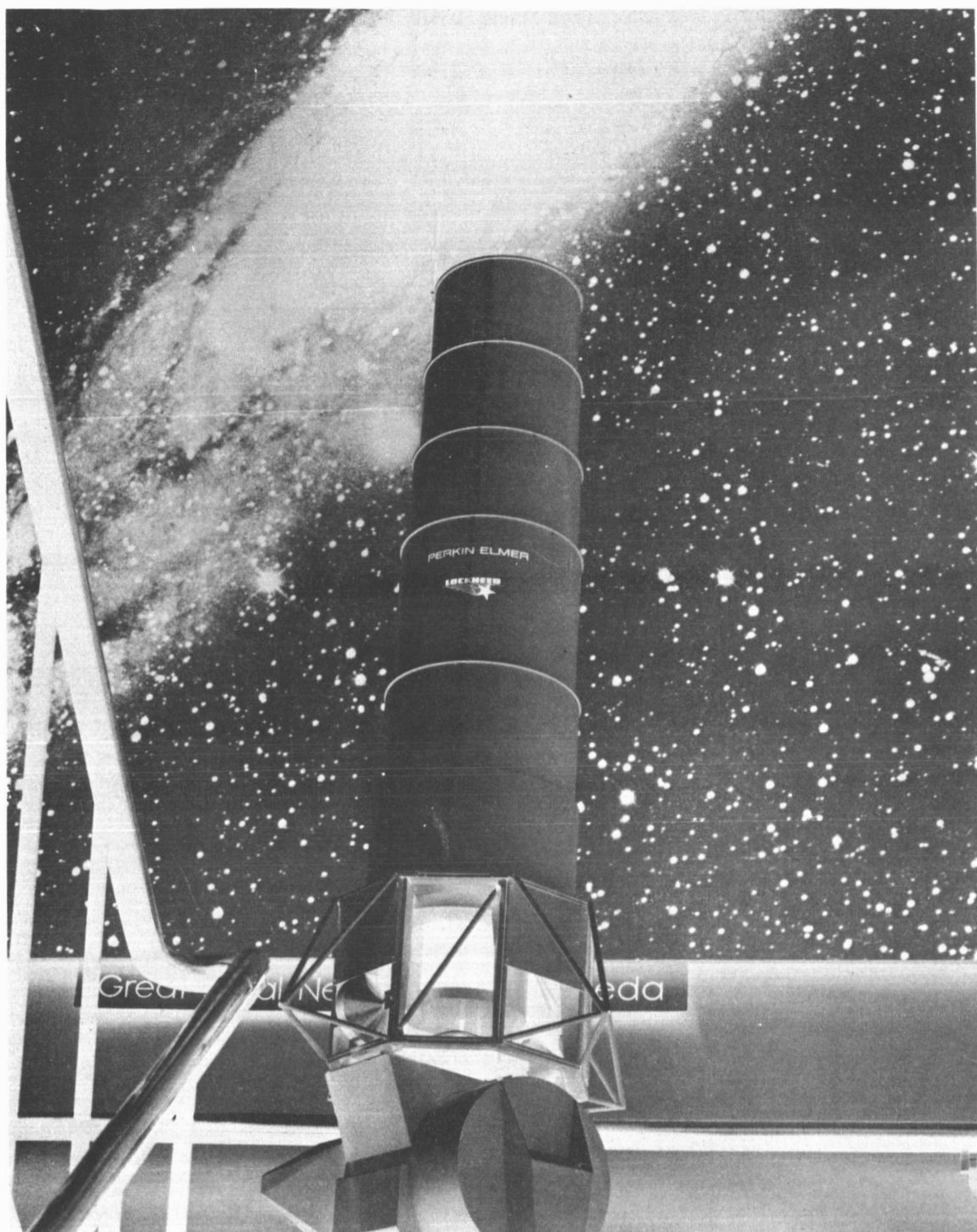


Figure 13. 1/10 Scale Model of the 2 Meter OTES

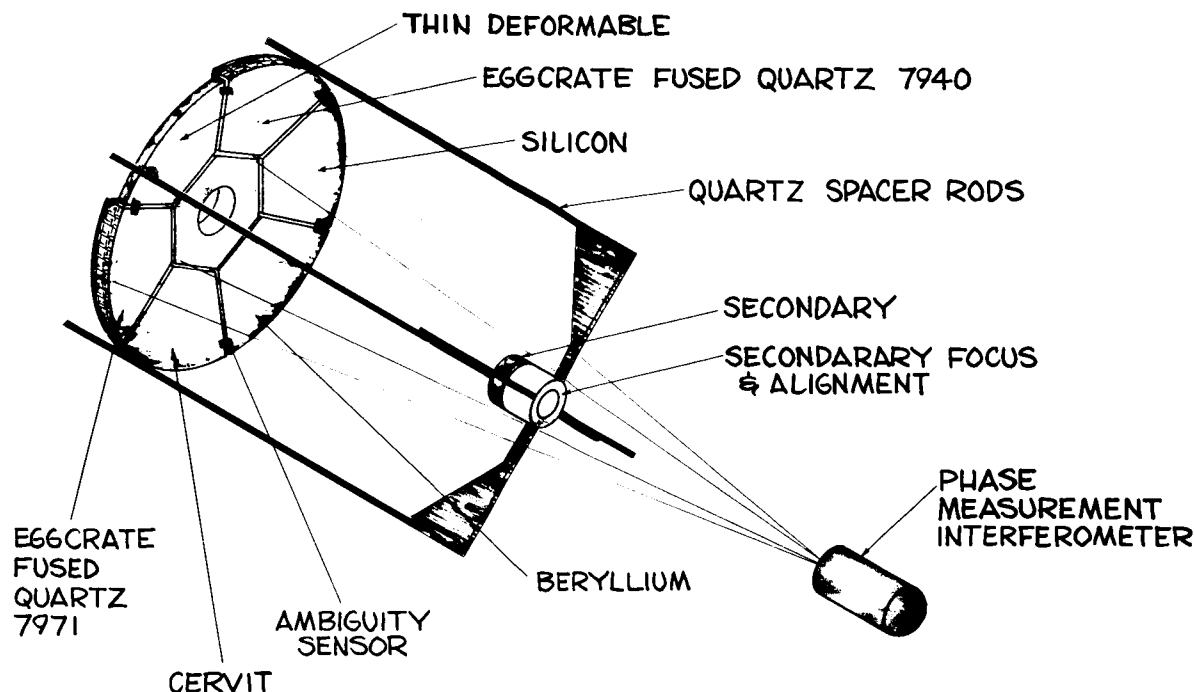
EXPERIMENT NO. 1 - PRIMARY MIRROR GROUP

Figure 14.

EXPERIMENT OBJECTIVE

The fundamental objective of the 2-meter Primary Mirror Group Experiment as illustrated in Figure 14, is to provide an engineering evaluation of the most promising technical approaches to achieving diffraction-limited performance of space optical systems leading to the space telescopes of the future with apertures of 200 to 400 inches.

The experimental 2-meter primary mirror is an array of seven individual mirror segments made of different materials. The individual segments would be aligned to each other to form the diffraction-limited 2-meter aperture. Each mirror segment would be sensed by the mirror figure sensor (a phase-measuring interferometer) and moved to the proper location by the Active Optics actuator servomechanisms. The figure of each individual segment would be individually determined and compared with the other segments of competitive materials providing a space evaluation of different mirror technology approaches.

The entire instrument would be useful as a large diffraction-limited telescope for evaluation of the astronomical observations which can be conducted with an Active Optics segmented primary mirror.

EXPERIMENT JUSTIFICATION

The justification for using an Active Optics primary in the 2-meter OTES is based on the need for a large, diffraction-limited orbiting astronomical telescope. The advantages of having such a telescope above the Earth's atmosphere have been described in the technical press.* Active Optics is the most promising technique for fulfilling this need by making possible the construction of a large telescope mirror which can maintain its figure to the diffraction-limited quality required.

There are important advantages of an active segmented optics primary mirror.

- Diffraction-limited performance in a large mirror.
- Weight saving in large mirrors.
- Maintenance in space of primary mirror by astronaut
- "Launchability" of a giant mirror by assembly of segments in space.

The 2-meter aperture OTES will function as a precursor to the 3-meter OTES or MOAT. The 2-meter telescope flight will be low altitude, concentrating on optical technology and manned observatory operations. The importance of the 2-meter OTES stems from the space experiments planned and the solutions to questions which cannot be answered until the flight data is reduced. The justifications for the 2-meter OTES telescope and, the optical experiments are listed below:

- Resolution of the daylight astronomy question.
- Resolution of the low-high altitude orbit question for space telescopes.
- Resolution of the primary mirror question.
- Help in resolving the astronomy mission for a National Space Station Observatory.
- Provision of space data on telescope suspensions for the next generation of less than 2-meter space telescopes.

* Lyman Spitzer, Jr., American Scientist, Vol. 50, No. 3, September 1962, pp. 473-484.

Zdenek Kopal, Astronautics and Aeronautics, December 1965, pp. 16-21
Space Research - Directions for the Future, Publication 1403 National Academy of Sciences.

- Resolution of some of the manned astronomy questions including the duties and performance limits of astronauts working with large space telescopes.
- Provision of space maintenance data in a large telescope conceived and designed from the very beginning for in-space flight maintenance.

The third item in the justification list above, the primary mirror question, is key to the future of each and every large optical system contemplated for the 1970's and beyond. The importance of the 2-meter segmented mirror as a flight experiment is clear because Experiment No. 1, as a space experiment, is based on:

- The seven most promising space optical mirror techniques are evaluated individually and comparatively.
- An eighth space optical system technique - Active Segmented Primary Mirror - is assessed with the identical equipment.

The flight experiment of the 2-meter telescope for collection of optical technological data is even more useful to NASA because the 2-meter OTES is able to function as a 2-meter telescope with diffraction-limited performance. Thus it can be used for astronomical observations at the conclusion of the optical technology experiments.

Rendezvous with other spacecraft from Earth would make possible updating and changing mirror segments to achieve the most successful primary mirror substrate approach. Thus space maintenance techniques for large orbiting telescopes (see Experiment No. 3) are developed by using the 2-meter OTES telescope.

BASIC EXPERIMENT HARDWARE:

- Seven unique and individual mirror segments: (See Figure 14)
 1. Thin deformable mirror.*
 2. Eggcrate fused quartz mirror segment made of material 7940.
 3. Silicon mirror segment.
 4. Beryllium segment.
 5. Cervit mirror segment.

* Perkin-Elmer Contract with Langley Research Center NAS1-7103.

6. Eggcrate fused quartz of 7971 material.
 7. Solid fused quartz mirror segment of 7940 quartz.
- Phase-measurement interferometer for figure sensing each segment and the entire surface (see Figure 15.)*
 - White-light interferometers for coarse segment alignment (See Figure 16).*
 - Actuators to align segments to each other in response to data from figure sensor (See Figure 17)*
 - Electronic analyzer and programmer to convert data from interferometers into actuator commands.

The segments of the 2-meter mirror are located and held in position (pitch, yaw, and in-out along the optical axis) to better than 1/50 wave by the phase-measuring interferometer functioning as a mirror figure error sensor. The 2-meter approach provides the necessary space operations for the evaluation of each of the seven promising space optical techniques, but, as noted, Experiment No. 1 provides a spaceflight evaluation of the eighth technique - Active Segmented Optics - as well. Figure 5 is a photograph of the complete segmented mirror assembly

Tilt and Positional Alignment Subsystem

The subsystem for active optical control consists of three equipments:

- The phase-measuring interferometer and its associated electronics at the center of curvature of the primary mirror.
- The segmented primary mirror.
- The actuator control electronics located behind the primary mirror in the central module of the Scientific and Engineering Modules, Unit A in Figure 60.

The helium-neon laser and image dissector tube are the components which control the weight, power, and volume of the interferometer subsystem; therefore, they are oriented to minimize the obscuration of the primary mirror.

The coupling optics map the gaussian intensity distribution (obtained from the fundamental laser TEM₀₀ mode) into the uniform intensity and phase front required by the interferometer. Because the two arms of the interferometer (beamsplitter-to-primary and beamsplitter-to-interferometer mirror) are of different lengths, it is important that the light transmitted from the coupling optics also be parallel. Proper operation of the interferometer requires active alignment of both the coupling optics and the interferometer mirrors.

* Perkin-Elmer Contract with Langley Research Center NAS1-5198.

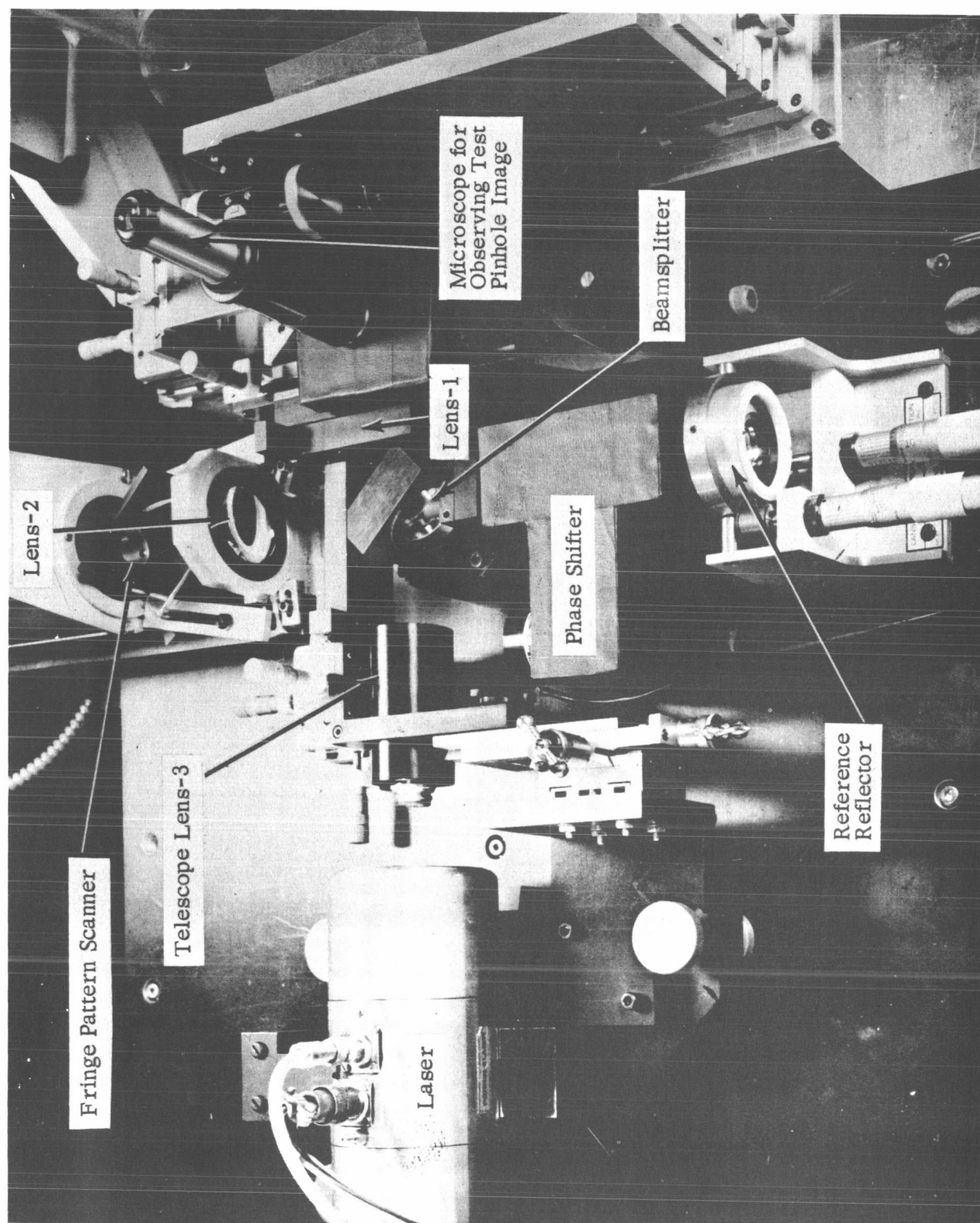
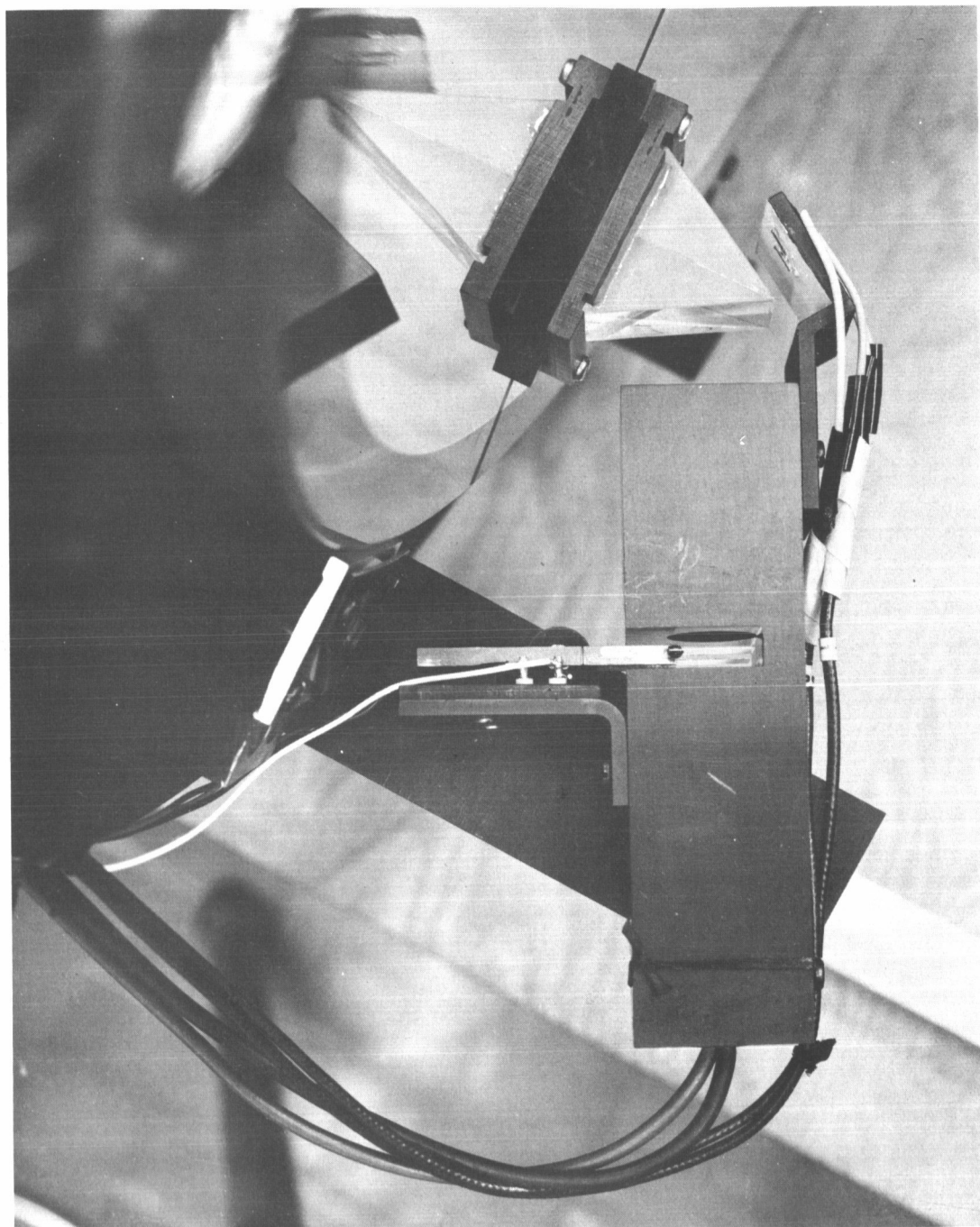


Figure 15. Phase-Measuring Interferometer



Showing Koesters prism mounted to one mirror segment; light source, chopper, and detector mounted to support frame.

Figure 16. Active Optics Experimental White Light Interferometer

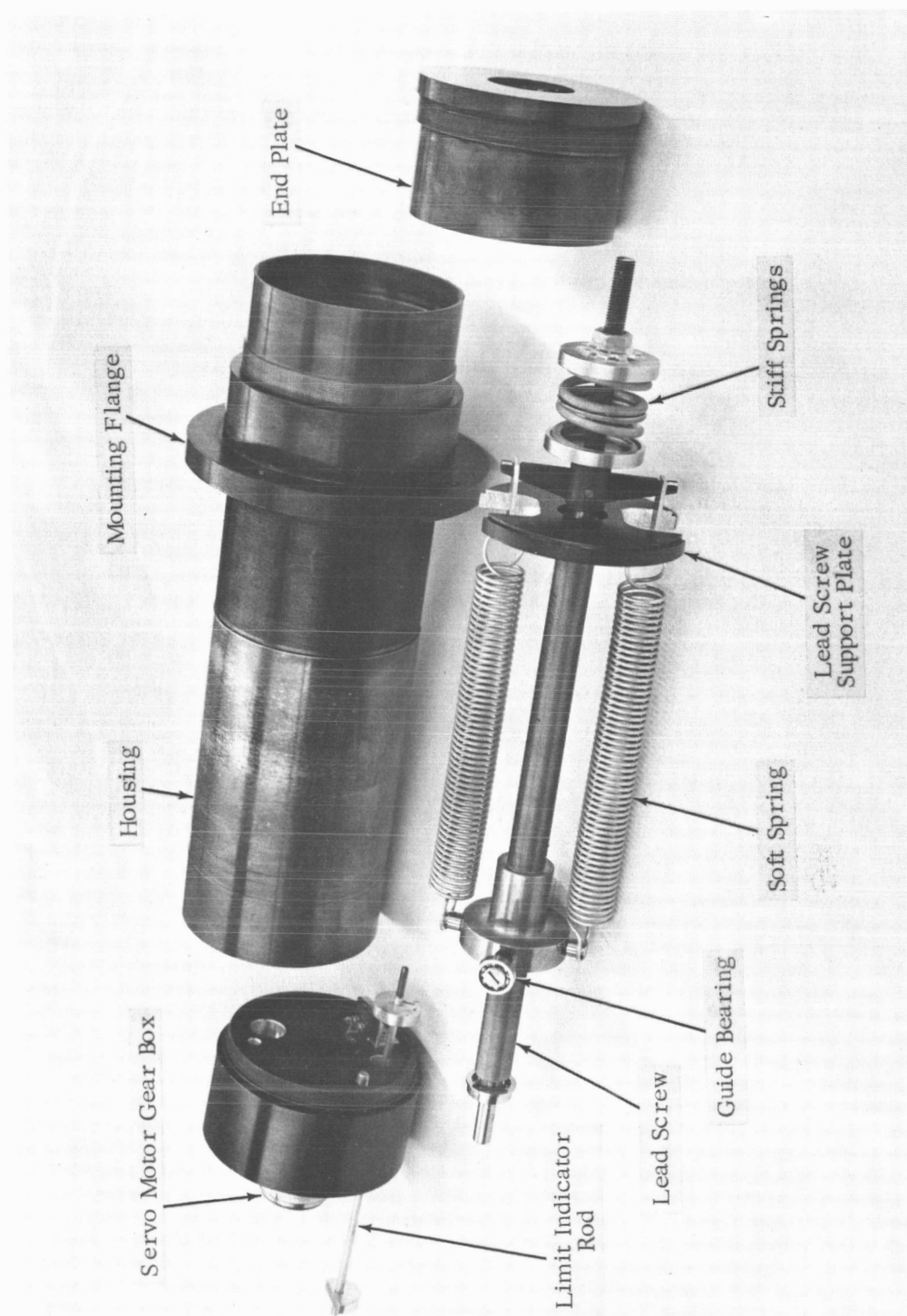


Figure 17. Active Optics Experimental Actuator Parts (Spring Damping Not Shown)

Flexing of the telescope structure caused by thermal distortions will move the interferometer with respect to the center of curvature of the primary. Small perturbations are compensated for by focusing or lateral translation of the Offner corrector/focusing lens pair. Large transverse deformation of the telescope structure greater than several millimeters requires translational movement of the interferometer assembly and is provided by the present conceptual designs of the 2-meter OTES.

The Offner corrector* is required since the primary is hyperbolic. The corrector makes the hyperbolic primary mirror appear to be spherical. That is, the optical path length of each ray in the long arm of the interferometer will be equal. A similar device was designed and used in the scatterplate figure testing of the parabolic Stratoscope primary mirror. The alignment of the corrector is critical for proper operation of the system.

The phase-measuring interferometer as shown in Figure 15 should be able to fit into a volume of 24x12x12 inches and its weight is estimated at approximately 30 pounds. The data processing electronics are placed in Module A behind the primary mirror (see Figure 60).

The phase-measuring interferometer is used for detecting both tilt and focusing errors of the secondary mirror. By polishing the rear face of the secondary, an auxiliary interferometer is formed with one interferometer arm between the beam-splitter and the rear face of the secondary. Since the Offner corrector/focusing lens pair is positioned with respect to the center of curvature of the primary, this secondary mirror alignment technique is independent of any flexing in the primary-secondary mirror support structure. However, fabrication errors and thermal gradients in the secondary mirror must be carefully controlled to avoid alignment errors.

In the detailed descriptions of active segmented optics components which follow, the Perkin-Elmer work for NASA's Langley Research Center (L.R.C.) in Contract NAS1-5198 has been drawn on wherever applicable for the OTES Experiment No. 1. This material, with additional details, is available in Perkin-Elmer Report Nos. 8255 and 8525. The work on the Active Optics Deformable Mirror is also supported by NASA's L.R.C. in Contract NAS1-7103.

Sensor-Analyser Operations

The sensor-analyser operation** is best described by going through the sequence of alignment steps listed in Table 1. It is postulated that, initially, we will be able to locate the mirror segments on the support structure with an axial accuracy of ± 0.04 inches relative to the desired spherical surface. This corresponds to an axial or focus displacement of 1600 wavelengths. The angular positioning accuracy is estimated to be within 2 minutes of arc or on the order of ± 0.01 inches at the mirror edge.

* Offner, A., A Null Corrector for a Parabolic Mirror, Applied Optics, Feb. 1963.
 ** The operation described has been reduced to practice. In order to make the system even more independent of spacecraft disturbances, a second generation analyzer has been developed and operated. It will be described in the future.

TABLE 1
SEQUENCE OF OPERATION

Step	Function	Interferometer Used	Scan Pattern	Electronic Detection	Actuators Used	Anticipated Resultant Alignment Errors Focus Tilt
"	Manual Alignment	-	-	-	-	0.04 inch (1600 λ) 0.01 inch (2 min.arc)
(a)	1st Segment Coarse Tilt Adjust	Twyman-Green	Orthogonal Lines at 3 sec period	Min. Frequency	#2 and #3 Sequentially	1600 λ $\approx$ 1 λ (note 1)
(b)	1st Segment Coarse Focus Adjust	Phase Measure	Orthogonal Lines at 10 sec period	Phase Difference (point 1 Ref.)	#1, 2, and 3 Simultaneously	16 λ (note 1) $< \frac{1}{2} \lambda$
(c)	1st Segment Fine Tilt Adjust	Phase Measure	Points 2 and 3 Sequentially	Phase Difference	#2 and #3 Sequentially	16 λ $< 1/20\lambda$ (note 2)
(d)	2nd Segment Edge Positioning	"Kosters' Prism & White Light"	None	Signal Polarity	#4, #5 & 6 Simultaneously	1/8 λ 150 λ (note 3)
(e)	2nd Segment Fine Positioning	Phase Measure	Point 5	Phase Difference (point 1 Ref.)	#5	1/8 λ $< 1/20\lambda$ (note 2,3) (note 2)
(f)	2nd Segment Fine Tilt Adjust	Phase Measure	Orthogonal Lines at 10 sec period	Phase Difference	#4 and 6 simultaneous then #6 only	1/20 λ $< 1/20\lambda$ (note 2,3) (note 2)

(g)(h) repeat Steps 4, 5 and 6 for 3rd Segment (i)

(j) Figure Verification.

NOTES: 1. The wavelength referred to here is 6328 $\text{\AA}$ or 25 x 10⁻⁶ microinch.
2. These values will be limited by the mirror segment figure.
3. These values are all relative to the first segment.

The first step of alignment, step (a), will be to adjust one mirror segment alone for a minimum tilt error by adjusting for a minimum number of fringes across the interference pattern. This will be done by two orthogonal scans, as shown in Figure 18, the first going from point No. 1 to point No. 2, and the second going from point No. 1 to point No. 3. The scan from No. 1 to No. 2 will generate control signals for actuator No. 2; and similarly for actuator No. 3. At the completion of this step, the focus error can still be as great as 0.04 inches, but the tilt error will be reduced to the order of 1 wavelength.

Step (b) will use the phase-measuring interferometer to correct focus error for the first segment. This will be done by scanning from point No. 1 to point No. 2 and from point No. 1 to point No. 3 and adjusting axial position with three actuators (Nos. 1, 2, and 3) simultaneously for a minimum phase shift across the scan. All phase measurements will be made relative to the phase of the interferometer pattern corresponding to point No. 1 on the mirror per Figure 18. For a phase accuracy of 4 degrees, this step will reduce the focus error to 16 wavelengths. This phase-measuring accuracy is considered conservative in the light of the breadboard results.

Step (c) will be a fine tilt adjustment, again using phase measurement and looking at point Nos. 2 and 3 sequentially. Control signals will be generated for the corresponding actuator. The breadboard results indicate that the alignment accuracy will be limited by the mirror segment figure.

It is assumed that at the end of step (c) the first segment will be properly aligned. Subsequent steps are intended to place the other two segments in their proper position relative to the first segment. In steps (d) and (g) the segment edges are positioned by use of the white-light interferometer. Breadboard results indicate that this step should place points No. 5 and No. 9 coplanar within ± 3.0 microinches of points No. 2 and No. 3. Steps (e) and (h) reduce this error to less than $1/20$ wavelength.

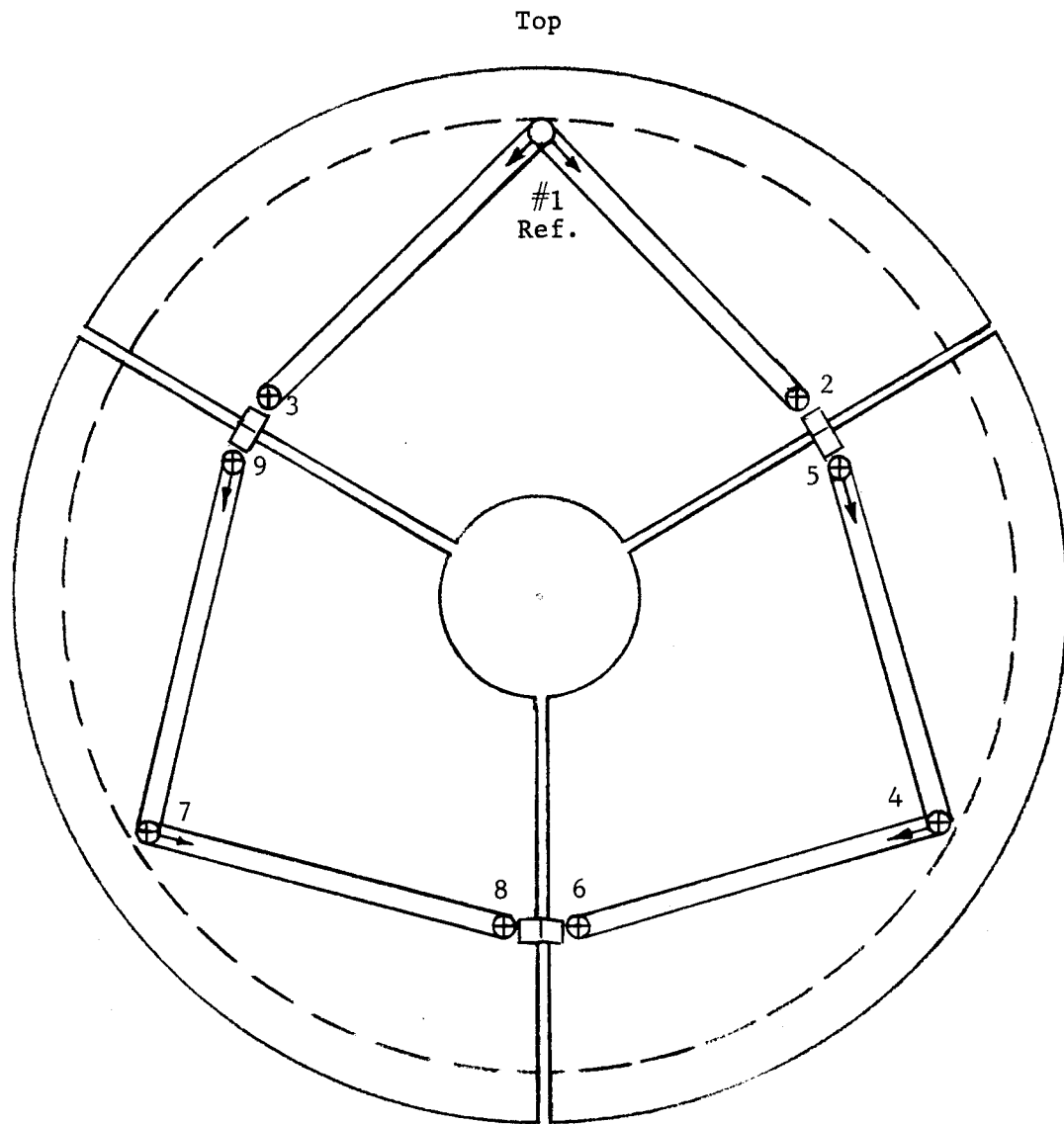
Step (f) requires two more orthogonal scans. In this case, the actuators are driven as the scans progress to the position for which no phase shift occurs between points No. 5 and No. 4 and then points No. 4 and No. 6. This will require 10 seconds or more per scan. Step (i) is identical for the third segment.

Alignment Tolerances

Study Results

During Phase 2 of the OTES program, work was directed towards establishing the tolerance requirements for the phase-measuring interferometer used to control the segmented primary mirror. This was necessary to establish the equipment conceptual requirements for the 2-meter OTES. The interferometer is sensitive to the errors illustrated in Figure 19, i.e.:

- Displacements along the optic axis.
- Displacements perpendicular to the optic axis.
- Rotations around the optic axis.



- ⊕ Actuator Positions
- → Sensor Scan
- Ref. Sensor Reference Point
- Koester's Prisms

Figure 18.. Scan Pattern

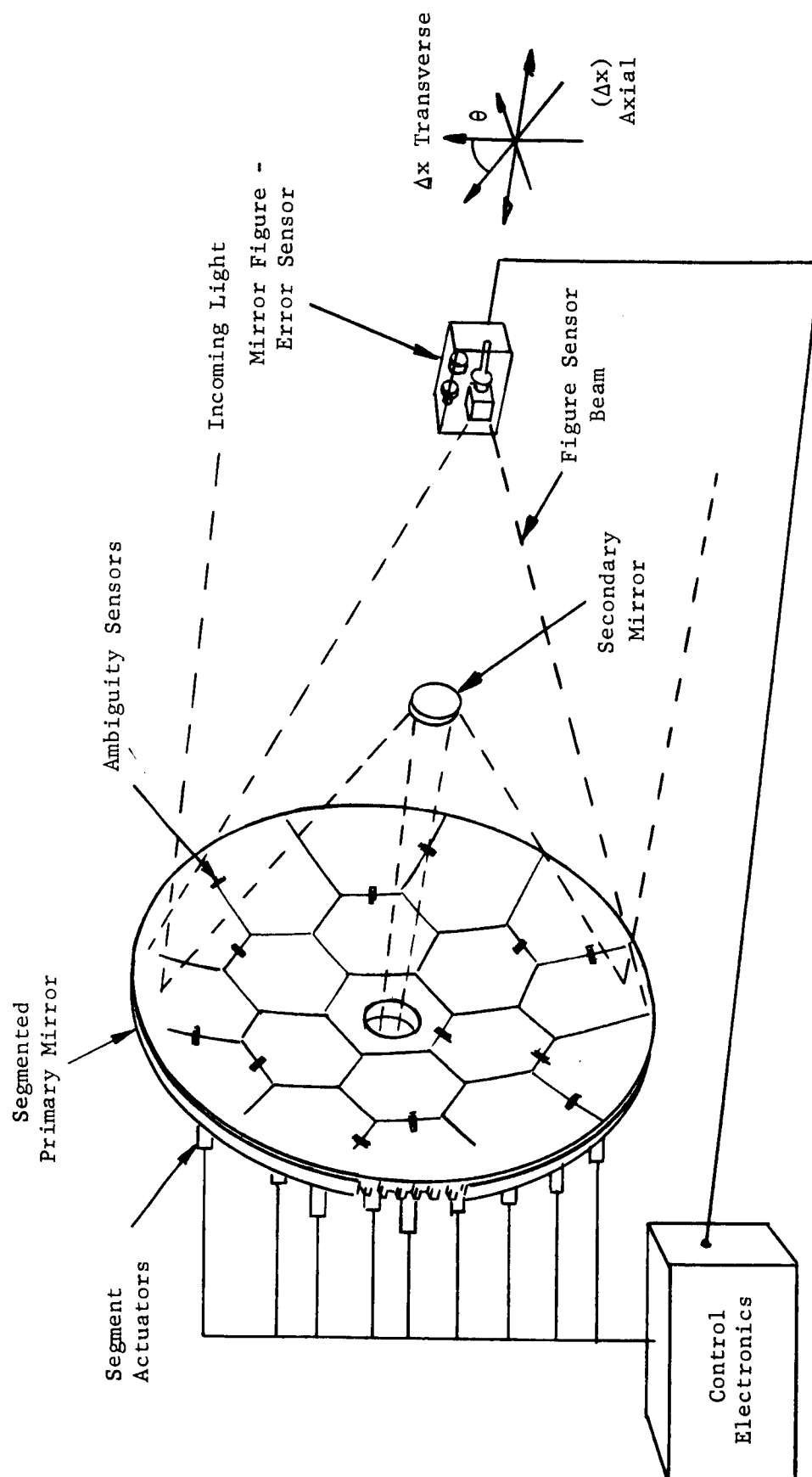


Figure 19. Active Optics Concept for MOAT Class Space Telescopes

The displacement Δx that can be tolerated along the optic axis will be shown to be

$$\Delta x = 16F^2 \Gamma (1 + 1/16 F^2)^{1/2} \text{ wavelength units}$$

where,

F = mirror f/number

Γ = fringe measuring accuracy of the phase-measuring interferometer

The displacements are shown in Figure 20 as a function of the mirror f/number with Γ as a parameter (full curve). Experimental comparison with the actual hardware at Perkin-Elmer for the present Active Optics system (f/8) shows that the measured tolerances check the analysis presented in the following pages. The OTES test on the Active Optics breadboard was done for a fringe measurement accuracy of $\Gamma = 1/50$.

The analysis of displacements transverse to the optical axis gives the tolerance as

$$x = \pm 8F \Gamma (1 + 1/16F^2)^{1/2} \text{ wavelength units}$$

They are also shown in Figure 20 (dotted curve) as a function of primary mirror f/number and fringe measurement accuracy. These tolerances are more strict than for axial displacement, but can be easily corrected by tilting the mirror segments to coincide with the best fit optical surface.

Any rotational error (θ) between the primary mirror and the interferometer will cause rotation of the image of the primary mirror on the image dissector surface. No calculations were made for this type of error since experimental measurements show that the Active Optics system is insensitive for rotational errors. ($\pm 1^\circ$ can be tolerated).

For the 2-meter OTES, which has an f/2 primary, the alignment tolerance must be commensurate with diffraction-limited performance. Using Figure 20, and an alignment requirement of $\Gamma = 1/50$ wave, the axial alignment tolerance is ± 1 wave and the tolerance perpendicular to the optic axis is $\pm 1/4$ wave. Due to these tight alignment tolerances, the 2-meter OTES concept as presented in this report includes active inflight alignment of the phase-measurement interferometer to the primary mirror central segment. (segment 7 in Figure 14).

Analysis

The phase-measuring interferometer (P.S.I.) used to detect the primary mirror figure errors is sensitive to positional errors both along and perpendicular to the optic axis of the primary mirror. A further source of error can arise from rotation of the interferometer around the optic axis causing a coordinate change at the image dissector. This confuses the logic circuitry but, in practice, rotations of $\pm 1^\circ$ can be tolerated.

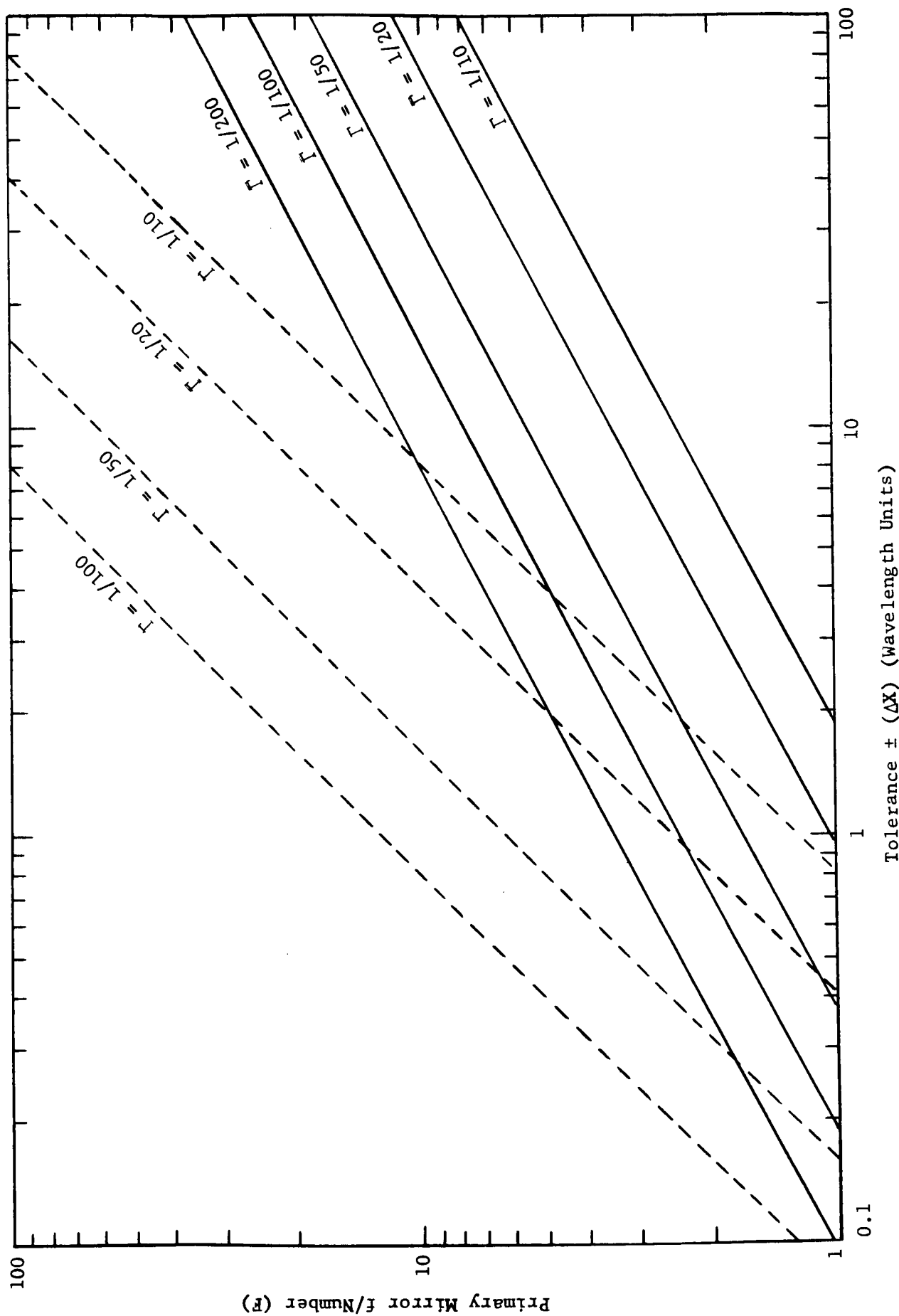


Figure 20. . . Alignment Tolerances for the Phase-Measuring Interferometer Axial Tolerance (Full Curves); Tolerance Perpendicular to Optic Axis (Dotted Curves)

The focus error caused by translation along the optic axis is illustrated in greatly exaggerated form in Figure 21. Light from the interferometer is focused at the center of curvature C and is reflected back along the same path when the primary mirror is correctly positioned at M₁. Relative displacement of the P.S.I. and primary mirror, by an amount Δx , causes the center of curvature to move to C' and the return light to be focused at P, a distance $2\Delta x$ from C. The P.S.I. now compares the primary mirror at position M₂ with a sphere at M₂ centered on C, and deduces that a figure error exists in the system. The error can be calculated from these two spherical surfaces.

An alternative way of visualizing the focus error, which takes into account the interferometer lenses, is to consider the light returning to lens L₁. This lens will see a beam of light which appears to come from infinity (the reference wave) together with light from the point P' (the virtual image of P). The plane reference wave and the spherical wave from P' will interfere to produce fringes at the image scanner. One can also consider the interference of the two spherical waves W₁ and W₂ to the right of lens L₂, where the wave W₁ is emitted from C and corresponds to the virtual image of the reference wave from mirror M₃. This avoids having to locate the position of the virtual image P'.

The path difference for some angle θ between the spherical waves of radii α and $(\alpha - 2\Delta x)$ is most simply calculated from the sag formula. If Δ is the required path difference at an angle θ , and x_1 and x_2 are the sagittas for the two wavefronts, we obtain (see Figure 21)

$$\Delta = \frac{(x_2 - x_1)}{\cos \theta}$$

If y is the vertical distance of the point of interference from the optic axis, the sag formulae can be written

$$x_1 = y^2/2\alpha$$

$$x_2 = y^2/2(\alpha - 2\Delta x)$$

where α is the distance between C and the center of the wavefront W₁.

The path difference is therefore

$$\Delta = \frac{y^2}{\cos \theta} \left(\frac{1}{2(\alpha - 2\Delta x)} - \frac{1}{2\alpha} \right) = \frac{y^2 \Delta x}{\alpha(\alpha - 2\Delta x) \cos \theta}$$

for small values of Δx this can be approximated by

$$\Delta = \frac{y^2 \Delta x}{\alpha^2 \cos \theta} \quad (1)$$

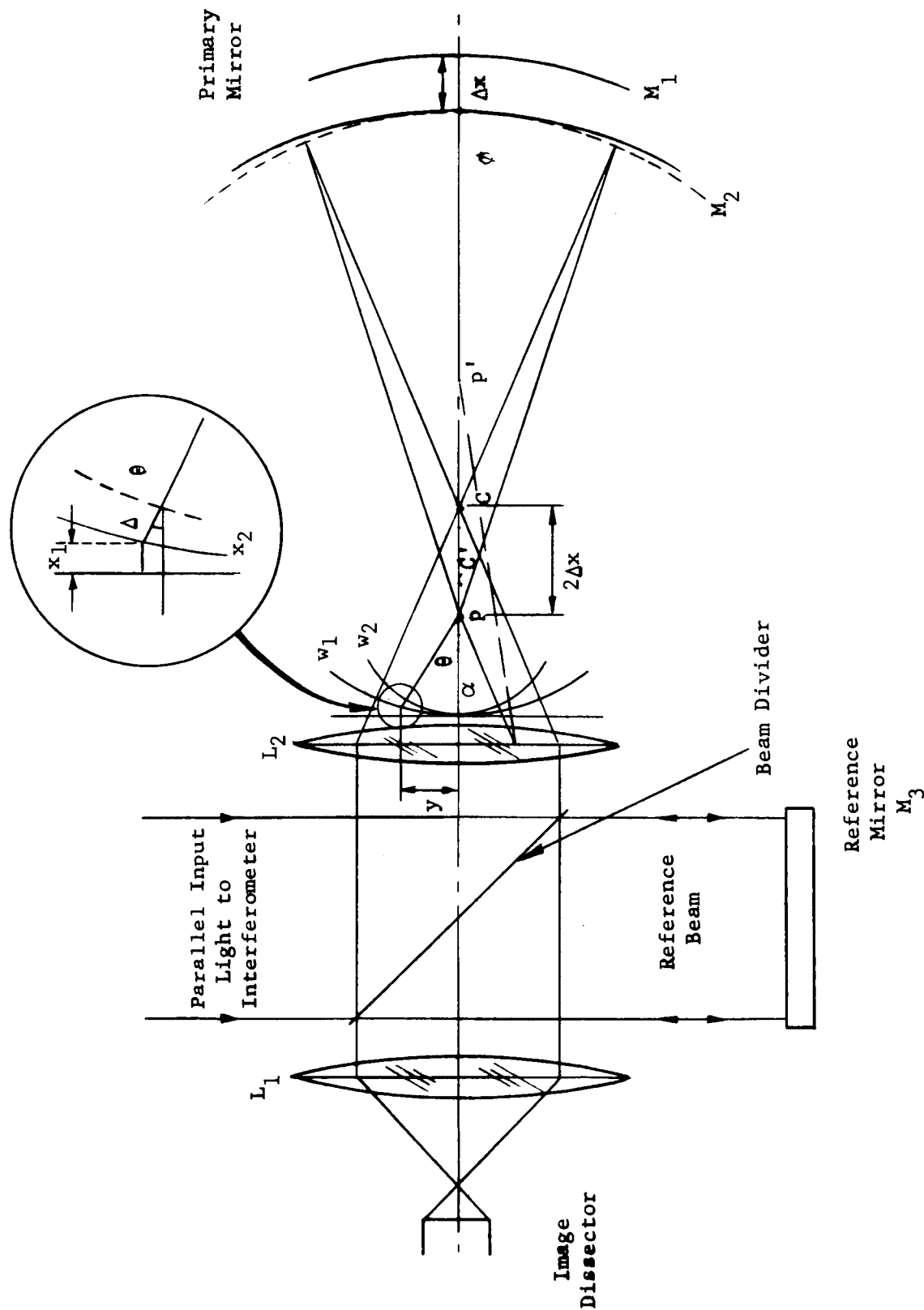


Figure 21. Focus Errors for Phase-Measuring Interferometer Schematic

If N is the f /number of the cones of light at C and P (the f /numbers for these two positions are approximately equal for small values of Δx) and if D is the diameter of the cones at an angle θ and distance α , then

$$N = \frac{\alpha}{D} ; y = \frac{D}{2} ;$$

and

(2)

$$\cos\theta = \alpha \left(\alpha^2 + \frac{D^2}{4} \right)^{-1/2} = \left(1 + \frac{1}{4N^2} \right)^{-1/2}$$

Substituting for y , α and $\cos\theta$ in the first equation, gives

$$\Delta = \frac{\Delta x}{4N^2} \left(1 + \frac{1}{4N^2} \right)^{1/2}$$

In terms of the f /number of the primary mirror

$$F = \frac{1}{2} N$$

Hence,

$$\Delta = \frac{\Delta x}{16F^2} \left(1 + \frac{1}{16F^2} \right)^{1/2}$$

In units of wavelength the path difference can be written as

$$\Delta = \frac{\Delta x}{16F^2 \lambda} \left(1 + \frac{1}{16F^2} \right)^{1/2}$$

Assuming that the fringe measurement accuracy of the P.S.I. is Γ , then the allowable focus error will be

$$\Delta x = \pm 16F^2 \Gamma \left(1 + \frac{1}{16F^2} \right)^{1/2} \lambda$$

this function is shown in Figure 20 for various measurement accuracies (Γ).

The alignment tolerance due to relative displacement of the primary mirror and P.S.I. perpendicular to the optic axis is calculated in a similar way. The virtual image of the reference wave will be located at C and the return wave from the primary mirror will be located a distance $2\Delta x$ from C due to a relative displacement of Δx (Figure 22). The path difference at some angle θ between the two spherical waves of equal radii α is therefore

$$\Delta = \frac{x_2^2 - x_1^2}{2\alpha \cos\theta} = \frac{y_2^2 - y_1^2}{2\alpha \cos\theta} = \frac{(2\Delta x + y_1)^2 - y_1^2}{2\alpha \cos\theta}$$

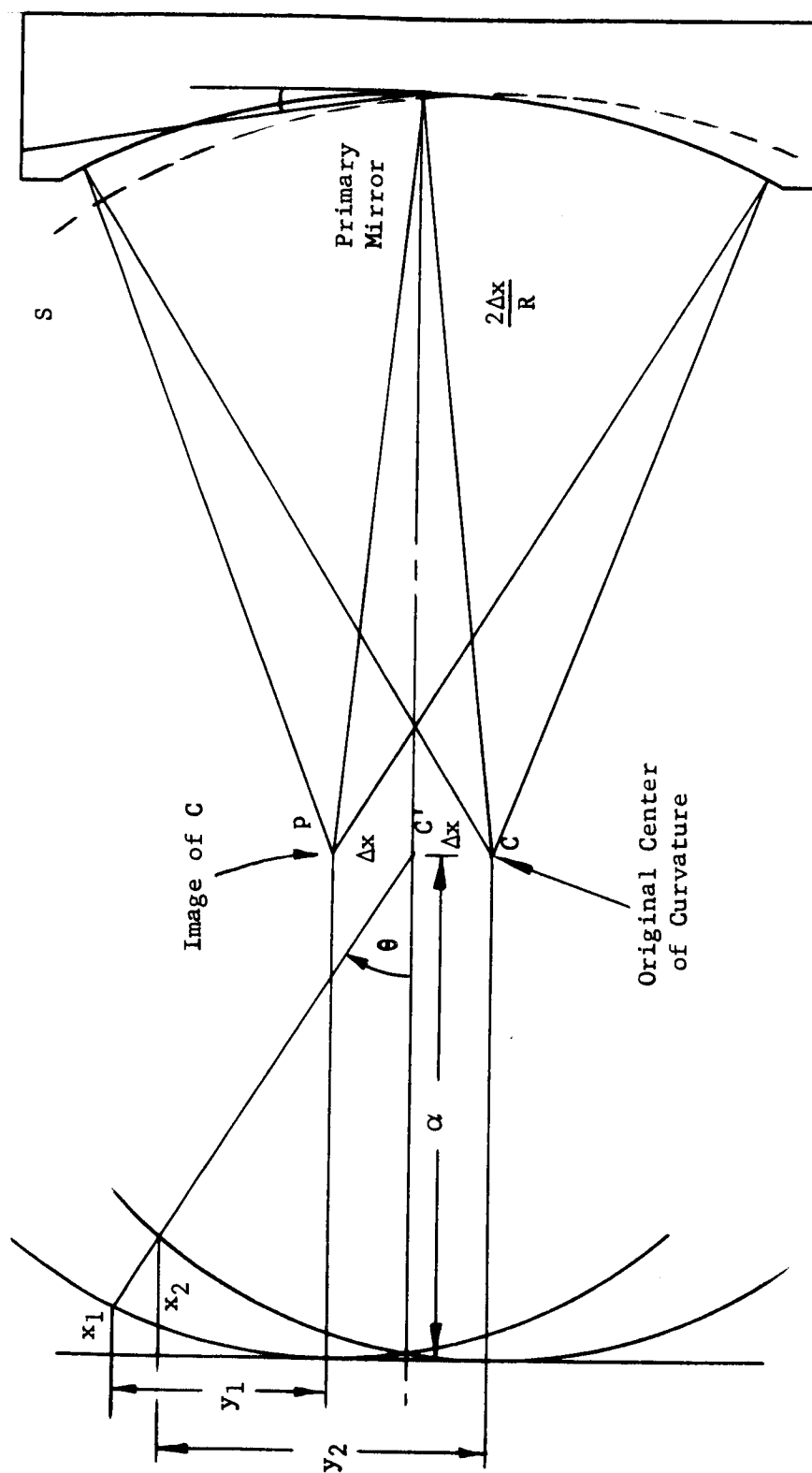


Figure 22.. Errors for Displacement Perpendicular to Optic Axis

Neglecting terms of order Δx^2

$$\Delta = \frac{\Delta x y_1}{\alpha \cos \theta}$$

Using the substitutions from the second equation:

$$\Delta = \frac{\Delta x}{4N} \left(1 + \frac{1}{4N^2} \right)^{1/2}$$

In terms of the primary mirror f/number, the path length difference becomes

$$\Delta = \frac{\Delta x}{8F} \left(1 + \frac{1}{16F^2} \right)^{1/2}$$

Therefore the tolerance for off-axis displacement in wavelength units is

$$\Delta x = \pm 8F \left(1 + \frac{1}{16F^2} \right)^{1/2} \lambda$$

These tolerances are also shown in Figure 20 (dotted curve) for various fringe measurement accuracies Γ . Although these curves give much stricter tolerances for off-axis displacement, this type of error can be corrected by tilting the whole mirror to bring it into alignment with the correct surface S (Figure 21). In other words, for a displacement Δx the outer edge of the mirror has to be moved a distance $\Delta x/4F$ to compensate for this error.

Figure Sensor-Analyzer Requirements

It is necessary to monitor a large number of points in the phase measurement interferometer fringe pattern (see Figure 18), either simultaneously, or in quick succession. Several different types of image scanning devices were evaluated during the course of the NASI-5198 contract. An image dissector camera was selected as most appropriate because it provided the desired resolution, spectral response, and frequency response. Because the fringe pattern is intensity modulated at a 60 Hz rate, it is not possible to use an integrating image scanner such as a vidicon camera.

The alignment sequences require both a scanning circle and sequential sampling of a number of fixed points. The scan pattern for the Active Optics project mirror is shown in Figure 23.

The qualitative requirement for the figure sensor and analyzer portion of the Active Optics scheme for OTES may be stated as follows: sense the departure of the surface of a segmented mirror from a perfect sphere; and generate error signals suitable for controlling alignment actuators to produce diffraction-limited optics for the 2-meter telescope. Quantitative numbers may be added to this requirement by defining a meaning for the term "diffraction-limited optics" to obtain the needed precision, and postulating possible sources of error to obtain the needed dynamic range and speed of operation.

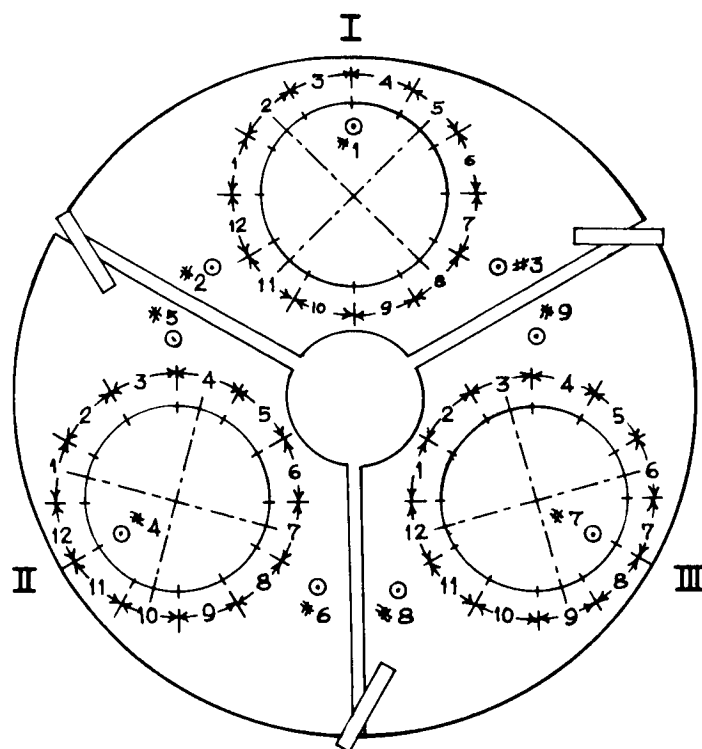


Figure 23. Image Dissector Circular Scan Pattern

The term "diffraction-limited" has been defined in a number of ways. Most definitions relate the quality of the image informed by the optics to the manner in which light rays from a single bundle arrive at the image plane. Rayleigh has been quoted as saying that if the wave front in the exit pupil departs from a best-fit reference sphere by a phase difference of less than $1/4$ wavelength, the resultant image will be acceptable. Marechal has shown that for the case of nearly perfect images, the intensity in the center of a diffraction maxima as a percentage of the intensity in a perfect image is given by,

$$I_{\max} = 1 - \frac{4\pi^2 \Delta^2}{\lambda^2}$$

Where Δ = the rms deviation of a wave front from a sphere centered on the image, that reference sphere is selected which makes the average deviation zero.*

In accordance with this relationship, a mirror with a $1/20$ wave rms figure error, where Δ then equals $1/10$ wave, will produce $I_{\max}$ equal to 60 percent of the theoretically perfect value. For a figure error of $1/50$ wave rms, Δ will be $1/25$ wavelength and $I_{\max}$ will be 94 percent of theoretical. A 10 percent to 15 percent loss of intensity at the peak of the spread function is normally not too critical. However, the misdirected energy is distributed to the side of the main peak, somewhat in the fashion shown in Figure 24, where the amount of spread is proportional to the frequency content of the figure error. In an astronomical telescope this hampers the ability to resolve two closely spaced objects with differing magnitudes.

Where a telescope is to be used to produce two-dimensional imagery, it is more meaningful to consider the effect of wave front distortion on the optical modulation transfer function. Recent studies at Perkin-Elmer have shown how this may be done. It has been shown that the ratio of the measured to computed one-dimensional modulation transfer functions for an optical system can be related to the autocorrelation function of a mirror figure error or wave front deformations as follows:

$$T(k_x) = T_L(k_x) \times M(k_x)$$

where,

$$M(k_x) = e^{-\left[\frac{4\pi^2}{\lambda^2} \left(C(o) - C(\lambda, R, k_x) \right) \right]}$$

The term $C(o)$ is the autocorrelation function of the design aperture, while $C(\lambda, R, k_x)$ is the autocorrelation function of the equivalent wave front deformation of the exit pupil. At very low spatial frequencies, $M(k_x) \rightarrow 1.0$. At high spatial frequencies or for a figure error consisting of only fine grain deformations,

* R.M. Scott, Applied Optics, July, 1962.

M. Born and E. Wolfe, Principles of Optics, Macmillan, NY, 1959, page 468

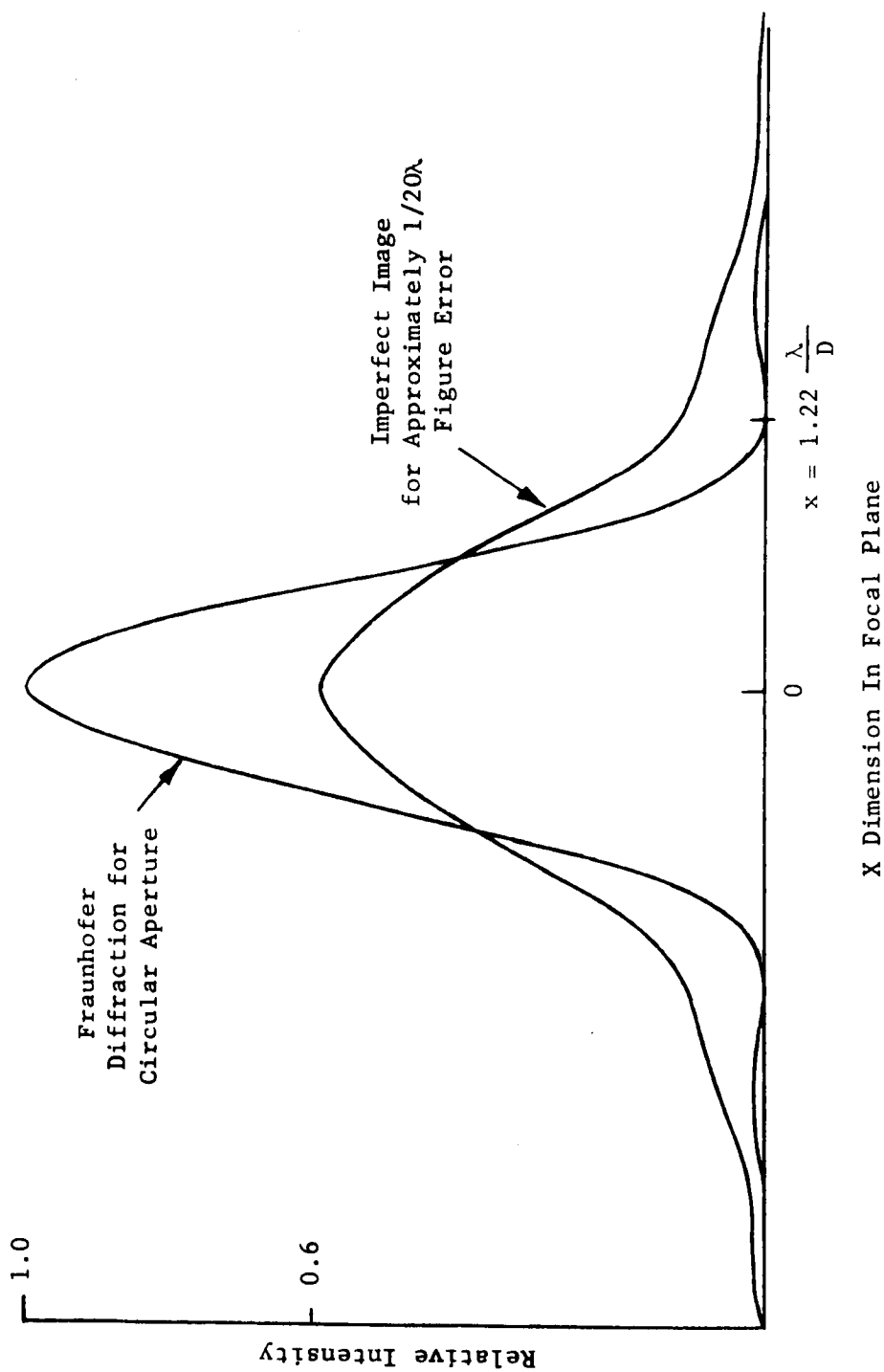


Figure 24. Effect of Figure Error Upon Diffraction-Limited Image

$$M(k_x) \rightarrow e^{-\frac{4\pi^2}{\lambda^2} \Delta^2}$$

where,

Δ = rms wave front deformation

Figure 25 shows how a 1/20 wave rms figure error affects the modulation transfer function of a 20-inch circular aperture.

It can be inferred from the foregoing that the term "diffraction-limited" is a qualitative one only, and that the permitted figure error for an optical system can only be established in terms of the particular circumstances. For this investigation it was decided that the mirror segments must be aligned to 1/20 of a wave rms. Hence, the figure sensor-analyzer must be capable of measuring with a precision better than this value, or approximately $1/50\lambda$.

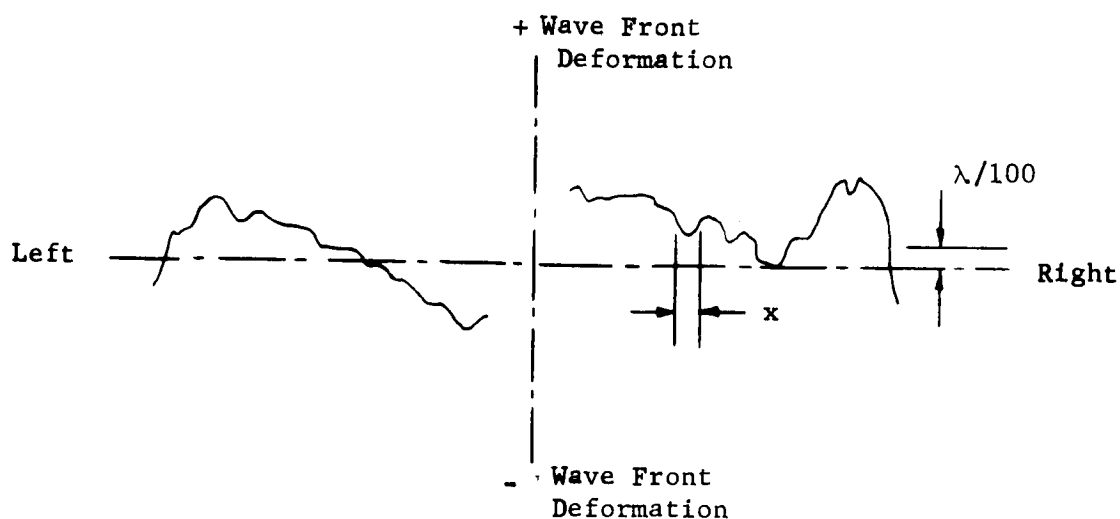
The requirements for dynamic range and speed of response are equally dependent upon the particular application. Dynamic range must be provided to accommodate structural instabilities, launch strains, thermal effects, and the inaccuracies of the segment location mechanism. However, it is clear that a minimum value of operating range will be set by the absence of gravity in orbital operation. A simple calculation of gravity-induced strains, for typical structures and materials which might be involved, shows that the sensor must operate over a range of 0.04 inch minimum to 0.125 inch maximum.

It is highly probable that the required speed of response will be determined by the diurnal thermal environment imposed upon a 2-meter OTES telescope housing structure due to solar illumination. For a relatively unsophisticated structure with a passive thermal system, and with the Active Optics sensor located at the center of curvature of the primary, it can be shown that the rates of displacement at the mirror edges will be on the order of 1 to 3 microinches per second.

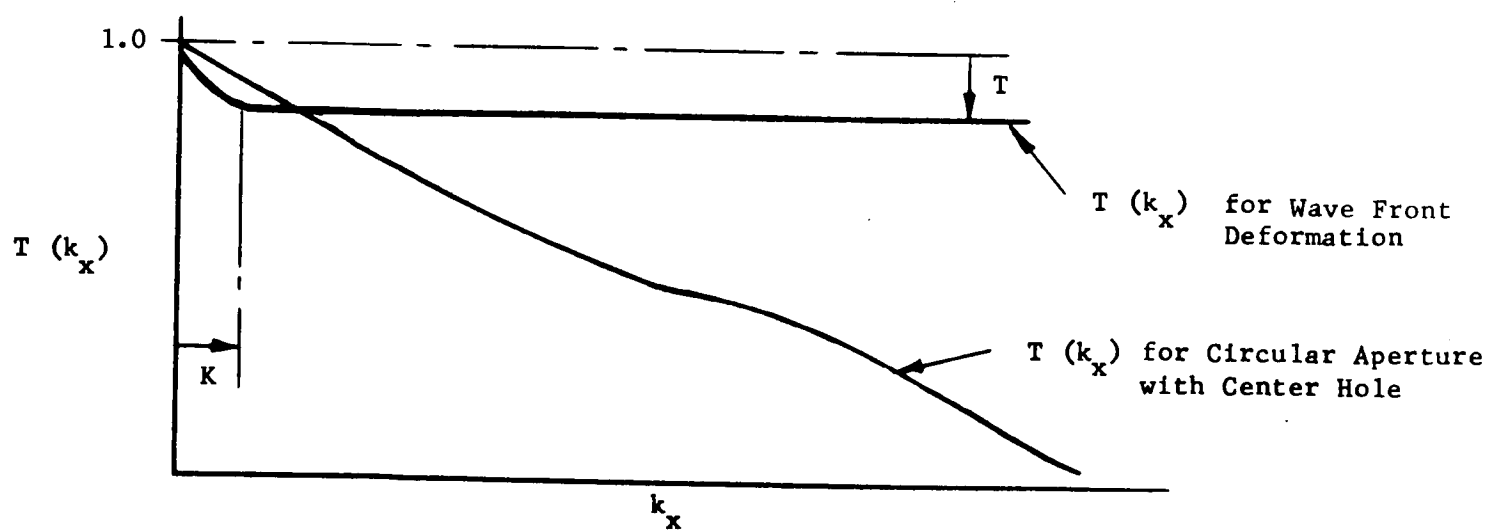
A comparison of the dynamic range requirement with the precision requirement indicates that the figure sensor must have a range of operation on the order of

$$\frac{0.125 \text{ inches}}{1/50\lambda} = 3 \times 10^5$$

resolution elements over a spherical plane consisting of at least 100 bins. The only known sensor which can produce this information capacity is the photographic plate. The complexity of film processing and mensuration are not compatible with the operational and simplicity requirements of the Active Optics concept. It was therefore decided to divide the figure sensing and adjustment into several steps which include tilt, coarse focus, segment relative position, and fine tilt. In view of the fact that there is no requirement for rapid operation, all steps are performed sequentially.



Typical Wave Front Deformation Across a Diagonal of the Aperture



$K \propto x$ or the period of figure error waveform

$T \propto \text{rms}^2$ or magnitude² of figure error waveform

Figure 25.. Modulation Transfer Functions

An interferometric figure-measuring scheme is used in Experiment No. 1 as the best method for sensing mirror misalignment because it can provide precision quantitative measurements with relatively simple automation. Image measurements such as the knife-edge test or Airy disk examination do not give numerical results which can be directly related to an alignment error for a particular portion of the mirror.

A large variety of interferometer arrangements are possible, where each is best suited to a particular measurement. A list of commonly used reflection-type interferometers, which were considered in the execution of NAS 1-5198, is given in Table 2. In place of discussing in detail **all of these types, those features** which must be available if the scheme is to be suitable for the selected mirror figure-sensing approach will be listed.

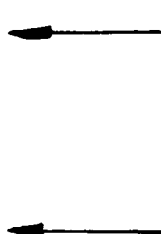
A dynamic phase-measurement technique has been selected by Perkin-Elmer to solve the problem of measuring fractional wavelength changes in the fringe pattern.* This technique consists of converting the static interferometer fringe pattern into a dynamic waveform and sampling the signal from only small areas at one time. Key to the operation of this technique is a continuously advancing phase shifter in one arm, hence, the use of this scheme requires separate arms in the interferometer. Thus, all of the common-arm interferometers listed in Table 2 are eliminated from further consideration, at least for fine-figure sensing.

A subsequent discussion describes why a single wavelength interferometer does not have adequate sensitivity for an unambiguous determination of the relative axial position of two mirror segments. As a solution to this problem, three approaches were considered: the use of two wavelengths; the use of white light or band-limited white light; or the use of two separate optical arrangements. The white-light schemes appeared most promising at first. This meant that the ambiguity interferometer should have common or equal arm lengths.

If an ultimate figure sensing accuracy of better than $1/50$ th of a wavelength is to be provided, it is best to examine the mirror at its exact center of curvature as compared to looking at points displaced slightly off axis or out of focus. For example, consider an $f/4$ mirror, with an 80-inch focal length. If the focus ability is examined at a point 5-mm off axis from the center of curvature, the aberration in terms of path difference between the ray to the mirror edge and return as compared to the ray to the mirror center and return is approximately $1/20$ th of a wavelength. It would be preferable not to have to compute a correction for this aberration. Of the interferometers listed in Table 2, only those which have a plane wave front at the point of interference can be adapted to the examination of a spherical mirror at its exact center of curvature. This eliminated from further consideration the spherical wave front interferometers such as the Burch scatterplate or Kösters prism with lens (sometimes referred to as the mutual-arm interferometer).

* Active Optical System for Space Stations, H.F. Wischnia, Perkin-Elmer Engineering Report No. 7648, 1964.

TABLE 2

INTERFEROMETER TYPES				
Interferometer Type	Categories			
	Beam Separation	Reference Arm	Wave Front at Point of Interference	Selected Interferometers
Michelson	Amplitude division	Separate	Spherical	
Twyman-Green	Amplitude division	Separate	Plane	
Rayleigh	Wave Front division	Separate and equal	Cylindrical	
Kosters	Amplitude division	Common	Plane	
Bates	Shearing	Common	Plane	
Ronchi	Diffraction	Common	Cylindrical	
Dyson	Polarization	Common	Plane	
Burch	Scattering	Common	Spherical	
Mach-Zehnder	Amplitude division	Separate and equal	Plane	
Savart	Shearing common	Common	Plane	
Twyman + lens	Amplitude division	Common	Spherical	
Koesters prism + lens	Amplitude division	Common	Spherical	

The best interferometer scheme would be one which would generate an interference pattern with the simplest possible relationship between pattern perturbations and mirror distortion. This means it would be desirable to have the patterns generated by interference between one beam from the mirror in question and the other beam from a known reference surface. Thus, beam separation by shearing is eliminated.

Because of these limitations, Perkin-Elmer developed the Twyman-Green and Koesters interferometers for Active Optics in NAS1-5198. These are the figure sensor techniques which seem most appropriate for Experiment No. 1 of the 2-meter OTES.

Figure Error Signatures

To develop the simplest possible overall system, it is necessary to consider the relationship between the sensor and analyzer functions. In particular, alignment errors to be corrected must be uniquely and automatically recognized by the analyzer.

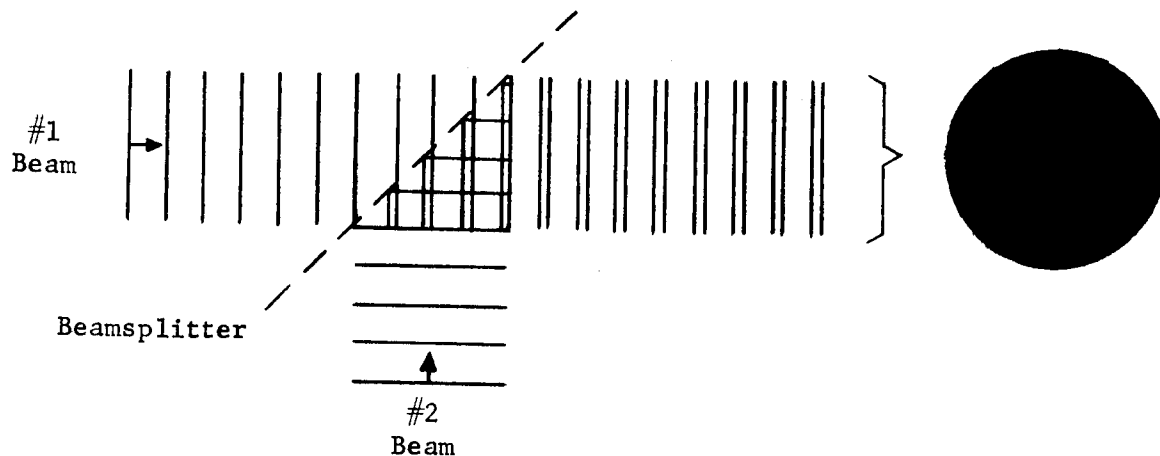
Figure measuring by analysis of interferometer fringe patterns has been developed to a fine art at Perkin-Elmer using a scatterplate interferometer and data-reduction by computer. However, for our application, intensity analysis has two serious limitations: first, spurious intensity modulations and fringe patterns superimposed upon the desired pattern limit the fringe position measuring accuracy to approximately 1/100 fringe for ideal conditions; second, an elaborate computer is required to extract the error data.

The error data sought is totally contained in the phase information. Furthermore, if the proper configuration is used, the phase information is unambiguous. Finally, if amplitude limiters are used in the signal processing, phase data can be made relatively independent of spurious amplitude modulation. These are compelling factors in the choice to use a direct phase-sensing technique. Unfortunately, where coherent light is used, the phase data becomes ambiguous every fringe or for every 1/2 wave of mirror departure from spherical.

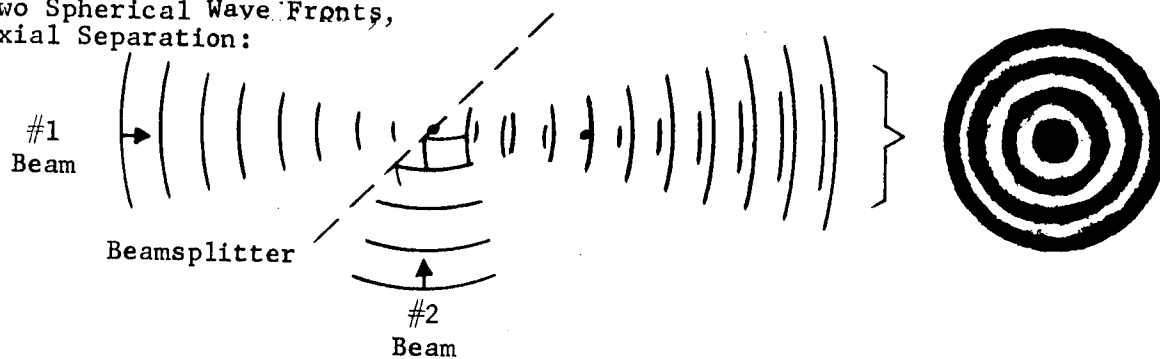
The question of preferred wave front shape at the point of interference needs further elaboration. In Figure 26, hypothetical fringe patterns are shown for three different wave front combinations. Where two plane waves are superimposed as in Figure 26, the fringe pattern will be equi-phase for the perfect alignment situation. Where spherical wave fronts are used, as in Figure 26 (b and c), either circles or lines will be produced depending upon whether the centers of curvature of the two wave fronts are displaced axially or laterally.

Table 3 shows how figure errors affect the fringe patterns for different wave fronts at the point of interference. In this context, segment axial position and focus errors are synonymous, as are boresight and tilt. It can be recognized that only the signatures in the first and last columns are simple to analyze. The best known interferometer capable of producing the wave fronts and exact mirror examination point of the last column is the scatterplate. This cannot be used because it does not permit use of the phase-measuring technique. Hence, we can conclude that two plane wave fronts are preferred at the point of interference.

a. Two Plane Wave Fronts:



b. Two Spherical Wave Fronts, Axial Separation:



c. Two Spherical Wave Fronts, Lateral Separation:

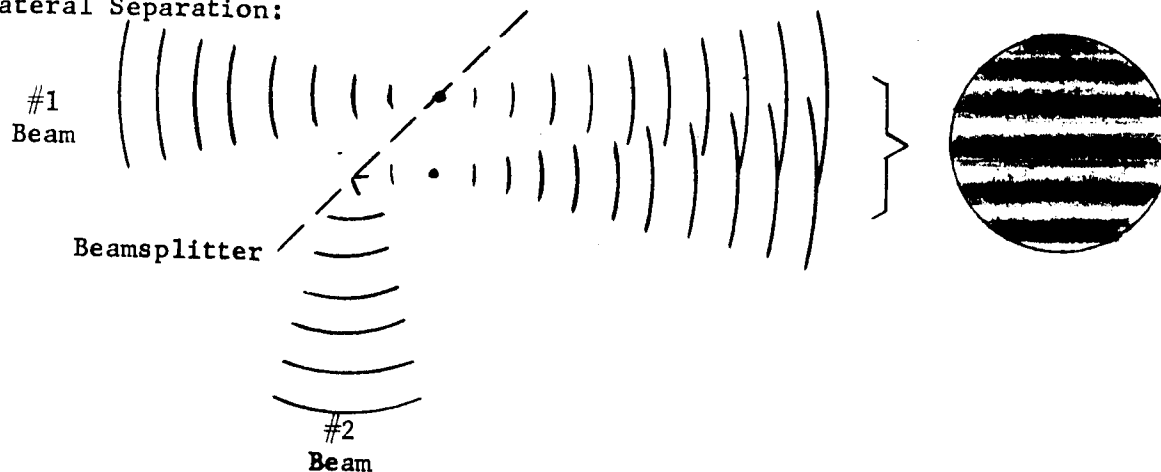


Figure 26.. Fringe Patterns for Different Wave Fronts at Point of Interference

TABLE 3

FIGURE-ERROR SIGNATURES IN FRINGE PATTERNS FOR
DIFFERENT WAVE FRONTS AT THE POINT OF INTERFERENCE

Wave Fronts at Point of Interference	Plane Plus Plane	Spherical Plus Spherical	Spherical Plus Spherical	Spherical Plus Spherical
Point of Mirror Examination	Center of Curvature	Displaced Axially From Center of Curvature	Displaced Laterally From Center of Curvature	Center of Curvature
Type of Error				
No Error Reference	Plane (equi-phase)	Circles	Lines	Plane (equi-phase)
Mirror Tilt	Lines	Ellipsoidal	Line Spacing	Lines
Boresight	Lines	Ellipsoidal	Line Spacing	Lines
Focus	Circles	Radii Change	Curved Lines	Circles
Segment Axial Position	Circles	Radii Change	Curved Lines	Circles

For plane wave fronts, the rate at which tilt errors affect the fringe pattern is straightforward. Focus signatures are a little more difficult to visualize. In Figure 27 the rudiments of the geometry are shown for one segment only. In this figure, point C is taken as the desired center of curvature, where C^1 is the actual center of curvature for a mirror with a displacement error of Δx . The departure of the actual displaced mirror from a true spherical surface centered at point C is noted as δ . D and F are mirror segments diameter and focal length respectively. (Note that as ordinarily defined, the focal length = 1/2 the radius of curvature.) It can be shown that for small values of θ and Δx

$$\delta = \frac{1}{2} \Delta x \cdot \theta^2$$

If

$$\theta = \frac{1}{4 f_{no}} , \quad \text{then} \quad \delta = \frac{1}{32} \frac{\Delta x}{f_{no}^2} .$$

For an interferometric measurement the two-way path difference, Δ , in units of wavelength is found from:

$$\Delta = 2 \frac{\delta}{\lambda} , \quad \text{then} \quad \Delta x = 16 f_{no}^2 \Delta \lambda .$$

When an interferometer is used to measure focus alignment with a fringe measuring accuracy of $\Delta = 0.01\lambda$, and a mirror segment $f_{no} = 10$, then the focus or axial alignment error will be:

$$\Delta x = \pm 16\lambda .$$

Comparison of Phase-Measuring and Scatterplate Interferometers

The LRC Contract at Perkin-Elmer (NAS1-5198) conducted an evaluation of the phase-measuring and scatterplate interferometers as potential sensors for the Active Optics system. A discussion of the operation of each interferometer is necessary as well as the reasons for the choice of the phase-measurement technique for this application.

Phase-Measurement Interferometers

Figure 28 shows the optical components used in the phase-measuring interferometer. This is a modification of a Twyman-Green interferometer to which the following has been added. Lens-1 converts the collimated beam of one arm to a divergent beam of spherical wave front with center of curvature located at a focal point of Lens-1, identified as point "C" in the figure. Ideally, the mirror being tested is located so that its center of curvature is also located at point "C". In this case, the divergent beam will be reflected back upon itself to converge again at focal point "C". The return beam is then re-collimated to have a plane wave front by Lens-1. The second arm or reference beam is reflected by a flat mirror. Thus, ideally, there are two plane wave fronts at the point of interference.

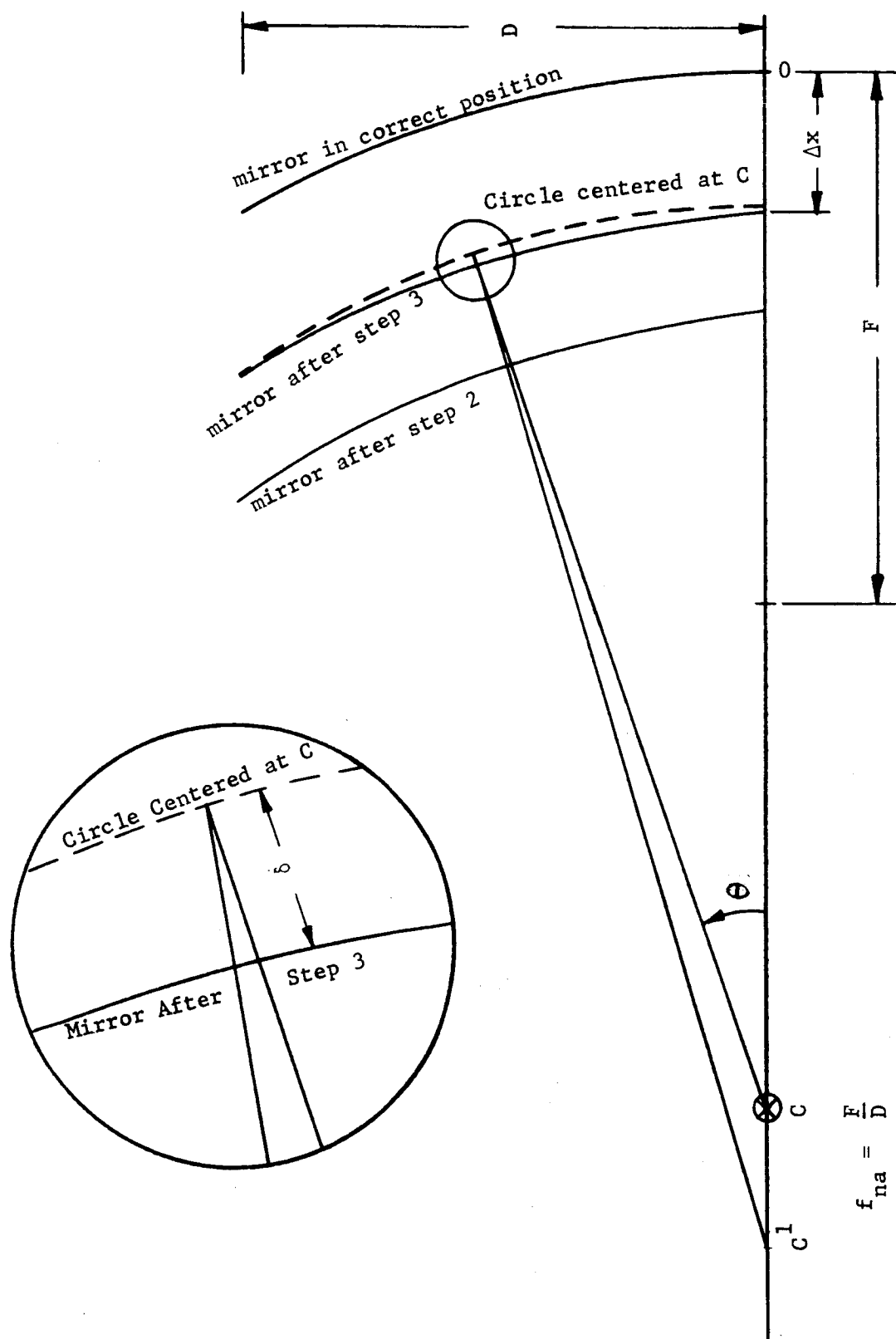


Figure 27.. Geometry of Focus Signature

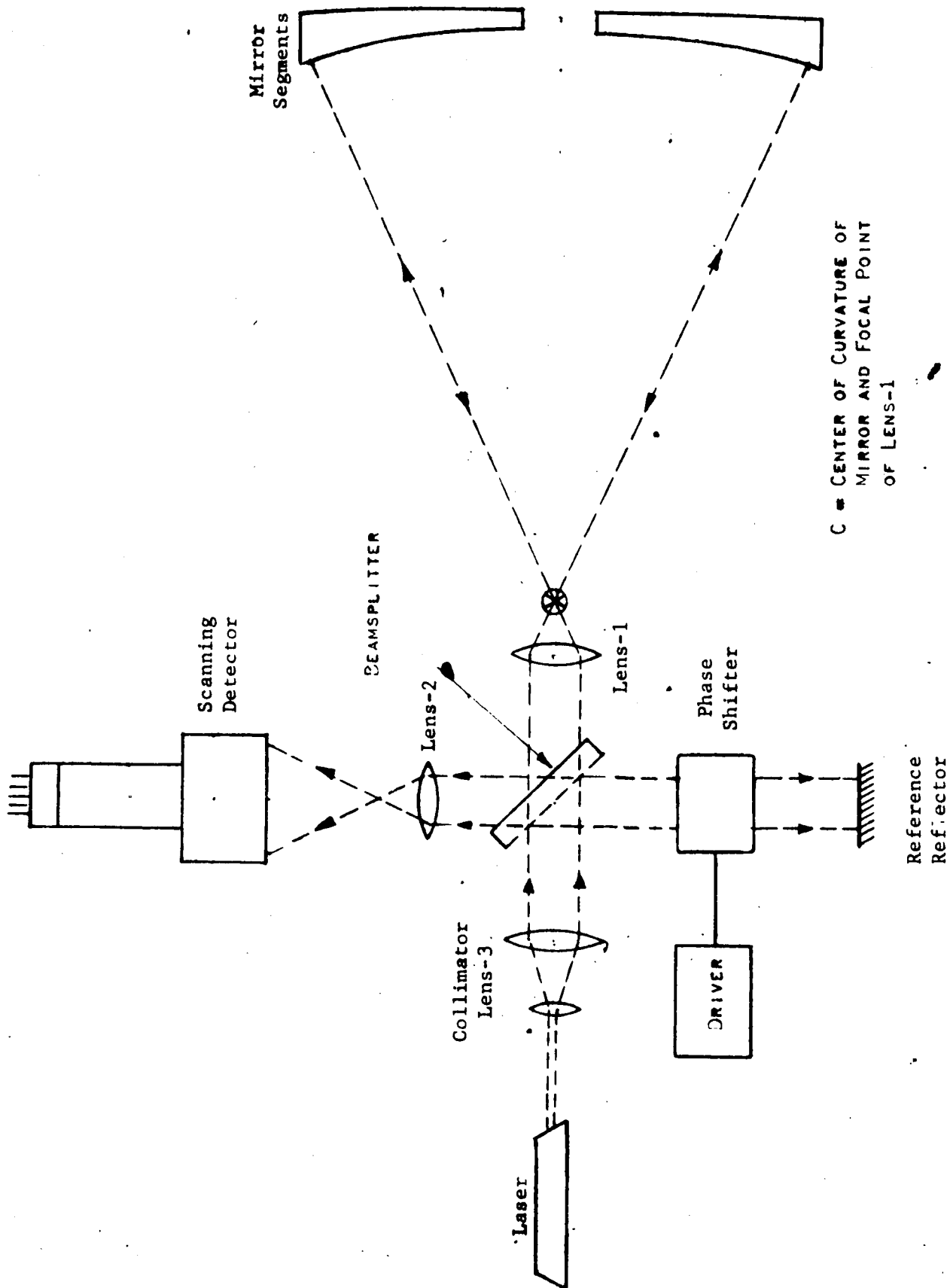


Figure 28. Phase-Measuring Interferometer

Lens 2 expands the interferometer output beam to a size which can be scanned by an image-dissector detector. Lens 2 also serves to focus the aperture of the mirror under test upon the scanner active surface.

In the reference arm, a dynamic phase shifter has been added which adds a steady-state rate of change of phase to the beam. Under ideal conditions, and with the phase shifter turned off, there is a fixed, uniform intensity across the interferometer output beam. When the phase shifter is turned on, the intensity varies uniformly across the beam in cycles from dark to light to dark, etc., as the phase shifter goes through successive cycles of 360 degrees. If one examines the waveform of the light intensity fluctuations under ideal conditions, it will be found to have a constant frequency and phase at all points within the beam.

If there is a deformation in the wave front reflected from a portion of the spherical mirror under test, it will cause a corresponding change in the phase of the interference pattern waveform as a function of time. This results in a change in phase of an electrical signal generated by the image scanner when it looks at the corresponding spot on its active surface. Thus, the phase-measuring interferometer, as its name implies, is sensitive to the phase of the wave front deformations which, in turn, are directly related to the mirror surface departure from a true spherical shape with center of curvature at point "C".

Scatterplate Interferometer

The Burch scatterplate interferometer has fewer optical parts but is more difficult to describe. The key element is the scatterplate itself, which is a glass plate with the front surface treated to produce pairs of random scatterers. Each pair of scatterers is located symmetrically about a center point. Figure 29 shows the optical arrangement as it is normally used.

When a large number of fringes are anticipated, a laser source is used. The first lens focuses the source at the center of the mirror surface to be tested. The beam passes through the scatterplate, which is located a distance "S" away from the center of curvature with its center of symmetry on the optical axis. At the scatterplate, a portion of the beam is scattered into a host of divergent bundles, one for each scatterer, and a portion passes straight through. These light paths are depicted in Figure 29 for one ray emanating from the source.

The mirror will return each bundle to a focus at a point diametrically opposite to the first scatter point relative to the center of curvature, point "C". For the sample bundle shown, this point is below and to the right of "C". The light of interest will then continue on in a divergent bundle and pass through the scatterplate undisturbed.

The portion of the original ray which passed straight through the scatterplate is returned by the mirror to the plate at a point diametrically opposite

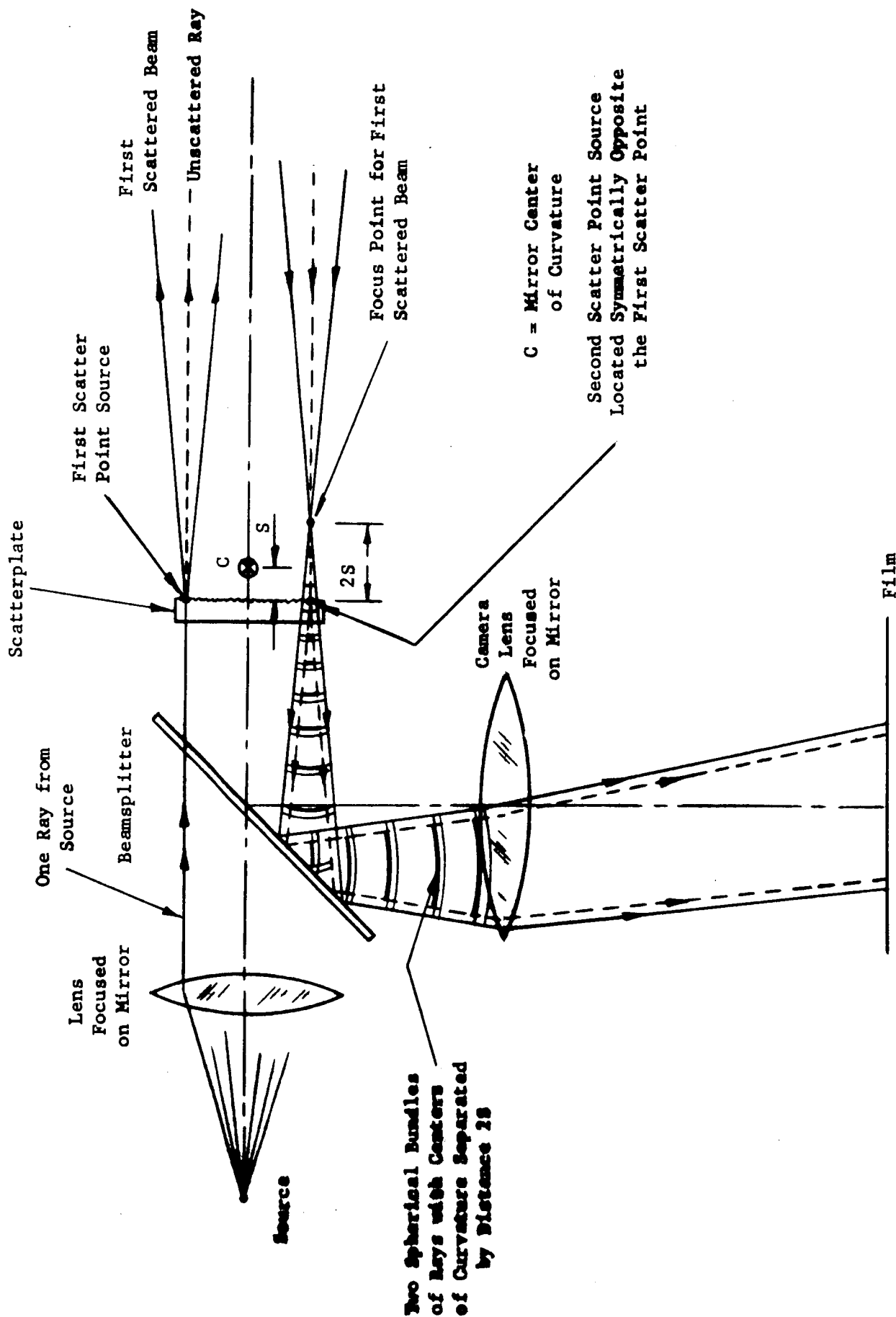


Figure 29. Scatterplate Interferometer
(With Scatterplate Displaced Axially
from Center of Curvature)

the original point of entry. If the scatterplate is true, there will be a scattering element at this spot which will produce a second divergent bundle.

Thus, two divergent bundles, or cones of light, will be produced from each original ray, with the centers of divergence separated by two times the distance "S" in the figure. The interference pattern produced by two spherical wave fronts with different radii (or displaced centers of curvature), consists of a series of concentric circles. The fringe patterns for all scatter-point pairs superimpose upon each other.

If the scatterplate center of symmetry is displaced laterally from "C" instead of axially, a series of lines is produced. For a spherical mirror, any figure error will produce a departure from spherical wave front in the light bundle which is scattered first. This will distort the symmetry of the circles or lines in the fringe pattern.

The advantages of these two types of interferometers are listed in Table 4. At the start of the Active Optics project it was clear that the possibility of using phase detection instead of intensity detection was a compelling argument in favor of the phase-measuring interferometer. It is also clear that the error analysis is considerably simplified by the use of plane wave fronts of the point of interference or spherical wave fronts with common centers of curvature. Thus, the phase-measuring interferometer was selected for one figure sensor in the Experiment No. 1 while the scatterplate interferometer is used to certify the results in Experiment No. 4

TABLE 4

COMPARISON OF PHASE-MEASURING AND
SCATTERPLATE INTERFEROMETERS

<u>Phase Measuring</u>	<u>Scatterplate</u>
a. Sensitivity determined by phase detection as compared to intensity detection.	a. No optical parts within interference paths except test mirror.
b. Plane wavefront at point of interference; therefore error signatures easily detected.	b. Fewer precision optical parts.
c. Reference point on mirror may be chosen at any point.	c. Fringe pattern is an integration of many individual patterns.
d. Mirror is examined at exact center of curvature.	d. Good optical efficiency, i.e., good fringe contrast.

Ambiguity Sensors

The fine figure sensor employs coherent light as the illuminating source with the result that it is impossible to recognize relative displacements of integral $1/2$ wavelength. The ambiguity sensor resolves this uncertainty, and generates a control signal for positioning the segments within ± 5 micro-inches of each other. The approach selected employs an equal-path interferometer located immediately above the gap between the two segments so that one beam is reflected from the surface of each segment. A white-light source is used so that good interference occurs only when the two paths are equal, that is, when both segments are the same distance away from the interferometer.

In principle, this is the inverse of the Michaelson interferometer spectrometer, in which the interferogram generated by varying the relative path length in a two-beam interferometer is analyzed to determine the spectral content, of the excitation energy. In this application, a wide-band excitation source and detector are used so that the zero order interference lobe is readily recognizable from any other order. Thus, it is possible to sense when the two segments are coplanar within a fraction of a wavelength. The implementation of the white-light interferometer is shown in Figure 30. A Koesters prism performs the function of beamsplitting and recombination. Wide spectral response is obtained by using a tungsten arc source and lead sulphide detector. A simple vibrating fork chopper modulates the light so that AC detection may be used in the electronics. A typical interferogram generated by translating one segment relative to another is shown in the bottom trace of Figure 31. The peak, or zero path difference point, is easily distinguished from the other orders of interference. The top line of Figure 31 is a calibration of relative displacement between the two segments as indicated by the phase-measuring interferometer. It can be seen that the white-light interference peak occurs at the cross-over point, or point of zero phase difference as indicated by the phase-measuring interferometer, and that the width of the peak is within the unambiguous range of the figure sensor. Figure 16 is a photograph showing the Active Optics white-light interferometer components mounted above the intersection of two segments in an actual setup. Thus, for resolving ambiguities in the 2-meter OTES, seven white-light interferometers are placed at the interfaces between the segmented mirrors as shown in Figure 14. The ambiguity of $n\lambda$ between the segments is solved by searching for the singular maximum of the white-light interferometer as described above. These interferometers consist of a Koesters prism, chopper, detector, and broadband light source as shown in Figure 30.

Two-Wavelength Interferometer (Alternate to Koester Interferometer)

It has been shown above that with a single wavelength interferometer, the most optimum axial location of a mirror segment, i.e., focus adjustment, is on the order of 16λ , or a two-way path difference of 32 wavelengths. If a second wavelength λ_2 is used in the interferometer, where λ_1 and λ_2 are very close together, it will be found that axial position ambiguity occurs at a wavelength displacement which is approximately the reciprocal of the percentage difference between the wavelengths; i.e., if the wavelengths differ by

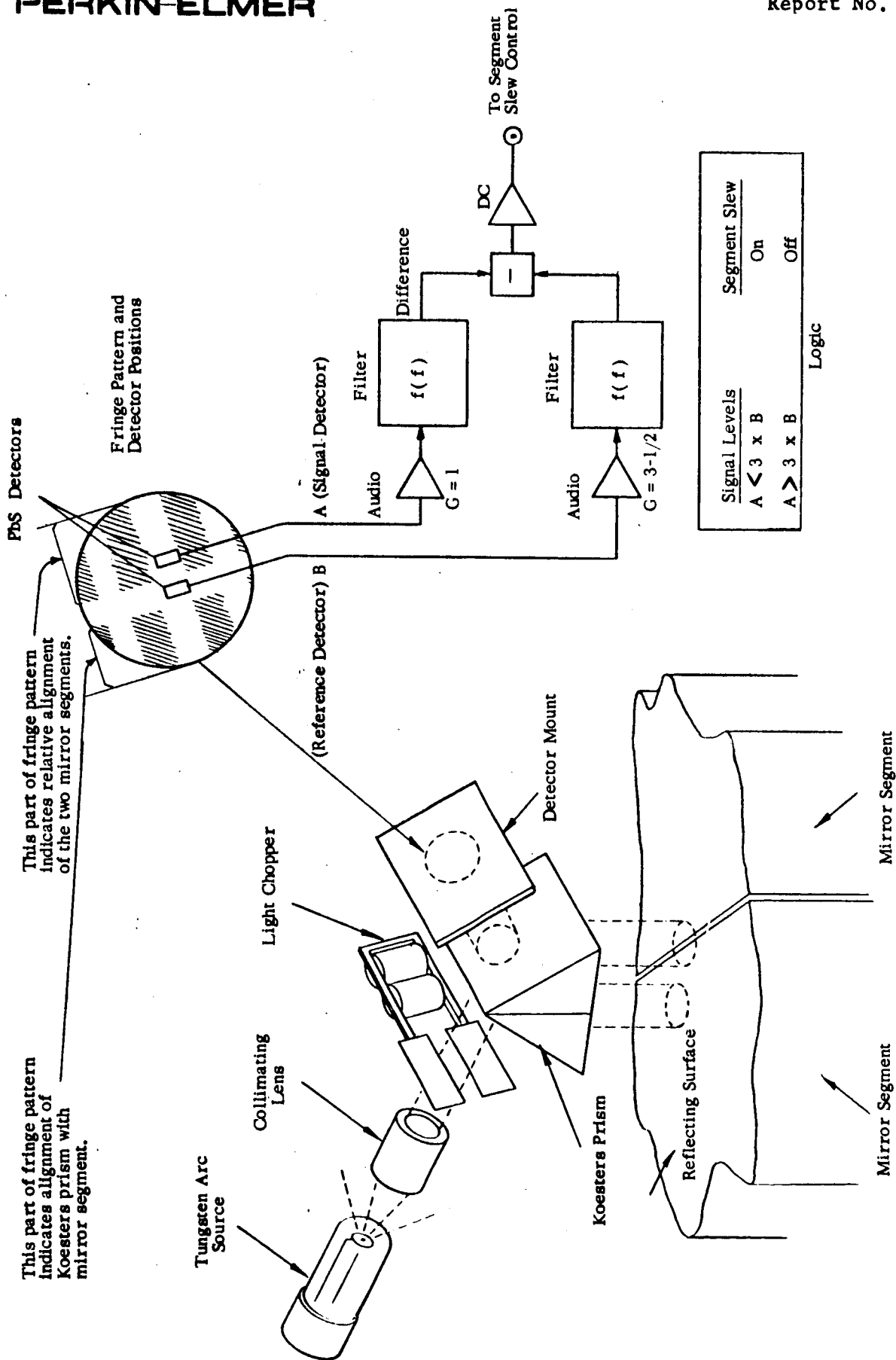
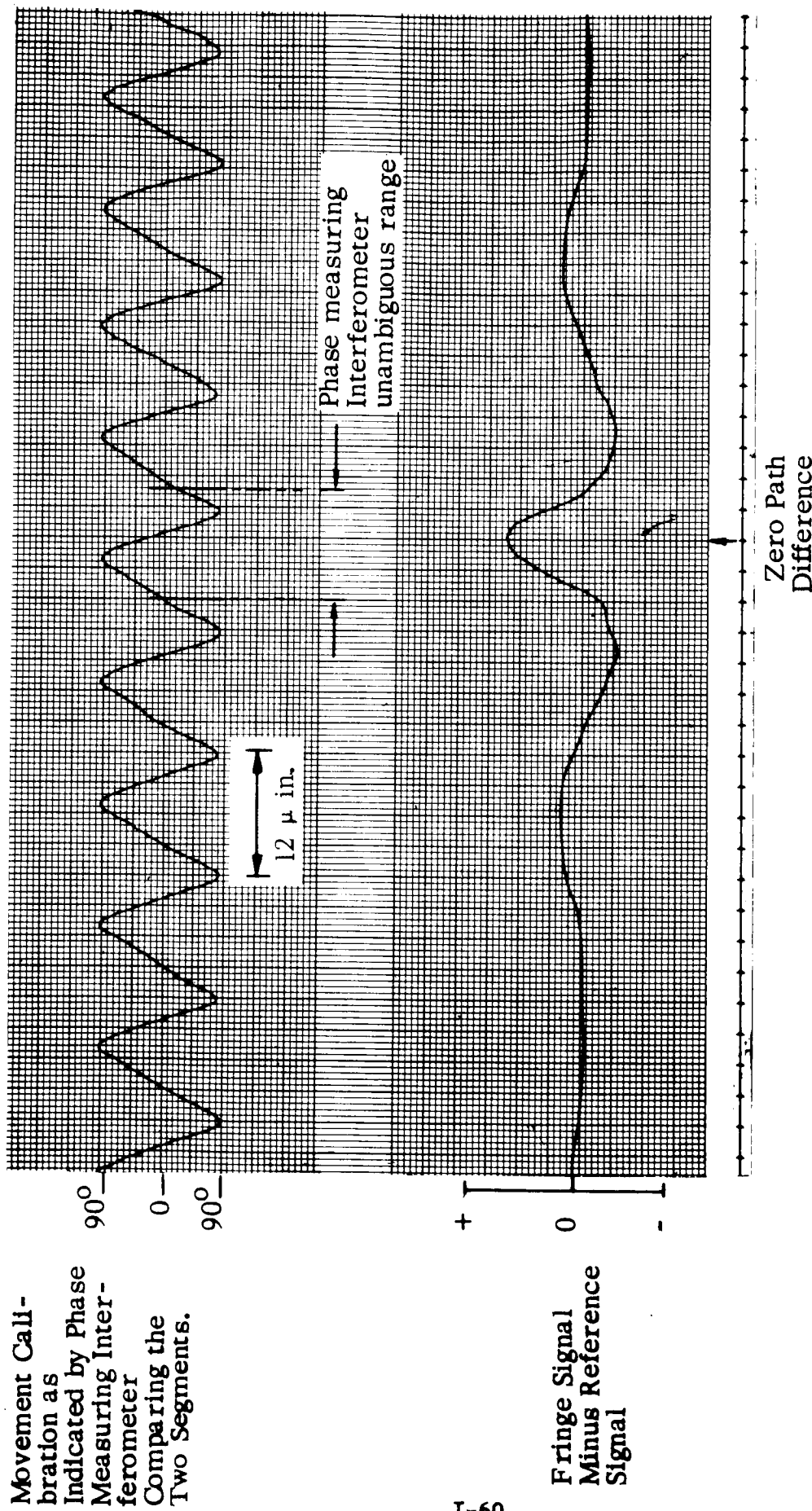


Figure 30. White Light Interferometer Arrangement



Showing difference between fringe signal and reference signal as Segment II is moved axially relative to Segment I.

Figure 31. White Light Interferometer Interferogram

5%, ambiguities occur every 20 wavelengths. For this case, where there is an uncertainty of ± 32 wavelengths, a two-wavelength position sensor requires the use of two laser sources with wavelengths differing by less than 3%. There are gas laser excitation levels which generate such closely spaced wavelengths. However, these do not represent principal modes and require long gas tubes for the lasers. For example, helium-neon will generate an output at 6352Å and 6401Å or an argon gas laser will generate energy at 4956Å or 5017Å. Both of these lasers require gas tubes and cavity lengths in excess of 36 inches. This is impractical for the space experiments of OTES.

It should be recognized that the phase-measuring technique allows the adjustment of individual segments to positions in which the two-way path length is an exact number of integral wavelengths, within a tolerance better than 1/100 wavelength. This means that the only ambiguities of concern are those that occur at these positions. If two wavelengths are arbitrarily chosen, it will be found that many ambiguities occur over the 32 wavelength position uncertainty. However, these do not occur at the zero phase shift position. This can be seen by referring to Figure 32 which is a graph of light intensity at the interferometer output for a small area on one mirror segment as a function of segment position in the axial direction. Three curves are shown; a reference waveform generated with λ_1 , a second waveform generated with λ_2 where $\lambda_2 - \lambda_1$ is small, and a third waveform generated where λ_2 and λ_1 differ by more than 10%. Positions of ambiguity along the X dimension are defined as those positions where the phase of λ_1 and λ_2 waveforms are equal. As can be seen, this may occur quite often. However, if observations are restricted to only those values of X for which the waveforms are at the axis or zero phase, the separation between ambiguity points is large. This would, for example, eliminate the ambiguity at S.

The requirement for the relationship between λ_1 and λ_2 as a function of ΔX for no ambiguity at the axis or zero phase positions will now be derived. In Figure 27, let

$$A = \sin(2\pi u_1 x)$$

$$B = \sin(2\pi u_2 x)$$

Ambiguities occur when

$$u_2 x = u_1 x \pm (\eta \pm \delta)$$

where:

$$u = \text{the wave number} = 1/\lambda$$

$$\eta = \text{any whole number}$$

$$\delta = \text{our phase-measurement accuracy}$$

then:

$$x = \pm \frac{\eta \pm \delta}{u_2 - u_1}$$

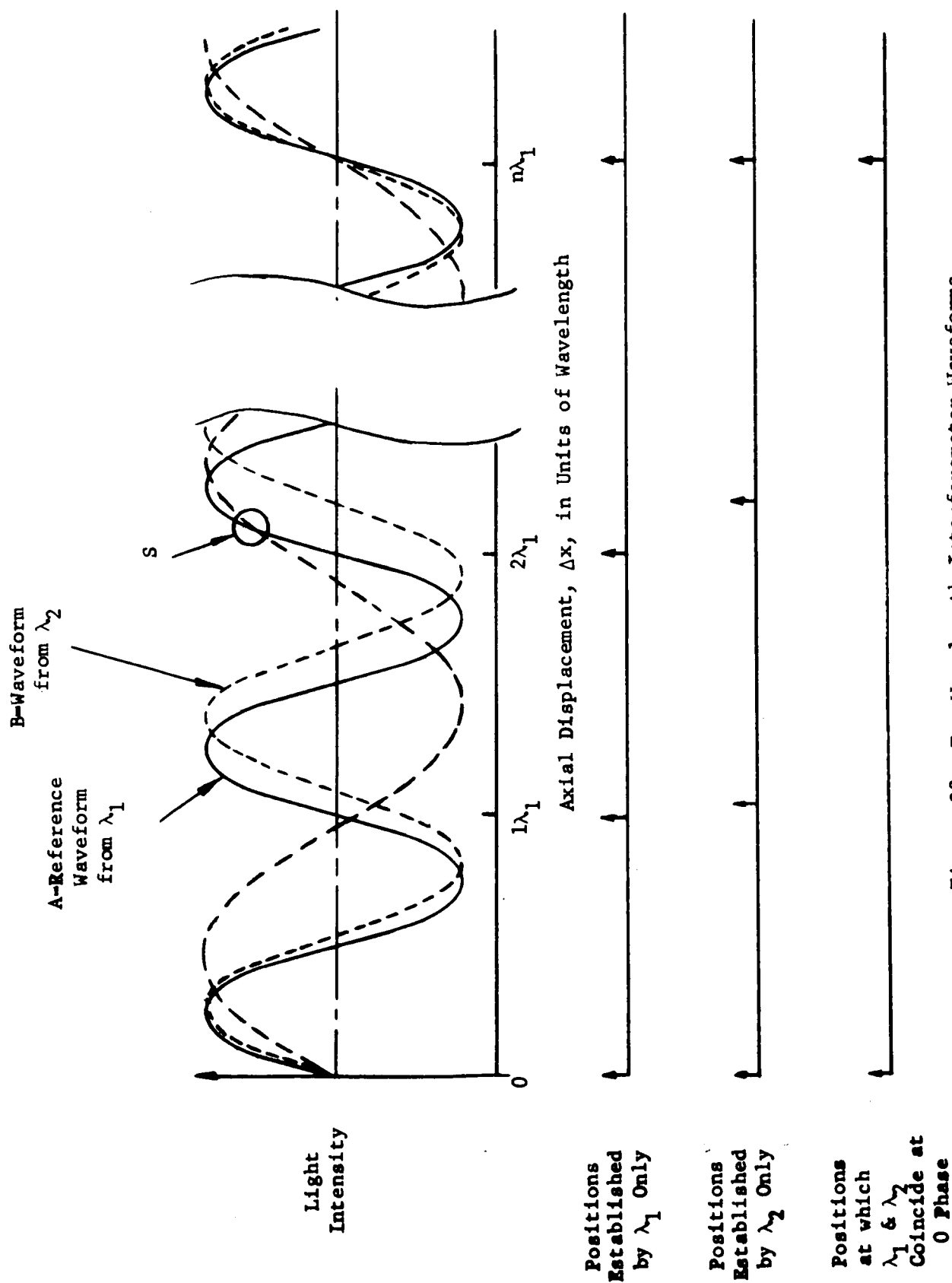


Figure 32.. Two-Wavelength Interferometer Waveforms

This expression is shown in Figure 33. Consider the positions along X at axis crossing of the A waveform only, or where

$$\frac{k-\delta}{v_1} < X < \frac{k+\delta}{v_1}$$

where

$$k \text{ is a whole number (in our case } k \approx \frac{\Delta X}{\lambda})$$

Then for positive values of X only

$$\frac{k-\delta}{v_1} < \frac{\eta \pm \delta}{v_2 - v_1}$$

$$\frac{k+\delta}{v_1} > \frac{\eta \pm \delta}{v_2 - v_1}$$

Solving for v_2/v_1

$$1 + \frac{\eta \pm \delta}{k + \delta} < \frac{v_2}{v_1} < 1 + \frac{\eta \pm \delta}{k - \delta}$$

This expression defines the values of v_2/v_1 for which ambiguities occur at zero phase. From this the forbidden values of v_2/v_1 can be seen to fall within the values found from

$$\frac{v_2}{v_1} = 1 + \frac{\eta \pm \delta}{k + \delta}$$

where

η = can be any whole number

δ = is the phase-measurement accuracy in fraction of a wavelength

k = is every whole number from one to $k_{\max}$ (in our case $= \frac{\Delta X}{\lambda}$).

Values for v_2/v_1 are tabulated in Table 5 for $k_{\max} = 30$, $\delta = 1/100$. It can be seen that the permitted values of v_2/v_1 are very restricted. None of the commonly available laser wavelengths will satisfy any of these ratios except for the 1.023 band discussed in the previous pages.

Although it was found that δ could be less than 1/100, this approach still did not look as promising as the one to be described subsequently.

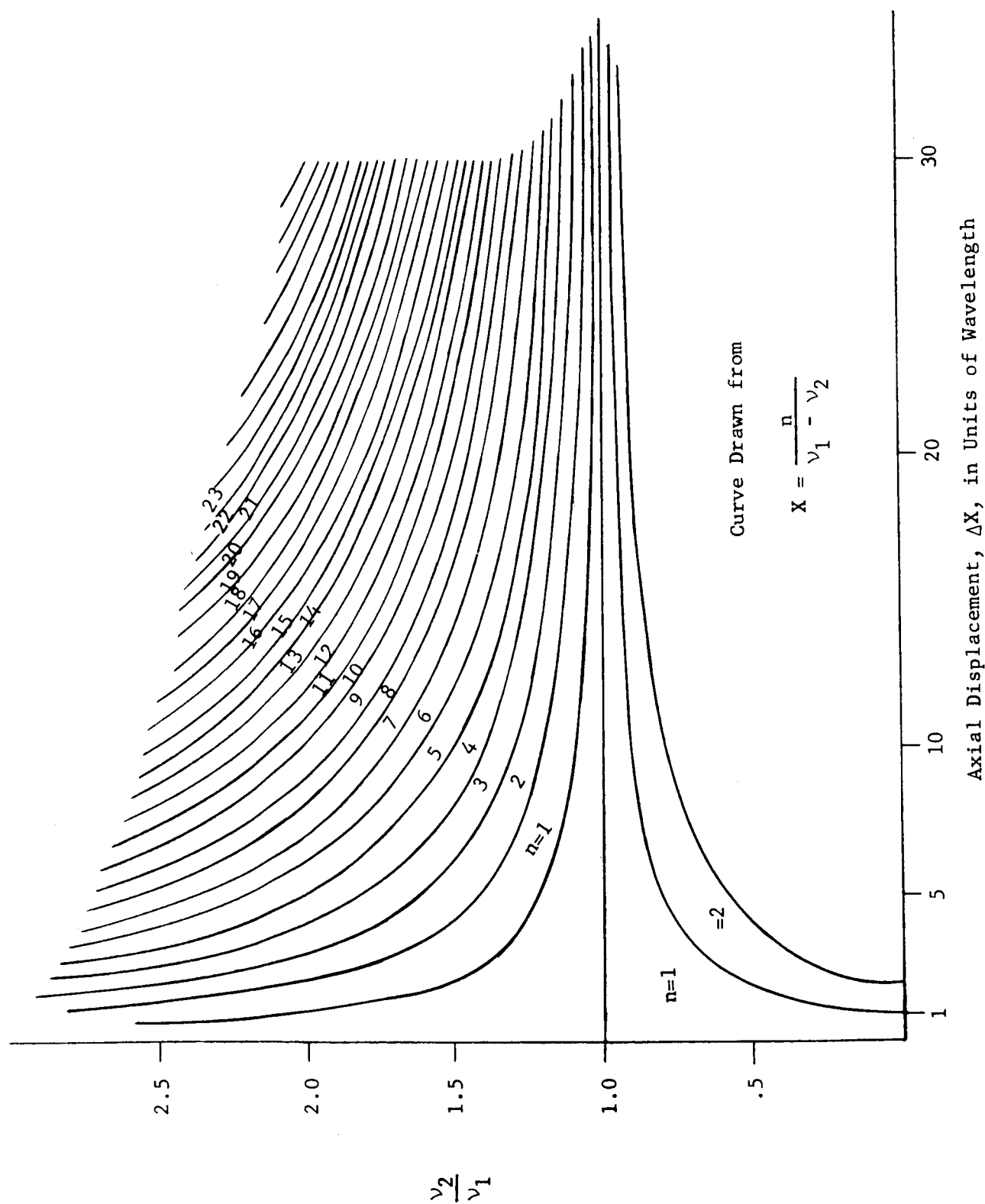


Figure 33... Ambiguities vs. Axial Displacement and Wavelength Ratios

TABLE 5

TABLE OF PERMITTED VALUES OF ν_2/ν_1
FOR NON-AMBIGUOUS POSITION SENSING
WITH TWO WAVELENGTHS

<u>ν_2/ν_1</u>	<u>Percent Band</u>
1.974	1.3
1.743	.3
1.657	.5
1.511	.9
1.487	.9
1.326	.7
1.245	.5
1.195	.4
1.162	.5
1.023	2.3

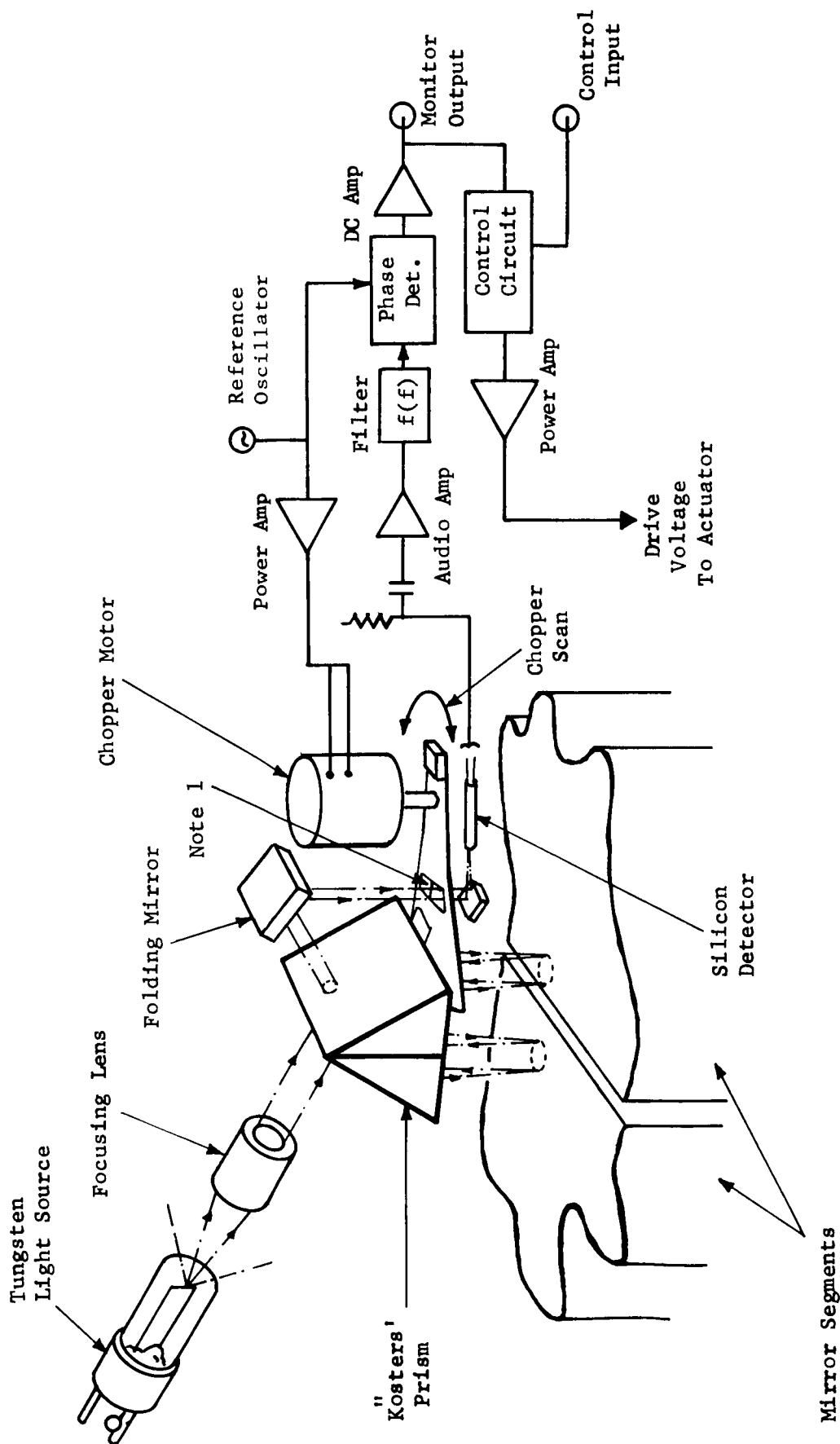
White-Light Interferometer

Earlier in this report, it was shown that the phase-measuring interferometer is not capable of sensing a focus misalignment to any better than $\pm 16\lambda$. It is also not able to recognize integral-wavelength axial displacements of two mirrors separated by a finite distance. It is, therefore, necessary to derive a second device to resolve these ambiguities. The requirements are as follows:

- Measure relative position of two mirror segments placed adjacent to one another.
- Accuracy better than the non-ambiguous range of the figure sensor which is approximately ± 6 microinches.
- Dynamic range should be on the order of ± 0.1 inches.
- It is preferable that the device be located at the mirror edges as contrasted to the center of curvature; therefore, the scheme must be relatively simple, because six units are mandatory for the 2-meter OTES.

Seven interferometers are shown in order to provide one redundant interferometer for additional reliability in the flight experiment.

The approach selected consists of a white-light equal-arm interferometer located at the juncture of two mirror segments. This is depicted in Figure 34. The light source and detector have been selected to provide a wide spectral response. This results in an interference pattern or interferogram



Note 1: This portion of the chopper blade is a neutral density attenuator of 3-1/2X.

Figure 34. White-Light Interferometer and Position Sensor

which consists of only one bright line flanked by two dark fringes centered about the point of zero path difference. This zero-order interference fringe is then readily recognizable electronically. The operation is such that, as one mirror is moved relative to the other and normal to its surface, the light intensity will vary as shown in Figure 35. The interference pattern will appear only in the vicinity of zero path difference. The peak will be exactly at the point of zero path difference. If this light is then detected and passed through a threshold which rejects all of the fringes due to higher-order interference, the zero-order lobe can be recognized. This interferometer signature is then used to stop the motion of the mirror.

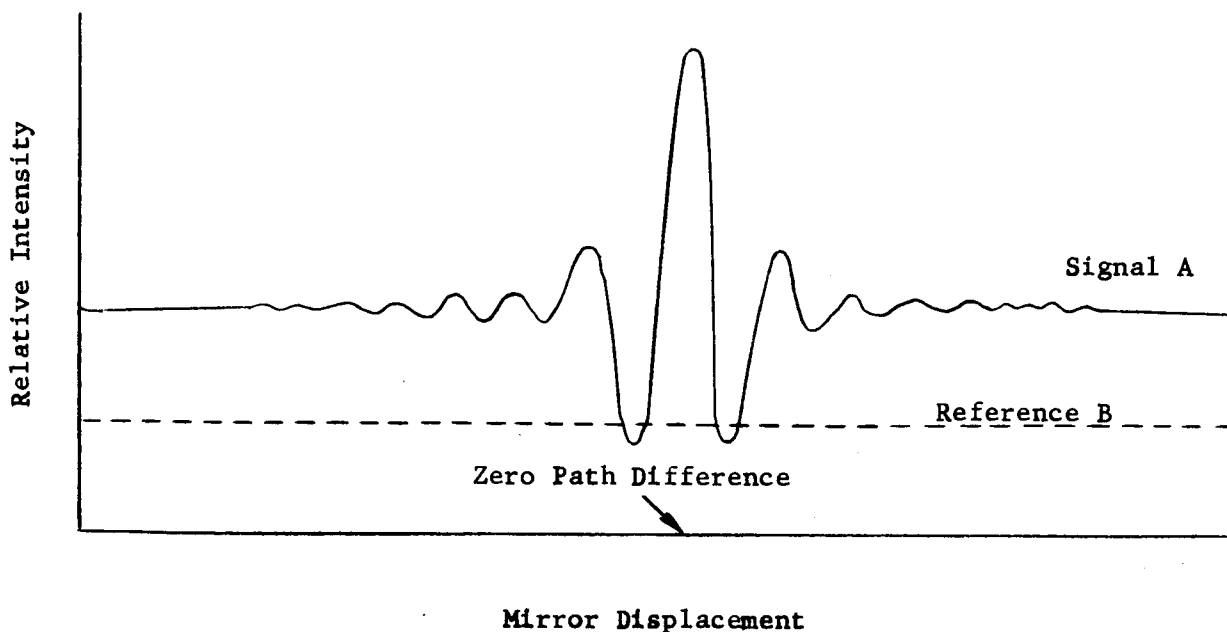


Figure 35. Hypothetical Interferogram with White-Light Interferometer

Refinements of the basic scheme include the use of a chopper to convert the signal to an AC wave. A neutralizing filter may be used to further broaden the effective spectral band. Dual channels may be used, one for a reference and the other for the interferogram signal. This permits the use of a difference detector as contrasted to an absolute magnitude detector. This is done by blanking one portion of one of the beams in the interferometer. Furthermore, difference detection may be replaced by ratio detection, that is, the mirror motion is stopped whenever signal A of Figure 35 is greater than three times the reference signal, or B. This makes the operation independent of the light level. The refinement can be carried one step further and place the 3-to-1 factor in the optical path. Thus, only one channel of detection and amplification is needed and the device is insensitive to source, detector, and amplifier drift.

During the course of contract NAS1-5198, an investigation of sources, detectors, and filters was performed to obtain an interferogram whose central lobe could be easily detected. The required interferogram should have side lobes that are small relative to the center lobe and a center narrow enough to resolve the ambiguities.

The source-detector spectral response curve is related to the interferogram by the Fourier transform. The interferogram shape can be controlled by choice of source, detector, and a spectral filter. For a simple response curve such as a square or triangular wave, the width of the central lobe is proportional to the mean frequency of the response, and the relative height of the side lobe is inversely proportional to the bandwidth. A response curve, with linear portions breaking at precise points, can be found which will give very low side lobes, but this type of curve is very difficult to achieve with a filter.

The general approach was to search for sources and detectors, measure their product curves, and calculate and measure the resulting interferograms. When the center lobes of the interferogram were narrow enough, filtering was considered to optimize the interferogram.

The most promising sources considered were tungsten, zirconium, and xenon. The tungsten concentrated-arc lamp by Sylvania was 2 watts and operated at a temperature of about 2800°K. The zirconium concentrated-arc lamp by Sylvania was also 2 watts and operated at 3200°K. The spectral response of these sources is a blackbody radiation curve in the visible with some lines in the infrared. Both of these lamps are small, about 1/2 inch by 1-1/2 inches. The intensity of the tungsten is much more stable than of the zirconium. The xenon short-arc lamp has a very wide band, 0.4 to 1.1 microns, but is large in size and is not commercially available in low power, less than 5-watt sizes.

The detectors used were lead sulphide, silicon, and S-5 and S-20 photomultipliers. The PbS photoconductor tested was an Eastman Kodak chemically deposited cell. Of the three detectors considered, this had a relatively wide bandwidth and low sensitivity. The silicon detector used was a N-P-N Diffused Silicon Photo-Duo-Diode type 1N2175 by Texas Instruments. This has medium bandwidth and medium sensitivity. The S-20 was a Dumont KM2485 photomultiplier with a narrow bandwidth and high sensitivity.

During the Active Optics project, the product curves were measured with a Perkin-Elmer Model 450 Spectrophotometer Monochromator with the tungsten arc source. The data was corrected for mirror spectral response and prism dispersion. The resolution at various slit widths was measured with a laser. The entering light was chopped and the detector output was measured with an AC voltmeter. The tungsten-PbS response includes the response of the glass which cuts off at large wavelengths.

The interferograms were calculated by a computer program set up to take Fourier transforms. The input data were amplitude points of the response curve in reciprocal-wavelength space and the output was amplitude points in path-difference space. The results were plotted as mirror separation which is one-half the path difference.

Several interferograms were actually measured in a Koesters Prism Interferometer. One mirror was moved by hand-turning a differential screw translator and the output was recorded on paper tape moving at constant speed so there was no horizontal scale on the measured interferograms.

The Active Optics project studies indicate that the best source is the tungsten concentrated-arc lamp because of its better stability. Also, it is slightly cooler than the zirconium. The xenon is too large and requires too much power. The size and reliability of a solid-state detector is best. The PbS was eliminated because of its low sensitivity and the wide center lobe of the PbS-tungsten interferogram.

Based on a measured response curve, filtering does not significantly improve the tungsten-silicon interferogram. However, the measured curve does not coincide with the calculated product curve based on a typical detector curve. Calculations based on a more typical detector than the one used may indicate a filter would be worthwhile.

The measured interferogram of unfiltered tungsten-silicon gives a sufficiently low side lobe with a sufficiently narrow center lobe. The unfiltered tungsten-silicon combination has been used successfully in a closed-loop operation.

Image Scanner

It was decided on the Active Optics project to use a form of electronic image scanner to permit the evaluation of the mirror surface. Electronic scanning has been selected because it offers the advantages of rapid response and hardware simplicity. It is also believed that the electronic scanning tubes will offer a better reliability factor as compared to their mechanical counterpart. Either the interferometer light source or the output interferogram could be scanned. For reasons of simplicity an arrangement again was selected in which a fixed source floodlights the complete mirror and an electronically scanned aperture analyses the fringe pattern.

The three most commonly used electronic image scanners are: the image orthicon, the vidicon, and the image dissector. In the near future there will also be available a fourth tube, the secondary-emission-conduction vidicon. The image orthicon was ruled out for two reasons: it is difficult to operate automatically from a remote point and its principal advantage compared to the other tubes, i.e., high sensitivity, is not required for this application. The SEC vidicon was not considered because it is still in the developmental stage and its reliability factors would be hard to predict at this time. The vidicon and image-dissector cameras were compared briefly as they might be applied to the dual problems of monitoring the two-dimensional interferogram and of generating error signals in the phase-measuring interferometer.

Table 6 contains a summary of the results. Numerical results are based upon published data for the RCA 8521, 1-1/2-inch vidicon and the ITT F-4011, 1-1/2-inch image-dissector tubes. The desired resolution of 300 TV lines for a 50-percent response is based upon the need to examine interference patterns

with a large number of fringes and the need to make phase measurements from an interference pattern for localized areas. Figure 36 shows the modulation transfer curves, and it appears that both tubes have adequate resolution. Unfortunately, neither tube has adequate resolution for the examination of the Airy disc for a completely aligned mirror without the addition of considerable magnification.

A good dynamic range is required if accurate phase measurements are to be made. Figure 37 shows the signal and noise levels to be anticipated for both tubes. If a one-milliwatt laser source is used, the vidicon offers the best dynamic range, and can be operated at standard TV scan rates. The image dissector has an inherently larger dynamic range, but suffers from lack of light level because it does not integrate the illumination as the vidicon does. If the dissector is operated at slower scan rates, it still suffers from the lack of illumination. Figure 37 shows that, numerically, the vidicon gives a 15 db greater dynamic range for frame scanning and a 5 db greater range for two spot or line scanning. As presently planned, two spot or line scanning will be used for all steps in the mirror segment alignment procedure. Frame scanning might possibly be required for an independent evaluation of how well the Active Optics scheme is working. This step has not yet been developed.

TABLE 6

SCANNER COMPARISON TABLE

<u>Factor</u>	<u>Desired Characteristic</u>	<u>Vidicon</u>	<u>Image Dissector</u>
Resolution	> 300 TV lines @ 50%	500	1200
Dynamic Range	> 40db for lmw Laser	≈ 35	20 to 30
Frequency Response	> 60 cps	≈ 10 cps	> > 1 mc
Operating Flexibility	variable scan, repeatable data, no spurious response	poor	good

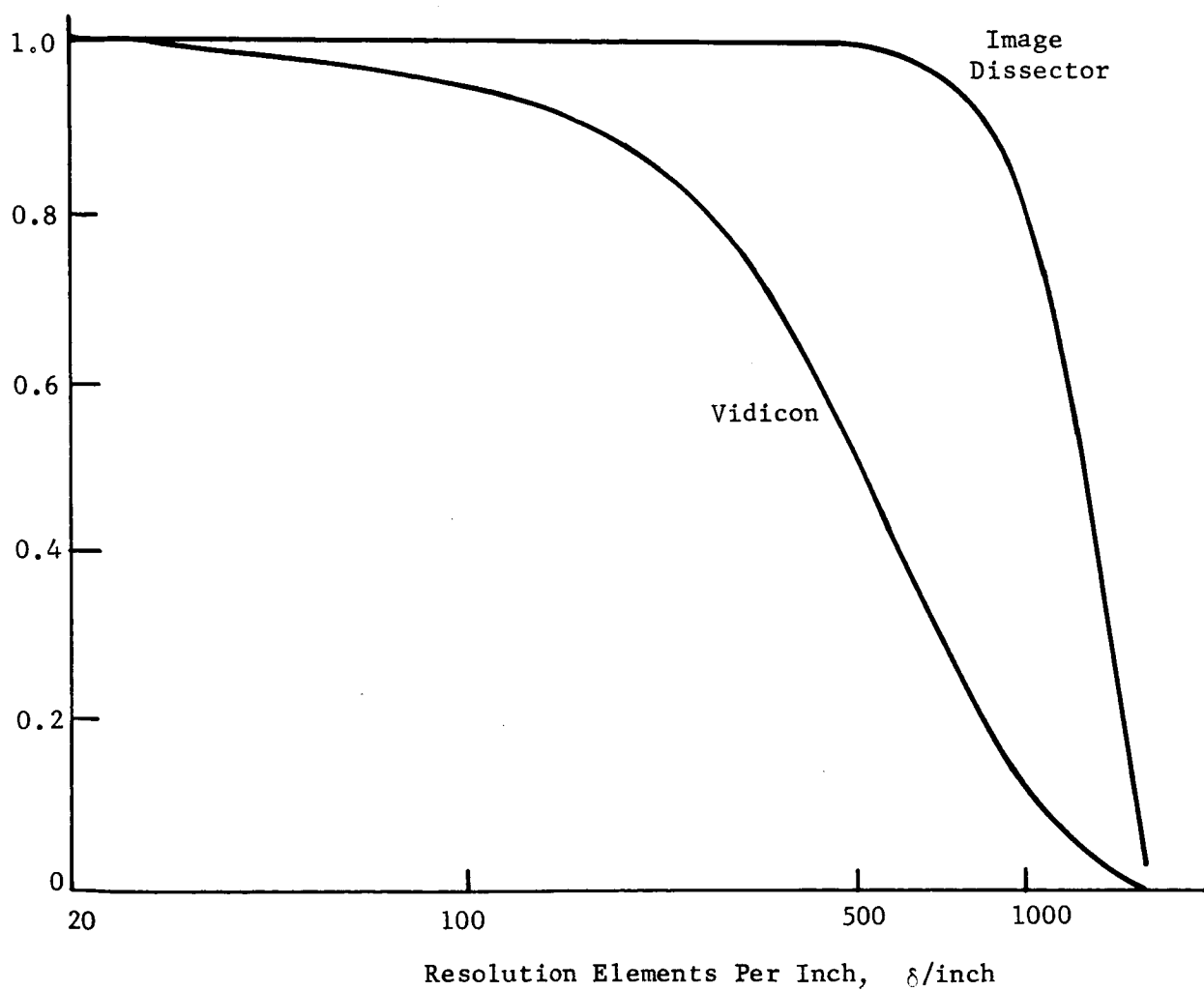


Figure 36. Modulation Transfer Functions for Scanner Tubes

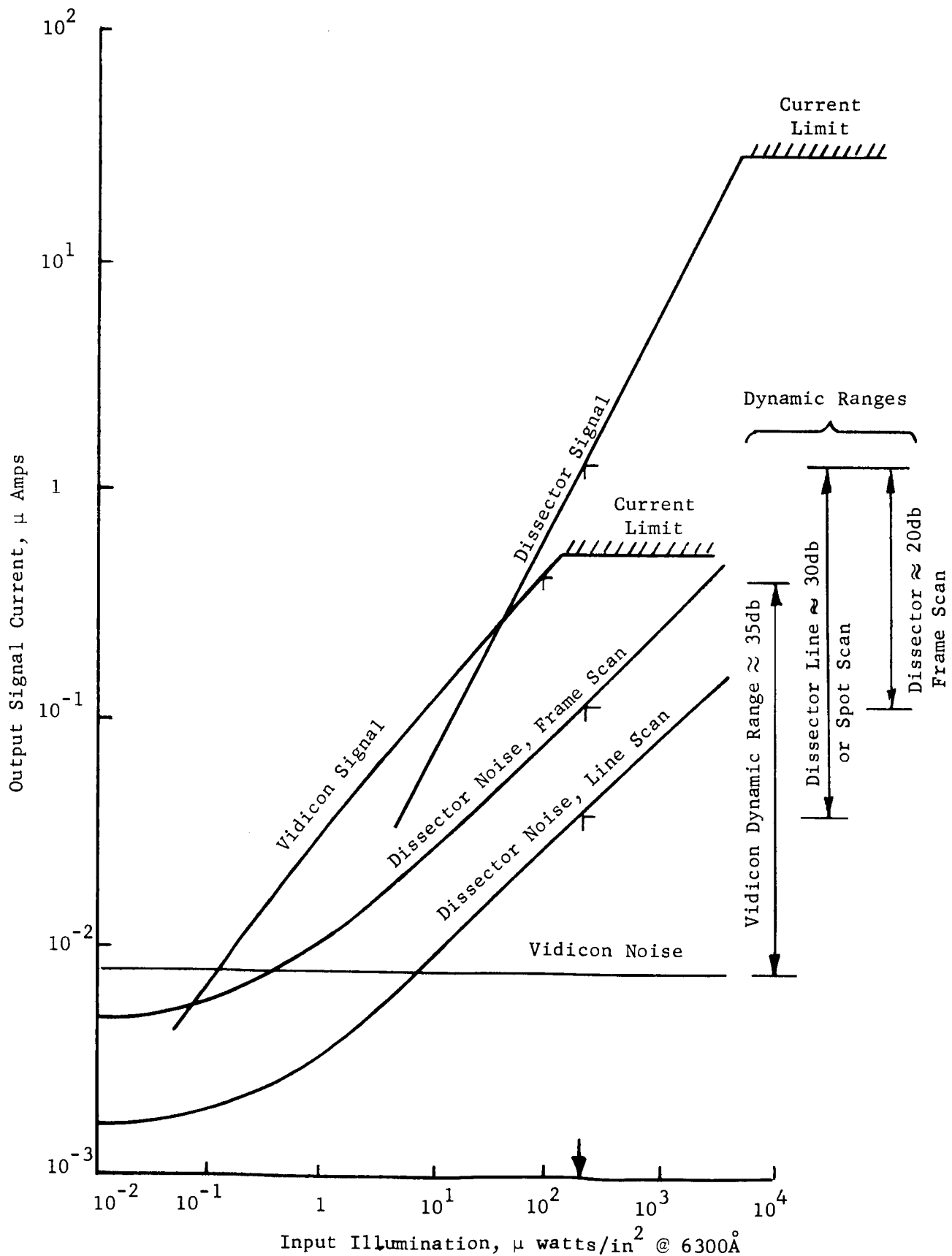


Figure 37. Scanner Signal and Noise Levels

There is a significant difference in the frequency response of the two tubes. In this case, the integration function in the vidicon photoconductor reduces its response time to the point that a large phase shift will be introduced into the phase measurement as it is currently planned. This may cause significant error if there is a temperature gradient or other anomaly across the vidicon tube face, thus the dissector is much preferred from this point of view. Spectral responses for the two tubes are comparable.

Where the exact nature of the measurement is still subject to experimental investigation, it is necessary to have a degree of flexibility in the scanning device. The vidicon is poor in this respect because the complete face must be scanned at all times. Also, measurements taken with the vidicon will not be as reproducible as those taken with the dissector because of the complexity of the semiconductor response in the vidicon.

Considering the data presented in Table 6, it is believed that the dissector is more useful because of its greater bandwidth, better resolution, and more reproducible data.

Segmented Optics Actuators

For the Active Optics Project (NAS1-5198), a differential spring actuator was selected which provides the precise motion desired (less than 1/2 microinch) and has an adequate range (± 0.010 inch). A diagram of the actuator assembly is shown in Figure 38 while a photograph appears in Figure 47.

In operation, an error signal generated by the phase-measurement interferometer is used to develop a rotation of the servo motor in the appropriate actuator. A lead screw advances a nut which varies the extension of the soft springs which pull against the stiff springs. The stiff springs are displaced 1/160 of the deformation of the soft springs. A change in dimension of the stiff springs results in a change in position of the mirror segment against which the actuator is located. A single turn of the lead screw changes the extension of the soft springs by 0.025 inch which results in a motion of the mirror segment of approximately 160 microinches. This means that one turn of the servo motor results in a mirror displacement of approximately 1/2 microinch.

In the Active Optics contract Perkin-Elmer investigated the various effects which might be used to obtain the small displacements required, numerous types of actuators were considered, and several devices were developed which should fulfill the requirements of the contract; demonstrating feasibility of the Active Optics concept. Some of these devices have been built and the principles involved in their operation will be described. Table 7 shows a comparison of the properties of experimentally investigated actuators.

The following paragraphs discuss the desirable properties which an actuator for displacing mirror segments in a space vehicle should have. Any realizable actuator will represent some kind of compromise among these requirements.

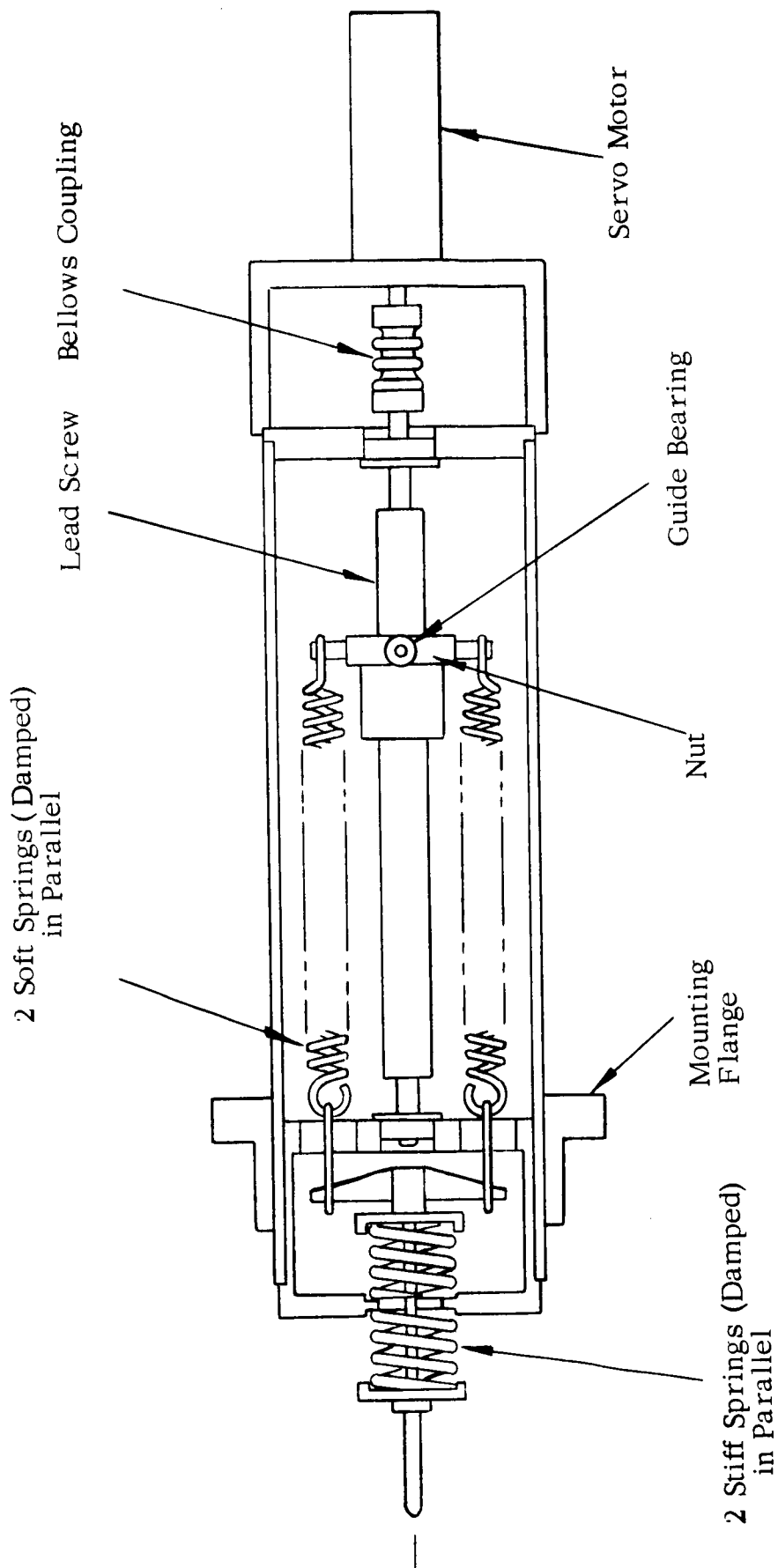


Figure 38... Actuator Assembly Diagram

TABLE 7

TABLE OF PROPERTIES OF ACTUATORS
EXPERIMENTALLY INVESTIGATED IN PHASE I

	Magnetostrictive Peristaltic Actuator	Magnetostrictive Load Actuator	Clamping Actuator	Differential Screw
Smallest Reliable Step Size Presently Obtainable	3×10^{-6} in.*	3×10^{-6} in.*	15×10^{-6} in.*	1×10^{-6} in.*
Maximum Range	> 4 in.	1/2 in.	1 in.	1/2 in.
Fastest Response	2.5×10^{-4} in/sec	2×10^{-5} in/sec	1×10^{-4} in/sec	2×10^{-4} in/sec
Backlash	0	0	0	5×10^{-6} in.*
Reliability in a Space Environment	Very Good	Very Good	Good	Poor*
Maximum Opposing Force	100 gm.*	1000 gm.*	2000 gm.*	> 10,000 gm.
Power Requirement	0.5 joules per step	3 joules* per step	3 joules per step	0.1 joules per step

*Should be improvable

The Ability to Make Small Displacements

As discussed previously, the accuracy to which a diffraction-limited mirror should be figured, to put 95% of the maximum possible energy at a given frequency into the central diffraction ring, is $1/50$ wavelength (RMS). It has been found possible to achieve this level of accuracy in mirrors such as the 36-inch mirror used in Stratoscope II. If this standard of accuracy is accepted for use in an orbiting astronomical telescope using segmented optics, it would be necessary to position the segments to at least this precision. A $1/50$ wavelength at 6328A is approximately 0.5×10^{-6} inches. Therefore, the need is for less than 0.5-microinch displacements for frequencies in the visible region of the spectrum. In the ultraviolet, positioning accuracy would have to be better than 0.1-microinch to achieve the same percentage of diffraction-limited capability.

The Ability to Make Reversible Displacements

It is not always the case that a device which can produce a very small displacement in one direction can also produce this displacement in the opposite direction. Furthermore, it sometimes occurs that a device which can make reversible displacements has excessive backlash or frontlash.

A Large Dynamic Range

There are two ranges which must be considered. One range is that imposed by initial misalignment of the mirror segments. Since this adjustment need only be made once, it could be done as a separate function, and a range of motion of the actuators which could include this initial alignment could be considered a bonus. The other range is that of the misalignments which could be expected to occur continually due to temperature cycling, materials creeping and warping, and slight inertial and vibrational effects.

It would be desirable from the standpoint of minimizing moving parts and simplifying the control electronics to be able to achieve a large dynamic range and precise positioning ability in the same actuator; this is by no means a rigid requirement. The function of coarse and fine positioning might also be divided between two or more actuators operating in tandem.

Low Power Requirements

It is obvious that the average power drain must be maintained below the continuous power level available with enough surplus to operate other peripheral equipment and still allow for statistically possible malfunctions.

A zero-power requirement, during the time displacements not being made, would be desirable and would allow the mirror to maintain its last corrected configuration in the event of a power failure.

The Ability to Operate in a Space Environment

Considerations of the problems of cold welding, evaporation, change of state, and change of properties and dimensions with temperature change and radiation bombardment must be made in the design of an actuator expected to operate reliably in space over a period of years. Hermetic seals, lubrication, and special temperature or pressure controls should be minimized or avoided.

The Ability to Work Against an Opposing Force

The forces opposing actuator displacement in a space environment are small, but not zero, and are due primarily to friction and inertia.

Response Time

The requirement on the response time will probably be determined by the rate of change of displacement expected because of thermal variations. This will further be dependent upon the geometry and thermal stability of the mirror mounting.

Small Mechanical Displacement Actuators

Some of the effects which could be used to obtain small mechanical displacements are listed below and discussed in the following paragraphs.

- | | |
|--------------------|----------------|
| • Magnetostrictive | • Hydraulic |
| • Electrostrictive | • Pneumatic |
| • Mechanical | • Electrolytic |
| • Thermal | |

A combination of two or more of these effects could be used in a single device. A combination of devices could be used to produce coarse and fine motions.

Magnetostriction

Magnetostriction is the small but powerful dimensional change which occurs in ferromagnetic materials due to domain realignment in a magnetic field. This effect has been made use of in three devices of which experimental models have been constructed and tested.

- The peristaltic actuator.
- The magnetostrictive load actuator.
- The magnetostrictive clamping actuator.

The peristaltic actuator and the magnetostrictive load actuator are discussed on the next few pages. Magnetostriction also has an effect on modulus of elasticity which could be used to produce small displacements.

Electrostriction

Electrostriction is the small dimensional change which takes place in certain piezoelectric materials when an electric field is applied. Analogs of the three magnetostrictive devices, the peristaltic, magnetostrictive load, and clamping actuators, could be made to work using piezoelectricity.

Mechanical

• Precision Screw

The classical method for obtaining small displacements with a large range is the precision screw. Control to better than 1/2 microinch has been shown to be possible in a ruling engine*. In this case, however, the screw was advanced continuously without reversing or even stopping and stiction problems were minimized by lubrication. Problems of stiction, backlash, and wear, in a reversible system using a precision screw for fine positioning, are formidable for a space flight project like OTES.

• Differential Screw

It is difficult to make a precision screw with a large number of threads per inch, however, it would be desirable to do so to improve control and reduce stiction problems. Differential screws can be made having a large effective number of threads per inch without having to cut and lap a fine screw thread. This is done by making two threads having slightly different pitches which work against each other such that the resultant effective pitch is equal to the product of the two pitches divided by their difference. Thus, a pitch of 1/20 inch, working against a pitch of 1/19 inch, gives an effective pitch of 1/380 inch providing less than 10-microinch axial displacement for an angular rotation of one degree. A differential screw of this type would have definite possibilities for a coarse control or even for a fine control if used in conjunction with a motion reducing device such as a lever arm. A differential screw drive was used in the experiment with the white-light equal-path interferometer. Its action will be discussed further.

• Differential Spring

The differential spring pits a small spring force against a larger one so that a large change in dimension of the soft spring will result in a very small deflection of the hard spring. This technique has proved very useful in the positioning of Fabry-Perot interferometer mirrors. When trying to achieve a large dynamic range as well as small displacement, however, a spring system can have undesirable resonances with relatively long decay times. If damping is used to reduce this Q, friction is introduced.

• Lever

Besides the obvious motion reducing properties of simple lever, an even larger reduction can be achieved by use of the bending geometry of a cantilever

* G.R. Harrison and G.W. Stroke JOSA Feb. 1955, pp 112-121.

beam. This device has been used as a motion reducer in combination with other types of actuators.

- Acoustic

Acoustic vibration might be used instead of magnetostriction to exercise the armature of the load actuator.

Thermal Coefficient of Expansion

Thermal expansion can be used to provide extremely small displacements. It is difficult to imagine a stepping device using thermal expansion which would have a reasonable response time, but it could have possibilities for providing fine analog displacements with a small dynamic range.

Hydraulic and Pneumatic

A hydraulic pump, such as used in a ruling engine described in Applied Optics*, has been used to obtain small displacements. However, this and other hydraulic and pneumatic devices would have the disadvantage for space applications of requiring close control of the thermal environment.

Electrolytic

Electrolysis could be used as the pump in an essentially hydraulic system, but the same space application problems exist.

Experimental Actuators

Peristaltic Actuator

- Description

The peristaltic actuator (Figure 39 and 40) consists of a cylindrical armature of ferromagnetic material which is telescopically mounted in tight fitting relationship for frictional movement within a tubular sleeve of non-magnetic material. Wound around this sleeve are a number of discrete coils positioned along the length of the sleeve. When current pulses are applied to these coils in overlapping sequence from one end of the sleeve to the other, a magnetic field is created which causes a localized magnetostrictive expansion or contraction of the armature. This localized expansion or contraction moves down the length of the armature with the same velocity that the pulse moves along the sequence of coils. The cumulative result, once the pulse travels the length of the armature, is an axial displacement of the armature relative to the sleeve. Accordingly, if the sleeve is fixed, the armature will move. If the armature is of a material having a negative coefficient of magnetostriction such as nickel, the displacement will be in the same

* W.R. Horsfield, Applied Optics, February 1965, pp 189-193.

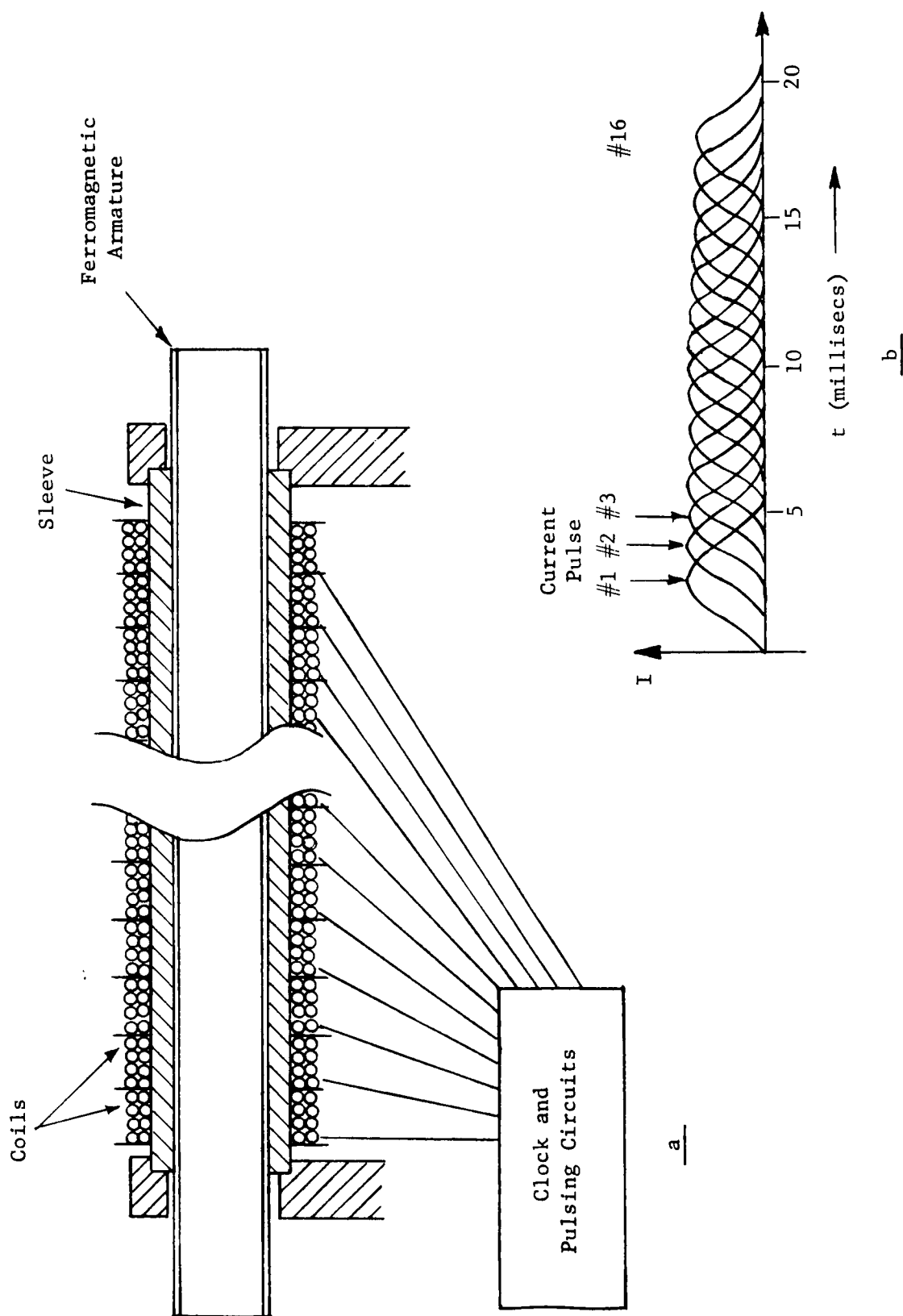


Figure 39. Peristaltic Actuator Diagram

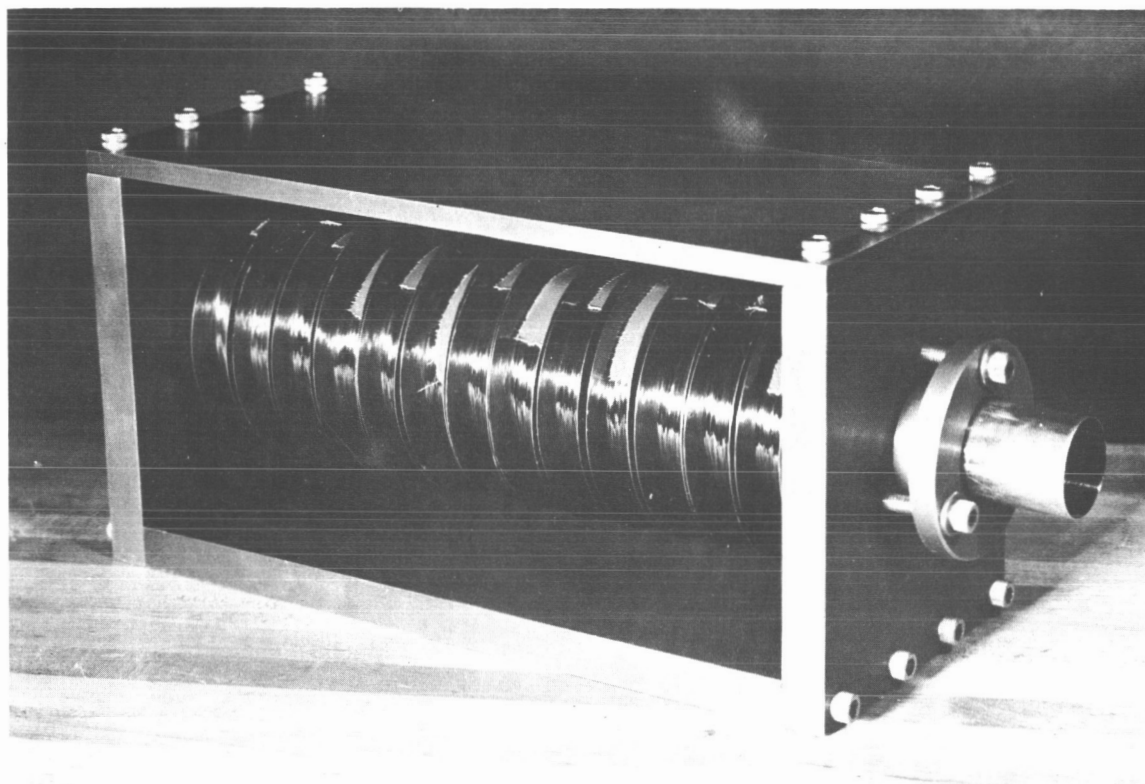


Figure 40 Peristaltic Actuator

direction that the pulse is traveling. If the armature is of a material having a positive coefficient of magnetostriction such as invar, the armature will be displaced in the opposite direction to that which the pulse is traveling.

• Results

The dynamic range of this actuator is quite large, being limited only by the difference in length between the armature and the sleeve which can be made as large as desired.

The step size of the peristaltic actuator reached a lower limit at about 3 microinches in the present models. Smaller displacements were obtained but the motion was not consistent and would eventually reach a sticking point at which the armature would cease to move. This difficulty is apparently caused by the elastic and friction properties of the sleeve and armature materials at their interface as well as the length of armature affected by the magnetic field at any given time. By appropriate selection of materials, careful design of the interference fits involved, and arrangement of the pulsing coils to obtain a shorter effective pulse length, it should be possible to significantly reduce the step size.

A further difficulty in the present model is its inability to move against any significant opposing force (over 100 gms). This is due to the relative length of the effective magnetic pulse in the armature compared to the length of the interference fit. The effective pulse length must be less than half the length of the interference fit for any cumulative displacement to occur at all, and it should be much less than half to work against any opposing force. This problem should also be amenable to design improvements which are being contemplated.

The maximum response of this actuator is determined by the maximum rate at which it can be cycled and the maximum step size available. As presently being pulsed, the rate would be 25 Hz for a 50% duty cycle. The step size has a certain flexibility depending on amplitude of the magnetic field, and could be greater than 20 microinches, although this would depend to some extent on what changes are made in the effective pulse length to achieve smaller steps.

The power requirement is presently about 1/2 watt-sec per step for a 10-micro-inch step.

The performance of this actuator in a space environment should be very good. It has only one moving part which involves a metal to quartz interface which should have little tendency to cold weld in a vacuum and, therefore, requires no special lubrication or hermetic seals.

Magnetostrictive Load Actuator

• Description

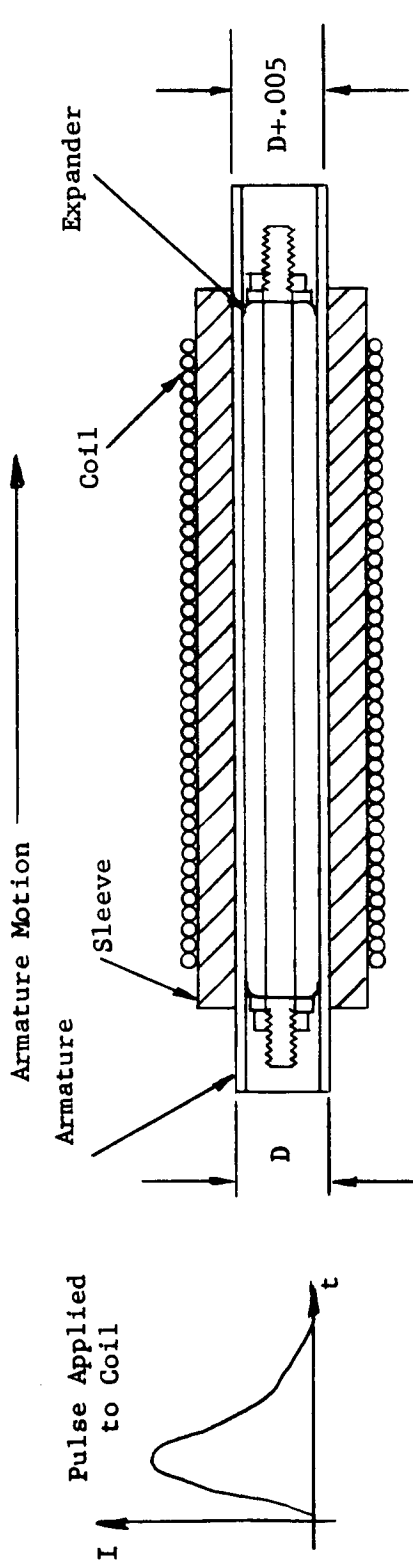
The idea for the magnetostrictive load actuator was engendered by an effect observed in one of the first models of the peristaltic actuator. It was observed that the motion of the armature proceeded with much greater facility in one direction than in the other. When the quartz sleeve was measured, its inside diameter was found to have a taper of about 0.003 inch from one end to the other. This taper apparently produced a wedge effect which caused the armature to prefer to move in the direction of the large end of the quartz sleeve. An actuator was then built (as shown in Figure 41) consisting of a coil wound around a quartz sleeve having a tapered inside diameter, and a cylindrical nickel armature inside it. It was observed that the armature would work its way out of the large end of the sleeve in small steps when the coil pulsed with no delay line or sequential pulsing being necessary as in the peristaltic actuator. Furthermore, it was observed that when two such actuators were placed back to back as in Figure 41, bidirectional motion could be obtained by pulsing one side or the other. Only a very light force was required to prevent such motion. However, a method of obtaining a larger bidirectional force than can be realized from the wedging action, is to apply a force to the armature externally by means of solenoids as shown in the schematic diagram of the Magnetostriction Load Actuator in Figure 42. The direction of the magnetic force due to the solenoids could be switched electrically.

The action of this device could be compared to the action of a block on an inclined plane. If the block is heated and then cooled, it will expand and contract depending on its thermal coefficient of expansion and it will move down the inclined plane an amount depending on the change of dimension, the friction forces involved, and the angle of the inclined plane. Similarly, in the magnetostrictive load actuator, the armature will move with respect to the quartz sleeve an amount depending on the change of dimension of the armature due to magnetostriction, the friction forces involved, and the external force applied by the solenoid, which in the analogy, is the equivalent of the component of gravitational force on the block, parallel to the inclined plane.

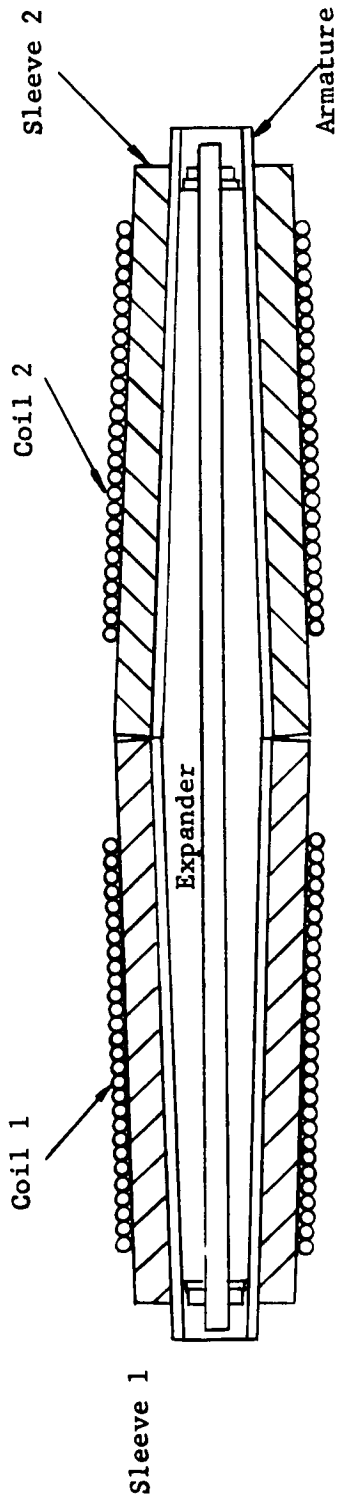
• Results

A model of such an actuator was constructed and was found to operate well against an opposing force as long as the difference between the applied magnetic force and the opposing force exceeded a certain amount. The actual magnitude of this minimum difference depends on several parameters involving materials, pressures, and pulse size, and is less than one pound in the present actuator.

It was found, as in the peristaltic actuator, that a minimum step size is reached with the load actuator, below which the armature tends to reach a sticking point. This point is between 3 and 5 microinches with the present



a



b

Figure 41. Wedge Actuator

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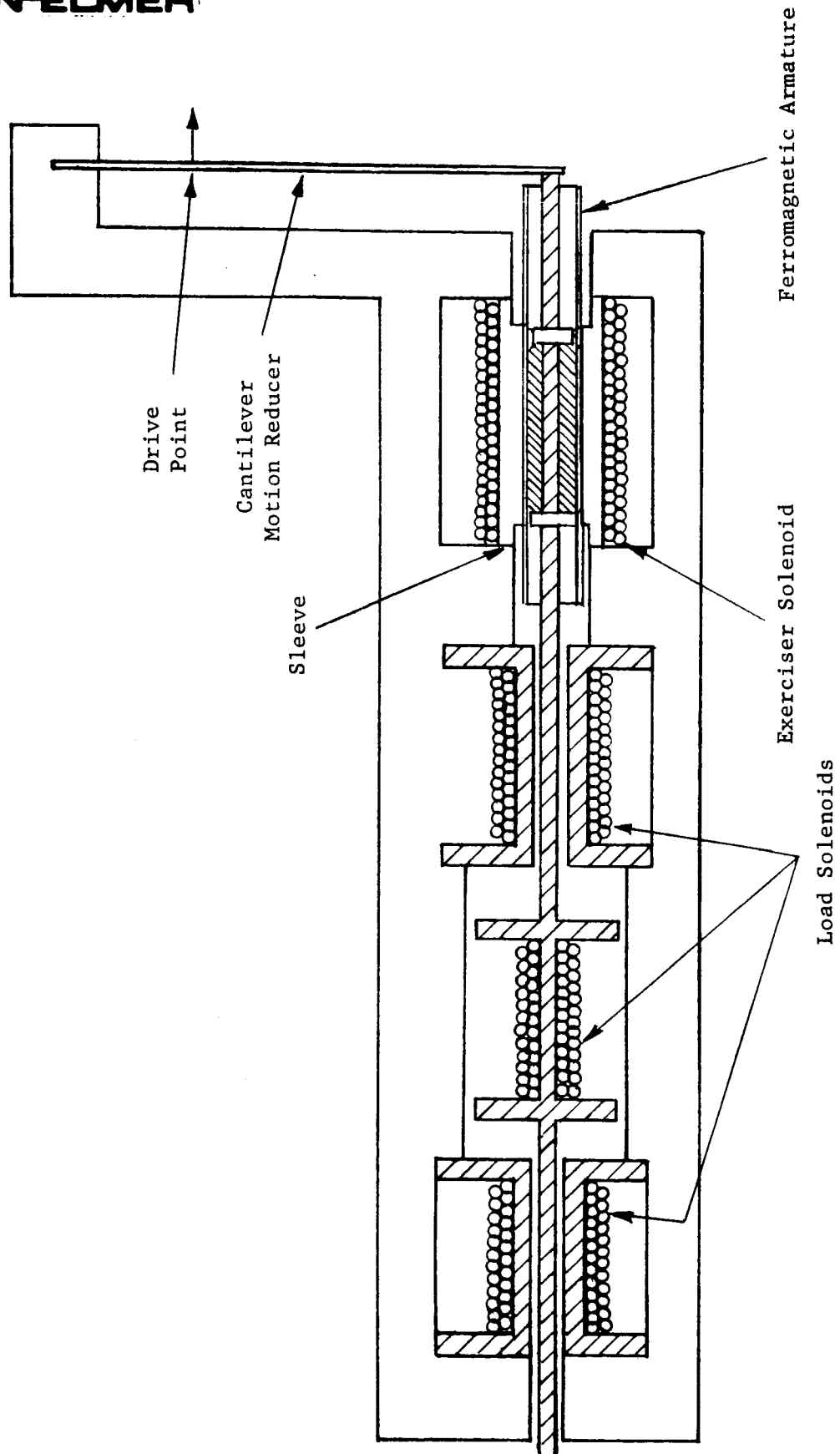


Figure 42. Magnetostrictive Load Actuator

models and, as the step size is increased above this point, the stepping action also becomes more consistent and uniform. This problem was overcome for the present by using a cantilever to obtain motion reduction. Displacements were less than 1/2 microinch and, therefore, supported the feasibility of the Active Optics concept. Any reduction in motion obtained in this way with the load actuator, however, will also reduce its effective range. The dynamic range of the armature is limited by the spacing of the solenoids in their present arrangement so that this spacing would need to be increased by the same factor that the displacement is reduced, to maintain the same range.

A model of the magnetostrictive load actuator, supplemented with a cantilever motion reducing arm, was connected to one mirror of the phase measurement interferometer to observe its action as part of a servo loop to maintain mirror alignment. The results were very encouraging. They proved the actuator's ability to function as part of a servo loop; however, to obtain a picture of the actuator displacement as a function of time, the output of the interferometer was observed on an oscilloscope while manually pulsing the actuator. The lever ratio was set to obtain approximately 1/60 wavelength per step. The minimum recovery time is approximately 1/4 second which, along with the maximum step size possible, determines the fastest response time. The step size is not very flexible in this arrangement since the maximum step size is reduced by the lever reduction ratio. A step-size range of 5 to 50 microinches, reduced by a factor of 10, becomes a range of 0.5 to 5 microinches.

Power requirements in the load actuator are relatively high (about 3 watt-sec per step), most of which is dissipated in the load solenoids. Schmitt triggers are employed as the input level detectors and unijunction transistors are used for the relaxation oscillators in combination with simple transistor clamping circuits.

EXPERIMENT DISCUSSION (Summary)

Experiment No. 1 is based, in part, upon the concept of Segmented Active Optics - a large primary mirror that is subdivided into smaller mirror segments that are, in turn, held in position by ultraprecise servomechanisms. The input data for the mirror-positioning servos come from the laser figure sensor signals. During the Phase IA of the OTES Program, the diffraction pattern for a simulated 3-meter segmented Active Optics system was obtained photographically and derived analytically. The analysis correlated exactly with the photographic simulation. The simulation was accomplished by obscuring the front of a quality mirror with a wire grid arranged in the pattern of the seven segments.

The wire grating used to obtain the photograph is shown on page I-33 of the Phase I and IA Report* and the resulting photograph is shown on page I-34*. The analysis of the diffraction pattern can be found on page I-285*. The analysis indicated that there was only a negligible degradation of performance of a large segmented primary as compared to the one piece or conventional

* Perkin-Elmer Report 8500

primary mirror. Further, what little degradation is present, is primarily due to the outer edge effects of the six outside hexagons rather than because of the separation between the individual hexagons. Therefore, the shape of the primary mirror for the 2-meter OTES as illustrated at the beginning of Experiment 1, is shown with a round periphery rather than the geometrical hexagons illustrated in the Phase I and IA Report. The seven segments, in an arrangement where the outside edges form a circle, have the advantages of:

- Minimum disturbance to the diffraction pattern of the optics.
- Maximum light-gathering power.
- More symmetrical heat transfer between telescope tube and primary mirror edge.

The analysis dealing with the field-of-view requirements for the 2-meter OTES telescope can be found on the pages immediately following. The total field of the optical system should be sufficiently greater than the recording field to ensure a reasonably high probability of containing at least two guide stars when the telescope is used in one of the astronomical modes. The tracking operations for the 2-meter telescope are analyzed and the conclusion is reached that the instrument can guide on the light from 13th magnitude stars when using cooled phototubes. If uncooled phototubes are used, brighter stars are required for guidance (11.5 magnitude). The field of view for the guidance system of the 2-meter telescope should be at least 15 to 20 arc-minutes, and for the 2-meter OTES optical design developed by Perkin-Elmer in this present Phase II, a 30 arc-minute corrected guidance field is produced. There is a 90% probability of obtaining two sufficiently bright guide stars (13th magnitude) in the vicinity of a very dim target (even at 90° latitude).

The 2-meter telescope must be pointed at the target object with a precision in the vicinity of 1/100 arc-second, or better, in order to utilize a 2-meter diffraction-limited space optical system. This subject is considered in more detail in Experiment No. 9 - 1/100 arc-second Telescope Pointing Technology. However, the reader of Experiment No. 1 must recognize that Experiment No. 9 is a corollary experiment.

In a similar manner, the accuracy of the 2-meter telescope about the roll axis (or roll about the line of sight) also must be determined. The analysis of the 3-meter telescope roll requirements can be found starting on page I-83*. This analysis shows that a 2 arc-second roll precision about the line of sight is necessary in order to use the 3-meter telescope for astronomical applications. For the 2-meter OTES proposed in this Phase 2 Report, the roll precision opens up to 3 arc-seconds at $\lambda = 0.1$ micron. In the visible range, around 0.5 micron, the precision has reduced to 15 arc-seconds. This is a level of roll precision many times coarser than the body-point precision designed into the Princeton OAO "C" - the Princeton Experimental Package develops pitch and yaw error angles and feeds these to the OAO spacecraft for a

* Perkin-Elmer Report 8500

body-point operation about line of sight to 1/10 arc-second. The roll about the line of sight requirement for astronomical observations with the 2-meter telescope in the OTES Program will be comparably difficult task to the OAO "C" pitch angle control even though the OTES requires 3 arc-seconds precision compared to 1/10 arc-seconds. It should be noted that this level of angular precision about the roll axis is more difficult than that required for the optical technology experiments. This subject is covered in more detail for optical communications in Experiment No. 24 (page I-155)*. For laser communications, the roll about the line sight (RLOS) must be maintained to 3.38 arc-minutes** compared to 3 arc-seconds needed for the 2-meter astronomical telescope***.

Experiment No. 1 Operations

The concept of active optics is applicable to both the 2-meter and 3-meter telescopes which have been proposed for the OTES program. The method of attaining a 2-meter diffraction-limited primary mirror for the OTES requires that the segments be aligned in translation and tilt to better than 1/50 wave and that they maintain a comparably accurate surface figure. The tilt and positional alignment of the individual segments is provided by 21 actuators controlled by the phase-measuring and white-light interferometer systems that were shown in Figure 14. Table 1 lists the sequence of operations for segmented Active Optics operations.

Both passive and active techniques are used to achieve an adequate surface figure for the individual segments. Segments listed previously, which utilize the most stable and known mirror materials available in descending order of confidence as of 1967 are:

- Solid fused quartz (7940)
- Fused quartz (ULE-7971)
- Cervit
- Silicon
- Beryllium

They represent the most promising material techniques yet developed to passively obtain the required surface figure. In contrast, the segment 1. - thin deformable mirror - and an eggcrate fused quartz with array of imbedded heaters - have their surface figure actively controlled by either mechanical or thermal deformations. The surface figures of the segments are compared to each other during the entire duration of the optical technology mission using the phase-measuring interferometer. The experiment will develop the data required to select the optimum material and structure technique for the mirrors for future large-aperture spaceborne telescopes.

OTES Segmented Mirror Operations

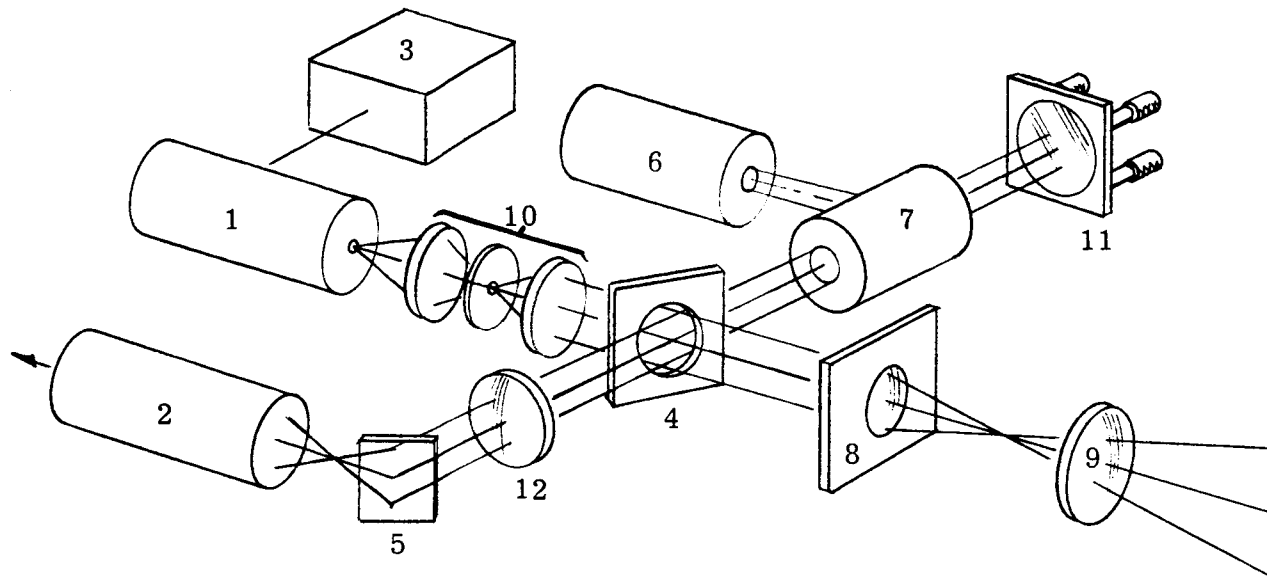
Figure 43 illustrates the Experiment No. 1 system. The overall electronic block diagram is shown in Figure 44. The Active Optics master programmer controls the automatic sequencing of the mirror segment alignment.

* Perkin-Elmer Report 8500

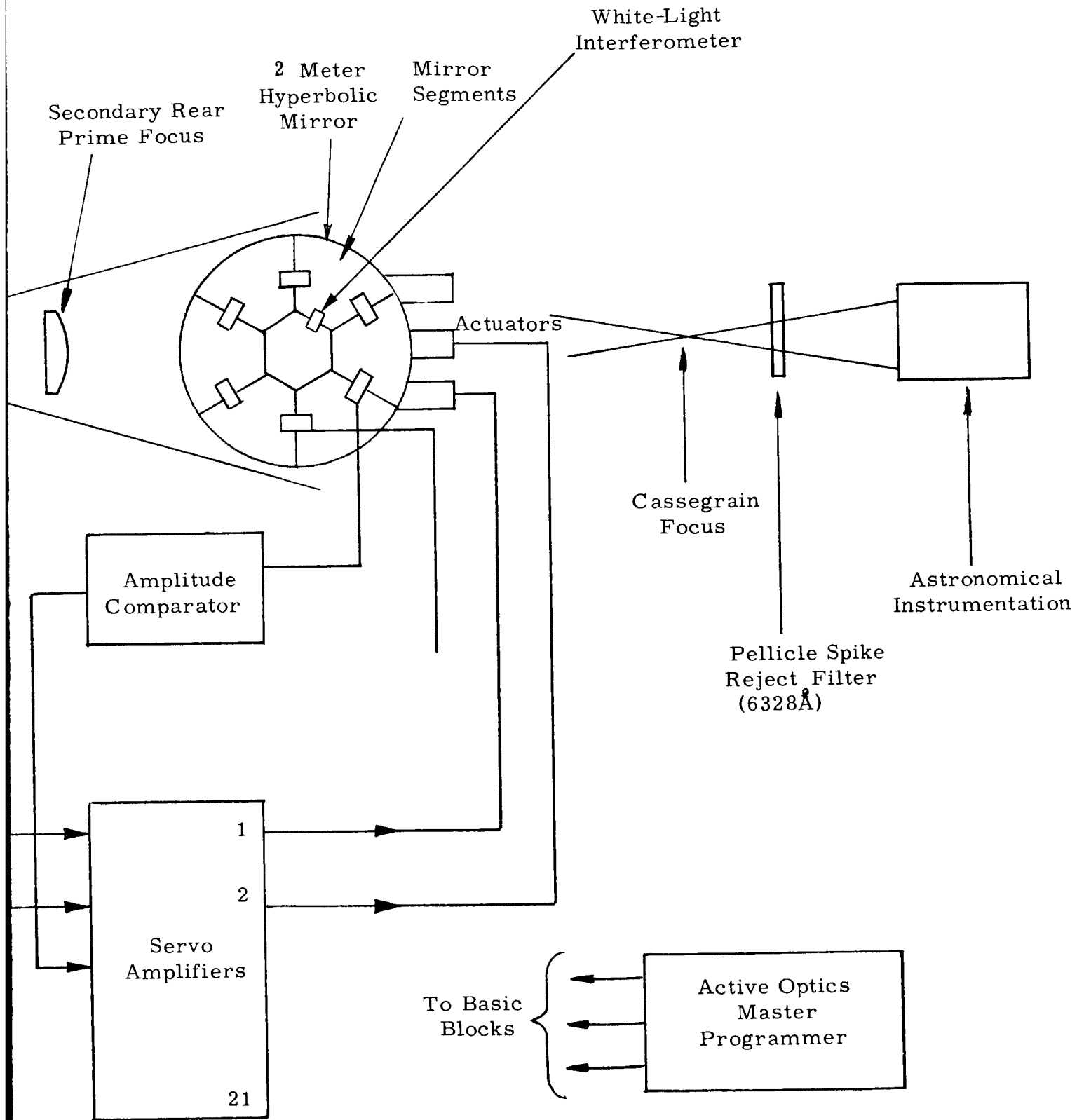
** Perkin-Elmer Report 7924, page B-3 (Contract NAS8-11408)

*** Page I-84 of Report 8500 with 2 meters substituted for 3-meters

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1. He-Ne Laser
2. Image Dissector
3. Laser Power Supply
4. Beamsplitter
5. Front Surface Mirror
6. Phase Shift Drive
7. Phase Shifter
8. Focusing Lens
9. Offner Corrector
10. Coupling Optics and Pinhole
11. Interferometer Mirror
12. Imaging Lens
13. Actuators (1 of 21)
14. Ambiguity Sensors
15. Actuator Control Electronics



I-90-2

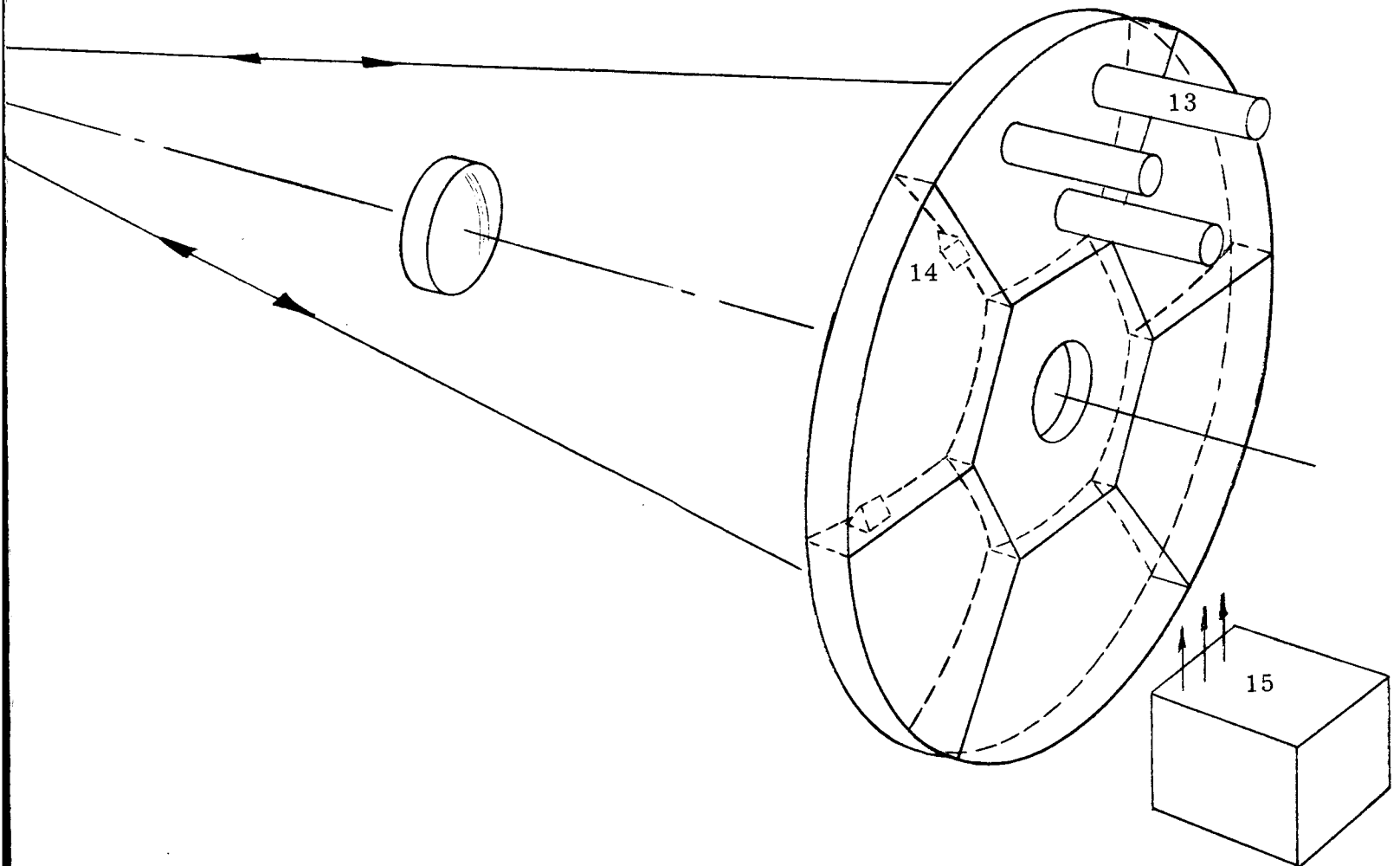


Figure 43 Active Optics

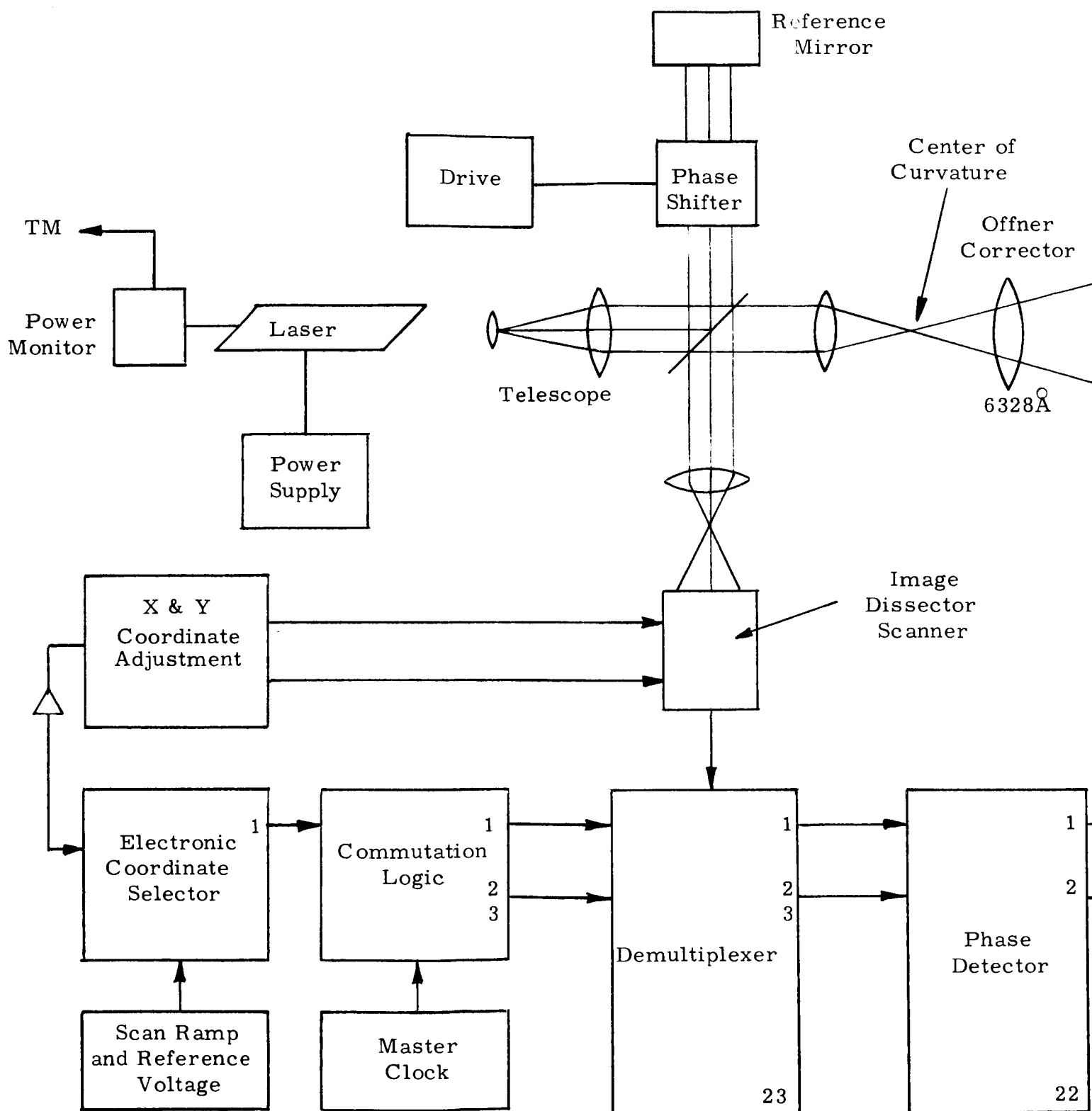


Figure 44 Active Optics Schematic

The phase-measuring interferometer sequentially searches a series of points and zones on each mirror segment. The equipment utilizes circular zonal areas on each mirror segment, one central reference point on each segment, and one designated point which serves as a reference for the entire mirror. The position of the circles and their diameters (as well as the points used) are determined by the X and Y coordinate adjustment and central electronics of the Active Optics system.

The electronic selector chooses specific sequences for each operation. First, the tilt of each mirror is reduced. By noting the interference pattern at the output of the phase-measuring interferometer, the segment is translated along the optical axis to reduce the focus errors. The gross focus error remaining for each segment is further reduced by the white-light interferometer. At this point, the system will operate in a closed loop fashion with the servo-amplifiers driving the actuators such that the error voltage from the phase detectors is minimized.

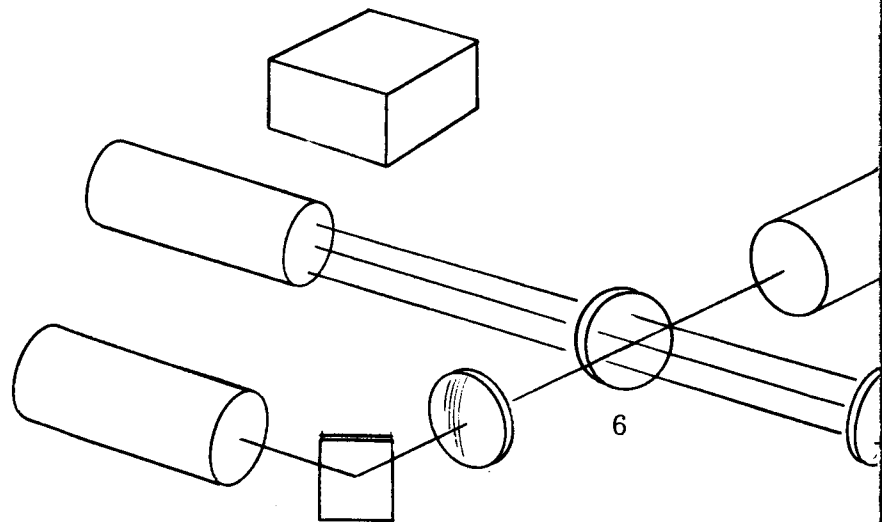
The active segmented optics system is operated continuously during the astronomical experiments. The light from the interferometer He-Ne laser will not be reflected directly into the astronomical instrumentation package since it emanates from the center of curvature. However, light that is diffracted from the secondary, or scattered from the primary or scattering particles, may enter the package. Thus, a 6328A spike rejection filter will be required for any low-light-level astronomical experiments.

Deformable Mirror Operations

The surface figure of a thin mirror segment may be controlled by mechanical deformations of the mirror material using the control system and actuator arrangement shown in Figures 45 and 46. In principle, many types of actuators can be used to produce the deformation but, in practice, there are only one or two types of actuators which can really do the job in a practical manner in space.

The actuator configuration consists of an array of actuators (less than 100) which are hard mounted between their mirror and the actuator mounting structure. This structure is connected to the three tilt and positional actuators to maintain the thin mirror segment in correct alignment with respect to the other segments. Some of the actuators are in compression, and the remaining actuators are in tension so that the resultant force is zero. The surface figure sensor (phase interferometer) is used to monitor the segment figure as well as maintain the seven segments in correct alignment and position. The electronic coordinate selector shown in Figure 43 is used to position the actuator mounting with respect to the other segments, and is then reprogrammed to scan the thin mirror segment. The relative position (i.e., mirror figure) of M points on the thin mirror surface will be used as inputs to an error computer. This computer is used to transform the surface figure distribution into the required actuator force distribution which is then used to control the individual actuators.

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1. Backing Plate
2. Thin Deformable Mirror Segment (quartz or beryllium)
3. Piezoelectric Actuators
4. Tilt and Positional Actuators
5. Primary Mirror Support Structure
6. Phase Measuring Interferometer

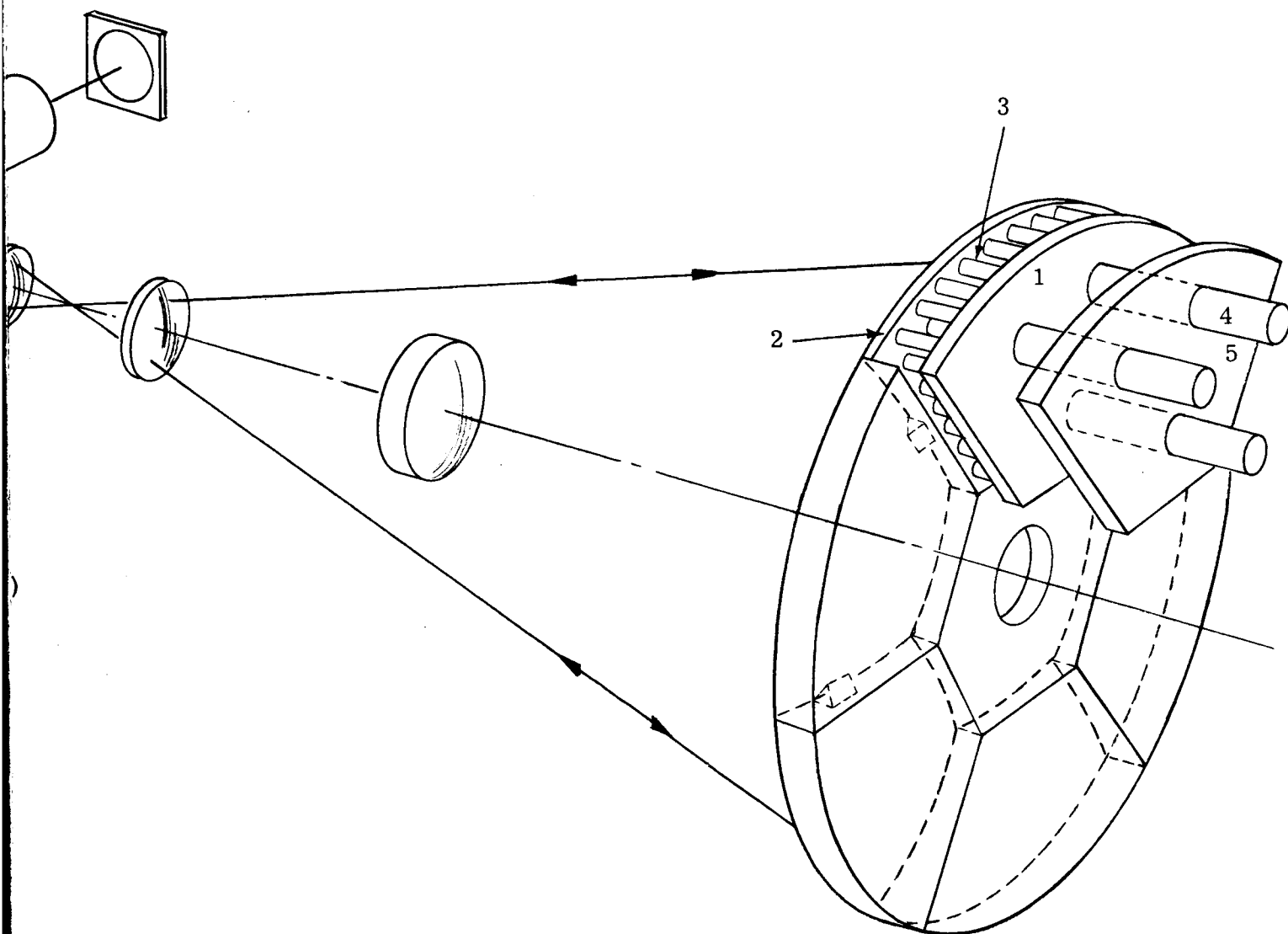
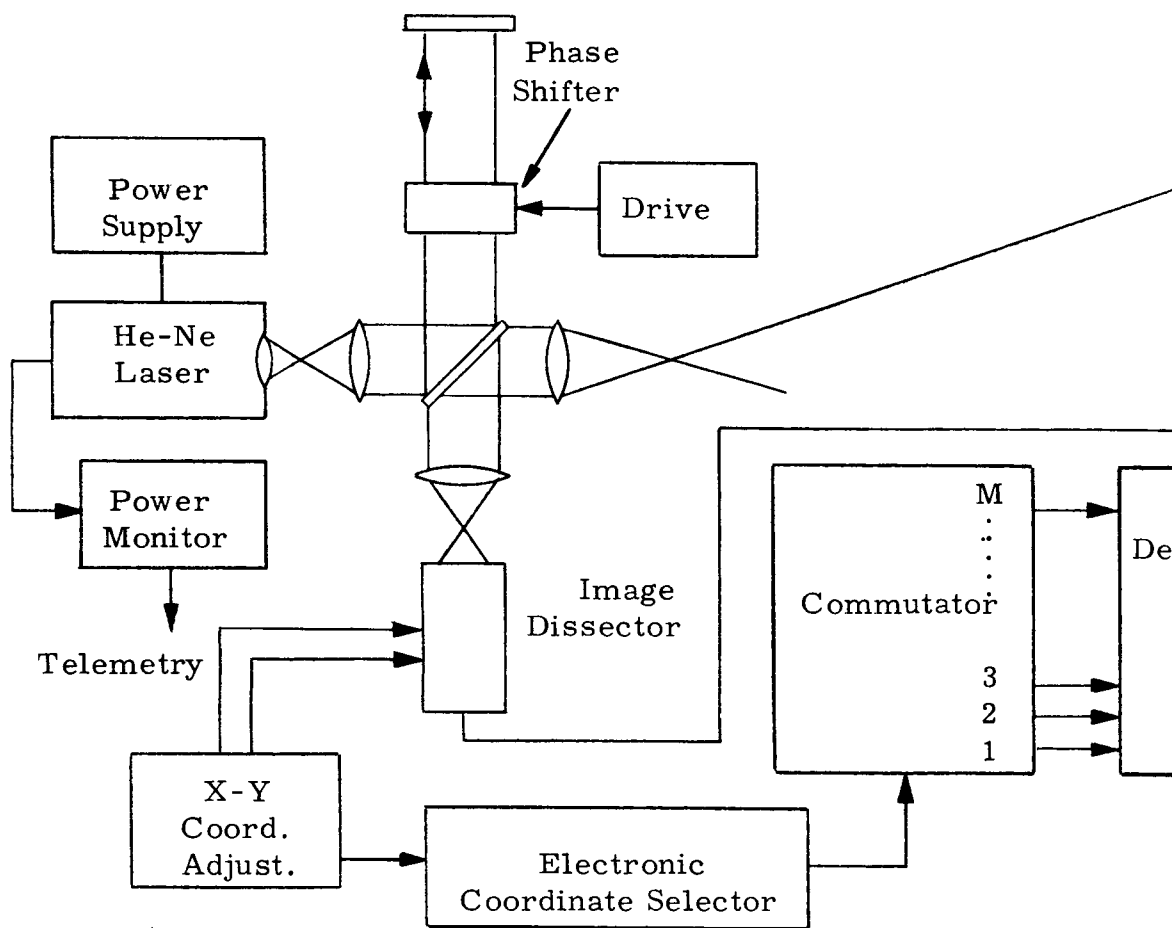


Figure 45.. Thin Deformable Mirror Experiment

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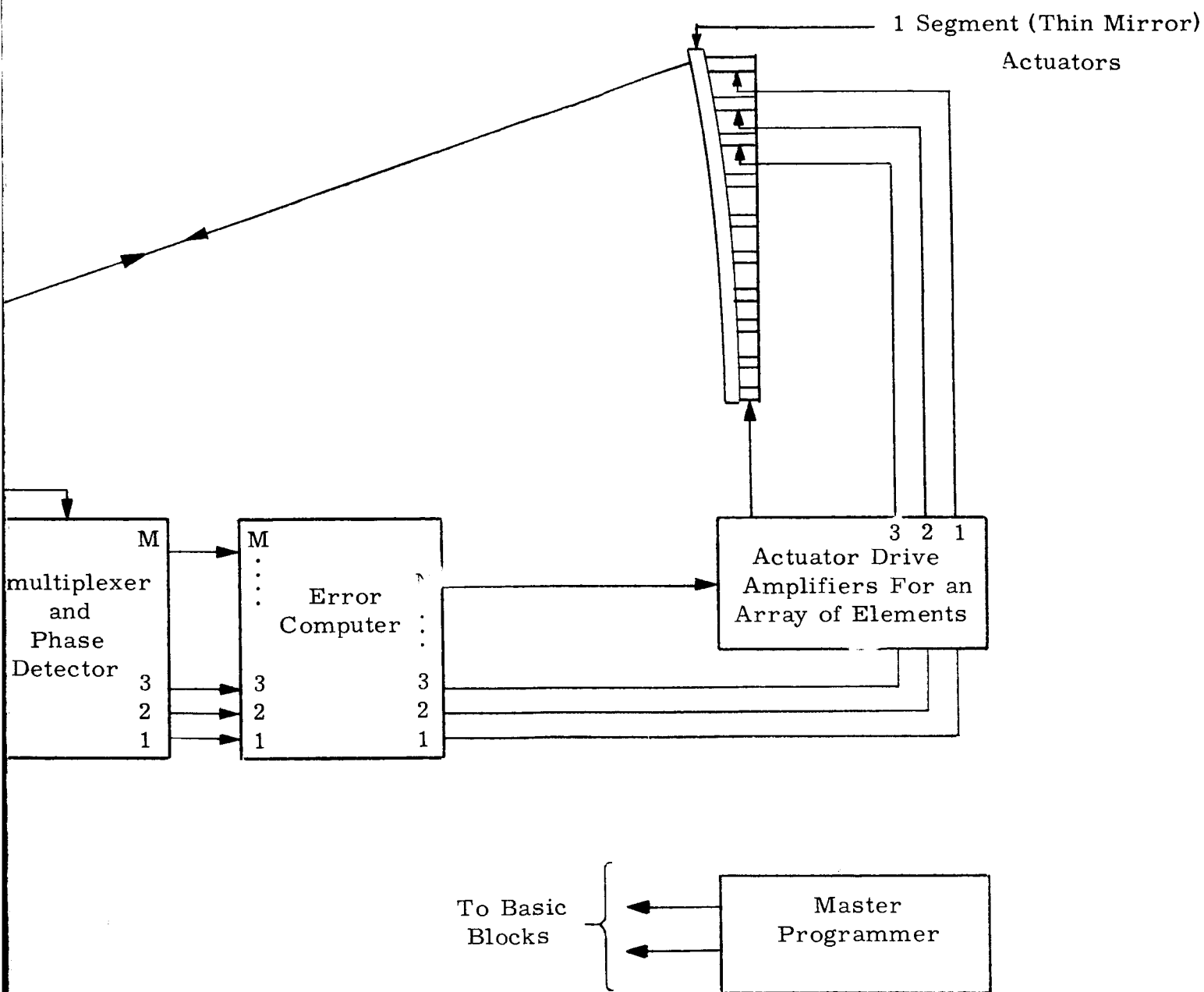


Figure 46. Thin Mirror

Thermal Controlled Mirror Operations (Refer to Experiment No. 8)

Mirror figure errors resulting from thermoelastic deformations are some of the most important problems faced by the designers of space telescopes. Thus, some degree of active thermal control to correct for thermally-induced figure error is plausible and also can be used to correct figure errors resulting from other causes. Figures 68 and 69 are for the active thermal control of mirror segment 5 as an alternative to the cervit segment.

A special segment is used to evaluate this technique: a quartz eggcrate segment with heaters. The mirror figure deformations are measured by the phase-measuring interferometer. The solution of the mirror segment thermoelastic equations requires a knowledge of the temperature distribution in the mirror (Experiment No. 12) and the mirror deformation information provided by the figure sensor. This large amount of information will be transmitted to Earth for computations. The data stating the amounts of heat which have to be added or removed from the mirror will be transmitted back to the spacecraft and used to control the array of heaters and coolers. Since the power required is only of the order of watts (OTES Experiment No.8), no significant change in the thermal design of the segmented mirror support structure will be required.

The results of this experiment will determine the feasibility of using active thermal control in the changing thermal environment of space for future telescopes of larger aperture.

Primary Mirror Materials for Segments of Active Optics

One of the very basic values of Experiment No. 1 of the 2-meter OTES is the comparative space evaluation of prospective mirror materials. The experiment operations are based on the ability of a single figure sensor not only to position individual segments to their optimum location to provide a diffraction-limited primary mirror, but also to be used to compare the stability and thermal performance of outstanding material candidates for the larger telescopes of the 3-meter OTES and MOAT class. The choice of the appropriate mirror materials for the segments should be delayed until the latest possible time because new materials for space mirrors are being developed, and the opportunity to evaluate them in a gravity-free space environment with a quantitative figure sensor is a most powerful engineering experiment. The illustration at the beginning of the Experiment No. 1 lists an allocation of materials to each of the segments. However, it should be noted that this allocation is tentative, and that there is a need for NASA to support further work in the

space mirror materials development. In addition to this suggested NASA-sponsored research, the work that Perkin-Elmer is doing for ARPA* in the development of a suitable beryllium for space mirrors is not complete (Summer 1967) and it is expected the results from that project will have a marked effect on the actual materials selection for segment 4.

The thermal tolerance curves for a $\lambda/50$ expansion of a 10 cm element of fused silica, cervit, silicon, and beryllium are plotted (see Figures 47 through 50). Thus, four of the five materials considered most frequently for large space mirrors can be compared with respect to one characteristic - change in length as a function of temperature. The fifth material, ultra-low-expansion glass (Corning ULE glass No. 7971) has a low coefficient of expansion (1/10 that of fused silica in the temperature range of 5°C to 35°C). This is a very recent material, and to date, Perkin-Elmer does not have the data necessary to plot a thermal tolerance curve (i.e., like Figures 47 through 50).

This new material, ULE, may solve an important thermal problem for the 2-meter OTES. The 2-meter OTES concept is based on having the telescope compatible with the ATM gimbals and cluster. Due to the low altitude of the cluster, 260 miles, the equilibrium temperature cannot be as low as desired for fused silica (-80°C), and consequently the thermal gradients which are tolerable in the instrument are small. If a special ULE is used at an elevated temperature, such as -60°C, the coefficient of expansion of the material is small and, therefore, the sensitivity of the mirror to thermal gradients is low.

Perkin-Elmer is working extensively with ULE in conjunction with Corning. Figure 51 is an electron micrograph of a ULE surface after optical grinding; while Figure 52 shows a ULE surface after polishing. Figure 53 shows a fused silica surface for direct comparison.

Relative Properties of Candidate Mirror Materials

The relative merits of a variety of possible mirror materials are shown in Table 8. On the basis of a stiffness-to weight ratio, beryllium is outstanding, being a factor of 3 better than silicon.

Beryllium also has a yield strength of 40,000 psi (not shown) which is considerably higher than the 24,000 psi yield strength of silicon or the tensile strength of fused silica which varies between 7,000 and 10,000 psi.

In terms of immunity to thermal distortion, silicon appears to be outstanding, having a $K/C_p\alpha$ value a factor of 10 better than aluminum and beryllium, and a factor of 30 better than fused silica. The coefficient of expansion of the type of invar used in the comparison does not compensate sufficiently for the low heat conductivity to provide any obvious advantage. There are special invar

*Optical Materials Study Program, Perkin-Elmer Report 8903 (DA-01-021-AMC-15092(Z))

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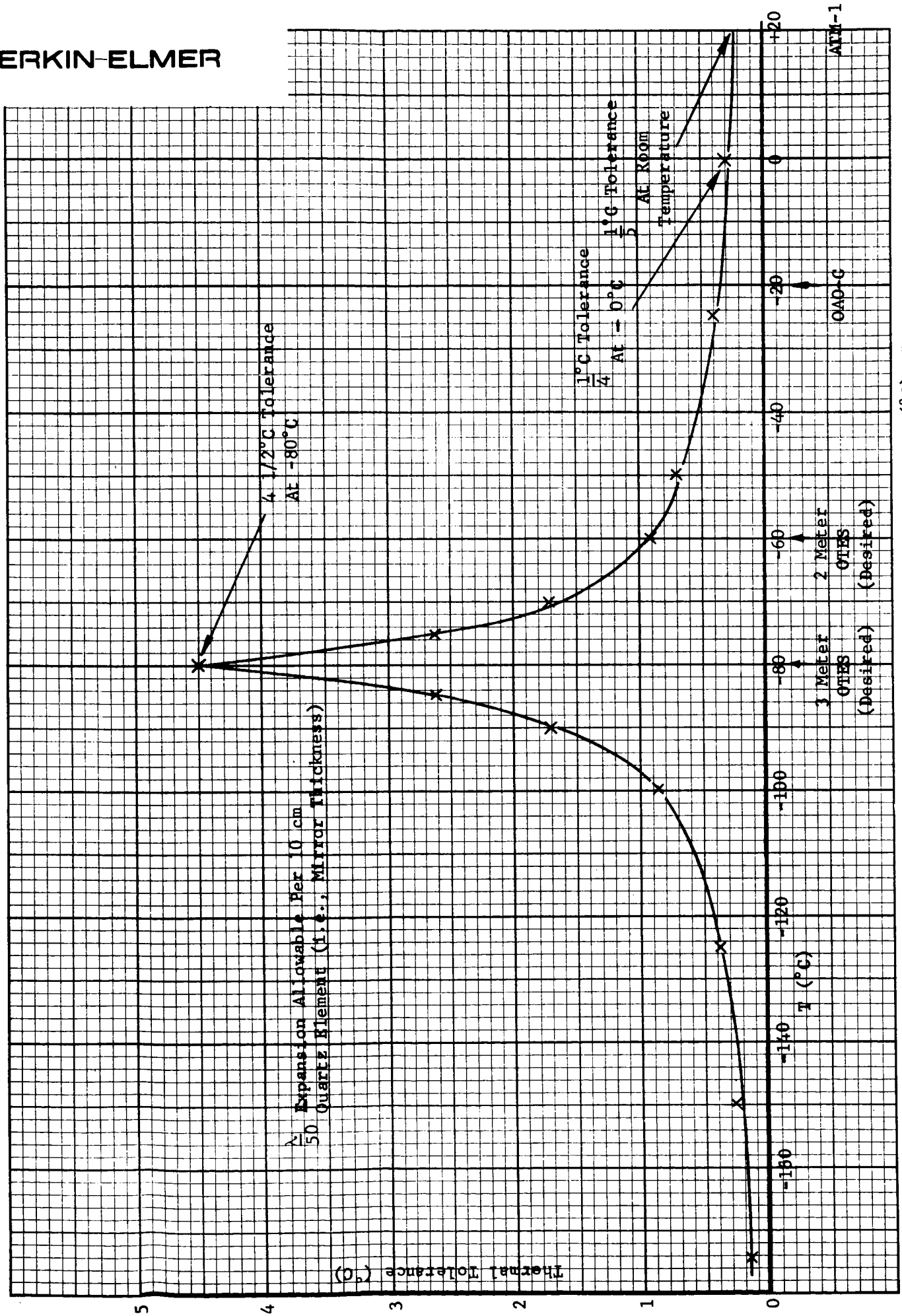


Figure 47 Operating Quartz Mirror Temperature (°C) #79409

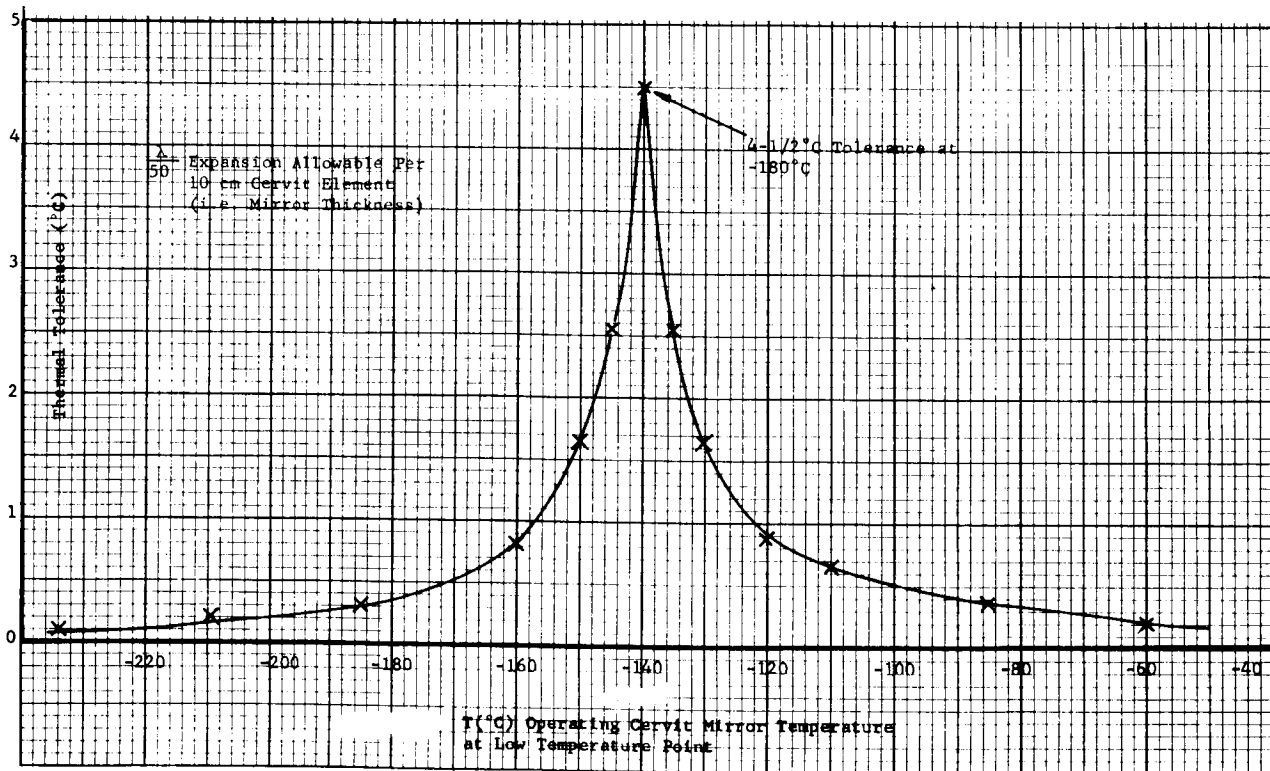
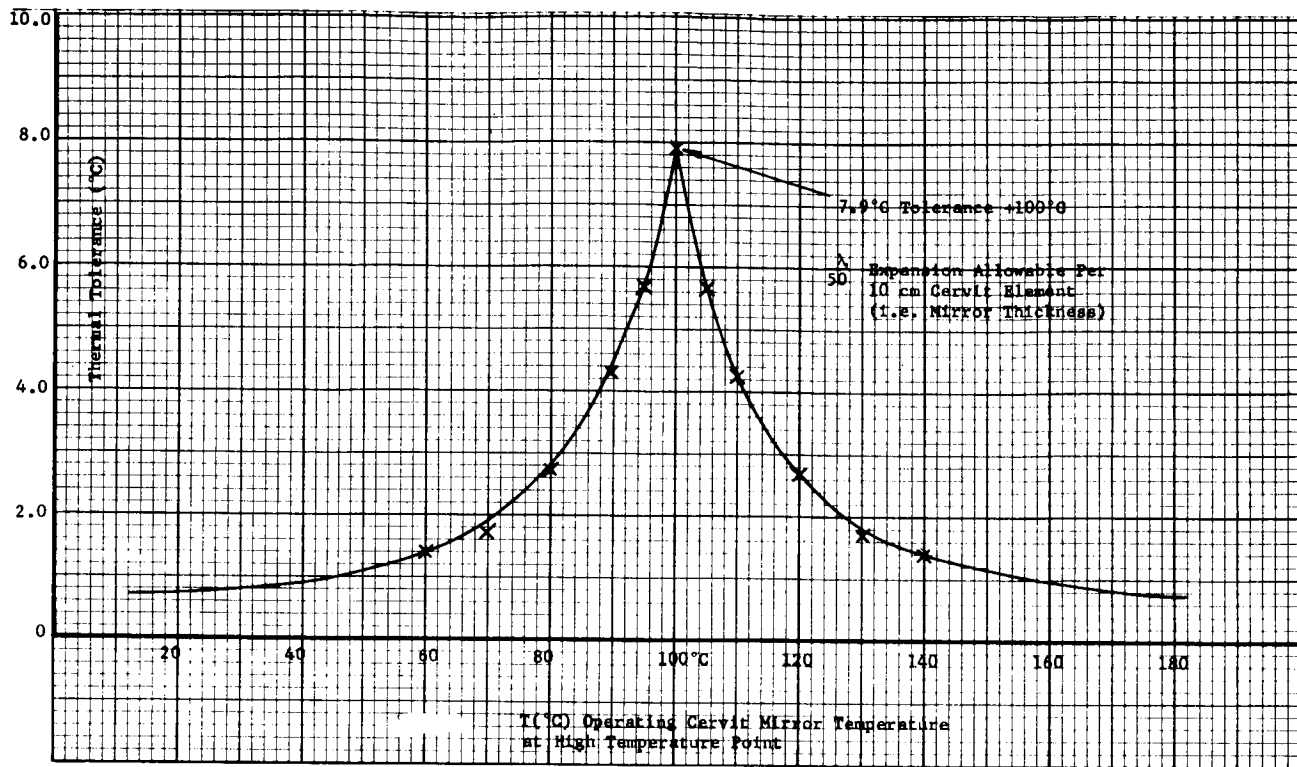


Figure 48.

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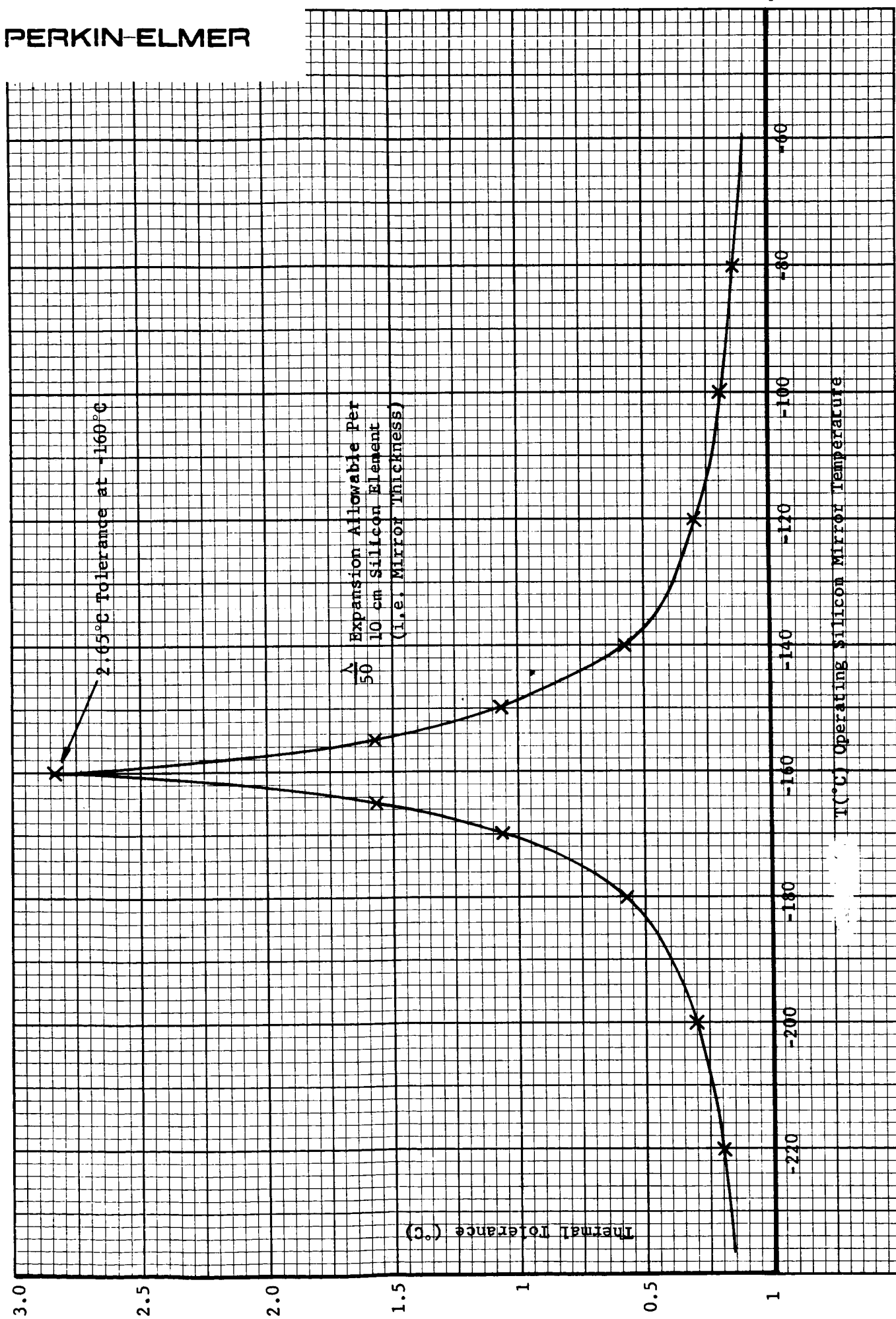


Figure 49

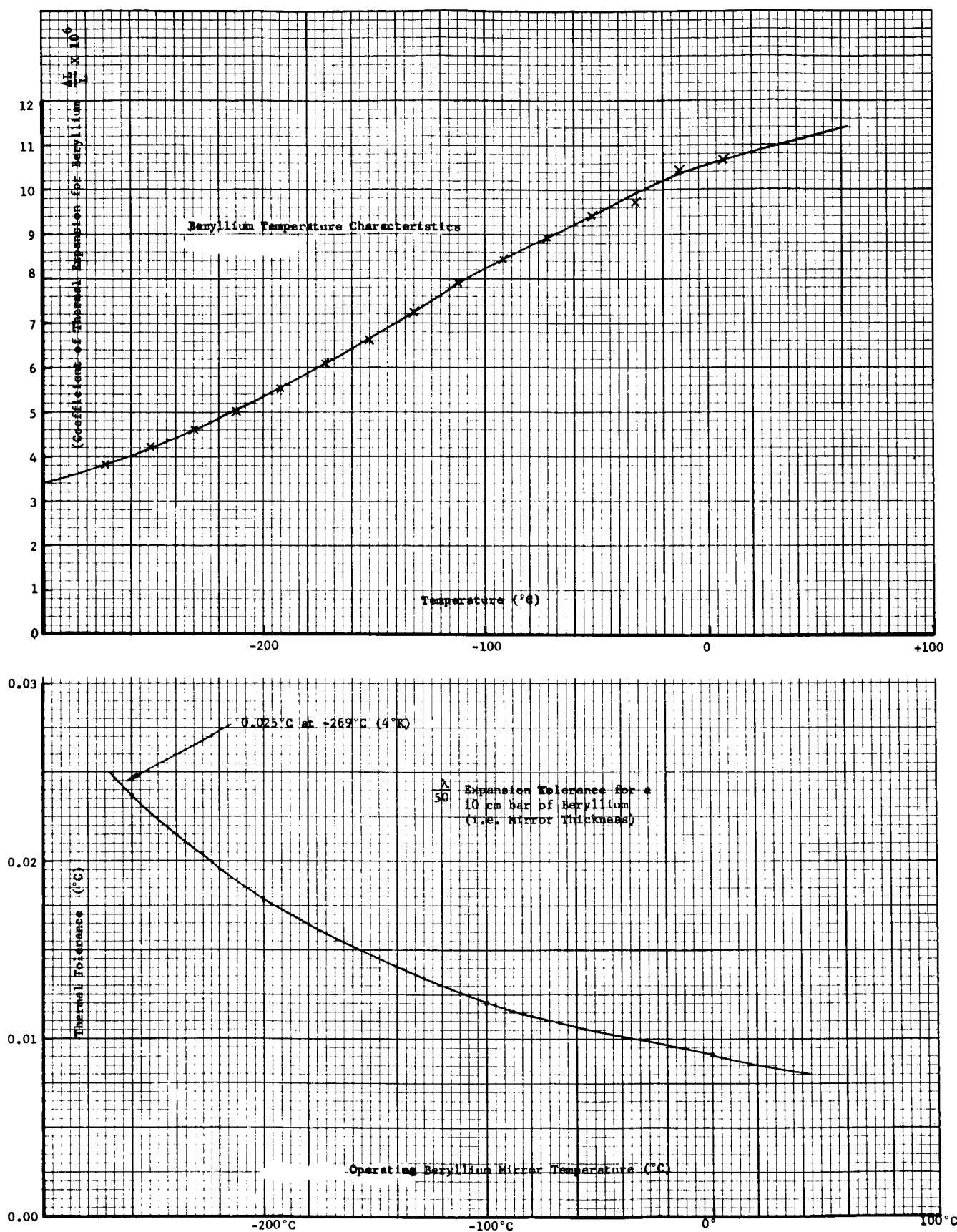
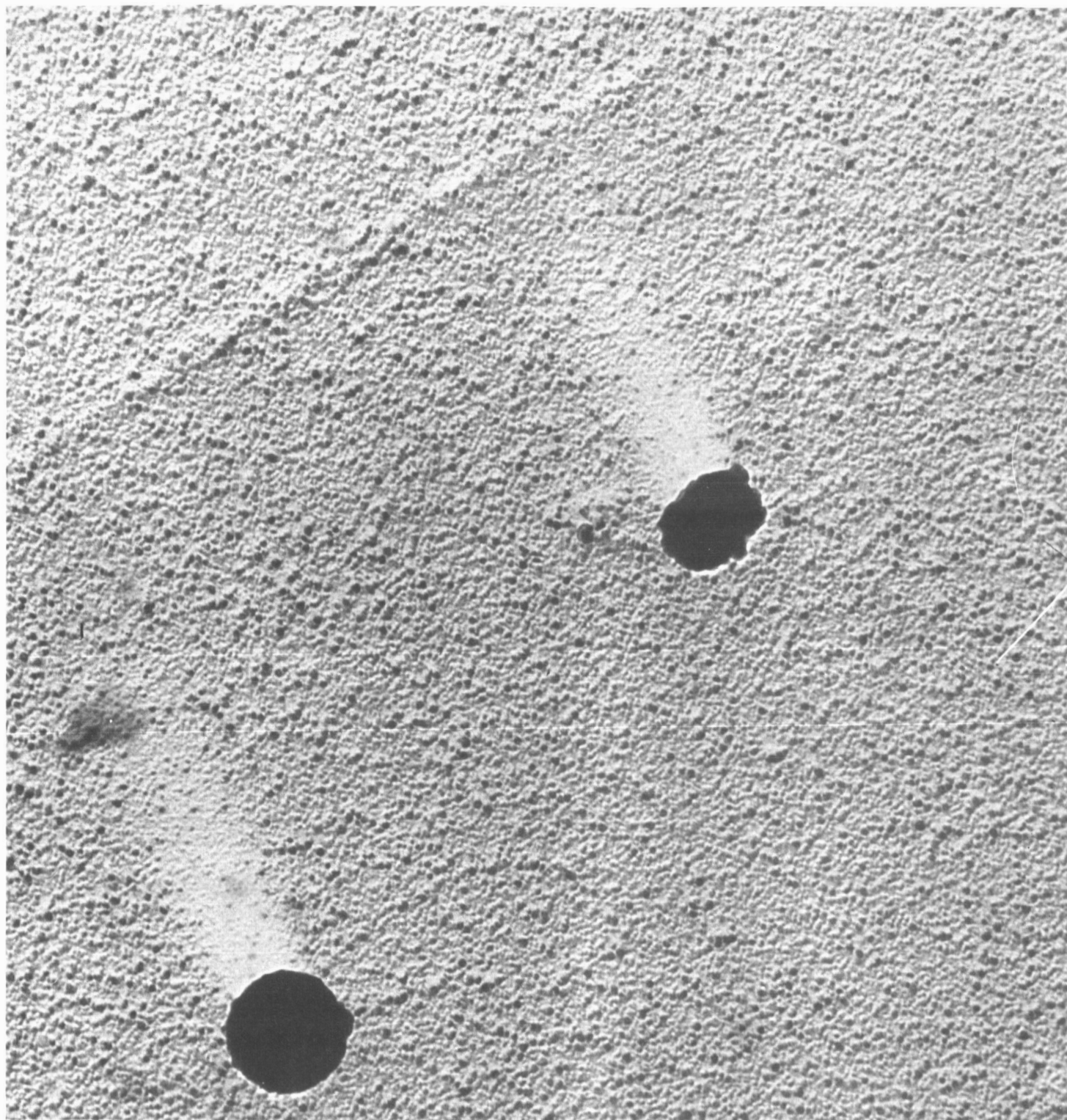


Figure 50



┌─┐ 1 micron

Figure 51. Electron Micrograph of Corning's Ultra-Low Expansion Glass No. 7971 after Grinding (Magnification: 9000X)



1 micron

Figure 52. Electron Micrograph of Corning's Ultra-Low Expansion Glass No. 7971 after 8 Hours of Polishing (Magnification: 65,000X)

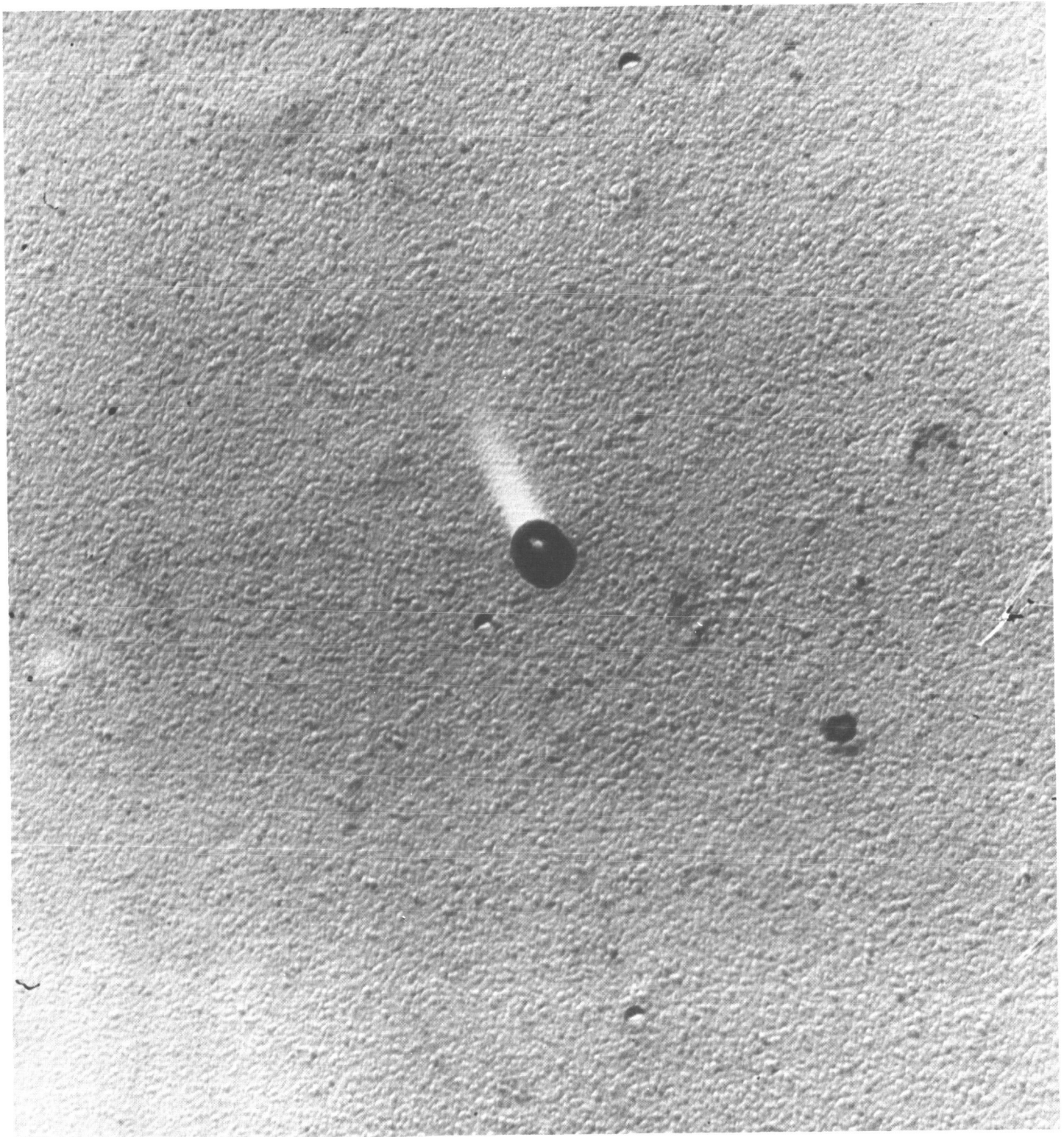


Figure 53. . Electron Micrograph of Corning's Fused Silica
No. 7940 after over 50 Hours of Polishing
(Magnification: 65,000X)

TABLE 8
PHYSICAL PROPERTIES OF MIRROR MATERIALS **

MATERIAL	DENSITY (ρ) gm/cm ³	MODULUS OF ELASTICITY (E) Newtons/cm ²	THERMAL CONDUCTIVITY (K) Cal/cm sec °C	SPECIFIC HEAT (C) Cal/ gm °C	COEFFICIENT OF EXPANSION (C) * °C ⁻¹	E/p	1/C α	K/C α	K/C ρ
Fused Silica	2.2	7.0×10^6	0.0033	0.188	0.55×10^{-6}	3.18×10^6	4400×10^3	14.5×10^3	0.008
Pyrex-7740	2.35	6.8×10^6	0.0027	0.250	3.20×10^{-6}	2.89×10^6	530×10^3	1.44×10^3	0.0046
Aluminum	2.70	6.9×10^6	0.53	0.215	23.9×10^{-6}	2.56×10^6	72×10^3	38.2×10^3	0.92
Beryllium	1.82	28.0×10^6	0.38	0.450	12.4×10^{-6}	15.4×10^6	99×10^3	37.5×10^3	0.465
Invar (36% Ni)	8.0	14.8×10^6	0.026	0.095	1.30×10^{-6}	1.85×10^6	1000×10^3	26.3×10^3	0.034
Silicon	2.33	13.0×10^6	0.39	0.168	2.33×10^{-6}	5.56×10^6	1065×10^3	427×10^3	1.0

* At 20°C

** All properties taken from reference 5 except for those of silicon which were taken from references 6 and 7.

compositions with coefficients of expansion that are smaller than the one chosen as an example,* but the coefficient is small only over a narrow temperature range which detracts from their usefulness.

In situations where radiation is the chief heat transport mechanism, as might be the case for very large glass eggcrate structures, the relative values of $1/Cp\alpha$ indicates fused silica to be a factor of 10 more advantageous than Pyrex. The use of $1/Cp\alpha$ as a mirror criterion does not appear justified in the case of other mirror materials.

Also shown in Table 8 is the thermal diffusivity (K/Cp) of the various materials. This is somewhat analogous to the reciprocal of the time constant in an electrical system so that a large value of K/Cp indicates a relatively short time to adjust to a new thermal environment.

The data in Table 8 provides a reasonably good comparison if the operating temperature range is close to that over which the coefficient of expansion was measured. In spaceborne systems, the operating temperature of mirrors and associated structures is often far below the nominal temperatures implied in Table 8 and, as a result, the coefficient of expansion can differ markedly. Both fused silica and silicon are such examples. The coefficient of expansion decreases with temperature and, in both cases, crosses zero and becomes negative. Figure 54 shows the variation of coefficient with temperature for a typical sample of fused silica (Englehard Industries, Inc., Hillside, New Jersey) and for a single crystal of silicon**,***. A number of devitrified glass materials such as Pyroceram (Corning Glass Works, Corning, New York) and Cervit (Owens-Illinois, Toledo, Ohio) have recently become available. These materials can be tailored to hug the zero coefficient of expansion line over an extended temperature range. Unlike the early types of Pyroceram, the new materials closely resemble true glasses, are polishable, and do not exhibit the severe scattering of earlier materials. A curve for one type of Cervit is also shown in Figure 54 †.

Thermal Immunity of Mirror Materials

Nonuniform temperature distributions create stresses and strains in the mirror structure and, consequently, a loss of optical figure. These can arise from variations in the radiant heat flux absorbed in the primary, or from conductive heat transfer at points where the primary is connected to other parts of the telescope structure. Whether the cause of a nonuniformity is conductive or radiative in nature, the predominant process responsible for the dissipation

* Noble, R.H., et al "Study and Analysis of Lightweight Optical Elements", ASD Technical Report 61-452, Perkin-Elmer Report No. 5857, October 1961.

** Gibbons, D.F., "Thermal Expansion of Some Crystals with the Diamond Structure", Physical Review, Vol. 112, No. 1, p. 136, 1958.

*** Dolling, G. and R.A. Cowley, "The Thermodynamic and Optical Properties of Germanium, Silicon, Diamond, and Gallium Arsenide", Proc. Phys. Soc., 1966, Vol. 88, p. 463.

† Meinel, A.B., "Introduction to the Design of Astronomical Telescopes", Technical Report 1, Optical Sciences, University of Arizona.

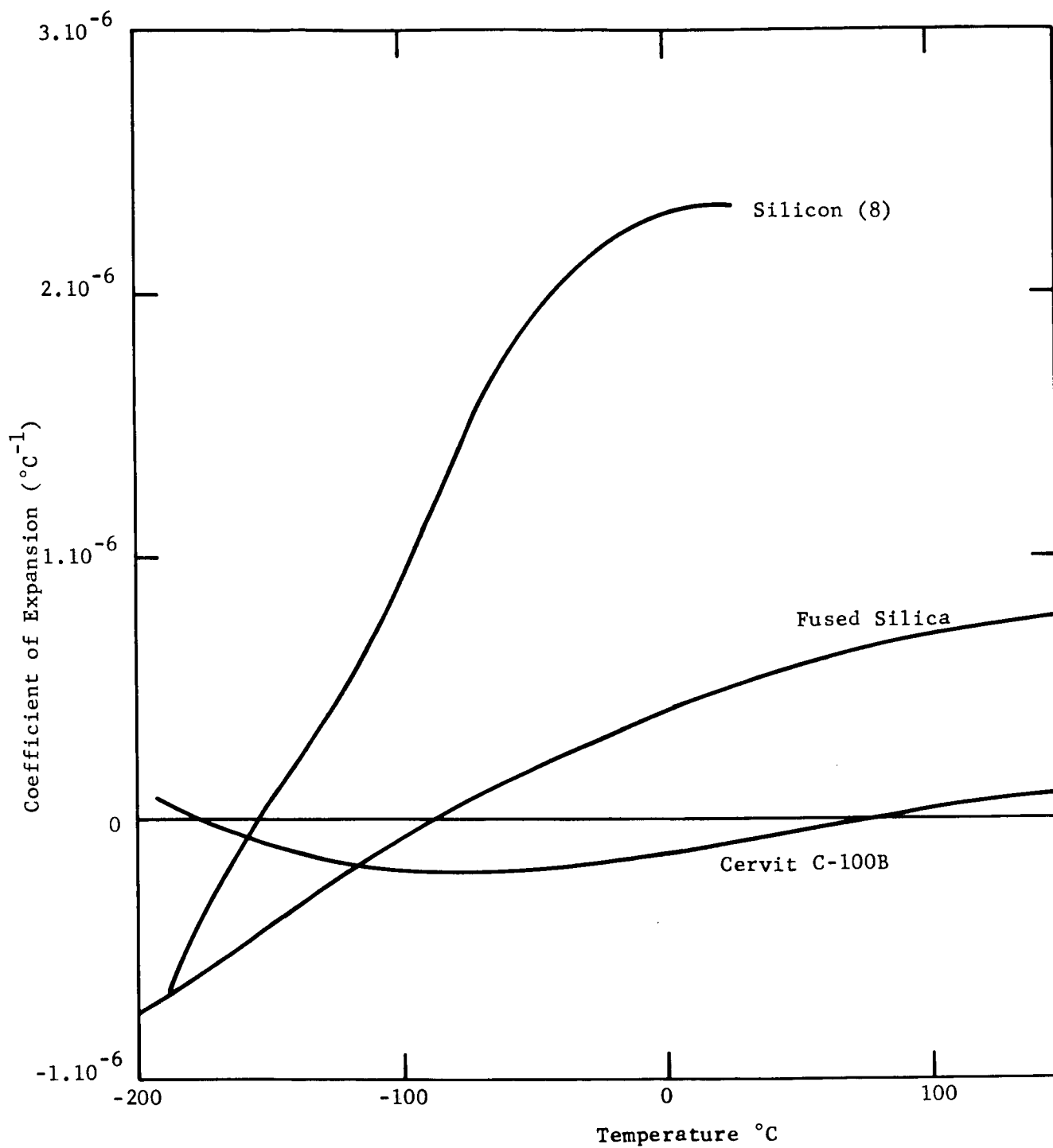


Figure 54. . . Coefficient of Expansion - Variation with Temperature

of the excess heat at an anomaly is almost always conduction. This can be illustrated by considering the change in radiative heat flux due to an incremental change in temperature which is given by:

$$\frac{dQ}{dT} = 4\epsilon\sigma T^3$$

where

dQ = incremental change in heat flux
 dT = incremental change in temperature
 ϵ = surface emissivity
 σ = Stefan-Boltzman constant
 T = absolute temperature

Taking a portion of the front surface of the mirror where the emissivity might be about 0.01 and the ambient 273°K,

$$\frac{dQ}{dT} = 1.1 \times 10^{-6} \text{ Cal/(cm}^2\text{) (sec) (}^\circ\text{K)}$$

Similarly, for a portion of the back surface of the mirror which might be painted black* to achieve an emissivity near unit (a potential design approach),

$$\frac{dQ}{dT} = 1.1 \times 10^{-4} \text{ Cal/(cm}^2\text{) (sec) (}^\circ\text{K)}$$

Assuming two points on a constant cross section with an incremental temperature difference between them to be a somewhat analogous situation for conductive heat transfer, then:

$$\frac{dQ}{dT} = \frac{K}{d}$$

where

K = thermal conductivity of the material

d = separation between the two points having the temperature difference.

The conductive heat path length required to balance heat dissipation due to radiation which, in turn, is due to conduction, can be determined by setting equations (1) and (2) equal and solving for d . For fused silica this amounts to 3000 cm for the case of a highly reflective front surface, and 30 cm for the case of a black back-surface. For most metals both numbers are over two orders of magnitude higher.

This type of comparison does not permit a rigorous classification depending on whether heat conduction or heat radiation plays the dominant role in dissipating heat from anomalous temperature regions. This is at least partially determined by the size and location of the anomaly, etc. However the comparison

* See Danielson, loc cit.

does indicate that radiative heat transfer is probably most significant in large, fused silica, eggcrate mirror structures. In this case, radiation serves to couple the front plate to the back plate and the back plate to its immediate surroundings (if it is not aluminized). Radiative heat dissipation probably plays a minor role in solid fused silica mirror structures which are aluminized front and back, and also in metal mirrors, whatever the configuration.

The amount of thermoelastic distortion accompanying a given temperature distribution is an extremely complex analytical problem* for any but the simplest physical configurations and temperature distributions. However, in situations where radiation rather than conduction plays the dominant role in dissipating the heat from anomalous temperature regions, and where a time dependent situation exists so that the volumetric heat capacity of the material is important, then $1/C\rho\alpha$ is a suitable mirror material criterion. For a dynamic situation involving conduction as the main heat transport mechanism then $K/C\rho\alpha$ appears to be a suitable criterion.

Dimensional Stability

Although mirror materials resistant to deformation in deleterious thermal and "g" force environments are desirable, the very possibility of a diffraction-limited telescope design depends upon the existence of materials that exhibit sufficient dimensional stability. If the operating temperature of the telescope is likely to differ from the ambient temperature at which the individual components are fabricated, then a second condition - that of an isotropic coefficient of expansion is necessary. If the latter condition is not met, then nominal changes in the operating temperature will warp the optical components and destroy the optical performance. Present evidence indicates that the stability and isotropy requirements of large telescope mirrors are so severe that suitable materials may be difficult to find; particularly in combination with desirable characteristics such as a high elasticity-modulus-to-density ratio and a high thermal-diffusivity-to-coefficient-of-expansion ratio.

One method of gauging the stability required in a large mirror is to compute the maximum strain in a mirror blank which, for some reason, has become bent so as to appear astigmatic. Assuming simple bending, then the maximum strain occurring at the front and back surfaces is given by

$$\epsilon_{\max} = \frac{4d}{D^2} \left(\frac{\lambda}{n} \right)$$

where

d = mirror blank thickness

D = mirror blank diameter

$\frac{\lambda}{n}$ = peak-to-peak mirror surface tolerance

*Thermal Deformations in a Satellite Telescope Mirror, L. Spitzer, Jr., and B.A. Boley, JOSA Vol. 57, No. 7 July 1967, p. 901

Taking Princeton's 36-inch Stratoscope mirror as an example, the RMS figure corresponds to about $\lambda/50$ at 5461A, which is equivalent to about $\lambda/20$ on a peak-to-peak basis. Assuming a dimensional instability tolerance equal to the figure error, and taking the mirror thickness as 5.5 inches, then from the above equation, the instability tolerance corresponds to a maximum strain of 2×10^{-8} . This is an incredibly small number. It lies at least two orders of magnitude below conventional material testing methods and illustrates the exceptional dimensional stability required by large diffraction-limited mirrors.

• Experimental Evidence of Instability

Generally speaking very little information is available on the dimensional stability of materials subject to low stresses and nominal temperatures. Of the available data, perhaps the most comprehensive is the research done by the M.I.T. Department of Metallurgy*,**. This work has included an investigation of dimensional changes occurring in a constant temperature environment as well as changes induced by cyclic temperature changes. The test specimens were rods 3/8 inch in diameter and 4-inches long, and included wrought and cast alloys of iron, aluminum, magnesium, copper, and nickel which had undergone various heat treatments.

The time stability of the various specimens was investigated for aging temperatures of 20°C and 70°C. Changes in specimen length were determined over the period of a year and were referenced to the length determined approximately 20 minutes after completion of the last step in the heat treatment. During the first 24 hours, dimensional changes were found to occur in nearly all the test specimens. Subsequent changes measured one month and twelve months after heat treatment varied widely from the experiment accuracy limit (± 3 microinches per inch) to 45 microinches per inch for one aluminum alloy. All groups of alloys were found to exhibit some instability with deformations of 10-microinches per inch being fairly common. Aluminum and invar were among the most unstable materials. For invar, it was concluded that room temperature changes are attributable to lattice changes in the austenite phase and to the relief of residual stresses***. Stability was enhanced by heat treatments aimed at stress relief and by reduced carbon content. Several combinations of aluminum alloys and heat treatments were found to be stable. Commercially pure aluminum proved to be too soft for the measurement technique.

The stability of alloys in a changing thermal environment was gauged by measuring changes in the test specimens after ten temperature cycles between 20°C and -70°C. A large spread was apparent in the results. Aluminum alloys exhibited a change ranging up to 190 microinches per inch.

*Jarosh, J.J., "The Dimensional Stability of Metals," August 1950, Instrumentation Laboratory, Massachusetts Institute of Technology.

** Lement, B.S. and B.L. Averbach, "Measurement and Control of the Dimensional Behavior of Metals," Instrumentation Laboratory, Massachusetts Institute of Technology.

*** Lement, B.S., B.L. Averbach, and Morris Cohen, "The Dimensional Behavior of Invar," Trans. Am. Soc. Metals, 43, 1951

Intercomparison of nine standard-meter bars by the National Bureau of Standards has also provided some information on material stability*. Comparative measurements carried out over the past twenty years to an accuracy of about 0.1 micron have shown that the length of the four platinum-iridium standards of length have remained within the accuracy of measurement; but, the standards composed of other alloys have varied appreciably. Meter 752 (Fix invar) has shown an approximately linear shrinkage with time amounting to over 7 microns in a twenty-year period, whereas meter 39 (invar) and meter 153R (42% nickel-steel) have expanded about 4.5 and 1.5 microns respectively. Measurements on meter 39 which extend over a period of nearly half a century indicate that the rate of change has decreased by about a factor of three or four since this standard was first acquired.

More recently, Meyerson et al, have examined the stability of gauge blocks using an interferometer**,***. Instabilities in the order of one-microinch per year were found to be relatively common; however, a number of materials were found that fell within the NBS goal of 0.2×10^{-6} per year.

Meinel has investigated the performance of aluminum mirror†. All of the large aluminum mirrors tested showed a figure degradation at low temperatures and, in one case, the figure loss was permanent, resulting in an edge curled above and below the mean surface by 0.003 inch.

The stability criterion used in judging the M.I.T. test specimens, and the NBS meter bars and gauge blocks was the absolute change in length in one direction. This criterion is not directly applicable to the mirror problem, since a uniform change in all directions would alter the size but not the figure of a mirror. Directional nonuniformity is inferred by the generally accepted theory that stress relief and metallurgical instabilities are chiefly responsible for dimensional changes, since there is no reason to believe that stresses or concentration gradients are symmetrically arranged in all structures. The Stratoscope mirror and the aluminum mirrors tested by Meinel provide data which are directly applicable to the mirror materials problem. Data for the former include tests conducted after the mirror had withstood the rigors of an extended operational period. This showed the figure to be virtually unaltered and indicates that fused silica is an exceptionally stable mirror material. Meinel's experience with aluminum mirrors does not indicate that aluminum is a promising telescope mirror material.

* Page, Benjamin L., "Calibration of Meter Line Standards of Length at the National Bureau of Standards," J. of Research of the National Bureau of Standards, Vol. 54, No. 1, January 1955.

** Meyerson, M.R., T.R. Young, and W.R. Ney, "Gage Blocks of Superior Stability: Initial Developments in Materials and Measurement," Journal of Research of the National Bureau of Standards, Vol. 64C, No. 3, July - September 1960.

*** Meyerson, M.R. and M.C. Soloi, "Gage Blocks of Superior Stability: III: The Attainment of Ultrastability," Trans. ASM, 57, 164 (1964).

† Meinel, A.B., "Report on the Optical Performance of Aluminum Mirrors," Unpublished, August 20, 1962.

- Anisotropy

Beryllium is an example of a material which has limited usefulness in telescope mirror blanks because of its anisotropy, even though its other properties are outstanding. Usually beryllium components are fabricated using powder metallurgy techniques since this removes much of the anisotropy inherent in the close packed hexagonal crystal structure. However, a small amount of anisotropy always remains depending on the particle size, geometry, fabrication technique, etc. Jennings et al,* using 1.25-inch cubes covered with resistance strain gauges, have determined the anisotropic thermal expansion coefficient produced by a variety of fabrication methods. This ranged from $0.05 \times 10^{-6}/^{\circ}\text{F}$ for some hot-pressed beryllium to $1.15 \times 10^{-6}/^{\circ}\text{F}$ for heavily worked forged beryllium. Taking the smaller value, which was close to the limit of experimental accuracy, then the maximum temperature excursion that could be tolerated by a 36-inch, $\lambda/20$ beryllium mirror amounts to only 35°F . Since the average anisotropy in a large mirror blank might reasonably be expected to be larger than in a 1.25-inch cube, the 35°F temperature estimate may be generous. Beryllium can therefore be excluded from serious consideration as a spaceborne mirror material because of its anisotropy and the large temperature excursions normally encountered by such mirrors between the testing and operating environments.

The stability of beryllium is a matter of some controversy. Atwood et al** have shown that cooling the anisotropic crystalline structure of beryllium from the phase transition temperature leads to 10^{10} times more strain energy than is required to strain a one-meter diameter mirror out of tolerance.

- Spontaneous Relaxation Mechanisms

The various mechanisms responsible for material instabilities are not well understood. Impurities or the presence of alloying elements can contribute to spontaneous changes in a variety of different ways***. These include phase changes resulting in different allotropic forms, precipitation of a second phase from solid solution, ordering of interstitial and substitutional atoms, grain boundary migration, and movement of magnetic domain walls. Even if the impurities remain segregated, then stress concentrations around the impurities caused by coefficient of expansion differences can cause plastic deformation of the host lattice. In the unlikely event that impurities are absent, then the relaxation of stresses originating from temperature differences in the casting during its formation in the mold can also cause spontaneous plastic deformation.

* Jennings, C.G., A.G. Gross, L.E. Colteryal, "Dimensional Stability and Thermal Expansion Characteristics of Beryllium," presented at the International Symposium of Beryllium Metallurgy and Technology, September 1964.

** Atwood, J.G., P.H. Lee, J.B. Schroeder, P. Forman, "Optical Materials Study," Perkin-Elmer Report No. 8028.

*** Holden, F.C., "A Review of Dimensional Instability in Metals," Defense Metals Information Center, Battelle Memorial Institute, Memorandum 189.

No hard and fast rules exist for the selection of dimensionally stable materials. It is known that yield in crystalline materials occurs through the motion of dislocations through the crystal lattice and that the number and mobility of dislocations varies widely depending on the binding energy between atoms, the lattice structure, the stress distribution, and the type and concentration of impurities*,**. Apart from glasses, which have a low thermal conductivity as a result of the amorphous molecular structure***,† the most promising mirror materials appear to be pure elements or compounds which form light, hard, cubic crystal lattices. A light crystal lattice is most likely to have a high elastic-modulus-to-density ratio and the immobility of the dislocations is exhibited in the bulk lattice as hardness. A cubic lattice ensures that the crystal is isotropic whereas hexagonal lattices are almost always anisotropic as, for example, in the case of beryllium.

• Silicon as a Mirror Material

Inspection of the top of the Periodic Table reveals lithium, beryllium, boron, sodium, magnesium, and aluminum as possible mirror metals. Only aluminum, sodium and lithium are cubic, and all are too soft to be useful. Both the transition elements, carbon and silicon, possess cubic lattice structures but the cubic form of carbon (diamond) has very obvious economic drawbacks. Silicon has found application as an optical material for infrared components such as lenses and domes. Polycrystalline silicon can be ground and polished using conventional curve generators and polishing laps.

The state of the art for silicon optical elements is about a tenth wave over a 12-inch-diameter surface. This sort of tolerance is characteristic of the best refractive optical elements, and implies a considerable degree of dimensional stability. Even more indicative is the work on a microscopic scale which has been done on the number, type, and velocity of dislocations in silicon crystals. The dislocations are generally rendered visible by an etching process which produces relatively large pits at the site of each dislocation. These can be observed directly at the surface of the specimen or internally by means of a decorating technique which coats the inside of each pit with an infrared absorbing precipitate. The motion of dislocations is a very sensitive vernier for the measurement of plastic strain. For example, in a single crystal having only one dislocation, a strain corresponding to one atomic distance would require motion of the dislocation from one side to the other of the crystal.

Silicon crystals typically have very few dislocations (10^1 - 10^3 per cm^2 as compared to 10^9 - 10^{12} for aluminum, etc.) and these appear to be frozen in

* Hume-Rothery and Raynor, "The Structure of Metals and Alloys," The Institute of Metals, No. 1, 1956.

** Barrett, Structure of Metals, McGraw-Hill, 1952.

*** Stanworth, Physical Properties of Glass, Oxford at the Clarendon Press, 1950.

† Morey, G.W., The Properties of Glass, Reinhold Publishing Corporation, 1938.

the lattice at temperatures below 500°C. As a result, when the yield strength of silicon is exceeded, it results in brittle fractures rather than bent or elongated test specimens characteristic of plastic deformation. Experimental work by W.T. Read and G.L. Pearson* on the tensile strength of silicon whiskers and small silicon bars has indicated that the locking of the dislocations is due to oxygen of which there is apparently more than enough even in the purest test samples. The immobility of dislocations in silicon at ambient temperatures is further supported by the work done by Chadburne, Patel, and Rubin,** who investigated the effect of stress and temperature on dislocation velocity.

* Read, W.T., Jr. and G.L. Pearson, Deformation and Fracture of Silicon - Dislocations and Mechanical Properties of Crystals, John Wiley & Sons.

** Chaudhuri, A.R., J.R. Patel, L.G. Rubin, "Velocities and Densities of Dislocations in Germanium and Other Semiconductor Crystals," Journal of Applied Physics, Vol. 33, No. 9, September 1962.



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Report No. 8900

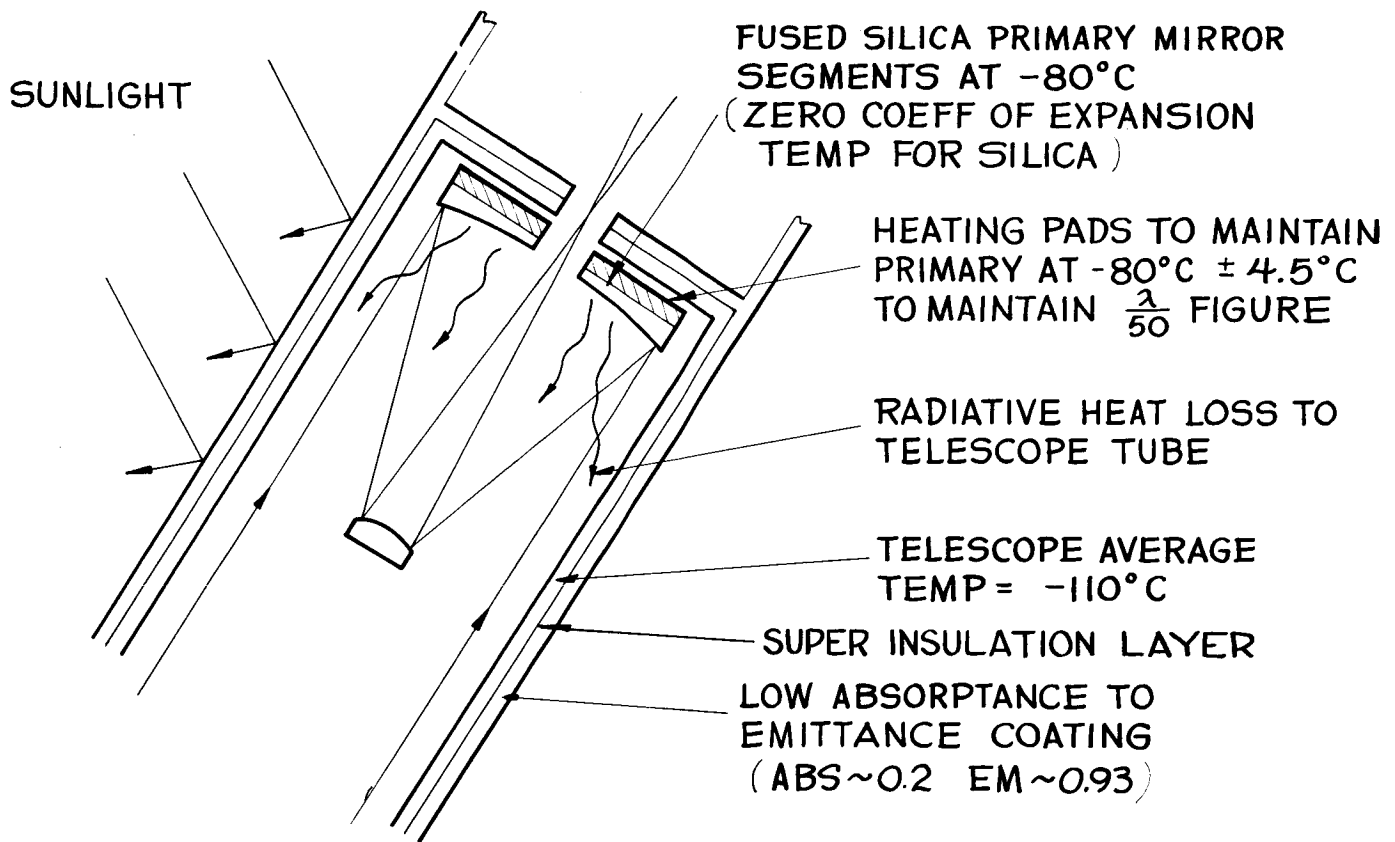
EXPERIMENT NO. 2 - SUPER COLD TELESCOPE

Figure 55

EXPERIMENT OBJECTIVE

If the temperature of the telescope structure and mirror are lowered to the point where the density of fused quartz is maximum (-80°C for Owens-Illinois fused quartz)*, then the mirror will be less sensitive to thermal gradients. Further, if the exterior of the telescope rejects most of the sunlight impinging on it, the thermal gradients themselves will be reduced. The objective of this experiment is to gather engineering data on a telescope structure and an optical system that are maintained at this low temperature, by passive means, over long periods of time on station in space. Surface coatings have been developed which have low absorptance-to-emittance ratios and, based on the utilization of coatings such as these, the very cold temperatures required for this experiment seem quite feasible and justifiable.

* Supporting calculations for a very cold mirror structure in a 260 mile orbit system and -80°F have been made by Lockheed and are presented in this report in Volume II.

BASIC EXPERIMENT HARDWARE

Since this experiment is an engineering evaluation of performance limits, no unique hardware is necessary. The telescope structure and the primary mirror thermal behavior at -80°C or as close to -80°C as can be obtained would be design considerations for the OTES.

EXPERIMENT JUSTIFICATION

The 1/50 wave rms figure performance of large-aperture optical systems in space is absolutely dependent upon the mirror behavior in the presence of thermal gradients. The sensitivity of optical systems to very small nonuniform temperature changes increases as the aperture diameter increases. The thermal analysis which determines the magnitude of mirror deformation can be found starting on page I-236 of Report 8500. This experiment is part of the search for space-worthy techniques which would minimize the sensitivity of the system to these unwanted thermal gradients and, at the same time, would lower the magnitude of the residual thermal gradients themselves. The need for this experiment will remain great until truly zero-coefficient-of-expansion materials are invented which are suitable for large-aperture optical systems. Zero coefficient of expansion, as it is used here, refers to materials which have $\alpha = 0$ at an achievable ambient temperature. Based on calculations performed during Phase I and IA of the OTES program, the ambient temperature will vary $\pm 20^{\circ}\text{F}$ over the year in space due to small changes in satellite attitude with respect to the solar vector. Therefore, while Owens-Illinois fused quartz has zero coefficient of expansion at -80°C , it is not considered a zero-coefficient-of-expansion material since the coefficient is finite at temperatures adjacent to -80°C as shown in Figures 56 and 57.

The problem of thermal deformation of the mirror figure is significantly eased if the mirror is operated around its temperature of zero thermal expansion. The advantage is illustrated by considering the deviation of temperature which expands a volume element 10 cm thick* by $\lambda/50 \approx 10^{-8}\text{m}$. This yields (for quartz at -80°C) a temperature range of as much as $\pm 4.5^{\circ}\text{C}$ in comparison to only $\pm 0.25^{\circ}\text{C}$ at room temperature for the 10-cm thick volume element.

This type of comparison was plotted for various candidate materials for space mirrors in Figure 47-49 in Experiment No. 1.

Specifically, great attention to thermal detail in the design of the spacecraft will be required to yield a temperature of -80°C for the primary mirror. If one considers the long life demanded of future large orbital telescopes, then additional means may be needed to heat or cool the primary to this optimum temperature as the exterior surfaces of the telescope age with the passage of time.

* If each mirror segment in Figure 14 is 0.76 meters (30 inches) from point to point of the hexagon, then a diameter-to-thickness ratio of approximately 8 would allow a mirror about 10 cm thick.

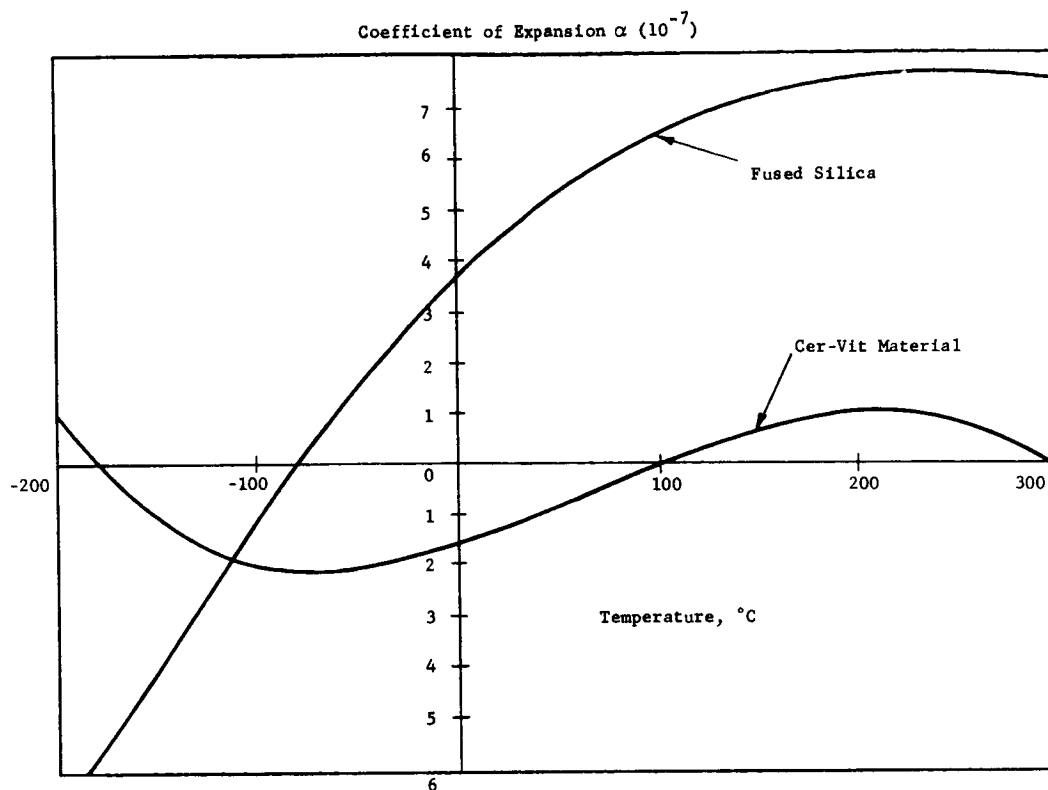


Figure 56. Thermal Expansion of Fused Silica and Low Expansion Cer-Vit Material

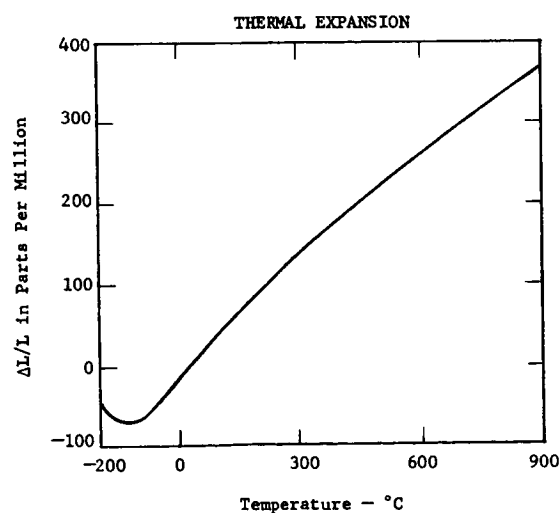


Figure 57. Corning Fused Silica Code 7940

For example, the following parameters relate to an f/3 paraboloid of quartz, 30-cm thick, 3 meters in diameter and made in one piece (i.e., not segmented). The tube of the telescope is assumed to have an average temperature of about -110°C (-165°F). A heating pad covering the entire back of the primary maintains its temperature uniformly at -80°C . The heat transfer from the primary to the "cold" tube should be only via radiation from the reflective coating (emissivity 0.05) and amounts to about 14 watts. The constant flow of heat from the back to the front of the primary entails a temperature distribution of uniform gradient in the quartz disk with a temperature difference between back and front of 0.3°C . The resulting thermoelastic deformation of the reflective surface was calculated. It consists of a turned up edge of the paraboloid but is of negligible magnitude. Even at a temperature which deviates from the optimum value of -80°C by $\pm 7^{\circ}\text{C}$ (i.e., -73°C to -87°C) the axial deformation, due to a front to back temperature difference of 0.3°C , is approximately $\lambda/50$.

The method of operating the primary at its temperature of zero thermal expansion has an experimental disadvantage when using active thermal control as described in Experiment No. 8. The isothermal approach of this experiment, and particularly the nonuniform temperature approaches of Experiment No. 8 and part of Experiment No. 1, are also useful to correct mirror-figure deformations which are not of thermoelastic origin (for instance, due to long-term stress relaxation). This thermal figuring capability obviously decreases when the thermal expansion coefficient (α) of the mirror material is reduced.

Note that the -80°C temperature which is specified for this experiment is optimum only for fused quartz #7940. This material is specified in the OTES for mirror segments number 1, 2, 6 and 7 as shown in Figure 58. The spacer rods between the primary and secondary and the secondary mirror itself are also specified as #7940 fused quartz and the -80°C temperature is optimum for these elements as can be noted by reference to Figure 47. The cervit mirror segment (segment number 5 should operate at either plus 100°C or -180°C as noted in Figure 48. Both of these temperatures are impractical for the 2-meter OTES in the 260 mile orbit and these temperatures are impractical for the 3-meter OTES or MOAT even at synchronous orbit altitudes. The mirror segment number 3, silicon, has an optimum ambient operating temperature of -160°C as noted in Figure 49. This too is an impractical operating temperature for an Earth orbiting telescope such as the 2-meter OTES. The mirror segment number 4, beryllium has an optimum ambient operating temperature approaching absolute zero as can be seen in Figure 50. Even the -269°C temperature (4°K) is not achievable for the Earth orbiting telescopes. Mirror segment number 6, fused quartz 7971, is of the ultra low expansion quartz (U.L.E.) and in theory this material can produce a zero coefficient of expansion crossing point at almost any point in the temperature scale. The specification for this mirror segment should be for a formulation of 7971 material which has a zero crossing point of -60°C in order to provide the technology data for future generations of specialized space telescopes such as the Princeton Advanced Satellite (PAS) instrument, or the future generation of OAO type of instruments.

The justification for the -80°C temperature specification for Experiment No. 2 as contrasted with the temperature specification of $+100^{\circ}\text{C}$, -180°C , -160°C , -269°C or even 0°C is to provide the maximum amount of technology data consistent with the need to provide the greatest degree of technological advance and reliability for the proposed 2-meter OTES flight.

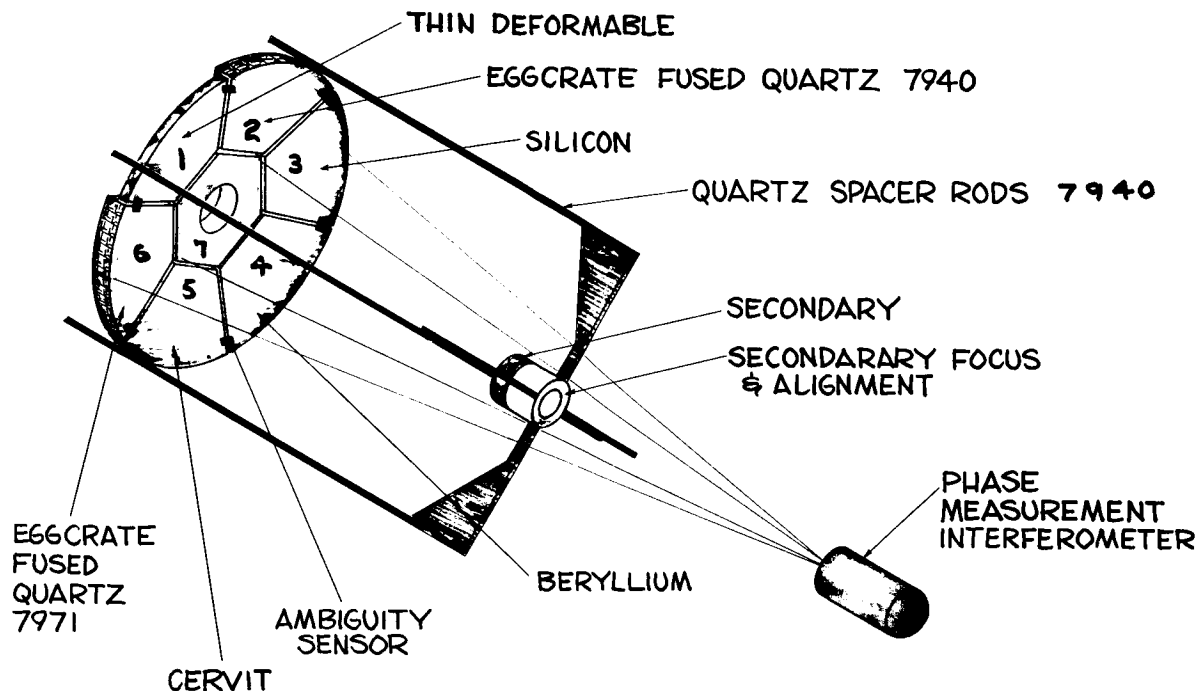


Figure 58. Segment Materials for Primary Mirror

TECHNOLOGY BENEFITS

The engineering evaluation flight of a large-aperture telescope structure and mirror operating at an ambient temperature at which the density of fused quartz is maximum, and the certification of the low-temperature gradients (obtained by rejecting most of the solar energy) would provide the technical approach for the giant space optical instruments of the future. The technology developed would influence the design of future large orbiting telescopes such as the MOAT.



PERKIN-ELMER

Report No. 8900

EXPERIMENT NO. 3 - UTILIZATION OF ASTRONAUT TO REPLACE OPTICAL
SEGMENTS AND SCIENTIFIC EXPERIMENTSTYPICAL EVA PROCEDURES:

1. ASSEMBLY of TELESCOPE
STRUCTURE
2. CHANGE SECONDARY
MIRROR
3. REMOVAL of MIRROR
SEGMENTS
4. MIRROR RECOATING
OPERATION

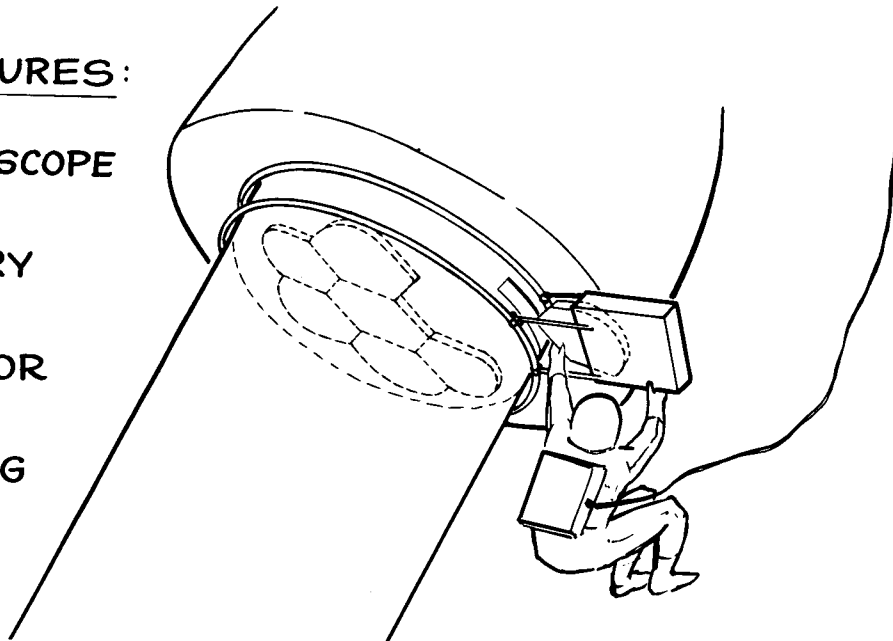


Figure 59

EXPERIMENTAL OBJECTIVE

The experiment objective is to develop the astronaut's skill in the operation and maintenance of large space optical systems. Thus, when the time comes to provide a MOAT, the astronaut optical skills will be developed by the OTES. The degree of astronaut participation will vary from minor troubleshooting to extreme involvement in the initial erection operations. On subsequent rendezvous with the OTES, major maintenance and configuration changes to the telescope optical system can be performed by the astronaut. For example, assume that an extreme focal length is required. The astronaut would select and substitute one of several different secondaries (available in the spacecraft) which could be used with the same primary mirror. The astronaut would also service the instrument by replacing the laser module B. He could change the analytical equipment or image-forming devices which are found in the focal plane of the OTES (see Figure 60).

Future large-aperture optical mirrors will be vulnerable to micrometeoroid damage, radiation damage, and coating deterioration when on station in space for many years. The ability of an astronaut to service the instrument by removing one of the damaged segments and replacing it with a new segment or recoating the segment, as described in Experiment No. 6, is a necessary step in the evolution of the future giant optical systems. Also, as described in Experiment No. 7 - Thin

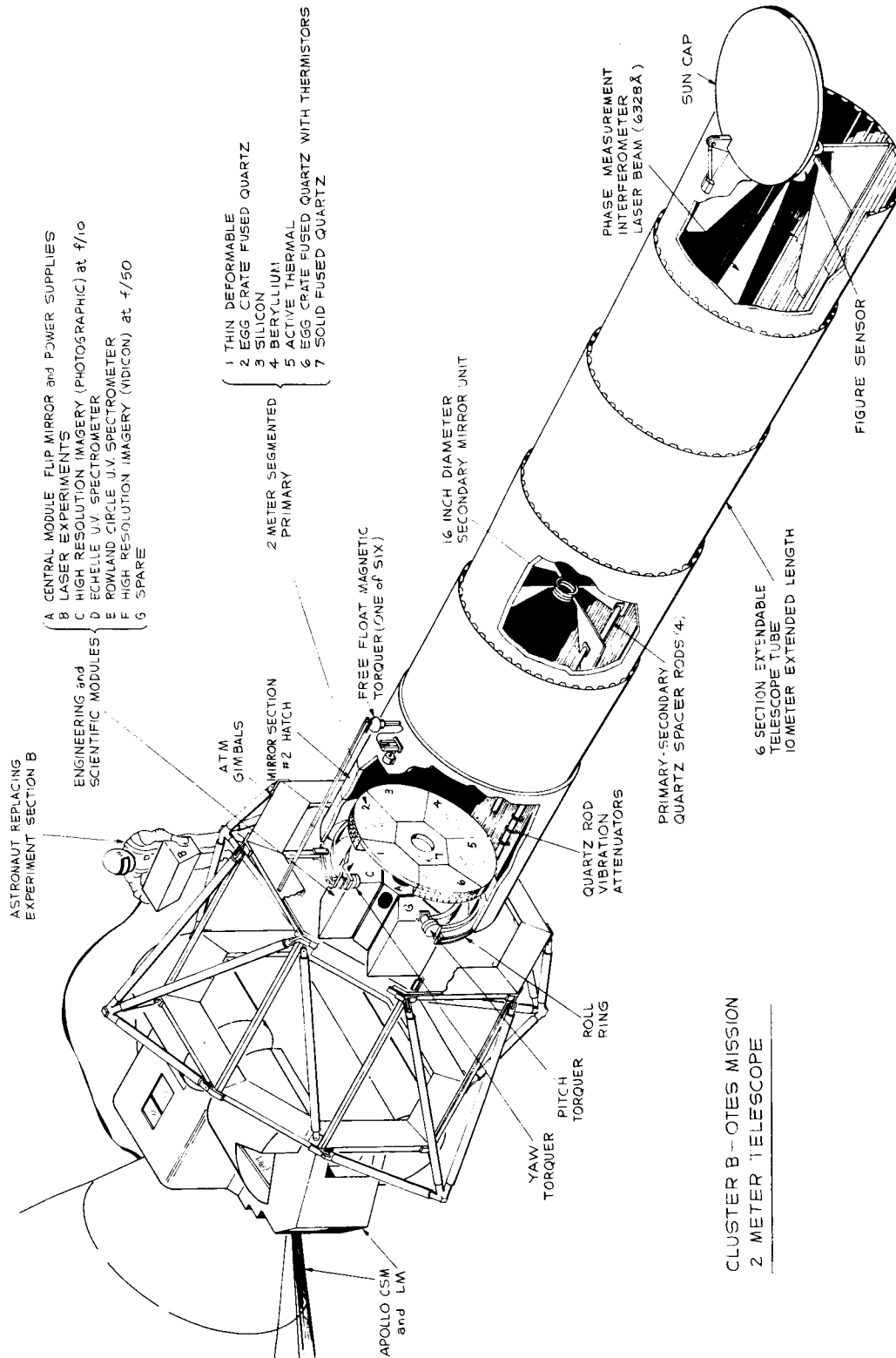


Figure 60. 2-Meter OTES with Astronaut Replacing Equipment Module

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Mirror, and in Experiment No. 4 - Scatterplate Test, the astronaut must demonstrate his utility in the servicing and maintenance of the primary mirror. It should be noted that at the end of the operations necessary to evaluate the various mirror segments described in Experiment No. 1, it will be the conclusion that some of the mirror segments are inferior to the balance of the segments. A future rendezvous would permit the inferior segments to be replaced so that the instrument could be used for scientific observations. This latter approach is dependent upon the astronaut having the capability in EVA to release and remove the inferior segment, and replace it with a new mirror segment as shown in Volume II.

EXPERIMENT JUSTIFICATION

Since the investment in a future giant-aperture telescope will be so large, it would be absolutely necessary to extend the life of the operating unit by routine and special maintenance operations on the part of visiting astronauts. The telescope would be too large to pressurize, so the astronaut would be required to develop the necessary EVA skills, and the equipment designed would be required to provide the astronaut with carefully engineered provisions for maintenance. This experiment would provide the development of the astronaut maintenance skills necessary for future space observatories.

The experiment justification is based on the need to develop techniques and procedures for the astronaut in the space stations of the future. The illustration shows the astronaut changing one of the segments of the primary mirror. Future space observatories will probably require recoating operations of mirrors in space since the ultraviolet reflectivity is maintained in a vacuum. Mirrors which are coated on earth have a serious loss in ultraviolet reflectivity by the time the optical system is on station in space. The ability of the astronaut to transfer mirror segments from the primary mirror to the space coating facility and then back into place as part of the primary mirror are the astronaut skills and procedures to be developed in this experiment. Details and additional illustrations of this experiment including time line analysis of astronaut operation can be found on pages II-56 to II-61 in the LMSC section of Perkin-Elmer Report No. 8500.

BASIC EXPERIMENT HARDWARE

The equipment needed for the astronaut to change primary mirror segments would be the special tools indicated by the final equipment design. In addition, some form of protective sheath might be required to house the large optical elements while they are being eased out of the telescope. The protective sheath for the mirrors would also be used in the reverse process of putting major optical elements back into the telescope.

EXPERIMENT NO. 4 - UTILIZATION OF ASTRONAUT TO MEASURE PRIMARY MIRROR
FIGURE WITH SCATTERPLATE TECHNIQUE

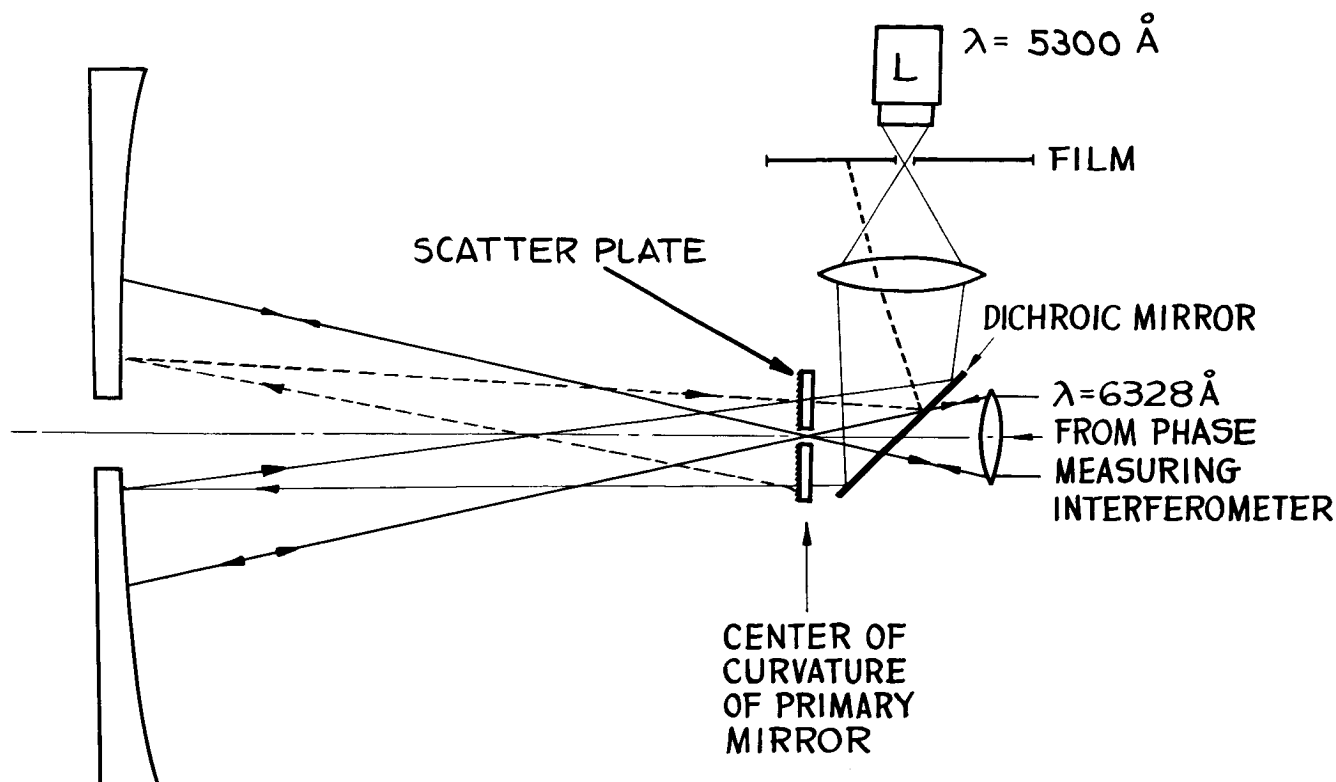


Figure 61

EXPERIMENT OBJECTIVE

Since the astronaut will be available immediately following telescope erection, he can use a small amount of additional apparatus to obtain scatterplate interferograms of the primary mirror. The interferograms would be recorded photographically as now done in the testing of the Stratoscope II mirror. The films could be developed in space using Bimat techniques, and preliminary interpretations of the quality of the interferograms could be established by the astronaut before concluding the space portion of the experiment. Although the astronaut could ascertain the contrast and general quality of the photographic interferogram, and, therefore, continue to expose scatterplate films until an adequate set of photographic plates was obtained, he would not be able to interpret the quality of the primary nor would he be able to telemeter the information contained on the plates back to Earth. The exposed plates would have to be returned to Earth with the astronaut for measurement, data reduction, and evaluation.

EXPERIMENT JUSTIFICATIONS

The utilization of the astronaut to provide certification of the quality of the primary would be of value, independent of the measurements of the figure sensor (from Active Optics) and independent of the figure measurement as described in

Experiment No. 5. The scatterplate photographs are much too difficult to obtain without human participation. However, astronaut time could be devoted to obtaining these interferograms. Their basic value in the OTES program, as presently envisioned, would be to provide the calibration of other figure-measuring techniques and certification of the quality of the primary mirror when it is on station in space.

EXPERIMENT PROCEDURE

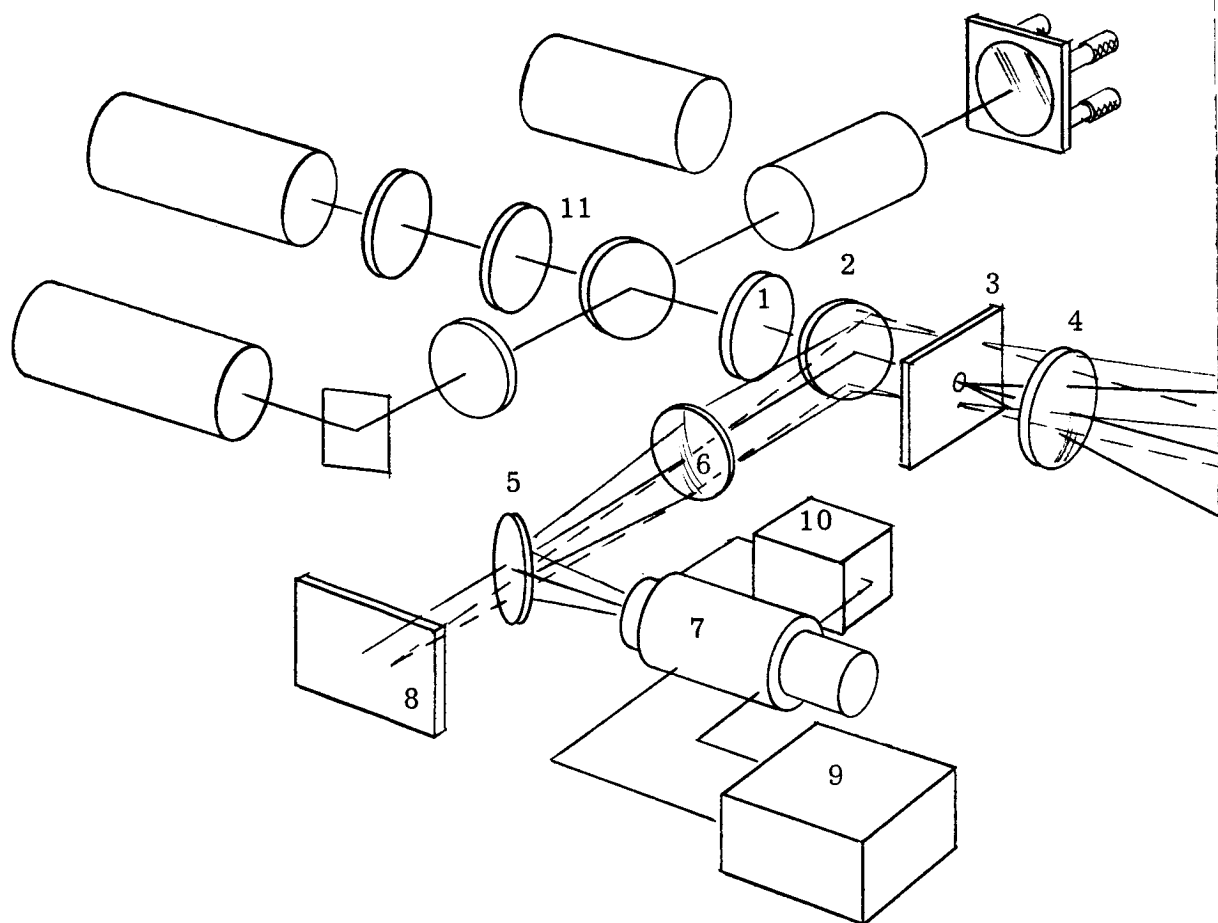
The astronaut can set up the scatterplate apparatus and expose the photographic film to obtain the scatterplate interferogram. The photographic plate could be developed in space and the astronaut could interpret the quality of the plate and continue to expose and develop plates until he had one of adequate contrast to take with him on his return to Earth. The plate would be measured and the data would be reduced back on Earth in order to certify the final figure of the primary mirror in space.

BASIC EXPERIMENT HARDWARE (See Figure 61)

The apparatus needed to conduct this experiment in space would include the auxiliary optical elements necessary to equalize the optical path distances from the scatterplate to the mirror surface (so that the mirror appears as an equivalent sphere to light rays leaving the scatterplate), scatterplates, photographic apparatus to record interferograms, and Bimat-type developing apparatus. The laser light source used in the figure-sensor equipment (Experiment No. 1) could be used as the illuminating source. However, since the laser is so small, a more convenient packaging arrangement would be to design an additional laser into the scatterplate apparatus unit.

The figure-sensing optics and servo control system can be combined with a scatterplate measurement of primary mirror figure using the equipment shown in Figure 62. The light (6328Å) from the phase-measuring interferometer is focused at the center of curvature of the primary mirror and passed through a small hole in the center of the scatterplate. Light from a small green laser (5300Å) is folded into the telescope optical axis by a beam divider and dichroic mirror and focused through the scatterplate onto a reference point on the primary mirror. The scatterplate affects a small portion of the incident light and scatters it over the entire mirror surface. Similarly, a small portion of the un-deviated return light is scattered on the second pass through the scatterplate. These two scattered components interfere to produce a circular fringe pattern on the photographic plate. The number of circular fringes recorded can be varied by displacing the scatterplate from the center of curvature of the mirror. The films will be developed in space to prevent damage to the emulsion by radiation exposure.

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1. Figure Sensor Focus Lens
2. Dichroic Mirror 5300A/6328Å
3. Scatterplate
4. Offner Corrector
5. 50% Beam Divider
6. Imaging Lens
7. Green Laser at 5300A
8. Photographic Plate
9. Laser Power Supply
10. Laser Cooling System
11. Phase Measuring Interferometer

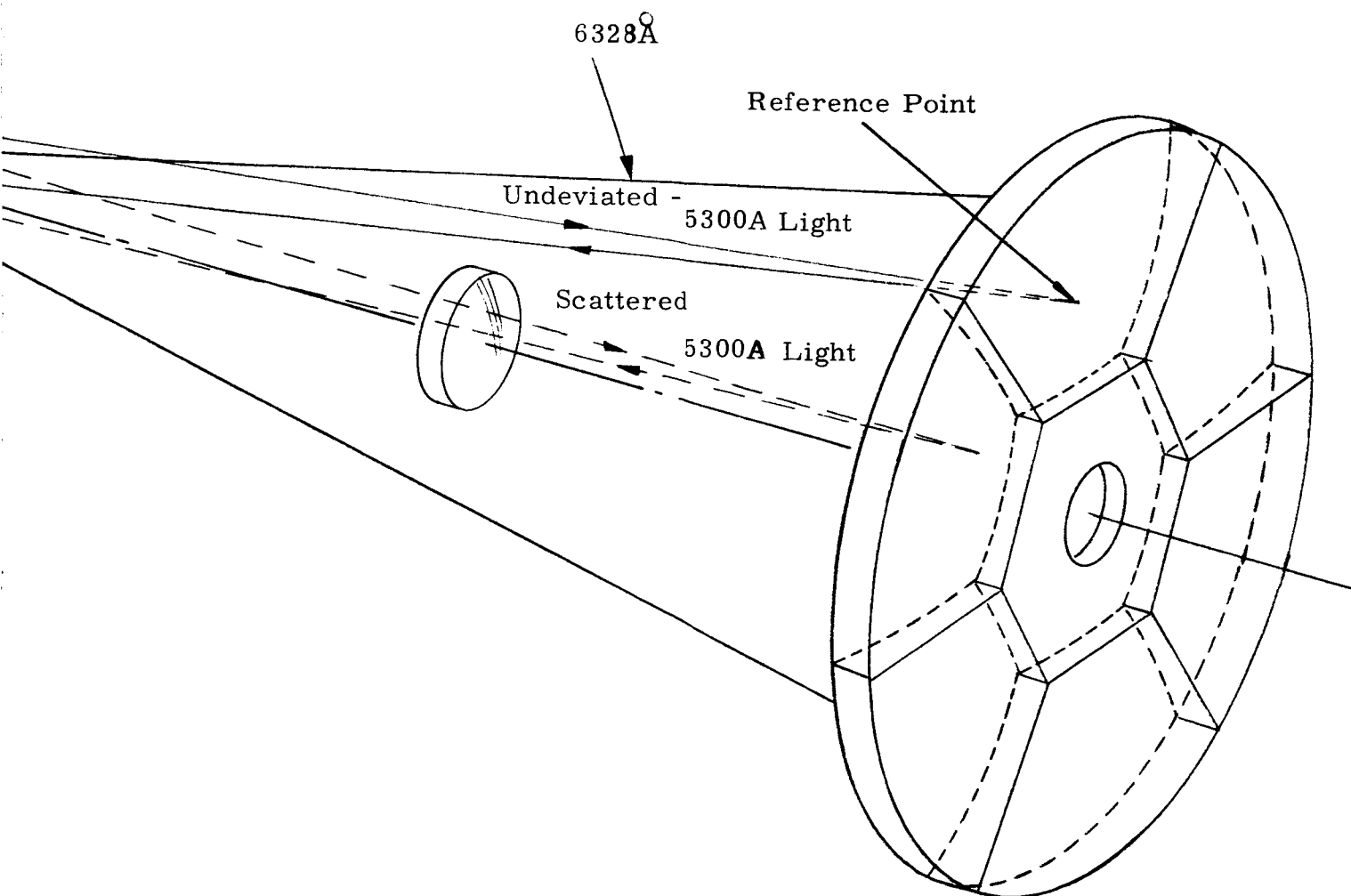


Figure 62. Scatterplate Figure Measurements

EXPERIMENT NO. 5 - MIRROR-FIGURE ASSESSMENT ON EARTH USING A SPACECRAFT LASER
(Deleted from the 2-Meter OTES)

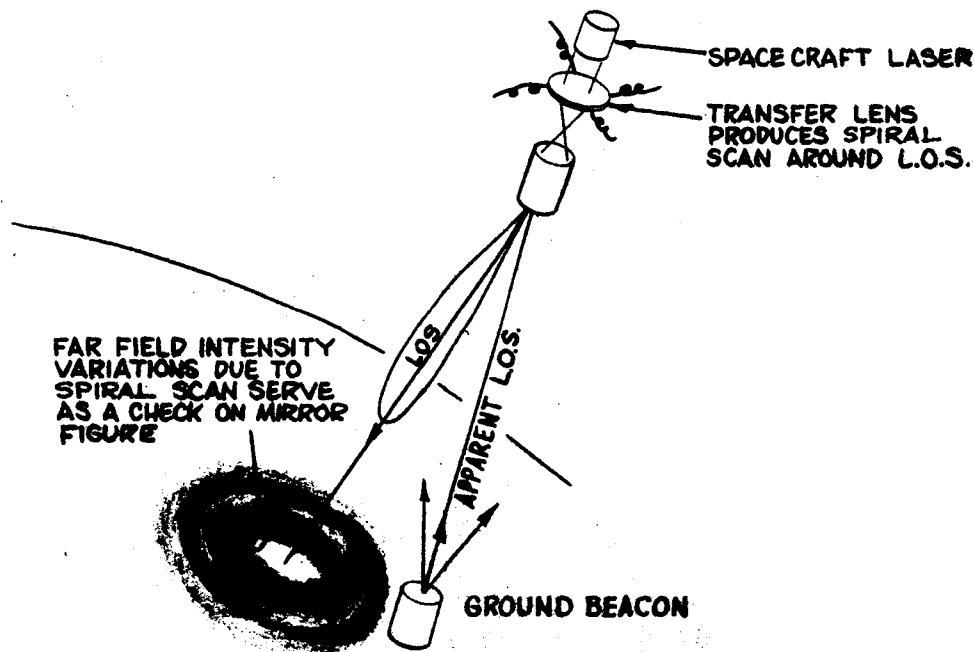


Figure 63

EXPERIMENT OBJECTIVE

The measurement of the Airy disk dimensions (and the associated intensity distribution of the concentric rings) of the spacecraft optical system can provide a quantitative evaluation of the performance of the optical system while the telescope is in space. These measurements can be made on Earth by utilizing a laser at the focal point and by steering the laser beam in a controlled pattern about the line of sight (LOS) of the uplooking telescope. Since the telescope in space is locked onto the Earth beacon which is adjacent to the uplooking telescope, and since the downgoing beam can be directed in a precise raster scan about the LOS of the Earth beacon, the uplooking telescope detector output can be correlated with the raster scan information. In this manner, a video-type display of the Airy disk of the spacecraft optical system is obtained.

This experiment cannot be conducted from a low orbit since the angular rate is much too high to permit locking onto the Earth beacon. For further details, refer to Perkin-Elmer Report 8500.

EXPERIMENT NO. 6 - MIRROR COATING FACILITY IN SPACE

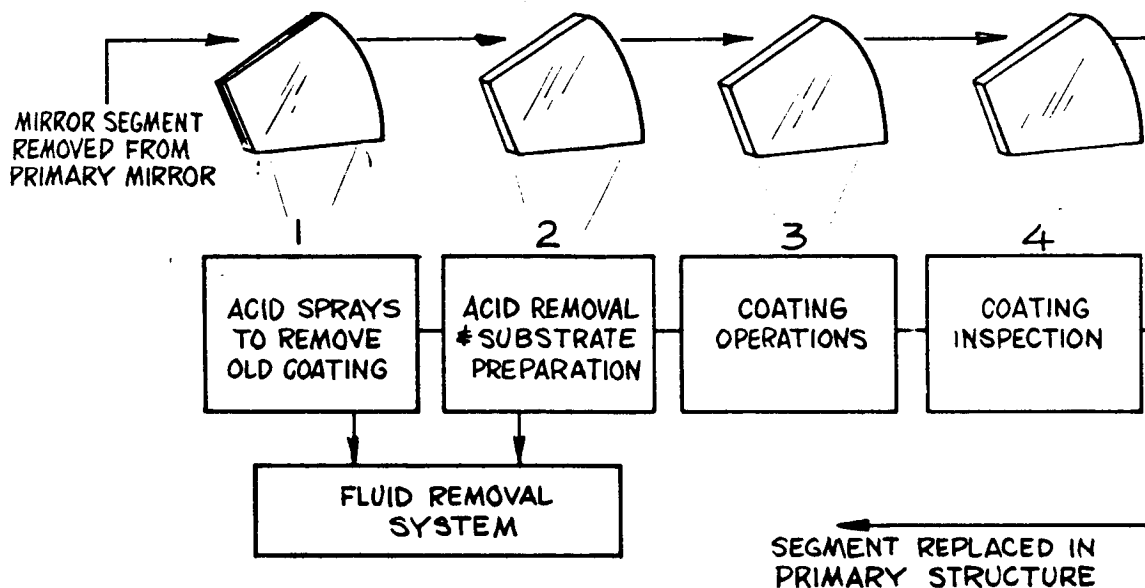


Figure 64

EXPERIMENT OBJECTIVE

To evaluate the effectiveness and utility of an equipment complex aboard the spacecraft which could accomplish:

- Removal of deteriorated reflective mirror coatings.
- Substrate preparation for new coatings.
- Application of new reflective coatings for mirrors.

EXPERIMENT JUSTIFICATION

It is a matter of practical experience that ultraviolet mirror coatings deteriorate significantly from the time they leave the coating facility until the time that they are in space. The long-time environmental effects of space equipment including rocket exhaust plume depositions, micrometeoroid impact, vacuum, and radiation are not known to date. However, it can be anticipated that even an adequate coating for one series of experiments will require alterations for other experiments. For example, enhanced reflectivity coatings are available for utilization with laser light. Yet, these coatings would be most inadequate for UV observations. Since a large-aperture telescope with a segmented primary would permit both the stripping of old coatings and special recoating operations, the proposed experimental facility would be of value. The equipment would be designed to function with astronauts in EVA removing mirror segments from the telescope and placing them in the recoating chamber.

The astronaut would then replace the mirror segments back in the telescope.
(Refer back to Experiment No. 3 and see page II-59 of Perkin-Elmer Report 8500.)

BASIC EXPERIMENT HARDWARE (See Figure 64 and Refer to Volume II, page ~~3-9~~ 50).

- Pressure chamber (which permits entry and exit of mirrors to be coated.)
- Structure and clamping arrangement to hold mirror in place.
- Acid sprayers (to remove old reflective surface and prepare substrate.)
- Neutralizer fluid sprayers.
- Fluid removal apparatus.
- Coating deposition apparatus.
- Coating inspection apparatus.

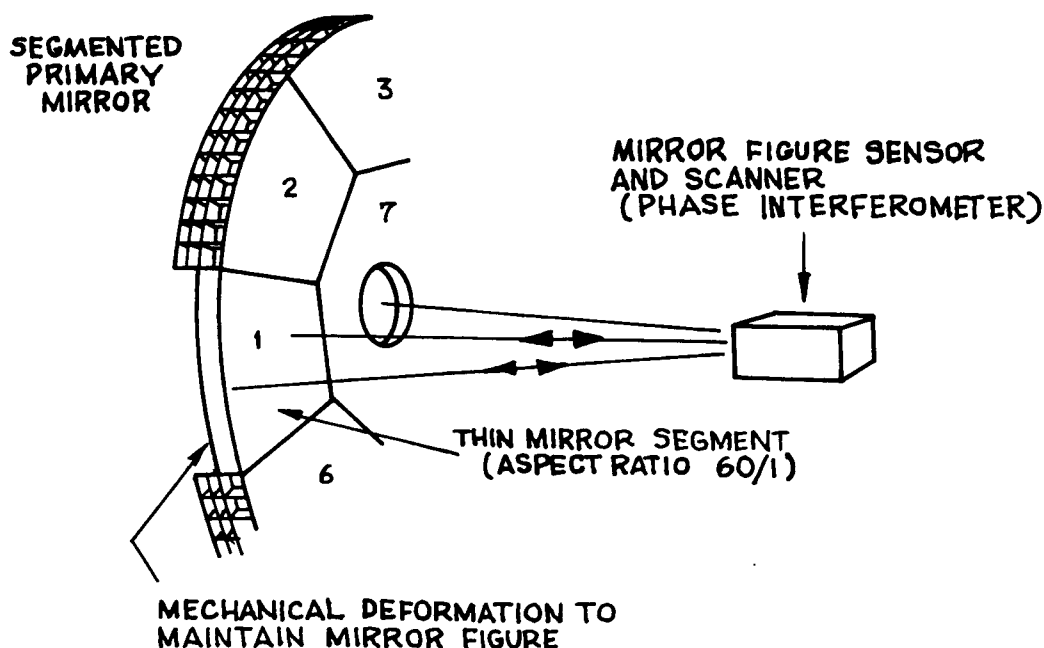
EXPERIMENT NO. 7 - THIN DEFORMABLE MIRROR

Figure 65

EXPERIMENT OBJECTIVE

A thin deformable mirror, which has advantages for use in space, has disadvantages. Its figure is most difficult to measure in the Earth's gravitational field. Using the rather elegant air bag support technique for the mirror* in uniform support, the deflections which still result can be large compared to the $1/50$ wave surface tolerance desired for diffraction-limited optics.** Therefore, the objective of this experiment is to provide the long-term monitoring of a thin mirror in the zero "g" field.

In addition, another objective for this experiment could be the attempt at figure maintenance of the thin mirror using active thermal control techniques, or mechanical deformation of the surface through the use of the active-optics-type of actuators. The active-thermal-control type of operation for figure maintenance is discussed in the following Experiment No. 8, and the approaches considered there are also applicable to thin mirrors. On the other hand, Figure

* See Figure 66.. The apparatus shown behind the mirror is the Perkin-Elmer developed equipment for the support of the OAO mirror in a 1 "g" field.

** For example, consider a thin beryllium f/3 mirror, 60 inches in diameter and 1.0-inch thick. (A mirror like this would be useful for laser communications at 10.6 microns.) This mirror would deflect to a steeper curve by 10 micro-inches at the edge even when supported on the "perfect air bag." Ten micro-inches corresponds to $\lambda/50$ at 10 microns.



Figure 66. Space Mirror Support Apparatus

maintenance of a thin mirror by mechanically stressing the mirror through the use of appropriate figure sensors and actuators is a part of the Primary Mirror Group discussed in Experiment No. 1. It is beyond the scope of the present project to consider either of these two special thin mirror approaches in the depth required to establish feasibility. Conceptually, these two thin mirror active optics approaches appear feasible and, for that reason, they are included here.

EXPERIMENT JUSTIFICATION

Thin mirrors have shorter thermal time constants than conventional eggcrate-type of mirrors. This might be a marked advantage for space astronomical instruments which are constantly subjected to changing thermal conditions when in orbit around the Earth. The "might be" factor of the previous statement depends upon the specific value of time constant appropriate to the mirror and the mission. Further, even with the large payload capability of the Saturn family of boosters, the weight of giant-aperture telescopes of the future is of concern. The thin mirror would provide the lowest weight possible. The weight advantage of a thin mirror would be useful for deep-space optical communication. The thin mirror should not be thought of only in the context of single contiguous surface mirrors, but, if the thin mirrors substantially outperform eggcrate-construction mirrors in the presence of spacecraft thermal gradients, the thin mirrors can be used as the individual segments of the Active Optics arrangement.

If we continue with the assumption that thin mirrors will have the better performance in spacecraft thermal environments, one can envision future space optical systems in which the mirror is manufactured on Earth as best we can in the one "g" field, launched, and then tested using the figure sensor of active optics (Experiment No. 1) to establish the precise figure of the thin mirror in the zero "g." Looking far into the future, the thin mirror could have its figure altered in space using the ion beam technique (Experiment No. 17), re-tested, and when the process is terminated, the figure of the mirror would be within the required 1/50 wave needed for diffraction-limited optics. The next step would be to have the astronaut remove the mirror from its mounting (Experiment No. 3) and place it in the coating apparatus (Experiment No. 6). After the application of the appropriate mirror reflector surface coating, the astronaut would reinstall the mirror segment into its proper location in the telescope.

The justification for this experiment rests on the need for a long period of time (at least 6 months) at zero "g" for testing a thin mirror.

TECHNOLOGY BENEFITS

The entire concept of the future space telescope, as described above in the experiment justification section, is completely dependent upon the long-term stability of a thin mirror in space and the validation of the theory that the thin mirror will outperform the eggcrate mirror in spacecraft thermal environments due to its shorter thermal time constant. A small thin mirror (less than 24 inches in diameter) might be tested on Earth using large drop towers such as the facility at MSFC, but the tremendous cost of a new facility for a really large mirror, when combined with the small amount of data collected from the

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operation, is prohibitive. It would be necessary also to conduct the tests over long periods of time (at least six months and preferably one to two years) before the microstability of the mirror is firmly established. All of these foregoing factors are space optical technology requirements, and the conduct of this experiment as part of the OTES program would provide the technological answers necessary to proceed with optical concepts for the 200-to 400-inch aperture, diffraction-limited telescopes for astronomy as well as the 1.5-meter aperture optical communicators operating at CO_2 wavelengths.

BASIC EXPERIMENT HARDWARE

The spaceborne equipment consists of the sample thin mirror which is to be monitored, and the figure sensor. The figure sensor may be the phase-measuring interferometer from the Experiment No. 1. Refer back to Experiment No. 1 for the block diagrams and equipment discussion of the thin deformable mirror (segment No. 1) in Figure 14.

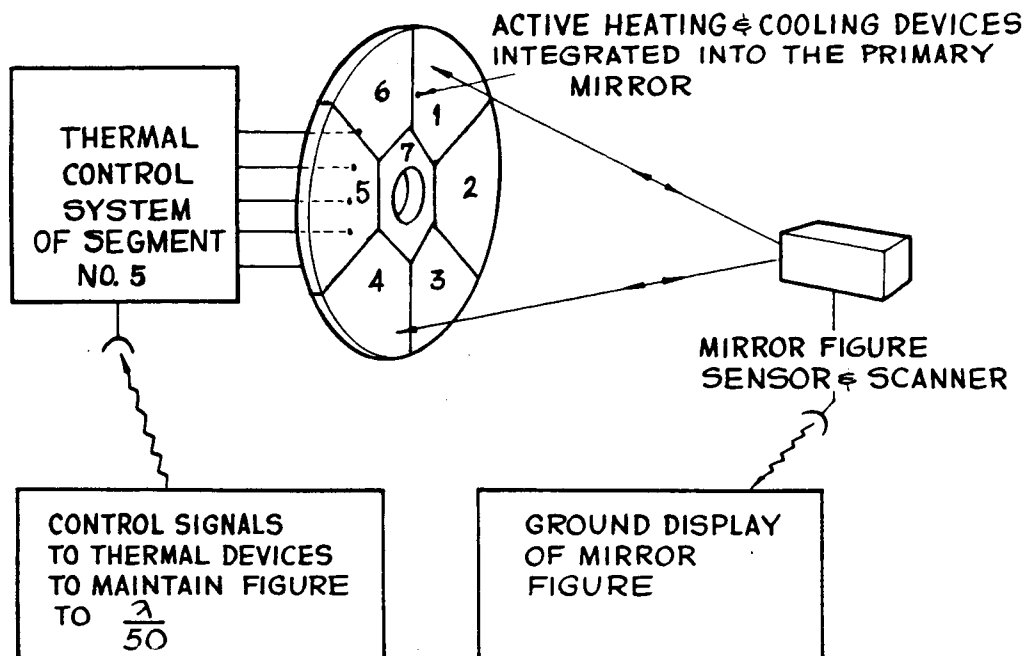
EXPERIMENT NO. 8 - ACTIVE OPTICS USING HEAT CONTROL

Figure 67

EXPERIMENT OBJECTIVE

The objective of this experiment is to monitor the figure of a suitably designed, special-purpose mirror segment using active heating and cooling devices, and to control the mirror thermal devices from the ground in coordination with a ground display of current mirror figure while attempting to maintain an overall rms figure of $1/50$ wave over the entire segment (#5).

EXPERIMENT JUSTIFICATION

It is clearly recognized that the need for a future, large, orbiting telescope will require some form of figure sensing (Experiment No. 1) and some form of active control to keep the figure of the mirror to $1/50$ wave rms. The segmented approach to Active Optics (Experiment No. 1) and the thin deformable mirror (segment 1 of Experiment No. 1) are two active approaches to the solution of maintaining diffraction-limited performance of a large-aperture optical system. A third approach is the utilization of heating and cooling elements integrated with the primary mirror system to force the mirror into an isothermal condition in the presence of undesirable thermal gradients. Active thermal control has been used successfully in France on an 0.8-meter ground telescope.*

*Beer, A.: *Vistas in Astronomy*, Vol. I, Pergamon Press, New York, 1955. p. 372.

The application of this approach to an orbiting telescope is considerably more complicated since the desired resultant figure is an order of magnitude (or two) more precise and the thermal environment is considerably more difficult. However, the technique itself is worthy of evaluation and, at this point in the OTES program, the preliminary analysis which has been conducted is sufficient to include the approach as a proposed experiment.

ACTIVE THERMAL CONTROL DISCUSSION

The nonuniform and constantly varying temperature environment of space will induce temperature gradients in a large mirror structure and, thus, deform the reflecting surface. The proposed experiment is concerned with various aspects of the solutions available to an equipment designer to correct thermoelastic figure deformations of a large mirror in orbit.

The approach described briefly in Experiment No. 1 is the technique of obtaining active optics through thermal control by using discrete heating (and/or thermoelectric cooling) cells in the back of the mirror. Such an arrangement cannot equalize a given nonuniform temperature distribution, but it can introduce appropriate additional thermoelastic deformations to the mirror in order to restore the figure of the reflective surface. Undoubtedly, this approach will involve complicated relations between the measured figure error and the appropriate activation of thermal cells.

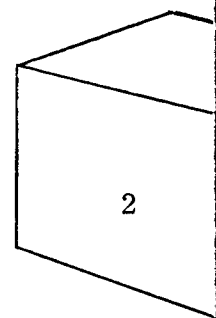
Additional ground experiment work is in order and should be performed before a space experiment is actually committed. A. Couder* in France used this approach some years ago for correcting mirror distortions which are symmetrical to the axis of the mirror. He has reported on the satisfactory correction of the "edge effect" by means of a circular heating pad applied to the back of a 0.8-meter mirror. The described "edge effect" is commonly encountered with Earth-based telescopes during the temperature drop of a night-time observation. The outer ring of the mirror disk adjusts itself faster to the environmental temperature than the center. This results in a "turned-down edge" of the optical surface. He found that a power of 3 watts into the heating pad corrected an "edge effect" of 1/2 wave. He also demonstrated with some knife-edge cut-off photographs that a power dissipation of 25 watts over-corrected the mirror and produced a pronounced turned-up edge.

The power necessary to implement the heating cell method described above for active thermal control of segment #5 has been calculated as less than 2 watts. This is based on the approach that the heat input required by the mirror is determined by the magnitude of the nonuniform part of the radiant coupling to the mirror from the telescope side walls and the open front end. Also, the thermal conduction through the mirror mount structure to the telescope and spacecraft structure can be controlled to negligible values. The telescope tube is relatively long as illustrated in the concept drawings for the 2-meter aperture telescope as shown in the Frontispiece.

The nonuniform heat input is due to absorption of the radiation from the nonuniformly heated tube of the telescope. This has been calculated by Lockheed to be a difference in temperature at the superinsulation surfaces inside the tube of 20°C at an ambient temperature of -110°C for the 3-meter mirror (see Perkin-Elmer Report 8500). For the 2-meter OTES mirror with its ambient temperature at -60°C, the difference in temperature at the superinsulation surfaces will be greater than 20°C.

*Beer, A.: *Vistas in Astronomy*, Vol. I, Pergamon Press, New York, 1955. P.372.

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1. Heating and Cooling Elements in or
of Primary Mirror
2. Figure Sensor
3. Secondary Mirror
4. Primary Mirror Support Structure
5. Tilt Alignment Actuators

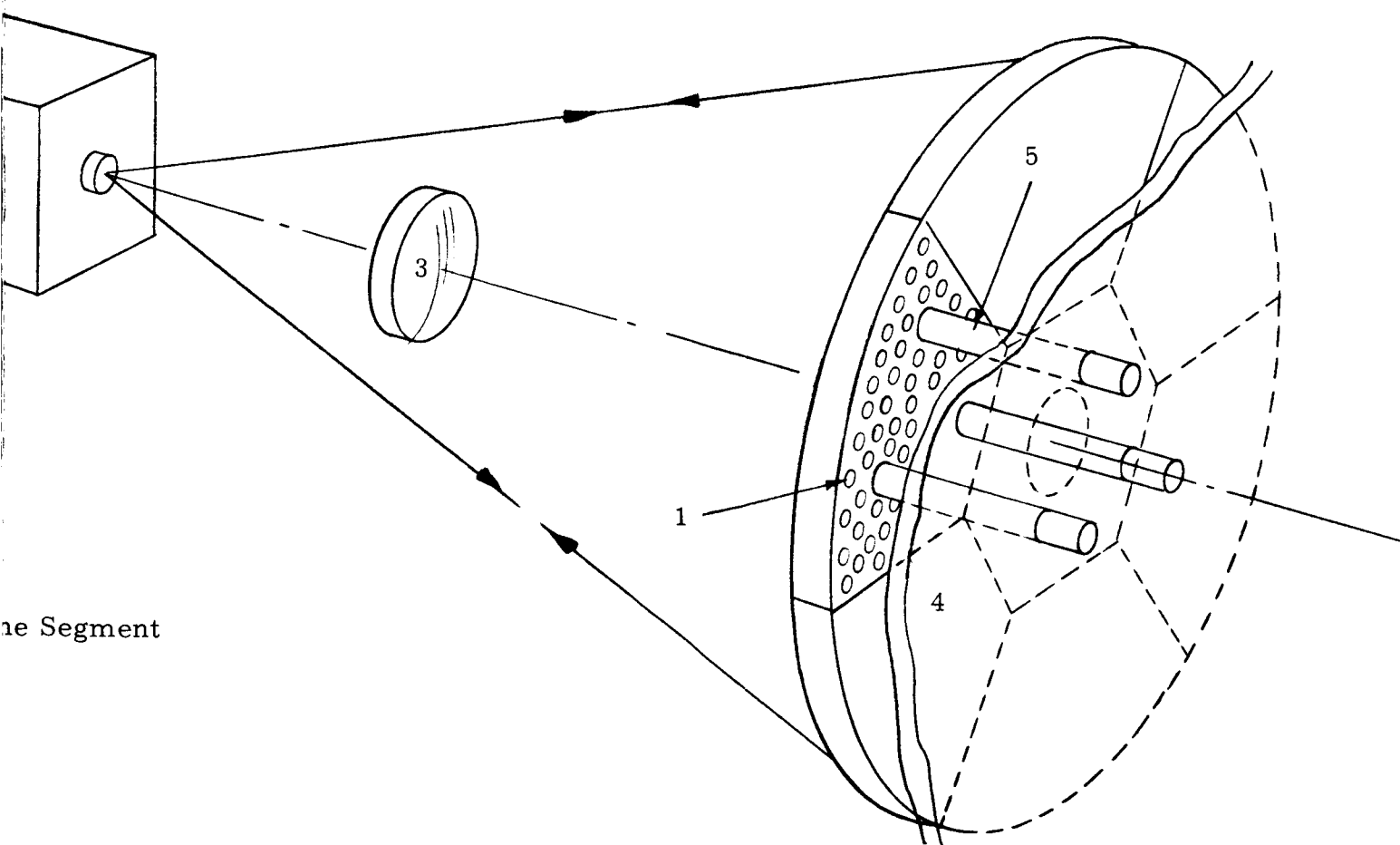
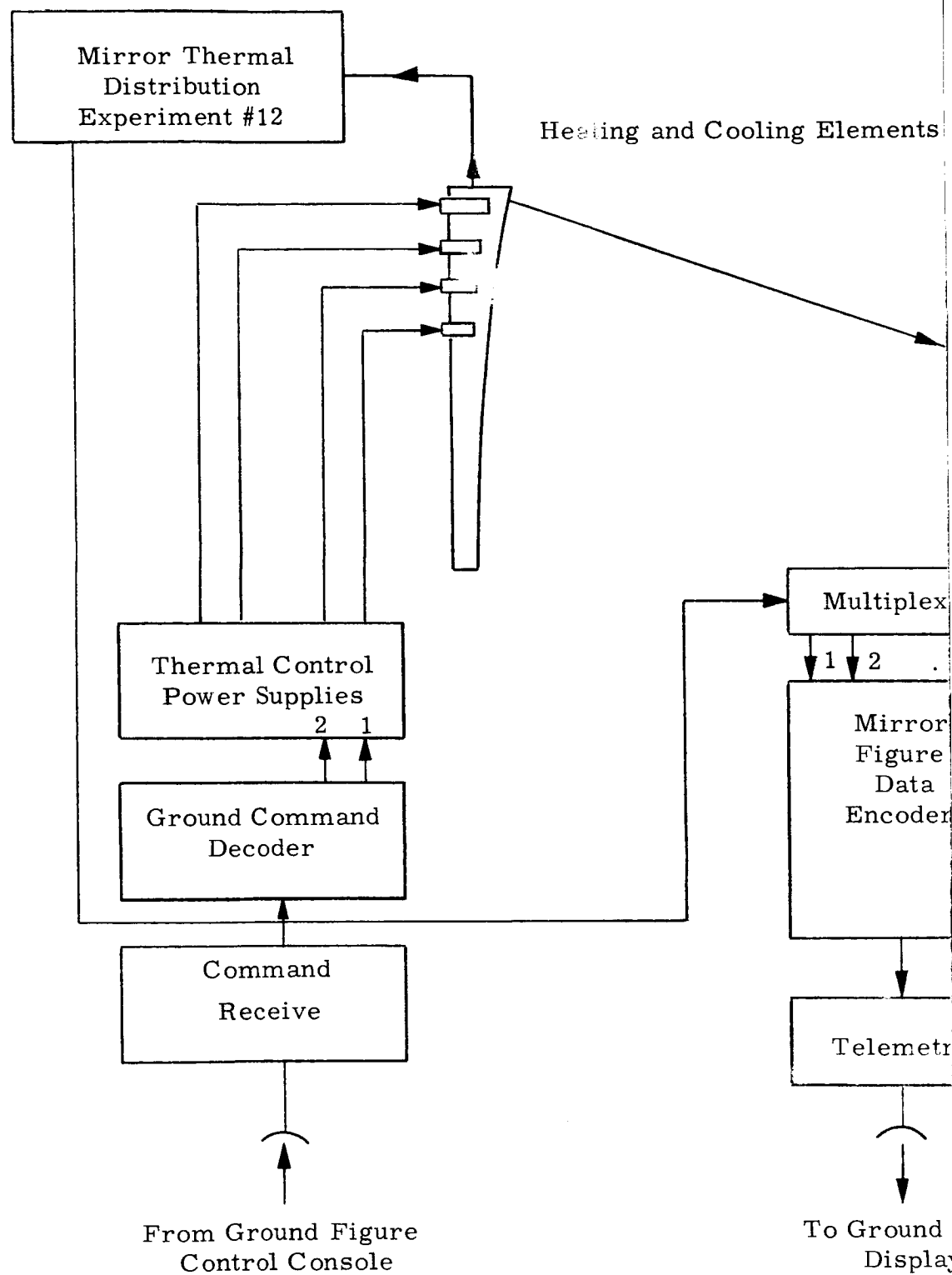


Figure 68. Active Thermal Control

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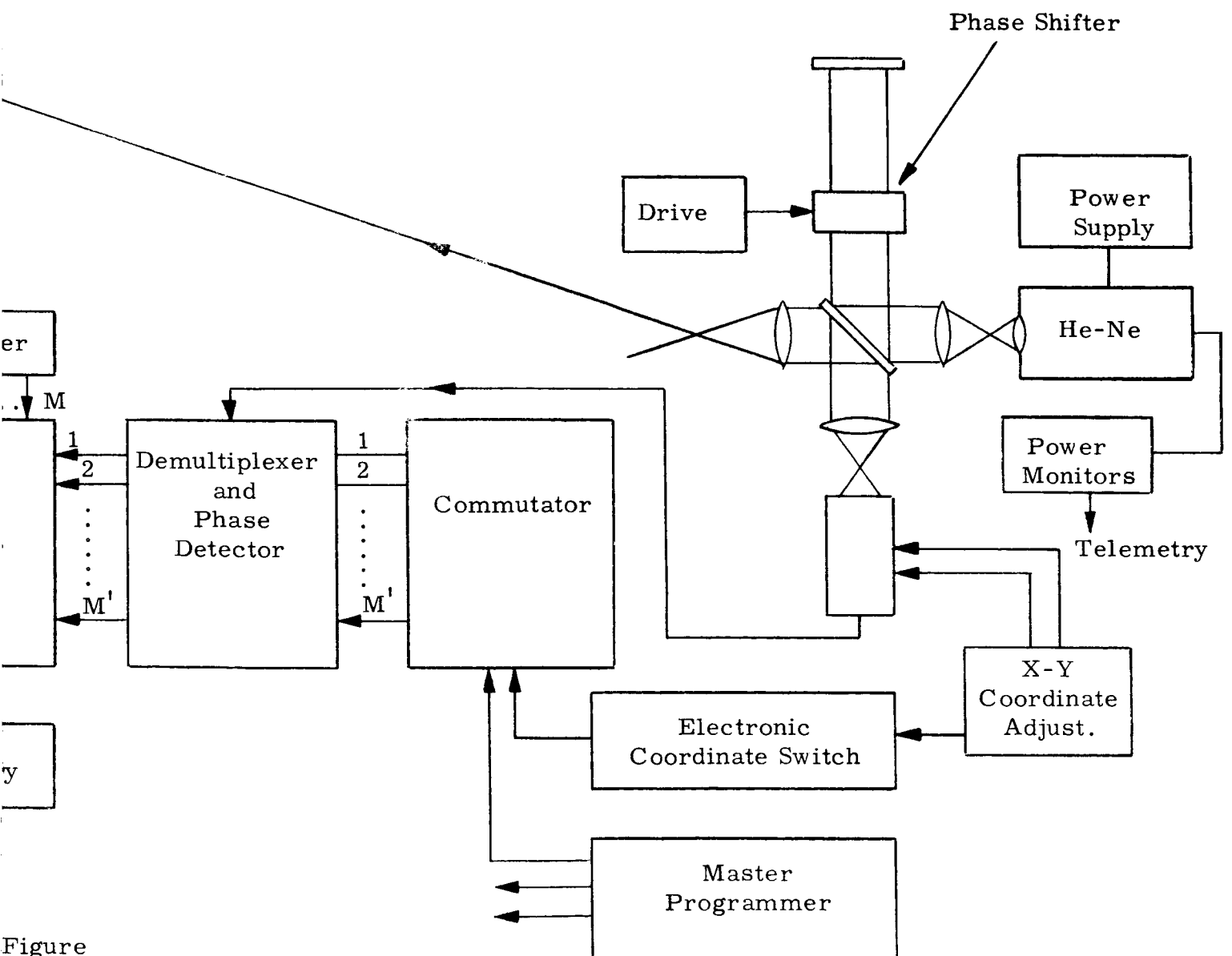


Figure 69.

Active Thermal Control

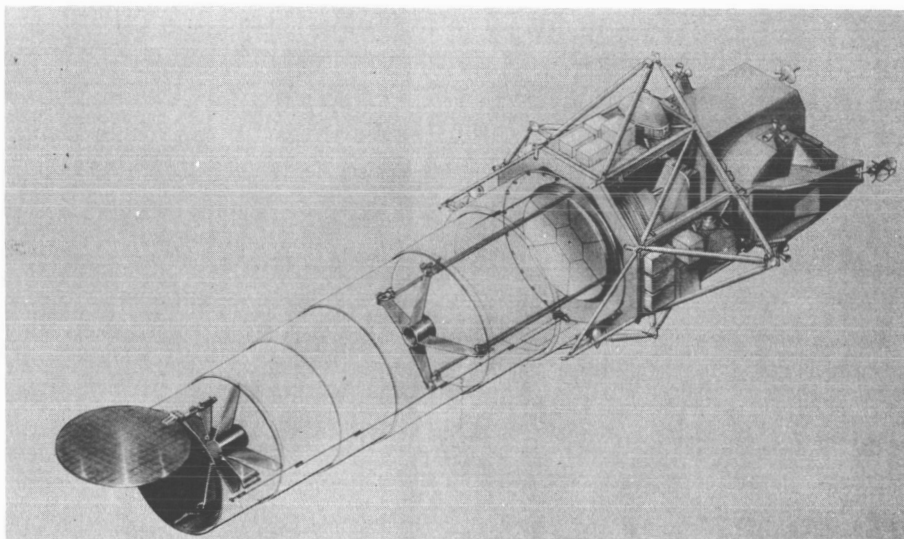
EXPERIMENT NO. 9 - 1/100 ARC-SECOND TELESCOPE POINTING TECHNOLOGY

Figure 70

EXPERIMENT OBJECTIVE

This experiment is concerned with the stringent requirements associated with 1/100 arc-second pointing of space astronomical telescopes.

The objective is to develop suitable space transfer lens techniques as well as body point techniques for orbital telescopes. The finest precision pointing techniques for large-aperture space optical systems are needed. This experiment will involve the compensation of pointing error sources and development of new technology to approach the pointing stability of 0.005 arc-seconds or less. This experiment can also provide knowledge of the design features required to optimize the pointing performance of an even higher resolution telescope such as the 3-meter OTES or MOAT with the corresponding improvement in pointing to 0.003 arc-seconds. Because of the low orbit, this experiment group must use stars as guidance targets but an attempt to use Earth laser beacons would be worthwhile.

EXPERIMENT JUSTIFICATION

Performing this engineering experiment in space can verify that 1/100 arc-seconds (or less) pointing systems can be reduced to practice and, therefore, permit the technical go-ahead of the generation of space observatories for the 1970-1985 period. The gathering of data of 1/100 arc-second pointing performance in the presence of orbital vehicle disturbances and during daylight as well as darkness provides the justification for this experiment.

In reality, Experiment No. 9 is a group of interrelated experiments that are all associated with the development of space optical technology, particularly in the area of ultra-fine pointing. The justification for conducting this group of experiments on the OTES is based on the principle that the performance of a precision space telescope is equally dependent upon both the stability of its guidance system as well as the quality of its optics. A diffraction-limited optical instrument in space is valueless unless there is a correspondingly precise pointing system.

There are very few pointing techniques that can provide the foundations for a space experiment in pointing to 1/100 arc-second or less. Specifically, the techniques are limited (to the best of our knowledge at Perkin-Elmer) to the following space telescope approaches:

- Transfer Lens Techniques (based on Stratoscope II laboratory and flight experience at Perkin-Elmer)
- Body Point Techniques with Free Float (based on Princeton Advanced Satellite laboratory experience at Perkin-Elmer)

This is obviously not a large basic inventory upon which to draw the concepts and designs for the future space observatory. Further, the transfer lens technique by itself does not handle the image rotational stability problem which is required for space astronomy. Rotational pointing operation about the line of sight (RLOS) requires expanding the list of the two techniques (above) to include RLOS approaches applicable to space telescope systems:

- Risley Prism Beam Orientation Techniques (which are only useful for laser communication experiments)
- Body Point Techniques with Vehicle Orientation (based on General Electric, Grumman and Perkin-Elmer experience)
- Body Point Techniques using Flexure Gimbals (based on Perkin-Elmer experience on Stratoscope II and ATM)
- Image Motion Compensation Techniques such as used in reconnaissance systems (Perkin-Elmer and three other camera companies in the U.S. are leaders of these techniques)

The Perkin-Elmer approach to Experiment 9 for the 2-meter OTES is based on conducting space flight experiments in 1/100 arc-second pointing using the instruments packaged into the Equipment Modules (located behind the primary mirror as noted in Figure 70) for independent experiments. Thus, Experiment No. 9 for the 2-meter OTES is considered to be a group of experiments which will provide the comparative data on the performance of the different precision pointing techniques that are likely to be used in the space telescopes for the

next two decades. These flight experiments will be independent of each other as much as practical to provide long-term flight reliability through individual redundancy. Further, each of the experiments will be conducted four times to accommodate the combinations of daytime-nighttime operations and cluster-autonomous mode operations.

The instruments which are used to gather the data on the fine pointing experiments are spectrometers, image systems and laser communication equipment. It is obvious that these instruments, in the individual equipment modules, can be used to gather astronomical data following the technology experiments. Imaginative use of these instruments, by the directors of space flight operations, will ensure achieving superior optical technology experiments.

The justification for the conduct of this group of experiments in 1/100 arc-second pointing is summarized below:

EXPERIMENT NO. 9 POINTING TECHNOLOGY

- | | |
|------------------------------|---|
| Transfer Lens Techniques | • Experiments with lasers with Equipment Module A |
| | • Experiments with Astronomical Film Imagery with Equipment Module B |
| | • Experiments with Astronomical Electronic Camera Imagery with Equipment Module E |
| Body Point - Free Float | • Experiments with Echelle spectrometer with Equipment Module C |
| Body Point - Flexure Gimbals | • Experiments with Rowland Circle spectrometer with Equipment Module D |

Today, despite existing calculations, no one can predict with reasonable certainty the pointing behavior of a large telescope pointing to 1/100 arc-second in the presence of the man and natural orbit disturbances, and with the effect of scatter from sunlight in space. Also, a necessary part of this experiment is the examination of the pointing idiosyncrasies associated with a 2-meter segmented optics primary as discussed in detail in the Phase I-IA Report. Thus, the justification for conducting this experiment in space rests entirely on the need for future space telescopes to point precisely.

BASIC EXPERIMENT HARDWARE

The experiments will require that the pointing control sensor and electronics be designed with a high degree of in-orbit controllability and replaceability so that optimization of pointing performance can be most readily obtained. Such characteristics as servo bandwidth, gain, and compensation characteristics could be readily varied to substantiate or contradict theoretical predictions. This would lead to a better understanding of basic limitations and to higher overall actual performance. Accuracy improvement obtainable by incorporating sensor signal pulse processing equipment, for example, could be determined if the results of Experiment No. 11 indicate that radiation effects on detectors are significant.

The method of determining tracking capability involves a different method than Experiment No. 19. Higher pointing precision and higher measurement accuracies are involved in a star tracking operation using the guidance equipment in each of the equipment modules. Also, the 2-meter diameter apertures will necessitate lower servo bandwidths while star tracking as compared to Earth laser beacon tracking.

The 2-meter telescope of Experiment No. 1 and as illustrated in the Frontispiece must be capable of operation over the UV through IR wavelength spectrum if the instrument itself is to be of maximum use to astronomers after the optical technology experiments are completed. Therefore, the 2-meter OTES telescope system needs pointing techniques with all-wavelength capability. While Experiment No. 26 is oriented to the search for the optimum suspension system for a space telescope in the 1-meter aperture size range, it should be clear to the reader that when one considers the 3-meter and larger aperture telescope (for future astronomical applications), the three pointing techniques listed in Experiment No. 26 are reduced to a single approach: body point plus transfer lens technique.

The free float body point with the transfer lens technique is at present the most promising approach for future later orbiting space telescopes. The fundamental disadvantage, which has limited the adoption of this technique earlier in the OTES program, has been the need for an all-wavelength pointing system. The transfer lens as it is presently used in the Stratoscope II system is a refractive element. This lens blocks the entire spectrum other than the visible light. Ultraviolet as well as infrared are both blocked. Since the large telescope must be effective in these regions of the spectrum, the Stratoscope II transfer lens itself is not good enough for the OTES Program. Therefore, attention was directed to the all-wavelength optical equivalent of the refractive transfer lens. Such a device was invented in Phase IA and this all-reflective transfer lens was described in Report 8500 starting in page I-90.

Laser Communications Experiments Module

The transfer lens technique is used for the line of sight and cross line of sight fine pointing in the laser communication experiment package (Equipment Module B). In this same module, the roll about the line of sight (RLOS) fine pointing system is handled by the Risley prism set. The data for RLOS in this portion of Experiment No. 9 comes from the sun tracker. The coarse RLOS is handled by the attitude control system of the spacecraft and this system is discussed in the Lockheed section of this report.

The transfer lens method is an excellent technique for fractional arc-second guidance which has been reduced to practice in the Stratoscope II system. A similar piece of equipment has been supplied to MSFC for use in the laser communication systems work in Contract NAS8-20115 and an all reflective version of this same transfer lens technique will be delivered to MSFC for use in the laser communication transceiver work in Contract NAS8-20841.

High Resolution Imagery Photographic f/10 Module

The transfer lens pointing technique is used also for the line of sight and cross line of sight fine pointing for the high resolution imagery photographic f/10 module (Equipment Module C). The very fine pointing operations for this portion of Experiment No. 9 are directed at star pointing using the common optical system for recording the target area on film. Thus, the essential difference between this portion of Experiment No. 9 and the section of Experiment No. 9 concerned with laser communications is the direction in which the OTES telescope is pointed. In the latter case, the telescope is pointing towards Earth at an argon laser beacon, while in this portion of the Experiment No. 9, the telescope is pointing at guide stars in the field of view near the target star. The RLOS data is developed by tracking two guide stars. The fine RLOS pointing process is implemented in a different manner than the laser communication experiments module with its Risley Prisms and in a different manner than the Stratoscope II RLOS pointing operation which uses a three-axis gimbal system (a mercury bearing in azimuth and two flexure bearings about the line of sight and the cross line of sight). The fine pointing technology experiments planned with this equipment module for RLOS are based on rolling the f/10 film camera with its associated image dividers for guidance signal generation about the optical line of sight inside Equipment Module C.

In summary, the space experiments associated with Experiment No. 9 (Equipment Module C) are based essentially on the concept of doing very fine pointing operations in space with the type of equipment utilized on Stratoscope II. The data that will be obtained from the flight will be high resolution photographs of selected celestial bodies and telemetry records of the performance of the various subsystems. This portion of Experiment No. 9 would be repeated in both daytime and nighttime conditions and for both the conditions of attachment to the cluster and in autonomous flight with no men present in the LEM.

Echelle Ultraviolet Spectrometer Module

The guidance experiment planned for the Echelle UV spectrometer module (Equipment Module D) as part of Experiment No. 9 uses the free-float body point technique for all three axes: line of sight, cross line of sight, and roll. The technology development that will ensue during the operations with Equipment Module D relates to the success of pointing operations in the free float mode using the image mover technique for the two star guidance signal generation. The 2-meter OTES will be pointed at a stellar target for these operations.

This portion of Experiment No. 9 will be repeated four times for various combinations of daytime, nighttime, cluster mode and autonomous mode operations. The Echelle spectrometer will supply the essential data necessary to establish the degree of proficiency of the instrument in each of the above modes and telemetry from the operating subsystems will be used to support the justification of orbital altitude for the future 3-meter OTES and/or MQAT. Although the free float mode will provide an RLOS stability of arc-second magnitude, the Echelle spectrometer itself will not provide data suitable for analysis of RLOS performance. However, it will afford the pointing data needed for establishing the pointing stability of the free float technique for the line of sight and cross line of sight. Also, it will provide the data for determining the UV performance in daylight in the presence of the gas discharge from the cluster (Experiment No. 34) and will, therefore, be very instrumental in guiding the design of the 3-meter type of telescope.

Rowland Circle UV Spectrometer

The guidance experiments that will be conducted with this instrument package (Equipment Module E) under the aegis of Experiment No. 9 will employ body point technique using the ATM flexure bearing gimbals. The data from the spectrometer will be evaluated and compared with the data taken from the free float body point technique obtained in the Echelle spectrometer instrument (Equipment Module D) to establish the procedure that will be most suitable to the class of smaller telescopes (about 1-meter aperture) of the future. The Rowland circle spectrometer does not require any precision about the RLOS and the ATM gimbals are suitable for this operation. The entire vehicle will be attitude controlled for roll. Roll attitude control by vehicle orientation is discussed by Lockheed later in this report. Image mover technology* for the line of sight and cross line of sight guidance data generation is planned.

The experiment will be repeated four times for day and night conditions as well as for cluster disturbances versus autonomous mode operations.

High Resolution Imagery Vidicon f/50

The guidance technique planned as this part of Experiment No. 9 will use secondary mirror tilting as the method of providing line of sight and cross line of sight fine pointing operations. This experiment could be attempted both for Earth pointing at the Earth argon beacon as well as for space pointing operations using a stellar source for guidance. The experiment attempt using the argon beacon as a stellar source would require a second laser for simulating the conditions of two bright sources for the RLOS data generation. The second laser is essential if the RLOS data is to be obtained in an Earth pointing mode of the 2-meter OTES Telescope; that is, the sun tracker attached to the body of the telescope tube would not be able to provide the required RLOS data precision.

* See Chapter 2 for the reasons why an image mover is required and for the optical layout to implement an image mover.

The telescope with its High Resolution Imagery Vidicon f/50 package should be tested in a space pointed mode as the primary experiment. However, at this point in time, it seems that the addition of the laser beacon tracking would represent a good investment for NASA. A second laser is required which would be at a different wavelength from the main argon laser beacon and which would be mounted on a movable up-pointing tracking telescope. The maximum separation between the two lasers would be approximately 200 feet for an orbital altitude of the OTES of 200 to 300 miles.

The data from the RLOS subsystem, whether Earth pointing using laser beacons or 2 stars, is transmitted to the electronic camera system which uses an image orthicon or vidicon. The rotational signals are used to rotate the image tube and the guidance sensors.

The reasons for the uncertainty in the success of the laser beacon portion of the experiment are related to the high angular rates which occur at a low orbit. For rates in the vicinity of 3 degrees per second, the system experiment is trying to track with a precision of 1/100 arc-second. Three degrees per second is an angular rate of approximately 10,800 arc-seconds per time second. The velocity constant of the system is tremendously high - $10^6 (\text{time seconds})^{-1}$. This figure, when coupled with the short view time available of the ground station - 4 minutes - leaves much doubt as to the ultimate success of this portion of Experiment No. 9.

TECHNICAL DETAILS

The minimum pointing error of a servo-controlled optical line of sight, tracking a star via image-splitting techniques, has been expressed in Figure 71 as a function of the telescope diffraction-limited resolution and the sensor signal to noise ratio.

$$E_{p \min} = \frac{1.22}{2D} \lambda (S/N)^{-1}$$

Where λ = WAVELENGTH
 D = APERTURE DIAMETER
 S $\propto$ MEAN ERROR VOLTAGE AT MAX ERROR
 N $\propto$ RMS NOISE VOLTAGE CONTENT IN S

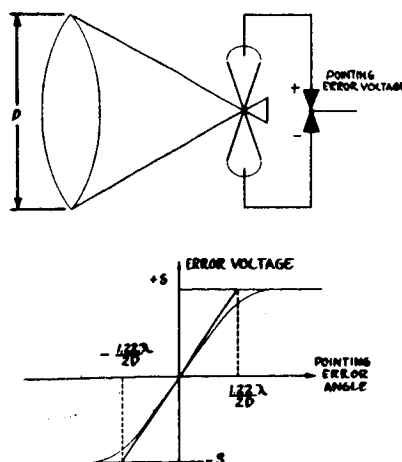


Figure 71. Image Splitting Techniques

Image-splitting techniques are used to furnish pointing error signals for controlling the telescope's line of sight. In a diffraction-limited instrument, the rms angular pointing error is approximately related to the sensor signal-to-noise ratio and the optical resolution. This result is applicable whether the image is that of a star or a laser source.

For the optical technology telescope tracking on a star of visual magnitude (M_v), the signal-to-noise ratio can be replaced by an expression involving M_v , the telescope aperture diameter (D), the telescope optical and sensor quantum efficiencies (N_o and N_q), and the effective noise bandwidth (Δf) of the pointing control servo. A pointing figure of merit can be derived (as shown in Figure 72) by dividing the required telescope pointing accuracy by the minimum possible error, to make more apparent the effects of scaling telescope size.

ASTRONOMICAL TELESCOPE

$$E_{p_{min}} = \frac{1.22 \lambda}{2D} (S_N)^{-1} \quad S_N \gg 1$$

$$S_N = \frac{P_s N_o N_q \Delta t}{\sqrt{(P_s N_o N_q + E_n) \Delta t}} = \sqrt{\frac{10^{10}}{2.51^m} \frac{\pi^2}{4} D^2 N_o N_q \frac{1}{\Delta f}}$$

$$E_{p_{min}} = \frac{K_1}{D^2} \sqrt{\frac{2.51^m \Delta f}{N_o N_q}}$$

$$E_{p_{reqd}} = \frac{1.22 \lambda}{K_2 D} \quad K_2 > 1$$

$$\text{Pointing Sensor Figure of Merit} = \frac{E_{p_{reqd}}}{E_{p_{min}}} \propto \frac{D}{\sqrt{2.51^m \Delta f}}$$

Figure 72 . Pointing Figure of Merit Derivation

As diameter increases, minimum pointing error reduces in square law fashion while the required pointing error reduces linearly. Hence, the system's figure of merit tends to increase with diameter if visual magnitude and bandwidth remain constant.

Figure 73 presents the basic data in an alternate form; minimum pointing error as a function of telescope diameter, servo bandwidth, and the product $NoNq$ (for the case of 5500Å wavelength). The curves show, for example see sample point, that the 2-meter OTES telescope, utilizing a one Hertz servo equivalent noise bandwidth and having 33 percent optical and 6 percent quantum efficiency, can theoretically achieve a 0.0005 arc-second rms performance tracking twelfth magnitude stars. Additional pointing errors caused by background light, phototube dark current, and noise from electronic control circuitry can generally be reduced by straightforward design measures and, like quantum noise, by a servo bandwidth reduction. The attainment of arbitrarily high performance by resorting to extremely low bandwidth unfortunately is prevented by the presence of telescope torque disturbances which cause increasing errors as the bandwidth is reduced in a given control system. Figure 74 presents the servo relationships which allow computation of angular errors due to noise inputs and torque disturbances. The torque disturbances produce additional pointing errors. While a smaller error due to noise results as servo bandwidth is reduced, torque-induced errors increase.

Figure 75 indicates how one might approach an optimum servo design via the choice of loop gain characteristics and bandwidth, provided that both the noise and torque disturbances are known. Total errors can be reduced by selecting servo system characteristics and bandwidth so that torque disturbance and noise produce comparable pointing error components. For example, while both systems will have equal errors due to torque disturbance, System 2, Figure 75 is superior since it has lower bandwidth and therefore less error due to noise. Moreover, for the case shown, a shift of the loop gain characteristic to the right will slightly increase the bandwidth (and therefore the noise-induced error), while rapidly reducing the torque-induced error. Minimum total error is obtained with a bandwidth corresponding approximately to that at which the noise- and torque-produced error curves intersect.

It is evident that torques should either be avoided or reduced in amplitude and frequency so that total errors, including those which are noise induced, can be reduced via bandwidth minimization. The concern regarding choice of a telescope suspension system arises from a desire to avoid torque disturbances from all external sources. This is summarized in Figure 76. Suspension systems chosen for a space optical system, as illustrated in Figure 76, , should provide greatest isolation from disturbance torques. While the free-floating approach appears optimum in this respect for apertures in the vicinity of 1 meter, ground testing seems impossible. The body point arrangement features rigid attachment of the telescope and vehicle and, thus, requires the highest pointing precision of the vehicle. This requirement can be avoided by including a transfer lens within the telescope to compensate for vehicle mispointing as noted in the discussion of experiment justification.

Since torque and noise affect a control system in different fashions, it would be desirable if the tracking and pointing precision experiments (Nos. 9 and 19) were conducted so that quantitative results could be obtained wherever possible for each of the separate sources of error. Additional data to indicate the magnitude of measurement error involved should also be obtained.

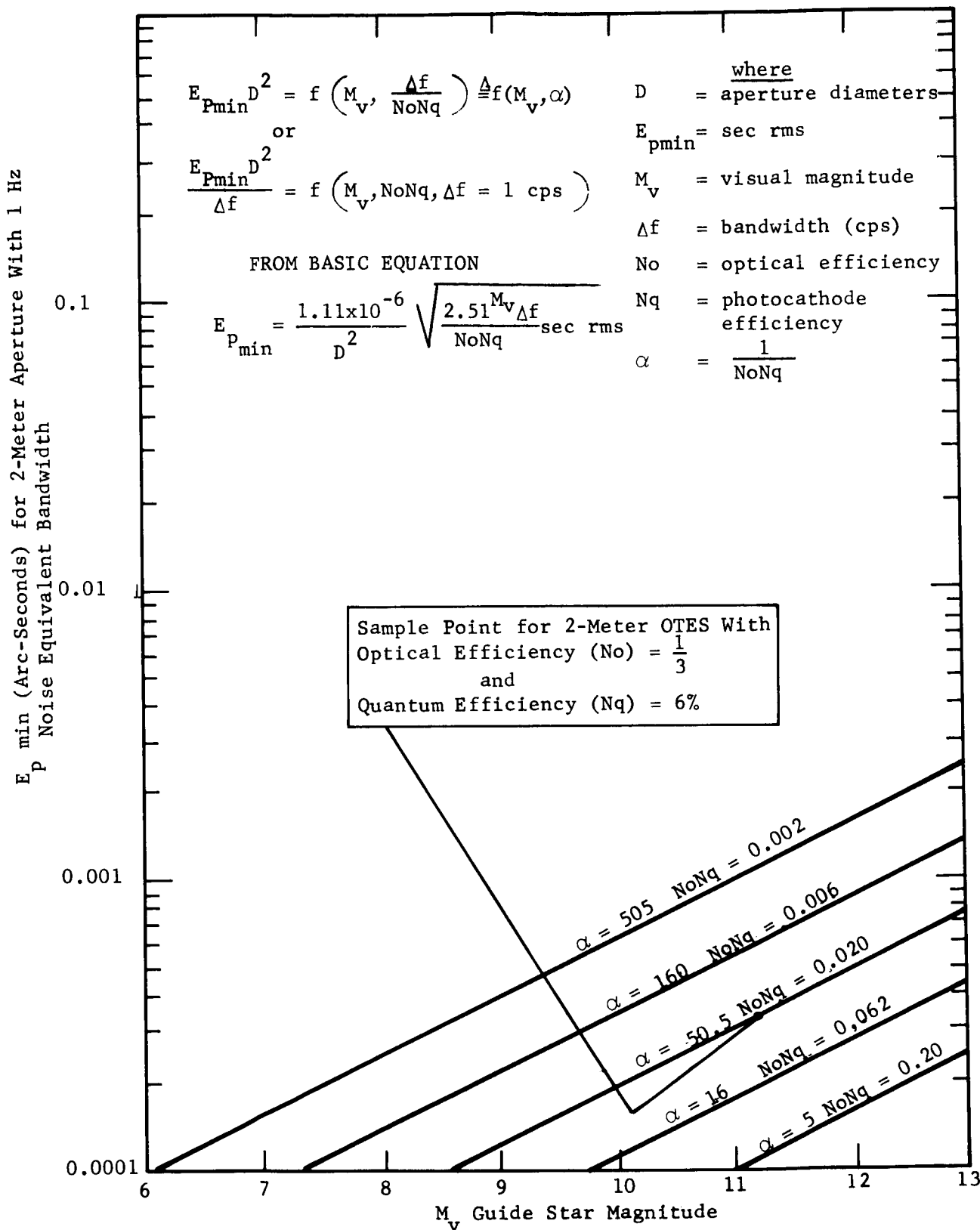
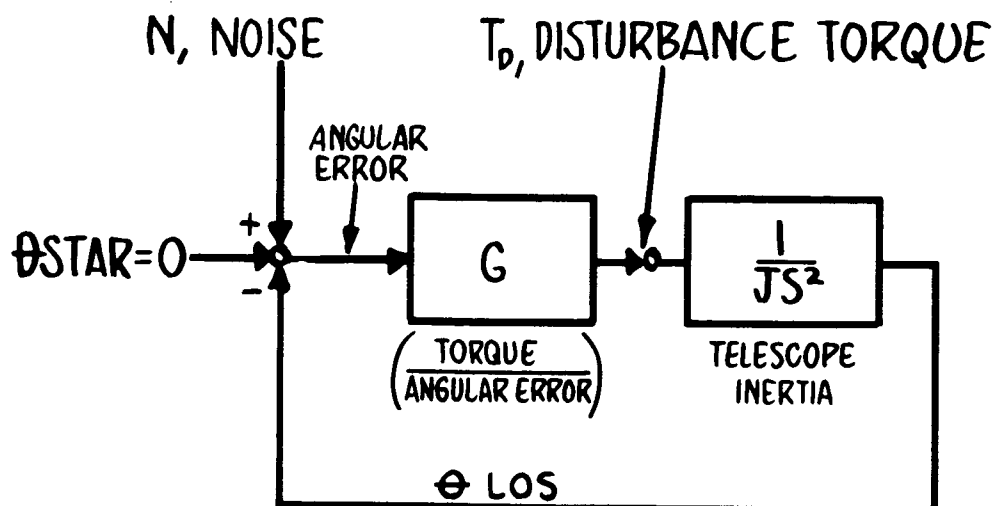


Figure 73. Limit of Stellar Tracking Capability



$$\text{ANGULAR ERROR} = \frac{\frac{G}{JS^2}}{1 + \frac{G}{JS^2}} N(s) \approx N(s) \quad ; \quad \frac{G}{JS^2} > 1$$

$$\approx \frac{G}{JS^2} N(s) \quad ; \quad \frac{G}{JS^2} < 1$$

$$\text{ANGULAR ERROR} = \frac{\frac{G}{JS^2}}{1 + \frac{G}{JS^2}} T_D(s) \approx \frac{\left[\frac{T_D(s)}{JS^2} \right]}{\frac{G}{JS^2}} \quad ; \quad \frac{G}{JS^2} > 1$$

$$\approx \frac{T_D(s)}{JS^2} \quad ; \quad \frac{G}{JS^2} < 1$$

Figure 74. Pointing Errors Dependence on Noise and Torque Disturbances

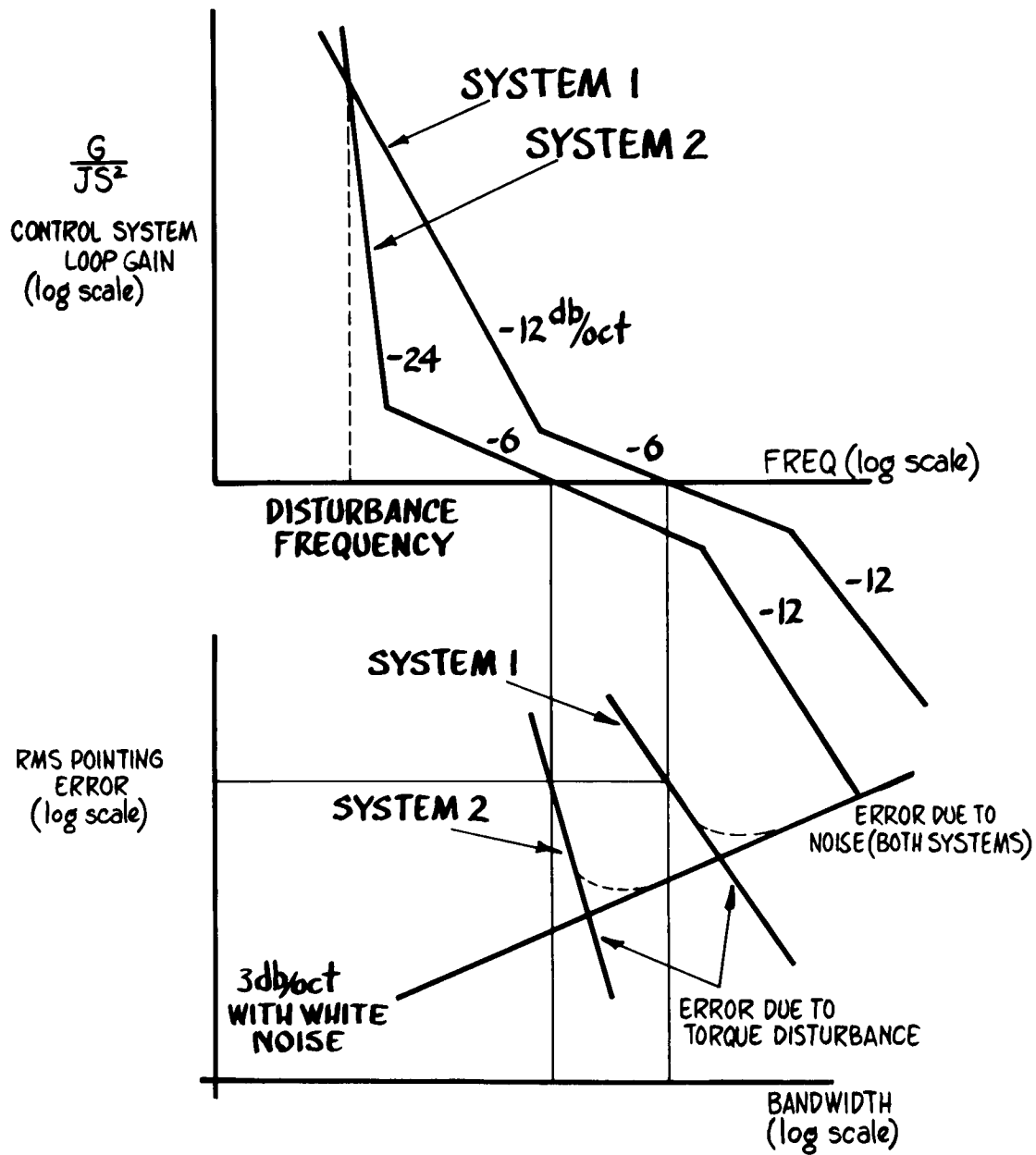


Figure 75. . . Pointing Servo Considerations for a Large Space Telescope Experiment

This general measurement philosophy leads to the approach depicted in Figure 77. The suggested method would involve the separate determination of photo-tube dark current, electronic noise, and background light level where each is significant. Pointing accuracy, using the method proposed previously, would then be evaluated utilizing maximum servo bandwidth and ground beacon laser power in order to minimize torque- and noise-induced errors or, equivalently, to enhance the relative magnitude of measurement errors. Measurement effects due to atmospheric refractions, scintillation at the Earth detector array, and other sources could be assessed. The error could be recorded as a function of time and analyzed to obtain the spectral distribution of measurement error. This procedure can be repeated for various other conditions such as with lowered bandwidth and/or beacon laser power and with alternate servo compensation to obtain data on total error and its separate components.

TYPICAL DISTURBANCE	SUSPENSION SYSTEM TYPE		
	FREE FLOATING	GIMBALLED	BODY POINT
• VEHICLE ORIGINATED: ASTRONAUT, MOMENTUM WHEELS, MISPOINTING	DECOUPLED	MINIMIZED BY GOOD BEARING ISOLATION AND OPTIMIZED VEHICLE - INSTRUMENT GEOMETRY	PRESENT
ENVIRONMENT ORIGINATED: SOLAR PRESSURE, GRAVITY GRADIENT	POSSIBLE	POSSIBLE	PRESENT
INSTRUMENT ORIGINATED: MOMENTUM WHEELS	PRESENT	PRESENT	—
ADVANTAGES	LEAST DISTURBANCES, VEHICLE POINTING UNCITICAL	MORE EASILY GROUND TESTED	THERMAL CONTROL AND INTERCONNECTION PATHS MORE READILY IMPLEMENTED
DISADVANTAGES	GROUND TESTING MOST DIFFICULT	VEHICLE POINTING MORE CRITICAL	VEHICLE POINTING REQ- UIREMENTS ARE MAXIMUM

Figure 76. Suspension System Experiment Considerations

In trying to justify the 2-meter OTES, it is possible to scale the aperture diameter up and down and determine the effect on the guidance system and establish new guidance system specifications for the optics. This process is illustrated in Figure 78.

Note that Figure 78 can be used by observing that decreasing the allowed field of view of the telescope, which results with increased aperture, requires the larger instrument to use dimmer stars for guidance (in order to maintain the same probability that the guide stars will occur with the field of view).

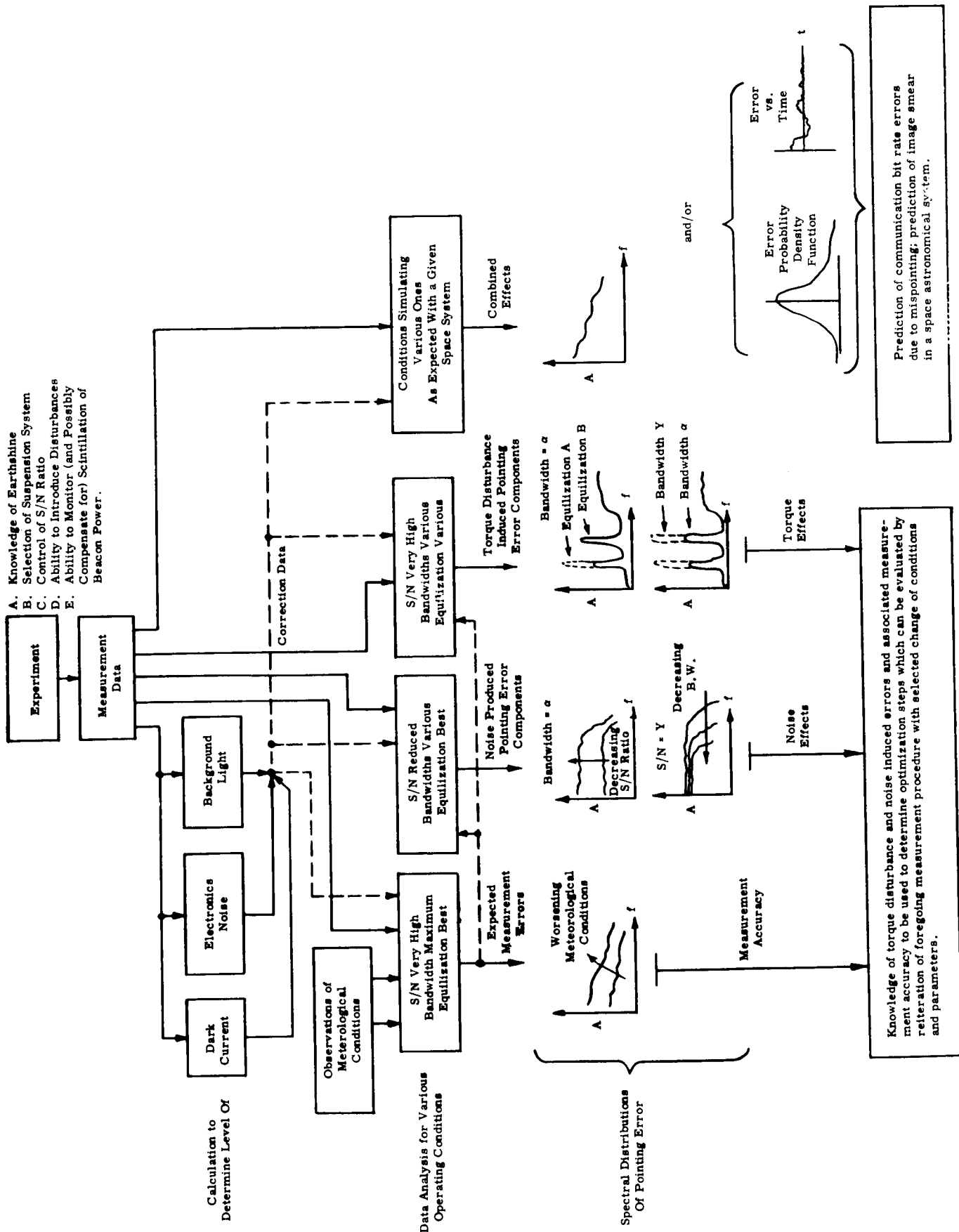


Figure 77, Experiment Data Reduction Approach

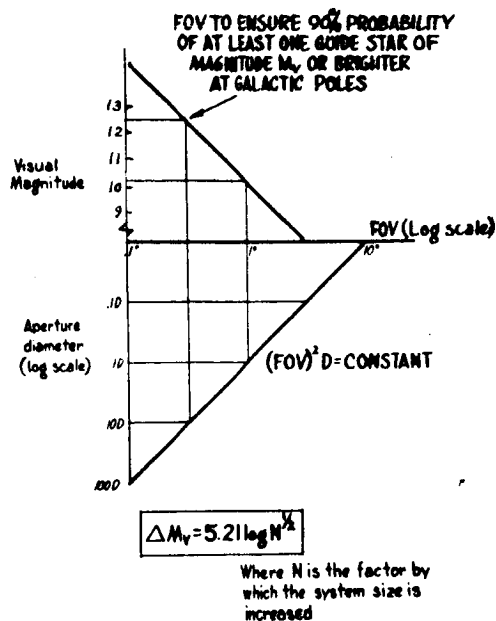


Figure 78. Scaling the Diameter and Its Effect on Visual Magnitude

Therefore, for the nomograph of Figure 78, which is for an aplanatic Ritchey-Chretien, consider what happens when the aperture (D) is increased by a factor of ten ($N = 10$). Enter the curves at an aperture diameter = 1D. The field of view (the abscissa) can be read from the bottom curve as 1 degree. The corresponding visual magnitude from the top curve is found to be 10 ($M_v = 10$). If the diameter is increased to 10D, the field of view is reduced and the corresponding visual magnitude is read from the top curve as 12.6.

From a guidance point of view, the figure of merit for pointing performance can be modified to include the probability factor that there are adequate guide stars. Again, consider the OTES case where the question of selecting an aperture size to conduct optical technology experiments in space must be answered by this study. In evaluating the 1/2-meter, 1-meter, and 2-meter apertures versus the 3-meter aperture, the figure of merit of the various aperture telescopes also can be evaluated. This figure of merit (FOM) is derived in the following table. The results indicate that a large aplanatic Ritchey-Chretien telescope (i.e., 3-meter aperture), can perform better than a small telescope (i.e., 1-meter aperture) if both have the same bandwidth in the fine pointing system. Since both telescopes would probably use an all-reflective transfer lens, the two systems would have the same servo bandwidth and, therefore, the 3-meter telescope would outperform the 1-meter system in the guidance operations by a factor of the square root of 3 (substitution into FOM in the following table).

FIGURE OF MERIT (FOM) OF A LARGE SYSTEM
COMPARED TO FOM OF A SMALL SYSTEM

$$\text{FOM} \triangleq \text{Figure of Merit} = \frac{E_{P_{\text{req'd}}}}{E_{P_{\text{min}}}} \propto \frac{D}{\sqrt{2.51 m_v \Delta f}}$$

Becomes

$$\text{FOM} \propto \frac{D}{\sqrt{\Delta f}}$$

and

$$\frac{\text{FOM}_{\text{large system}}}{\text{FOM}_{\text{small system}}} = \frac{N \frac{\Delta f_{\text{small system}}}{\Delta f_{\text{large system}}}}{1}$$

where N is the factor of (> 1) by which the system sizes differ.

A more general expression for aplanatic Ritchey-Chretien two-mirror arrangement, including the effects of background light and phototube dark current, is shown below.

FIGURE OF MERIT (FOM) INCLUDING BACKGROUND
LIGHT AND DARK CURRENT EFFECTS

$$\text{FOM}_{\text{LS}} = \text{FOM}_{\text{SS}} \sqrt{N \frac{\Delta f_{\text{SS}}}{\Delta f_{\text{LS}}} \left(\frac{1 + R_{\text{SS}}}{1 + \frac{R_{\text{SS}}}{N}} \right)}$$

where R_{SS} is the background light plus dark current expressed as sensor input energy divided by that due to signal only --- for the small system

and N is the size increase factor under consideration

In this table, the assumption is that the phototubes and the size of the field stop (used ahead of the image splitter) are independent of system size.

Structural resonance frequencies can limit the servo bandwidth Δf such that $\Delta f_{SS}/\Delta f_{LS} = N$; hence

$$\frac{FOM_{LS}}{FOM_{SS}} = N \sqrt{\frac{1 + R_{SS}}{1 + \frac{R_{SS}}{N}}}$$

This indicates that pointing precision in the presence of photon noise improves N times faster than resolution improves, when size increases by a factor of N.

Torque Disturbances

Consider the effect of torque disturbance as a function of telescope diameter. The basic assumption will be that scaling the size by a factor of N means that all telescope dimensions are increased by N. The angular error, ϵ_p , due to torque disturbances, T_D , acting upon a servo controlled telescope of inertia J can be expressed as

$$\epsilon_p = \frac{T_D/JS^2}{1 + G/JS^2}$$

where G/JS^2 is the servo open-loop gain characteristic. Since gravity gradient torques increases as N^5 , magnetic torques as N^4 , solar pressure torques as N^3 , and inertia as N^5 , the foregoing expression can be written as

$$\epsilon_p = \frac{T_D N^X/JN^5 S^2}{1 + GN^K/JN^5 S^2}$$

where X is, for example, 5 when considering gravity gradient torques and K indicates the allowed variation of G with scaling. In a later section, the derivation is presented, which indicates that GN^K/JN^5 must reduce as N^{-2} if structural resonance limits the servo bandwidth; hence, with this assumption $K = 3$ and

$$\epsilon_p = \frac{N^{X-5} [T_D/JS^2]}{1 + \frac{G}{JS^2} (N^{-2})}$$

Pointing error due to torque disturbances can be approximately expressed by

$$\epsilon_p = N^{X-3} \frac{T_D}{G} \quad \text{where} \quad \frac{G}{JS^2} N^{-2} \gg 1 \quad (1)$$

and

$$\epsilon_p = N^{X-5} \frac{T_D}{JS^2} \quad \text{where } \frac{G}{JS^2} N^{-2} \ll 1 \quad (2)$$

These equations can be interpreted in the light of the fact that pointing accuracy should increase directly with N (or optical resolution).

For a lead-lag stabilized 2-meter torqued telescope, disturbances that are within the servo bandwidth and vary as N^2 will cause a pointing error, which reduces as fast as telescope resolution increases. This is also true for disturbances outside the servo bandwidth which vary as N^4 .

If it is logically assumed now that gravity gradient, magnetic, and solar pressure-induced disturbance torques are at constant frequency and within the servo bandwidth, all three disturbance sources could potentially limit system performance. If, however, the system bandwidth is not structural-resonance limited, but maintained constant, only gravity gradient disturbances would be of concern. Whether or not such disturbances are a problem, of course, depends upon the many system parameters including those that determine torque magnitude (and frequency) such as orbital altitude, and asymmetry of mass distribution. It is noteworthy that an orbital change from a 20,000 mile orbit to a 260 mile orbit will increase the gravity gradient magnitude by the cube of the radius ratio or

$$\left(\frac{20,000}{260} \right)^3 = (77)^3 = 600,000 \text{ times}$$

The corresponding disturbance frequency, moreover, would increase by a factor of 16 and, hence, appear at a frequency where the lead-lag stabilized telescope could have its gain increased by proportional plus integral characteristics. The gravity-gradient-induced error for a telescope in synchronous orbit is negligible in comparison to near-Earth orbits. Similar considerations for magnetic torques also indicate the desirability of a synchronous orbit. Solar pressure, on the other hand, primarily induces static or bias torque, which is very effectively combatted by incorporating this proportional plus integral servo control.

While no quantitative conclusions can be drawn from the foregoing paragraphs, it should be clear that torque disturbances will limit the overall pointing accuracy for the 2-meter OTES at a 260 mile orbit. Control of mass centers and shaping of servo gain-frequency characteristics will tend to avoid such torque disturbance limitations for the 2-meter OTES telescope.

Roll Pointing Precision

Up to this point only cross line of sight pointing errors due to torque disturbances and noise have been considered. The roll (about the line of sight) telescope error is equally important and magnitude constraints can be computed based upon the assumption that **recorded image smear due to roll should be**

no larger than that due to cross line of sight errors. If one assumes that the X-Y guide star is directly on axis and the diameter of the recorded field is θ_R , then a telescope resolution of

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

implies that X and Y guidance errors should be

$$\frac{1.22\lambda}{K_1 D} \quad (2)$$

Roll of the image $\pm\theta_V$, which causes an equivalent photographic degradation, can now be determined from the expression,

$$\frac{\theta_R}{2} \sin 2\theta_V = \frac{1.22\lambda}{K_1 D} \quad (3)$$

which reduces to

$$\sin 2\theta_V = \frac{2.44\lambda}{K_1 D \theta_R} \quad (4)$$

For the 2-meter OTES in the ultraviolet, $\lambda = 0.1\mu$, $D = 2$ meter, $K_1 = 10$ and $\theta_R = 3$ arc-minutes, then

$$\theta_V = \frac{\sin 2\theta_V}{2} = \frac{2.44 \times 0.1 \times 10^{-6}}{2 \times 10 \times 3 \times 2} \frac{60 \times 57.3}{1} = 1.5 \text{ arc-seconds}$$

Even greater roll stability is required if one considers the case where the rotations occur about the (cross line of sight or) translational guide star image, which is some angular distance from the center of the recorded field. Such a situation arises, as in the Stratoscope II system, when transfer lens corrections are made much more rapidly than roll corrections. With such an arrangement, the telescope required roll stability is

$$\sin \theta_V = \frac{1.22\lambda}{K_1 D (\theta_T - \theta_{GA} + \theta_R)} \triangleq \frac{1.22\lambda}{K_1 D \theta_{X_{\max}}} \quad (5)$$

where θ_T is the total field angular diameter

θ_{GA} is the guidance photosensor acquisition field diameter

$\theta_{X_{\max}}$ is the maximum distance of the translation star from the film. (See Figure 79).

For the 2-meter OTES in the ultraviolet, $\lambda = 0.1\mu$, $D = 2$ meter, $K_1 = 10$, $\theta_R = 3$ arc-minute, $\theta_T = 30$ arc-minute and $\theta_{GA} = 2$, then

$$\theta_V = \frac{1.22 \times 0.1 \times 10^{-6}}{10 \times 2 \times (31)} \frac{57.3 \times 60}{1} = 0.14 \text{ arc-second}$$

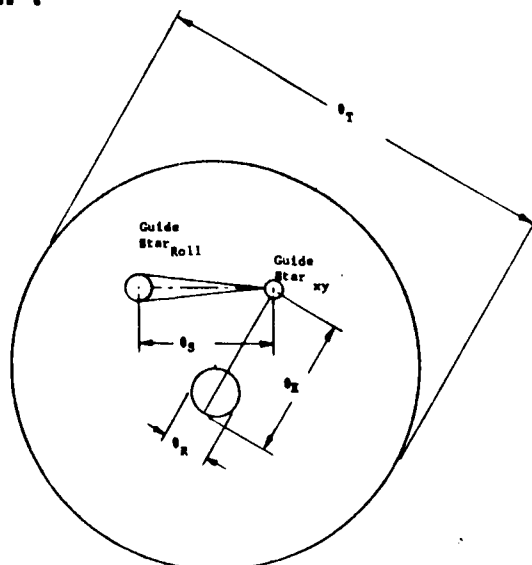


Figure 79. Guide Star Image Geometry

Let us now consider the difficulty involved in achieving this degree of precision. The roll guidance geometry indicates that the linear sensing signal of the roll star is equivalent to

$$\frac{(1.22\lambda)}{\frac{D}{\theta_s}} = \text{L.R.} \quad (6)$$

where θ_s is the distance between the two guide stars.

The minimum signal-to-noise ratio required to achieve the desired accuracy can be determined from the relation

$$E_p = \frac{\text{LR}}{2} \left(\frac{S}{N} \right)^{-1} \quad (7)$$

or

$$\frac{S}{N}_{\min} = \frac{\text{LR}/2}{E_p} = \left(\frac{0.61 \lambda/D}{\theta_s} \right) / \frac{1.22\lambda}{K_1 D \theta_x}$$

$$\frac{S}{N}_{\min} = \left(\frac{K_1}{2} \right) \left(\frac{\theta_x}{\theta_s} \right) \quad (8)$$

Based upon the same criterion, the signal-to-noise ratio required for translational guidance is simply

$$\frac{S}{N}_{\min} = \frac{0.61 \lambda/D}{\frac{1.22\lambda}{K_1 D}} = \frac{K_1}{2} \quad (9)$$

The following three points are worth noting in regard to Equations (8) and (9).

- In the numerical example following Equation (5), the vehicle roll accuracy requirement appears to be much worse than that required about the other two axes (i.e., $\frac{1.22\lambda}{K_1 D} = \frac{1.22 \times 0.1 \times 10^{-6}}{10 \times 2} = 0.006 \times 10^{-6} \text{ rad} = 0.0012 \text{ arc-second}$).

However, Equations (8) and (9) indicate that the S/N ratio requirements are comparable for roll and translational guidance.

- Best roll accuracy, in the case of two equally bright stars, results when the ratio of θ_x/θ_s is minimum. This means that the star closest to the film should be used for translation. For differing star intensities, the choice of translation star is not so obvious but the optimum is determinable.
- Since the extreme values of θ_x/θ_s are not strong functions of FOV, roll requirements are relatively independent of field size.

The preceding paragraphs indicated that the required roll stability, θ_v , can be approximately expressed as

$$\theta_v = \frac{1.22\lambda}{K_1 D \theta_{x_{\max}}}$$

where $\theta_{x_{\max}}$ is the maximum distance of the translation star from the film. Since the required translation (or cross line of sight) stability, moreover, was expressed as

$$\theta_{x,y} = \frac{1.22\lambda}{K_1 D},$$

then

$$\theta_v/\theta_{x,y} = 1/\theta_{x_{\max}} \approx 2/\theta_T.$$

Figure 80, a plot of $\theta_v/\theta_{x,y}$ versus θ_T , also indicates the gyration radius ratio $\frac{R_{x,y}}{R_v}$, corresponding to the constraint that a given input sinusoidal

torque produces equivalent axis motions.

It seems valid to assume that increase of telescope size will be accompanied by a field decrease and that the actual radius of gyration ratio will be less than shown graphically. For this reason, plus the fact that roll torque disturbances are not expected to exceed those for X and Y, it is concluded that attainment of X and Y pointing accuracy shall be the most critical from a torque disturbance

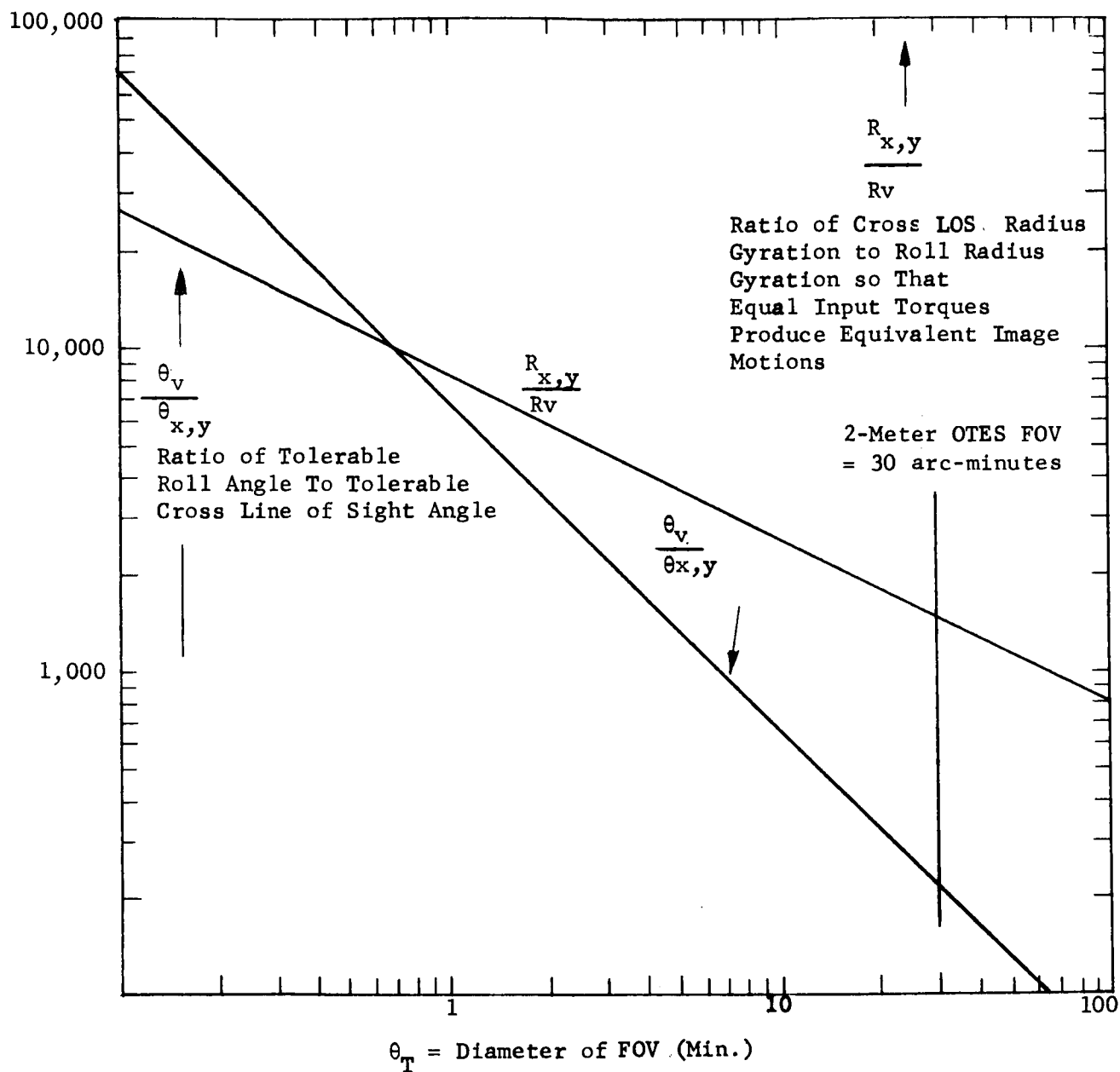


Figure 80. Roll Angle Effects

standpoint. From a signal-to-noise standpoint, it should be remembered, the roll servo may or may not be more critical than the cross-line-of-sight servos depending upon whether θ_X/θ_S is greater or less than unity. These conclusions are valid independent of telescope size.

All Reflective Transfer Lens

A technique for controlling the image field in translation, without attendant field tilting, would be to use an all reflective transfer lens such as the double porro mirror arrangement shown in Figure 81. This device was analyzed in detail on pages I-91 through I-102 in Perkin-Elmer Report No. 8500 and it has been breadboarded and tested for functionality in the laboratory.

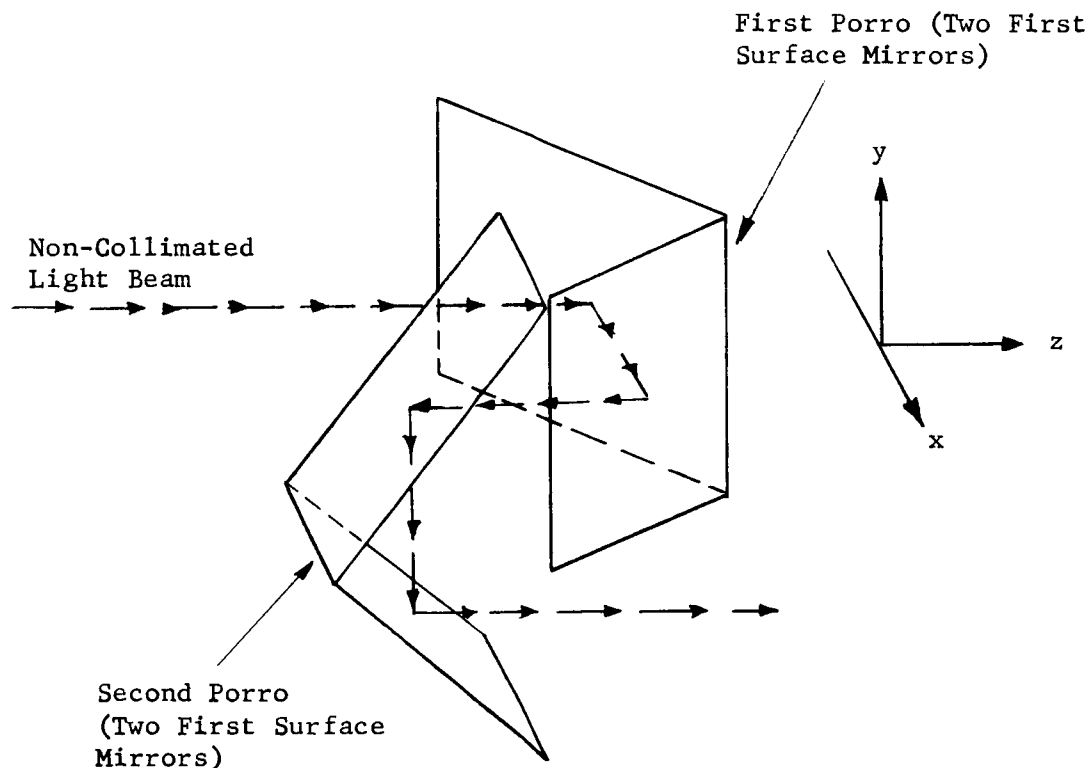


Figure 81 . Double Porro Mirror Arrangement for Line of Sight Correction

The refractive transfer lens is discussed in Experiment No. 19 while the free float body point and the body point flexure gimbal systems are part of Experiment No. 26.

Field-of-View Analysis

The total field of view of the 2-meter OTES (ϕ_T) must be somewhat larger than the recorded field of view (ϕ_R) to ensure a reasonably high probability of containing at least two guide stars. The guidance field must be large enough so that the guidance photosensors can see the guide stars with the maximum initial mispointing angle of the telescope. The diameter of the guidance field during tracking (ϕ_{GT}) may be smaller than the guidance field required for acquisition (ϕ_{GA}) in order to avoid excessive degradations due to stellar background light (see Figure 82).

The values of ϕ_T , ϕ_{GA} , and ϕ_{GT} were derived in the OTES Phase I analysis based upon the 3-meter aperture OTES and in the table below shows the 2-meter parameter.

The 3-meter telescope structural pointing error of 7.5 arc-seconds peak was assumed in Phase I to exist at a frequency of one cycle per twelve hours for the synchronous orbit. For the 2-meter OTES, the structural pointing error is still estimated at 7.5 arc-seconds, while the frequency is changed to 1 cycle per 90 minutes due to the lower orbit. This structural pointing error frequency can be used to determine the open-loop gain required at this frequency to reduce optical pointing error to one-tenth the telescope diffraction-limited resolution.* A minimum wavelength of 1000Å was used to establish the

2-METER TELESCOPE PARAMETERS FOR GUIDANCE

Telescope weight	6,000 pounds
Telescope radius of gyration about cross line-of-sight axes	3 feet
Frequency of disturbance torques	1 cycle per 1.5 hours (260 mile orbit)
Peak structure pointing error	
Acquisition	1 arc-minute
Track	7.5 arc-seconds
Recorded field size, ϕ_R	5 arc-minute diameter
Telescope wavelength range	0.1 to 20 microns
Telescope aperture diameter, D_A	2 meters
Guide star optical efficiency	$N_O = 31.6\%$
Guidance photosensor quantum Efficiency	$N_Q = 10\%$
Stellar background light	225 11th magnitude stars/square degree

* Large Telescopes in Orbit, R.E. Danielson, International Science and Technology, July 1967 p. 54.

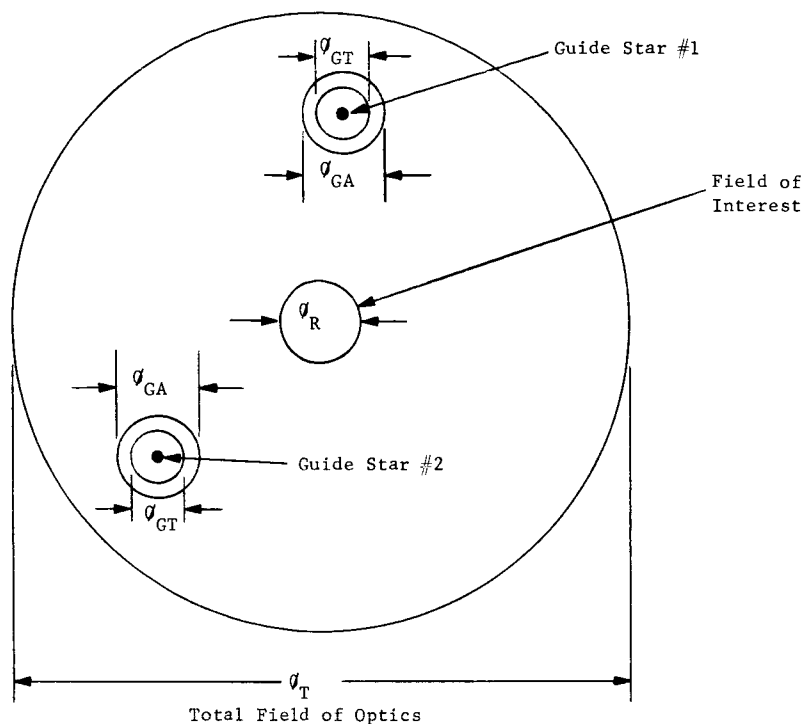


Figure 82. Diagram Illustrating Field Relationships

pointing requirement for the 2-meter OTES telescope. There will be a deterioration of the guidance precision due to photon noise. The disturbance due to photon noise is to be held to 1/10 the diffraction-limited performance of the 2-meter telescope at 1000Å. The guidance error contribution allocated to photon noise was developed in this analysis* to be 0.00084 arc-second. Note that the pointing precision needed to take advantage of the 2-meter diffraction-limited aperture is 0.005 arc-second.** As noted in Experiment No. 9, the pointing precision desired is 0.01 arc-second, which is essentially the same as 0.0084 arc-second. The magnitude of this pointing degradation due to photon noise is small. The pointing precision of the space telescope should be 1/10 of D.L. Stratoscope II which has a 36-inch aperture achieved this precision while guiding on 9th magnitude stars (1/10 of 1/6 arc-second or 0.016 arc-second).

The transfer lens servo bandwidth will be 0.004 Hz based upon the assumption that the loop gain falls at 12 db/octave (except around zero db where it crosses at 6 db/octave). The equivalent noise bandwidth will thus be near 0.01 Hz, a figure that was then used to determine required guide star magnitude (M_V). The value of M_V was found to be in the range of 13, while the total field diameter, ϕ_T , was determined as 15 to 30 arc-minutes.

* Perkin-Elmer Report 8500.

** Large Telescopes in Orbit, R.E. Danielson, International Science and Technology, July 1967 p. 54.

In this Phase II effort, the aperture under consideration is 2 meters, and image movers are included in the optical design*. The analysis is still applicable, and the new parameters associated with the 2-meter OTES are included in this study. A consideration of phototube-dark-current-induced pointing errors in the Phase I analysis indicates that a cold tube environment is worthwhile.

The guide field diameter, ϕ_T , of 30 arc-minutes is extremely desirable in the operation of the telescope.

Guidance Analysis

The OTES system shall evaluate a transfer lens type of servo and a free float body point guidance to compensate for line-of-sight errors which arise from structural mispointing. If it is assumed that the telescope motional disturbances can be expressed as

$$\theta_T = (7.5 \text{ arc-second}) \sin 2\pi \frac{1}{1.5 \times 3600}$$

which must be reduced in magnitude to one-tenth the optical resolution, then the transfer lens servo open loop gain requirement can be expressed as

$$OLG_{T1} \geq \frac{\theta_{T \text{ peak}}}{0.1 \left(\frac{1.22 \lambda_{\text{min}}}{D_A} \right)} = \frac{7.5}{0.1 \times 1.22 \left(\frac{.1}{2} \right) \times 0.206} = 6000$$

at the disturbance frequency

Figure 83 shows that this could be obtained with an open loop characteristic (-2, -1, -2) which has a zero db gain crossover of 0.004 Hz and an estimated equivalent noise bandwidth of 0.01 Hz.

This last figure of 0.01 Hz is especially important since it can now be used to compute the dimmest guide star that can be used (highest permissible M_V) and the minimum possible size of the total field of view, ϕ_T .

This is accomplished with the aid of Figure 84, which indicates the minimum possible pointing error (induced by noise in signal) as a function of the transfer lens servo equivalent noise bandwidth ($\Delta f = .01$ Hz), the optical and quantum efficiencies (N_O and N_Q) and the guide star visual magnitude (M_V).

For this case, $N_O N_Q / \Delta f = 3.16$ and best possible tracking accuracy versus M_V varies as shown in Columns 1 and 2 below.

*See Chapter 3.

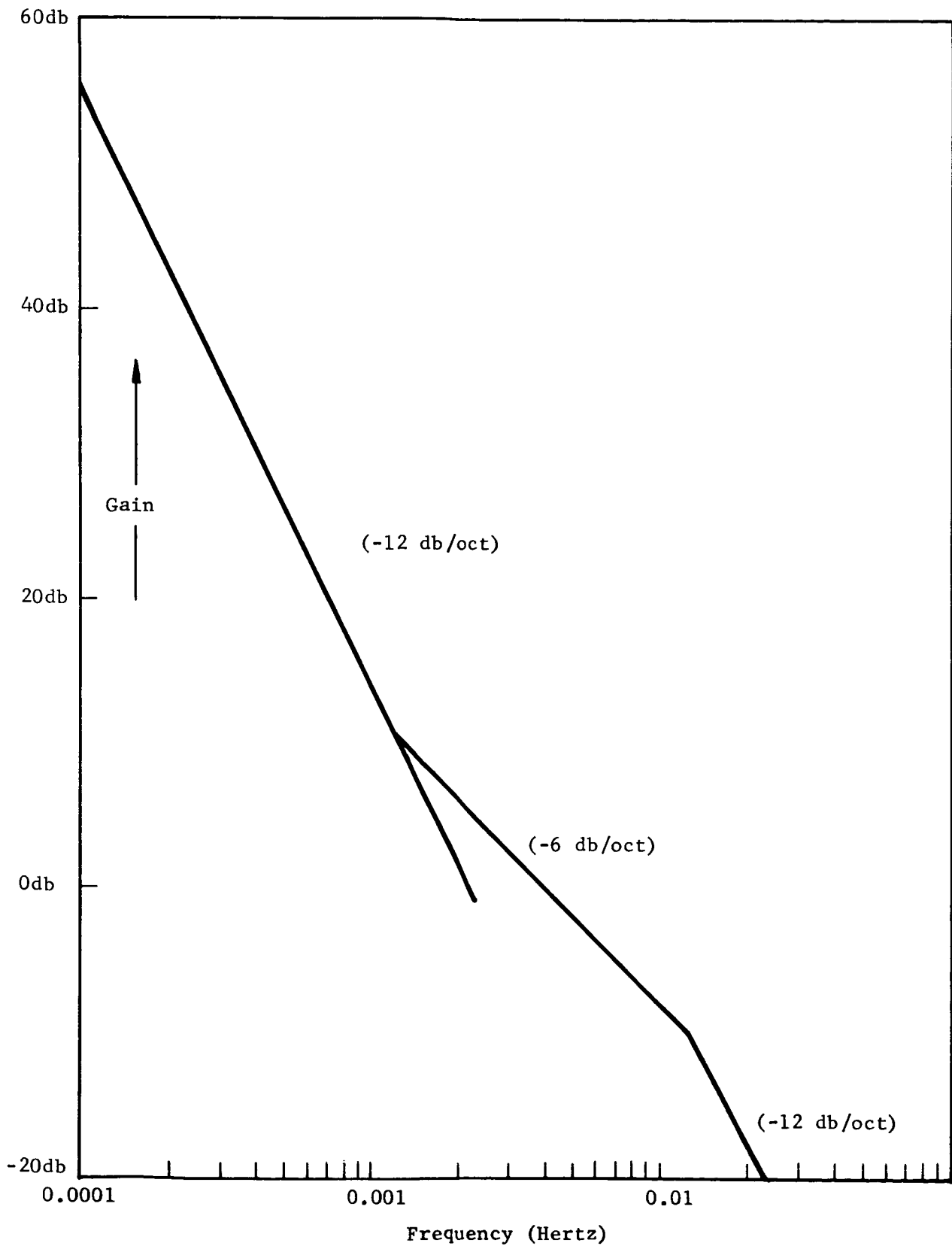
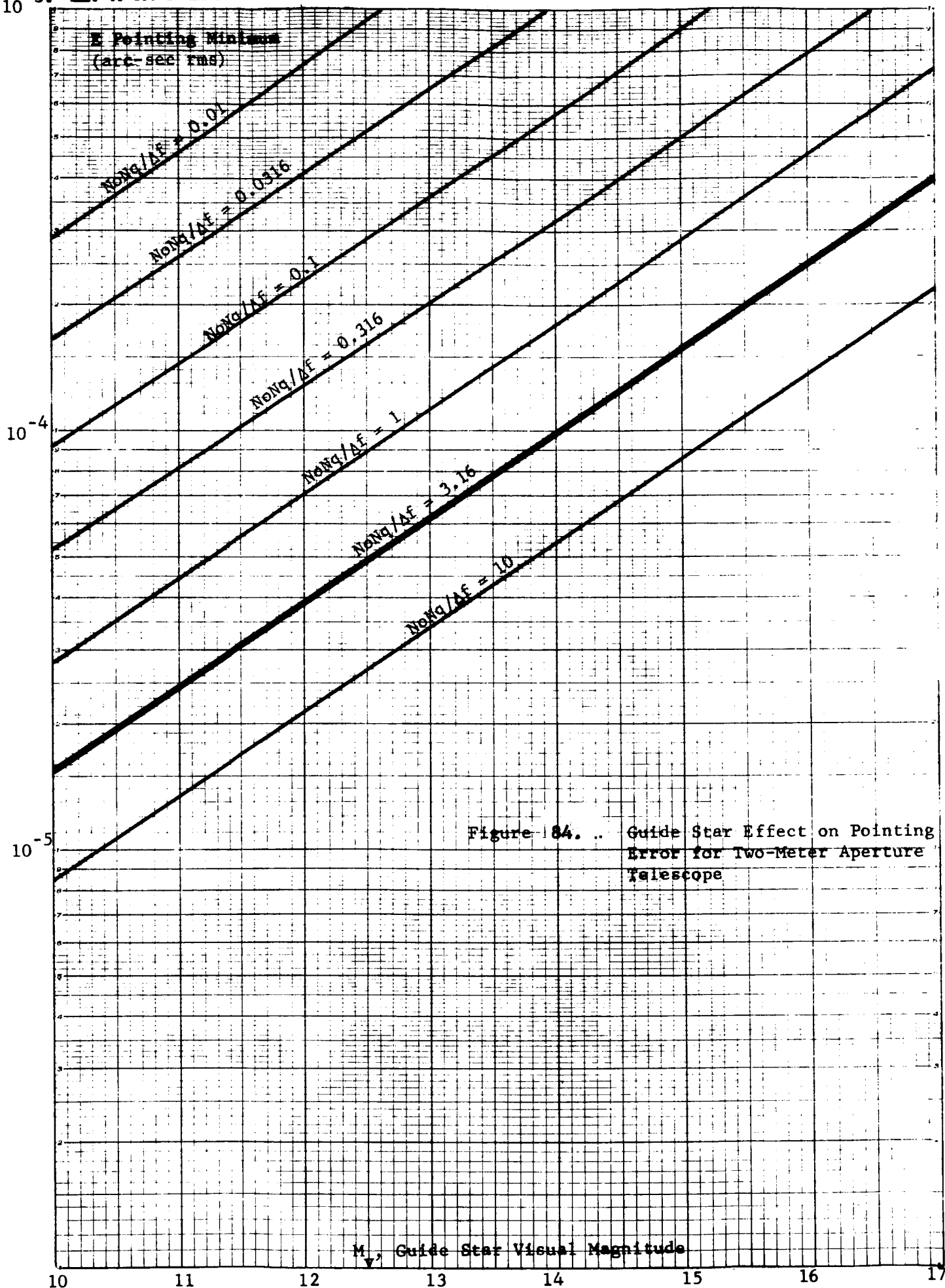


Figure 83. Telescope Guidance Open Loop Response



$\underline{M_v}$	$\underline{E_{p/min}}$ (arc-seconds rms)	$\underline{E_p}$
10	0.000015	0.00015
11	0.000025	0.00025
12	0.00004	0.00040
13	0.00006	0.00060
14	0.00010	0.00100

More realistic values of pointing errors are shown in Column 3 as ten times the Column 2 values in order to include some design safety margin (see Figure 85).

If the allowed photon noise induced error, E_p , is one-tenth the optical resolution at the minimum wavelength of $\lambda = 0.1$ micron, then

$$e_p = 0.1 \frac{1.22\lambda}{D} = \frac{0.1 \times 0.122}{2} \times 0.206 = 0.0015 \text{ arc-second}$$

and the maximum guide star magnitude will be 15 for the 2-meter OTES and 15.4 (see Figure 85) for the 3-meter. The area of the total field can now be estimated with the aid of Figures 86 through 89. Figure 86 shows the average number of guide stars per square degree as a function of galactic latitude and star magnitude (viz., approximately 240 per square degree for $M_v = 15.4$ at 90° latitude). Figures 87 and 88 indicate the probability statistics of star occurrence in the field assuming a Poisson occurrency spatially (viz., from Figure 88 the area of field required for 90% probability is $(\pi/4) (8.6)^2$ square arc-minute field area). Figure 89 shows the results based upon 90% coverage. Since the total field area available for selection by the guidance is not $(\pi/4) \phi_T^2$, but rather

$$\pi/4 \left[(\phi_T - \phi_{GA})^2 - (\phi_R + \phi_{GA})^2 \right]$$

at most, the actual value of ϕ_T depends upon the required values of ϕ_R and ϕ_{GA} . Assuming ϕ_R as 3 arc-minutes, ϕ_{GA} shall be taken as 2 arc-minutes, a value which allows an initial structural pointing error of ± 1 arc-minute. The values of ϕ_T required are then approximately 12 and 14.1 arc-minutes for 90% and 99% probability, respectively.

Figure 90 expresses the amount of background starlight in terms of number of equivalent stars of any magnitude. Since a ϕ_{GT} field of 30 arc-seconds contains a background light equivalent to seven-tenths of a 15.4 magnitude star, tracking accuracy will be degraded by a factor of $\sqrt{1 + .7} = 1.3$. Therefore, the value of ϕ_T should be increased slightly to allow use of brighter

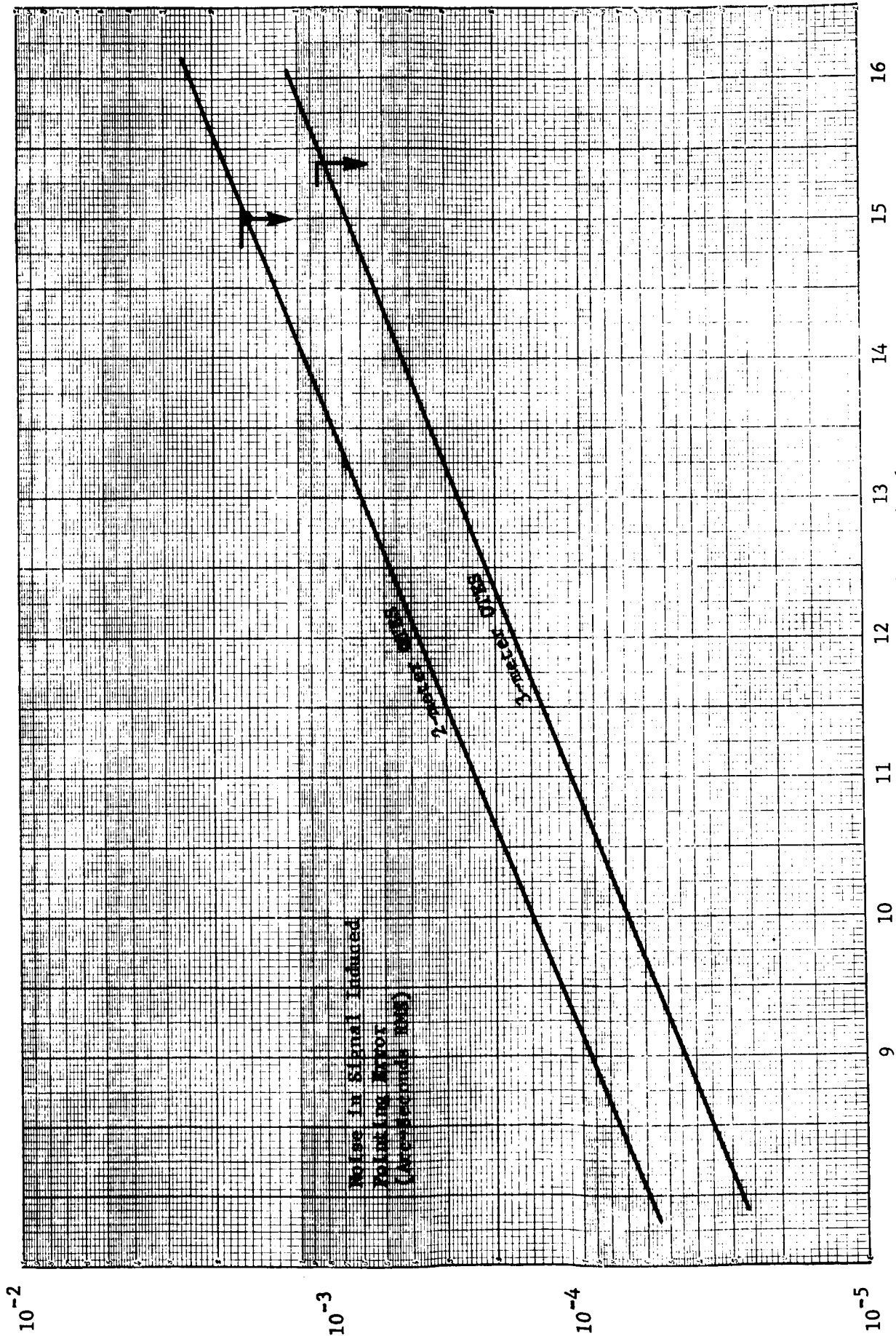


Figure 85. Photon Noise for 2 and 3-Me. Telescope Guidance

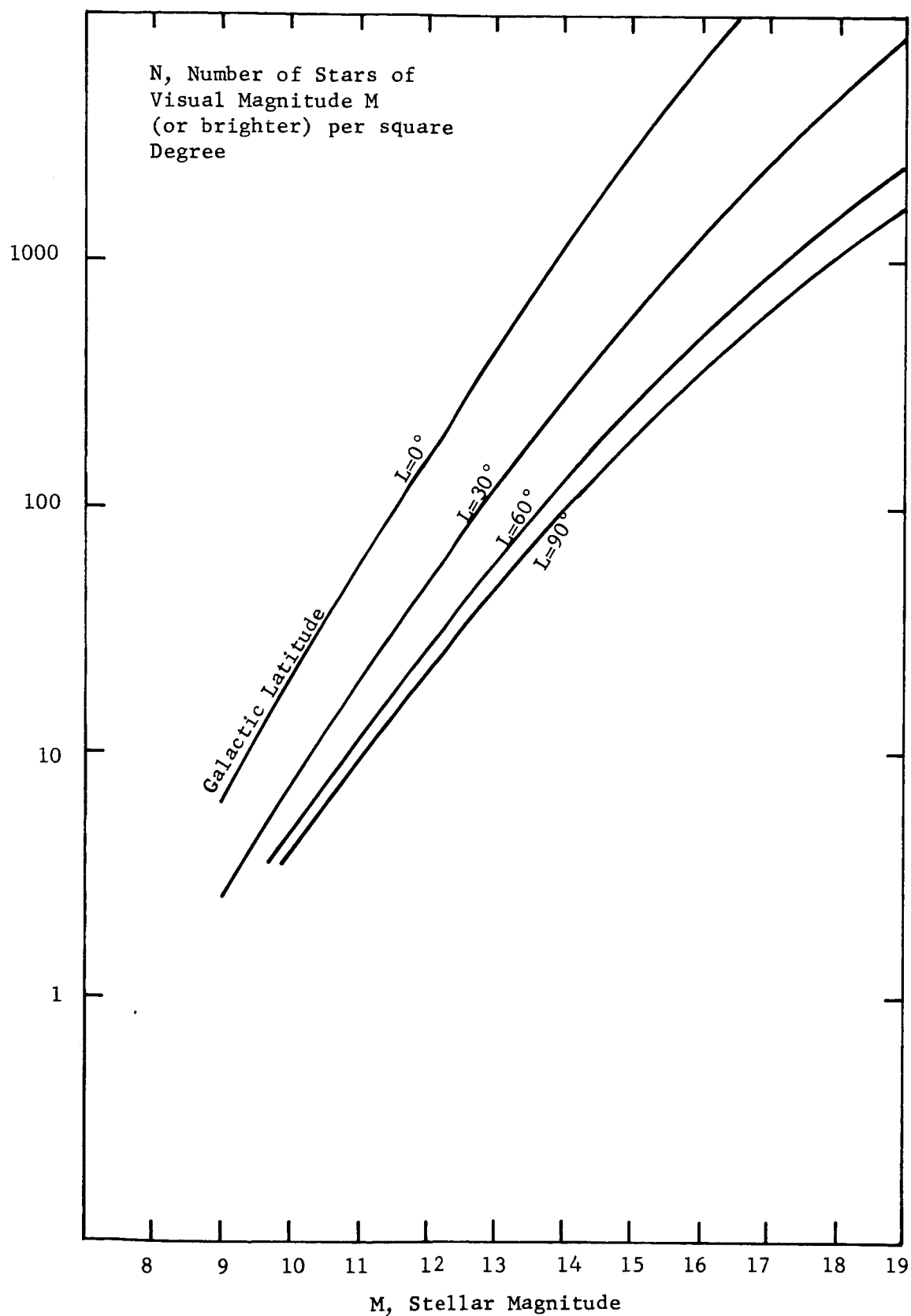


Figure 86. Availability of Guide Stars

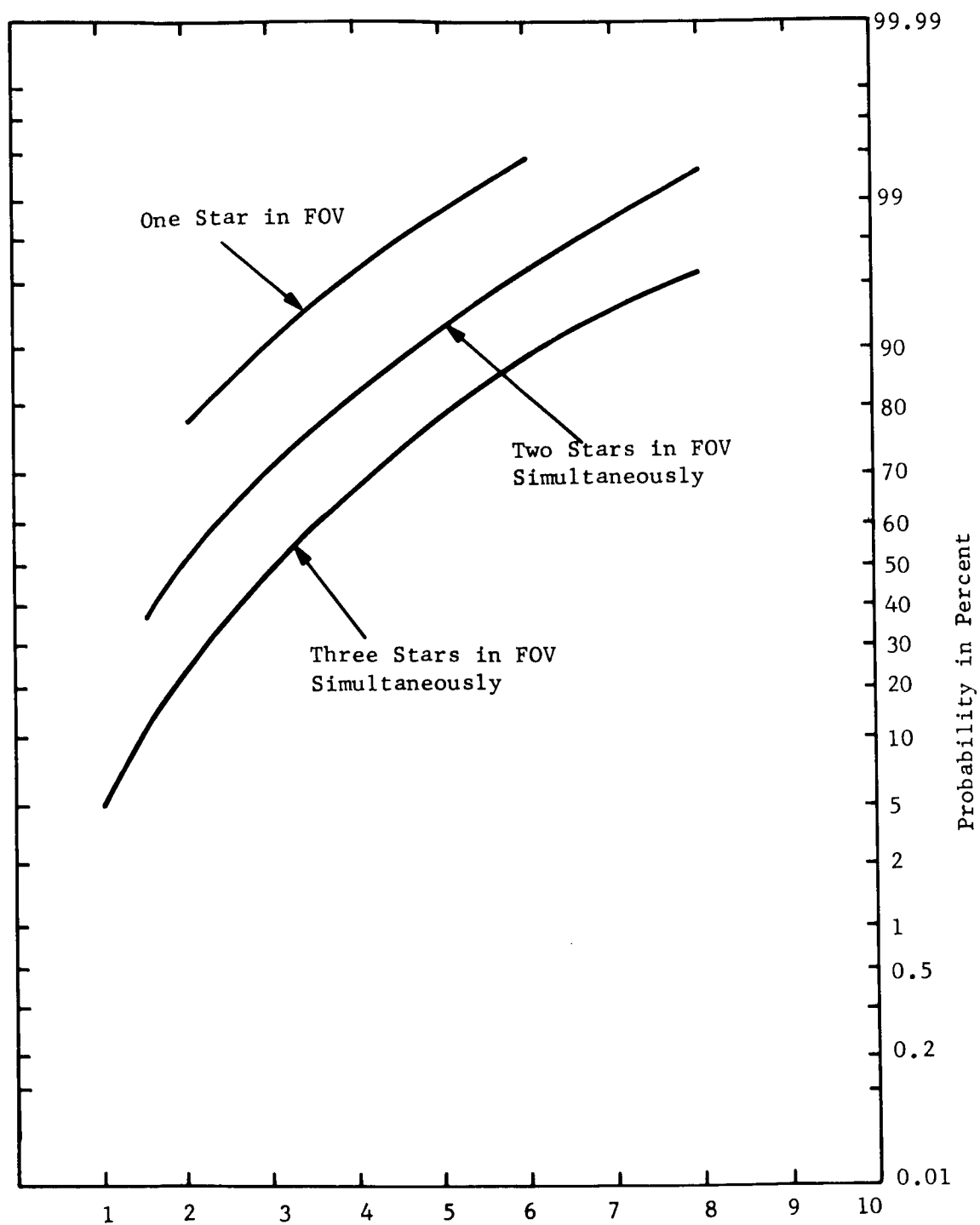


Figure 87.. Guide Star Probability

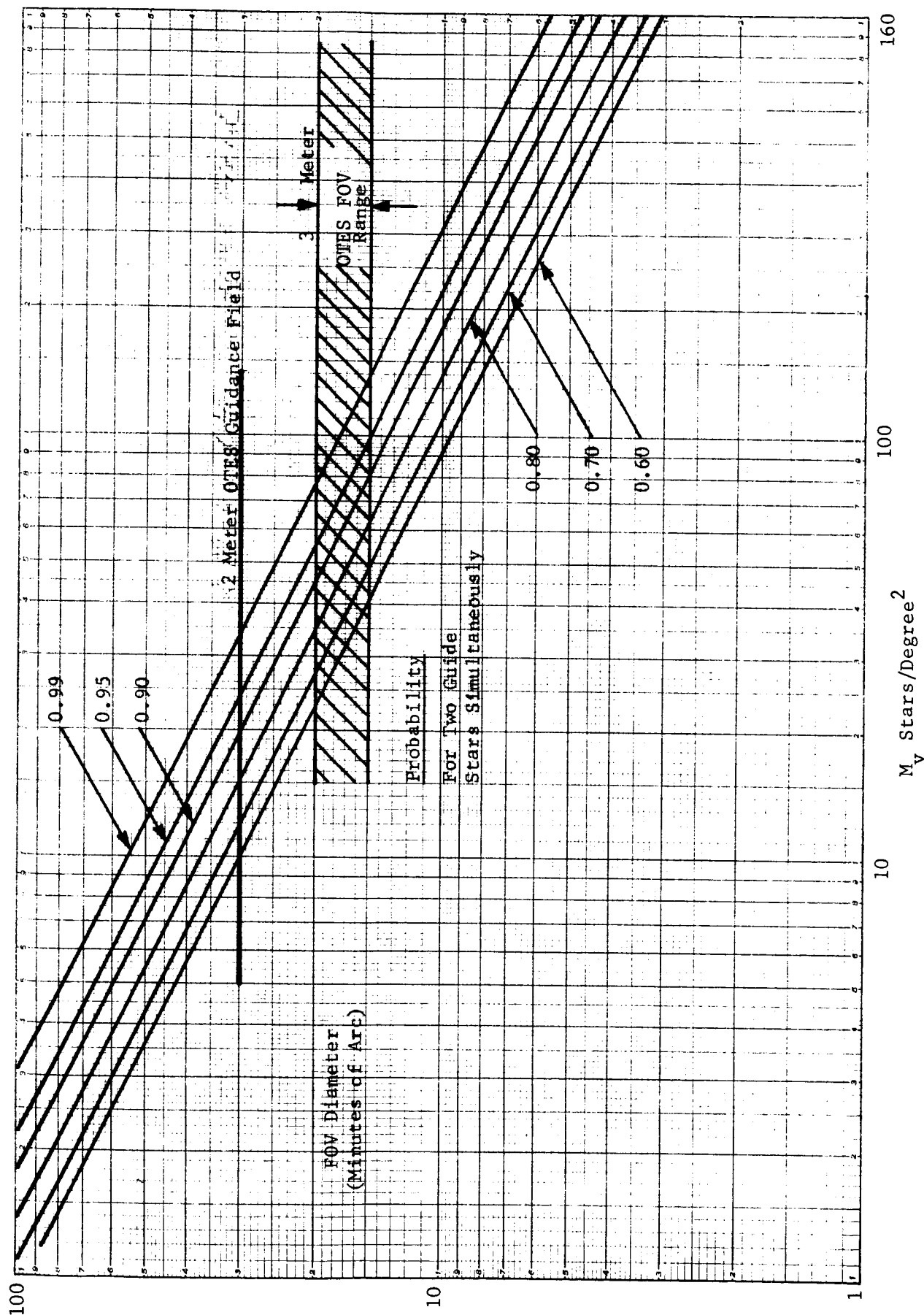


Figure 88. 2- and 3-Meter Telescope Guidance Field of View

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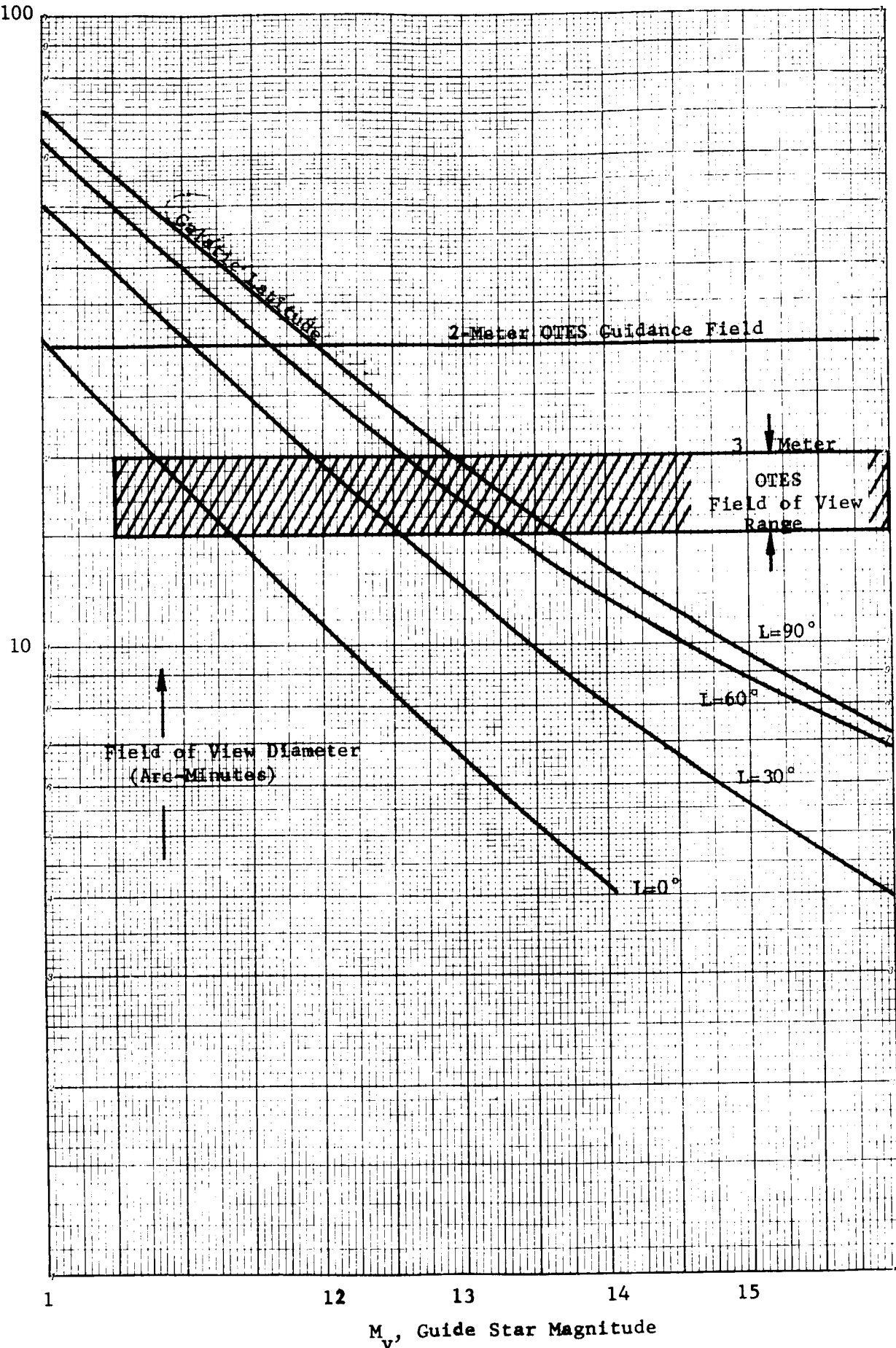


Figure 89... 90% Probability of at Least Two Guide Stars

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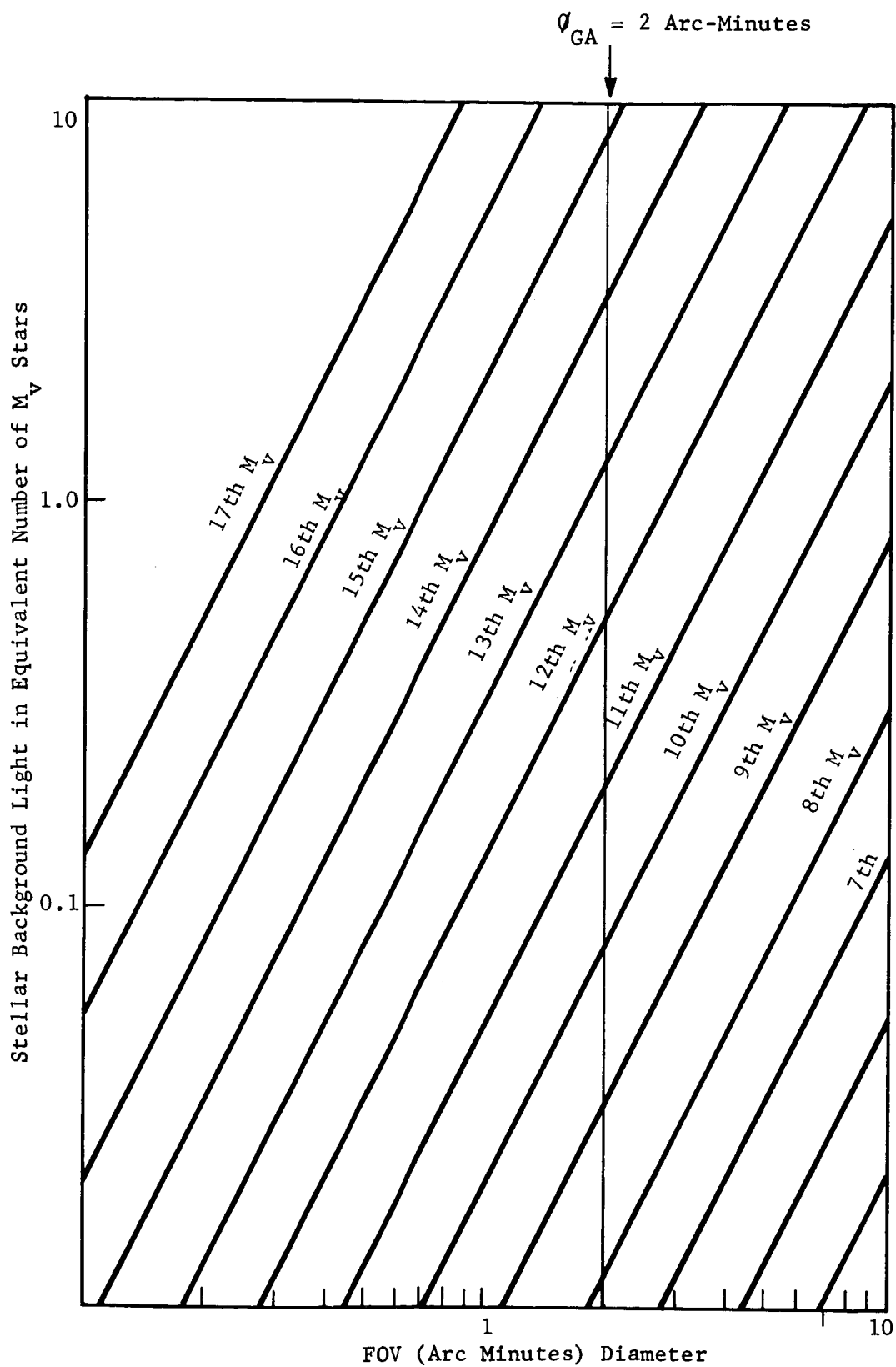


Figure 90.. Stellar Background Light

guide stars and/or the 30 arc-second field stop should be reduced, if practical. A value of 15 to 20 arc-minutes for ϕ_T would thus appear appropriate, providing approximately 99% probability of obtaining two sufficiently bright guide stars even when viewing at 90° latitude. Reasonable values of ϕ_R , ϕ_{GA} , ϕ_{GT} would appear to be 3, 2, and $1/2$ arc-minutes, respectively.

One last point which is worth checking is the degradation effects due to phototube dark current. RCA type 7265 S20 phototubes operating at 300°K (200°K) offer dark currents equivalent to 4×10^{-14} (1×10^{-15}) incident watts/tube at 5500Å or 2.76×10^{-11} (6.90×10^{-13}) lumens.

The light from a 15th M_V star is approximately

$$\frac{(2.4 \times 10^{-6} \text{ lumens/m}^2) \left(\frac{\pi}{4} D_A^2 \right) N_0}{10^6} = 5.4 \times 10^{-12} \text{ lumens}$$

which indicates that cooled phototubes will be required to prevent excessive degradation of pointing accuracy. It is worth noting that if cooling is impractical, then a 20 arc-minute field diameter will provide 90% probability at the galactic poles for guide stars of magnitude 13.5 or brighter. These stars can provide tracking accuracy in the order of 0.00035 arc-second, while 0.00084 is required.

$$\left(\text{Note: } \frac{8.4 \times 10^{-4}}{3.5 \times 10^{-4}} = 2.4 \right)$$

Since the 13.5th M_V star light at the phototubes is approximately 1.3×10^{-11} lumens and the phototube dark current is $[2.76 \times 10^{-11} \text{ (lumens/tube)}] \times [2 \text{ tubes}]$, the pointing degradation factor will be

$$\sqrt{(1) + \left(\frac{2 \times 2.76}{1.3} \right)} \approx 2.3$$

Hence, pointing performance will be the required one-tenth of diffraction-limited resolution, only 90% of the time at the galactic poles as a consequence of using uncooled phototubes.

EXPERIMENT NO.10 - OFF-AXIS TELESCOPE PERFORMANCE

(Deleted - Refer to OTES Interim Report* for Additional Details)

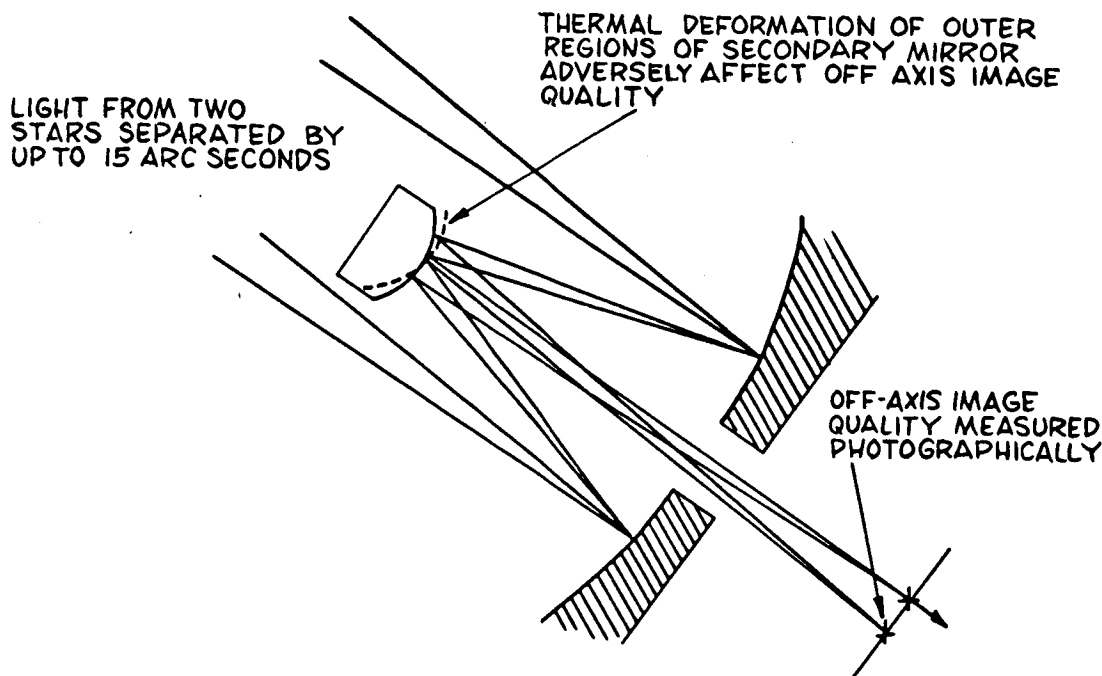


Figure 91

EXPERIMENT OBJECTIVE

A large-aperture, space optical telescope must have excellent off-axis performance as well as on-axis performance. This is necessary since the guide stars used to stabilize the line of sight for the telescope will not be on-axis, and it is these dim guide stars which are used to keep the telescope pointing at the target of interest.

Therefore, the objective of this experiment was to measure the off-axis performance of the astronomical telescope by analyzing images at several points in the focal plane. While photographs might be taken of the magnified image, this is a difficult task for a large telescope on station in space.

This experiment was removed from further consideration as a recommended experiment because the significance of the results, when obtained, would not be comparable with the importance of the other recommended experiments.

* Perkin-Elmer Report No. 8319

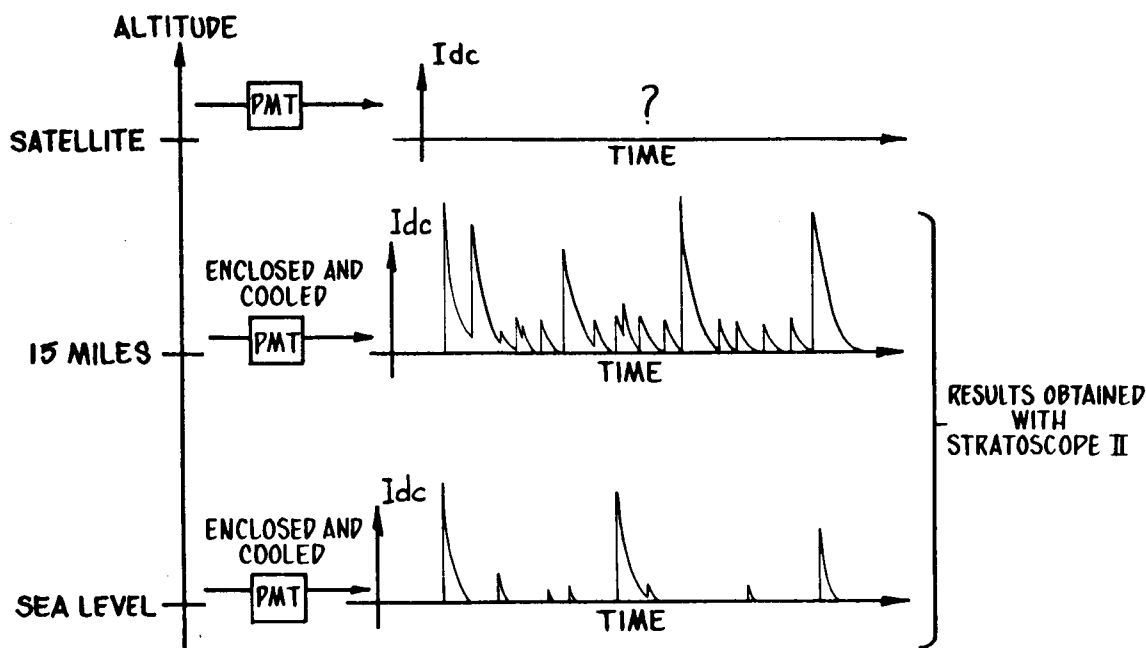
EXPERIMENT NO. 11 - RADIATION NOISE EFFECTS ON DETECTORS IN POINTING LOOPS

Figure 92..

EXPERIMENT OBJECTIVE

Pulse-height-versus-frequency measurements* on S20-type photomultiplier tubes indicate that both DC dark current and anode pulses of high amplitude are increased with operating altitude inside the Earth's atmosphere. It is suspected that these increases are attributable to cosmic rays (or the secondary radiation caused by cosmic rays). Ground tests with a Co^{60} radioactive source have yielded pulse-height-versus-frequency curves with changes very similar to those caused by operation at increased altitude. While the amount of DC current increase was modest, the noise in this additional component appeared significantly higher than predicted by Schott noise theory. This was due to the presence of very infrequent, yet unusually high magnitude, anode pulses. The objective of this experiment would be to obtain similar data, for one or more photosensors, corresponding to satellite environments. The motivation for the experiment is simply that such noise could severely degrade tracking performance in a space optical system.

EXPERIMENT JUSTIFICATION

This experiment, if performed in space, would be an economic trade with simulation of the radiation environmental conditions expected in space. The space data collected can be used to predict the degradations of photosensor performance to be expected as a function of shielding techniques. For example, the

*Performed on the Stratoscope II Program at altitudes less than 100,000 feet.

type of data that could be developed during the conduct of this experiment is illustrated in the sketch shown in Figure 93. The block diagram necessary to implement this experiment is shown in Figure 94.

TECHNOLOGY BENEFITS

The information obtained would be of significant value from both the communication and the tracking standpoints. Correlation between the pulse analyzer and radiation monitoring equipment measurements would lead to a better understanding of the phenomena involved and possibly the use of presently available radiation data in photosensor output noise calculations. Photosensor design changes and shielding techniques to obtain greater radiation immunity could influence the design of future telescopes for astronomy as well as deep-space laser communication systems.

BASIC EXPERIMENT HARDWARE

On the Ground

- Computer (to supply data on satellite position versus time)
- Data storage (for data transmitted from satellite)

In Space

- Photosensor(s)
- Pulse height analysis equipment
- Data storage capability
- Time reference
- Light source(s)
- Radiation monitoring equipment

EXPERIMENT DISCUSSION

The radiation noise induced in photosensors operating at low light levels can critically affect the performance of pointing and tracking loops and the detectors used for optical communications experiments. Experiment No. 11 is designed to measure the pulse height distribution from a variety of photosensors and is illustrated in Figures 93 and 94. In addition to the amplitude distribution, the temporal statistics of the radiation-induced noise should also be measured since this can influence the error characteristics of an optical communication channel.

Of equal importance to optical technology is the deleterious effects of high radiation fields on the optical components required for optical tracking, imaging, and communications experiments. Figure 95 shows the optical parameters which could be changed by various forms of radiation and the equipment required to measure these changes. Earth simulation experiments can be performed to estimate the effects of the Van Allen radiation belts by bombarding samples with high energy electrons and protons, but the integrated effect of the long-term exposure to the Van Allen belt environment is best performed by experiment in space.

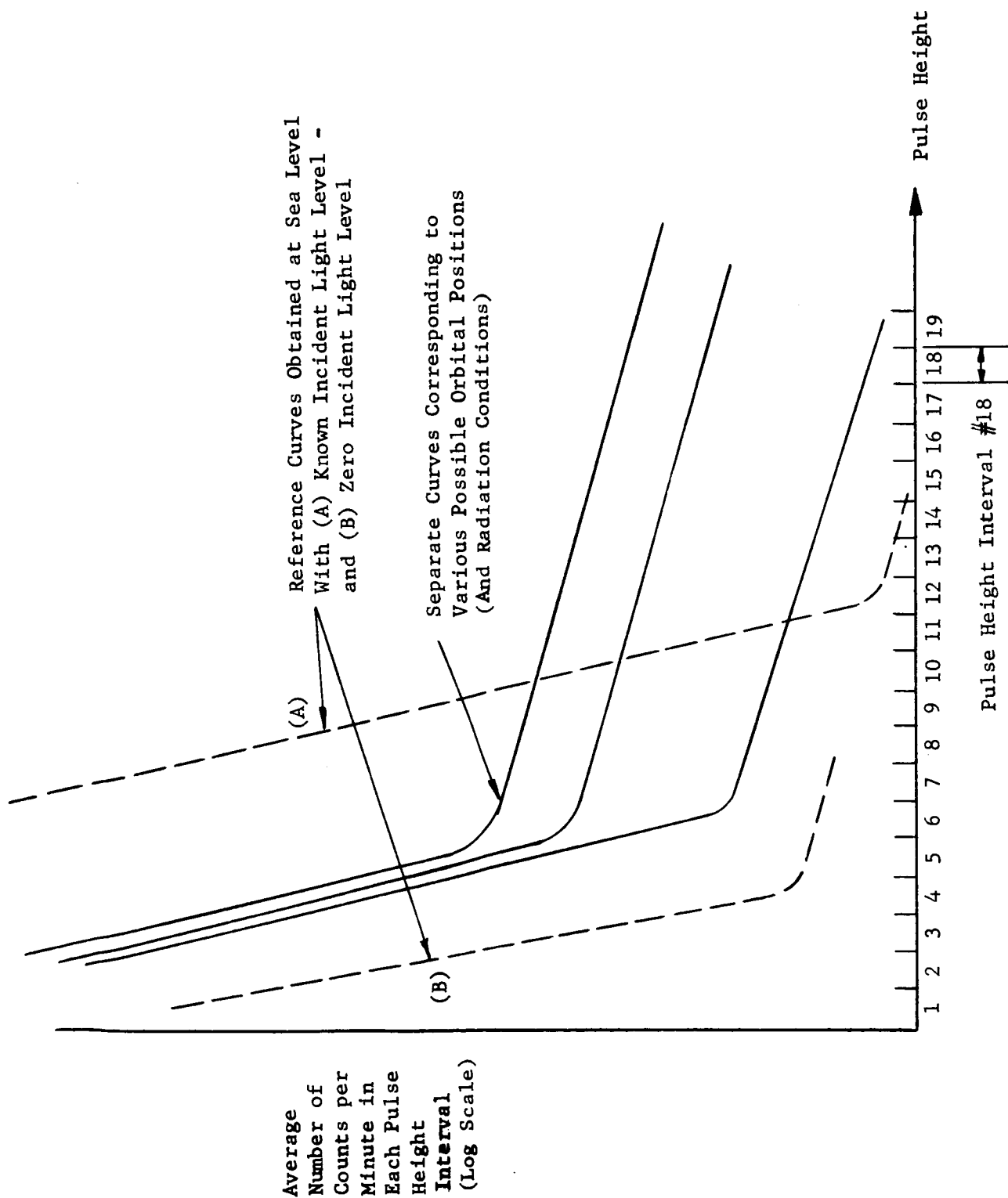


Figure 93... Type of Data Expected for Radiation Effects Experiment

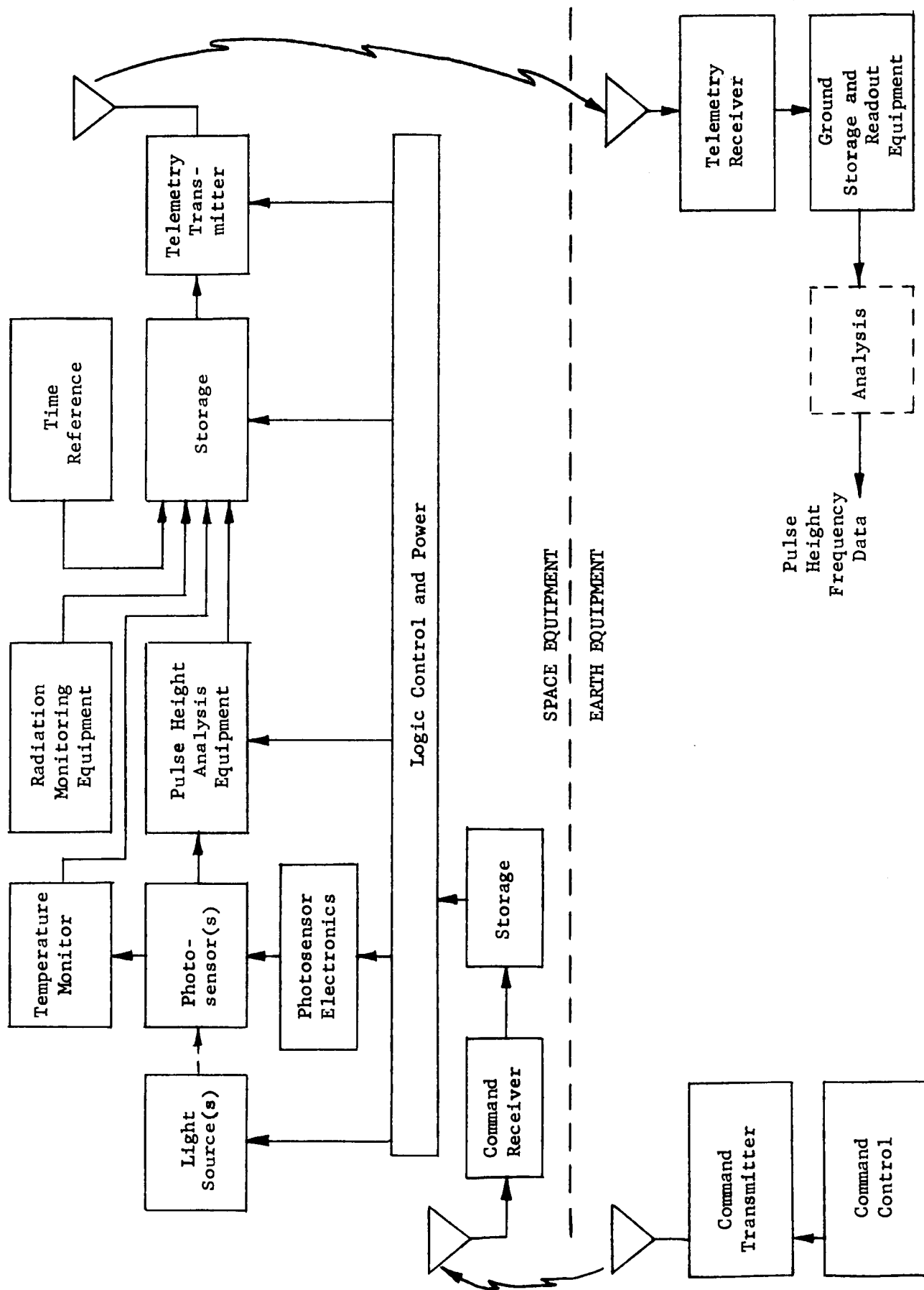
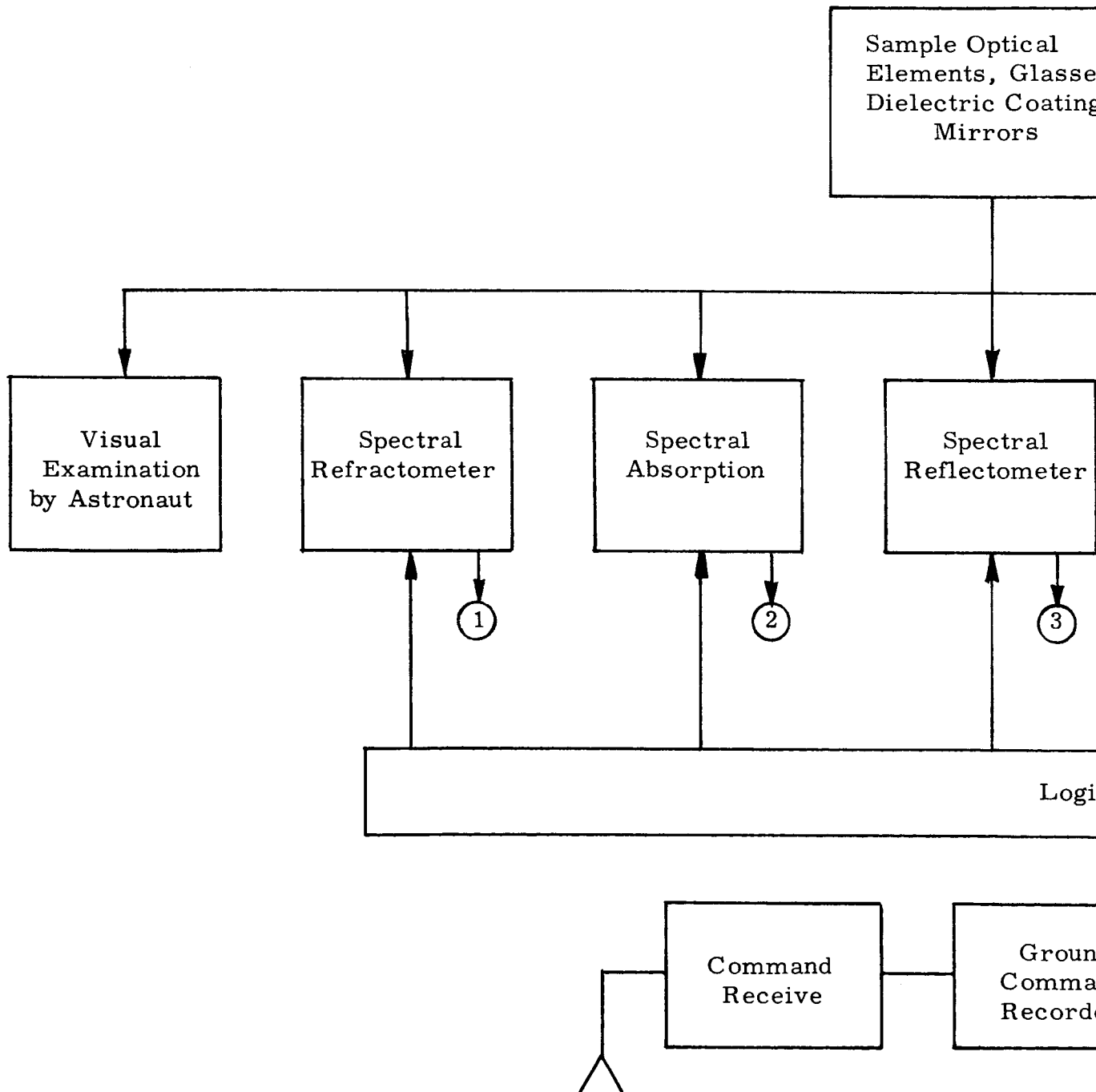


Figure 94. Block Diagram of Radiation Noise Effects on Detectors in Pointing Loops Experiment



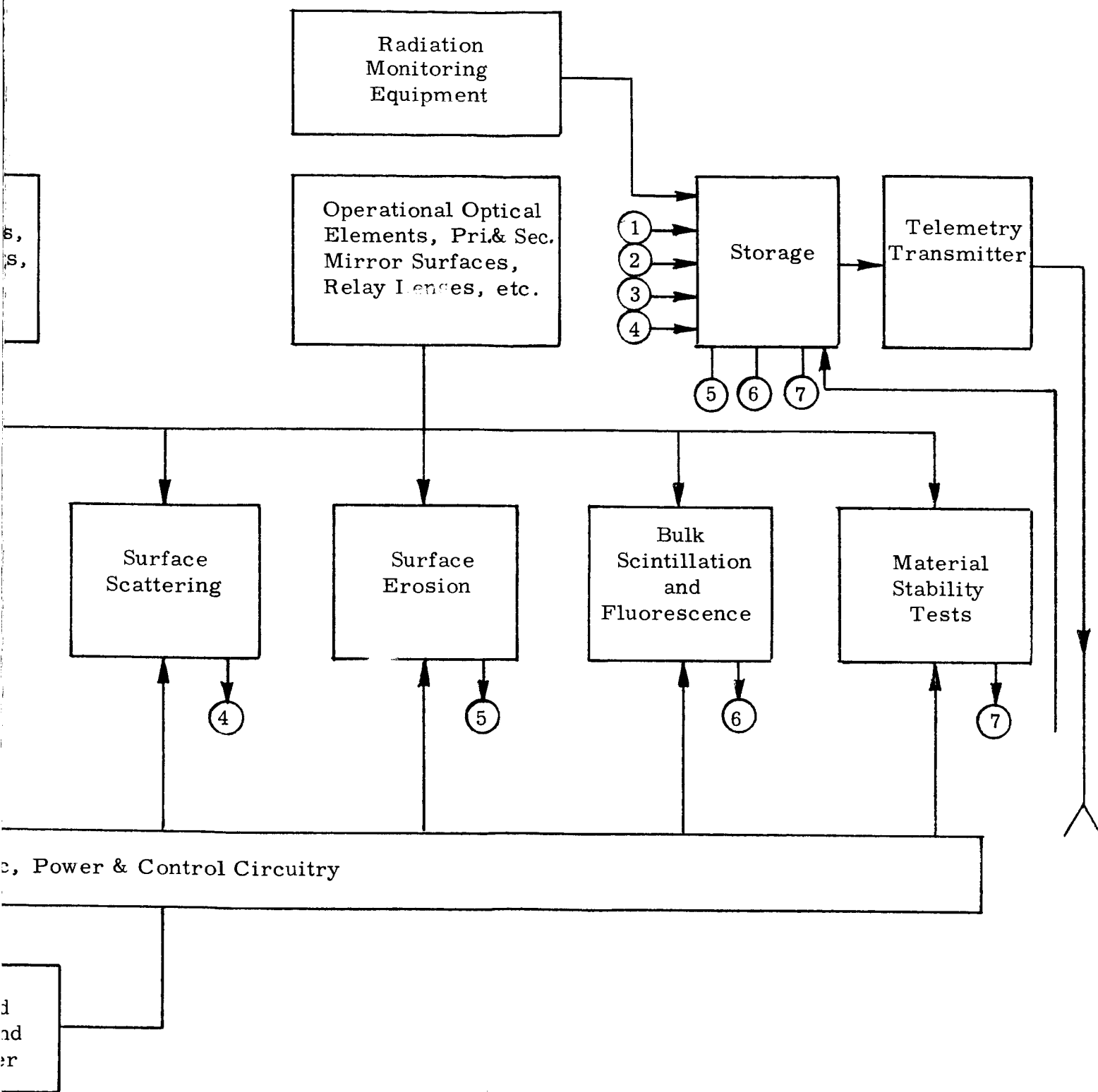


Figure 95. . Radiation Effects on Optical Elements

EXPERIMENT NO. 12 - MIRROR-FIGURE MEASUREMENTS CORRELATED WITH NUMEROUS TEMPERATURE SENSORS

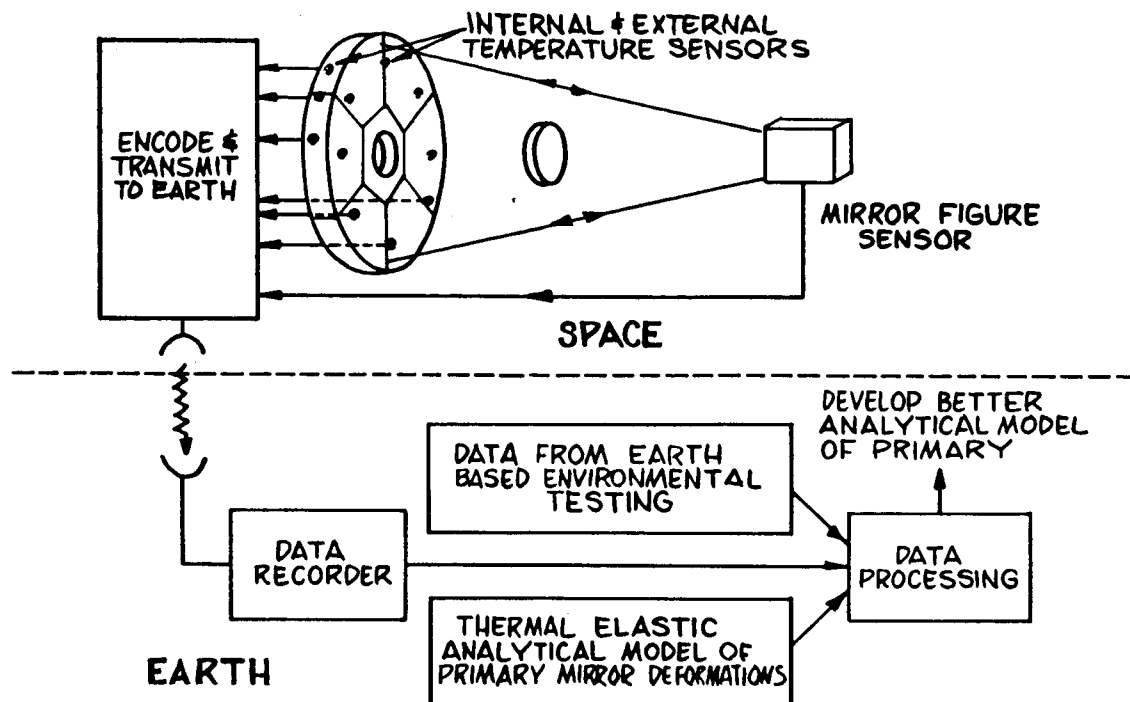


Figure 96

EXPERIMENT OBJECTIVE

The objective of this experiment is to verify that the temperature distributions assumed in the thermal design (and simulated during the Earth-based environmental tests) are actually realized in space operation.

Future large-aperture space telescopes must maintain diffraction-limited performance in the space thermal environment. In order to assess the effect of the thermal environment, with varying thermal gradients on mirror performance, it is necessary to estimate the expected range of operating temperatures, as well as the lateral and longitudinal thermal distributions. The satellite capsule itself is almost always exposed to the direct rays of the sun on one side and to the cold of space on the other. The expected temperature history also involves radiative interaction with the Earth as well. In space applications involving operation in a vacuum, temperature gradients assume substantial proportions in the absence of the equalizing effects of convection currents which exist at normal atmospheric pressures.

It is, therefore, important to verify experimentally if the temperature distributions assumed in the thermal design (and simulated during the Earth-based environmental tests) are actually realized in space operation. These Earth-based tests consist of superimposing controlled temperature distributions on the primary mirror of the space telescope and correlating this information with measurements of primary mirror-figure error.

EXPERIMENT JUSTIFICATION

This experiment will allow verification of the thermal elastic analytical models for the temperature distributions and primary mirror deformations as well as verification of the Earth-based thermal simulation tests.

This spaceborne experiment will consist of monitoring the operating temperature distributions and figure-error deviations of the primary mirror. This data will then be encoded for real-time return transmission to Earth for data processing and correlating with results of analytical thermal elastic models and Earth-based environmental simulation tests of primary mirror deformations.

TECHNOLOGY BENEFITS

This experiment will provide useful empirical data on temperature distributions that will have deleterious effects on the diffraction-limited primary mirror performance.

BASIC EXPERIMENT HARDWARE

On the Spacecraft

- Primary mirror with external and internal temperature sensors
- Mirror figure sensor and scanner
- Real-time data transmission to Earth

On Earth

- Telemetry receiver
- Data recording and processing and special display equipment

The basic equipment, illustrated in Figure 96 will provide the experimental data which is needed to comparatively evaluate the thermoelastic performance of the candidate mirror materials.

- | | |
|---|---|
| • Thin fused quartz mirrors | • Beryllium Mirrors |
| • Eggcrate fused quartz mirrors of Ultra Low Expansion (ULE)(7971) material | • Solid fused quartz mirrors of 7940 material |
| • Silicon mirrors | • Cervit |

A flight program such as the one proposed in Experiment No. 12 must be preceded by an experimental ground program to provide the basis for evaluating the data that would result from the spacecraft.

Although it is beyond the scope of the present phase of the OTES Program to do the appropriate ground testing, Perkin-Elmer has performed thermal vacuum testing of a large, 32-inch eggcrate fused quartz mirror. Princeton University made available the OAO program mirror to evaluate thermoelastic deformation

behavior. In addition to the controlled thermal deformation work, Perkin-Elmer has conducted the analytical work that is necessary to construct mathematical models which will establish the magnitude of the figure deformations resulting when nonsymmetrical thermal gradients are applied.

To date several scatterplate interferometer plates have been taken without* and with** heating of the support points. The data from these interferograms will be extracted by measuring the locations of the bright circles and then having the computer reduce the data to establish the best fit surface from the mirror. Figures 97 and 98 are photographs of the instrumented mirror. The measurements that have been reduced from the Thermal Vacuum Test Project photographs (Figures 99 and 100 indicate that for a 10°C rise in temperature at the mounting points of the eggcrate fused quartz mirror, the front faceplate of the mirror directly over the mounting point with the higher temperature has a corresponding rise of 7 to 8°C. Thus, in the 2-inch distance, there is a 2 to 3°C drop in temperature or an average gradient in the vicinity of 1 to 1-1/2°C per inch. The gradient along the faceplate of the mirror disappears within 6 inches from the location above the mounting point. The photographs (Figures 99 and 100 EX79) show some of this effect, but the overall magnitude of the effect can only be established by densitometer measurements of the scatterplate negative slides. The backplate of the mirror in the tests indicated above was about 1/10°C warmer on average than the frontplate due to the heat inputs at the three mounting points.

The mounting points are indicated in Figure 100. The fine looking lines on the surface of the mirror are not scratches but wires going to the various thermistors. These are quite apparent in Figures 97 and 98.

Surface and internal temperature measurements of the primary mirror must be correlated with the figure measurement data derived from the phase-measuring interferometer (Experiment No. 1) in a similar manner to that described in the Thermal Vacuum Mirror Test Project. Experiment analysis is performed on Earth using data supplied by the temperature measuring system shown in Figure 101. All temperatures are measured relative to an insulated reference cavity maintained at constant temperature by a thermistor controlled servo system. The array of thermocouples (Cu-Constantan) is interrogated by a stepper motor commutator upon command from the ground and each thermocouple is compared with the reference cavity. The difference signals are amplified and encoded for transmission to Earth. The preamplifier gain is controlled from the ground to provide a wide dynamic temperature range for the temperature measurement system. Calibrated thermistor temperature sensors are used for this flight experiment. In these devices, the thermistor resistance is read directly by a digital voltmeter and transmitted to Earth.

* Figure 99

** Figure 100



Figure 97



Figure 98

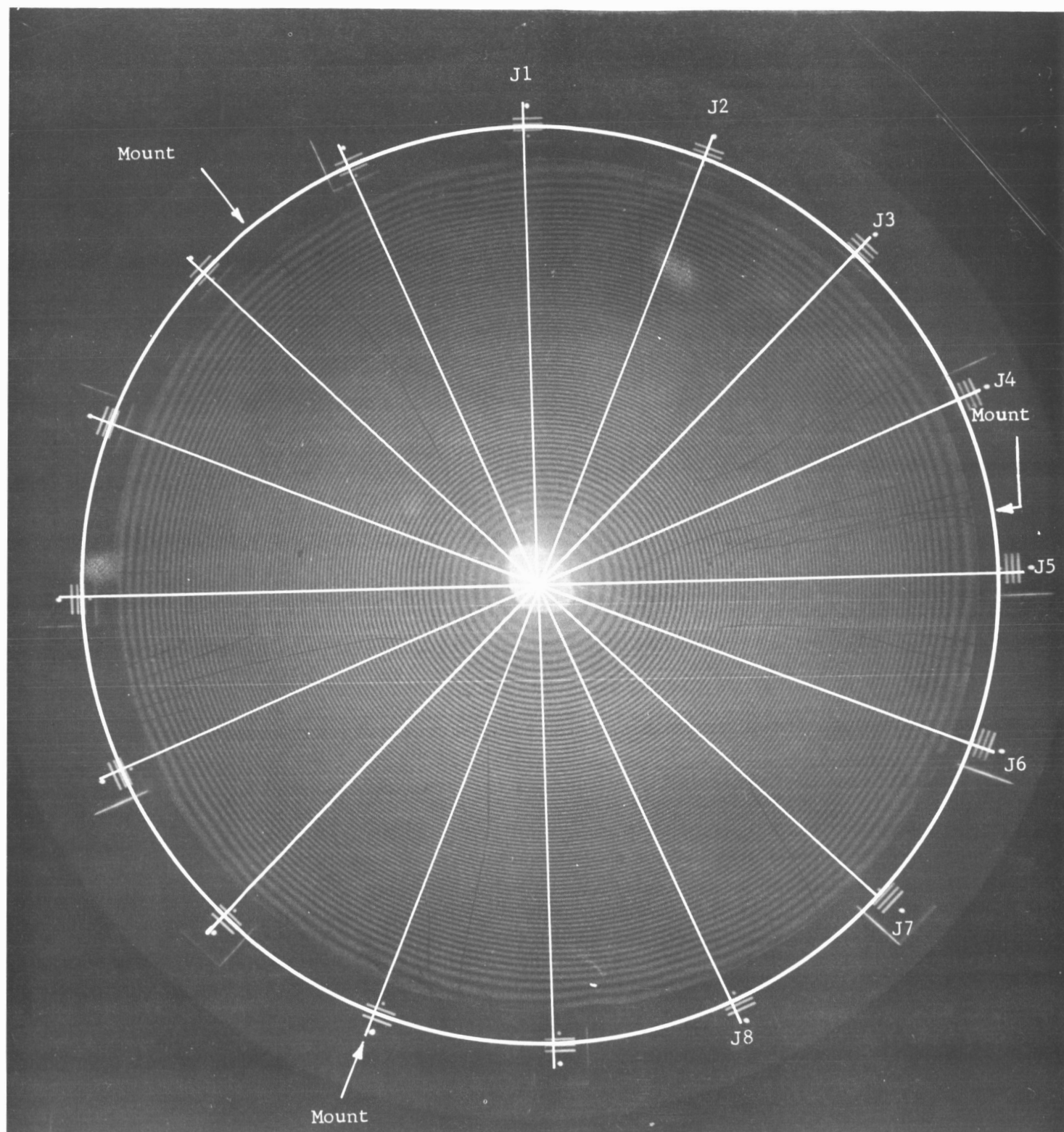


Figure 99. Reference Scatterplate

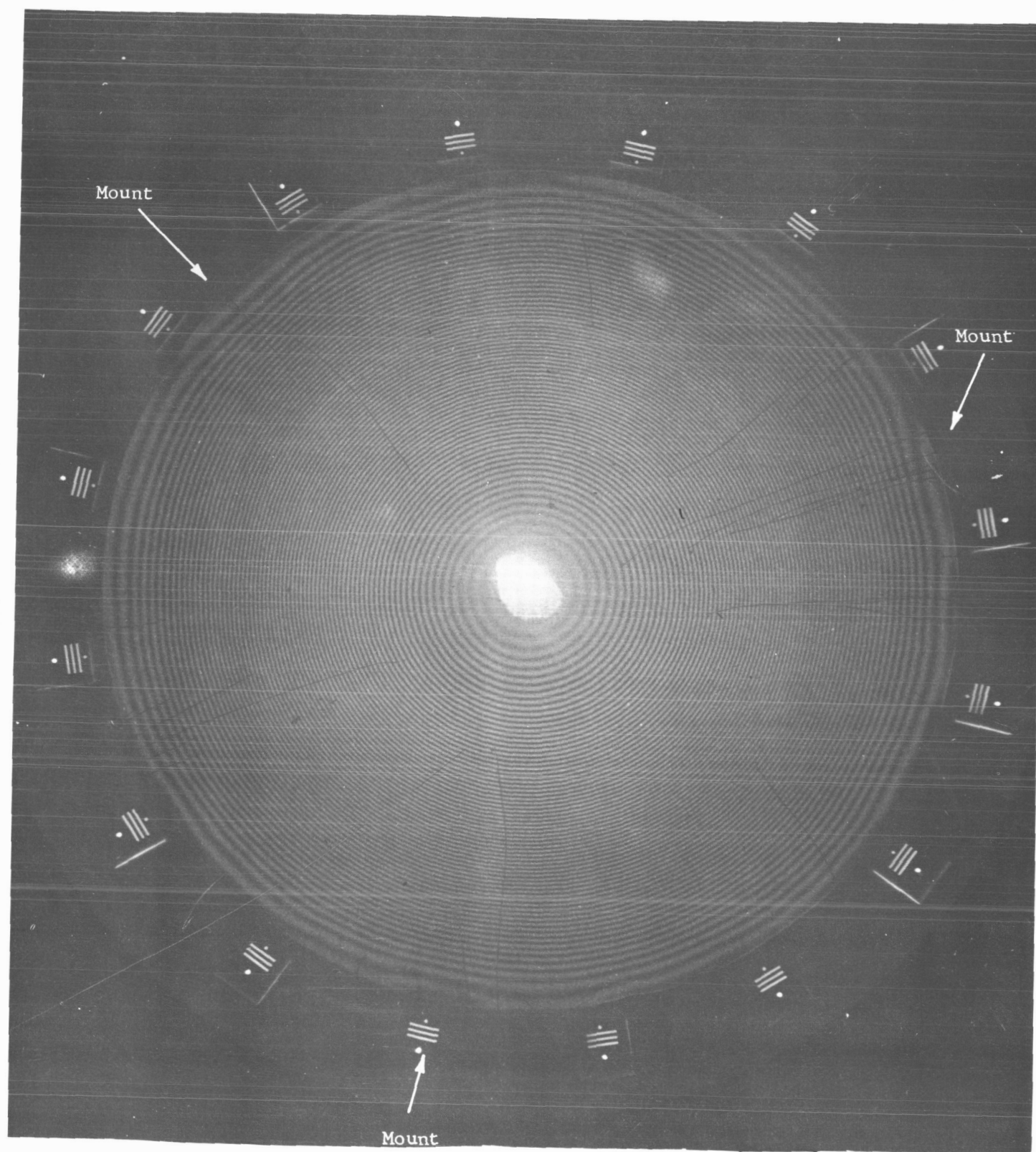
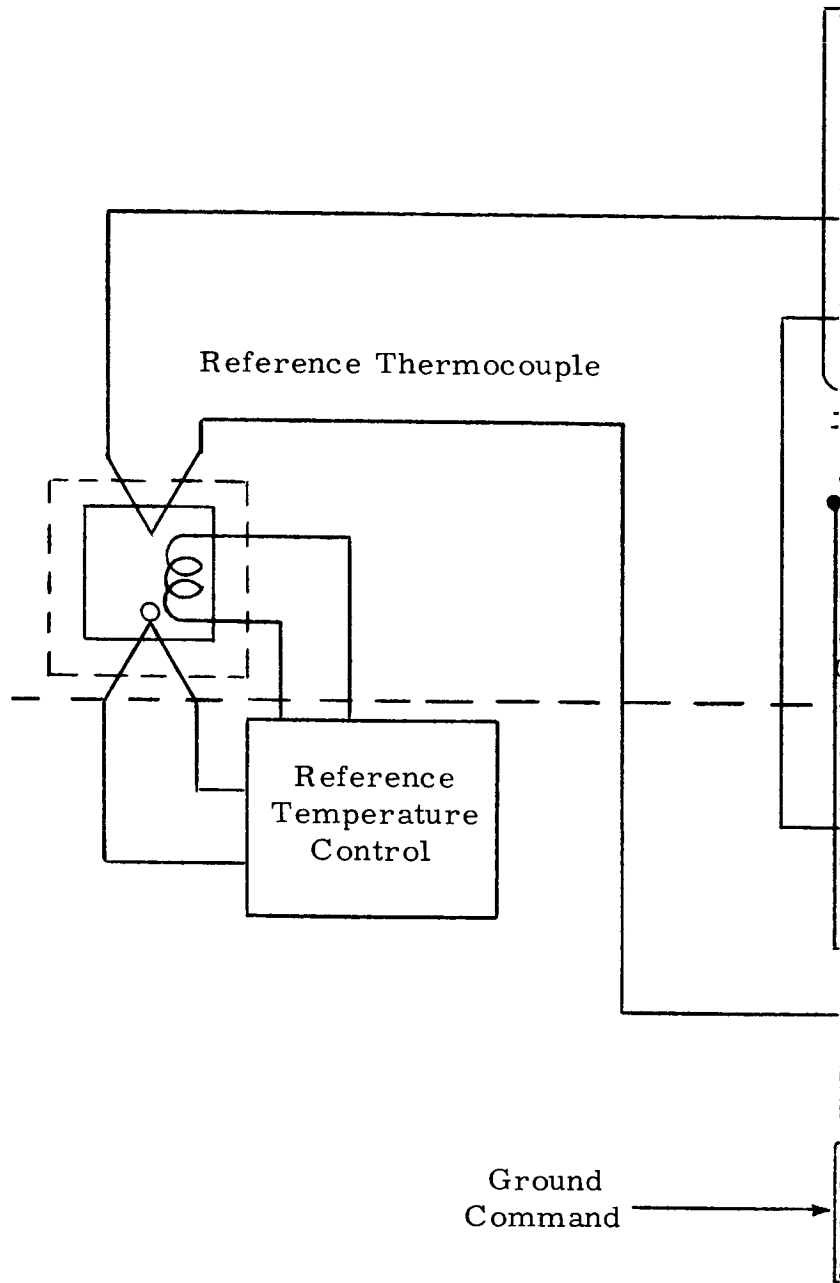


Figure 100. Scatterplate Taken with 12°C Temperature Rise at Mounting Points

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Insulated
Reference
Cavity
Reference
Thermostat



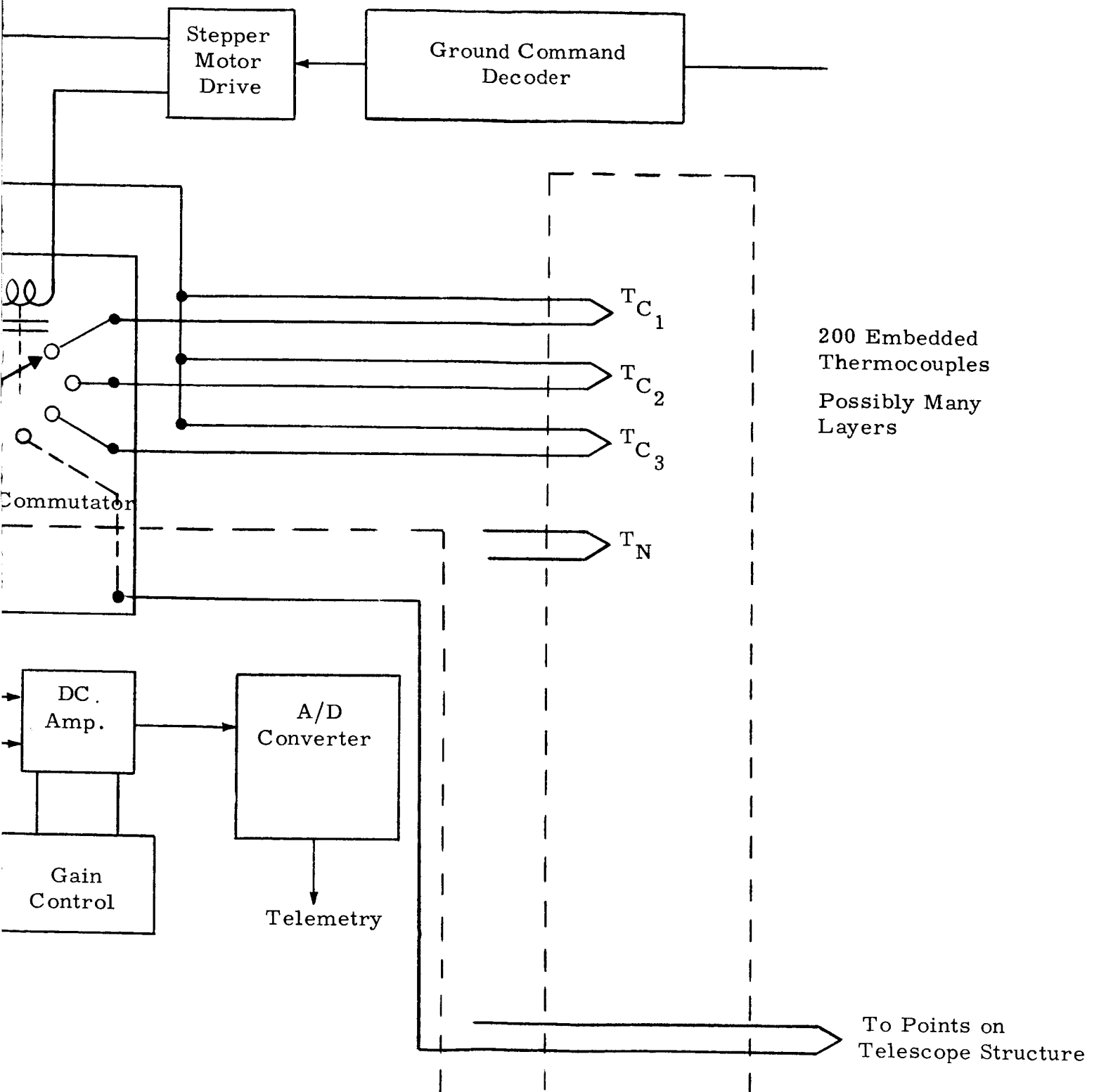


Figure 101. . . Thermal Diagnostics

PERKIN-ELMER THERMAL VACUUM TESTING
OF A SPACE MIRROR

This section of the OTES report describes the set-up and techniques employed and the results obtained in the initial stages of a test program to determine the surface deformation incurred in a mirror due to thermal inputs. During this initial phase, preliminary scatterplate measurements were made of a 32-inch diameter primary mirror subjected to heat inputs at the three mounting points of the mirror.

The experiment was conducted using the 72-inch vertical test tank at the South Wilton facility. The tank was operated at a pressure of 1 mm Hg to permit temperature difference measurements of better than 0.1°C accuracy. Various considerations indicate that the temperature measurements taken during the experiment were of this accuracy. For example, allowing the mirror to stabilize for about twelve hours with no heat input to equalize possible initial temperature differences results in thermocouple readings across the entire mirror surface which stay well within $\pm 0.1^{\circ}\text{C}$ of a given average temperature. This proves the random error associated with the measurement routine better than $\pm 0.1^{\circ}\text{C}$. As to the potential systematic errors incurred with surface temperature measurements* a few thermocouples were mounted in close proximity to thinistors. These are semiconductor sensors particularly developed for surface temperature measurement and accordingly capable of an accuracy in the order of 0.01°C . Thinistors and thermocouple readings agreed also within $\pm 0.1^{\circ}\text{C}$ in all cases. From these results we can assume that both the random and systematic errors involved are in accordance with the required accuracy of 0.1°C . Moreover, a separate experiment is contemplated - utilizing a 10-inch diameter glass disc in a bell jar environment - to further substantiate our knowledge on the potential accuracy of surface temperature measurements by means of thermocouples and thinistors.

The mirror was mounted horizontally on the special Perkin-Elmer air bag support system shown in Figure 66 to minimize mechanical deflections due to the weight of the mirror and to simulate the gravity-free condition encountered in space application.

Instrumentation

Temperature sensors (thinistors and thermocouples) were mounted on the front and back faceplates of the mirror to provide the required thermal gradient data. Figures 102 and 103 show the mirror structure and the relative location of thinistors and thermocouples used in the experiment. In these experiments, the locations of the sensors are exactly the same for both front and back faceplates.

A Honeywell digital multimeter (0.005 percent accuracy) was used to record resistance from the thinistors and this data was converted into measurements

* Perkin-Elmer Engineering Memo, "Systematic Errors in Surface Temperature Measurements" 2/15/67, S. Habijanac

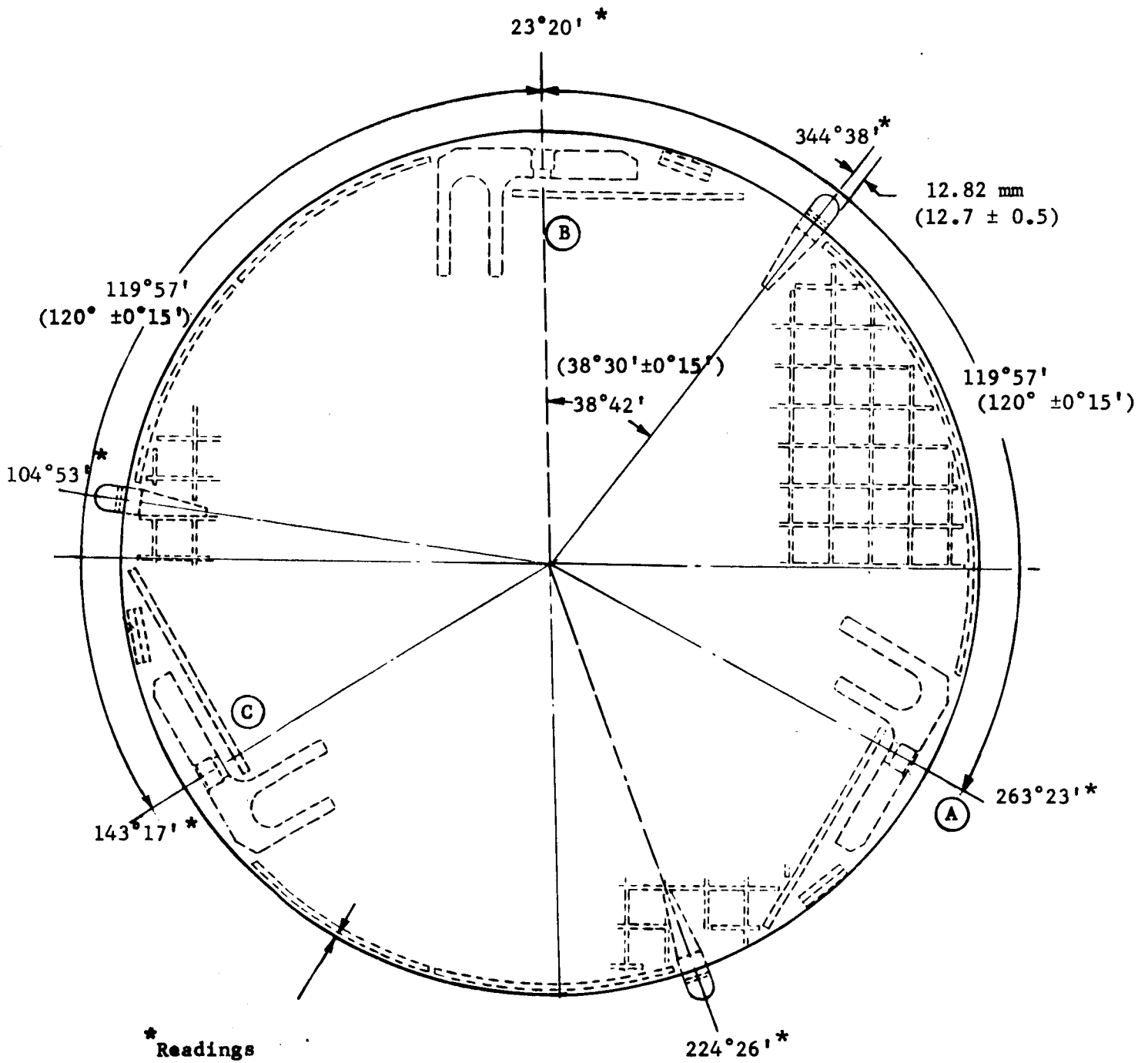


Figure 102. Test Mirror Structure

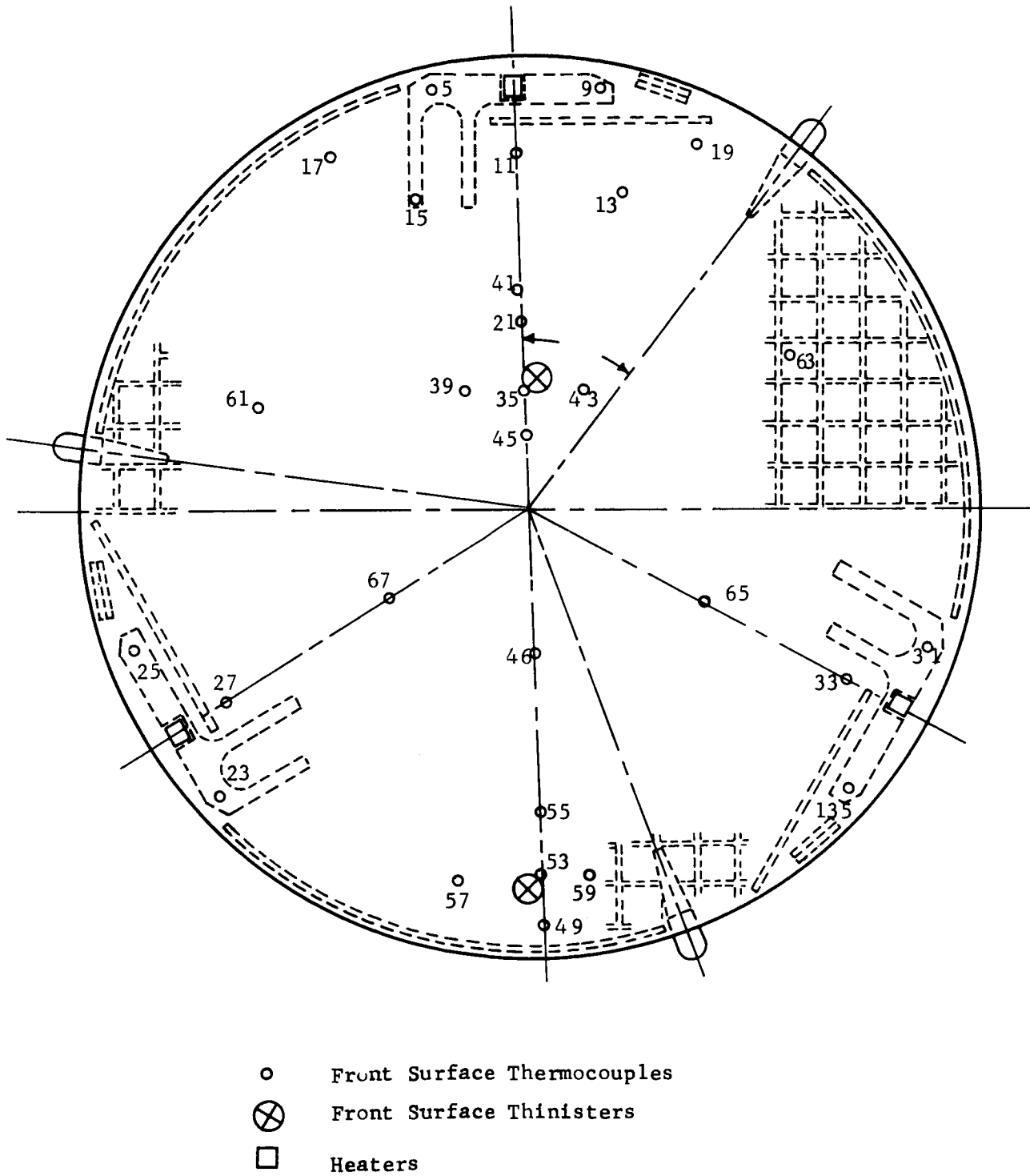


Figure 103. Location of Sensors and Heater Pads

of absolute temperature at the surface. The 5 mil copper constantan thermocouples were monitored by a Leeds and Northrup Type K-5 potentiometer. By comparing the potentiometer readings to a thermocouple in an ice bath reference, and a reference thermocouple located at the center of the back faceplate, absolute as well as differential temperatures were determined to an accuracy of better than 0.1°C .

Figure 103 also shows the location of the three side-mounted heated pads used to excite the required thermal patterns. These pads were cemented with RTV into mounting points (normal ball joint location) in the three "F" members of the mirror structure. This arrangement simulates the heat input (or output) anticipated due to the mirror mount being warmer (or colder) than the mirror itself. An external controller was used to monitor and control the temperature of each pad.

Test Results

Surface temperature profiles were plotted for temperature rises at the mounting points of 6°C and 11°C . Thermal contour maps of the front faceplate for these two cases are shown in Figures 104 and 105. Only the front faceplate is considered since the data plotted in Figure 106 shows the symmetry of the thermal profiles taken at the front and back faceplates.

Once the thermal profiles were established and recorded, scatterplate interferograms of the mirror surface were taken. Analysis of the resulting fringes and subsequent computer processing provided rms figure deformation resulting from the particular thermal gradients imposed on the mirror. A reference interferogram (Figure 99) was taken with the mirror in a steady-state ambient condition prior to each experiment. As evident in this figure, a circular array of reference lights was mounted around the mirror. Diagonals taken through the center of each light (J1, J2, J3, etc.) and a circle formed by the lights perpendicular to these diagonals form the reference grid for measuring the scatterplate data.

Examination of the scatterplate shown in Figure 100 qualitatively shows the deformation of the mounting points due to an 11°C rise in temperature. Note that in the reference interferogram in Figure 99, the fringe pattern is quite circular at the mount points, whereas in Figure 100, the fringes tend to pinch towards the center of the mirror indicative of an elevation of the mirror surface at these locations.

The optical path differences were plotted against mirror position from the scatterplate data. Figures 107 and 108 show the reference plot and a plot at 11°C along the eight diagonals shown in Figure 99. From this figure it can be seen that diagonal J2 runs directly through a mounting point. By comparing OPD's at J2 in the graphs of Figures 107 and 108, the steep deformation is evident. This plot also shows the extremely localized nature of the deformations. On this basis, approximate contour maps of the deformation at the mounting points were plotted. That is, since the gradients were localized, a composite was created by reading diagonals J4 and J5 on both sides of a

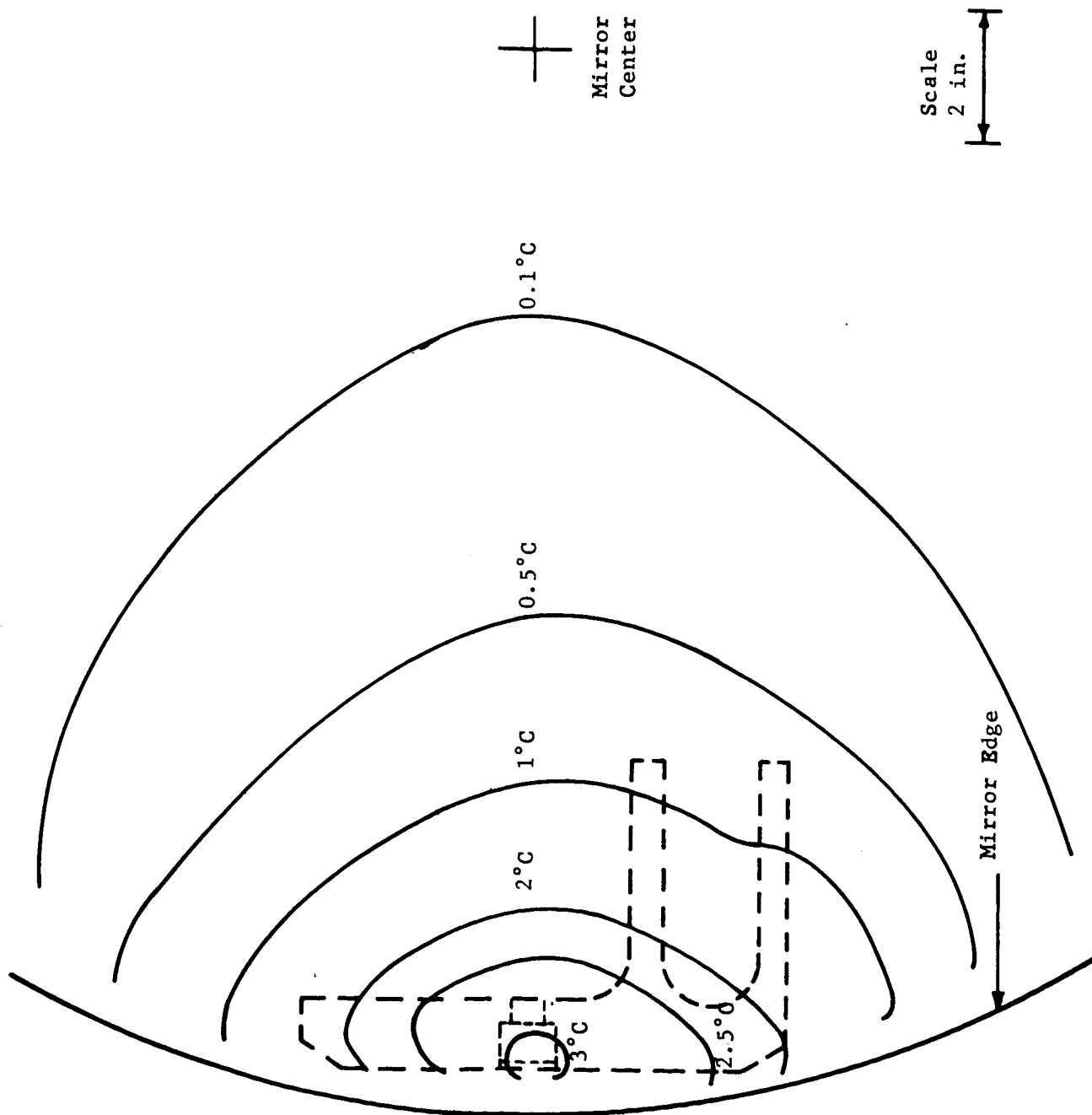


Figure 104. Thermal Contour Profile at Mirror Mount Point (Front Faceplate)- 6.0°C Rise at Mount Point

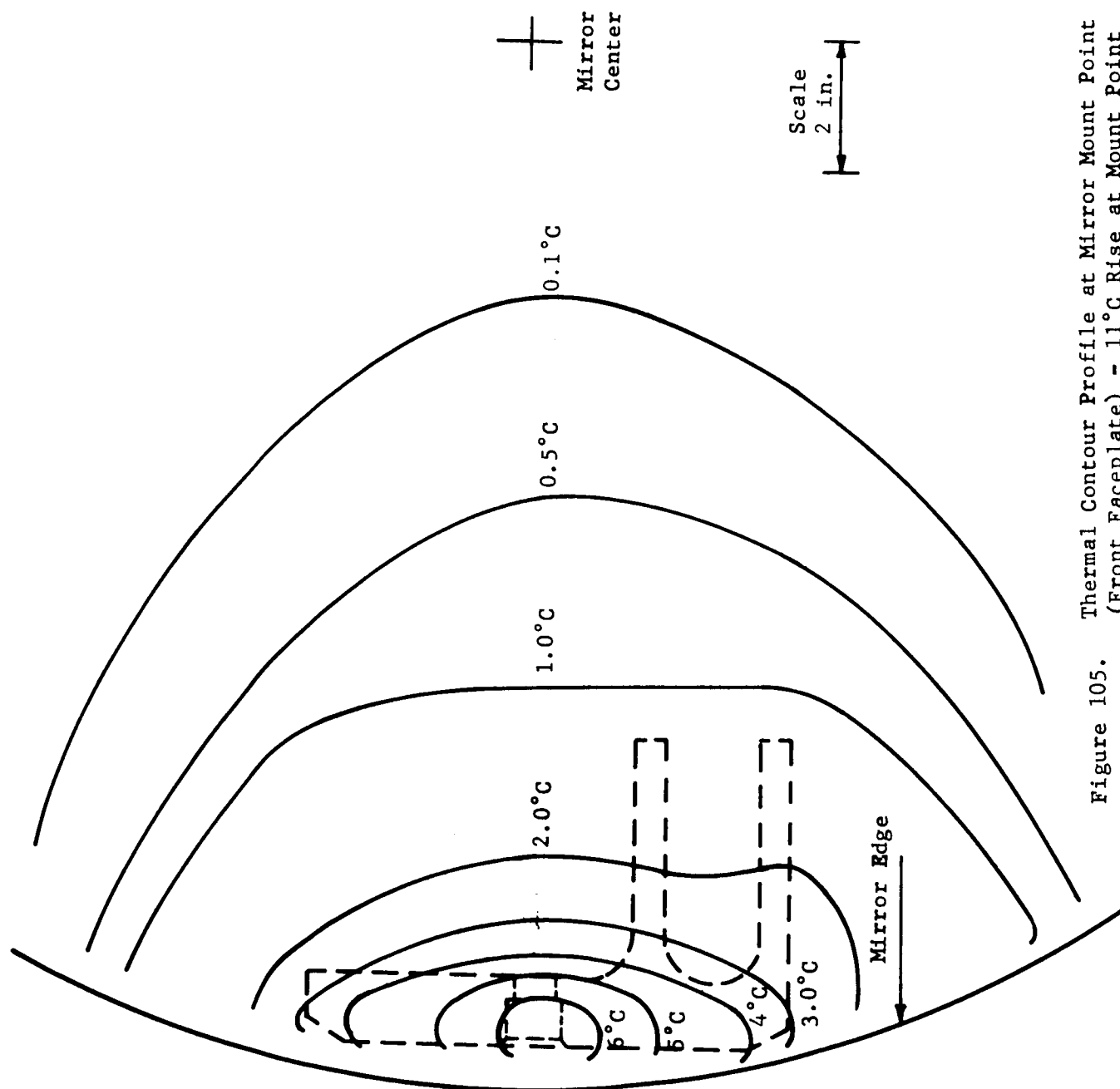


Figure 105. Thermal Contour Profile at Mirror Mount Point (Front Faceplate) - 11°C Rise at Mount Point

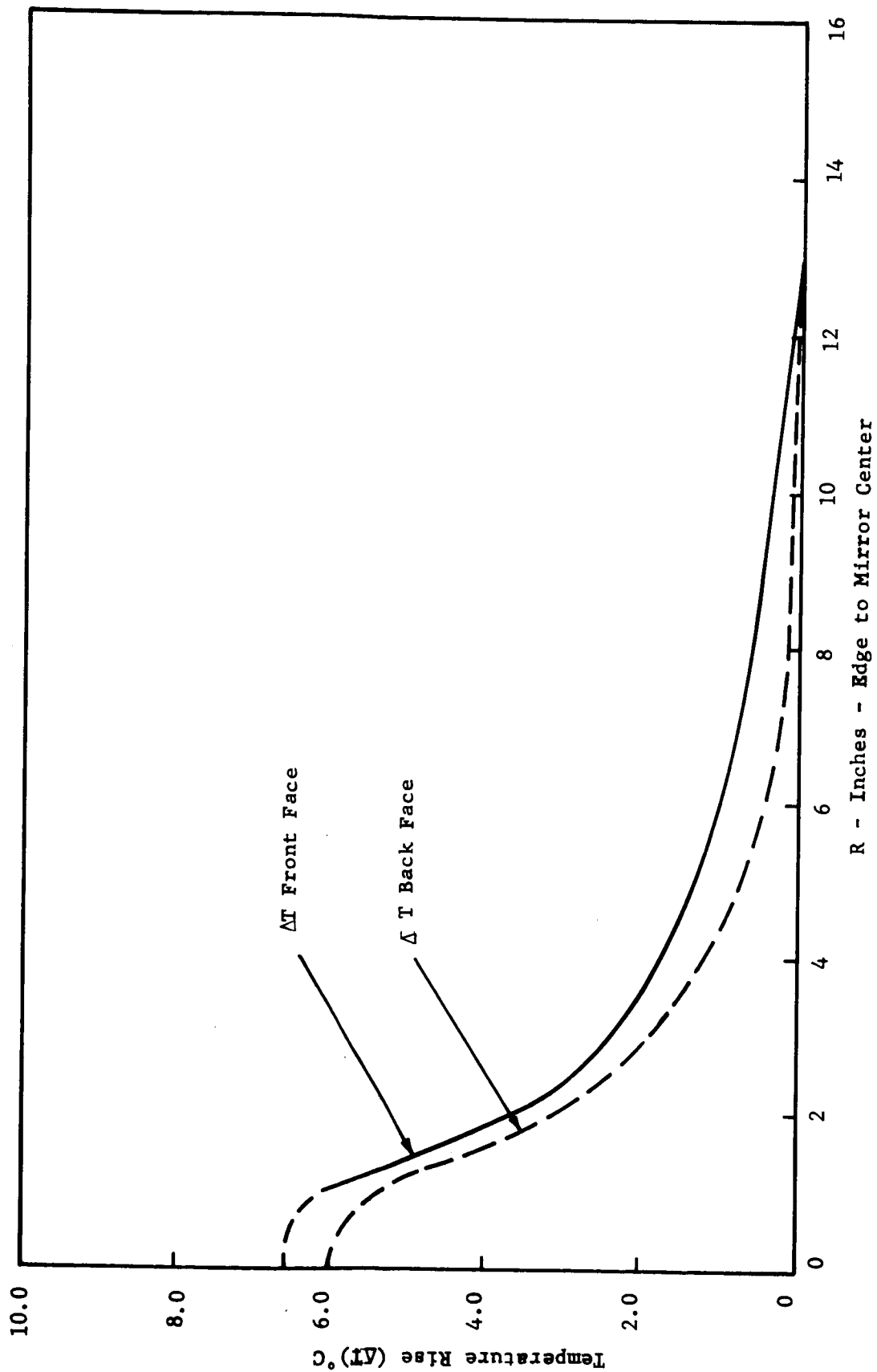


Figure 106. Plot of Temperature Profile of Mirror Faceplate Section Running Through F-Member (11°C Rise at Mounting Point)

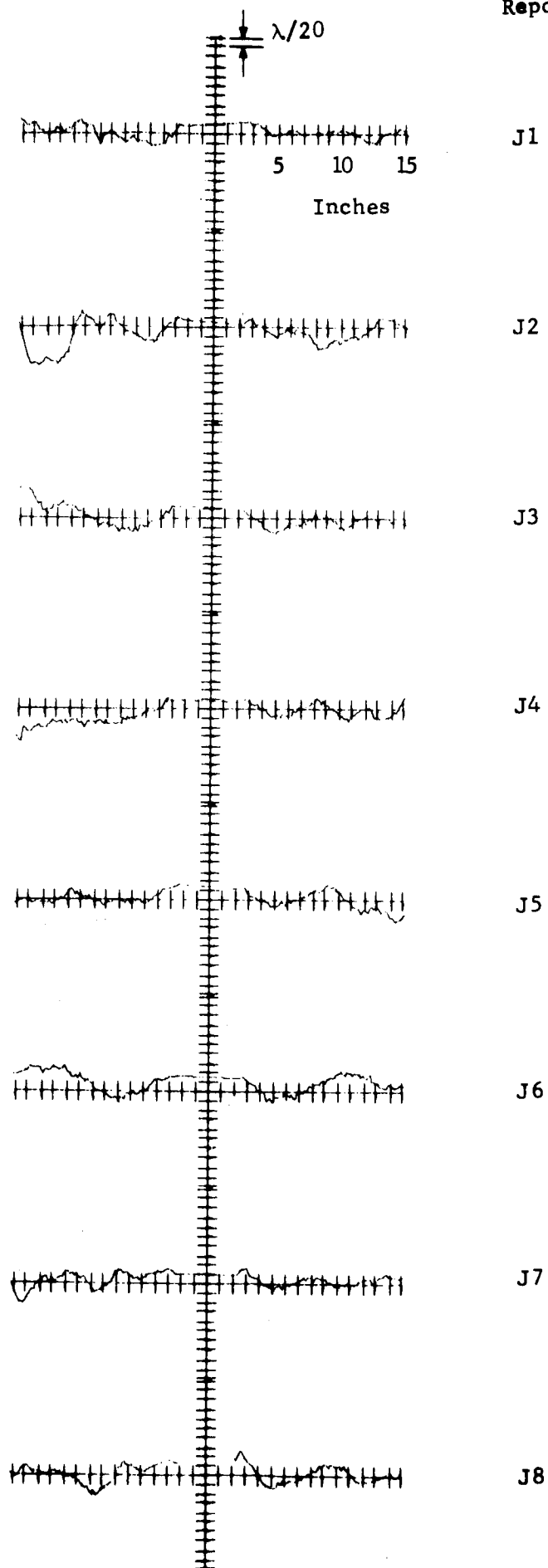


Figure 107. Reference Profile of Surface Deformation
I-204

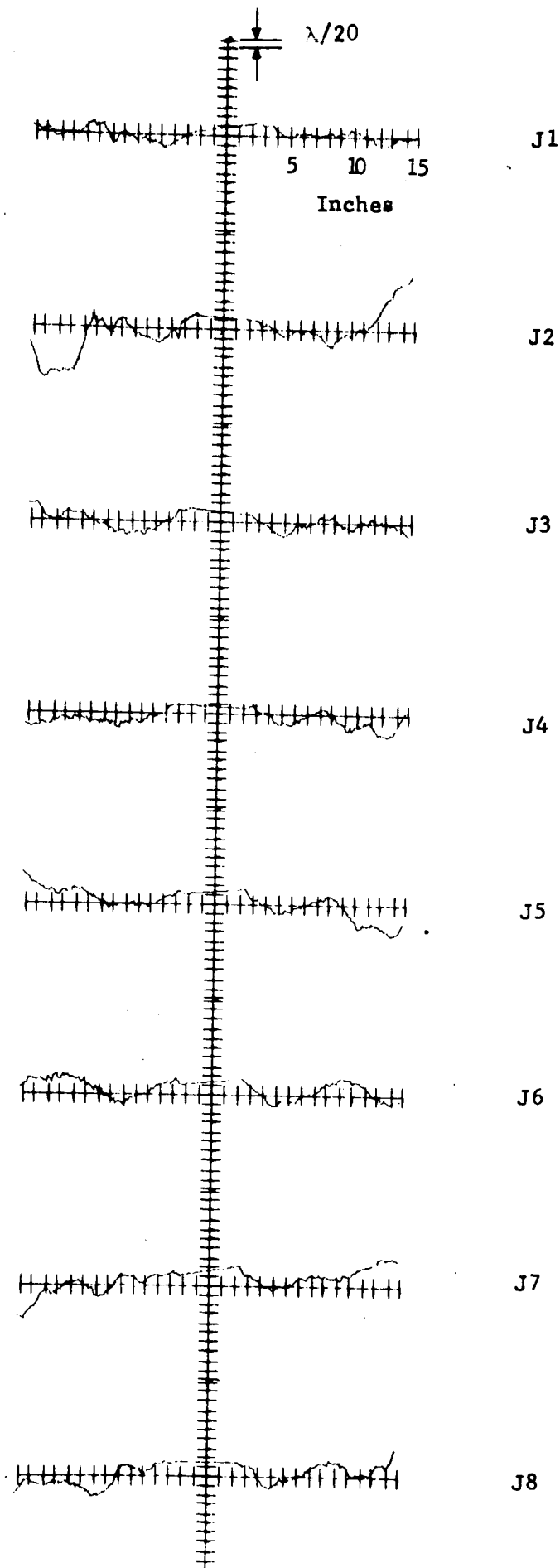


Figure 108. Profile of Surface Deformation with 11°C Temperature Rise at Mounting Points

mounting point as well as J7 and J8. The composite was generated by mapping these diagonals into one mount point, assuming symmetry at each point. The resulting contour maps for 6°C and 11°C rises are shown in Figures 109 and 110.

An attempt to read the scatterplate fringes between the boardwalk lights to verify the results obtained for the composite is presently underway. These data will be reported in the future OTES reports.

Conclusions

From the cases considered, it is evident that the results agree quite well with those predicted by C. Barrow* for lightweight mirror structures. The deformations are highly localized and are nearly completely attenuated at a radial distance from the mount point equal to the thickness of the mirror. In this case the mirror thickness was approximately 4 inches. The peak-to-peak deformation at the front faceplate is approximately $\lambda/20$ per degree Centigrade rise at the faceplate. In other words, for a temperature rise of 6°C at the mount point, the rise at the faceplate was 3°C and the resulting deformation was 0.145λ . When the mount point temperature was doubled (11°C) the resulting deformation was also doubled (0.28λ).

It is quite significant to note that the "F" member in the core which is used as the mount structure, has a strong influence on the shape of the thermal and OPD contours. Note also that there is an apparent elastic effect in the mirror as the thermal contours are more extensive than the surface deformations, which is to be expected.

Data presented below shows the results obtained for the cases considered. The results obtained for the rms degradation also show a near linear relationship as a function of temperature rise at the mounting points.

RESULTS OF COMPUTER RUN ON SCATTERPLATE DATA

<u>Mirror Condition</u>	<u>Fig.-Tol. (rms)</u>
Thermal Uniformity	$\lambda/16.8$
6°C rise at mount points	$\lambda/15.0$
11°C rise at mount points	$\lambda/13.2$

The gradients treated are extremely large from the standpoint of good thermal design; however, they show dramatically that localized thermal deformations have a small effect on the optical performance of a large optical element.

* C. Barrow (Perkin-Elmer) Calculations of Some Thermal Distortions in Lightweight Elements presented at OSA, Oct., 1966 Meeting.

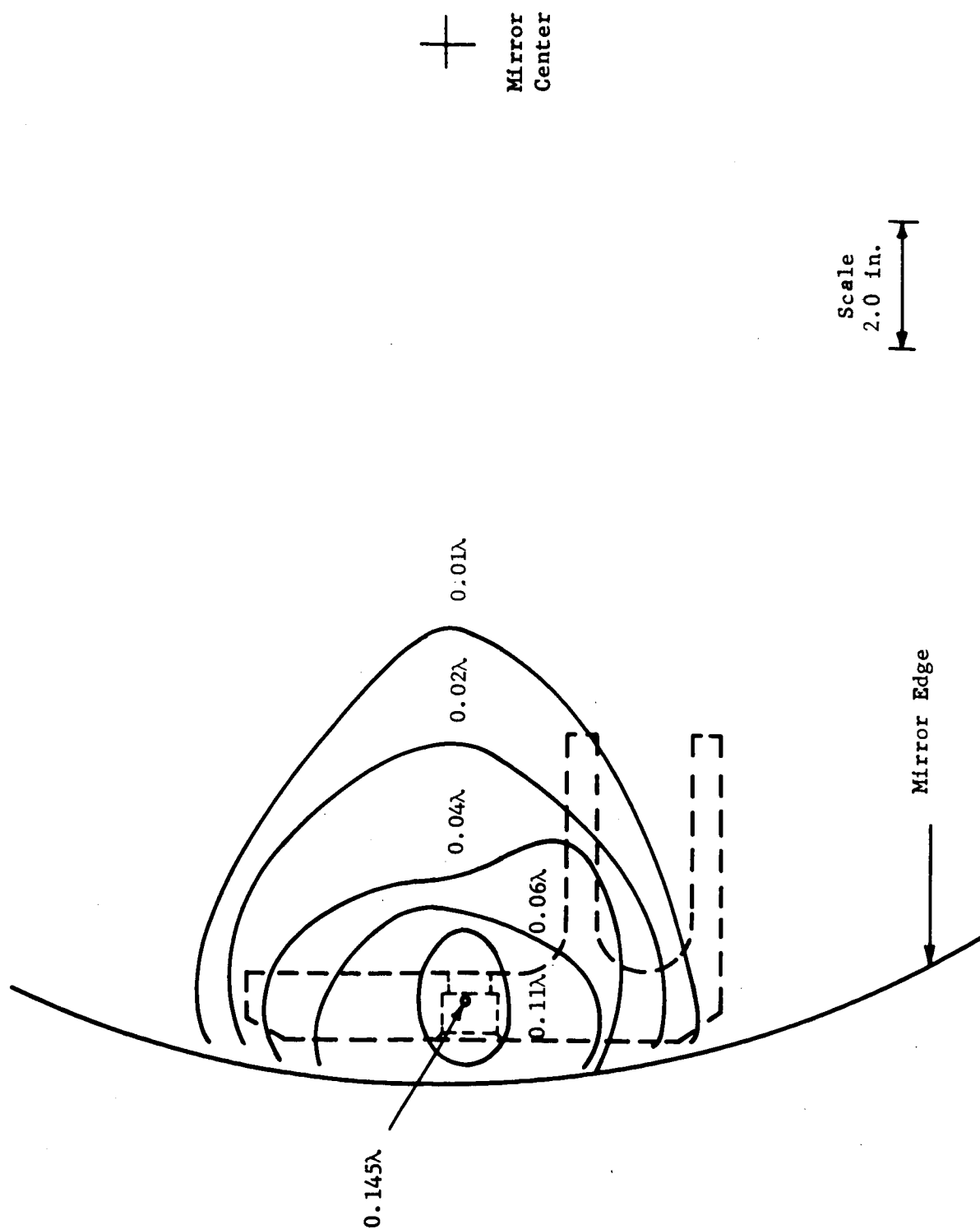


Figure 109. Contour Map of Surface Deformations Due to Temperature Rise at Mount Point of 6°C (Rise at Front Faceplate was 3°C)

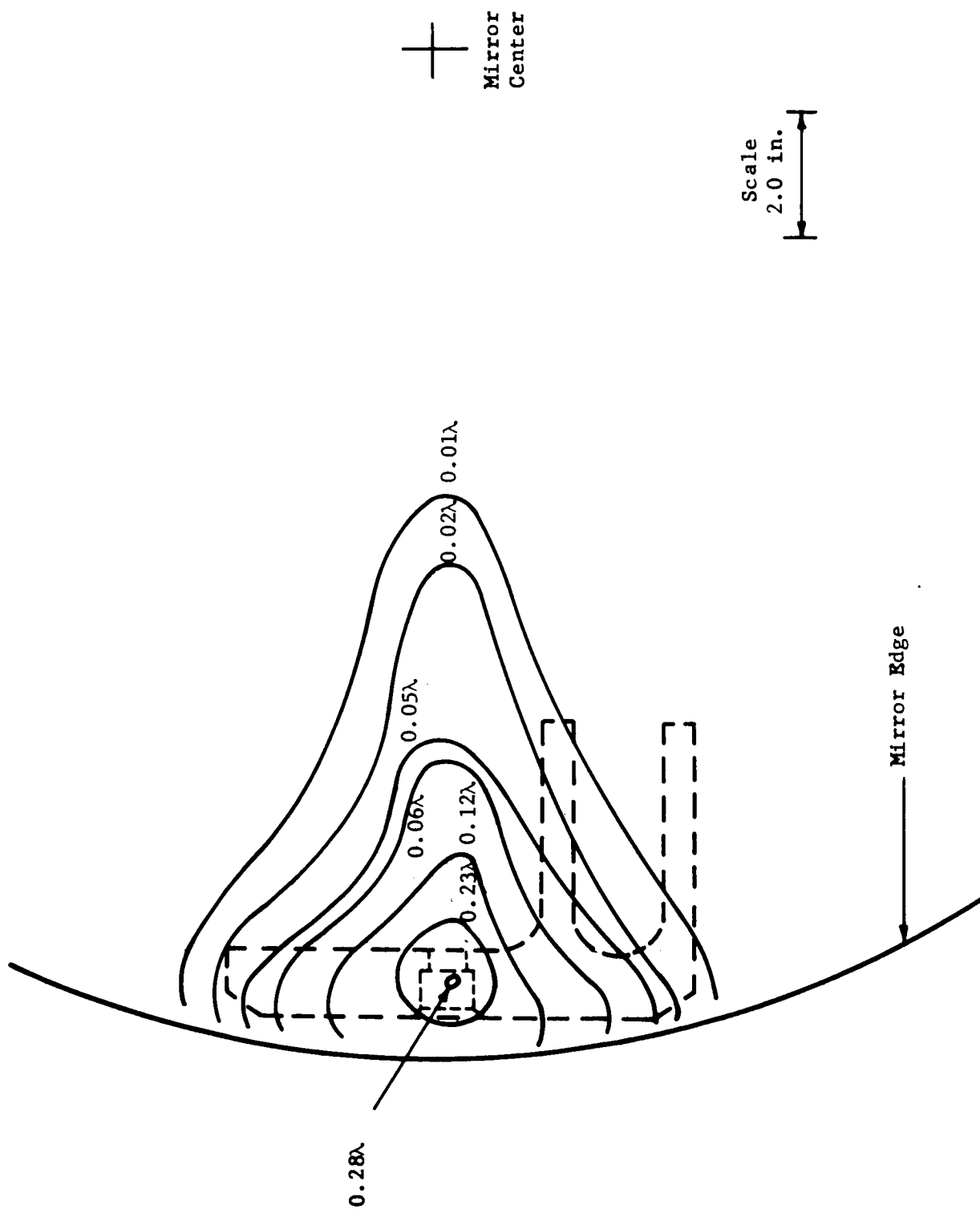
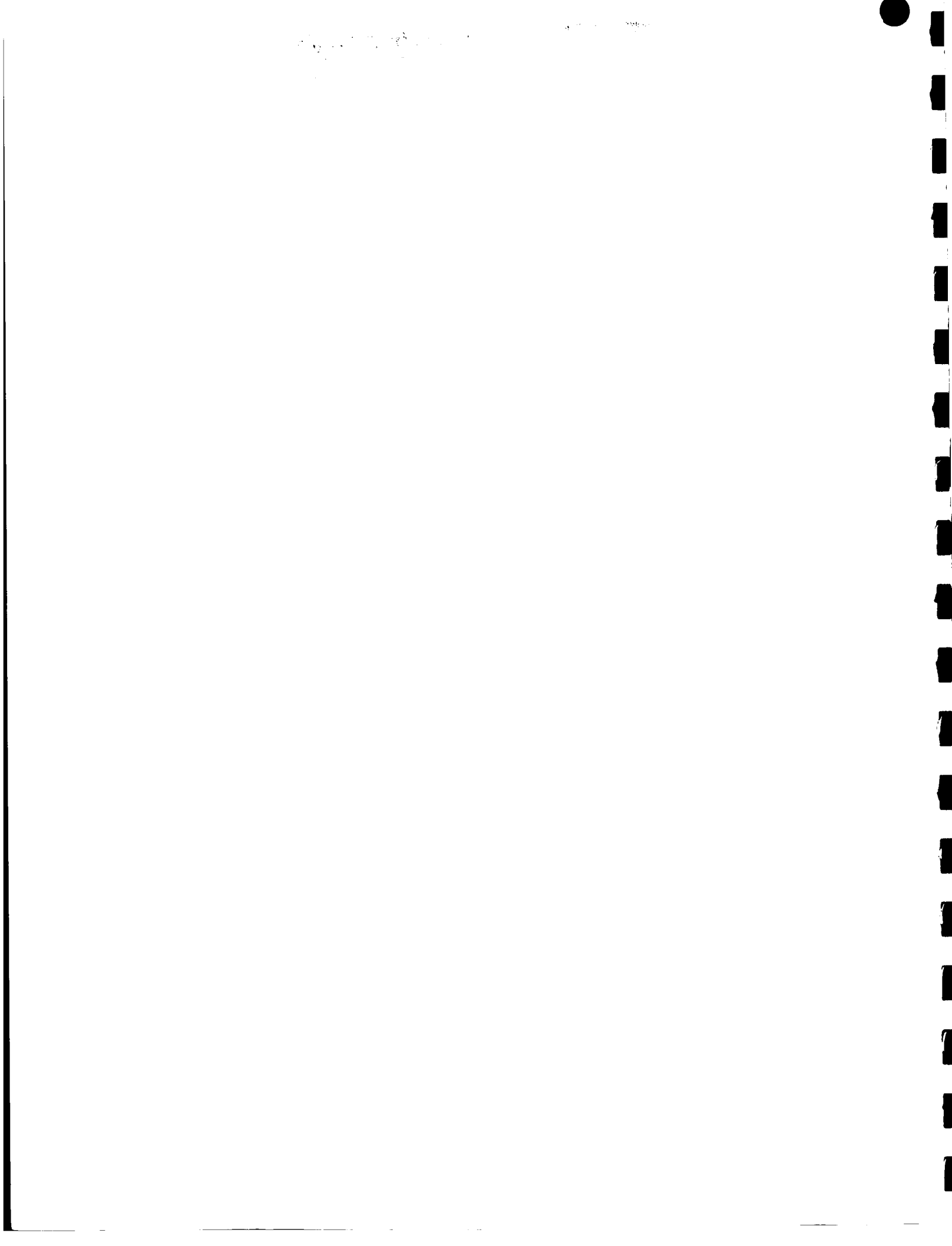


Figure 110. Contour Map of Surface Deformations Due to Temperature Rise at Mount Point of 11°C (Rise at Front Faceplate was 6°C)

The work presently under study on this program will be more significant as more extensive gradients are considered such as nonlinear radial, axial and transverse gradients. These experiments have already been completed; however, quantitative evaluation of the test results will not be available until the next phase of the OTES. Computer programs have been written* whereby deformations due to radially symmetric and nonlinear gradients can be determined. An attempt will be made to arrive at a satisfactory mathematical model to predict the effect of thermal deformations in lightweight mirrors and to correlate analytic and experimental results.

* S. Habijanec. Axial Temperature Variation in Mirrors, Perkin-Elmer Eng. Memo dated 25 April 1967.

S. Habijanec. Thermoelastic Deformation of a Circular Thin plate by an Axis-symmetrical Temperature Field (in preparation)



PERKIN-ELMER

Report No. 8900

EXPERIMENT NO. 13 - TELESCOPE ALIGNMENT MEASUREMENTS CORRELATED WITH
NUMEROUS TEMPERATURE SENSORS

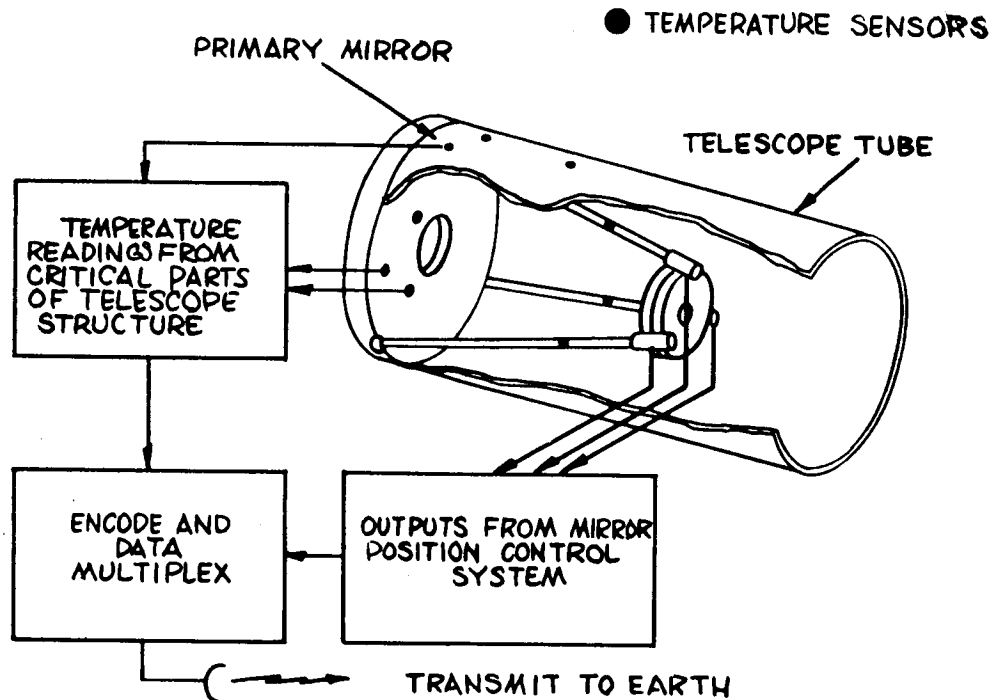


Figure 111

EXPERIMENT OBJECTIVE

The objective of this experiment is to measure the temperature at critical locations of the telescope structure and supporting optical subsystems. Temperature data originating from the primary/secondary telescope structure can be compared to the outputs of the secondary mirror positioning control system.

Temperature variations leading to differential expansion or contraction of various portions of the telescope structure will cause misalignment of the optics. This may be caused by inclusion of materials of different coefficients of expansion, by temperatures differing from point to point, or by a combination of both.

EXPERIMENT JUSTIFICATION

This experiment provides measured data from space equipment for diagnostic evaluation of the telescope point-to-point thermal distributions. The measured temperatures are correlated in both magnitude and location with alignment

design requirements and alignment measurements. Future large orbiting telescopes will be dependent upon experimentally verified design values for alignment devices.

TECHNOLOGY BENEFITS

Telescope structure design changes to obtain greater immunity to the space thermal environment could be one potential outcome of the experimental results.

BASIC EXPERIMENT HARDWARE

On the Spacecraft

- Temperature sensors
- Secondary mirror positioning control system
- Telemetry transmitter

On the Earth

- Telemetry receiver
- Data storage

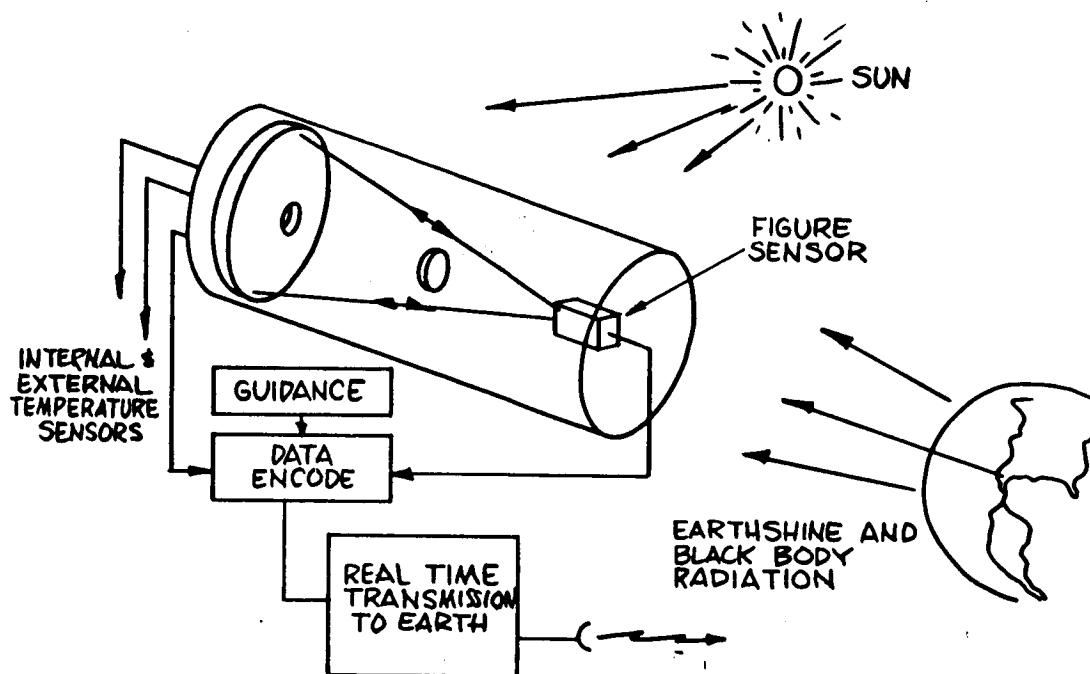
EXPERIMENT NO. 14 - EFFECTS OF EARTHSHINE ON MIRROR FIGURE

Figure 112

EXPERIMENT OBJECTIVE

The objective of this experiment is to obtain experimental verification of primary mirror figure errors and deformations as a function of the earthshine and Earth self-emission input to the primary mirror. For this experiment, the telescope is oriented earthward such that all or part of the primary mirror is subjected to earthshine radiation. The resulting change in figure is then monitored. The temperature sensors on the primary (Experiment No. 12) and the orientation and intensity of the earthshine and radiation are monitored also.

EXPERIMENT JUSTIFICATION

Earthshine and self-emission, which are incident on the primary mirror can introduce significant primary figure errors which depend upon aperture and altitude. Special off-pointing or telescope capping would be required to keep the Earth's image out of the field of view of the telescope for these cases of the Earth occulting the target star or planet.

At 260-mile altitudes, the maximum earthshine is 481 watts/m^2 . Assuming a mirror reflectivity of 95%, the additional heat flux from earthshine incident on the mirror is, thus, 24 watt/m^2 . This energy corresponds to a 75-watt input for a 2-meter aperture, which is enough to cause a temperature gradient in the mirror. The long thermal time constants expected in the primary mirror are not compatible with the 1-1/2 hour cycle between the maximum and minimum of earthshine. Thus, transient thermal measurements are required to determine how detrimental earthshine is to a large primary (3-meter) mirror figure at various prospective altitudes. If the earthshine creates significant mirror errors, this experiment will help define proper operating procedures for the MOAT telescope viewing stars near the Earth disk. The experiment will provide useful data for large-aperture terrestrial and planetary reconnaissance systems.

BASIC EXPERIMENT HARDWARE

This experiment requires the data outputs from the figure sensing equipment, (Experiment No. 1), the temperature monitoring system (Experiment No. 12), and an earthshine measuring device located at the front of the telescope. A simple device would consist of a sensitive bolometer mounted at the focus of a small lens in a telescope tube, which is a scaled-down version of the main telescope tube. This allows the bolometer to receive radiation from the same field of view as the main telescope. The total radiation incident on the primary mirror from various sources can then be monitored and transmitted to the ground as sketched in Figure 113.

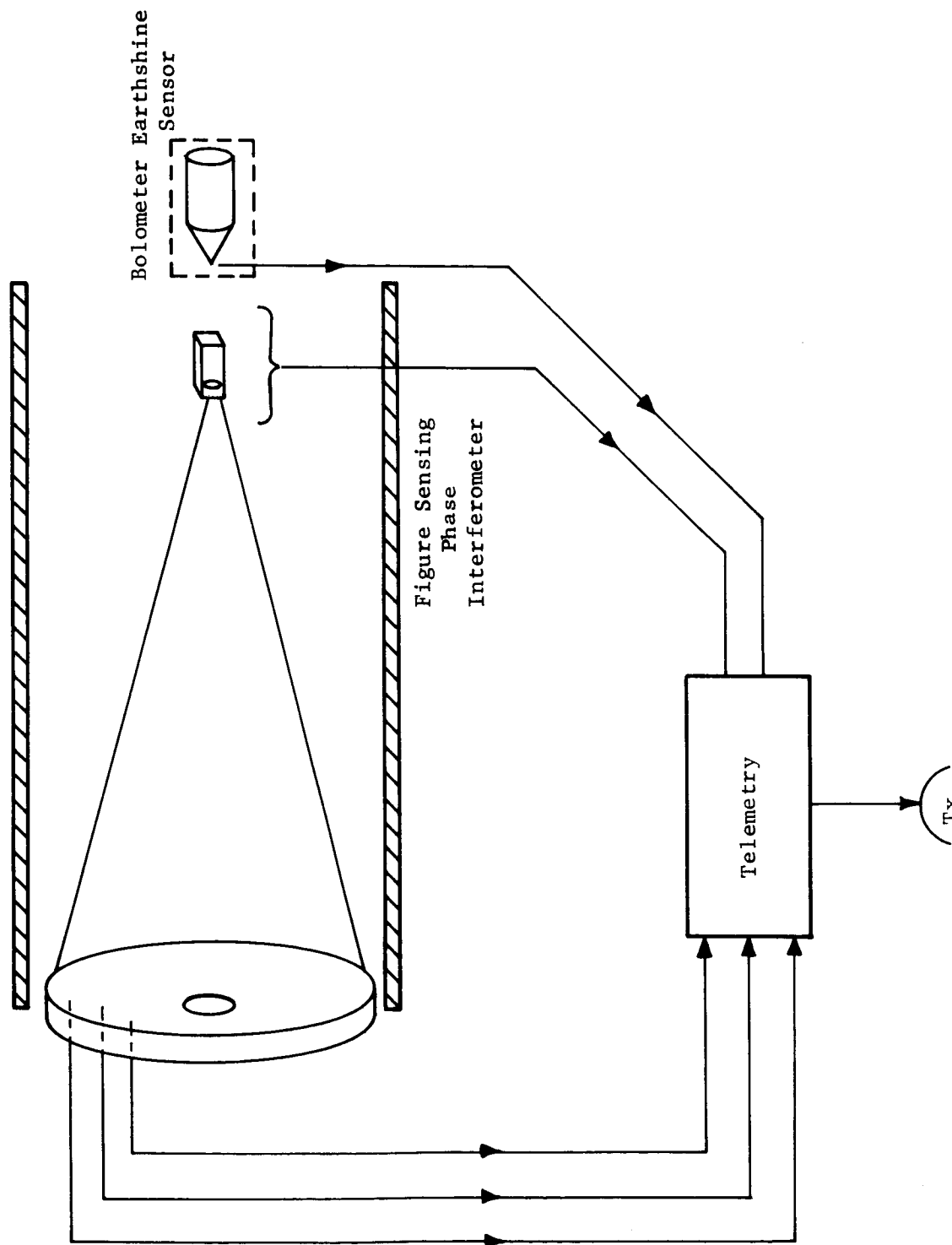


Figure 113. Earthshine Effects on Mirror Figure



EXPERIMENT NO. 15 - SPACE AND RADIATION EFFECTS ON OPTICAL ELEMENTS

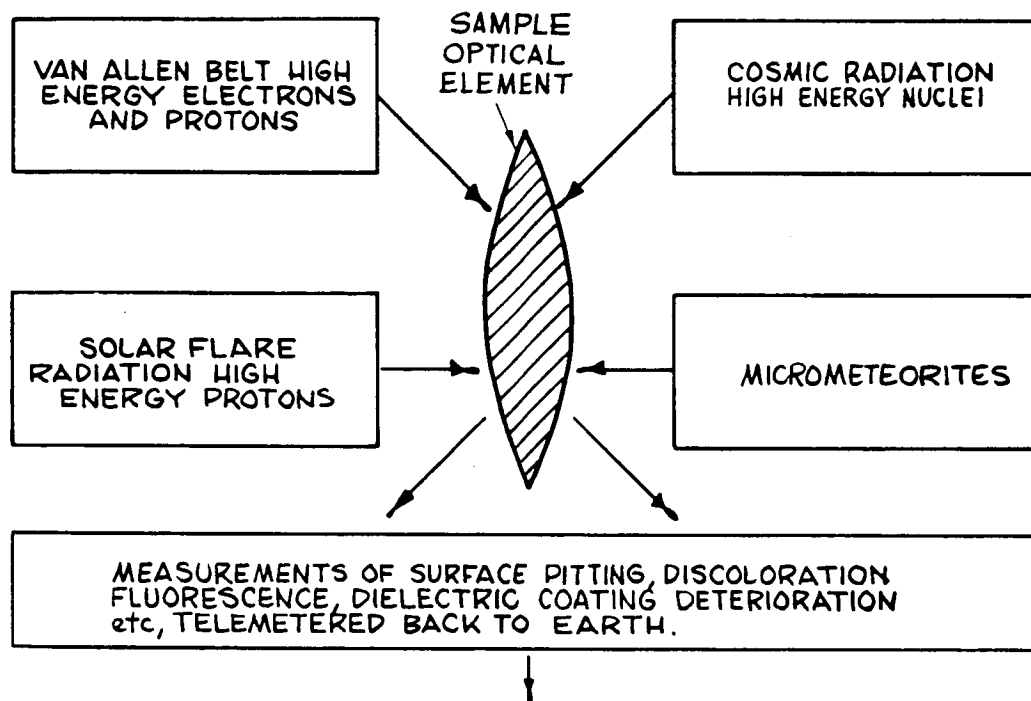


Figure 114

EXPERIMENT OBJECTIVE

The experiment objective is to determine the space and radiation effects over a prolonged period of time on sample and operational optical elements of the OTES. The operational optical elements are the primary and secondary mirrors; transfer, field, and relay lenses; dichroics, filters, and phototubes. The effects of sputtering and micrometeoroid erosion of the reflective surfaces will be monitored. Discoloration, surface erosion, and striation of anti-reflective coatings of the refractive elements also will be monitored. Monitoring of these effects will be done by suitable analyzers (as yet unspecified) whose outputs are telemetered to Earth. Also, the astronauts on routine maintenance visits to the OTES will visually examine all accessible optical components and note any excess deterioration.

In addition to the above, another important experiment objective is to determine the space and radiation effects over a prolonged period of time on selected optical materials and elements. These samples could be placed in mountings at appropriate locations in the spacecraft. For example, sample mirror coatings should be mounted on an external surface of the spacecraft. The effects of space environment, including the radiation, which might take place are surface pitting and erosion caused by micrometeoroid bombardment, sputtering, discoloration and creation of color center, outgassing, fluorescence, change in refractive index, and deterioration in dielectric coatings.

Monitoring of these effects will be done by suitable analyzers. The experimental data will then be telemetered to Earth. Samples of special interest may be returned to Earth for more exhaustive examination and evaluation by the astronauts returning from telescope maintenance missions.

EXPERIMENT JUSTIFICATION

The examination of the deterioration of the optical components after a prolonged exposure to the space environment is a logical step in the development of space optics. The experimental data is valuable for the diagnosis of the system operation and allows a better understanding of the effect of the space environment on optical elements. Future optical design to obtain greater radiation immunity could be one potential outcome of the experimental results.

BASIC EXPERIMENT HARDWARE

On Spacecraft

- Auxiliary package containing elements to be tested
- Reflectometer
- Spectral transmissivity detector
- Radiation and micrometeoroid detectors
- Data encoder
- Real-time telemetry

On Earth

- Telemetry receiver
- Data recorder

EXPERIMENT NO. 16 - REMOTE MANUAL OPTICAL ALIGNMENT

(Deleted - Refer to OTES Interim Report* for additional details)

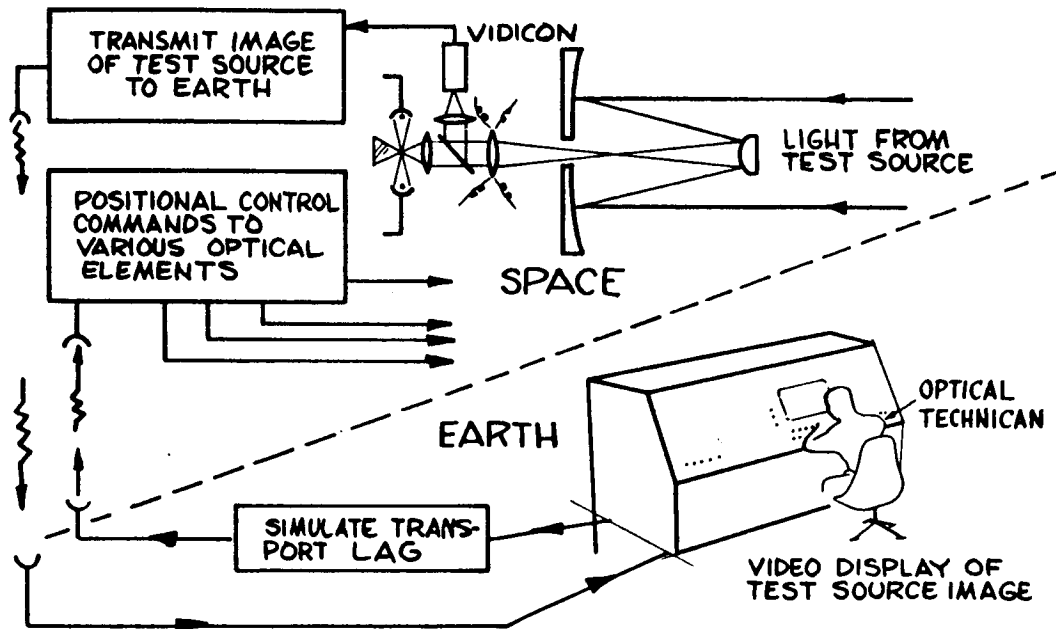


Figure 115

EXPERIMENT OBJECTIVE

The experiment considered the equipment requirements and the feasibility of realigning a large-aperture system in space. The performance of both the remote control system and the human operators was to be evaluated. Since the operator will need information about system performance which is essentially visual (image quality at various places in the optical path), the real-time television capability of the spacecraft was to be utilized. The communication transport lag of a deep-space vehicle can be simulated easily with ground equipment, and its effects on human performance could be evaluated.

The experiment is deleted at present from the group under consideration because it is essentially a demonstration in space of a laser communication application rather than a basic optical technology experiment.

*Perkin-Elmer Report 8319.

PERKIN-ELMER

Report No. 8900

EXPERIMENT NO. 17 - FIGURING OPTICAL SURFACES IN SPACE BY ENERGETIC

IONIC BEAMS (Deleted - Refer to OTES Interim Report* for additional details)

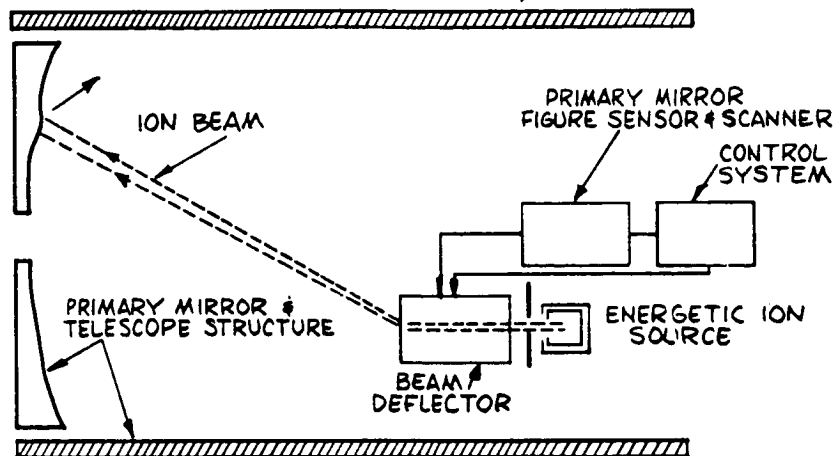


Figure 116

EXPERIMENT OBJECTIVE

The objective of the experiment is to test the ion polishing technique of mirrors while the primary mirror is in the zero "g" field in space.

The recent discovery** that a directed beam of heavy ions effects a uniform removal of a surface of fused silica upon which the beam impinged offers exciting possibilities for the OTES. Ionic polishing can be used on board the spacecraft to make small corrections to the primary mirror figure while the mirror is in space. Electronic deflectors may be employed to direct the ion beam to the required zone on the mirror. An ionic polisher used in conjunction with the primary mirror figure sensor and scanner, operated in a servo mode, could be used to remove localized high areas in the primary mirror while the mirror is in the zero "g" field.

Errors in compensating for and simulating zero gravity, vacuum, and thermal conditions on Earth will create deformations in the mirror surface when the telescope is placed in space operation. The ionic polishing process would allow figuring of the mirror to $\lambda/50$ accuracy after the OTES is placed into synchronous orbit. This new and novel technique has the potential of revolutionizing the methods for final figuring of diffraction-limited optical primaries.

The experiment is deleted at present from further consideration (Phase B) of the OTES Program due to its very immature state. While this technique might well be used in the future, it is too early to include in the present OTES Program.

* Perkin-Elmer Report 8319.

** Meinel, A.B.; Bashkin, S.; and Loomis, D.A.: Controlled Figuring of Optical Surfaces by Energetic Ion Beams. J. Appl. Opt., vol. 4, no. 12, Dec. 1965, p. 1674.



EXPERIMENT NO. 18 - OCCULTING DISK EXPERIMENT

(Deleted - Refer to OTES Interim Report* for additional details)

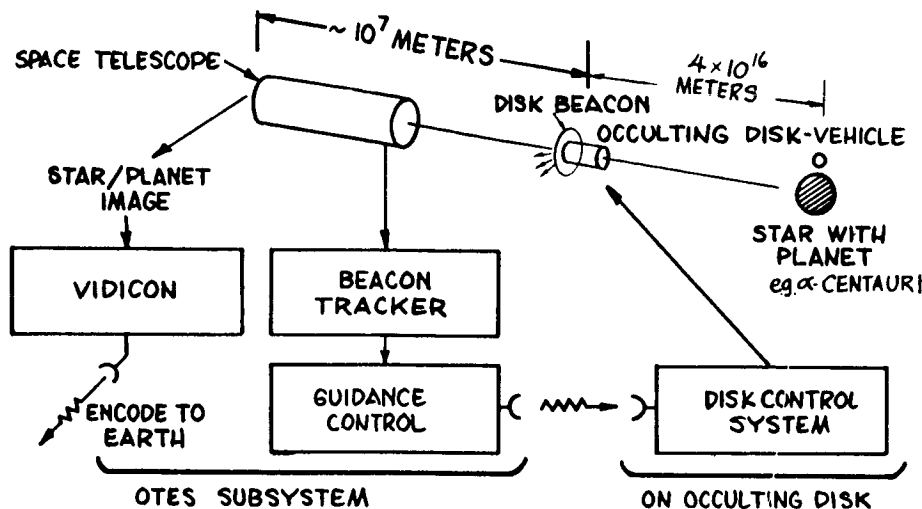


Figure 117

EXPERIMENT OBJECTIVE

The discovery of planetary systems around nearby stars having a physical relationship similar to the relationship between our Earth and our sun is an exciting realization for optical astronomy. If the target star's planetary system resembles the solar system, then the target star is 25 magnitudes brighter than its brightest nearby planets. A spaceborne, three-meter telescope can have a diffraction-limited resolution in the visible spectrum of 0.06 arc-second. This angular resolution is probably inadequate to see major planets in the reflected light from their parent star. Even with an order of magnitude increase in diameter of the space telescope, the scattered light from the parent star is still bright enough to obscure a nearby planet.

There is a possible technique** that would ameliorate the scattered light problem at the price of extremely precise guidance. This method involves the use of a large opaque occulting disk launched far in front of the space telescope to reduce the direct light from the star. During the observation of the star, the space telescope would track a beacon on the occulting disk. Controlled and very precise remote positioning of an occulting disk in a closed loop mode is required to locate the disk precisely in the line of sight to the star. The magnitude of relative motion between the occulting disk and the telescope line of sight determines the observation time. This observation would have to be repeated some time later in order to distinguish planets, by means of their orbital motion around the parent stars, from faint stars in the background. Apodization of the occulting disk will increase the contrast between the scattered light of the star and planet.

This experiment is too ambitious for the OTES Program since it requires an additional space vehicle acting as the occulting disk with very precise positioning of the occulting vehicle required.

* Perkin-Elmer Report 8319.

** Spitzer, L., Jr.: Beginnings and Future of Space Astronomy. American Scientist. Vol. 50, no. 3, Sept. 1962, p. 473.



EXPERIMENT NO. 19* - PROPAGATION OF DIFFRACTION-LIMITED LASER BEAMS
 (Deleted from the 2-Meter OTES in a 260 mile orbit)

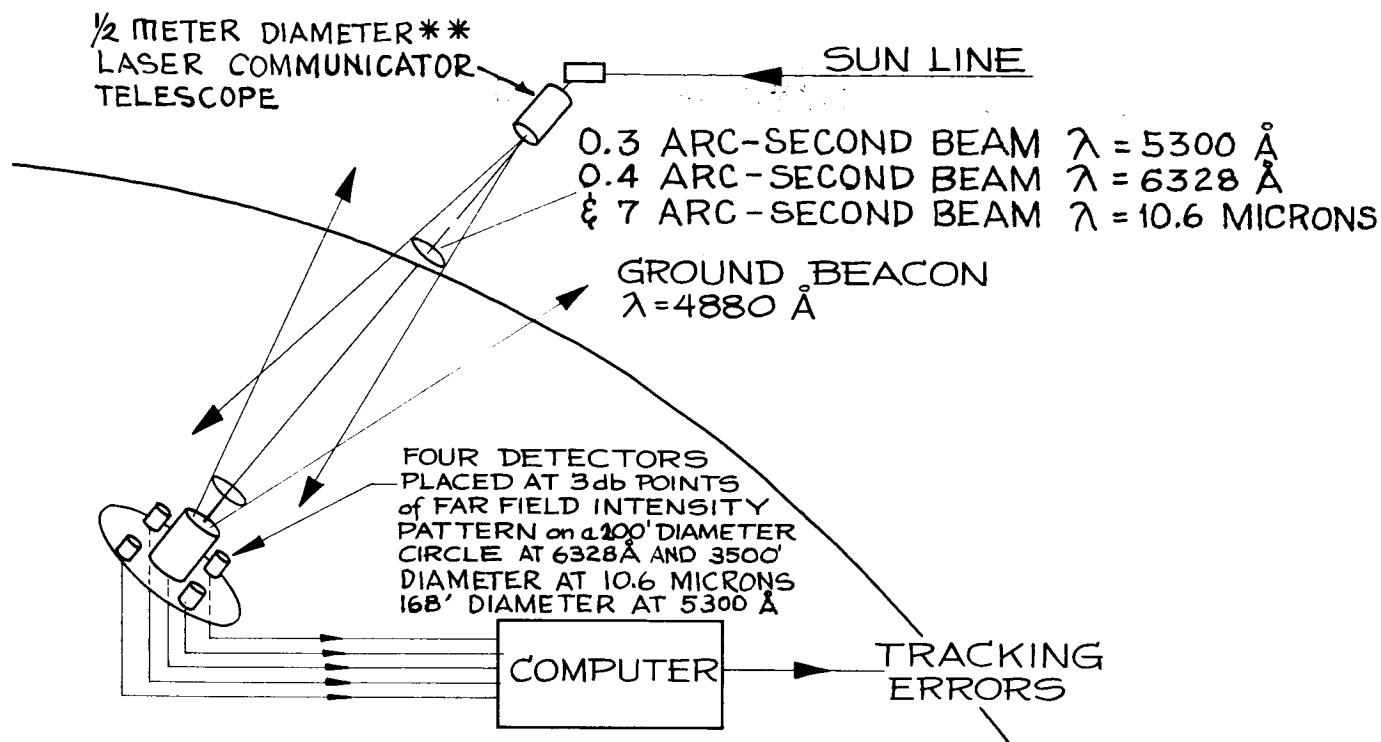


Figure 118

EXPERIMENT OBJECTIVES

Earth reception of a narrow laser beam transmitted from a deep-space communication telescope requires that the beam be very precisely directed. The space measurements of fractional arc-second laser beam tracking capability is the purpose of this experiment. More specifically, if the allowed angular pointing error should not reduce the Earth-received power by a factor of more than two, the line of sight (LOS) must be directed within $0.61 \frac{\lambda_T}{D}$ (where λ_T is the transmitted wavelength and D is the telescope aperture diameter) assuming that the far-field intensity pattern has the familiar diffraction-limited $\left(\frac{J_1(X)}{X} \right)^2$

* This experiment is of such high interest and importance to the technology area of laser beam propagation from deep space that the updated Experiment No. 19 description is included in this Phase A Report despite the requirement that a synchronous orbit is necessary. The 2-meter OTES version of this experiment is packaged in Equipment Module B (Figure 60) and the layout details are developed in Chapter 3 of this report.

** The 1/2-meter diameter is based on Perkin-Elmer Report No. 8399 prepared for MSFC on NAS 8-20115. (See Figure 118).

characteristic. For the three cases where $\lambda_T = 5300\text{\AA}$, $6328\text{\AA}$ and 10.6 microns, and the space telescope diameter is 1/2-meter, the allowed beam pointing error varies from 0.15, 0.20 and to 4.0 arc-seconds. Previous reports* proposed that one method of achieving such performance was to point ahead the transmitter line of sight, by the required amount of up to 36 arc-seconds, from the "vehicle-apparent beacon" position reference direction. The reference direction is established by tracking a ground beacon at the Earth receiver site.

Since errors in establishing the reference direction contribute directly to transmitter LOS errors, it is important to determine the ground beacon tracking capability of a space telescope. This can be accomplished by monitoring the position of the space telescope's transmitted laser beam striking the ground while the space receiver line of sight is tracking a ground beacon.** While this could be accomplished with a ground array of movable intensity detectors and a fixed beacon, the approach recommended would utilize a point-ahead mechanism in the space telescope to allow use of a common fixed site for both the beacon and the array of intensity detectors.

EXPERIMENT JUSTIFICATION

The ability to communicate at high information rates over interplanetary distances requires the use of narrow beams to avoid excessive transmitted power requirements. While small beamwidths require very large antennas at microwave frequencies, much more practical antenna sizes are needed to accomplish the same ends at optical frequencies. Even if one ignores the transmit time and aberration effects on pointing to be expected in a working system, a major problem arises with beamwidth reduction in that pointing accuracy becomes increasingly more stringent.

If one considers, for example, a diffraction-limited optical system of aperture diameter, D , transmitting at wavelength, λ , to a distant receiver, the pointing error, ϵ , should be less than $1.22 \lambda/D$, the value which results in essentially zero-power density at the distant receiver. For the case of 5300A transmission and telescope aperture of 1/2-meter for the laser communicator, the pointing errors should be less than 0.15 arc-second.

A deep-space telescope guiding on an Earth laser beacon, however, not only experiences the optical effects of the whole Earth's atmosphere (mostly scintillation) but also the degradations induced by significant amounts of background light (reflected sunlight which may even contain appreciable modulation components). Angular disturbances in a manned flight, would be quite large (i.e. 2 arc-seconds in the cluster to arc-degrees in LEM) due to the disturbances generated by astronaut body motions.

* Perkin-Elmer Reports 7846 and 7924 prepared for MSFC under Contract NAS8-11408.

** Synchronous orbit only. See Experiment No. 27.

This engineering experiment should be conducted to collect the data on an Earth orbiter to verify the practicality of 0.1 arc-second tracking at visible wavelengths such as 5300Å or 6328Å, and 0.7 arc-second for 10.6 microns.* Angular tracking rates will be simulated by an appropriately inclined synchronous orbit. The approach under consideration is shown in the block diagram of Figure 119. This approach involves the use of the two-axis telescope which directs its LOS toward a laser ground beacon while transmitting laser energy back along this line of sight. Measurements of the transmitted beam pattern, as received on Earth from the diffraction-limited optical system in space, will be made to assess tracking accuracy and to provide some measure of the diffraction-limit capability of a space optical system. (See Figure 120.)

Laser beam tracking in space of the 4880Å argon ground beacon should be evaluated under conditions which include beam modulation (scintillation) induced by the Earth's atmosphere. This can only be accomplished with space experiments. These measurements must be made in the far field and, at 4880Å, the far field exists (for distances R above the turbulent atmosphere whose lateral coherence length D_A is 0.1 meter) at:

$$R > \frac{D_A^2}{4\lambda} = \frac{(0.10 \text{ meter})^2}{4 (0.4880) \times 10^{-6}} = 5130 \text{ meters}$$

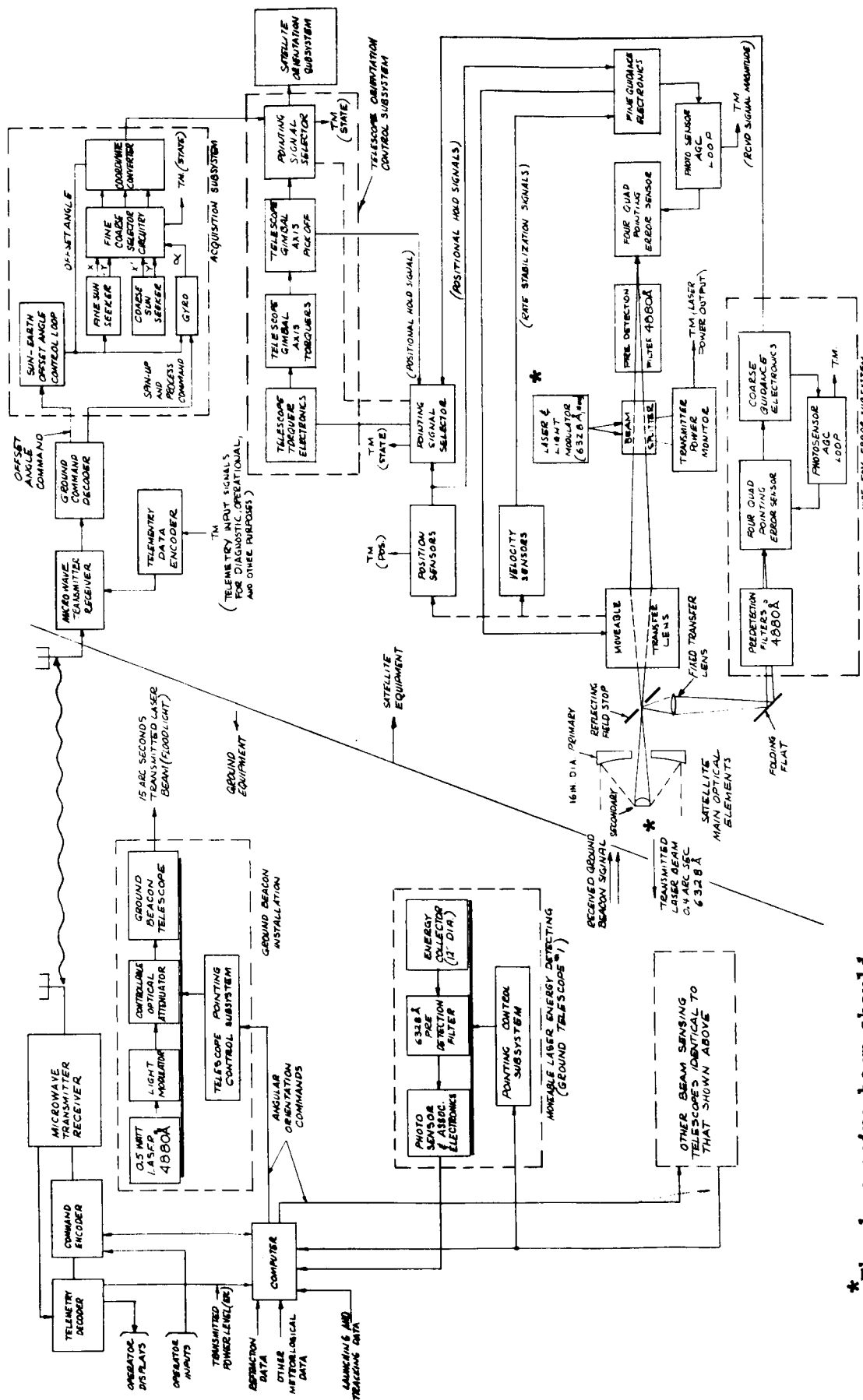
The modulation due to scintillation at 20,000 miles is the same as that for 100 million miles provided the satellite aperture is small compared to the coherence diameter, D_c , of received wave. Since D_c is approximately 1 meter per hundred miles of distance above the atmosphere, deep-space scintillation tests for ground telescopes with diameters up to 20 meters can be evaluated at synchronous altitude. The 2-meter aperture of the low orbit OTES can be used for the purpose of measuring the upgoing 4880Å intensity modulation due to atmospheric scintillation. (See Experiment No. 28).

To assist in the justification for conducting a fractional arc-second laser propagation experiment, the relationship between the key parameters which establish the pointing precision has been derived using the basic relationship of:

$$E_{p_m} = \frac{1.22\lambda}{2D} \left(\frac{S}{N}\right)^{-1}$$

The theoretical minimum pointing error ($E_{\text{pointing}_{\text{minimum}}}$) is:

* At 10.6 microns, the pointing precision is 0.7 arc-second for a 1.5 meter transmitting aperture.



*The down going beam should also include a 5300Å laser system.

Figure 119. Block Diagram for 0.1 Arc-Second Tracking Experiment at 6328Å

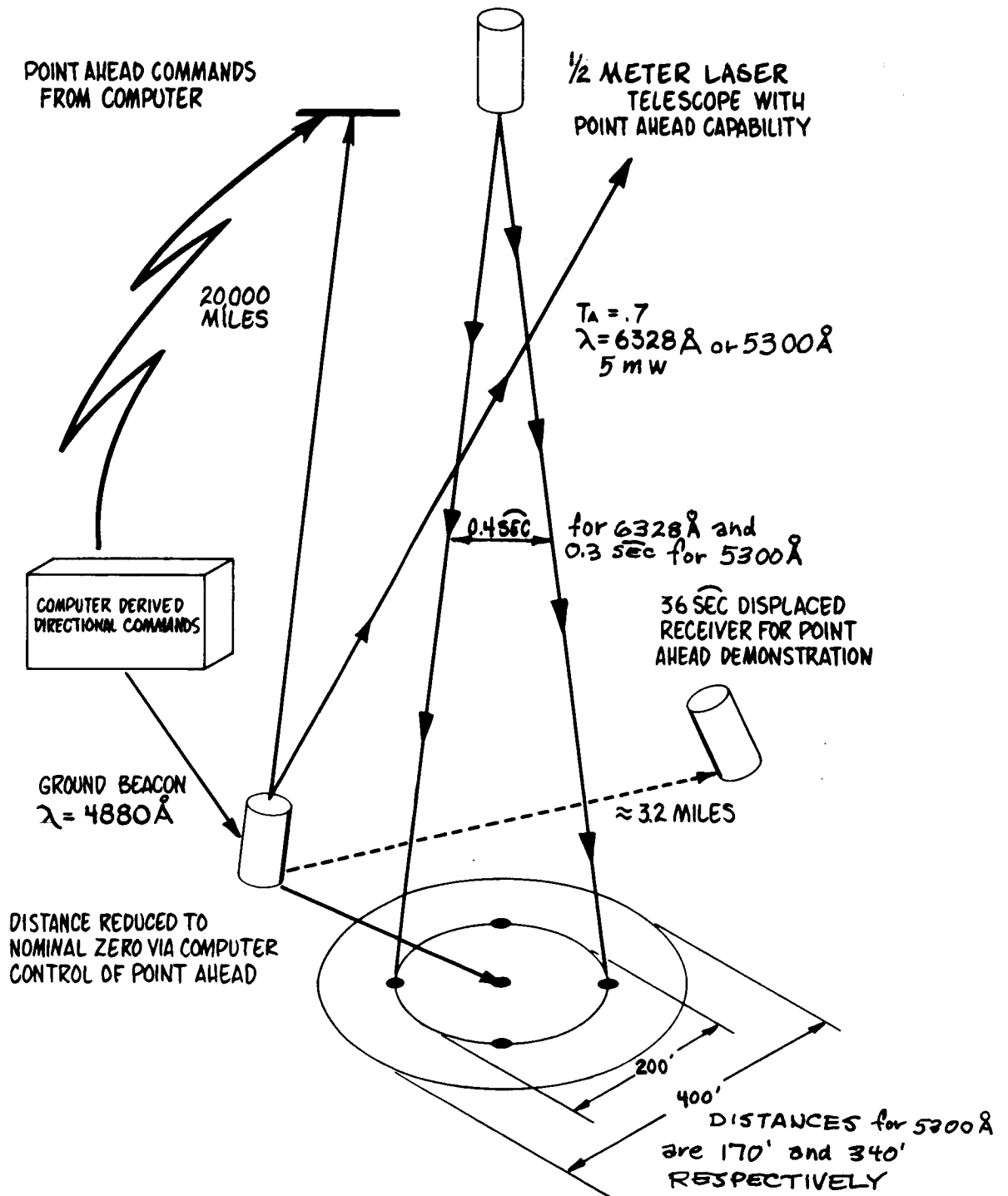


Figure 120. Basic Equipment Arrangement for Pointing Experiments With Lasers

$$E_{\text{pointing}_{\text{minimum}}} = 8.95 \times 10^{-8} \frac{\lambda^{1/2}}{D^2} \sqrt{\frac{\Delta f}{P_D N_o N_q}} \text{ in arc-seconds rms}$$

The minimum pointing error for ground beacon tracking is a function of:

- D , space telescope aperture diameter (m)
- λ , ground beacon wavelength (m)
- Δf , pointing servo equivalent noise bandwidth (cps)
- P_D , received power density (w/m^2)
- N_o , optical efficiency, and
- N_q , photosensor quantum efficiency.

The calculated theoretical limit of pointing precision for the 1/2-meter aperture laser communicator and the 2-meter OTES have been plotted in Figure 121. The pointing precision limit relationship is applicable to all orbits as well as deep-space operations by the substitution of appropriate power density terms.

As can be seen from the above relationship for the theoretical limit of pointing precision, the pointing is dependent upon the wavelength selected for the ground beacon and the quantum efficiency of the photomultiplier used in the guidance system. The equation can be restated as

$$E_{\text{pointing}_{\text{minimum}}} = \sqrt{\frac{\lambda}{N_q}} \left[\frac{8.95 \times 10^{-8}}{D^2} \sqrt{\frac{\Delta f}{P_D N_o}} \right]$$

where the first term, $\sqrt{\frac{\lambda}{N_q}}$, can be plotted for various wavelengths and

for known photomultiplier tubes. The inverse of this term has been plotted in Figure 122 in order to select the optimum ground beacon laser for space tracking. Note that at 0.5 micron (argon), the S-20 photomultiplier is inferior to the S-17. If gallium arsenide lasers are ever chosen for ground beacons, then the S-1 photomultiplier should be used since the wavelength is 0.84 micron. If the pointing error of the spacecraft telescope can be optimized with all other factors ignored, then the argon beacon using an S-17 PMT aboard the spacecraft would have a figure of merit of 0.7, while a GaAs beacon has a figure of merit on the same scale of 0.06. That is, the argon is better than the gallium arsenide by a factor of 12. If, in addition to the wavelength and quantum efficiency factors, one considers the atmospheric transparency, then the argon laser is better than the gallium arsenide laser ground beacon by a factor of 8. Naturally, laser beacons with wavelengths shorter than 4000Å are excluded due to the increasingly

* For the sample points on Figure 121, 1 microwatt of argon laser power radiated in a 3 arc second beam is all that is required for a theoretical limit of 0.006 arc seconds for LCSE and 0.001 arc seconds for the OTES (in synchronous orbit).

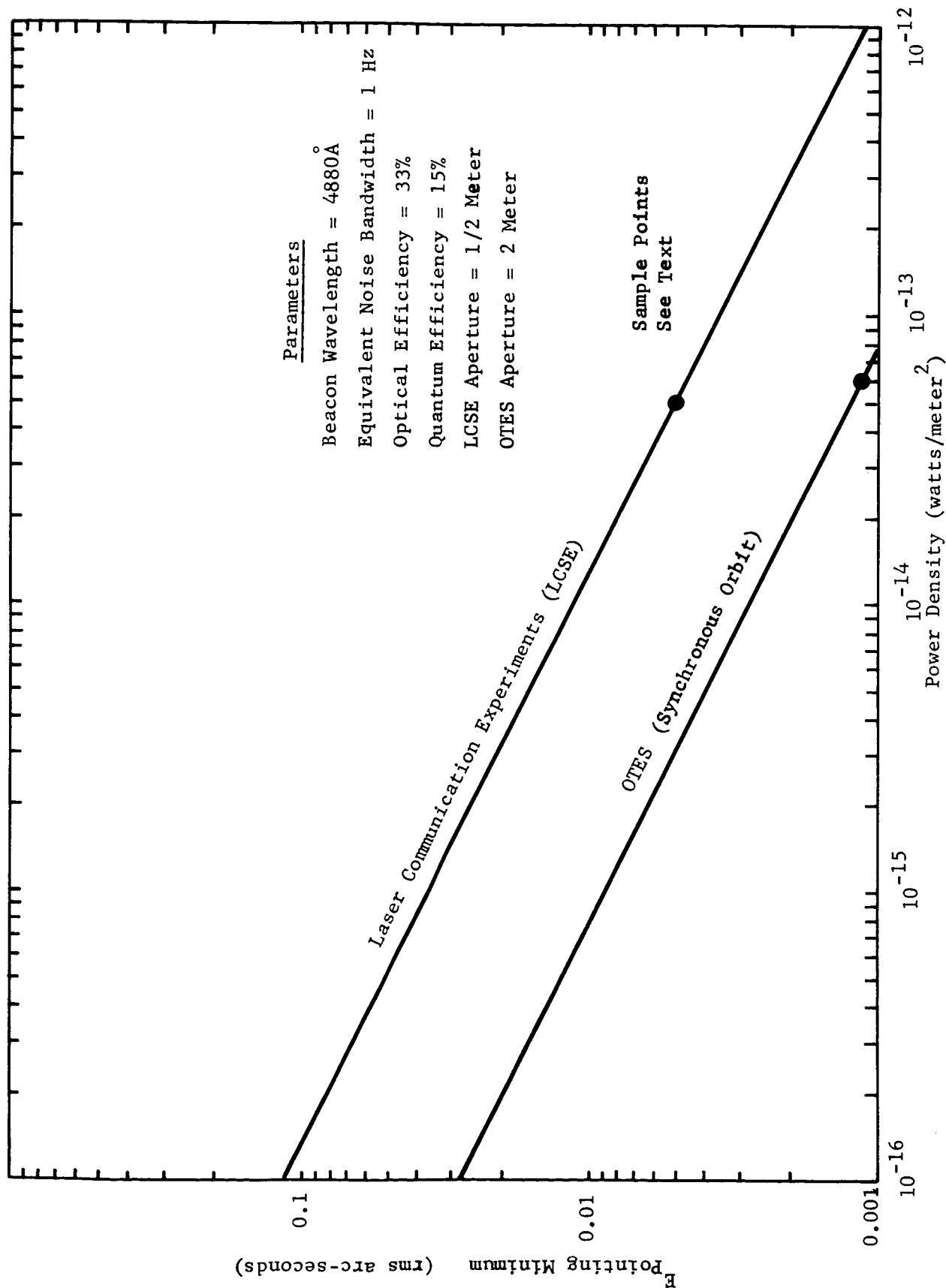


Figure 121. Telescope Theoretical Pointing Precision Limit (Argon Laser Beacon)

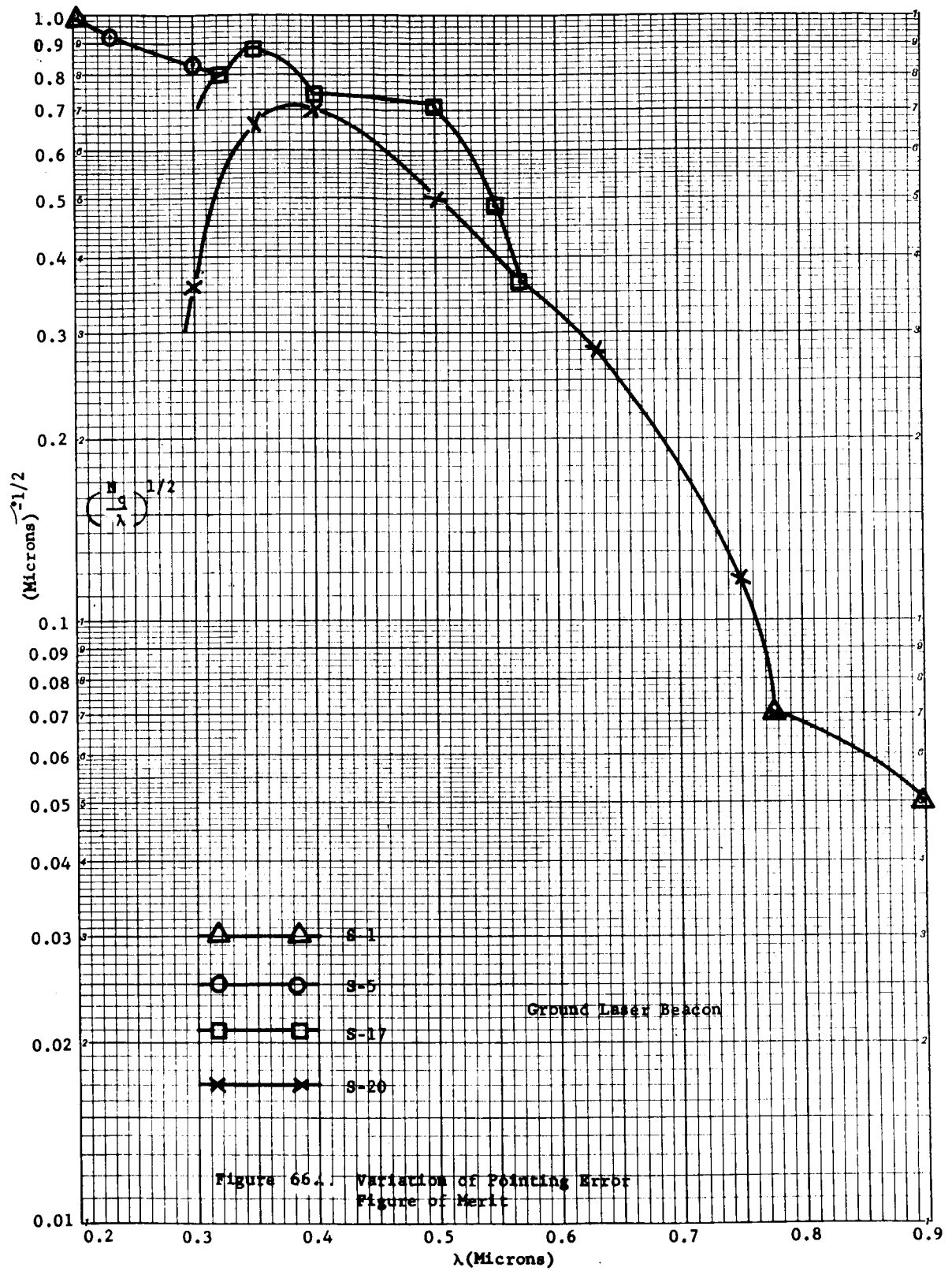


Figure 122. Variation of Pointing Error
Figure of Merit

significant effects of atmospheric absorption. This is illustrated in the curves of Figure 123.. As one considers the longer wavelengths for Earth laser beacons, the selection process is determined by windows in the atmosphere:

Infrared Windows in the Atmosphere	
~	2.2 microns
~	3.8 microns
~	5.0 microns
~	8.13 microns

These numbers cannot be taken as the sole justification for choice of ground beacon laser since other factors enter into the final decision. For example, if the spacecraft performance is to be maximized using existing lasers as beacons, then, an argon laser is better for the ground beacon. The maximum power argon beacon available today is in the range of 10 to 100 watts while the argon beacon of the future can be expected at 1000 watts. High power gallium arsenide lasers are obtained by arrays of low power devices. This arrangement introduces some problems in the optical system, but they could be overcome if need be.

In conclusion, since this experiment is an engineering experiment to collect data on precise angular tracking using lasers on a spacecraft in a synchronous orbit, measurements must be made of tracking accuracy as a function of SNR, angular jitter, zero drift, pointing stability, velocity error, acceleration error, and dynamic range of control.

TECHNOLOGY BENEFITS

The quantitative scientific measurements of the up-going laser beams which are needed to correlate the atmospheric models developed by atmospheric scientists* will be obtained. Thus, the atmospherically-induced modulation due to scintillation and the degradation effects on ground beacon tracking sensors shall be established.

The collection of engineering data on a fractional arc-second pointing and tracking system from the spacecraft to the Earth with laser beams will reveal the feasibility of future optical communications systems in space.

* Tatarsky, V.I. (U.S.S.R)
Hufnagel, R.E. (Perkin-Elmer)
Lumley, J.L. and H.A. Panofsky
(Pennsylvania State University)

Monin, A.S. (U.S.S.R)
Obukhov, A.M. (U.S.S.R.)
Atlas, D. (University of Chicago)
Fried, D. (North American Aviation)

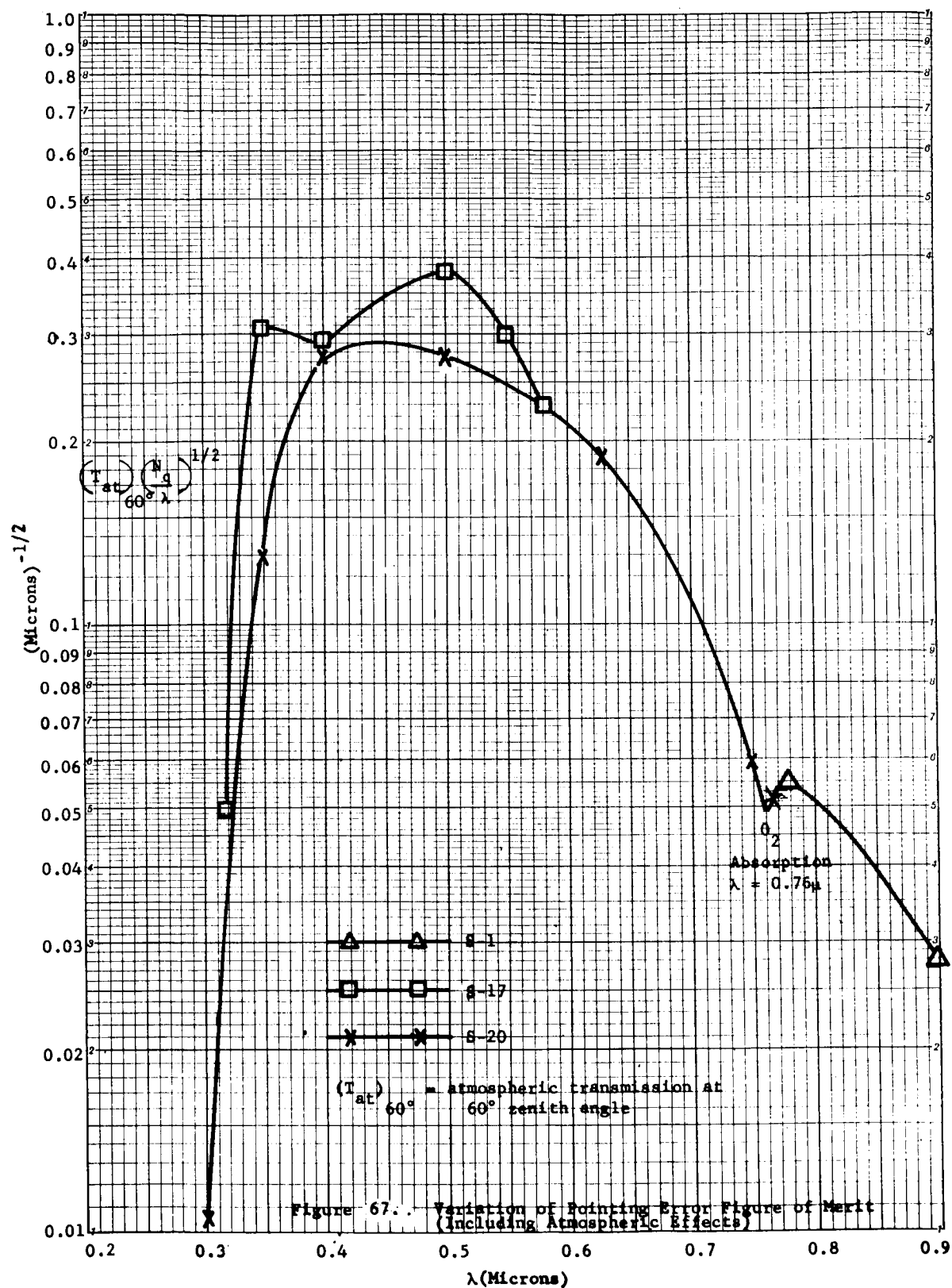


Figure 123. Variation of Pointing Error Figure of Merit (Including Atmospheric Effects)

BASIC EXPERIMENT HARDWARE

In Space

- Laser telescope
- 4880Å tracking sensor
- 5300Å transmit laser
- 6328Å transmit laser
- 10.6 micron transmit laser
- Laser modulators
- Point-ahead mechanism
- Predetection filters
- Transmit-receive dichroic beamsplitters
- Acquisition subsystem

On the Ground

- 24 to 30 inch telescope
- 4880Å laser beacon telescope
- Laser modulator
- Ephemeris computer
- Predetection filters
- Intensity detector array of four 12 inch telescopes with suitable PMTs

Other

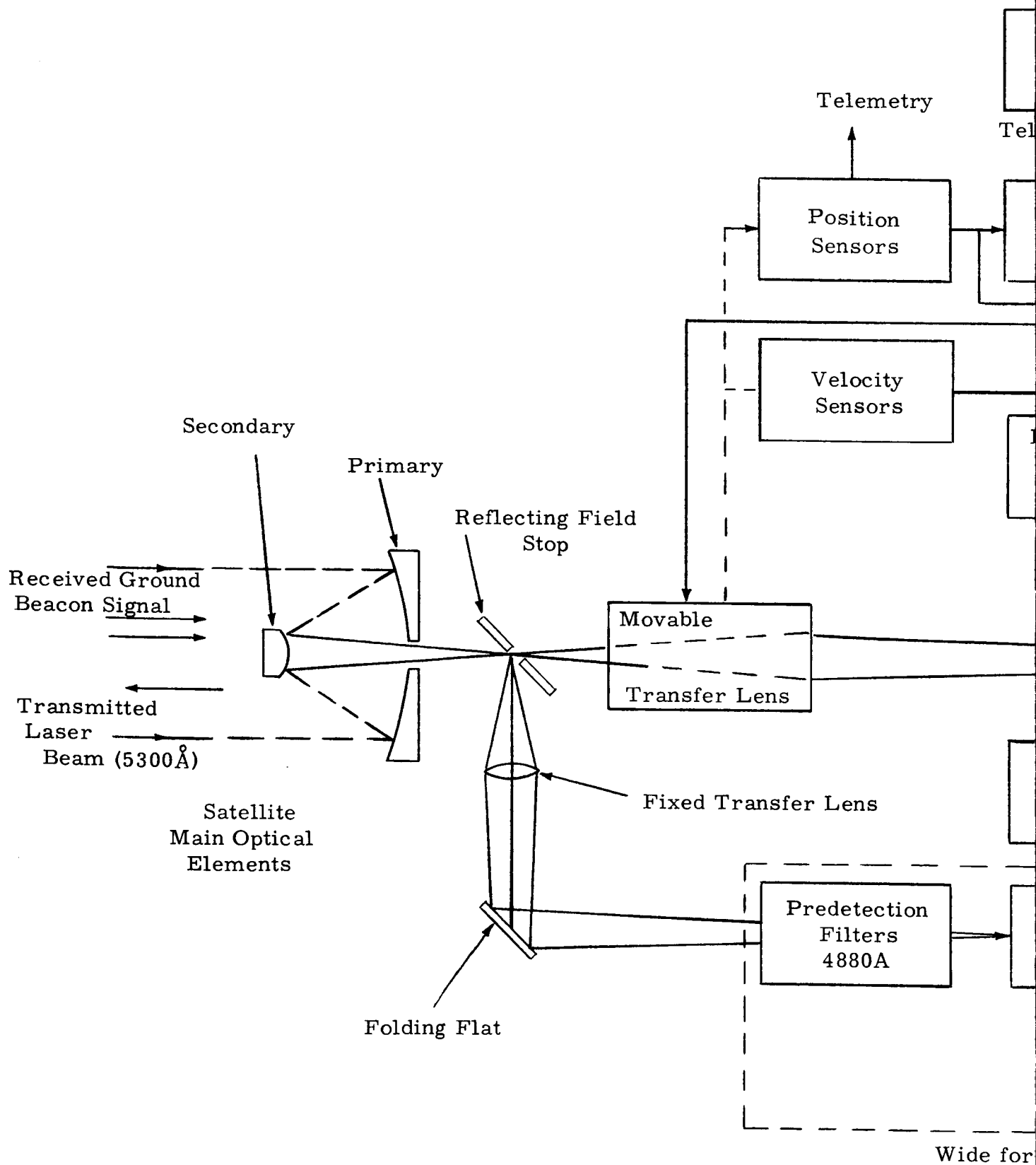
- Command system
- Telemetry

An image of the ground beacon is formed on the apex of the fine tracking subsystem as shown in the block diagram of Figure 124. Also, an image of the transmitted He-Ne light is formed on the Earth. One must determine the position stability of both images to verify 1/10 arc-second tracking for the noise sources in the tracking system: shot noise, background noise, atmospheric scintillation, and dynamic perturbations of the communicator structure and gimbal mountings.

The two fine tracking systems shown (Figure 125, Apexes #9 and #13) are conceptual drawings of the basic components of a tracking system. The beamsplitter #7 is constructed such that most of the light is directed toward apex divider #9. Assuming that signal shot noise (i.e., insufficient received beacon optical power) limits the tracker, one tracker can operate on a large received signal (i.e., negligible shot noise) and, thus, act as a reference. The light passed by beamsplitter #7 is further attenuated by the variable density filter. By comparing the output of apex divider #9 (the reference) and the output of apex divider #13 (the signal-shot-noise-limited detector), the ultimate sensitivity of the tracking system to low-light-level signals will be determined. Also, the effect of high background levels can be simulated by the calibrated variable light source #19. All data is transmitted to an Earth station for analysis and data processing.

The second tracking system can increase the reliability of the system by removing the beamsplitter #7. Thus, in case of a catastrophic failure of the reference fine tracking subsystem, the tracker with apex divider #13 will be used to complete the other communication experiments.

The alignment of dichroics and beamsplitters #1, #2, #7, and #14 is critical. Calculations indicate that the system may be prelaunch aligned and that in-flight alignment is not required. However, inflight alignment is provided as a back-up for conditions which may occur that are not anticipated.



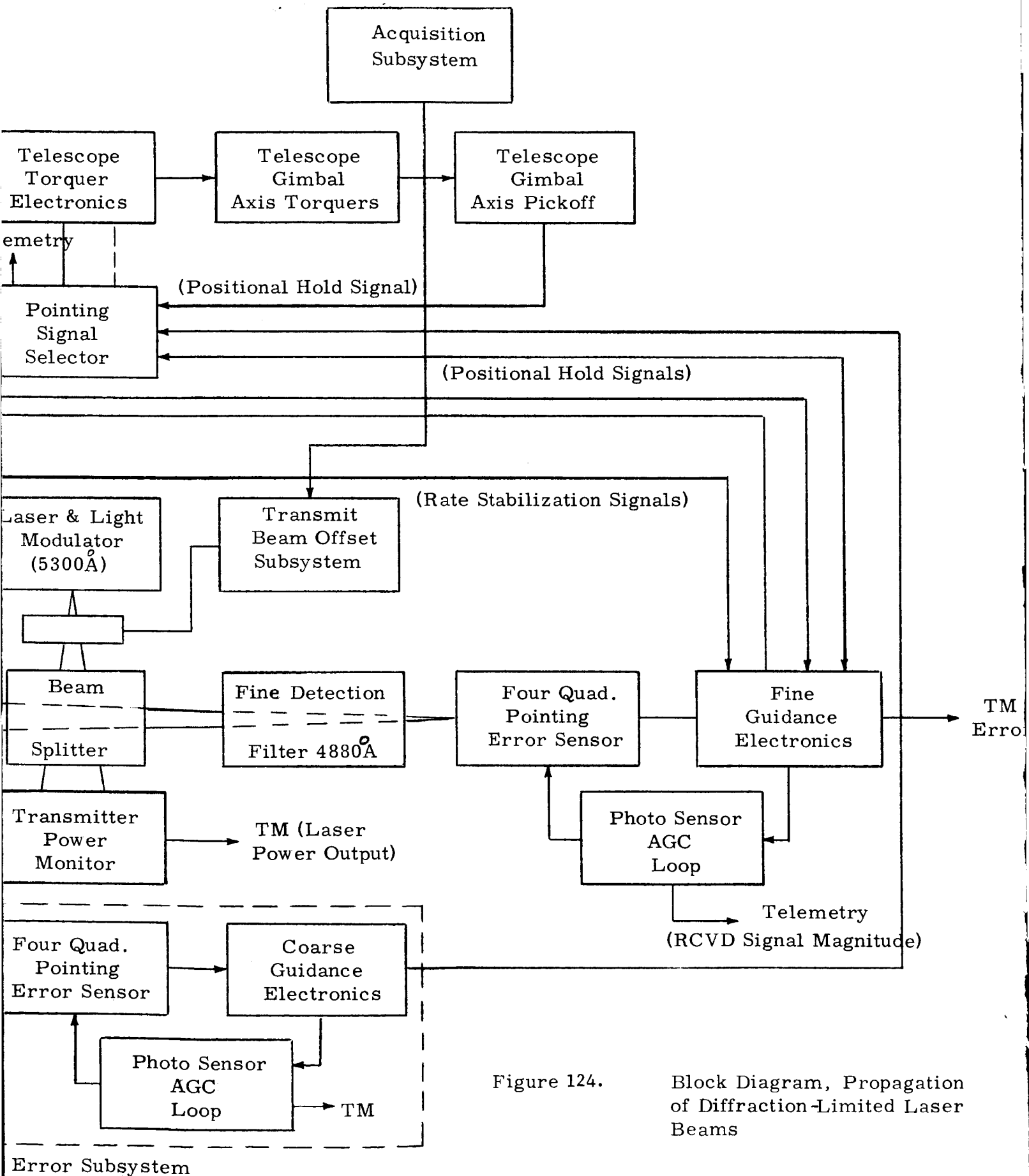
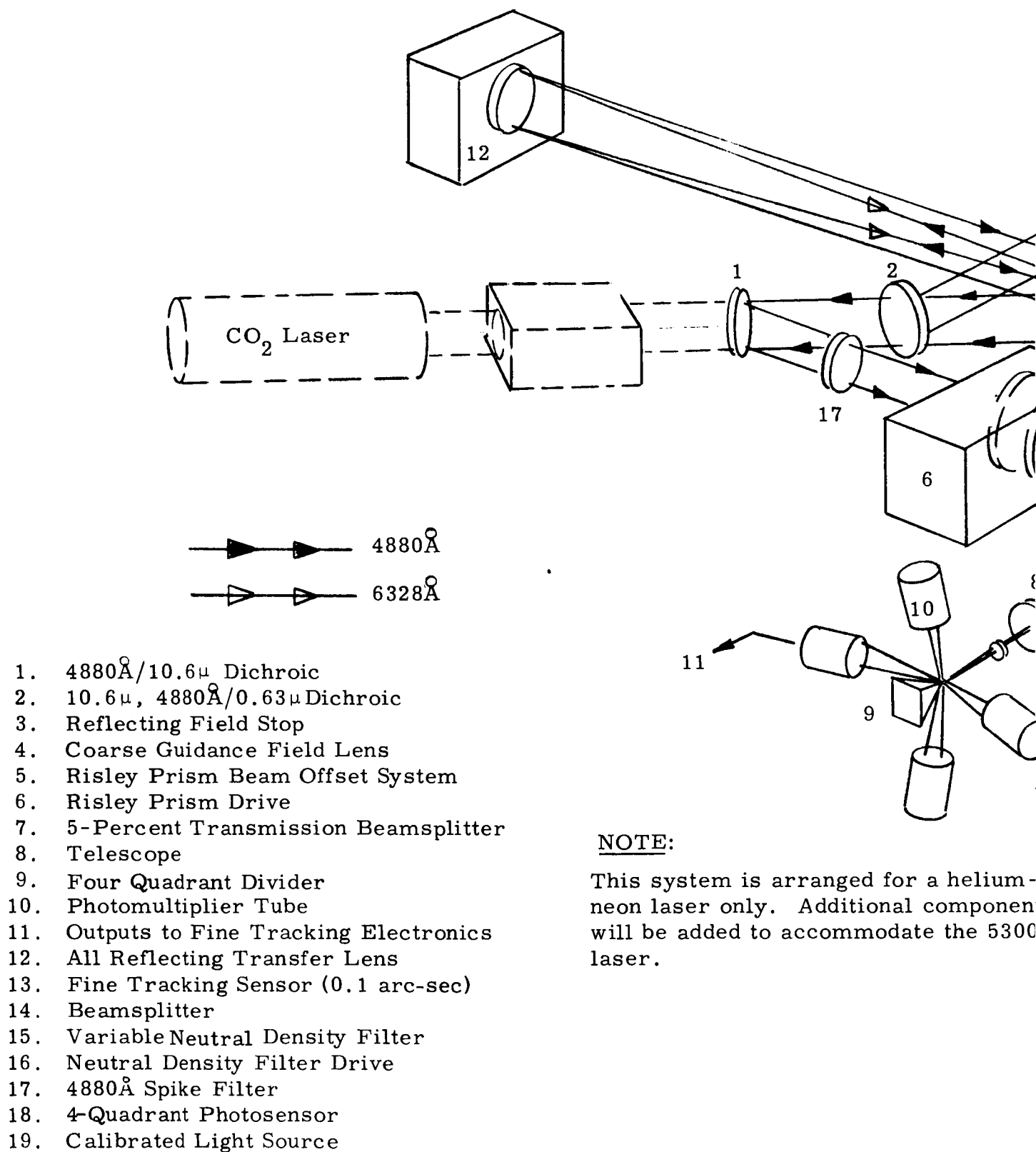


Figure 124.

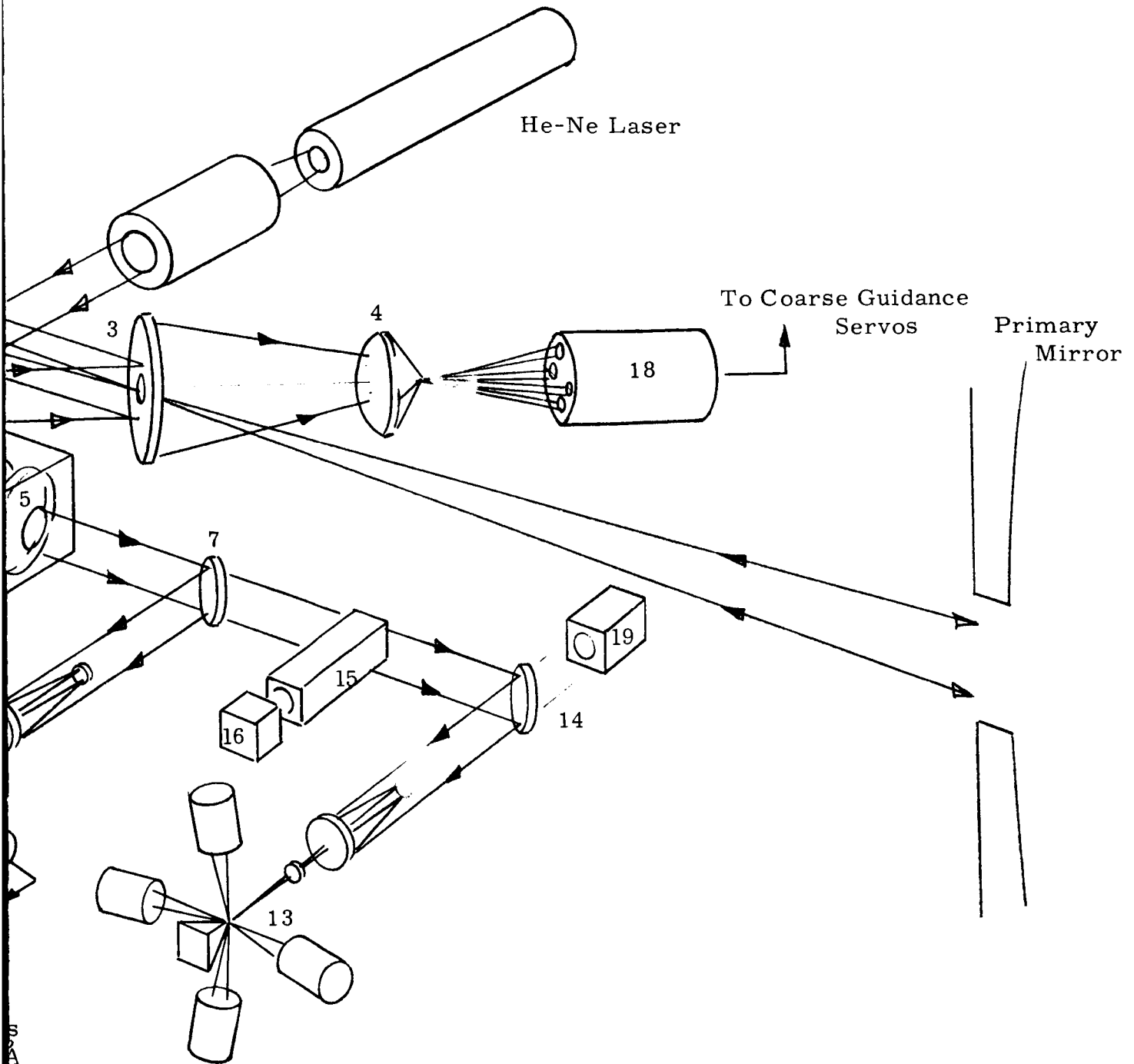
Block Diagram, Propagation of Diffraction-Limited Laser Beams



NOTE:

This system is arranged for a helium-neon laser only. Additional components will be added to accommodate the 5300 laser.

Figure 125. Fine Tracking System



I-258-2

1/10 ARC-SECOND TRACKING EXPERIMENT DISCUSSION

1/10 arc-second pointing for laser beams in optical communication modes has been the subject of numerous technical papers over the last few years. While some of the material that has been published is factual, the tenor of many of the papers is related to the technical worry about the ability of the equipment to point this precisely. The authors of this report concede that fine pointing is not a trivial task, but, based on work at Perkin-Elmer in space astronomical instruments such as Stratoscope II and OAO, the technical feasibility of pointing to 1/10 arc-second has been demonstrated in the laboratory. On Stratoscope II, the optical line of sight is directable by transfer lens action towards target stars with pointing errors well within the 0.15 arc-second diffraction limit of the instrument. Preflight measurements with the equipment tracking simulated stars indicated that expected LOS errors are in the order of 0.02 arc-second.

Although high pointing accuracy has already been demonstrated to some extent by Stratoscope II infrared flights, it is important to realize that a deep-space communication telescope will not be completely analogous to Stratoscope II. The latter instrument operates at a nominal 80,000-foot altitude and guides on stars viewed through only two or three percent of the Earth's atmosphere and so avoids most of the optical degradations caused by air turbulence and refractive index inhomogeneities. Moreover, the equipment is subjected to the soft launch environment of a balloon. Pointing disturbances during tracking arise from very small fluctuating wind components acting directly on the structure and, in addition, from torques due to suspension axis bearing imperfections which allow coupling of the instrument to the low-frequency pendulous motions of the balloon suspension. Also, the Stratoscope II does not have a point-ahead problem, but can guide on an apparent star image.

The question can be raised concerning the interrelationship between this experiment and Experiment No. 9 ($< \frac{1}{100}$ arc-second experiment). The two experiments have been separated in this report due to the difference in need between astronomy-type operations and optical-communication-type operations. Experiment 9 addressed itself to the absolute maximum pointing precision which a telescope of fixed aperture could obtain. This experiment is the evaluation of pointing precisions in the vicinity of 0.1 arc-second by the most reliable techniques compatible with the lower value of precision. Optical communication systems such as envisioned in the O.T.S.* studies require a pointing precision of 0.1 arc-second in order to achieve the high channel capacities. Assume for the moment that the identical equipment (of the O.T.S. Reports) were capable of achieving 1/100 arc-second pointing precision instead of the 1/10 arc-second specified. The improvement in optical communication performance (channel capacity) would be negligible. Therefore, the need between these two technologies is different and it is reasonable to assume that the equipment that would be developed to satisfy these needs would also be different. This is the reason for the separation of the pointing

* NASA Report CR-252, Perkin-Elmer, Contract NAS8-11408.

experiments into the two individual experiments — one experiment oriented towards astronomy technology with its requirements for pointing systems of 1/100 arc-second or better, and one experiment oriented towards optical communication technology with its requirements for pointing systems of 1/10 arc-second.

The experiment procedure would involve pointing the ground beacon to the vicinity of the satellite and proceeding through acquisition operations:

- on the spacecraft lock, onto the ground beacon,
- use a ground station array of 4 telescopes as shown in Figure 126 so that the received signal on the ground can be detected as a function of spacecraft beam deflection,
- use this data in a closed loop procedure (space-Earth-space) as described in Experiment 27 to establish optimum pointing of the space beam.

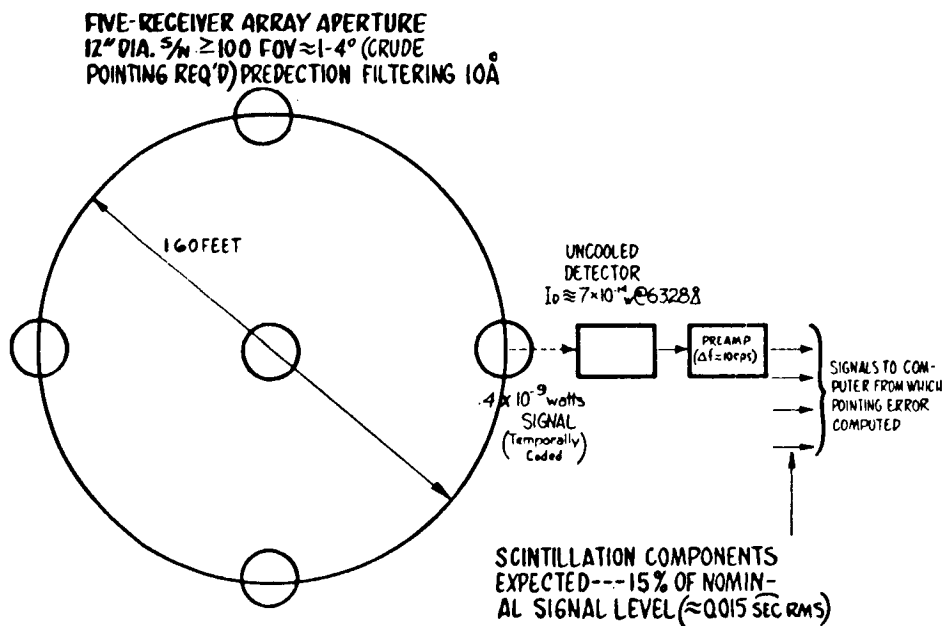


Figure 126. Some Parameters Associated with the Five Receiver Array of Ground Telescopes for Pointing Experiments

The use, for example, of a 1/2-meter diameter aperture and a 6328 Å laser beam results in a diffraction-limited resolution of 0.32 arc-second. At the ground station range of approximately 20,000 miles, the beam's diffraction pattern first dark ring will be in the order of 320 feet in diameter. The ground receiving telescopes can sense the position of the vehicle transmitted laser beam. A comparison of this actually sensed position with that computed from ephemeris data will yield the desired pointing error information. Some appreciation for the measurement sensitivity can be obtained by considering the magnitude of

difference signal generated between collectors A and B by a beam shift in the x direction. With the beam symmetrically positioned, the energy at collector A or B is equal to X and that at C is nearly 2X. For a beam shift of 100 feet along the X axis corresponding to 0.20 arc-second telescope pointing error, the energy at apertures A, C, and B becomes 2X, X, and zero, respectively, indicating a difference signal magnitude of approximately 2X per 0.2 arc-second. The aperture size of the ground telescope used in the array shown in Figure 126 has been tentatively chosen as 12-inches diameter* in order that atmospherically-induced scintillation fluctuations shall introduce only small beam position measurement errors. The signal-to-noise ratio dependence on the field of view is shown in Figure 127.

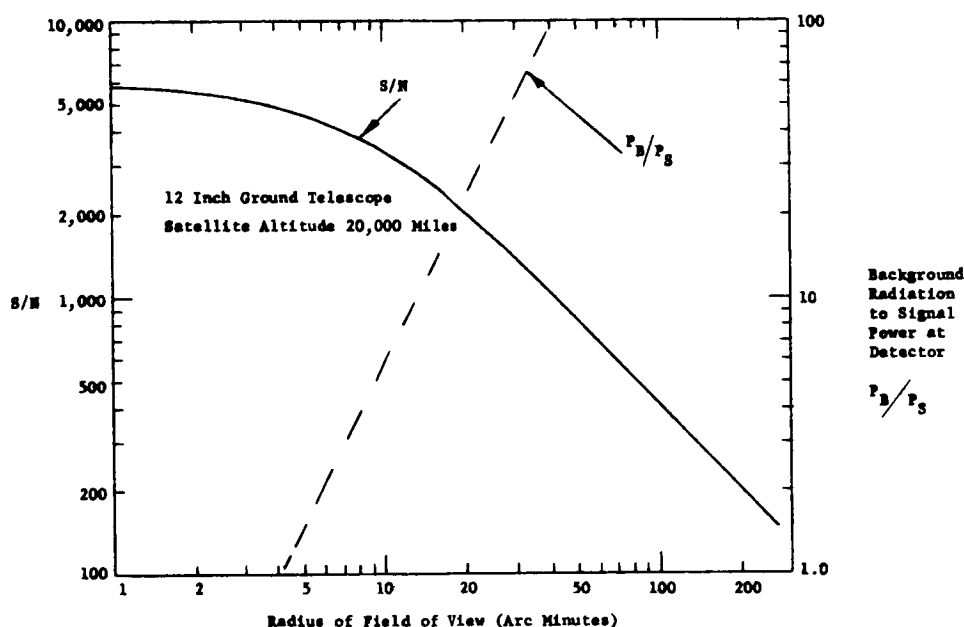


Figure 127.. Signal-to-Noise Ratio Depending on Field of View

Since the pointing error is not expected to contain components above, say, 10Hz, signal filtering can remove higher frequency scintillation components and reduce scintillation-induced fluctuations to approximately 15 percent of the nominal signal intensity magnitude for each of the selected 12-inch apertures. This represents only a small equivalent pointing error (approximately 0.024 arc-second) and is, therefore, acceptable.

Selection of the aperture size also allows use of uncooled ground telescope detectors. The RCA 7265, S-20 photomultiplier operating at 25°C, for example, has a dark current equivalent input power of 7×10^{-14} watts at 6328Å while the input laser power to the aperture will nominally be about 10^{-6} watts assuming no optical transmission losses. The statistical noise fluctuations for this

*The central telescope in the array should be at least 24 to 30 inches in diameter for other experiments.

dark current level will certainly be negligible, as will be seen below, for any reasonably expected optical attenuations and can be ignored compared to that in the temporally coded signal itself.

The relatively large amount of signal power expected at each aperture is significant in that the signal-to-noise ratio (S/N) of each detector will be substantial even with wide sensor field of view. Quantitatively, the (S/N) can be expressed as

$$S/N = \frac{Q N_g N_v \frac{P_s}{8} \left(\frac{D_g}{B_s R} \right)^2 AC}{\left[2\Delta F C Q \underbrace{\left(N_v N_g \frac{P_s}{8} \left(\frac{D_g}{B_s R} \right)^2 A \right)}_{\text{Signal Power at Detector}} + \underbrace{N_g \frac{D_g^2}{2} \pi F N_r \Delta \lambda}_{\text{Sky Background Power at Detector}} + \underbrace{P_t}_{\text{Dark Current Equivalent Power of Detector}} \right]^{1/2}}$$

where the following definitions apply and the indicated values are conservative.

- Q = S-20 phototube quantum efficiency = 0.05 electron/photon
- N_g = ground telescope optical efficiency = 0.2
- N_v = vehicle telescope optical efficiency = 0.2
- P_s = satellite laser power output = 10^{-2} watts
- D_g = ground telescope collector diameter = 12 inches
- B_s = satellite telescope resolution = 0.3 arc-second
- R = satellite range = 20,000 miles
- A = atmospheric transmission at $6328\text{\AA}$ = 0.7
- C = conversion factor from watts to photon/sec at $6328\text{\AA}$ = 3.2×10^{18}
- F = ground detector FOV = 2 min radius = 10^{-6} steradians
- N_r = day sky background = 0.017×10^{-5} watts/cm²/steradian/ $\text{\AA}$
- P_t = phototube (S-20) dark current equivalent power = 7×10^{-14} watts
- ΔF = detector frequency response = 10 cps
- $\Delta \lambda$ = predetection filtering bandwidth = $10\text{\AA}$

Substitution of the indicated values into the foregoing expression yields

$$S/N = \frac{6 \times 10^8}{\left[3.2 \times 10^{18} \left(\underbrace{0.13 \times 10^{-9}}_{\text{Signal Power}} + \underbrace{0.2625 \times 10^{-9}}_{\text{Sky Background Power}} + \underbrace{7 \times 10^{-14}}_{\text{PMT Equivalent Power}} \right) \right]^{1/2}}$$

The high ratio obtained above indicated that acceptable S/N will also result with substantially larger ground collector fields of view (see Figure 127) and/or with protection filters wider than the assumed 10Å.

The proposed scheme would utilize collectors of about 1-to4-degree diameter fields to minimize pointing accuracy requirements while maintaining $S/N \geq 100$. This is especially important when one considers the experimental constraints imposed by transmit time and aberration effects.

As considered, the ground beacon will be a fixed installation, controlled by a ground computer with ephemeris and meteorological data to direct a laser beam towards the predicted vehicle position with necessary precision.

Ground receiver array motions can be used to compensate for point-ahead effects, which result in large, but not impractical, receiver array-to-beacon displacements. Transit time effect due to Earth spin will cause a displacement, d_T , equal to the positional change of the beacon during the round trip time at the speed of light. The Earth beacon velocity (Figure 128) is nominally directed tangentially eastward with magnitude $\omega_e r_e \cos(\text{latitude})$ and the vehicle-beacon separation range, corresponding to zeniths from 0 to 90°, can vary a minimum

$r_s - r_e$ and a maximum of $\left[r_s^2 - r_e^2 \right]^{1/2}$. Assuming that $r_s = 19,752$ nautical miles, $r_e = 3444$ nautical miles, and beacon latitude = 30°, values for d_T range from 262 to 312 feet. This, in itself, would call for a receiver array located 287 feet to the west of the beacon with computer corrections equivalent to ± 0.050 arc-seconds to account for the ± 25 -foot error. These numbers should not be used in context since aberration of light effects are not included. Instead, the Bradley Effect point-ahead angle can be calculated and this includes the above transit time term.

The beam displacements due to Bradley Effect at synchronous altitude due to the relative difference in velocity, between an earth station moving with a tangential velocity of 900 nautical miles/hour and a synchronous spacecraft moving at a tangential velocity of 5950 nautical miles/hour, is 1.79 arc-seconds. The system under consideration locks onto the apparent Earth beacon, and radiates along the apparent line of sight of the Earth beacon. The effect

is doubled so that the point-ahead angle due to this effect is 3.58 arc-seconds (at zenith). At a 20,000-mile range, this corresponds to a displacement on the Earth surface of 2000 feet. A point-ahead angle correction can be made of 3.58 arc-seconds on the spacecraft (Experiment 20) to bring the spacecraft transmit beam back to the Earth beacon.

For a 28° OTES orbital inclination (see Page II-143* for orbit definition) the maximum angular velocities in the east-west and north-south directions are given** as 1.0×10^{-5} and 3.8×10^{-5} rad/sec, respectively. The time variation of the spacecraft over a 24 hour period is such that the ground track of the vehicle describes a "figure 8" pattern on the Earth while the spacecraft angular rates vary as described above.

The relatively small pattern dimensions and the slow rate of beam motion should provide a realistic simulation of deep-space angular rates.

It is important to note that the relatively large atmospheric refraction effects (up to 90 arc-seconds) will introduce very small vehicle tracking measurement errors. If one considers a random refraction angle effect as large as 90 arc-seconds (the worst case) occurring at a slant range of 15 miles in the Earth's atmospheric layer, the beam displacement error at Earth would be in the order of 42 feet which is equivalent to only 0.084 arc-second mispointing.

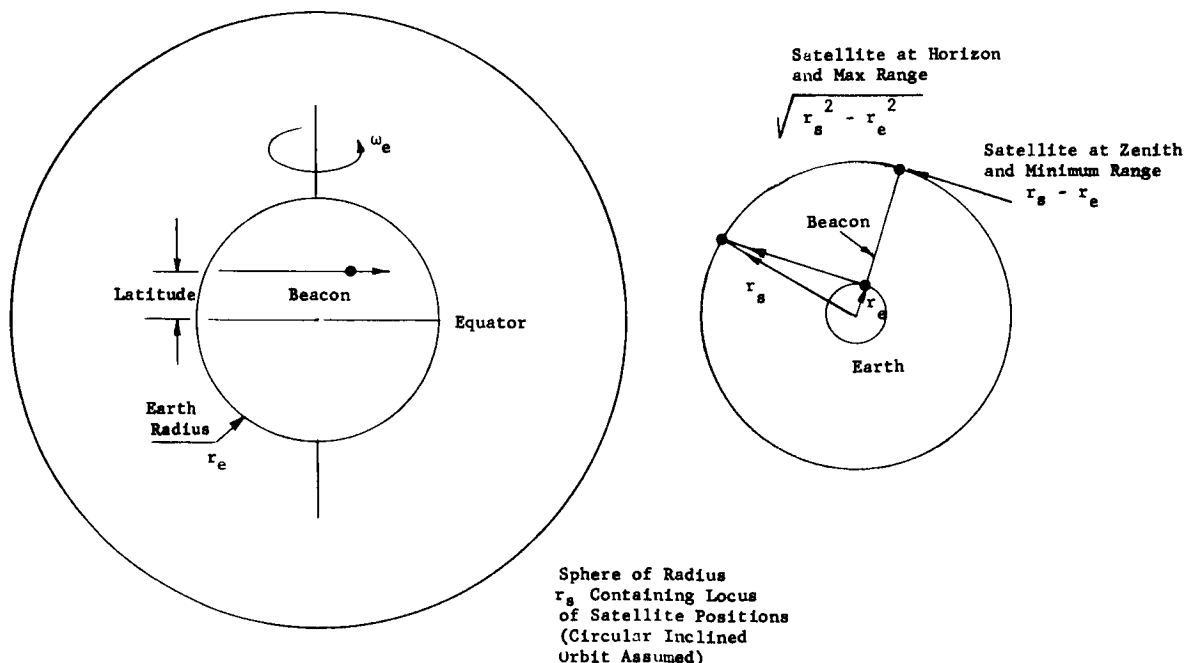


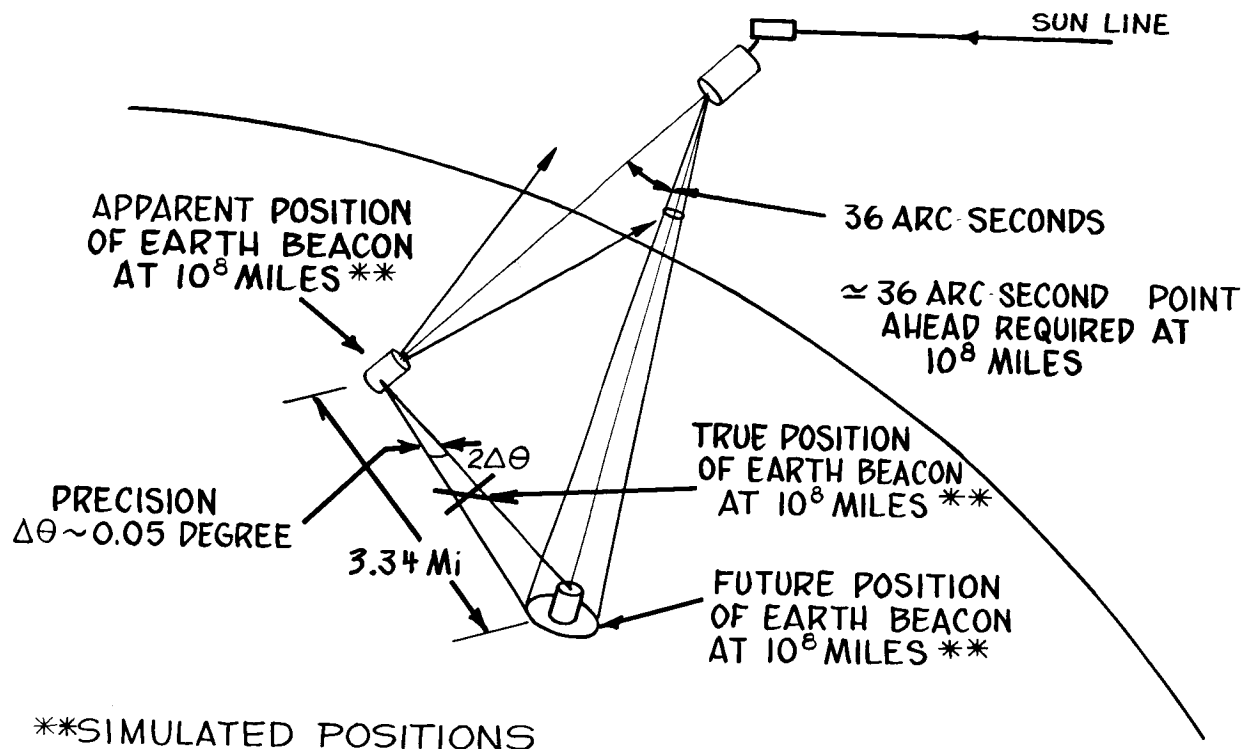
Figure 128. Geometry for Transit Time Calculations

* Perkin-Elmer Report No. 8500

** OTS Perkin-Elmer Report No. 7846, pages B-14 and B-16.

EXPERIMENT NO. 20* - POINT AHEAD

(Deleted From the 2-Meter OTES)



**SIMULATED POSITIONS

Figure 129.

EXPERIMENT OBJECTIVES

To demonstrate that it is feasible to point a space telescope's transmitting LOS ahead of its receiving LOS, by up to approximately 36 arc-seconds. The LOS to be accurate enough to establish an optical communication link back to the Earth receiving station whose transmit laser beacon is radiating.

EXPERIMENT JUSTIFICATION

Successful execution of this satellite experiment on OTES at 20,000 miles, under conditions which are closely equivalent to those anticipated at 10^8 mile ranges, will establish the feasibility of deep-space-to-Earth laser communication systems which utilize narrow beams.

A successful deep-space communications link must have the ability both to receive or track a distant transmitter and, in addition, to accurately point the local transmitter in the correct direction. Since the transmitted beam should be narrow in width to achieve high communication rates with reasonable power, the pointing accuracy requirements are stringent. In the case of a 1-meter diffraction-limited transmitting telescope, pointing errors exceeding about 0.05 arc-second result in substantial reductions of field intensity at the distant receiver. The Perkin-Elmer approach for obtaining high angular pointing accuracy for deep-space optical communication systems is to use the receive

* See first Footnote of Experiment No. 19.

beacon as a reference direction from which to offset the transmitter LOS. The maximum displacement from this reference, for the case of the deep-space vehicles transmitting to Earth, is in the order of only 36 arc-seconds which makes possible, for example, the attainment of 0.036 arc-second precision with a 0.1 percent point-ahead mechanism. While offset angular magnitude could thus be accurately implemented, some way of deflecting the transmitted beam in the correct direction (RLOS) must also be provided. The precision necessary is in the order of one half the beamwidth divided by the offset magnitude, which, in the case of 0.1 arc-second beamwidth and 36 arc-seconds point ahead, is within 0.05 degree. (See Experiment 24.)

While the pointing accuracy requirements are precise in the conventional sense, based on Perkin-Elmer experience they are considered practical to achieve in a deep-space optical communication system. It would be desirable, however, in any such system to minimize the vehicle equipment complexity and, therefore, achieve the highest possible reliability. The implicit operations required to establish the offset magnitude and direction data are best computed on the ground and telemetered to the vehicle. The slowly varying magnitude of data could be conveniently transmitted on the microwave signal.

EXPERIMENT PROCEDURE

The experiment procedure (see Figure 129) occurs after the satellite has locked its receive beam onto the ground station transmitter. The ground station sends up the command on its own beacon to move the spaceborne transmit beam ahead (i.e., 36 arc-seconds in azimuth). These angles are set up about a reference for the rotation of the LOS (RLOS). A second complete ground station is required, located 3.34 miles away from the main station. This corresponds to a point ahead of 36 arc-seconds at 19,323 n. miles. This second station will transmit at a different laser frequency. For this test all computational equipment will be located on the ground at the main station. The satellite must have the equipment on board to receive and store commands of point-ahead angle. It must have also an optical beam displacement subsystem for the transmit beam which will point away from the received line of sight (LOS) from the main station in the necessary direction.

With a ground station located 3.34 miles away from the main station, "static or bias errors" introduced into the spacecraft by launch environmental conditions can be detected and corrected. For example, a focal length change of the vehicle's optics can change the scale factor of the transmit beam deflection mechanism. This can be assessed by noting the multiplying constant required by the otherwise correct computed point-ahead angles to obtain minimum tracking errors. The performance of the point-ahead system can be measured as a function of naturally occurring daily and seasonal changes of spacecraft temperature, background light level, and/or manually adjusted beacon transmitted power level.

Pointing the telescope's transmitting LOS ahead of its receiving LOS is accomplished by the Risley Prism Beam Offset System (RPBOS) which includes elements #5 and #6 of Figure 125. . Also, the device can be used for roll

correction, alignment of transmit and receive channels, and the mirror figure assessment of Earth (Experiment No. 5). Because of the wavelength dependence of the Risley prism index of refraction, the point ahead should not be done in a polychromatic bundle of light. Thus, the RPBOS has been placed in the 4880Å monochromatic light of the fine tracking subsystem. (See Figure 130).

The commands to the RPBOS consist of a RLOS signal (Figure 131) which gives the rotational angle about the line of sight and the point ahead signal (Figure 132) which gives the angle offset from the line of sight.

In case of equipment failure of the RPBOS, the beam spoiling optics will increase the divergence of the transmit beam thus negating the requirement of point ahead and decreasing the energy density on the Earth.

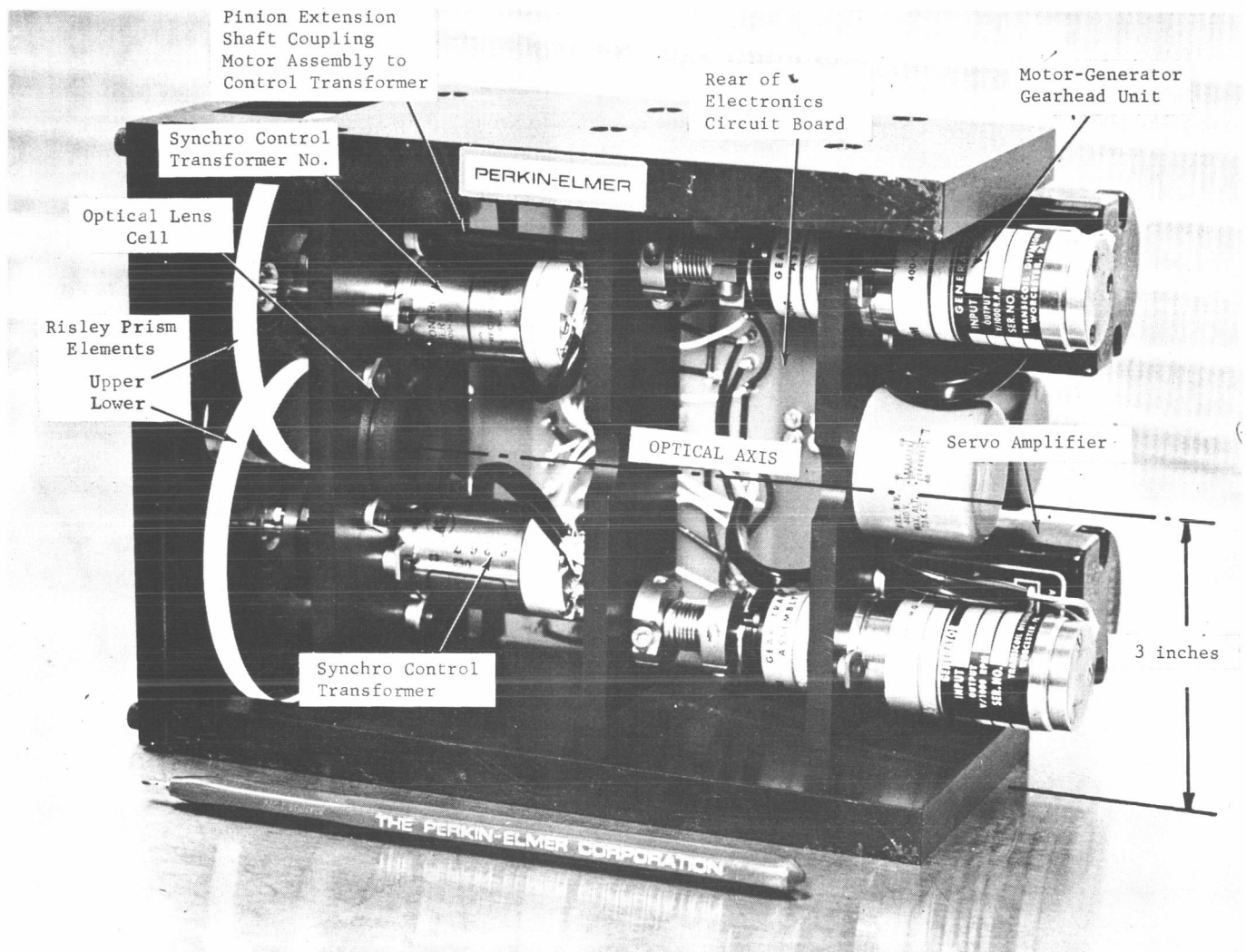


Figure 130. Risley Prism Subsystem

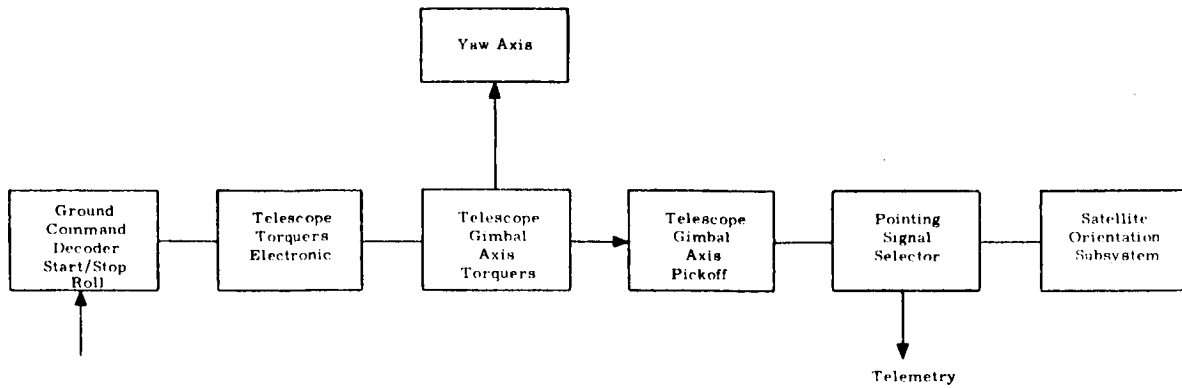


Figure 131. Rotation About Line of Sight (RLOS)

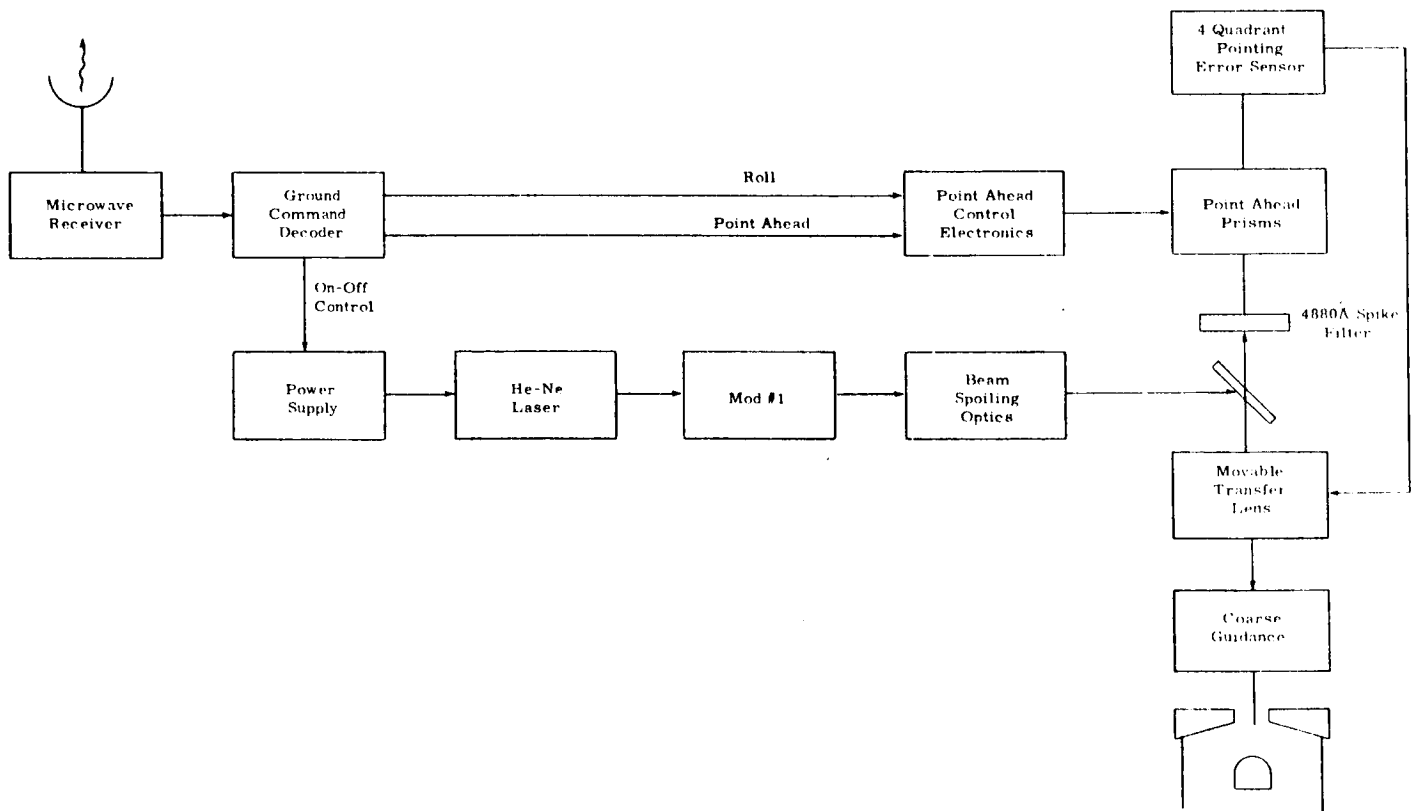


Figure 132. Point Ahead Experiment

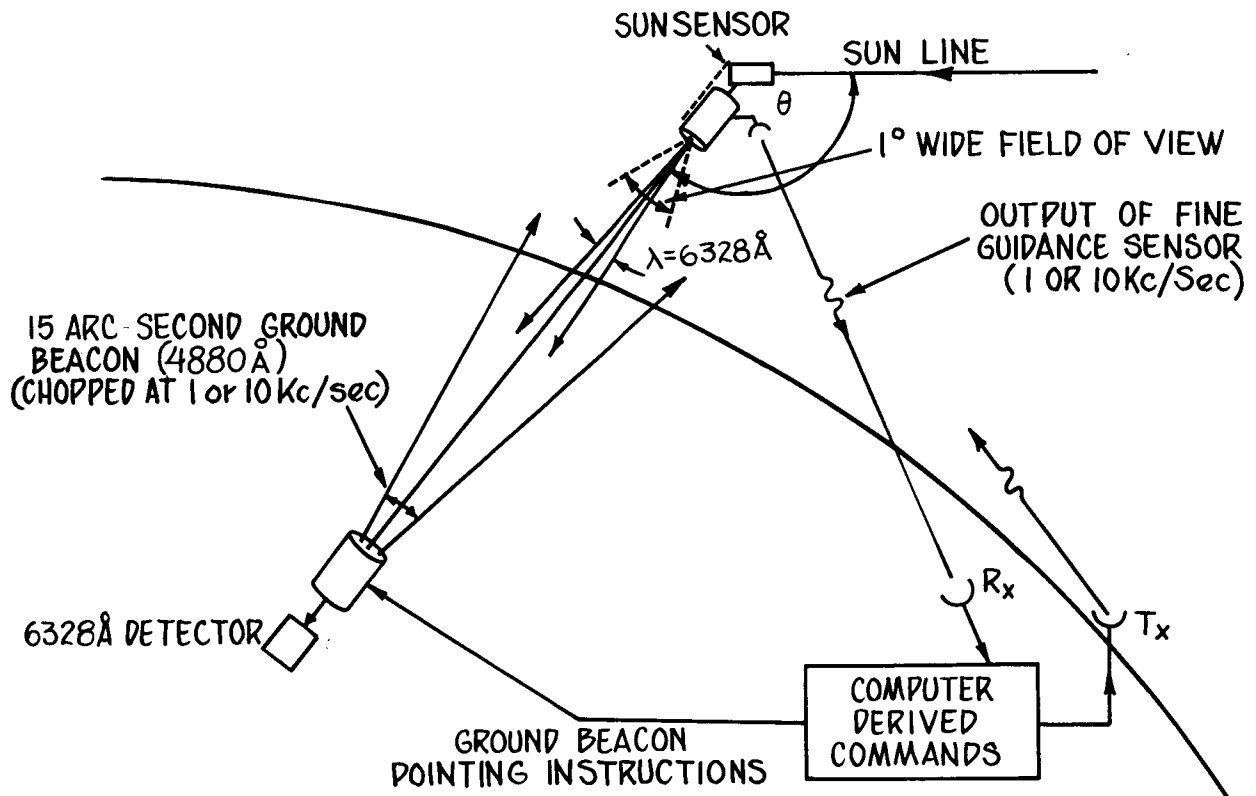
EXPERIMENT NO. 21 - LASER BEACON ACQUISITION IN SPACE

Figure 133

EXPERIMENT OBJECTIVE

Assess the merits of one or more acquisition methods for finding (or acquiring) a laser ground beacon. The reliability, simplicity, and acquisition speed of each approach should be determined. Many acquisition schemes are possible. A deep-space vehicle, for example, could search with a relatively wide FOV ($\sim 1^\circ$) at a given angle from the vehicle-sun reference line until beacon power is received. This approach might benefit by incorporation of auxiliary earthshine detectors to enhance the detection ability under high albedo and Earth illumination conditions. Another approach might be to utilize vehicle star tracking equipment, if present, to establish perhaps a two-axis reference with stored angular data to locate Earth and the beacon without a search mode. A third approach might conceivably involve both microwave and laser ground beacons to provide both coarse and fine position error detection capability during acquisition. Since eleven synchronous satellite experiments (viz. 5, 20, 23, 24, 26, 27, 28, 29, 30, 31, 32) are dependent upon the acquisition of a ground laser beacon, the 2-meter OTES at the 260 mile orbit should execute as much of Experiment 21, as originally described in Report 8500, as practical from the low orbit. (See Figure 133.

EXPERIMENT JUSTIFICATION

Acquisition capability must be provided if the eleven synchronous orbit experiments are to be performed. An engineering experiment, devoted to performance evaluation and optimization procedures, is consistent with the importance of developing a truly spaceworthy laser beacon acquisition system. Further, the provision of two completely redundant acquisition subsystems aboard a technology satellite such as an OTES stems from the need for a high confidence factor subsystem. The provision of a last-ditch backup acquisition system is justified for the low orbit flight of the 2-meter OTES.

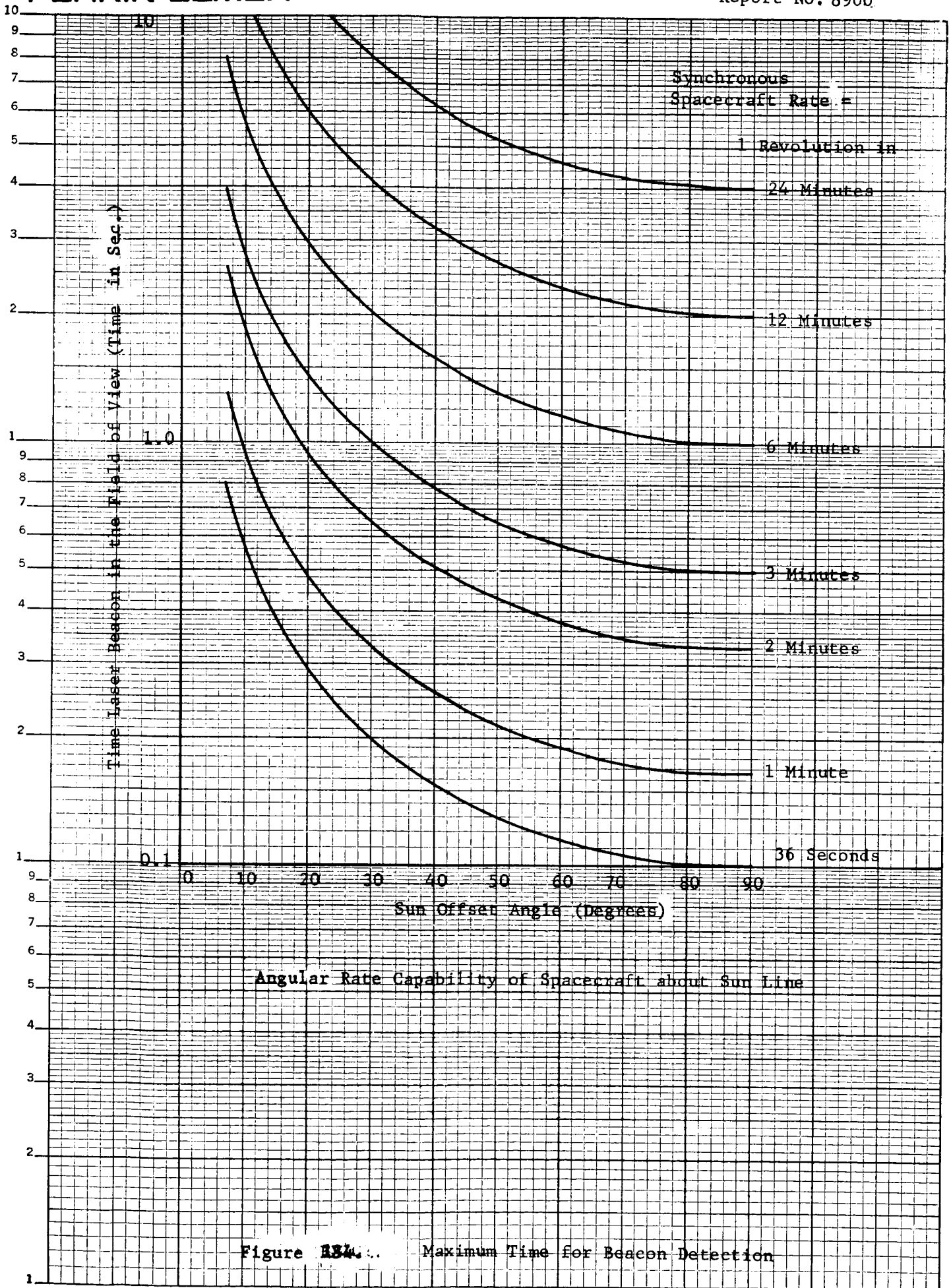
The attached parametric family of curves in Figure 134 considers the capability of the synchronous spacecraft to rotate rapidly or slowly about the sun line and the effect of this capability upon the time during which the Earth beacon image will travel through a 1° field of view. Since the sun offset angle can vary from small angles (but no less than a few degrees or the direct rays of the sun would enter the telescope) to large angles approaching 90° , the sun offset angle is plotted as the abscissa or independent variable of the parametric curves. The synchronous spacecraft rotational rate capability about an arbitrary axis is considered over the range from 1 complete revolution in 1/2 minute to 1 complete revolution in 1/2 hour. The faster the spacecraft rate, the shorter the period of time that the Earth beacon image will be inside the 1° field of view.

Note that the rates are measured by values in the range of revolutions per minute for this synchronous orbit simulation of deep space. For the 2-meter OTES, the angular rates are in the vicinity of several degrees per second, and the corresponding time that a laser beacon image would traverse a 1° field of view is now a matter of a fraction of a second. The acquisition problem at low orbital altitudes is considerably more difficult and the likelihood of success is correspondingly lower. However, the number of opportunities to conduct acquisition experiments will be high due to the long life of the orbiting vehicle.

BASIC EXPERIMENT HARDWARE

The basic method for acquiring an Earth laser beacon utilizes a search about the vehicle-sun reference line (as described above); the basic hardware involved includes the following:

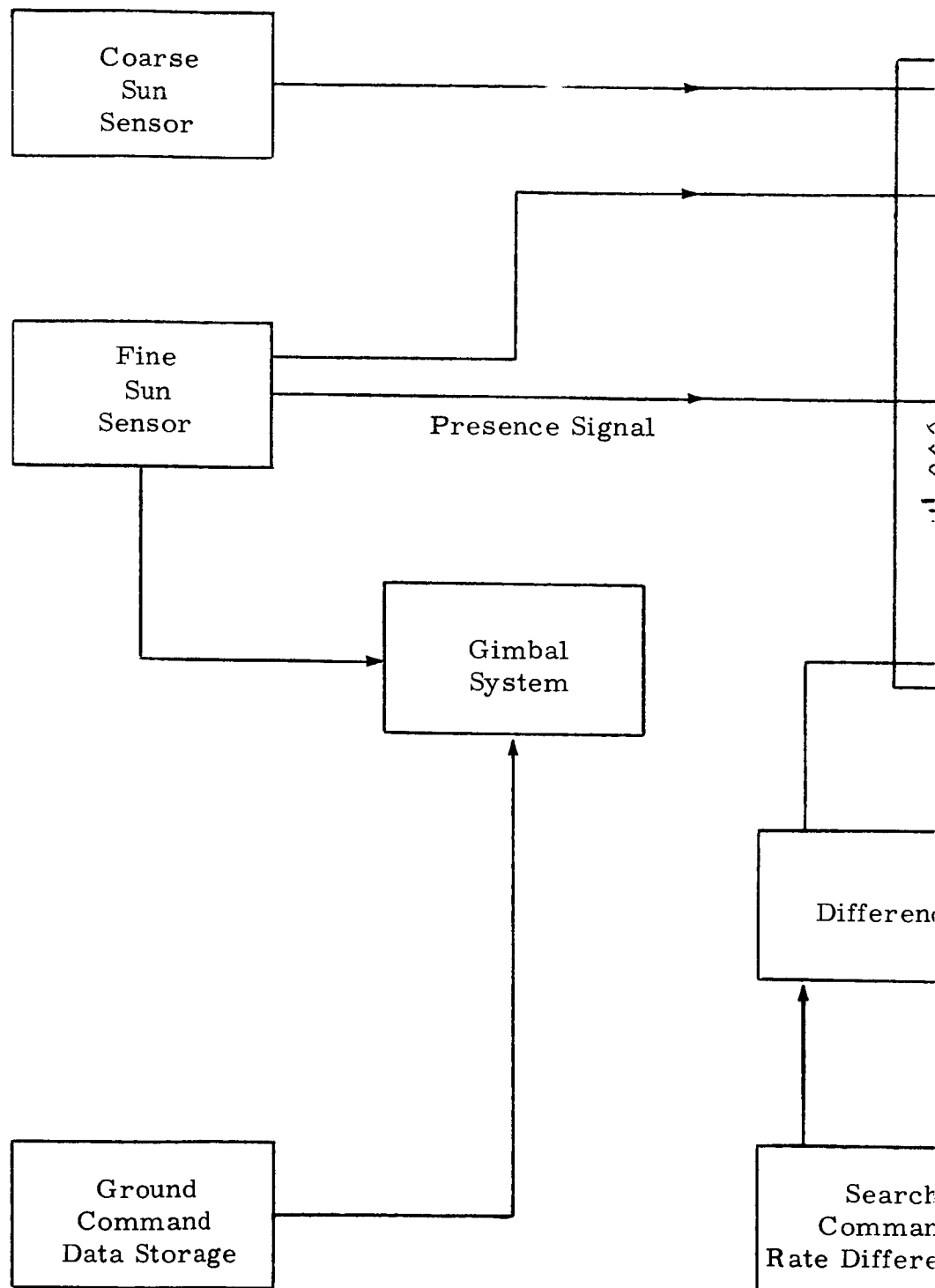
<u>On the Ground</u>	<u>In Space</u>	<u>Other</u>
• Computer	• Optical telescope with wide detection FOV	• Command and telemetry subsystems
• Laser	• Optical pointing error sensor (viz. 4-quad detector, PMT, etc.)	
• Laser modulator	• Predetection filtering	
• Optical telescope	• Field stop (automatic or remotely controlled)	
• Telescope gimballed mount	• Acquisition subsystem a) sun sensor, coarse b) sun sensor, fine and gimballed Attitude controllable vehicle Suspension subsystem	



The acquisition subsystem includes elements #3, #4, and #18 in Figure 125. The reflecting field stop divides the coarse (reflected) field and the fine (transmitted) field. As the image of the ground beacon enters the coarse field of view, the beacon energy is focused by the field lens on one or more of the quadrants of the 4-quadrant photosensor. This signal, when fed to the pointing control selector (Figure 135) causes the vehicle to rotate and consequently forces the beacon image toward the central hole of the reflecting field stop.

The first operation during acquisition is to determine the approximate position of the sun by using the coarse sun sensor. The output signal of this device is used to roll the telescope to a position where the sun is in the FOV of the fine sun sensor. Once the fine sun sensor has acquired the sun, the telescope rolls about the sun LOS. The rotation rate is controlled by the difference amplifier with the rate gyro and rate reference inputs.

PERKIN-ELMER



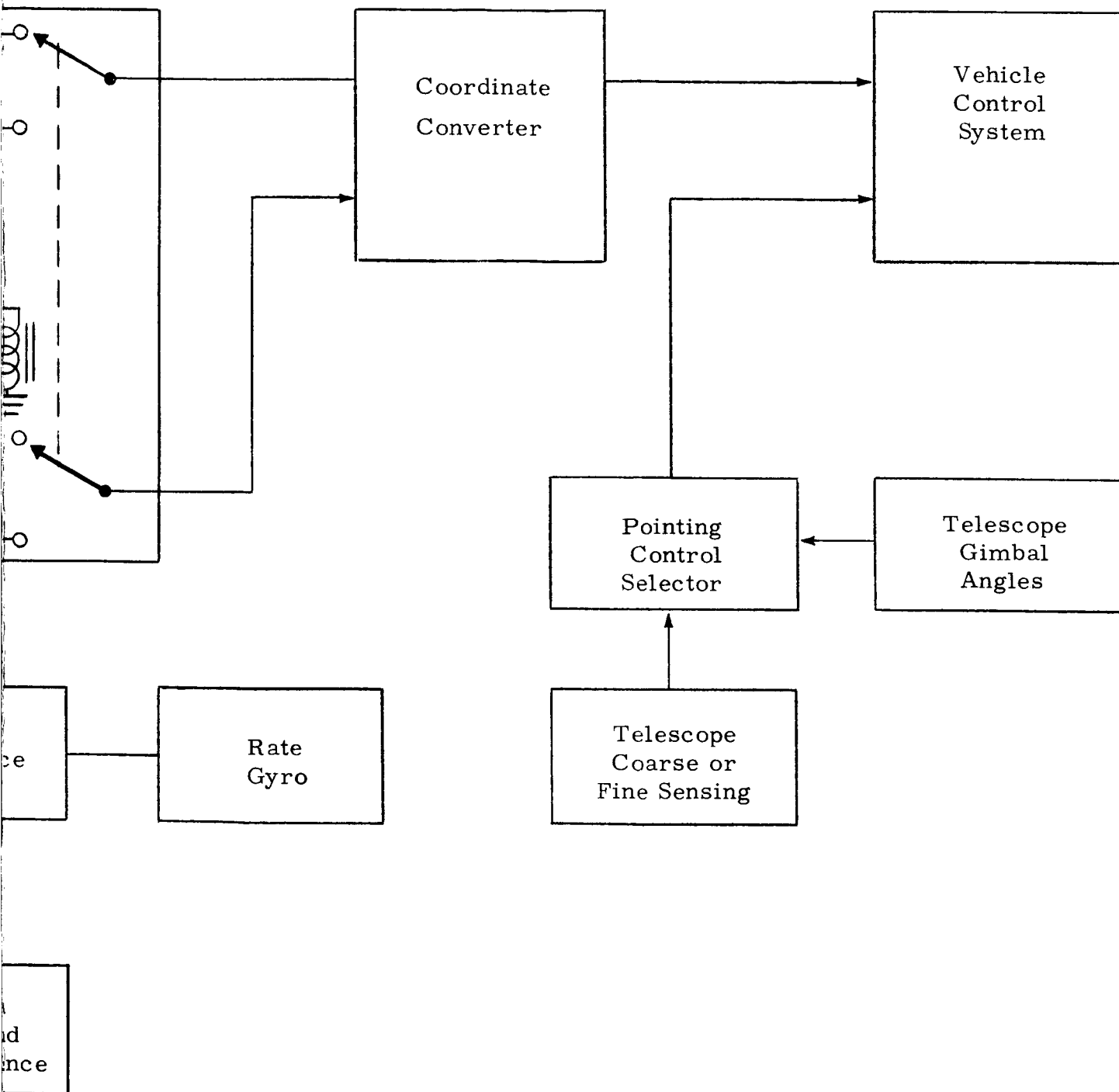


Figure 135. Acquisition

EXPERIMENT NO. 22 - EARTHSHINE AND CLOUD COVER EFFECTS ON ACQUISITION AND TRACKING (Deleted from the 2-Meter OTES)

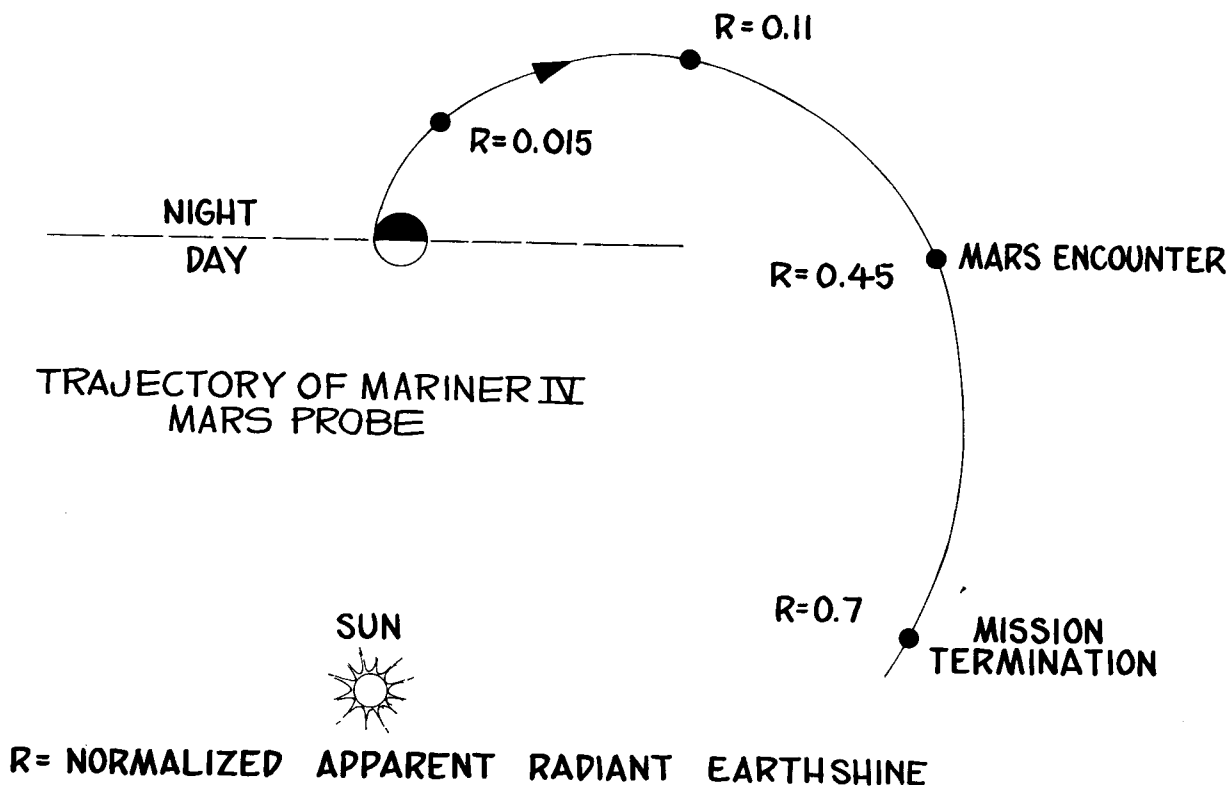


Figure 136

EXPERIMENT OBJECTIVE

Figure 136 above illustrates the variation in the earthshine as seen by a Martian space vehicle looking back at Earth. The figure shows the trajectory of Mariner IV in a coordinate system fixed with respect to the Earth and sun. Note that during the early part of the mission the probe is viewing the "night" Earth. After encounter, the probe is assumed to be in orbit around Mars.

The experiment objective is to assess the ability of a space optical (acquisition and tracking) system to acquire and track a laser ground beacon in the presence of degradations induced by naturally occurring earthshine. The range of conditions should include those occurring on moonless nights through those occurring with high-noon sun with effects of various albedo conditions (water glint, snow fields, clouds, etc.). Tracking measurements are also needed for various cloud cover conditions. Experiment data is needed to support the selection of future lasers based on their ability to penetrate cloud layers. For example, Perkin-Elmer has made some laboratory measurements which indicate that CO_2 laser light will penetrate artificially generated aerosols when the light

from visible lasers is almost completely reflected by these same aerosols. In the 1966 experiment (the data is plotted in Figure 137) it was found that the CO₂ laser at 10.6 microns penetrated an artificial fog with only a 3 percent loss, while the light from a helium-neon laser at 6328A was attenuated by 98 percent. While it is too early to draw any conclusions on the penetration capability of 10.6 micron light through natural clouds, the measurements indicate the need for some carefully engineered laser propagation measurements through the atmosphere.

If 10.6 micron light effectively penetrates high thin cloud layers such as found in arid western zones of the United States, then, a laser communicator using this wavelength would have a unique "almost all-weather" capability. The measurements proposed as part of this experiment would establish the acquisition and tracking capability in the presence of cloud layers.

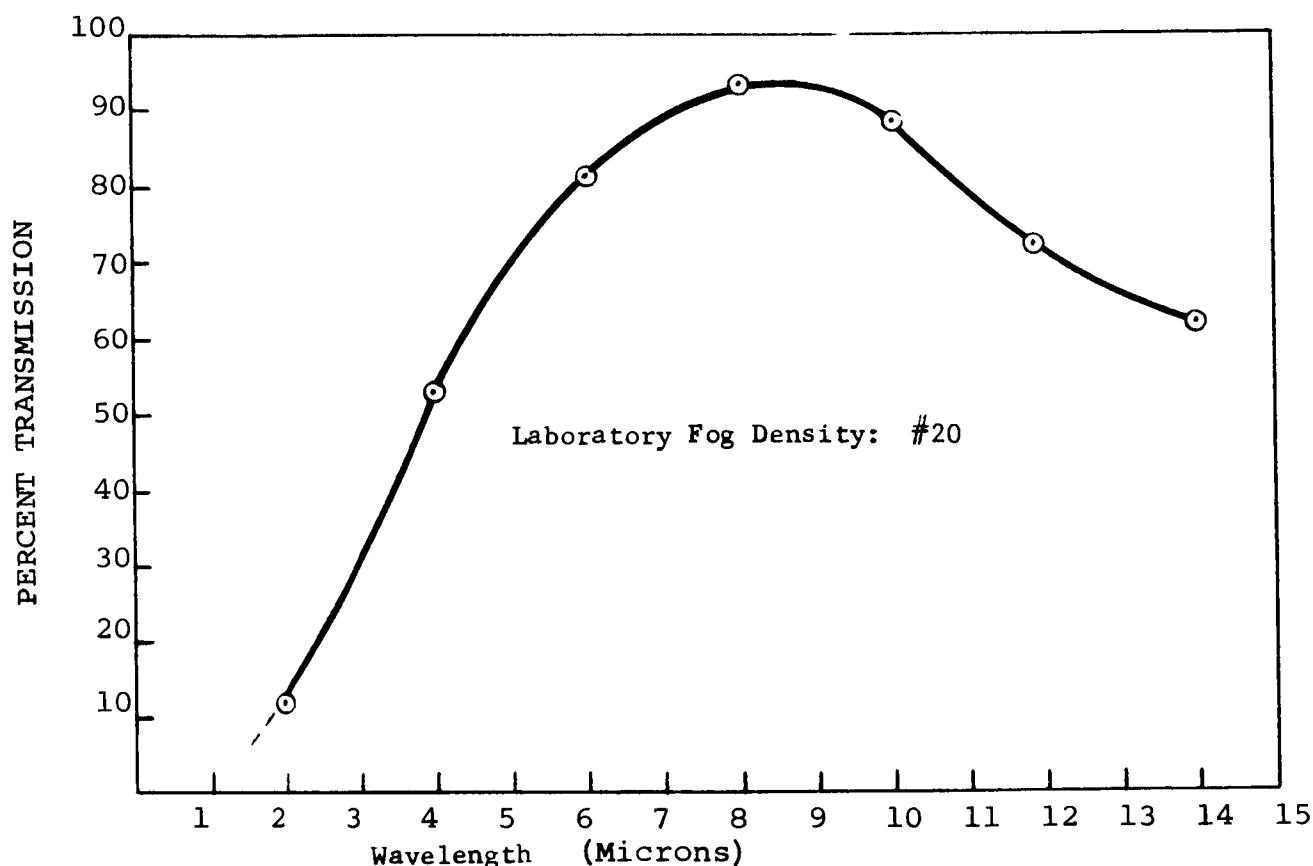


Figure 137 . Laser Light Transmission Measured Through Fog

This experiment is deleted from the 2-meter OTES because of the low orbit condition. In order to effectively conduct this space experiment, an Earth laser beacon must be tracked and, in turn, an Earth receiver must measure the attenuation of a spaceborne laser. Further details of this experiment can be found in Report 8500 starting on page I-140.

This experiment is important to that part of optical technology concerned with laser communication. Experiment No. 22 remains a recommended flight experiment for a synchronous orbit payload such as the 1/2 Meter Laser Communication Satellite Experiment (LCSE).

EXPERIMENT NO. 23 - ONE-MEGABIT LASER COMMUNICATIONS EXPERIMENT
 (Deleted from the 2-Meter OTES)

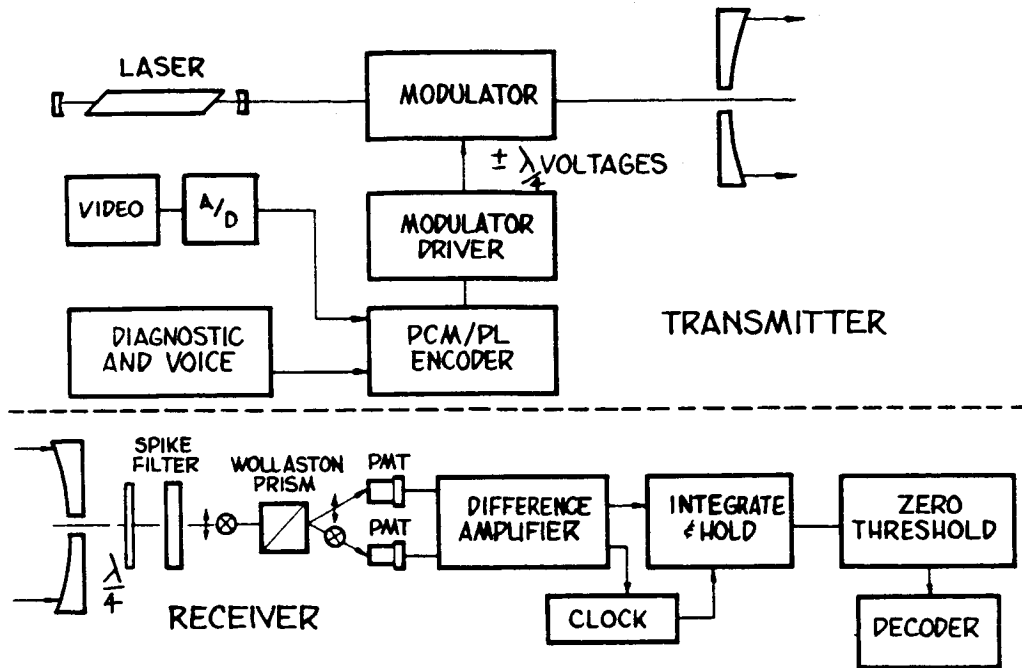


Figure 138

EXPERIMENT OBJECTIVE

This experiment proposes to gather the experimental data necessary to establish the feasibility of interplanetary megabit optical communications. Since the free space loss of a Mars-to-Earth communication link is 74 db greater than the 22000 mile path, the power requirements of the experiment system can be significantly smaller than the requirements for future interplanetary links. However, all the requirements for acquisition, tracking, encoding and decoding, operation of laser and modulator, and reliability can be adequately simulated and tested. The data to be transmitted would consist of digitized TV and telemetry from the spacecraft diagnostics equipment as shown in Figure 138.

This experiment, which requires a synchronous orbit vehicle, will develop the engineering and scientific data needed to design future deep-space optical communication systems that can operate with a channel capacity in the vicinity of one megabit/second. Since the 2-meter OTES flight is based on a 260 n.m. orbit, the experiment must be accomplished on the 1/2 Meter Laser Communications Satellite configuration or equivalent. Refer to Report 8500 page I-145 for additional details.

EXPERIMENT NO. 24 - ROTATION ABOUT THE LINE OF SIGHT (RLOS)
(Deleted from the 2-Meter OTES)

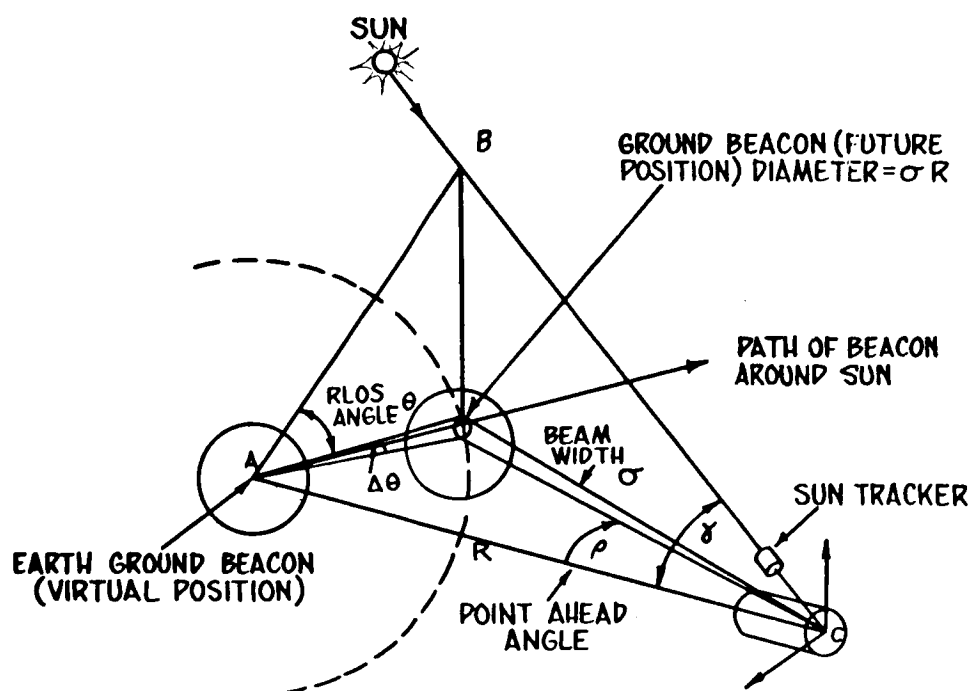


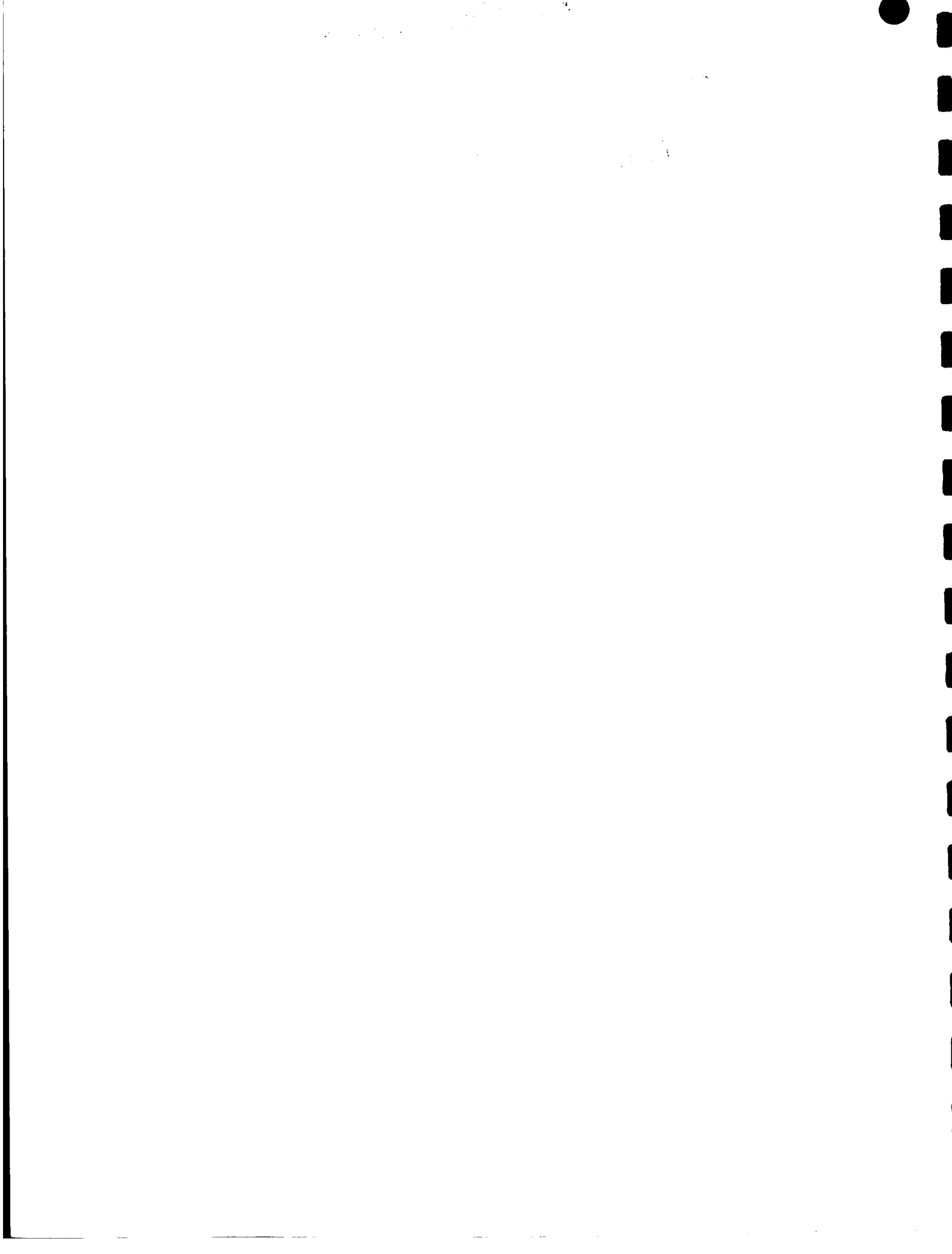
Figure 139

EXPERIMENT OBJECTIVE

There is a requirement to provide a rotational reference about the line of sight (RLOS) for the transmitting optics of an optical communications system on a spacecraft located in space. One experiment objective is to evaluate on the OTES an optimal RLOS technique for a megabit optical communication system operating at 10^8 miles. The RLOS technique assumed for deep-space employs an auxiliary onboard sun tracker working in conjunction with the vehicle telescope viewing the Earth laser beacon.

A second experiment objective is to investigate RLOS techniques which are feasible for Earth satellite applications. For example, the intersatellite communication link will require an RLOS technique.

The RLOS experiment is required for any space optical communication link which has the point-ahead capability. It is recommended for the 1/2-Meter Laser Communication Satellite Experiments in a space flight operating at a 24-hour orbit. See Report 8500, p. I-155 for additional details.



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EXPERIMENT NO. 25 - TRACKING TRANSFER EXPERIMENTS
(Deleted from the 2-Meter OTES)

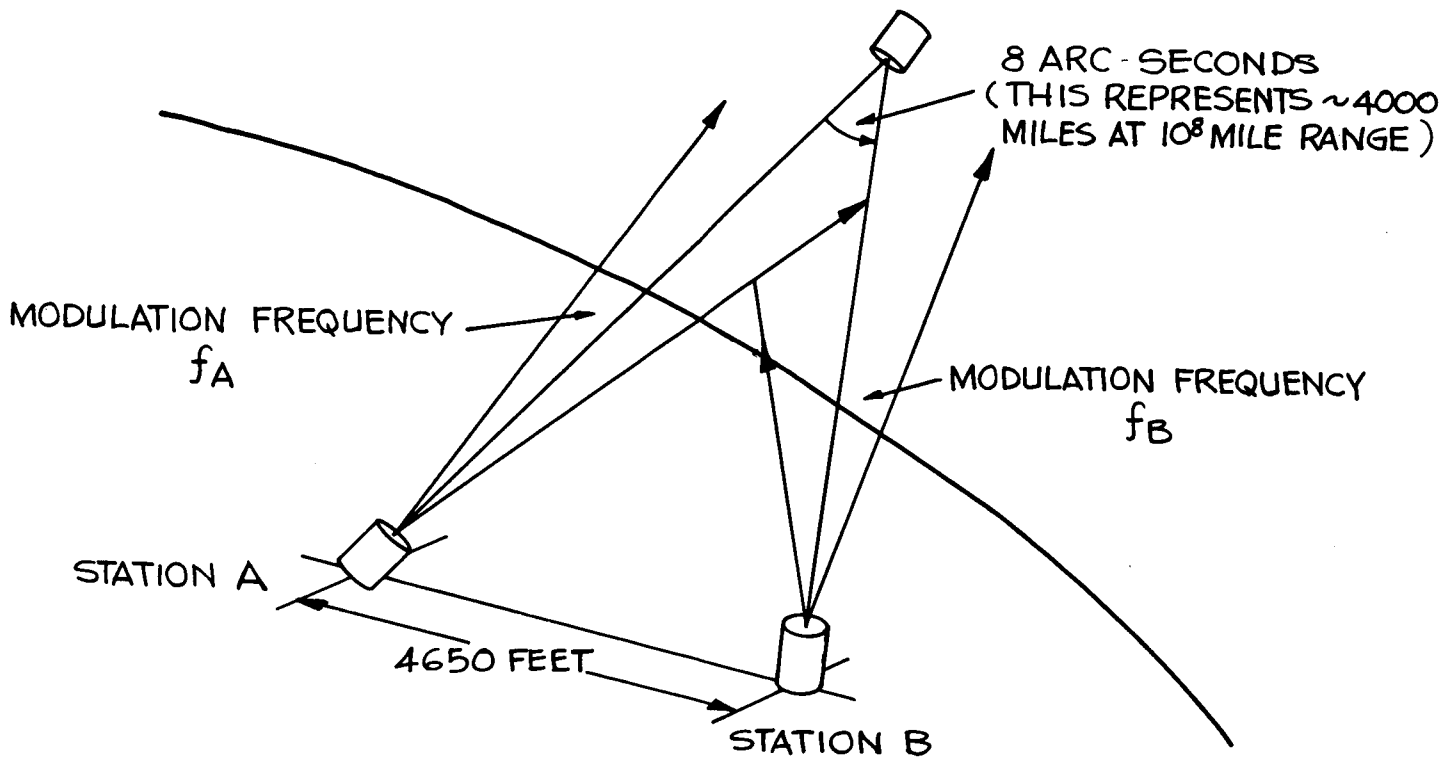
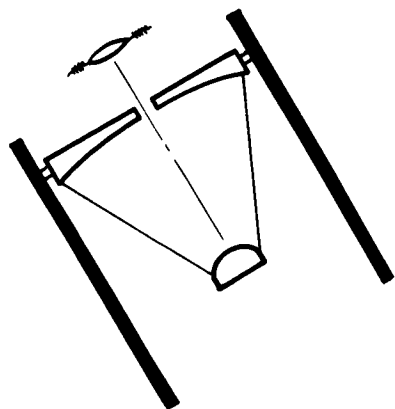


Figure 140

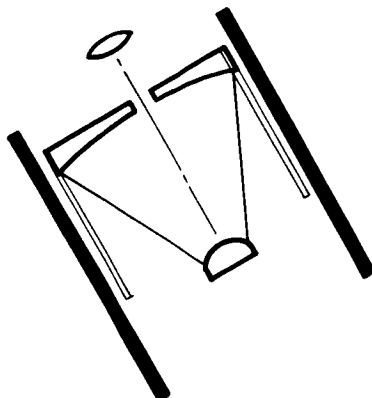
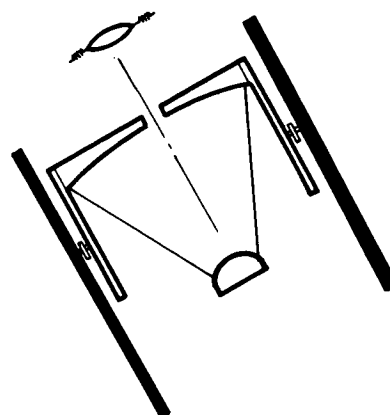
EXPERIMENT OBJECTIVE

Following the period of time during which the satellite has been tracking Station A, the optical communication link must be shifted to Station B (an angular displacement of some known number of arc-seconds). This procedure will simulate the condition in deep space when the vehicle has locked its receive optical system onto the apparent position of the ground station and is now faced with the problem of transferring communication to a different ground station. It is important that the deep-space optical communication system have the capability of transferring its beam from one station to the next without going through an acquisition operation between each station transfer.

This experiment requires a 24-hour orbit rather than the 260 n.m. orbit of the 2-meter OTES. It is recommended for the Laser Communication Satellite Experiments. For additional details, refer to Report 8500, p. I-160.

EXPERIMENT NO. 26 - POINTING SYSTEM TECHNIQUES

1. BODY POINT & TRANSFER LENS

2. FREE FLOAT SYSTEM
(MAGNETIC TORQUING)3. GIMBAL SUSPENSION
& TRANSFER LENS

GATHER TRACKING DATA WITH AND WITHOUT
KNOWN FORCING DISTURBANCES

Figure 141

EXPERIMENT OBJECTIVE

Fractional arc-second tracking errors due to natural disturbances can be reduced by providing highest isolation against external disturbances, thereby allowing bandwidth minimization. A space telescope for communications or astronomical use will have its line of sight disturbed by extraneous torque inputs. While resorting to higher pointing servo bandwidths can reduce the torque-induced pointing errors, such increase is undesirable in that it enhances the magnitude of pointing errors due to noise, both in signal plus background light, and noise that originates in the control electronics. Since reduction of torque disturbances will result in increased pointing precision, telescope suspension systems which provide greatest isolation from external torques are desirable. The objective of this experiment would be to assess the isolation capabilities of various promising suspension systems by measuring telescope pointing errors when other conditions are maintained essentially constant.

EXPERIMENT JUSTIFICATION

The most promising suspension system for the large telescopes such as the 3-meter OTES or the MOAT is the body point plus all reflective transfer lens technique. This takes advantage of the zero "g" space environment by having the telescope floating free of the cluster during tracking operations. Such an arrangement provides complete isolation from manned vehicle originating torques.

This experiment is an engineering evaluation, in space, of basically different pointing techniques for space telescopes. It also provides experimental evidence on the level of spacecraft disturbing torques which can be tolerated by each of the space telescope pointing techniques. As considered for the OTES, the experimental approach will include the gathering of tracking data from Experiment 9. The performance of each pointing system can be evaluated and the results incorporated in future manned observatory design. There is equipment (such as control moment gyros) aboard the LEM Rack that can introduce motion disturbances in each of the three rotational degrees of freedom.

Figure 142 below shows some calculated disturbances introduced aboard a 100,000 slug-ft² telescope by normal motions of a 200-pound crewman. Figure 142 illustrates that torso or body motions would cause disturbances greater than the large telescope could tolerate. That is, the basic tolerance level is about 0.01 arc-seconds while the torso motions and body motions introduce disturbances in the range of 3.6 to 36 arc-seconds.

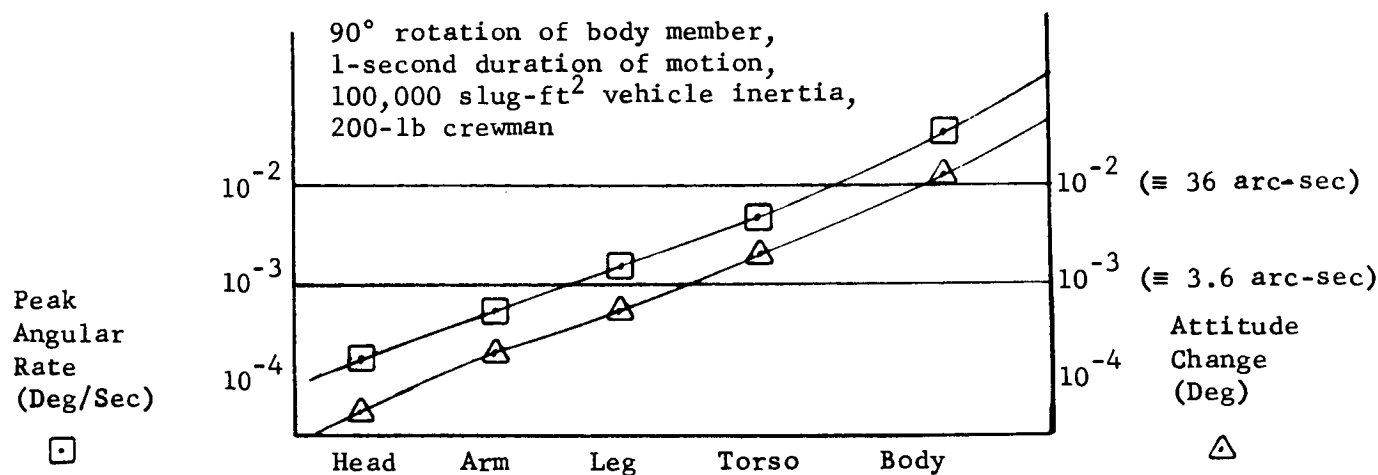


Figure 142 . Vehicle Motion Due to Crew

Thus, it can be seen that some form of fine pointing system control (beyond that provided by the spacecraft attitude control) is required for a large space telescope.

The three pointing techniques in this flight experiment to be evaluated against each other are:

- The body point technique with a transfer lens
- The free float technique using magnetic torquing
- The gimbal suspension with a transfer lens.

The body point technique with a transfer lens is the appropriate approach for the large orbiting telescopes such as the 3-meter OTES, the Manned Orbiting Astronomical Telescope (MOAT), and the Large Orbital Telescope (LOT). The free float technique is considered very appropriate for smaller orbital telescopes such as the 2-meter OTES and, the Advanced Princeton Satellite (1-meter, diffraction-limited aperture). The gimbal suspension with a transfer lens is appropriate for ATM and smaller telescopes. The latter technique is the system used on Stratoscope II, and is the technique which Perkin-Elmer is developing in the VCPS (Vernier Control and Pointing System) for the ATM for MSFC.

The experience Perkin-Elmer has had with the transfer lens in the Stratoscope II and the Laser/Optics Techniques work in NAS 8-20115 is adequate to draw on during the feasibility study work of the current phase of the OTES. However, with respect to the free float technique, the Advanced Princeton Satellite (APS) work is the project that is most advanced.* This space telescope project has been in study, design and breadboard since 1966. The project has an inertia model of the telescope supported by unique air bearing for testing of the free float techniques. This equipment was used by the OTES Project Team at Perkin-Elmer to conduct a laboratory experiment of special interest to the OTES Experiment No. 26.

Laboratory Free Float Pointing System Experiment for OTES

The experiment that was conducted with the APS magnetic suspension pointing system breadboard in support of OTES Experiment No. 26, was the measurement of the magnitude of isolation achievable by a free float telescope in the presence of simulated spacecraft motions. The laboratory layout is shown in Figure 143. The experimental procedure was to physically displace the magnetic pusher over large distances (equivalent to spacecraft motion) and measure the resulting displacement of the breadboard axis. The magnetic pusher magnet was moved over distances which were variable to a maximum of 1.0 inches and at a rate of 0.38 inches/second. The results were measured with an autocollimator and the disturbances resulting from these tests were noted to be less than the resolution limit of the autocollimator (this is about 0.2 to 0.5 arc-seconds). While the tests are really incomplete without going down to measurements in the vicinity of 0.01 arc seconds or less, the magnitude and rate of the disturbances induced into the equipment are unusually high.

* Perkin-Elmer Report 8688, Section 5 contains a full technical report on the Free Float system, its design, construction and test results.

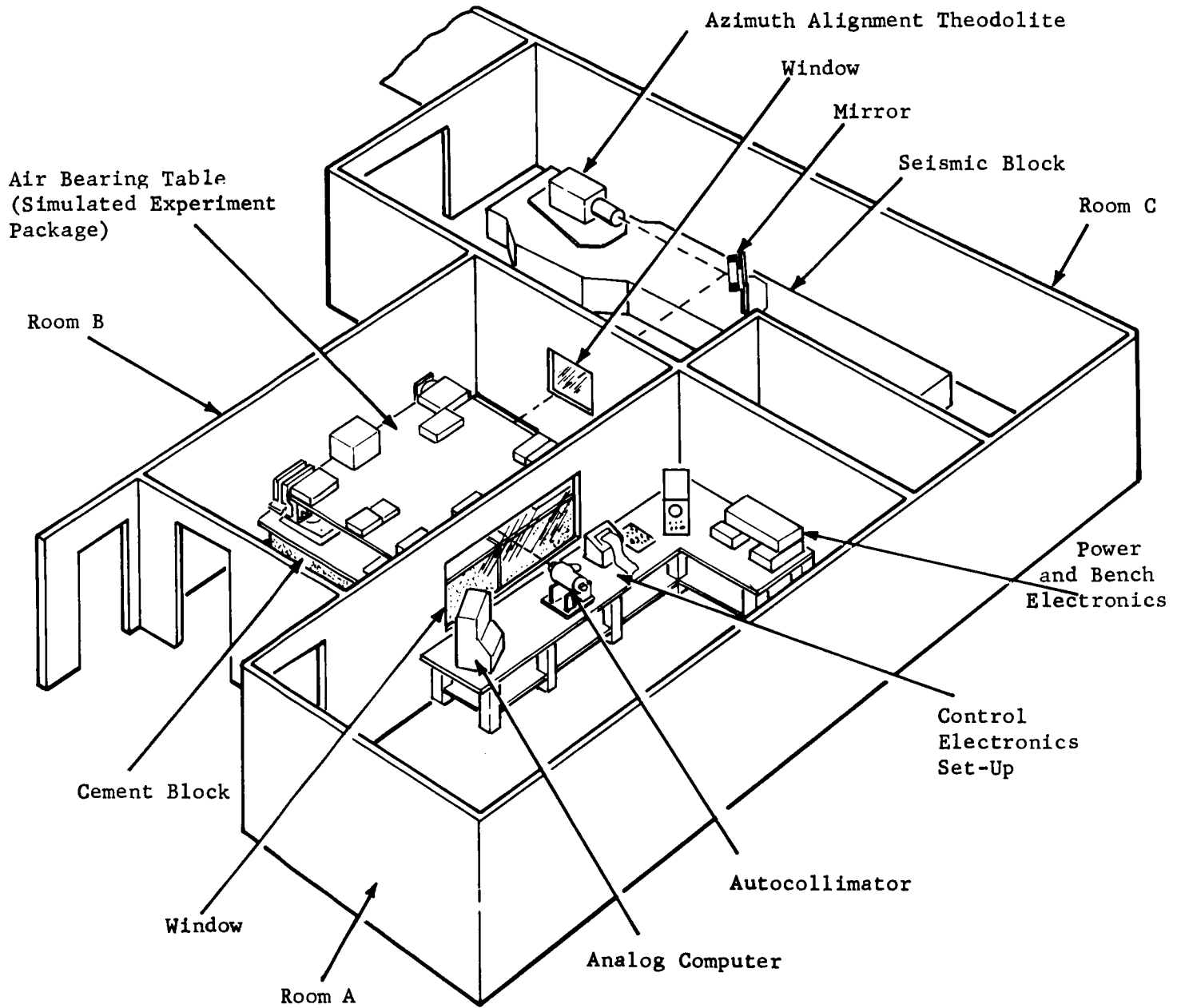


Figure 143. Laboratory Layout

One of the main features of the APS system is that its experiment package is physically disconnected during operation from the outer spacecraft which in this case is the OAO spacecraft. Although the experiment package pointing control system uses the OAO spacecraft as an inertial torquing reference to achieve its pointing control, it is not in turn subjected to the disturbances created by the motions of the spacecraft.

One of the special components used in the APS system to achieve control is a magnetic "pusher" which is similar in principle to solenoids on loud speaker coils. This unit consists of a permanent magnet with an "air gap" that contains a coil where the permanent magnet is located on the outer spacecraft and the coil is attached to the experiment package. In operation, an electrical signal (current) is derived from the experiment package angular displacement sensors and fed to the coils which in turn set up magnetic repulsion or reaction forces in the pusher which effectively "push" against the spacecraft to control fine pointing.

In this OTES laboratory experiment, one of the permanent magnets (See Figures 144 and 145) of the APS breadboard was mechanized to allow it to travel "in and out" with respect to its coil mounted on the simulated experiment package. The pointing system was activated, placed into its final operating or pointing control mode and the pusher was commanded to move to a specific position at a fixed linear slewing rate. In each case the magnet was allowed to return to its original position and the experiment was rerun for a different magnet position.

At the present time, neither the APS Project nor the OTES Project have adequate funds to make the measurements in the 1/100 arc-second region. The measurements could be made only by placing the entire breadboard into a vacuum tank and using a very precise instrument in the vacuum tank to note the angular disturbances resulting from simulated spacecraft motions.

Before a flight project is committed to this free float concept, the vacuum tank tests should be conducted. This work is recommended to NASA in Chapter 1 of this report.

JUSTIFICATION SUMMARY

One of the most important aspects of the 2-meter OTES flight is that the data gathered can be used to evaluate the ability of the space telescope to point with adequate precision in the 260 n.m. orbit. As previously shown in this report, the disturbances due to earth anomalies, magnetic field, and air drag are several orders of magnitude higher than the disturbances that take place at the synchronous orbit. Thus, there is a conflicting set of conditions for the future large orbiting telescopes:

- High Orbit - with advantages of low disturbances but with potential disadvantages of daylight operations only.
- Low Orbit - with advantages of night time operations, but with potential disadvantages of excessive input disturbances to the pointing system.

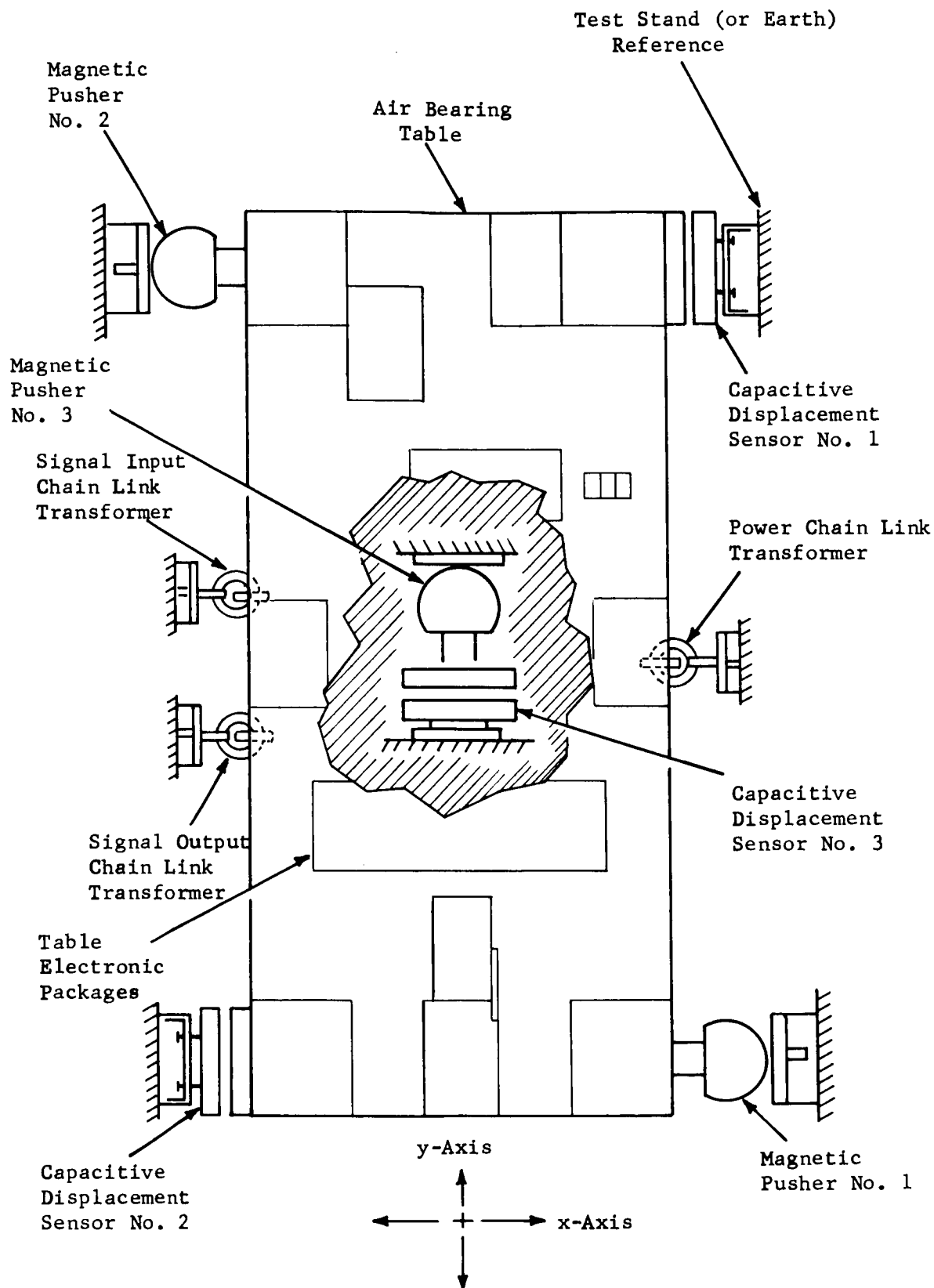


Figure 144. Pointing System Experimental Setup

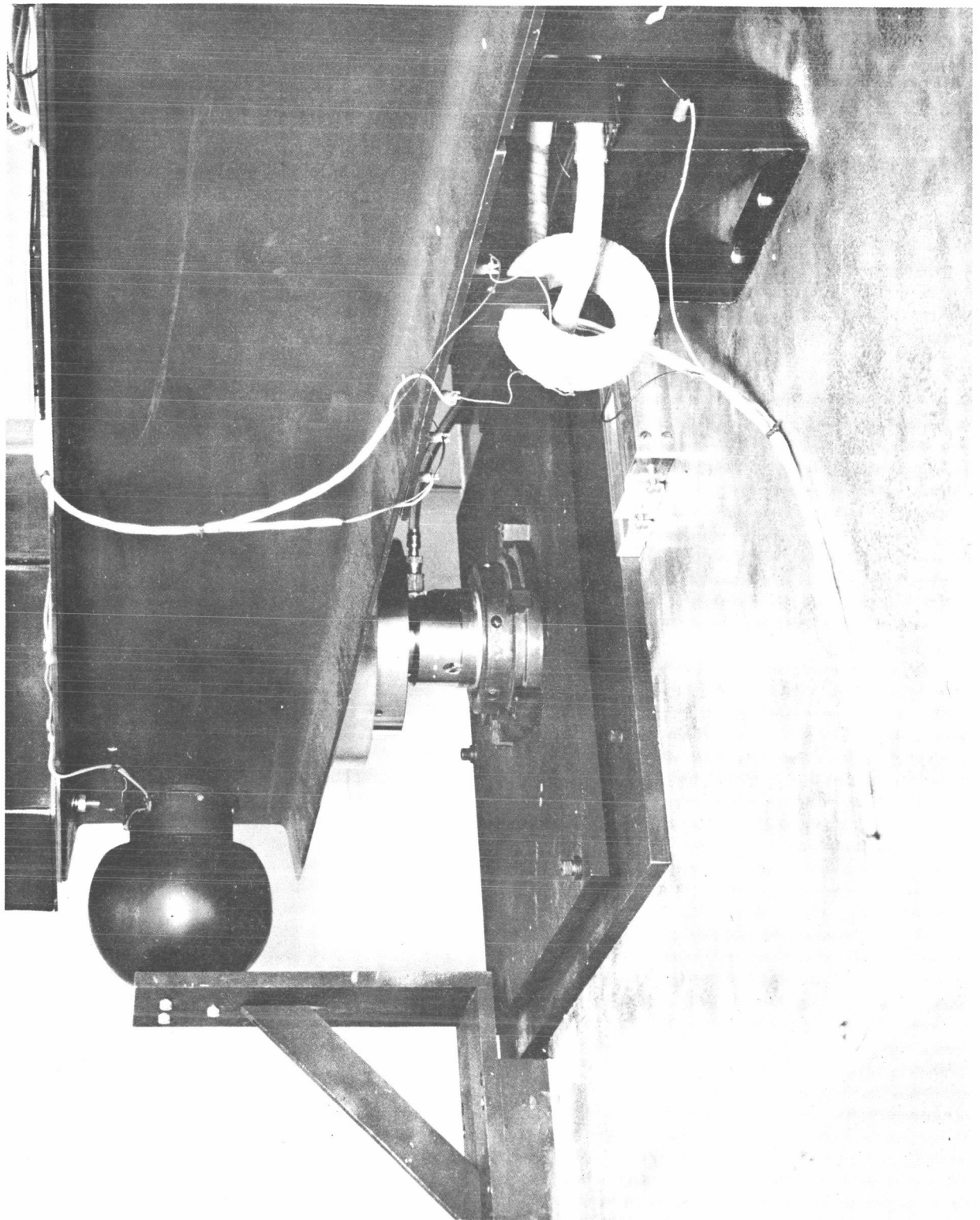
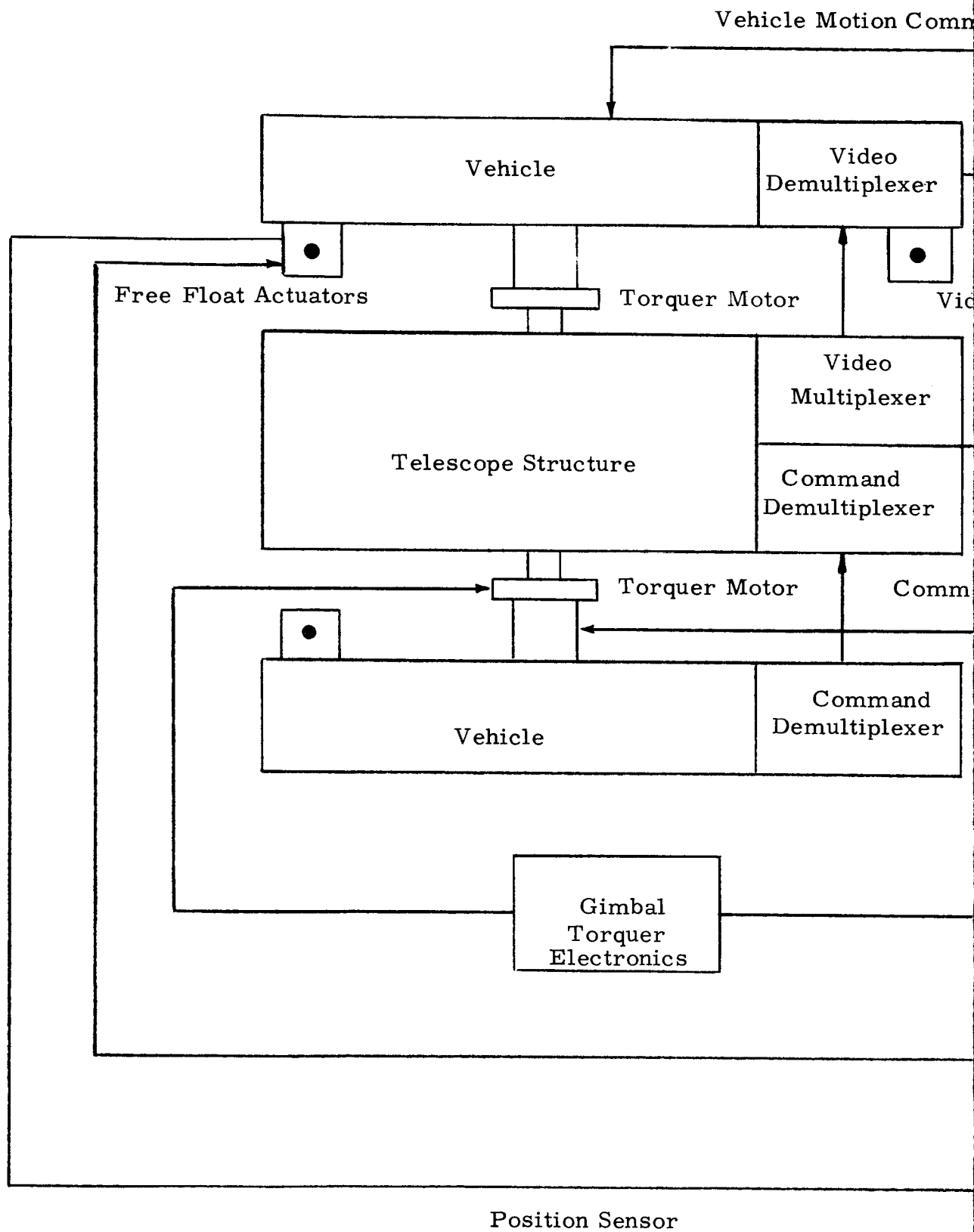


Figure 145. Free Float Pointing System

The proposed Experiment No. 26 will provide information and answers which, in turn, will guide NASA personnel in their decisions on orbital altitude for the 3-meter OTES and/or MOAT.

EXPERIMENT PROCEDURE

The three types of suspension systems to be compared in this experiment are the body point mode, gimbals and torquer motor mode, and the free float mode. The body point mode is used in conjunction with a movable transfer lens to achieve fine tracking when the torquer motors are locked and the telescope is rigidly caged to the vehicle. The gimbal mode uses the torquer motors to provide coarse guidance and a transfer lens for the fine guidance system. The free float mode occurs when the telescope is disconnected from the vehicle structure and utilizes an active magnetic control system to provide fine pointing. See Figure 146. Refer back to Experiment No. 9 for additional details.



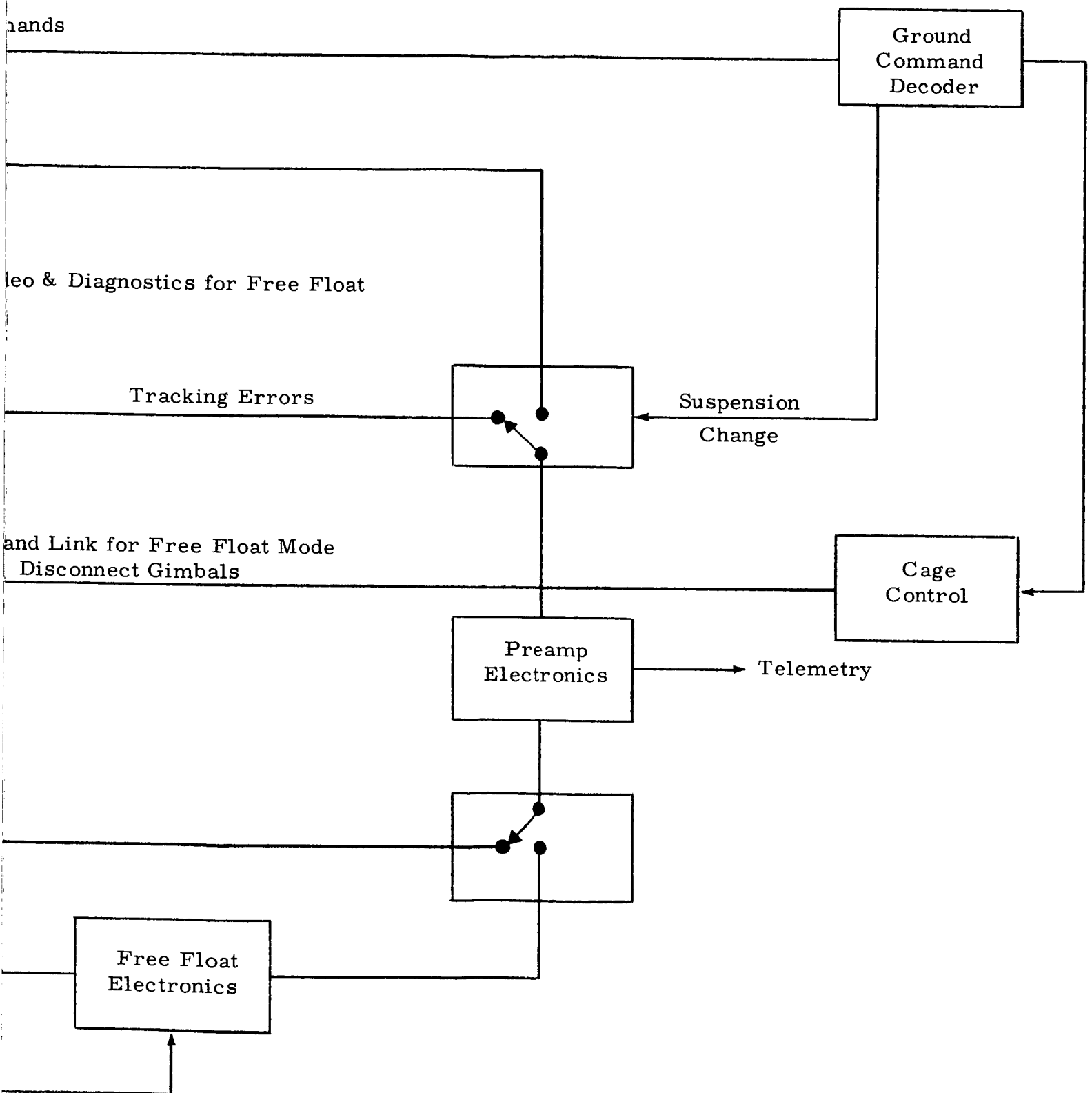


Figure 146. . . Pointing System Techniques, Block Diagram

EXPERIMENT NO. 27 - SPACE-TO-GROUND-TO-SPACE LOOP CLOSURE
 (Deleted from the 2-Meter OTES)

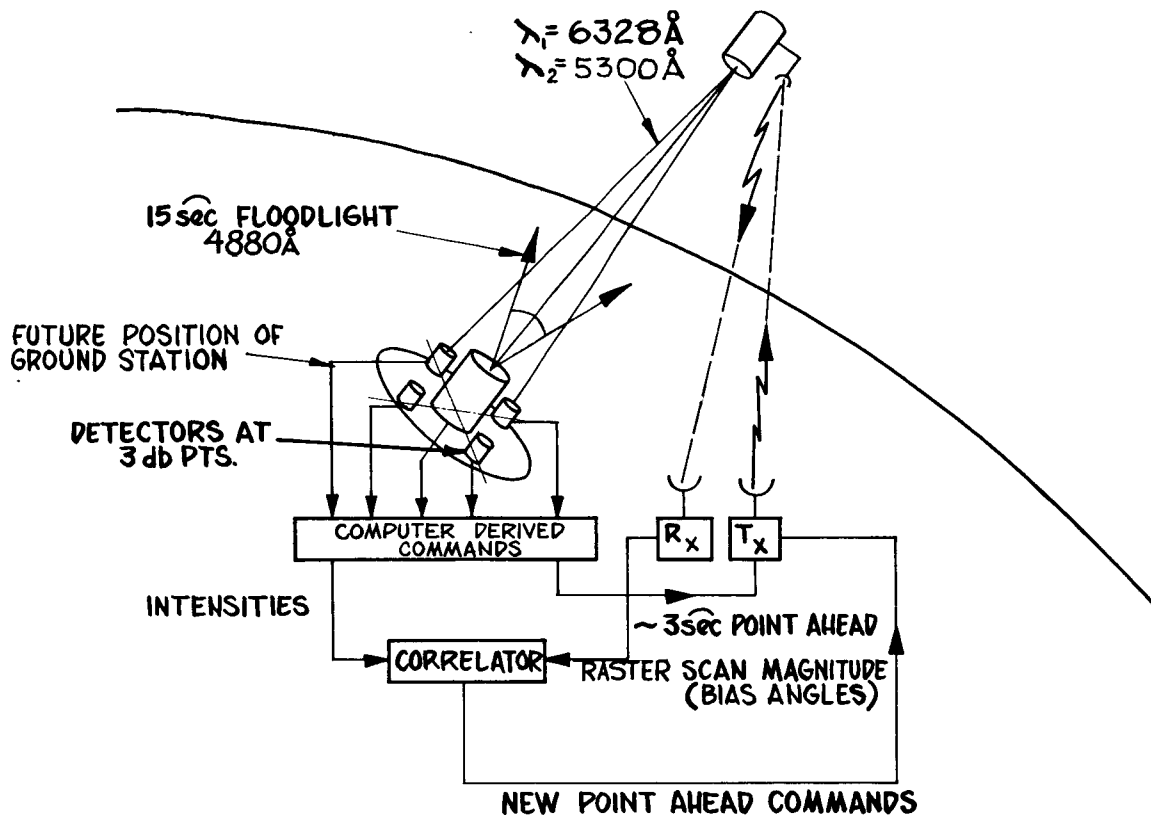


Figure 147

EXPERIMENT OBJECTIVE

Whenever pointing performance (to a precision of 1/10 arc-second down to 1/100 arc-second) of a space optical telescope is considered, the question of verification of performance is raised. In a synchronous orbit optical communication experiment system, the verification is obtained by using the illustrated technique. This experiment is an instrumentation procedure that can be used to calibrate the accuracy of space-transmitting beam control loops. The objective of the experiment is to develop the effectiveness of this instrumentation loop. The utility of the loop at longer ranges (with corresponding increases in the transport lag of the photons between Earth and the spacecraft) will decrease. At synchronous altitude, transport delays of 0.2-second round trip can be accommodated.

This experiment can not be conducted at the 260 n.m. orbit of the 2-meter OTES. The spacecraft is in the line of sight of the ground station for less than 4 minutes and the angular rates between the laser beam and the space telescope are impractically high. The experiment remains recommended for a synchronous orbit flight. Further details can be found in Report 8500 starting on page I-164.

EXPERIMENT NO. 28 - ATMOSPHERIC SCINTILLATION AND IMAGE JITTER EXPERIMENT
(Deleted from the 2-Meter OTES)

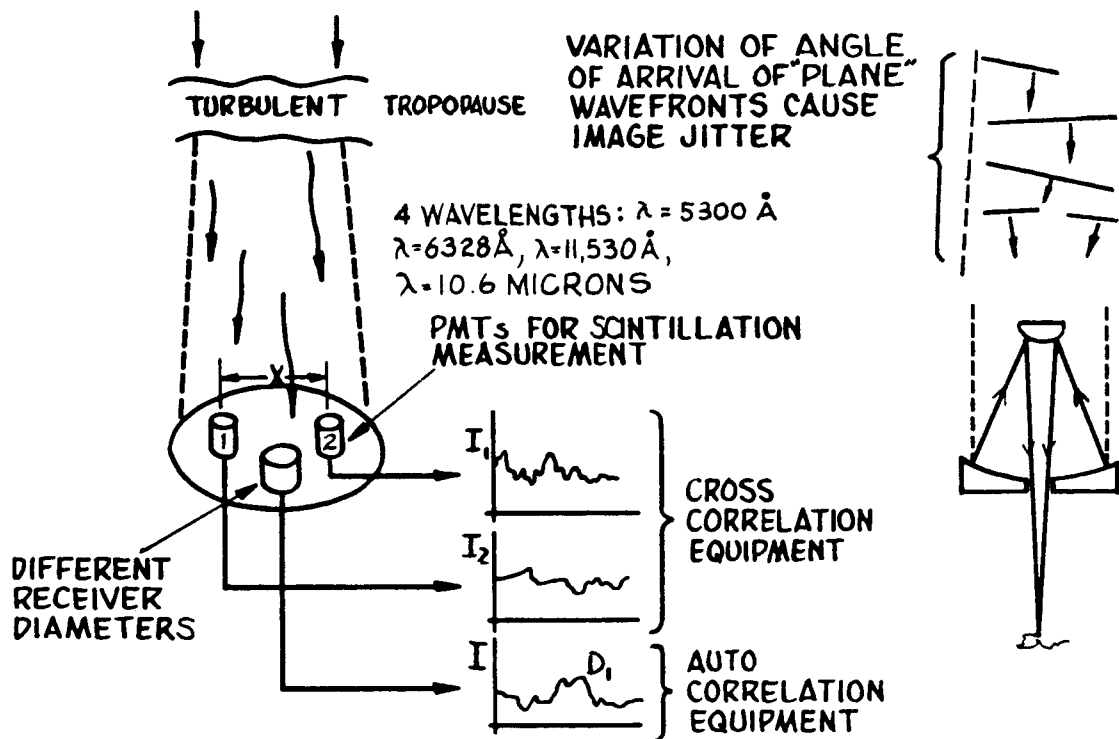


Figure 148

EXPERIMENT OBJECTIVE

The experiment objective is the measurement of fluctuations of light intensity and image jitter from a coherent source (after passage through the entire atmosphere). This experiment should be conducted for up and down transmission of coherent light between the spacecraft and Earth. These intensity and image fluctuations will be correlated with measurements of intensity and image fluctuations of starlight. This should be done for several small receiver aperture sizes, for at least two laser wavelengths, for day and night operation, for several zenith angles, and for various meteorological conditions. In addition, there should be determination of the auto- and cross-correlations and power spectral densities of the intensity and image jitter fluctuations. This information should be correlated with the outputs of a meteorological data collection system.

This experiment is recommended for a synchronous orbit vehicle; however, it cannot be executed in the low orbit 2-meter OTES. Additional information is published in Report 8500 starting on page I-168.

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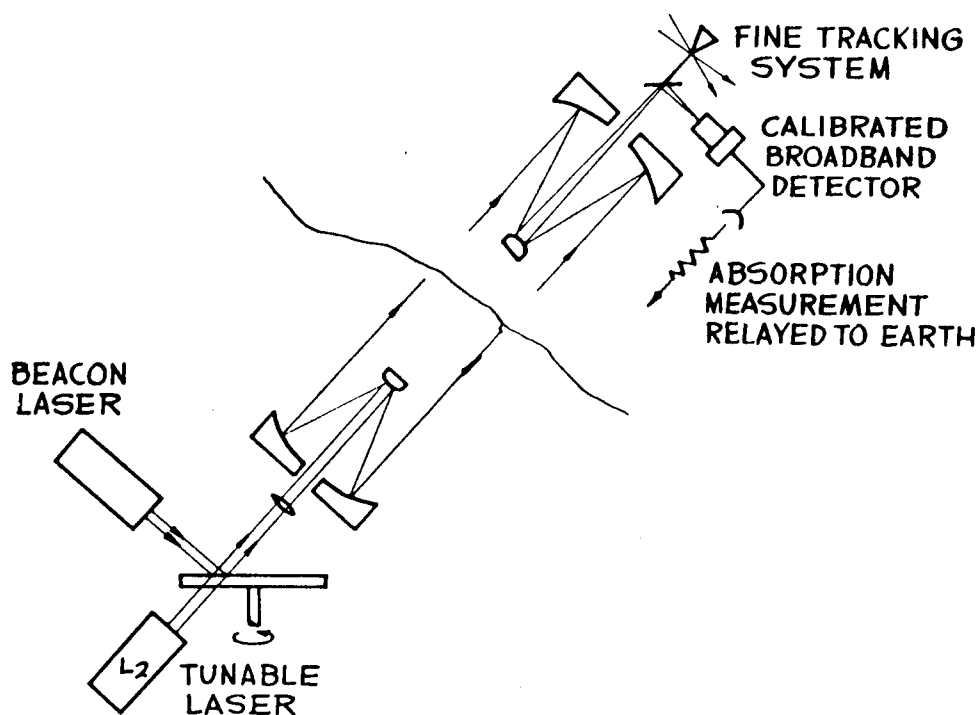
EXPERIMENT NO. 29 - HIGH-RESOLUTION ATMOSPHERIC ABSORPTION MEASUREMENT

Figure 149

EXPERIMENT OBJECTIVE

A sketch of the laser spectroscopy experiment is shown in Figure 149. The rotating reflective chopper time multiplexes the argon beacon with the output from a continuously tunable laser. The argon beacon is used as the reference in determining the absolute absorption of the tunable laser radiation. Tunable lasers are being developed, which utilize parametric oscillation in LiNbO_3 and operate over sufficient ranges with very small linewidths.

A tunable laser on the Earth could be used for the atmospheric absorption measurements. Since the power output of this device is low, a large aperture collector will be required on the orbiting vehicle such as the OTES. Thus, the large astronomical telescope could be used as the receiver aperture. By continuously tuning the device over the spectrum, a high-resolution absorption profile of the atmosphere is obtained. There is no other technique known for collecting this high-resolution absorption data of the full atmosphere.

EXPERIMENT JUSTIFICATION

When continuously tunable lasers with narrow and stable emission linewidths are developed in the future, the fine structure of atmospheric absorption at all visible and near infrared regions may be obtained. Thus, absorption measurements of great accuracy and resolution may be obtained.

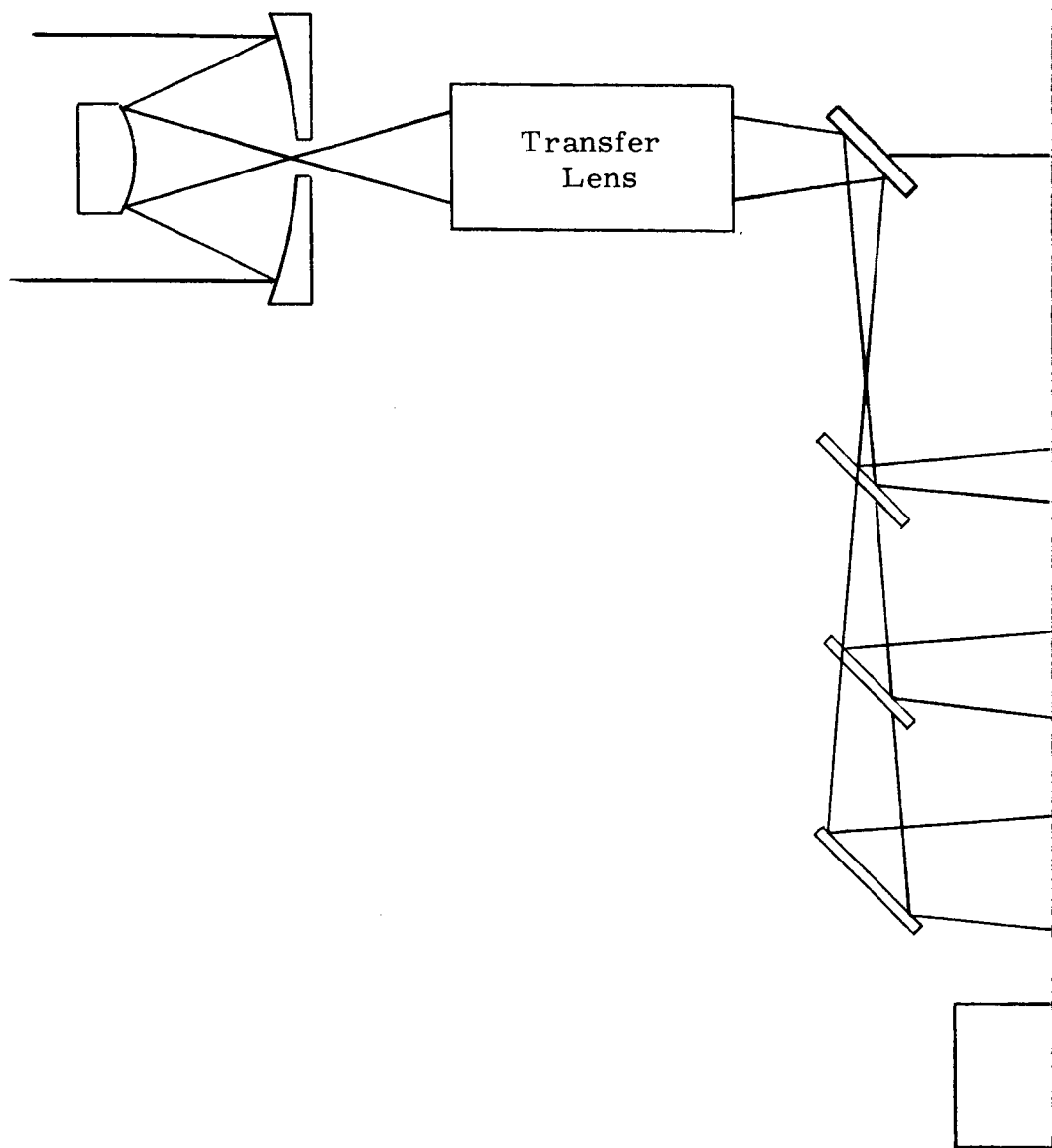
The continuously tunable laser used in conjunction with OTES will also allow examination of the dependence of atmospheric absorption on the wavelength. Thus, the validity of the mathematical models for the atmosphere may be tested.

The data collected from the proposed experiment will be of benefit to future designers of optical communication systems which have an Earth terminus. In addition, the astronomers who are using telescopes on Earth and making observations and measurements by looking through the atmosphere, will receive atmospheric absorption data with higher wavelength resolution than that obtained by looking at the sun or stars. Numerous scientific parties and expeditions have been formed, even in recent years, to gather this absorption data. The proposed experiment will supplement these efforts by providing data that could not be obtained by classical methods before the invention of the laser with its high energy-content-per-wavelength interval.

The inversion of the experiment (that is, locating the tunable laser in space and looking upward) does not seem feasible at this time since the tunable laser will be most complex piece of scientific equipment. Also, the development of the laser is still beyond the state of the art even though various organizations (Perkin-Elmer and Bell Laboratories) are conducting research on this technology today. Thus, it would be unwise to commit a space vehicle with its attendant schedule requirements to lofting this equipment. But, the telescope could be lofted, and when the tunable laser is developed, it could be utilized with the perhaps already orbiting spaceborne equipment.

Tunable lasers achieve a much higher resolution than Fabry-Perot interferometers when used for atmospheric absorption measurements. The equipment aboard the spacecraft shown in Figure 150 includes an array of detectors covering the wavelength regions where tunable lasers are available. The tunable laser output is time multiplexed with the ground argon beacon and the two signals are separated using a spike dichroic filter which transmits the 4880Å ground beacon. The reflected light is separated into the required wavelength regions by a series of dichroic mirrors and is detected by cooled photosensors.

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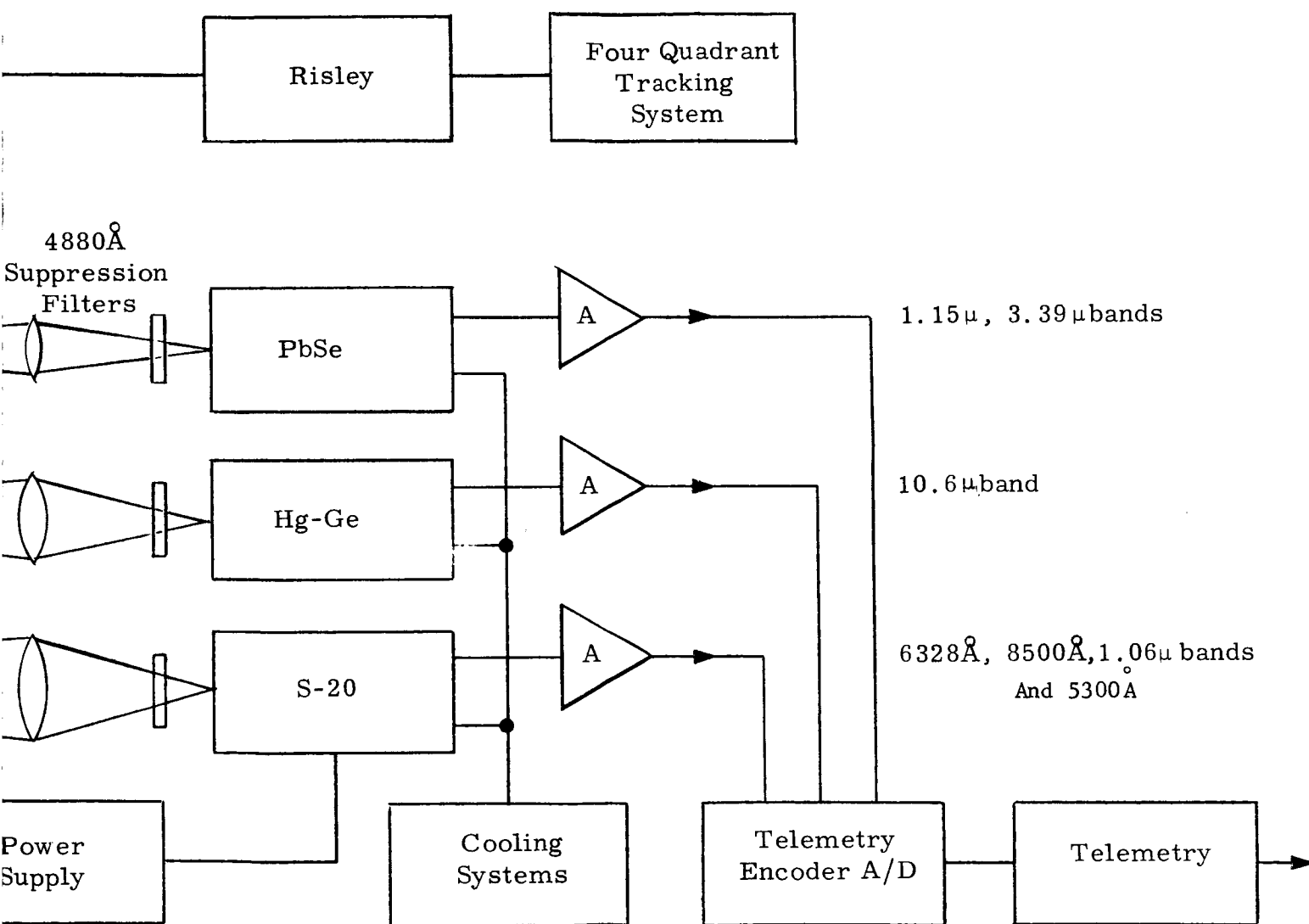


Figure 150. High Resolution Atmospheric Absorption Measurements (Block Diagram)

EXPERIMENT NO. 30 - OPTICAL HETERODYNING ON EARTH
(Deleted from the 2-Meter OTES)

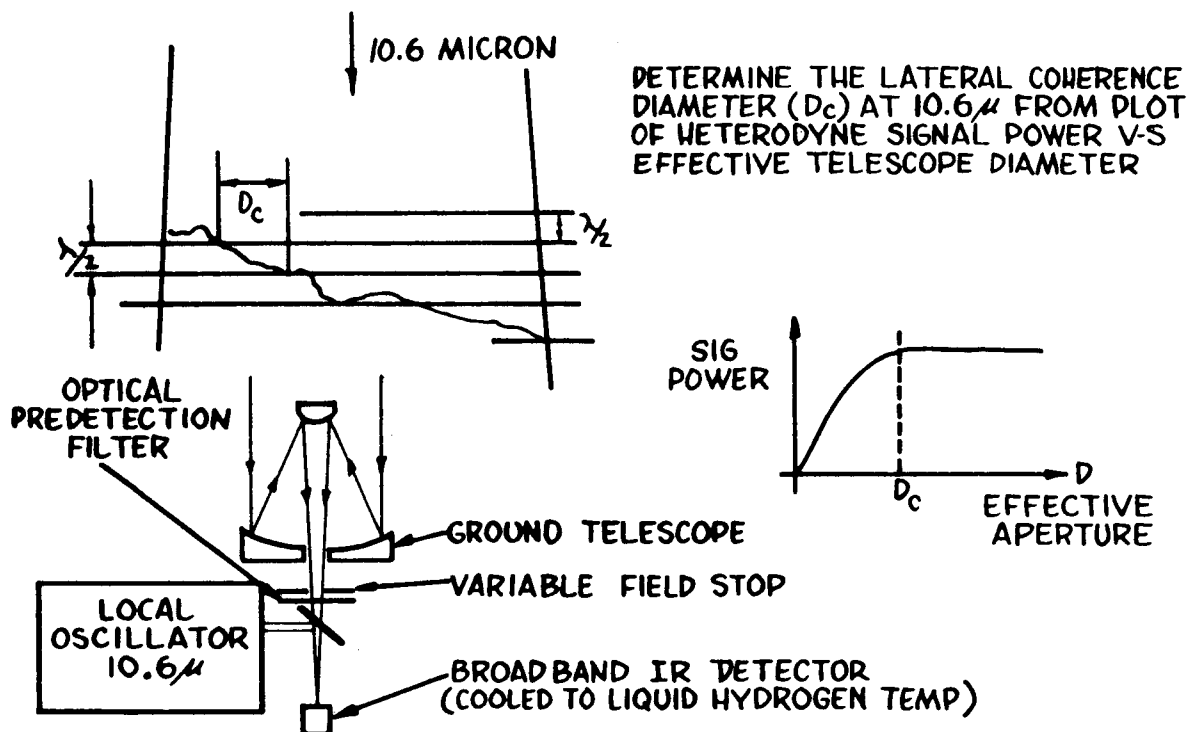


Figure 151

EXPERIMENT OBJECTIVE

The experiment objective is to determine the extent to which atmospheric turbulence affects space-to-Earth optical communications, when the carrier is 10.6 microns and optical heterodyne detection is employed on Earth. Atmospheric turbulence will produce phase fluctuations in the optical signal. These fluctuations are the result of refractive index changes produced mainly by random temperature variations.

This experiment requires a synchronous orbit flight such as the Laser Communication Satellite Experiments. It can not be conducted on the 2-meter OTES at the planned 260 n.m. altitude.

In Report 8500 starting on page I-197, Experiment No. 30 is analysed in considerable detail. The material is not repeated here, but it represents the basis for the conduct of a synchronous optical technology flight.

A basic problem in the use of 10.6 micron laser light for deep-space laser communications was unearthed in the beginning of the present phase of work. Despite the removal of this experiment from the 2-meter OTES, the analysis is so germane to the development of this phase of optical technology, that it is included in this report as part of Chapter 5 starting on page I-474.

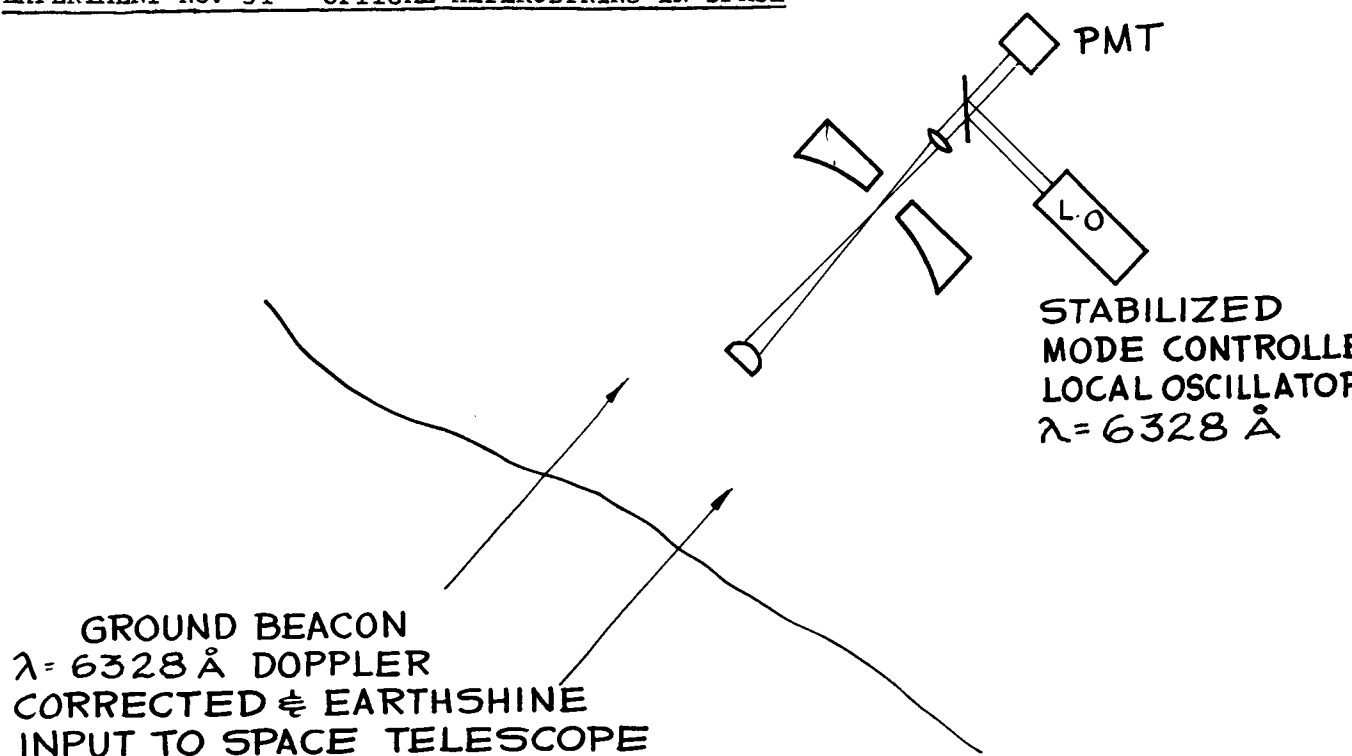
EXPERIMENT NO. 31 - OPTICAL HETERODYNING IN SPACE

Figure 152

EXPERIMENT OBJECTIVE

The objective of this experiment is the development of sufficient engineering experience with the design and operation of a spaceborne optical heterodyne system so that its feasibility, reliability, performance, and cost can be evaluated relative to an alternate intensity detection scheme using predetection filtering. Due to the low Earth orbit of the 2-meter OTES, moderately large Doppler shifts will be developed in the optical carrier. The development of techniques that can accommodate large Doppler shifts will be aided by the conduct of Experiment No. 31.

EXPERIMENT JUSTIFICATION

The advantage of optical heterodyne detection in space appears at present to be substantially outweighed by several disadvantages: the requirement for high-power, frequency-stabilized, and mode-controlled lasers; severe tuning requirement; and the necessity for broadband photodetectors.

Careful examination of the mission parameters for a deep-space planetary orbiter is required before a decision can be made as to whether optical heterodyne detection in space has sufficient advantages over intensity detection to justify the additional equipment complexity. The proposed experiment would provide the flight experience type of data for this technique.

TECHNOLOGY BENEFITS

This experiment would help define the engineering choice between intensity and heterodyne detection. This experiment will also provide data on the effects of the atmosphere on the frequency spectrum of upward propagating coherent light.

BASIC EXPERIMENT HARDWARE

On the Earth

- 6328Å, frequency-stabilized laser*
- Tracking transmitter telescope for laser beacon
- Frequency tuning system
- Optical modulator
- Tracking signature signal generator
- Microwave transmit and receive channel
- Data recorders

On the Spacecraft

- Tracking receiver telescope
- Frequency-stabilized laser local oscillator 6328Å
- Power-and frequency-stabilized microwave reference
- Narrow bandpass filters
- Doppler frequency filters
- Real-time return transmission to Earth

The classical method of heterodyning is shown in the basic block diagram, Figure 153. The wave fronts of the frequency stabilized He-Ne laser and the received signal must be superimposed so that the maximum variation between the two phase fronts is less than $\lambda/2$. The phase front of the light entering the telescope aperture is plane and has no time dependent angle-of-arrival variations. Since the fine tracking subsystem removes the effect of spacecraft perturbations on the telescope optical axis, the argon laser light transmitted by beamsplitter #6 (Figure 154) will suffer no time varying angular errors. By properly orienting beamsplitter #13, the spatial alignment requirements for heterodyning are satisfied.

The laser frequency stability requirements for heterodyning are more difficult to satisfy. The predictable Doppler correction will be done at the Earth beacon. However, the random time variations of the laser output frequency must be compensated for in space.

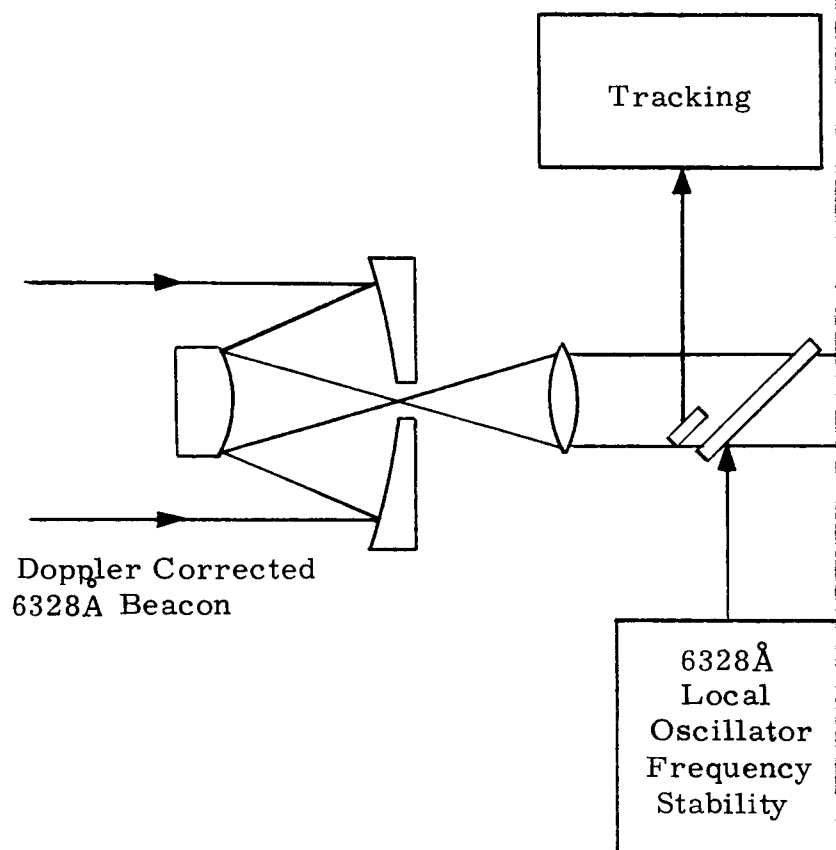
The interface required between heterodyning equipment and the basic hardware is feasible as shown. The large additional power (in excess of 1 kilowatt) for an argon laser has caused Perkin-Elmer to shift to 6328Å for this experiment.

EXPERIMENT DISCUSSION

The experimental procedure that is employed for optical heterodyne detection aboard the satellite consists of tracking the Earth beacon by the tracking

*The results obtained at 6328Å are applicable to the 4880Å band.

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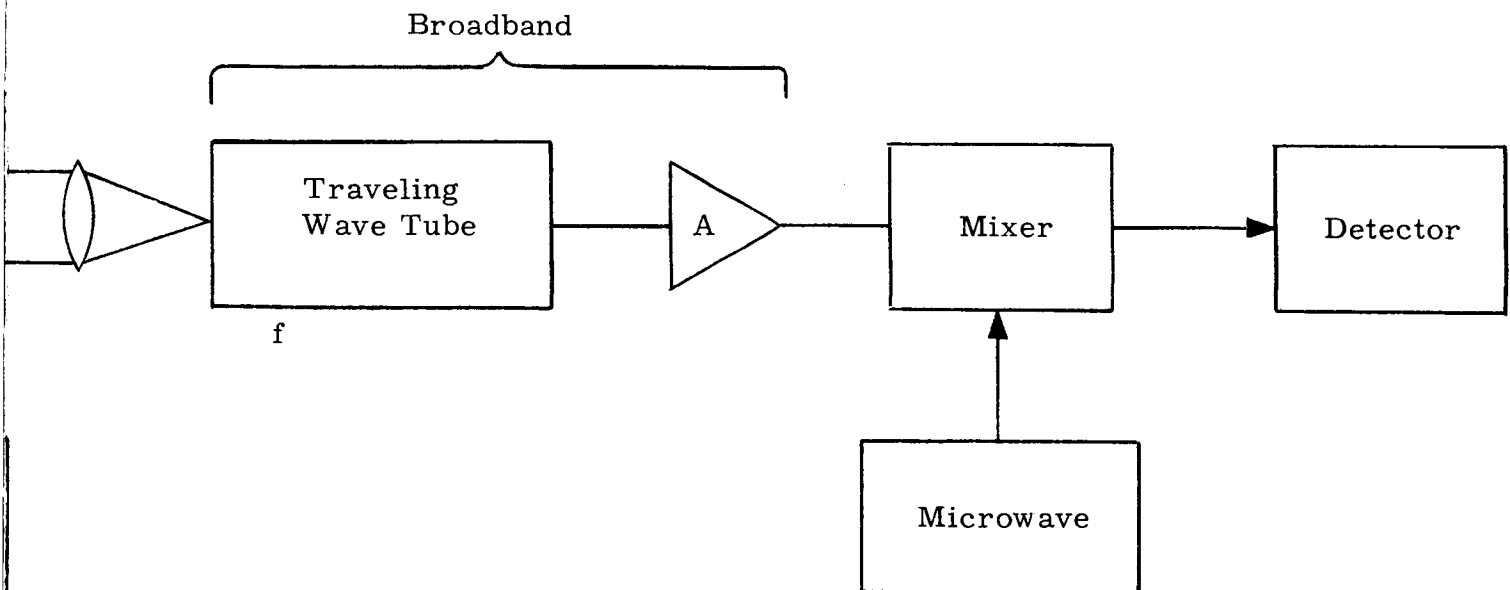
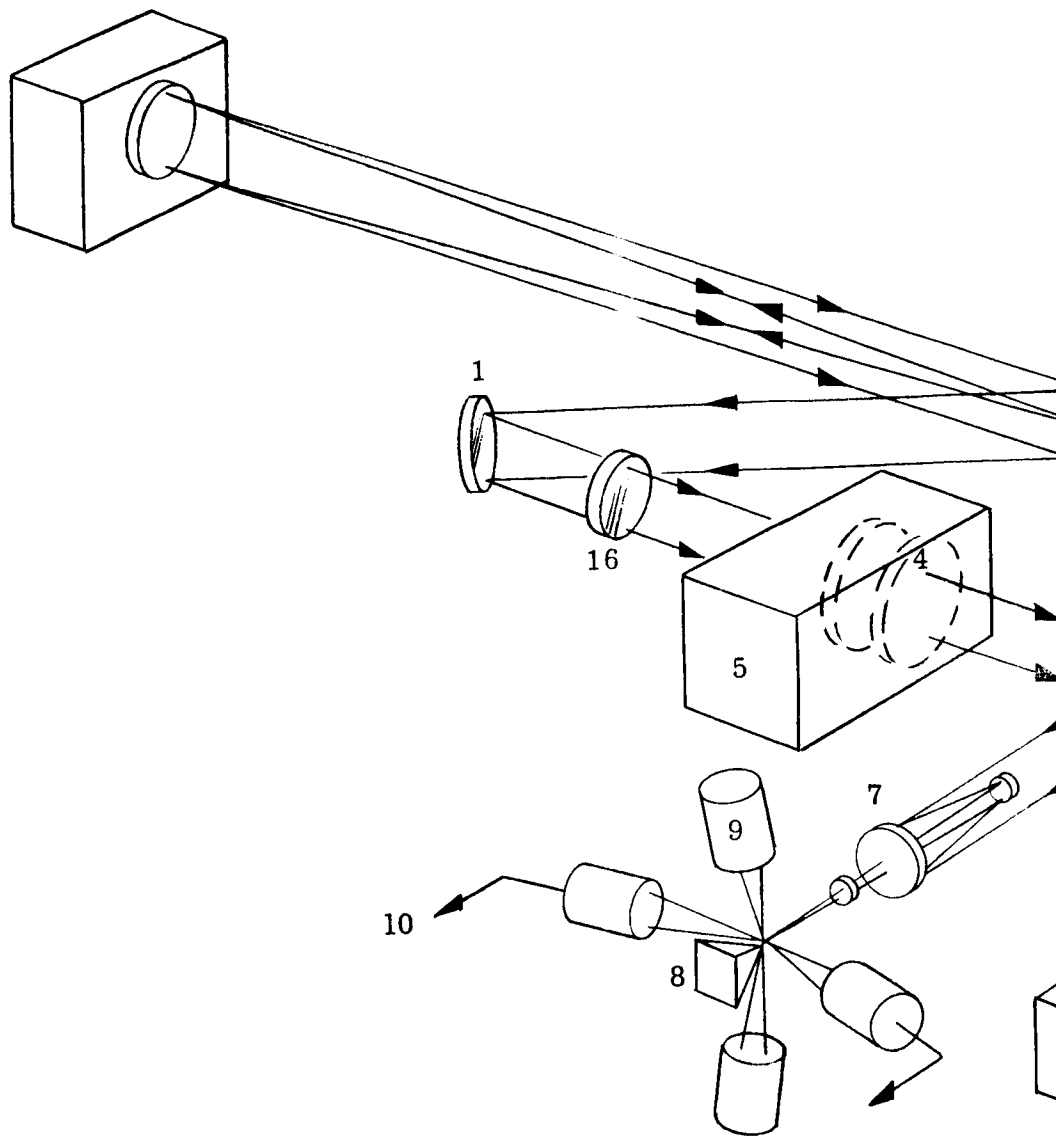
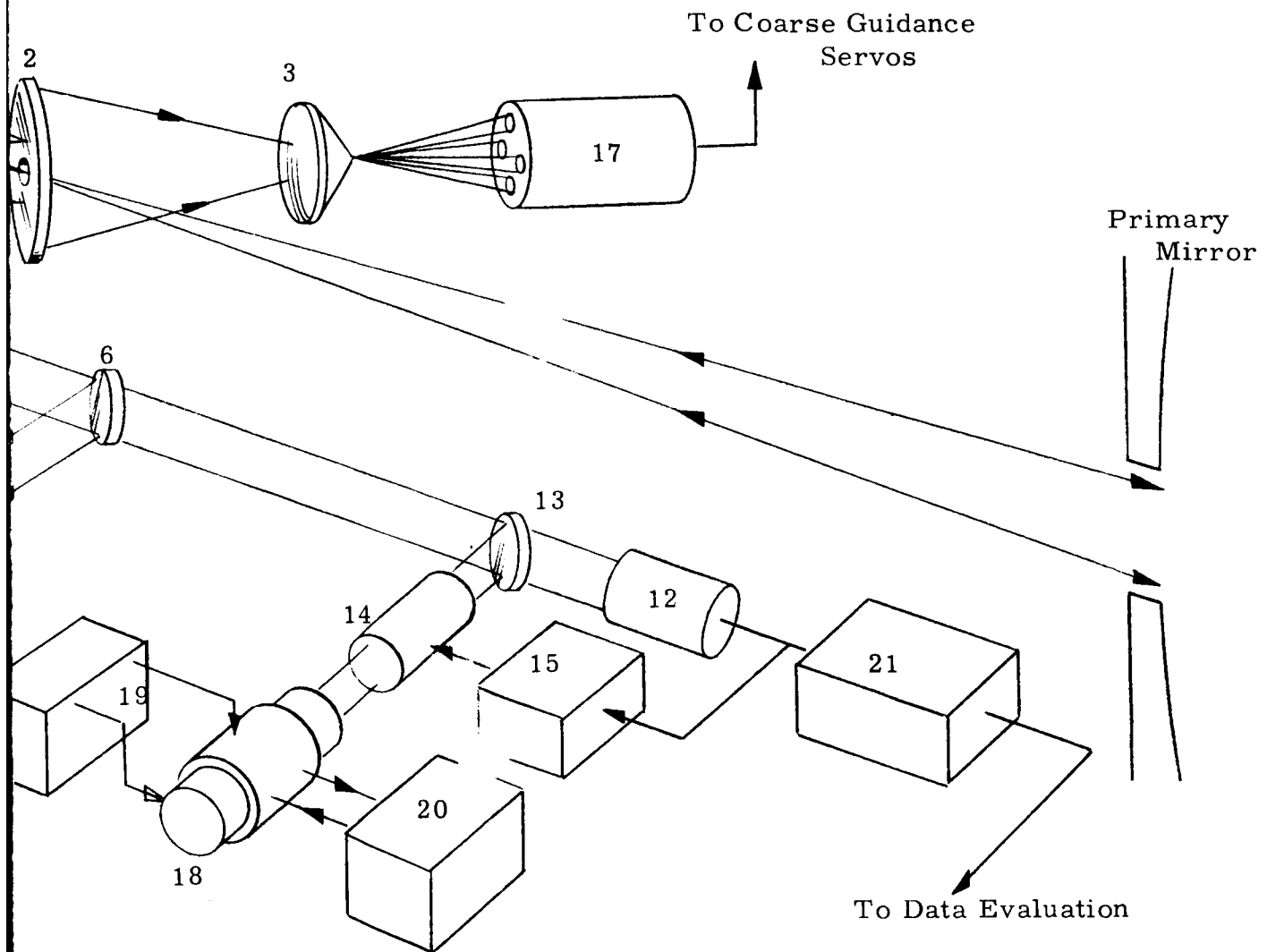


Figure 153. . Basic Block Diagram for Optical Heterodyning in Space



- | | |
|--|------------------------------|
| 1. 6328Å/10.6μ Dichroic | 17. 4 Quadrant Photosensor |
| 2. Reflecting Field Stop | 18. He-Ne Laser |
| 3. Coarse Guidance Field Lens | 19. Power Supply |
| 4. Risley Prism Beam Offset System | 20. IF Frequency Control |
| 5. Risley Prism Drive | 21. Mirror Alignment Control |
| 6. Beamsplitter | |
| 7. Telescope | |
| 8. Fine Tracking Sensor (0.1 arc-sec) | |
| 9. Photomultiplier Tube | |
| 10. Outputs to Fine Tracking Electronics | |
| 11. All Reflecting Transfer Lens | |
| 12. Heterodyne Detector | |
| 13. Beamsplitter | |
| 14. Optical Frequency Control | |
| 15. Control Electronics | |
| 16. 6328Å Spike Filter | |

Figure 154.. Layout of Optical Heterodyning in Space



2-286-2

receiver telescope, and measurement of the signal-to-noise ratio, tracking performance and frequency shifts. These data are encoded for real-time return transmission to the Earth via the microwave telemetry link.

Although it is felt that satellite optical heterodyne detection may be extremely difficult to accomplish, a tentative block diagram of such an experiment is presented to indicate the magnitude of the problem. Refer to Figure 155 for a block diagram of the Earth equipment required for this experiment. A suitable low-frequency tracking signature, as well as the information-bearing signal will modulate the transmitted laser beam and be transmitted through a telescope for satellite reception. In addition, control signals for the microwave tuning requirements at the satellite will be telemetered from Earth to the satellite via the microwave link.

At the satellite receiver (refer to block diagram of Figure 156, a frequency stabilized laser local oscillator will be employed to beat with the incoming signal photons on the detector photocathode and produce a desired beat frequency. The possible large Doppler shift at optical frequencies can present serious problems in the heterodyne system. As the radial component of vehicle velocity changes, the Doppler shift frequency changes, causing a change in difference frequency. In order to accept this change, the I.F. must either be extremely broad or must be rapidly tunable over a broad range. The latter alternative is shown in Figure 156. Both alternatives present serious problems in the present state of the art, since microwave broadband amplifiers are of one octave or less, and narrow-band microwave amplifiers cannot be tuned over more than one octave.

A traveling wave phototube and amplifier combination consisting of a standard TWT with a photocathode is shown as a possible detector candidate having gigacycle capability. Although questionable at the present time, if the traveling wave phototubes can meet the gain requirements of detection of a shot-noise-limited signal, the wide bandwidths of the microwave phototube can afford a reduction in the stiff tolerances on local oscillator and signal frequency stability and also give maximum useful bandwidth for heterodyning. *

A power- and frequency-stabilized microwave reference, oscillator frequency multipliers, and microwave mixer will be required to demodulate the microwave signal. The output of the microwave mixer would then be sent to a bank of bandpass filters covering the Doppler frequency range of interest. Also, the tracking signature would be extracted by a narrow-bandpass filter at this point. The output of the Doppler bins could be sampled and encoded for real-time return transmission to Earth via the microwave link. This data will be recorded and processed on Earth. Control signals from Earth for the satellite frequency multiplier system will be transmitted by the microwave telemetry link.

Bandwidth Considerations

Refer to Figure 157 for a sketch (not to scale) of the bandwidth requirements for satellite heterodyne reception.

* Ross, M.: Optical Receiving Devices. Electro-Technology, April 1964.

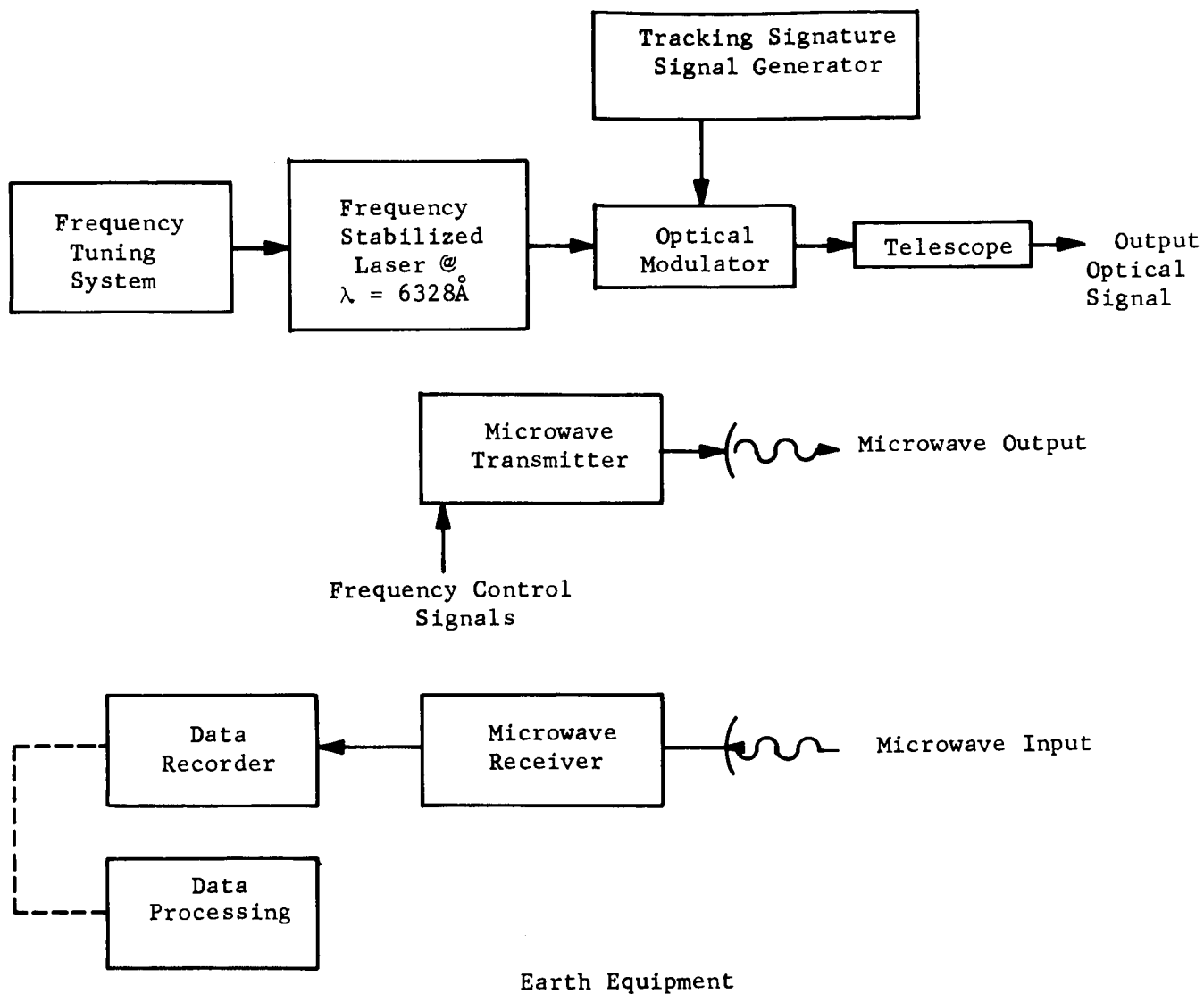


Figure 155. Block Diagram of Earth Equipment Required for Optical Heterodyning in Space Experiment

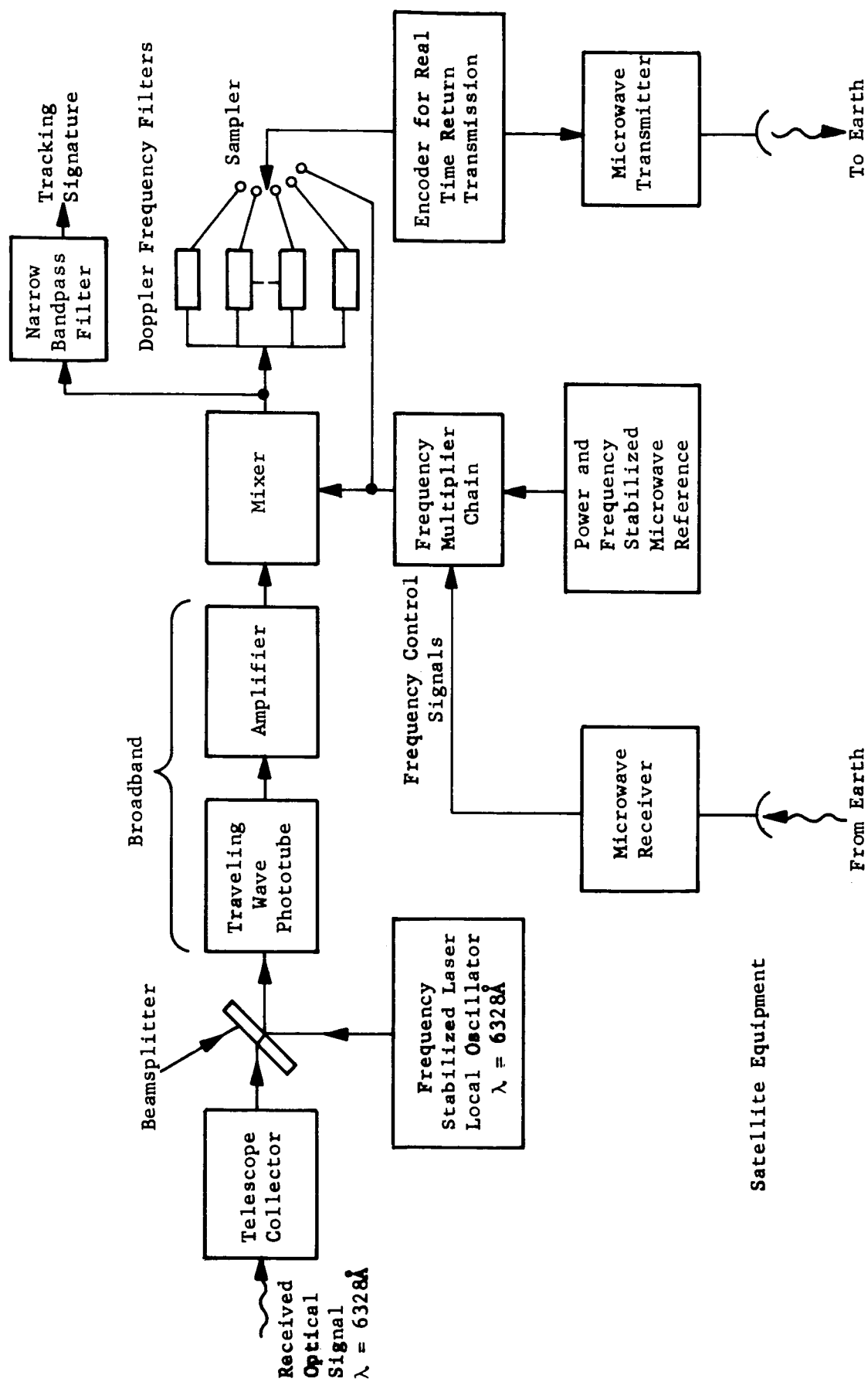


Figure 156. Block Diagram of Optical Heterodyning in Space Experiment

The magnitude of the background noise in an intensity detection optical communication system is proportional to the bandwidth of the predetection optical filter. Even the narrowest $0.1\text{\AA}$ Lyot filter has a frequency bandwidth of approximately 10 GHz for visible light.

The bandwidth of the background noise in an optical heterodyne receiver is determined by the intermediate frequency bandpass filters in the receiver. This is approximately equal to the signal bandwidth. Thus, there is no need for the ultra-narrow predetection optical filters in the optical heterodyne receiver.

Very large Doppler shifts may be expected in a deep-space coherent optical communication link. The maximum velocity of a Mars probe with respect to the center of the Earth is 18 km/sec. This amounts to a frequency shift of the

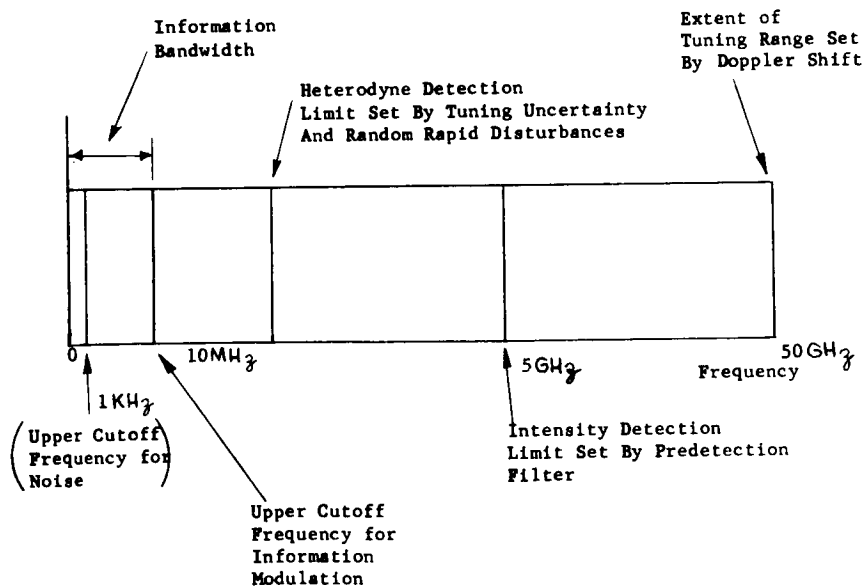


Figure 157. Bandwidth Requirements for Satellite Heterodyne Reception

carrier frequency of 40 GHz and 2 GHz for the transmitter wavelengths 0.48μ and 10μ , respectively. However, the velocity components along the line of sight, caused by the rotation of the Earth and the probe intersecting or orbiting the planet, can create relative velocities of up to 50 km/sec. Thus, Doppler shifts of up to 90 GHz may be expected in some interplanetary optical communication systems.

The time-rate-of-change of the Doppler for a Mars probe may approach 10 kHz/sec. The local oscillator may be tuned to track this center frequency drift over limited ranges. Other sources of frequency perturbations in the I.F. that must be contended with are: transmitter and local oscillator instability, path refraction in the atmosphere, and vehicle and receiver vibration. The tunable local oscillator, argon and CO₂ lasers, can compensate for frequency shifts of less than 1 GHz and 30 MHz, respectively. This range is sufficient for the local oscillator to track all frequency errors except the Doppler shifts. The application of the Zeeman split or use of a single-side-band optical modulator has been suggested as the technique to use for introducing the large frequency shifts required in the Doppler tracking subsystem. In addition, mode control of the lasers would be necessary.

For this experiment, the offset frequency synthesizing the Doppler shift should be accomplished on Earth. Even with a reasonable projection forward into the rapidly advancing laser field, the attainment of a frequency controlled and frequency shifted, high power, single mode laser is doubtful. The Doppler shift as a function of relative velocity and wavelength is plotted in Figure 158.

Noise Analysis of Traveling Wave Phototubes

The information-bearing optical signal is mixed at the photocathode surface of the traveling wave tube with a laser local oscillator reference. The light output causes the emission of a current-modulated photoelectron beam, which contains the difference or beat frequency signal between the local oscillator and signal light. The current-modulated beam is passed through a helical slow-wave structure (broadband microwave circuit). Power at the difference frequency is efficiently coupled to the circuit if the electron beam velocity is roughly equal to that of the electromagnetic wave on the circuit. This condition can be instantaneously realized over an octave bandwidth.

McMurtry* has shown that the signal-to-noise ratio for an optical heterodyne system employing traveling wave phototubes, operating against a shot-noise background caused by the direct beam current in the tube, can be expressed as

$$\frac{S}{N} = \frac{\eta n_s}{B}$$

where:

- η is the quantum efficiency of the photocathode surface
- n_s is the arrival rate of signal photons
- B is the traveling wave tube amplifier bandwidth.

If the amplifier resolution time, τ , is defined as the reciprocal of the bandwidth, B , then the minimum detectable number of signal photons per second is equal to:

*McMurtry, B. J.: Research on Techniques for Light Modulation. AD-284453.

$$n_s \text{ (min)} = \frac{B}{\eta} = \frac{1}{\eta\tau} = \frac{1}{\eta} \frac{\text{photons}}{\text{amplifier resolution time}}$$

Some interesting conclusions can be drawn from the above analysis. The signal-to-noise ratio is independent of local oscillator strength and of the magnitude of the direct current. Therefore, a strong local oscillator signal can be used and a large direct current is obtained to aid in the amplifying process without degrading the signal-to-noise ratio. Increased shot noise at large direct currents is balanced by increased conversion efficiency. It can also be seen that the larger the cathode quantum efficiency, the better the sensitivity and performance against noise. Obviously, for a quantum efficiency of unity, the minimum detectable signal arrival rate equals the ultimate detectable for any ideal linear receiver, namely, one photon per resolution time.

Feasibility of Experiment

Optical heterodyne detection has several advantages over intensity detection techniques. Optical heterodyne detection enjoys a 3-decibel advantage over intensity detection, and background discrimination is provided without use of an optical filter. Because of the directional requirement for heterodyning, only the background energy that arrives parallel to the local oscillator energy will generate difference frequency components that are amplified. Background noise is further limited since only those noise components that fall within the I.F. bandwidth will be amplified. However, in order to avoid the necessity for an I.F. bandwidth large enough to accommodate the envisioned deep-space Doppler shifts with the attendant background noise, frequency tuning is required over wide bandwidths.

The advantages of optical heterodyne detection appear at present to be substantially outweighed by several disadvantages: the requirement for high-power, frequency-stabilized and mode-controlled lasers; severe tuning requirements; and the necessity for broadband photodetectors.

However, time is on the side of a project such as OTES, since the state of the art is advancing so rapidly. Therefore, before a decision is made as to whether to include an optical heterodyne experiment for OTES, a reexamination of the state of the art should be conducted.

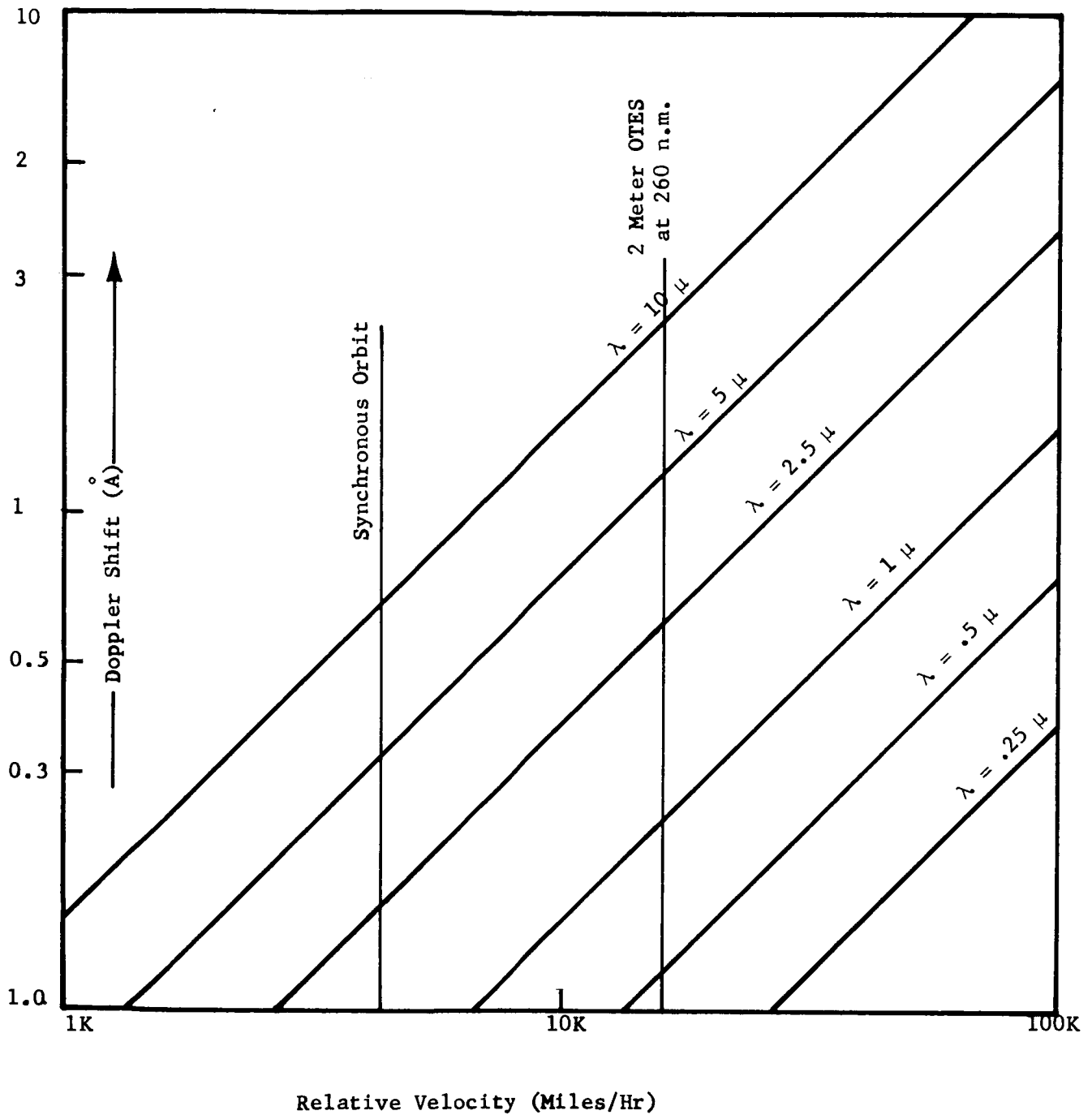


Figure 158, Doppler Shift versus Relative Velocity and Wavelength

EXPERIMENT NO. 32 - ATMOSPHERIC EFFECTS ON POLARIZATION
(Deleted from the 2-Meter OTES)

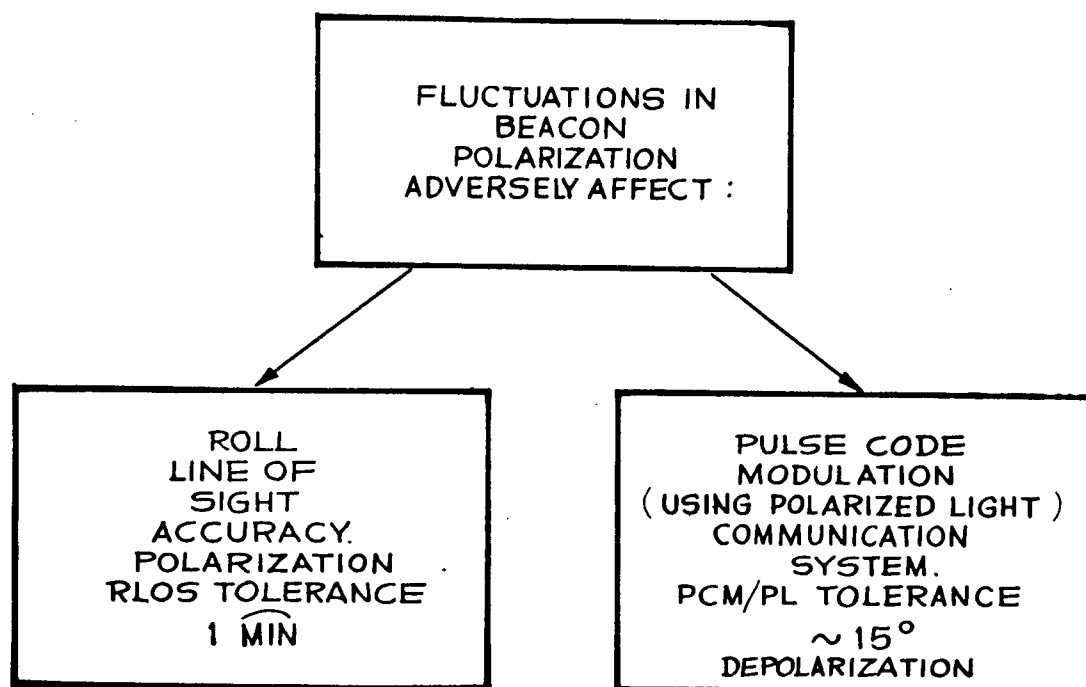


Figure 159.

EXPERIMENT OBJECTIVE

The objective of Experiment No. 32 is the measurement of polarization effects of the atmosphere on a down-going laser beam. The interaction of a magnetic field (such as the Earth's magnetic field) with a material medium (such as the atmosphere) causes a rotation of the plane of polarization of transmitted light. This is the Faraday effect. For the Earth's atmosphere, a Faraday rotation of the order of 1 arc-minute may be observed.* Faraday rotation is unimportant to communications** and attitude control, but there may be other unknown effects.

This experiment is impractical to conduct from the 2-meter OTES at the 260 nautical mile orbit. Experiment 32 remains a recommended optical technology experiment, but it should be conducted from synchronous orbit. Further details on the experiment can be found in Perkin-Elmer Report No. 8500 starting on page I-215.

* Derived in Perkin-Elmer Report No. 7846, pages 3-24.

** Peters, W.N. and Arguello, R.J., Fading and Polarization Noise of a PCM/PL System, IEEE Conference on Laser Engineering and Applications, June 1967.

EXPERIMENT NO. 33 - CLEAR AIR TURBULENCE RESEARCH
(Deleted from the 2-Meter OTES)

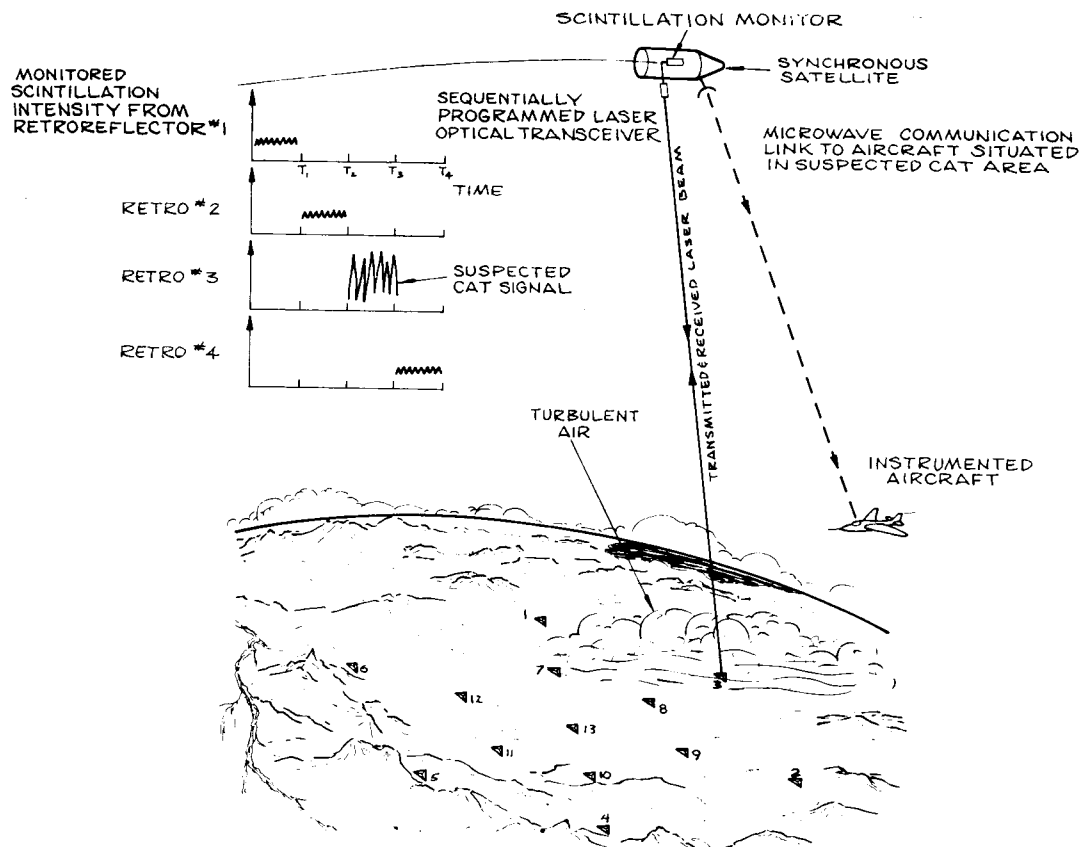


Figure 160.

EXPERIMENT OBJECTIVE

The objective of the proposed experiment is to utilize the spaceborne laser telescope system of the OTES Program to aid the Clear Air Turbulence (CAT) research activities. At present, one of the most difficult problems facing research workers is locating the Clear Air Turbulence area. The proposed experiment would assist by taking advantage of the programmable laser beam aboard a synchronous spacecraft, which can be detected after passing through the suspect regions during the daytime as well as the nighttime. The concept of the experiment stems from the theoretical work that has been done in correlating starlight image scintillation to CAT. If there is correlation between starlight scintillation and CAT, then there will be correlation between laser light and CAT. Since the real problem is to locate the area where CAT exists, the OTES can make a real contribution by using inexpensive and unattended retroreflectors at various sites on the Earth. By programming the laser beam from the satellite to these areas (and note that an extremely large number of retroreflectors can be used, because their cost is low), that area where CAT is indicated can be investigated by an instrumented chase plane.

At the present time, Experiment No. 33 is a recommended experiment for the OTES at synchronous orbit. The experiment is impractical from a low-orbit system such as the 2-meter OTES because the spacecraft cannot monitor the CAT test areas continuously. The photometry has been worked out and is included in this report. The analysis shows that this CAT experiment can be conducted from the Laser Communication Satellite Experiment using the new 5300Å laser. The experiment cannot be conducted with the 6328Å laser (5mw) and the 1/2-meter aperture of the LCSE because of power limitations which degrade the signal-to-noise ratio to unacceptable levels. However, the 5300Å laser with a 2-watt CW capability has more than enough power to conduct this experiment which requires 0.3 watt when using the 1/2-meter LCSE.

Perkin-Elmer Report No. 8500 briefly describes the experiment procedure on page I-227.

EXPERIMENT PROCEDURE

Assuming that the correlation between clear air turbulence (CAT) and optical scintillation can be established, observations over a large area could be performed from a synchronous satellite to detect areas of clear air turbulence. The block diagram in Figure 161, includes a laser transmitter with, a high-powered CW solid state laser operating at 5300Å, precisely aimed at an array of retroreflectors that are placed on the ground in areas where CAT is prevalent. The reflected light is detected and its scintillation is analyzed to determine a clear air turbulence "signature."

Clear Air Turbulence Detection Analysis

A first step in establishing the feasibility of the CAT location experiment is to determine how practical the experiment is in terms of the required laser transmitter power and the number and size of the retroreflectors comprising the ground array. The real case consists of a satellite moving in a circular geocentric orbit with angular velocity ω_s and aiming a laser beam at a retroreflector array moving in a circular path around the polar axis. A calculation of the received power which takes into account the retroreflector diffraction pattern and the complicated variations in velocity aberration is algebraically cumbersome and is not justified at the present time. The following calculation therefore assumes the much simpler case of a satellite moving parallel to a flat Earth with a relative velocity, ΔV .

Figure 162 defines the satellite to retroreflector geometry together with a list of symbols used in the calculation. If the output power of the transmitter laser is P (watts) then the amount of power received by one retro-reflector is

$$P_1 = \tau_1 \tau_a P \left(\frac{A_r}{\omega_t r^2} \right) \text{ watts} \quad (1)$$

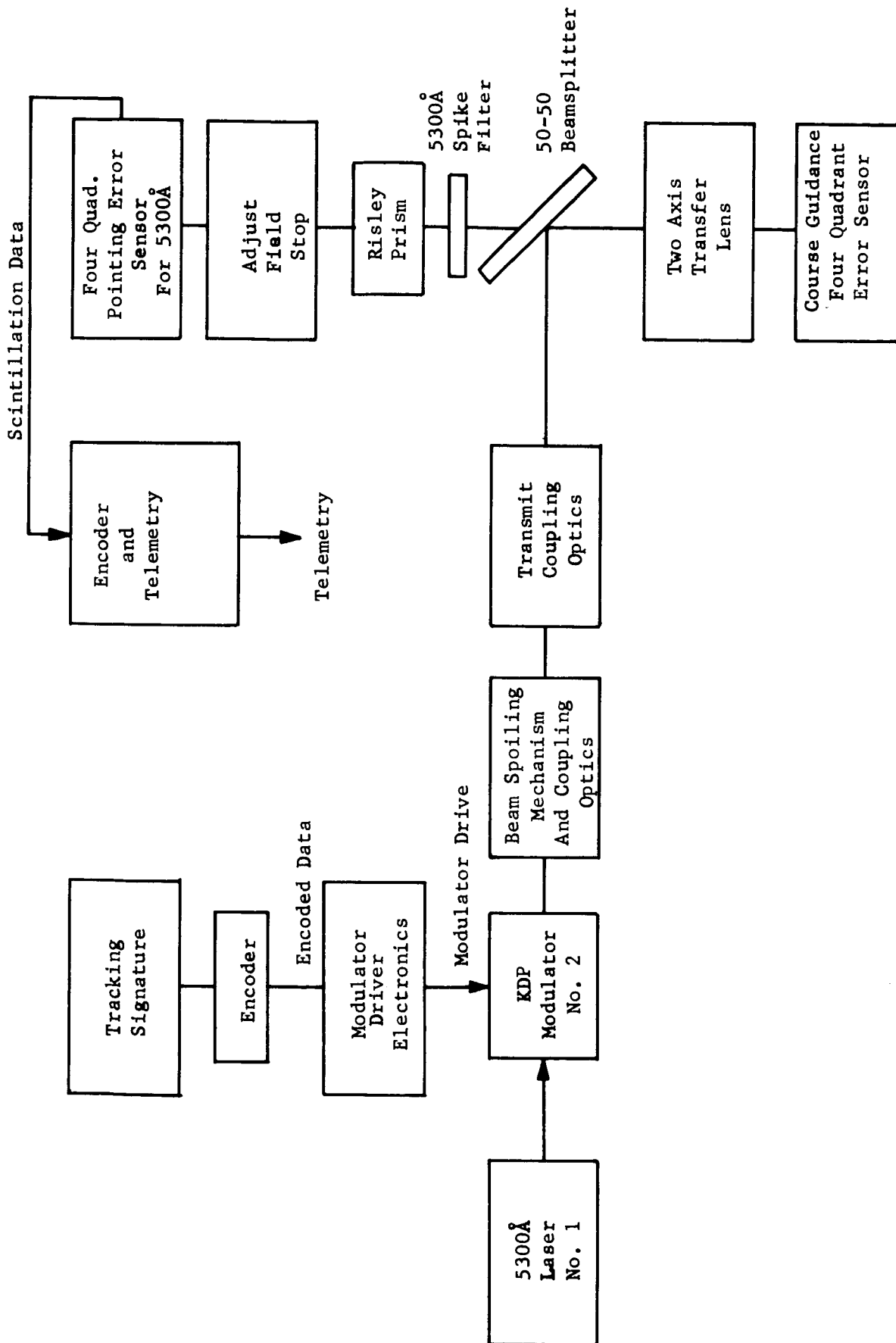


Figure 161. Block Diagram of Clear Air Turbulence Research

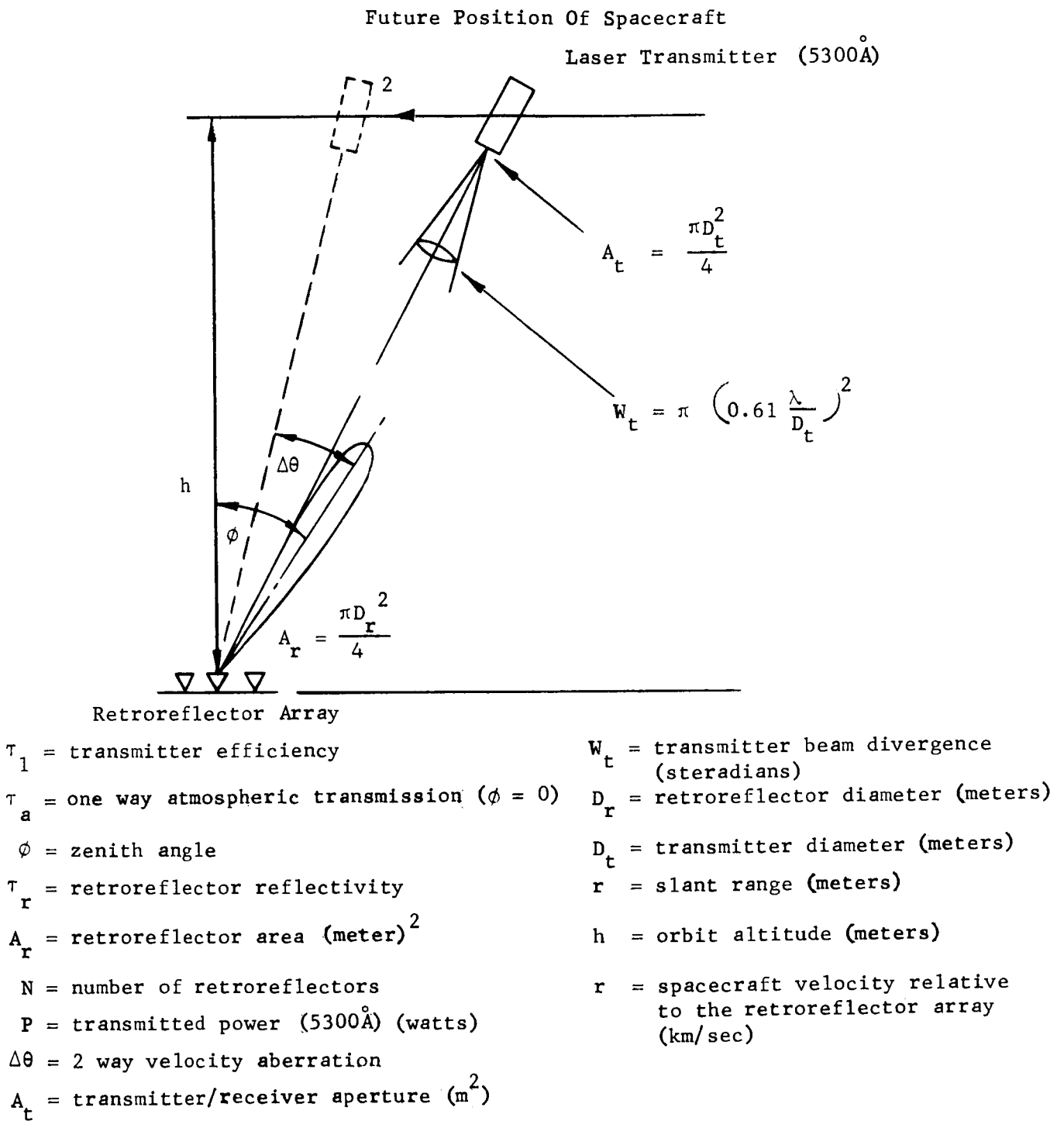


Figure 162. Spacecraft-Retroreflector Geometry for CAT Detection

The retroreflected power is therefore

$$P_2 = \tau_r \tau_l \tau_a P \left(\frac{A_r}{\omega_r r^2} \right) \quad (2)$$

and is distributed into the diffraction pattern of the retroreflector. In practice the diffraction pattern from a diffraction-limited retroreflector possesses six point symmetry but most of the radiation is concentrated in the central maximum. For this reason we approximate the angular variation of intensity with that due to a circular aperture, i.e.,

$$I_\theta = I_0 \left[\frac{2 J_1 \left(\frac{\pi D \theta}{\lambda} \right)}{\frac{\pi D \theta}{\lambda}} \right]^2 \text{ watts/(m}^2\text{)} \quad (3)$$

The reflected signal to the spacecraft corresponds to that from an angle $\Delta\theta$ (two-way velocity aberration angle) from the central maximum ($\theta = 0$) since the spacecraft has moved a distance $\frac{2V}{C}r$ during the transmission time. The total power radiated into 2π steradians is therefore

$$P_2 = \int_0^\pi 2\pi \sin \Delta\theta I_0 \left[\frac{2J_1(K \Delta\theta)}{(K \Delta\theta)} \right]^2 d\theta = \rho I_0 \quad (4)$$

where

$$K = \frac{\pi D r}{\lambda}$$

The power radiated into the solid angle subtended by the spacecraft receiver aperture is therefore

$$P_4 = \frac{A_t}{r^2} \left(\frac{P_2}{\rho} \right) \left[\frac{2J_1(K\theta)}{(K\theta)} \right]^2 \quad (5)$$

and the power at the receiver detector is

$$P_5 = \tau_a \tau_2 \frac{A_t}{r^2} \left(\frac{P_2}{\rho} \right) \left[\frac{2J_1(K\theta)}{(K\theta)} \right]^2 \quad (6)$$

From Equation (2) we derive

$$P_5 = \tau_r \tau_a^2 \tau_1 \tau_2 \left(\frac{PA_r}{n_t^2 r^2} \right) \left(\frac{A_t}{\rho r^2} \right) \left[\frac{2J_1(K\theta)^2}{(K\theta)} \right] \quad (7)$$

The integral, ρ , defined in Equation (4) can be evaluated for small angles by putting $\sin\Delta\theta \rightarrow \Delta\theta$. Changing the variable to

$$t = \frac{\pi D_r \Delta\theta}{\lambda} ; \quad dt = \frac{\pi D_r}{\lambda} d(\Delta\theta)$$

$$\rho = \int_0^\infty \frac{\lambda}{\pi D_r} (t) \cdot 2\pi \left[\frac{2J_1(t)}{t} \right]^2 \frac{\lambda}{\pi D_r} dt$$

$$= \frac{8\lambda^2}{\pi D_r^2} \cdot \int_0^\infty \left[J_1(t) \right]^2 \frac{1}{t} dt = \frac{4\lambda^2}{\pi D_r^2} \quad (8)$$

Substituting for ρ , A_r , A_t and n_t in Equation (7) gives

$$P_5 = \tau_r \tau_a^2 \tau_1 \tau_2 \left(\frac{P}{r^4} \right) \cdot \left(\frac{\pi^2}{64} \right) \frac{D_r^4 D_t^4}{(0.61)^2 \lambda^2} \left[\frac{2J_1(K\Delta\theta)}{(K\Delta\theta)} \right]^2 \text{ watts} \quad (9)$$

This equation has to be modified for non-zenith transmission in three ways.

- a) The effect of atmospheric absorption at zenith angle ϕ requires that τ_a be replaced by τ_ϕ where

$$\tau_\phi = (\tau_a)^{\sec\phi}$$

- b) The velocity aberration angle for a zenith angle ϕ is given by*

$$\Delta\theta = \phi - \tan^{-1} \left(\tan\phi - \frac{2v}{c \cos \phi} \right)$$

* Velocity Aberration and Atmospheric Refraction in Satellite Laser Communication Experiments, L.J. Nugent and R.J. Condon, Applied Optics, Vol. 5, No. 11, November 1966, p. 1832.

- c) The effective aperture of the retroreflector changes with different zenith angles and the area of the elliptical aperture at an angle, ϕ , is

$$A_2 = \frac{\pi D_r^2}{4} \cos^2 \phi$$

Therefore D_r is replaced by $D_r \cos \phi$ in Equation (9).

If h is the altitude of the satellite path above the ground station, then $h = r \cos \phi$.

The expression for the power at the receiver detector thus becomes

$$P_6 = \frac{\pi^2}{64} \left(\frac{\eta P}{h^4} \right) (\tau_a)^{2 \sec \phi} \cos^8 \phi \frac{D_r^4 D_t^4}{(0.61)^2 \lambda^4} \left[\frac{2J_1 \left(\frac{\pi D_r \cos \phi \Delta \theta}{\lambda} \right)}{\left(\frac{\pi D_r \cos \phi \Delta \theta}{\lambda} \right)} \right]^2 \quad (10)$$

where

$$\eta = \tau_r \tau_1 \tau_2$$

Equation (10) can be simplified by assigning values to the following parameters as follows:

$$\begin{aligned} D_t &= 1 \text{ meter} \\ \text{although } \lambda &= 0.53 \times 10^{-6} \text{ meters, for the calculations which follow} \\ \lambda &= 0.6 \times 10^{-6} \text{ is used} \\ \eta &= \tau_r \tau_1 \tau_2 = (0.9)(0.5)(0.5) = 0.22 \\ \tau_a &= 0.8 \text{ (at } \lambda = 0.6 \times 10^{-6} \text{ meter)} \\ P &= 2 \times 10^{-2} \text{ watts} \end{aligned}$$

If the ground array consists of N_i retroreflectors of diameter D_i then the total detected power, assuring that the individual retroreflector returns add incoherently, will be

$$P_7 = N_i \cdot 1.33 \times 10^{22} (0.8)^{2\sec\phi} D_i^4 \left(\frac{\cos^8\phi}{h^4} \right) \frac{J_1 \left(\frac{\pi D_i \cos\phi \Delta\theta}{\lambda} \right)}{\left(\frac{\pi D_i \cos\phi \Delta\theta}{\lambda} \right)} \quad (11)$$

The detected power for a given zenith angle and altitude can be maximized by a correct choice of retroreflector diameter. This is most simply shown by choosing an array of N_i retroreflectors of diameter D_i such that the total area of the array is constant, i.e.,

$$N_i \cdot \frac{\pi}{4} (D_i)^2 = \alpha$$

Substituting into Equation (11), the received power simplifies to

$$P_7 = \frac{4\alpha}{\pi} \cdot 1.33 \times 10^{22} (0.8)^{2\sec\phi} \frac{\cos^8\phi}{h^4} \left[\frac{J_1 \left(\frac{D_i \cos\phi \Delta\theta}{\lambda} \right)}{\left(\frac{\pi \cos\phi \Delta\theta}{\lambda} \right)} \right]^2 \quad (12)$$

and therefore maximum power is obtained for an array of N_i retroreflectors of diameter D_i such that

$$\left[J_1 \left(\frac{\pi D_i \cos\phi \Delta\theta}{\lambda} \right) \right]^2 \text{ is a maximum}$$

$$\text{i.e., } \left(\frac{\pi D_i \cos\phi \Delta\theta}{\lambda} \right) = 1.9, 5.3, 8.5 \text{ etc.} \quad (13)$$

Thus there is an optimum diameter of retroreflector for each zenith angle and velocity aberration angle $\Delta\theta$ (determined by the orbit altitude). The received power in watts is shown in Figure 163 as a function of orbit altitude for zenith viewing using a figure of 0.1 (meter)^2 for the total area of the retroreflector array. The retroreflector diameter is maximized for any altitude using the condition in Equation 13. The optimum diameter D_i and the number required to form an array of 0.1 m^2 area is shown in Figure 164 as a function of altitude; the optimum diameters being chosen for zenith viewing. The variation in received power for a 20,000 km orbit is shown in Figure 165 as a function of zenith angle.

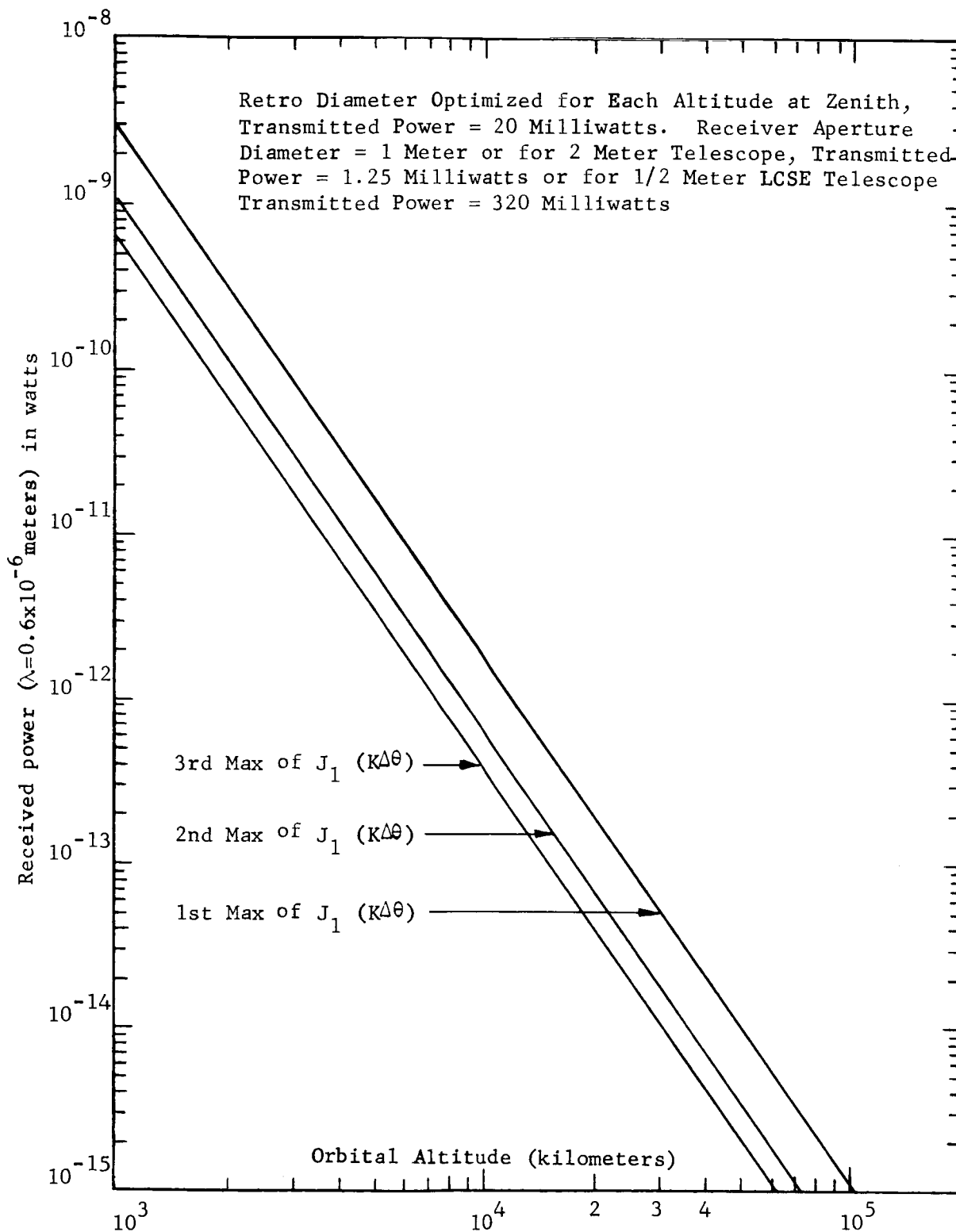


Figure 163. Received Power from a 0.1 Square Meter Array of Retroreflectors for Zenith Viewing.

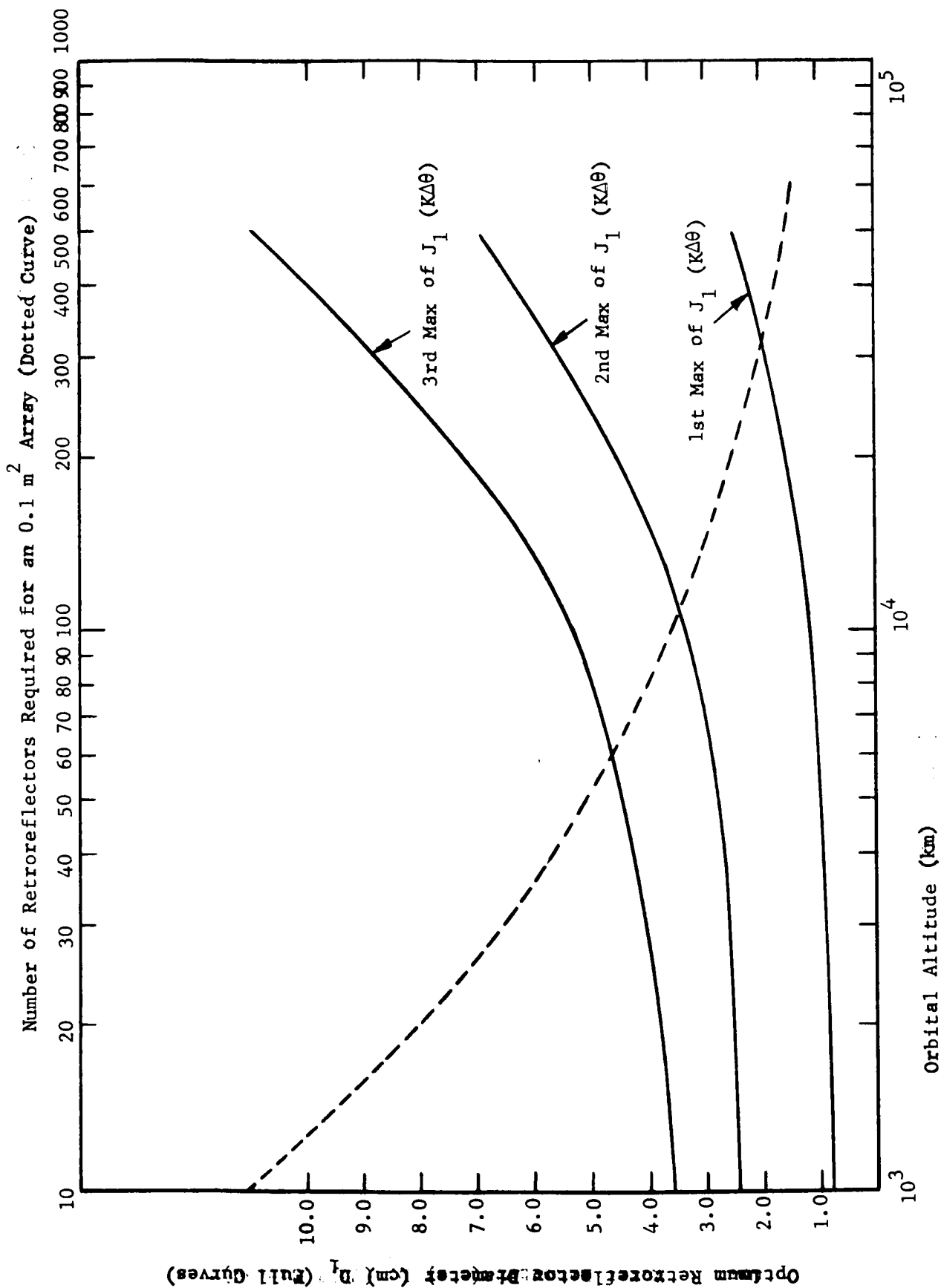


Figure 164. Optimum Parameters for an 0.1 m^2 Array of Retroreflectors as a Function of Orbital Altitude

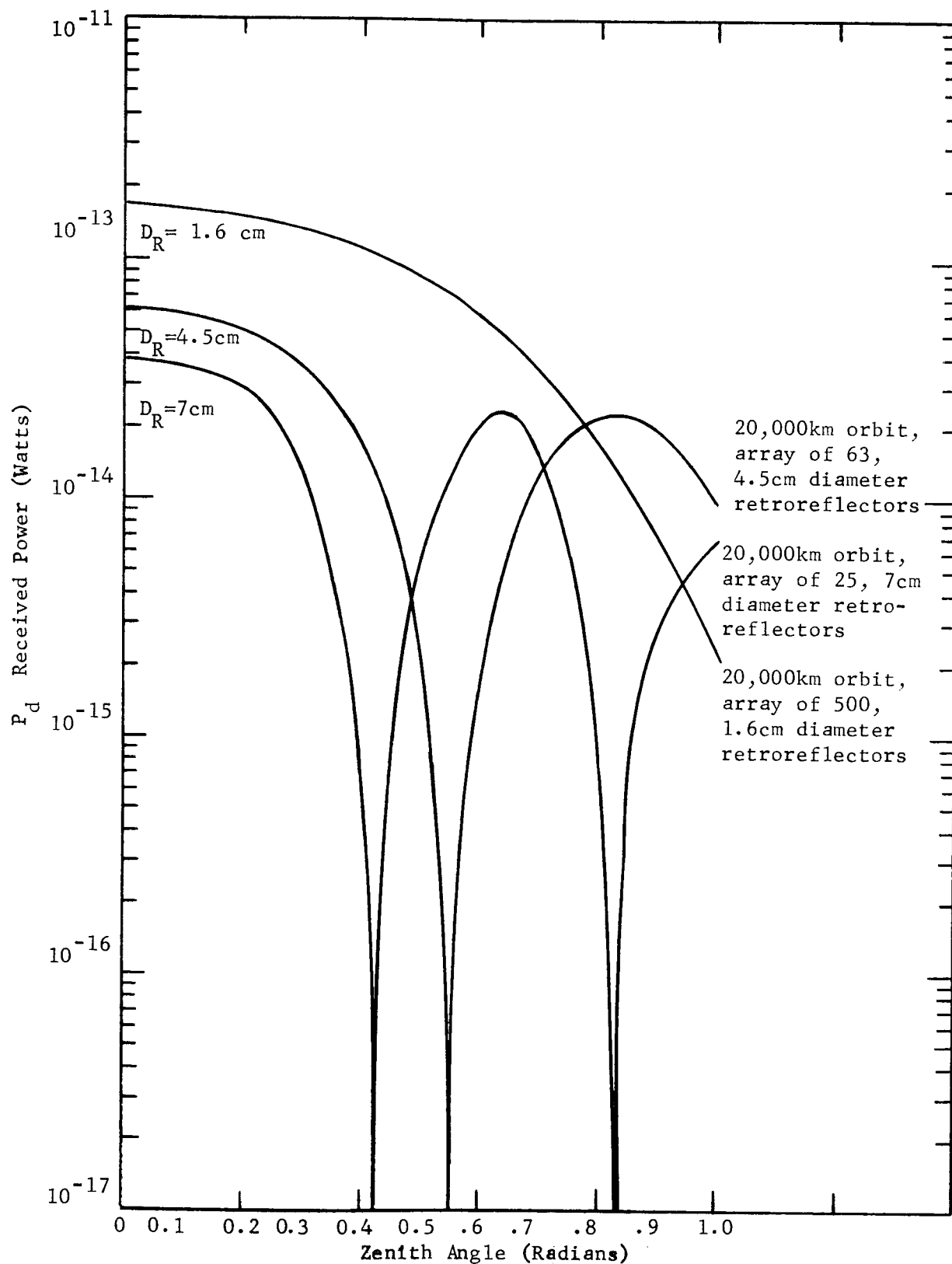


Figure 165. Retroreflected Power from a 0.1 m^2 Array for High Orbit (20,000km)

Experimental measurements from synchronous orbit should be made using the retroreflected light in the central maximum to avoid the six point symmetry present in the first bright ring of the diffraction pattern of a real retroreflector. It is therefore evident from Figures 163 and 165 that measurements from synchronous altitude require a large number of small retroreflectors to form the ground array. A large increase in power can be obtained by using a lower orbit but the problem of hitting the retroreflector array from a fast moving satellite becomes increasingly difficult. The return power can be significantly increased by using a more powerful CW laser and, by using a larger transmitter/receiver aperture, this may be more practical than making measurements from lower orbit.

The scintillation signal which is expected from areas of clear air turbulence will be some fraction of the powers shown in Figures 163 and 165. The detection of this signal is also hampered by the nature of the return from an array of retroreflectors. The return signals from each retroreflector can have random phase components and the diffraction pattern resulting from the coherent addition of all the return signals will have a time varying component which could be similar to the CAT signature being sought.

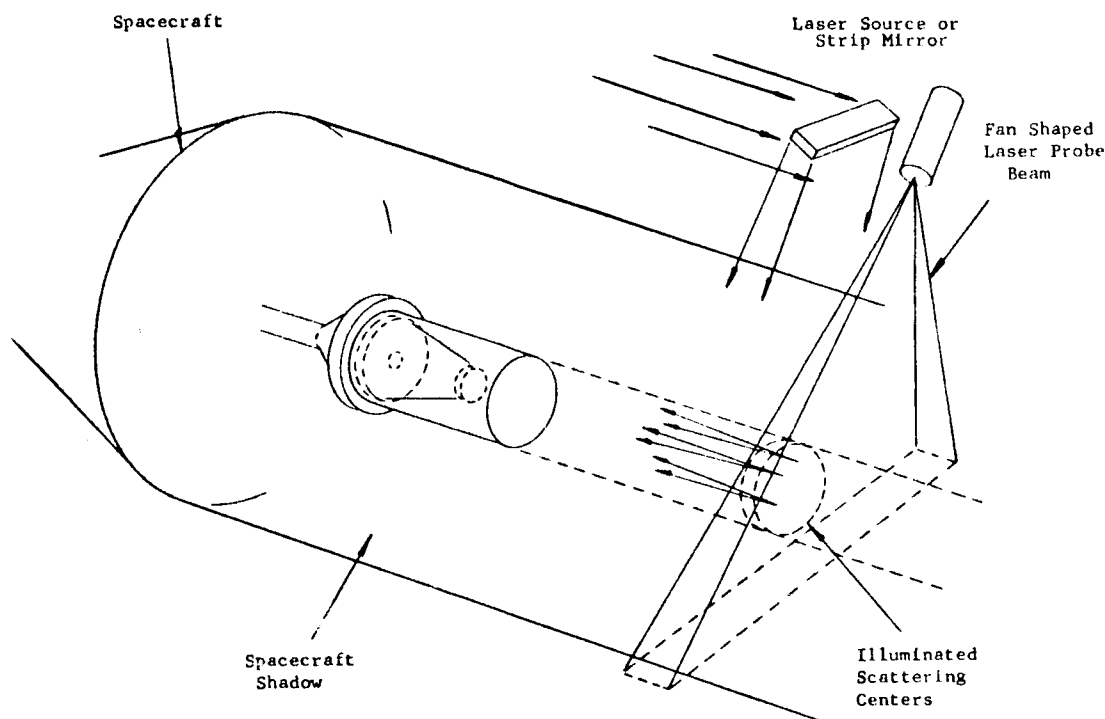
EXPERIMENT NO. 34 - OPTICAL SCATTERING ENVIRONMENT

Figure 166

EXPERIMENT OBJECTIVE

Observations made by several astronauts from the Mercury and Gemini vehicles suggest that limiting optical environment of the spacecraft is determined by the amount of debris surrounding the vehicle.* Sunlight scattered from the debris provides a background radiance which has, so far, prevented visual observation of stars greater than second magnitude. The object of the experiment is to give a quantitative measure of the amount of sunlight scattered into an orbiting telescope by the cloud of debris accompanying the spacecraft. The measurements should also be made using a monochromatic beam to help in determining the scattering function for the particles as a function of scattering angle.

EXPERIMENT JUSTIFICATION

The scattered light from a particle in front of the telescope can adversely affect an orbiting telescope in two ways:

- By providing a uniform background irradiance in the telescope focal plane which, in turn, determines the magnitude of the dimmest star that can be detected.
- By producing mispointing in the tracking system.

* Ney, E.P.; Huch, W.F.: Science 153, July 1966.

If the scattering from individual particles is isotropic, they will not begin to be imaged at the infinity focus if they are within a distance

$$R_C = \frac{D}{\theta}$$

where θ = the total field of view of the telescope, and D is the telescope aperture. Therefore, for a large aperture, small field-of-view telescope, isotropic scatterers will produce a uniform background irradiance which will decrease the tracking system S/N ratio. The amount of scattered light per resolvable angle determines the limiting visual magnitude which can be detected. If the scattering function contains strong forward or side lobes, whose angular width is less than θ , the particle will be "imaged" for distances less than R_C . The particle thus behaves as a "star" and can seriously affect the tracking system.

The illustration at the beginning of the experiment shows the proposed method of measuring the scattering function as a function of angle γ and distance of the scattering volume in front of the telescope, R. The telescope is mounted to a space vehicle which is oriented so that the telescope line of sight near the front of the telescope is within the shadow of the space vehicle. A light beam whose lateral size is much larger than the telescope aperture (to reduce the need for precise probe beam pointing) is directed onto various parts of the shadow region. The light beam can either be a fan-shaped laser beam or can be produced by using a strip mirror to reflect sunlight into the shadow region.

EXPERIMENT DISCUSSION

Large Debris Particles

Many theoretical models can be used to estimate the amount of scattering from molecules and particles of debris in the front of the aperture. The scattering from particles whose diameters are much larger than the wavelength of the scattered radiation ($d > 10\lambda$) can be estimated if it is assumed that the particle is a Lambertian reflector and also diffracts light into the forward direction.

The amount of light scattered into a direction, γ , from a Lambertian sphere illuminated by sunlight of intensity I_s (watts/cm²) can be described by

$$I = I_s \cdot \frac{\rho}{\pi} \cdot \frac{2}{3} r^2 [(\pi - \gamma) \cos \gamma + \sin \gamma] \text{ watts/steradian}$$

where r = particle radius and ρ is the particle reflectivity. The amount of light scattered into each resolvable angle of the telescope is thus

$$I = I_s \frac{\rho}{\pi} \frac{2}{3} r^2 [(\pi - \gamma) \cos \gamma + \sin \gamma] \left(\frac{\pi}{4} \cdot 1.22 \frac{\lambda}{D} \right)^2 \text{ watts/res. element}$$

This is shown as a function of scattering angle and particle size for a 1-meter aperture telescope in Figure 167. Since the peak solar radiation occurs for $\lambda \sim 0.5$ micron, a value of $1.22 \times 5 \times 10^{-7}$ is taken as the angular limit of resolution. Calculation of the total amount of light scattered into the telescope requires a knowledge of the size and number density distribution of the debris particles, but is independent of distance in front of the telescope for ranges less than R_C .

Figure 167 also includes a star magnitude scale calculated by assuming the sun's usual magnitude = -27 and that a 1-meter diameter dish is used to image a star. The curves indicate the severity of the problem since the scattered power per resolution element is shown for only one particle of a given radius in front of the telescope. In practice, one expects many thousands of debris particles to contribute to the scattering.*

The forward scattered power per resolution element can be calculated from diffraction theory by assuming from Babinet's principle that the total scattered power is given by

$$I_{\text{scatt}} = \pi r^2 I_s \text{ watts}/4\pi \text{ steradian}$$

The angular dependence is given by**

$$I(\beta) = I(0) \left[\frac{2J_1(u)}{u} \right]^2 \cos^4 \left(\frac{\beta}{2} \right) \cdot \text{watts/unit area}$$

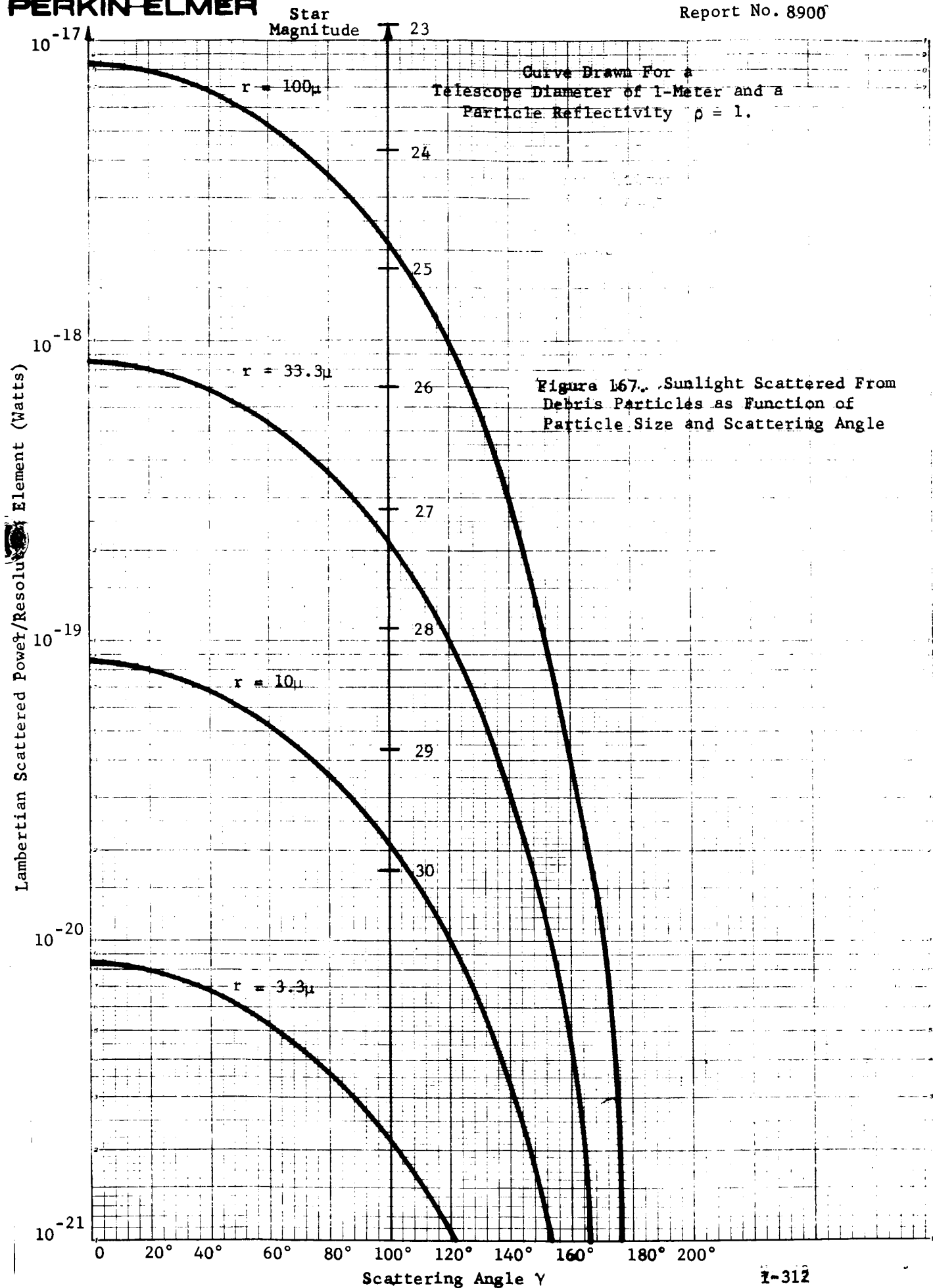
where $u = \frac{2\pi r}{\lambda} \sin \beta$, $I(0)$ is the intensity in the forward direction. Since most of the light goes into the first two maxima of the diffraction pattern and, assuming angles sufficiently small such that $\sin \beta \sim \beta$, $\cos \beta \sim 1$, it can be shown approximately** that

$$I(0) = \frac{\pi^2 r^4 I_s}{\lambda^2}$$

The diffracted power per resolution element is derived as

* Newkirk, G. Jr.: Planetary & Space Science, August, 1967, p. 1267. Submitted August 1966.

** Middleton: Vision Through the Atmosphere. P.31, Equation (3-13).



$$I_{\text{diff}} = \frac{\pi^2 r^4 I_s}{\lambda^2} \left[\frac{2J_1(u)}{u} \right]^2 \cdot \frac{\pi}{4} \left(\frac{1.22\lambda}{D} \right)^2 \text{ watts}$$

The envelope of the function I_{diff} is calculated from the asymptotic expansion for $J_1(u)^*$, i.e.,

$$J_1(u) = \sqrt{\frac{2}{\pi u}} \cos \left(u - \frac{3\pi}{4} \right) + e^{I_m(u)} \left[\text{terms of order } \left(\frac{1}{u} \right) \right]$$

and is shown in Figure 168 as a function of particle radius and scattering angle $\gamma = (\pi - \beta)$.

The diffracted light occurs most strongly in the forward direction and, for this reason, will not limit the performance of an orbiting telescope since a telescope cannot be used close to the sun line.

Small Particles

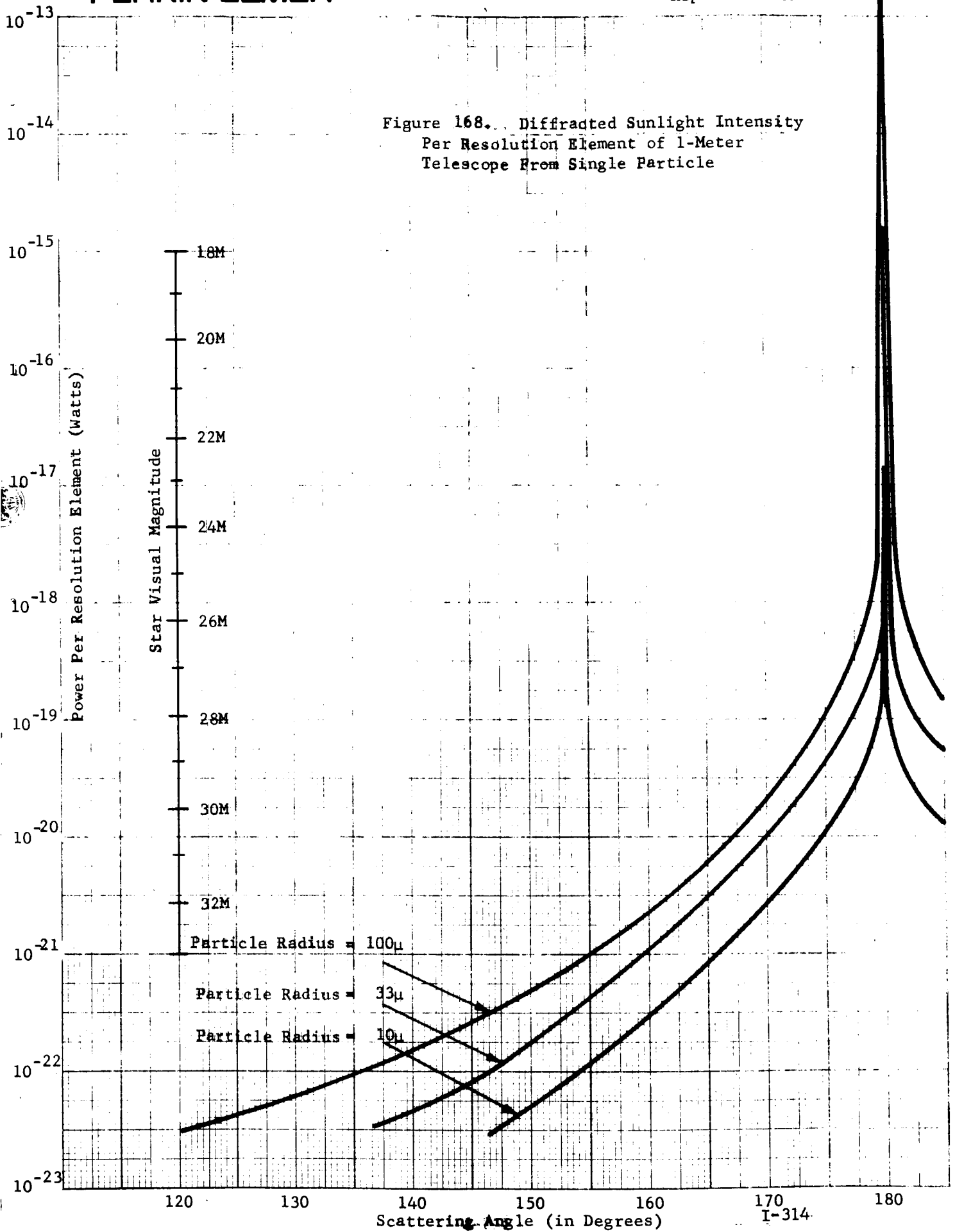
The scattering from small particles (0.1 to 5 micron) can be computed rigorously by using Mie scattering functions which are well tabulated as functions of particle size, refractive index and wavelength. Little is known about the particle size distribution or the particle refractive index for space debris and consequently meaningful calculations have not been performed at present.

In the photograph (Figure 169) supplied by Dr. Newkirk in a preprint of his paper,** tracks of scattered light from dust motes floating in front of a balloon-borne coronagraph are plainly visible. This illustration is graphic evidence of the need to collect data in this scattered light area in space in order to proceed with future space observations.

* Abramowitz, M.; Stegun, I.A.: Handbook of Mathematical Functions

** Newkirk, G., Jr.: Planetary and Space Science. To be Published.

Figure 168... Diffracted Sunlight Intensity
Per Resolution Element of 1-Meter
Telescope From Single Particle



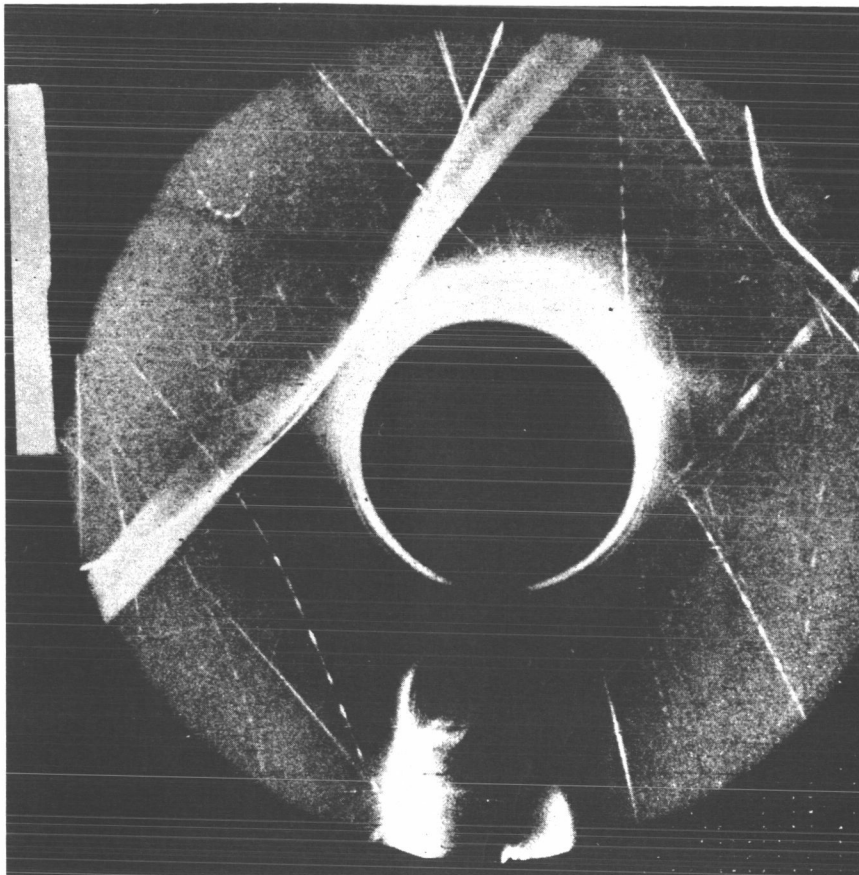


Figure 169. Light Scattering by Dust Motes

EXPERIMENT PROCEDURE

The experiment measures the amount of light that is scattered into the telescope field of view by debris particles orbiting with the spacecraft and telescope system. As shown in Figure 170, the spacecraft is oriented so that the telescope is pointing away from the sun with its optical axis aligned along the direction of the solar vector. A modulated light source (He-Ne laser) or reflected sunlight is then used to illuminate the scattering particles in front of the telescope. The strip mirror redirects sunlight into the region in front of the telescope so that the total scattered light can be measured as a function of the distance in front of the telescope aperture.

The laser source is used to obtain scattering data for a specific wavelength by illuminating the particles with a fan-shaped beam. The single wavelength results will simplify the data reduction required to estimate the size and particle distribution around the spacecraft.

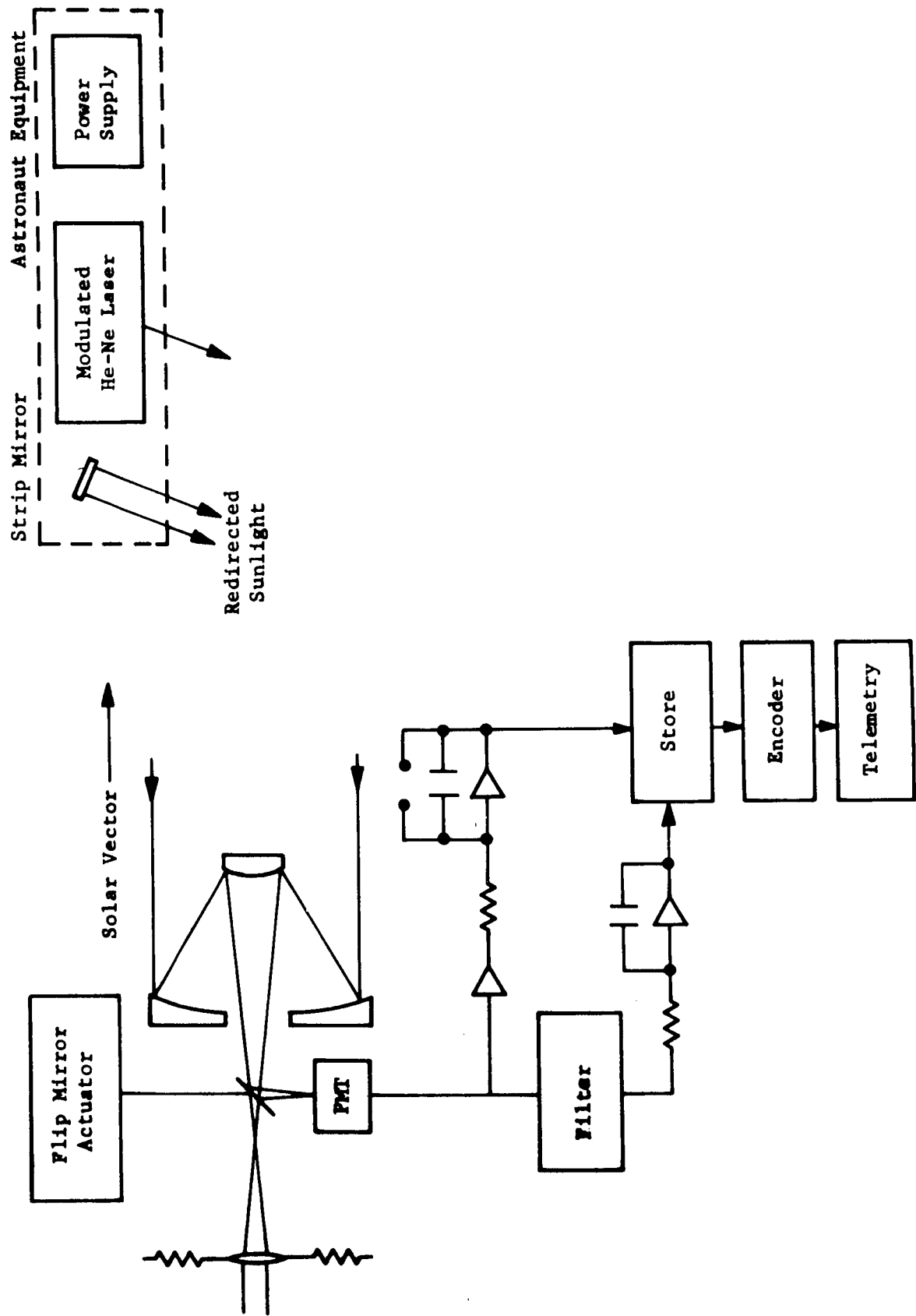


Figure 170. Block Diagram of Optical Scattering Environment Experiment

CHAPTER 3 - OTES OPTICAL DESIGN CONCEPT

OPTICAL INSTRUMENT APPROACH

The direction of the efforts applied to the OTES in the optical area have been established as identifying the optical technology which would benefit significantly by the conduct of suitable space experiments. Phase A of the OTES Program is the determination of space experiments and then the conceptual feasibility of these experiments to develop the cost plus the resources of conducting the program. The work cannot proceed in a step one-step two type of progression since the nature of the experiments requires knowledge of the anticipated missions of future optical instruments. Also, as was shown in the Phase I-A Report 8500, the most important single parameter in the decision process for the OTES is the diameter of the telescope primary mirror. In Report 8500, it was shown that while certain thermal measurements could be made with extreme precision in an optical technology flight system, in order to extrapolate the data to larger telescopes, there is a technical limitation on the validity of the thermal data in the extrapolation process. In Report 8500, pages 263-269, the thermal scaling laws were analyzed to the point that it was shown that a factor in the vicinity of 1.2 (that is, measure on 2-meter mirrors and extrapolate the data to 2.4 meters) is a maximum.

Thus, the justification for the 2-Meter OTES is based on the situation that it is as close to the future 3-meter aperture telescopes in size as is practical and yet it is small enough to fit into the ATM gimbals and LEM Rack of the AAP Cluster Program. Equally important in terms of justification for the OTES is the ability of the OTES to accommodate astronaut experiments and astronaut assistance in the maintenance of the telescope system in space. The importance of developing space worthy techniques for applying astronaut operations is underscored by the OTES Experiments which are designed around the concept of providing flexibility to the scientific payload. The OTES arrangement of having six identical and interchangeable instrument packages arranged behind the primary mirror permits in-flight changing of scientific instruments as well as the removal of a specific instrument module from its nominal location and servicing the instrument module in the manned space workshops.

Since the identical and interchangeable instrument modules are so important to this concept of the OTES, the concept was developed further by including the design of important and useful scientific instruments in five of the six instrument modules. Fundamentally, the equipment which is shown packaged into individual compartments, represents important scientific interests. Figure 171. The basic reason for including these instruments in a technology oriented flight program is to assist in the collection of data germane to the technology flight. Thus, the spectrometers and image systems will be collecting engineering data on the performance of the various pointing systems in the technology experiments (transfer lens, free float, gimbals) under the various conditions of daylight and night time, coupled and uncoupled to the cluster and possibly for both low orbit and high orbit.

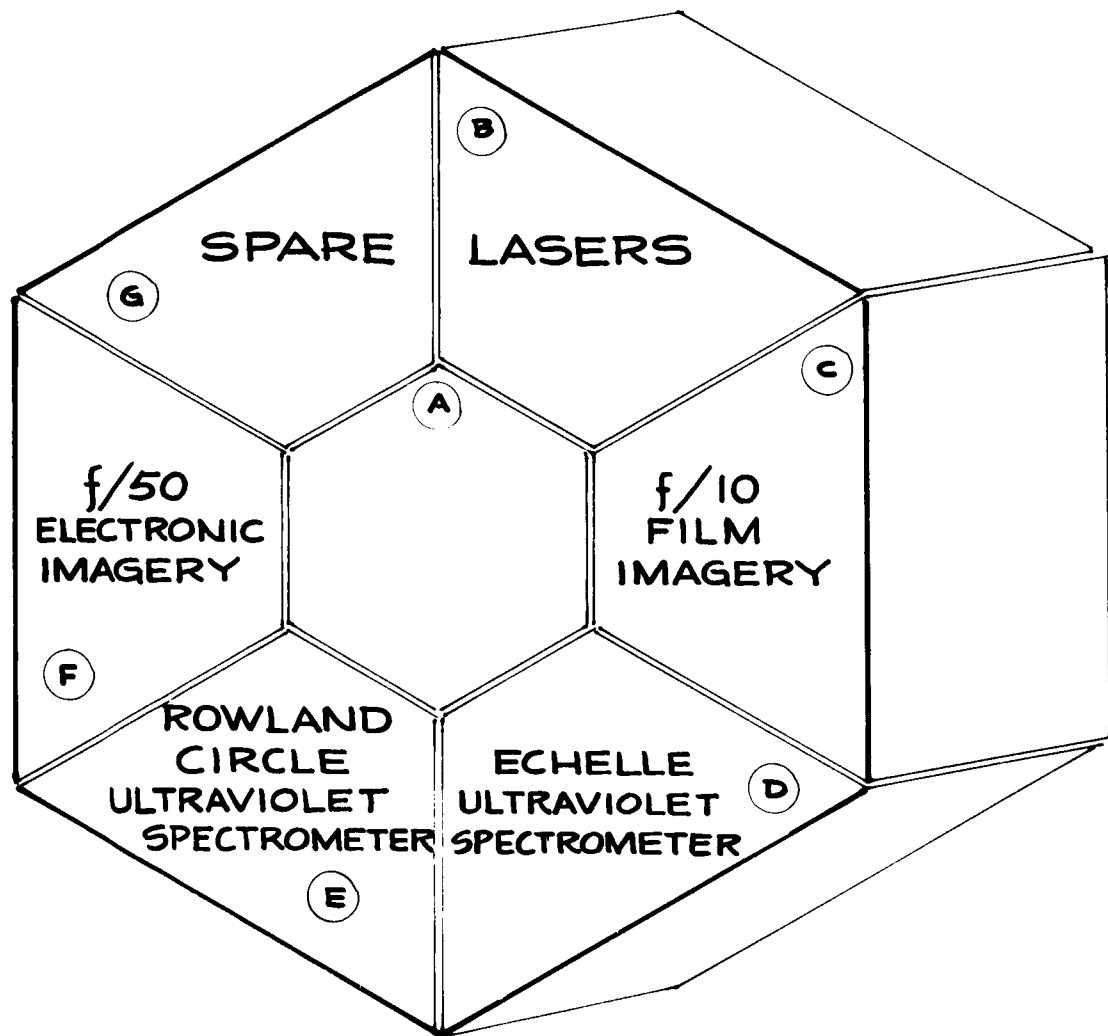


Figure 171. OTES Instrument Module Concept

The instruments which are packaged into the equipment modules are instruments modified from other Perkin-Elmer designs to fit the constraints of the OTES. This was the most expeditious method that we could employ to illustrate the flexibility of the OTES concept, and yet provide enough engineering data to clarify the problems and approaches.

The decision process on the most appropriate scientific instruments in these modules is left to NASA. What is illustrated in the following section is the type of equipment each instrument would represent, and how the technology program would benefit. The sixth instrument module is left blank at the present time, and it should be left blank until the latest possible time in the flight schedule in order to accommodate the suggestions from the scientific community.

It must be noted that the basic priority of the OTES is assigned to the gathering of technology data and not to conduct astronomical experiments. (See Table 9.) At the conclusion of the technology data operations, the instruments can be used for their more classical operations in astronomy at the option of NASA.

DIFFRACTION-LIMITED SPACE TELESCOPES

A 2-meter, diffraction-limited, space borne, optical system will have a resolution capability which is about an order of magnitude greater than Earth-bound telescopes. This increase in resolution will probably bring forth astronomical details which are as yet unimagined and also will extend the limits of the visible universe by increasing the limiting stellar magnitude which can be distinguished against the faint zodiacal light scattered within our own solar system. Thus, the step into space with large apertures will be a quantum jump in astronomy, comparable to Galileo's first telescope or the invention of the radio telescope.

Many potentially rewarding tasks await the first space borne telescope. Some of these, such as UV spectroscopy, will take advantage of the increased spectral range. For the largest telescopes - especially those capable of achieving the resolution limited by the diffraction at the aperture - the prime goal is almost certain to be imagery.

Diffraction-limited imagery also presents the most formidable design problems since it is necessary to stabilize the field of view to a fraction of the diffraction-limited image size for periods which might typically be several hours. Since the diffraction-limited image size is about 0.05 seconds of arc for a two-meter aperture, the required guidance accuracy is about 0.01 seconds of arc. This corresponds to about 5×10^{-8} radians or one inch in 300 miles.

The only feasible method of achieving this degree of stability is to use stars within the telescope field of view as a guidance reference. Any other method, such as a separate boresighted guidance system, is doomed to failure by the thermo-elastic deformations occurring in the entire telescope structure as the satellite sweeps in and out of the earth's shadow. With common guidance and imaging optics, it is possible to achieve a very high degree of immunity

TABLE 9
EQUIPMENT MODULE TABLE OF TECHNOLOGY

Equipment Module	Identification	Pitch Yaw Guidance Technique	Roll Guidance Technique	OTES Experiment No.	Comment
A	Flip Mirror Power Supplies Active Optics Electronics			1	
B	Laser	Transfer Lens	Risley Prisms	5, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33	
C	f/10 Film Imagery	Transfer Lens or Free Float Body Point	Rotation of Film and PMT Package	9, 34	Stratoscope II in space
D	Echelle Spectrograph	Free Float Body Point	Image Mover	9, 34	Adaptation of Princeton Advanced Satellite
E	Rowland Circle Spectrometer	Flexure Gimbals Body Point	None	9, 34	OA0 C
F	f/50 Electronic Imagery	Secondary Tilt	Rotation of Vidicon & PMT Package	9, 34	
G					Spare

to structural changes since these produce identical changes in the guidance and image fields which are indistinguishable from guidance errors and which are nulled by the guidance system.

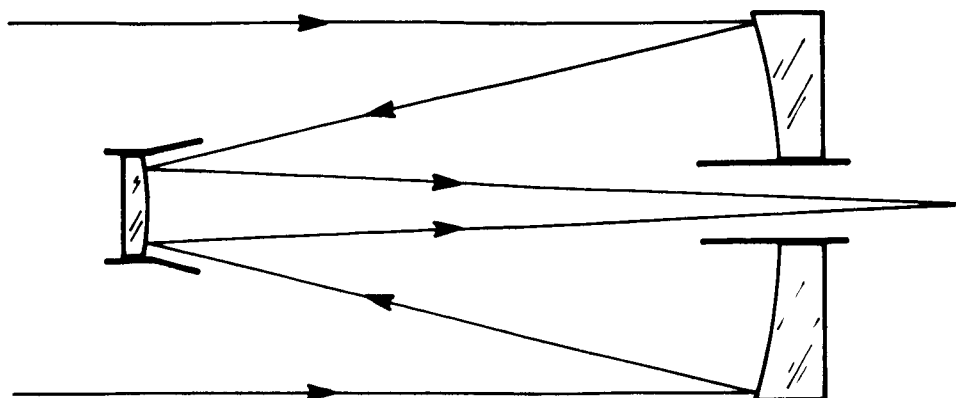
Telescope Optical Requirements

One of the most stringent requirements imposed by the OTES package is that of a fast telescope primary mirror. This is necessary in order to keep the total length of the telescope tube in bounds since the telescope structure must extend out to the center of curvature of the primary where the active optics sensing unit is located.

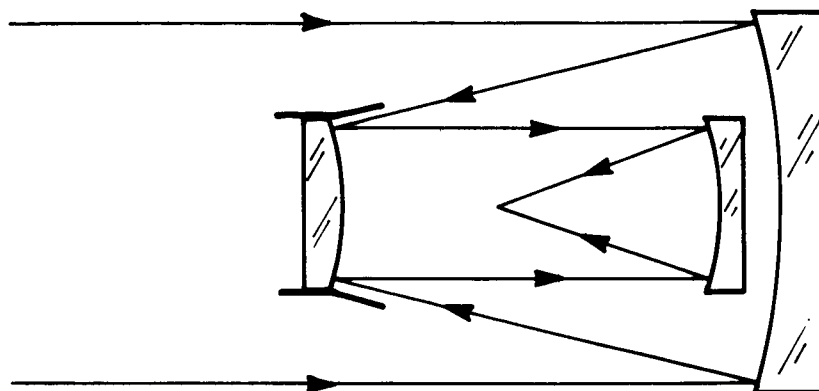
The size of the telescope field is also a consideration. A minimum size is determined by the probability of finding at least two guide stars of sufficient brightness sufficiently close to an arbitrary image field that they may be used for guidance. For a 2-meter aperture telescope operating on twelfth and lower magnitude guide stars, a guidance field between twenty and thirty minutes of arc diameter is required. This is a rather large field for a 2-meter, diffraction-limited telescope, especially if it has to have a fast, $f/2$ primary in order to keep the overall length within bounds.

A number of possible telescope configurations are shown in Figure 172. The Baker 3 Mirror Telescope is a relatively new discovery which came to light during a systematic survey of the properties of 3 mirror telescope systems*. The design utilizes a parabolic primary and two nearly spherical reflective corrector elements. It is capable of producing a strictly flat field free of spherical aberration, coma and astigmatism. In fact, the correction afforded in the Baker design is sufficient to render a 200-inch diameter $f/3.3$ paraboloid diffraction-limited over a 66 minute of arc field. This is comparable with a field of a few seconds of arc for an uncorrected paraboloid. The principle drawbacks with the Baker telescope are the large obscuration, the inconvenient location of the focal plane, the low f /number at the focal plane, and the long baffle required to shield the focal plane from radiation directly incident off the tertiary mirror. For the 2-meter OTES application, the location of the focal plane in front of the telescope is an advantage for the manned optical technology mission. However, the Baker telescope would restrict the size of the instrument package to about twenty inches diameter maximum, thereby severely limiting the variety and flexibility of optical experiments. Therefore, the Baker design is not suitable for the 2-meter OTES telescope despite the remarkable field size provided by this instrument. The 3 mirror Baker design remains a most promising candidate for the larger telescopes of the future such as MOAT.

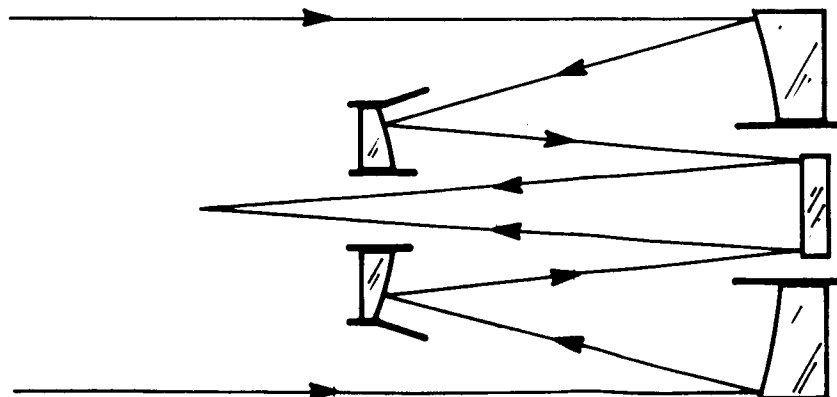
* Baker James G.; In Improving the Effectiveness of Large Telescopes, presented on October 12, 1965 at the meeting of the National Academy of Science in Seattle, Washington.



Cassegrain (Ritchey Chretien) Telescope



Baker -3 Mirror Telescope



3 Mirror Telescope

Figure 172. Telescope Configurations Considered in the OTES Design

There are other 3 mirror systems which have a more conveniently located focal plane at the cost of introducing third order aberrations. A typical example is the bottom illustration in Figure 172. Assuming the three mirrors were suitably aspherized, it should be possible to eliminate spherical aberration, coma, and astigmatism, leaving only field curvature. In some applications field curvature can be accommodated by the use of a curved film plate or vidicon face, but it is not conveniently handled if the outer portion of the telescope field is used for guidance. Furthermore, the large obscuration ratio of baffled 3 mirror telescope systems has a profound effect on the diffraction-limited image profile. This is illustrated in Figure 173, which shows a cross section through the diffraction-limited image profile as a function of the obscuration diameter ratio. As the obscuration ratio increases, more energy is removed from the central core and placed in the outer rings. For an obscuration of 20% ($\alpha = 0.2$) which is representative of a Cassegrain telescope arrangement, the loss in intensity at the image core is only about 4% (Figure 173). However, for 60% obscuration which is representative of a 3 mirror system, the loss from the central core is a very considerable 36%. These are diffraction losses only; a further loss occurs because the obscuration reduces the effective collecting aperture area so that a 20% obscuration causes an 8% energy loss and the 60% obscuration causes a 60% loss. The deleterious effect of a larger obscuration is also evident in Figure 174, which shows the diffraction-limited transfer function for various obscuration ratios.

Of the three telescope configurations considered, the Cassegrain has the minimum obscuration. Other advantages of the Cassegrain arrangement include: a long focal length, a conveniently located instrument package, a minimum number of reflections, and a low obscuration ratio. The number of reflections is extremely important in the far UV where the amount of scattering and absorption on reflection is high and where the wave front errors, due to surface imperfections and misalignments are appreciable.

Unfortunately, of the three telescopes thus far considered, the Cassegrain arrangement has the smallest field. In the conventional Cassegrain employing a parabolic primary and a hyperbolic secondary, the field is limited by coma and thus is very small. However, with an appropriate combination of aspherics on the primary and secondary, it is possible to eliminate spherical aberration and coma, thereby achieving a moderate size field. This modification is known as a Ritchey-Chretien telescope.

A 2-meter Ritchey-Chretien employing an $f/2$ primary and a secondary with magnification of 5 would have a flat field of about 5.5 minutes of arc which is limited by field curvature and astigmatism. This is much smaller than the twenty or thirty minutes of arc diameter field required by the guidance system, so that it is necessary to extend the field further with a Ross type of refractive corrector situated near the focal plane. Ordinarily, the addition of refractive components places narrow bounds on the spectral range of a telescope, but this can be avoided by cutting a hole through the center of each of the corrector elements so that the center portion of the telescope field used for imaging or spectroscopy, remains all-reflective and the outer portion of the telescope field, used for guidance, contains the refractive components.

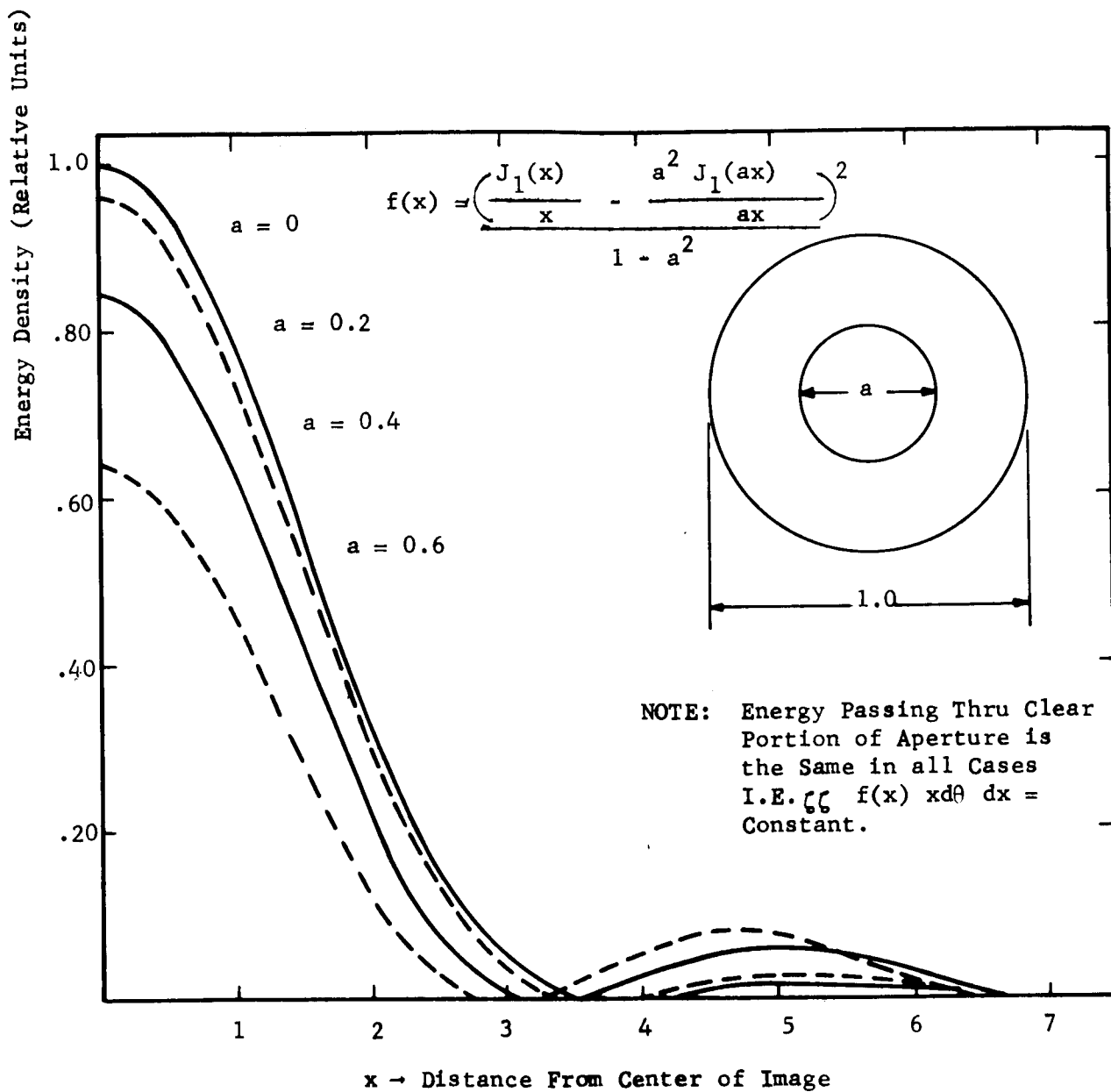


Figure 173. Change in Diffraction-Limited Energy Distribution with Obscuration Ratio

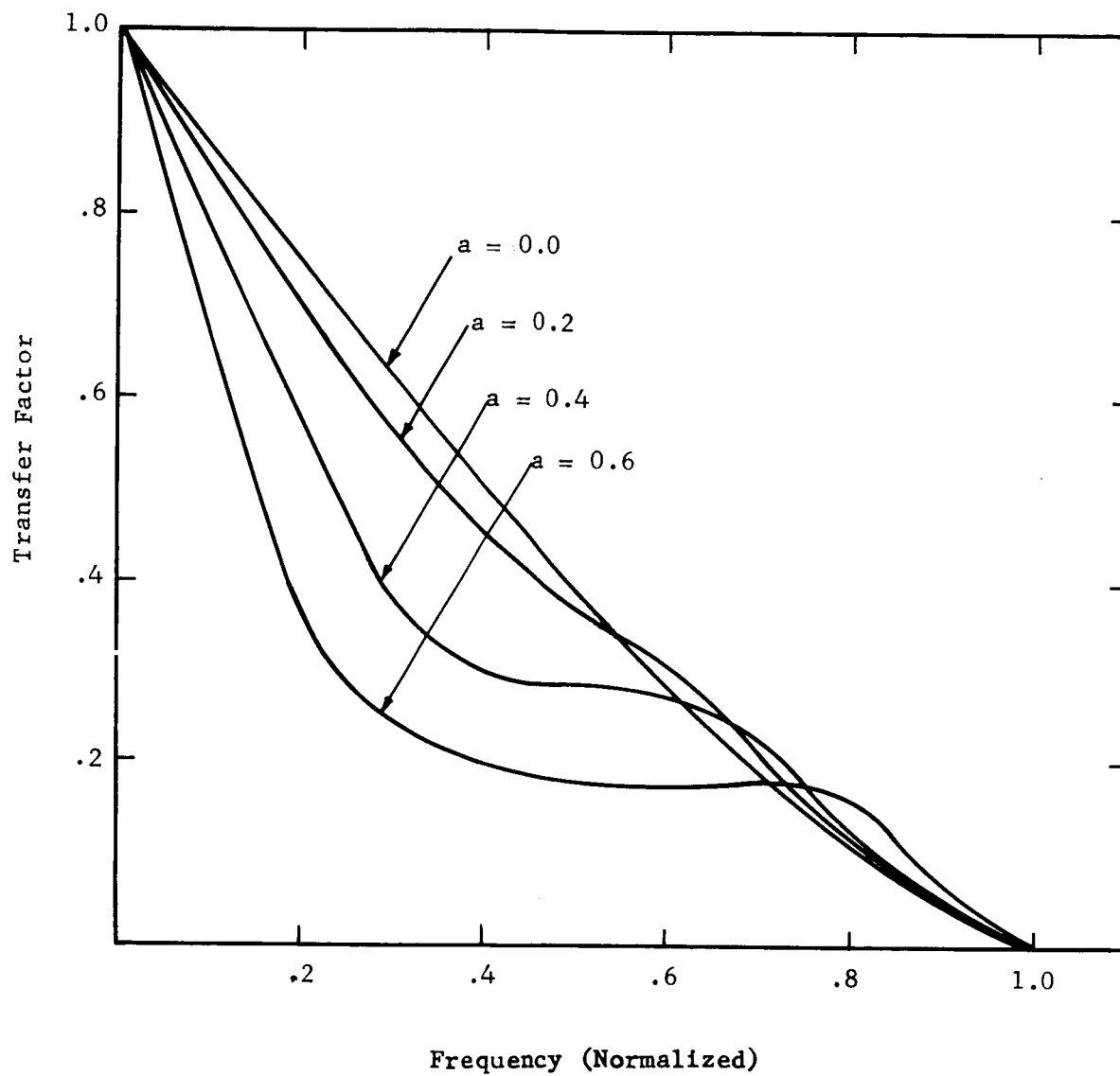


Figure 174. Effect of Obscuration Ratio on Diffraction-Limited M.T.F.

A well-corrected Ritchey-Chretien telescope might typically have an image size of about one second of arc at the edge of a half degree field. This is adequate for Earth-based astronomy, but is a factor of 20 too large for diffraction-limited imagery in a 2-meter aperture space borne telescope. Since the guidance error is directly proportional to the image size, a one-second of arc image size would be prohibitive on any but the brightest stars of which there are too few. Previous optical design on a similar optical system* had indicated that very significant improvements could be obtained on the field performance of the Ritchey-Chretien design. Continuation of this work on an appropriately scaled system finally led to a four element corrector design which is close to diffraction-limited out to the edge of a 30 minute diameter field. This is described in detail in the section on OTES Telescope and Corrector Optical Design.

OTES Experiment System Optical Layout

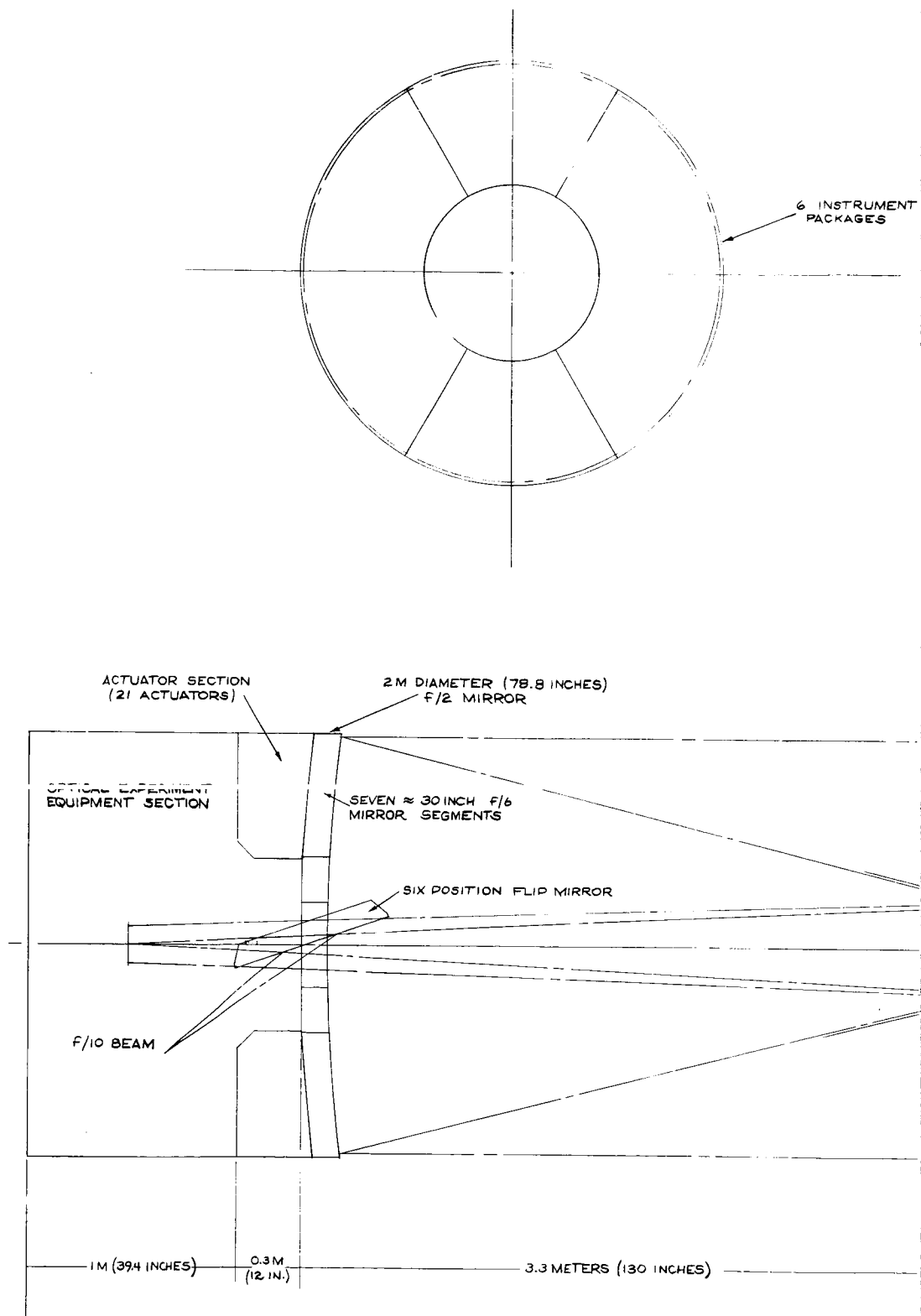
The optical arrangement of the OTES experiment package is shown in Figure 175. The middle of the package contains a fast, 2-meter aperture Cassegrain telescope. Behind the segmented primary mirror, and at one end of the experiment package, is a large instrument package which is divided into 6 pie shaped segments located around a hexagonal central core. The core contains electronics for active control of the mirror segments and an indexing motor for a large folding flat which can be positioned so that the f/10 telescope focal plane lies in the center of any of the 6 individual instrument sections. At the other end of the experiment package, and at the center of curvature of the primary, is a small package containing an interferometer which senses the figure of the segmented primary mirror. Immediately beyond the active optics interferometer is the sun shade. This is oriented so as to shield the open end of the telescope tube from direct sunlight when in the open position, and is closed automatically when ever the sun approaches closer than 45° from the optical axis.

The instruments contained in the 7 instrument sections are as follows:

- A. Active Optics Electronics and Flip Mirror
- B. Laser Propagation Experiment Package
- C. f/10 Wide Field Photographic Camera
- D. Echelle Spectrograph with Redundant Vidicon Readout
- F. f/50 Vidicon for Imaging, and Multi-spectral Spectrophotometry
- E. Rowland Circle Spectrometer with Far UV Capability
- G. Spare

* Princeton Advanced Satellite Study - Final Report, Perkin-Elmer Report 8688 for Princeton University Observatory

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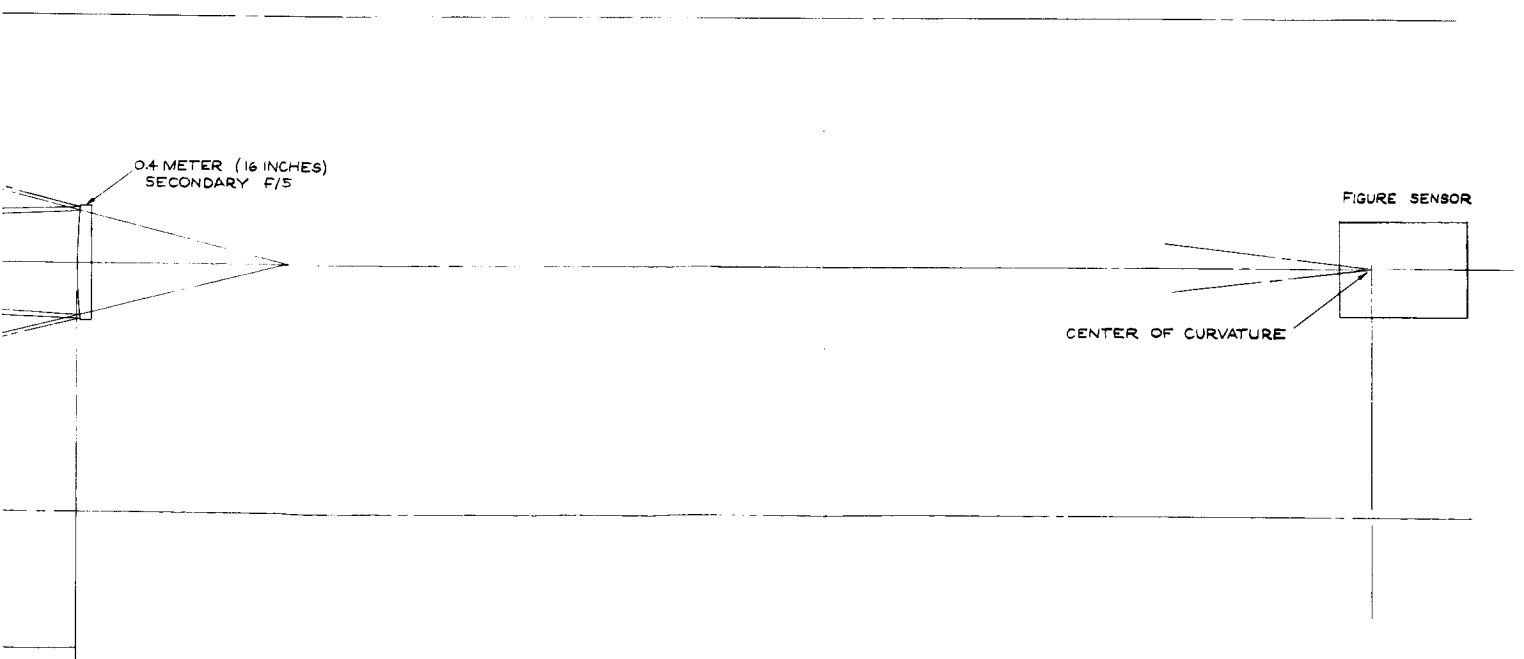


Figure 175. OTES 2-Meter Telescope Optical Layout

Three instruments (C, D and F) utilize a pair of guide stars in the instrument field of view for guidance and are capable of obtaining images or spectra of very weak stellar objects. The fourth instrument (E), the Rowland Circle spectrometer, uses the target star for guidance and is limited to brighter stars. The laser propagation experiment is not stellar oriented, but is designed to lock on to and track an Earth-based beacon.

The optical design of the telescope was a key factor in providing the wide range of optical instruments and experiments which are incorporated in the OTES package. In order to stabilize the telescope field on virtually any portion of the sky, it was necessary to approximate diffraction-limited imaging out to the edge of a 30 minute of arc diameter field. This represents roughly an order of magnitude improvement over many similar designs proposed for Earth-bound astronomy. The use of pierced corrector elements extends the useful spectral range from about $4000 \text{ \AA}$ where most glasses start to absorb, to the far UV beyond the important Lyman Alpha and Lyman Beta hydrogen emission lines. Most importantly, the telescope optical design is compatible with the associated guidance and remaining systems. For these reasons, the telescope optical design is discussed separately in the following section.

OTES Telescope and Corrector Optical Design

The OTES telescope optical system is shown in Figure 176.. A fast $f/2$ primary and a secondary with 5 times magnification form an $f/10$ optical system with a focal plane about 925 mm behind the primary vertex. The primary-secondary combination is free of spherical aberration and coma but is limited by field curvature and astigmatism. Using the Rayleigh quarter wavelength tolerance criterion and a wavelength of 0.5 microns, the uncorrected field is about 5.5 minutes of arc diameter.

The field is increased to 30 minutes of arc diameter by a four element refractive corrector array positioned immediately in front of the focal plane. The corrector details are shown in Figure 177.. It was designed to be compatible with the requirements of the $f/50$ vidicon imagery package since these were believed to be the most stringent, and because a corrector compatible with this instrument section would be compatible with the other sections. Improvements in the performance of the corrector could undoubtedly be made providing the latitude available in the other packages was utilized. However, since the present optical design is sufficient to demonstrate feasibility, further optical design reiterations were not attempted.

Inherent in a compact high f /number Cassegrain telescope is a highly curved focal plane requiring a corrector with net negative power. In the present optical design this changes the f /number from $f/10$ to $f/11.12$ and shifts the position of the focal plane backwards about 34.2 mm. The negative power in the corrector also shifts the position of the exit pupil from a position normally behind the secondary to a point much closer to the primary. This results in an appreciable angle between the marginal chief rays and the optical axis which, in turn, can prove to be a serious handicap to the performance of a reimaging microscope or other optical system designed to operate with the telescope. The $4^\circ\text{-}45'$

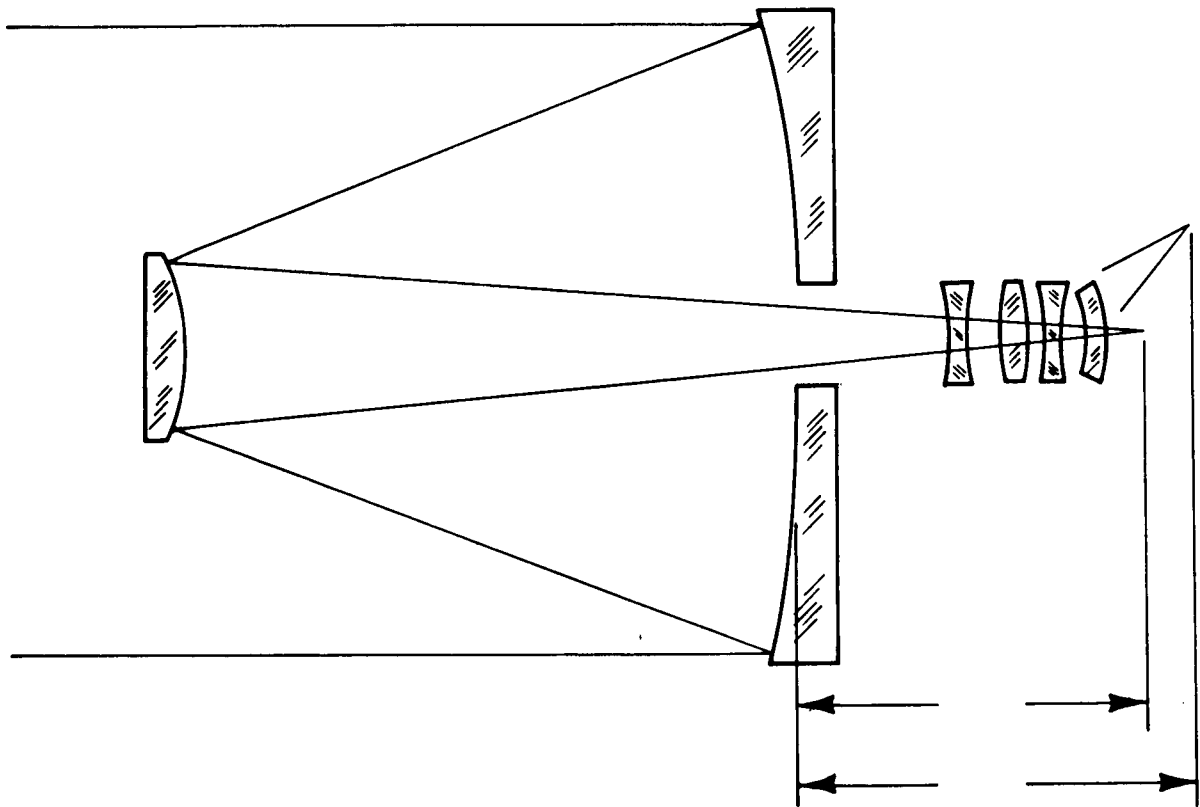


Figure 176. OTES-2-Meter Telescope
and Corrector Optical Design
Concept (without folding flat)

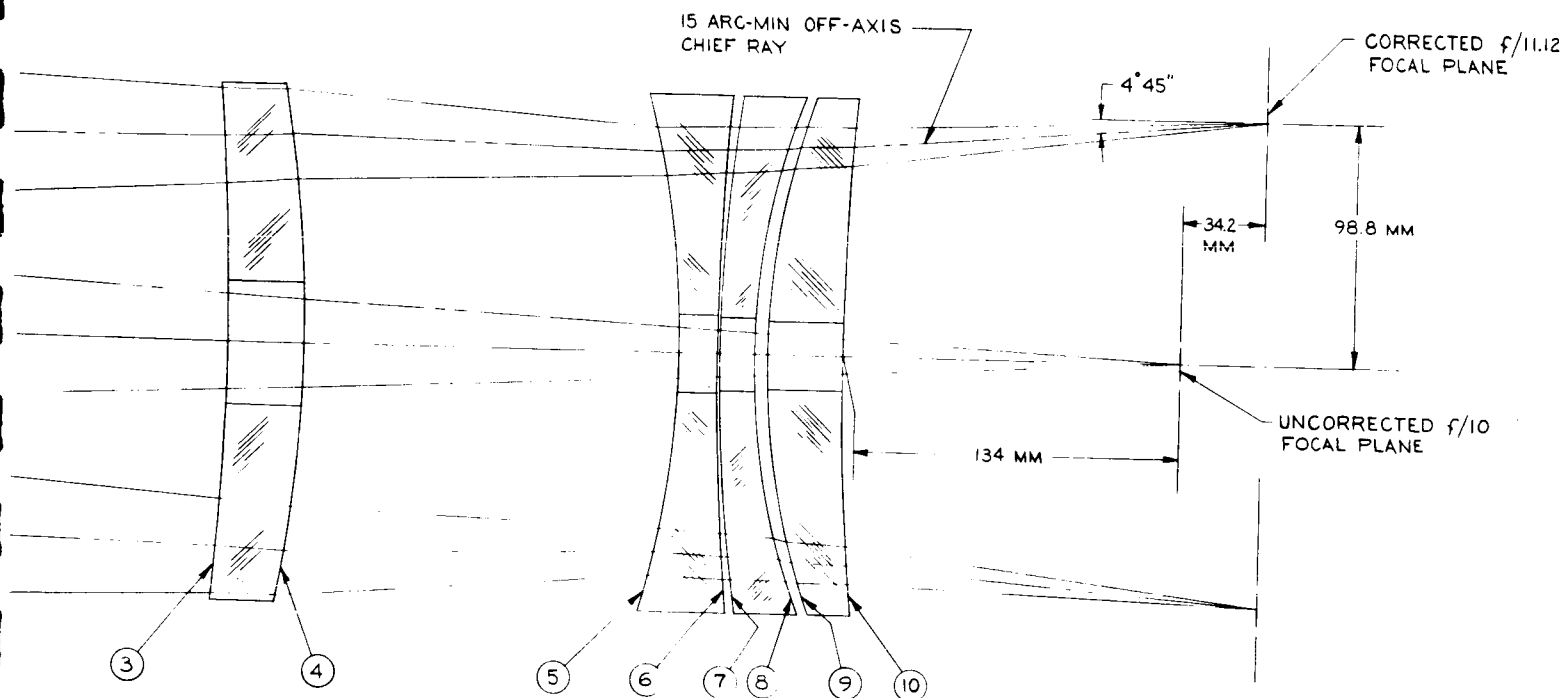


Figure 177. Telescope Corrector Details

divergence angle of the chief rays in the present optical design was imposed as an optical system constraint which undoubtedly compromised the field performance of the telescope but enhanced the performance of the f/50 imaging microscope. Other optical design constraints included the maximum and minimum distances between the corrector elements and the focal plane. A minimum distance was necessary to insure sufficient room for the image moving system which locates the guide stars in the f/50 vidicon image package. A maximum distance reduced the amount of the telescope field which would be vignetted with the transition from an uncorrected field to a corrected field.

Figure 178 shows the results of an exact geometrical ray trace through the Ritchey-Chretien telescope and corrector. The meridional and skew ray fans used in the ray trace are illustrated schematically in Figure 179.. The field angle is assumed to lie in the Y,Z plane and is defined as the angle between the optical axis and an incoming chief ray which passes through the center of the entrance aperture. In most astronomical telescopes (with the Schmidt being an obvious exception) the primary mirror acts as the entrance aperture. The aberrations are calculated by subtracting the focal plane coordinates of the chief ray $\bar{X}_K, \bar{Y}_K$ from the coordinates of a skew or meridional ray. Since meridional rays are confined to the Y-Z plane by definition, the aberrations of these rays are given by $\bar{Y}_K - \bar{Y}_K$. In general the coordinates of skew rays differ from those of the chief ray in both X and Y directions. However the X direction aberration usually predominates and since $\bar{X}_K$ equals zero, the skew ray aberrations are described approximately by X_K . The skew fan plots cover only half of the aperture since the aberrations are symmetrical across the aperture. The aberrations of colors either side of the central 4861A color for which the system is corrected are also shown in Figure 178.. In this case, the chief ray is defined from the central color only and the central rays for the other colors do not pass through zero because of chromatic aberrations.

There are several ways of assessing image quality. One of the simplest is to compare the geometrical image size with the diffraction image size. At 0.5 microns wavelength the latter is about 6.8 microns radius or 13.6 microns diameter at the first diffraction-limited dark-ring. This compares favorably with a geometrical image size of 12 microns at 10.2 minutes of arc off-axis and less favorably with an image size of about 20 microns at 15 minutes of arc off-axis. The comparison depends on the focal plane chosen and could be altered so that the image size at both off axis positions were equal to 15 microns.

An alternate method of assessing the effects of aberrations on the theoretical diffraction-limited performance is to compare the aberrations with the tolerances derived by Rayleigh on the basis of a quarter wavelength wave front deformation. In the presence of several aberrations this technique breaks down somewhat but is still useful if applied to the predominant aberrations. At the edge of the field the worst aberration appears to be lateral color which amounts to about 8 microns. This compares to a quarter-wave tolerance of 5.5 microns for lateral color. At 10.2 minutes off-axis the lateral color almost equals the quarter-wave limit. It may therefore be concluded that although the present corrector does not quite meet the most stringent criteria for imagery at the edge of the field, it does provide adequate imagery for guidance.

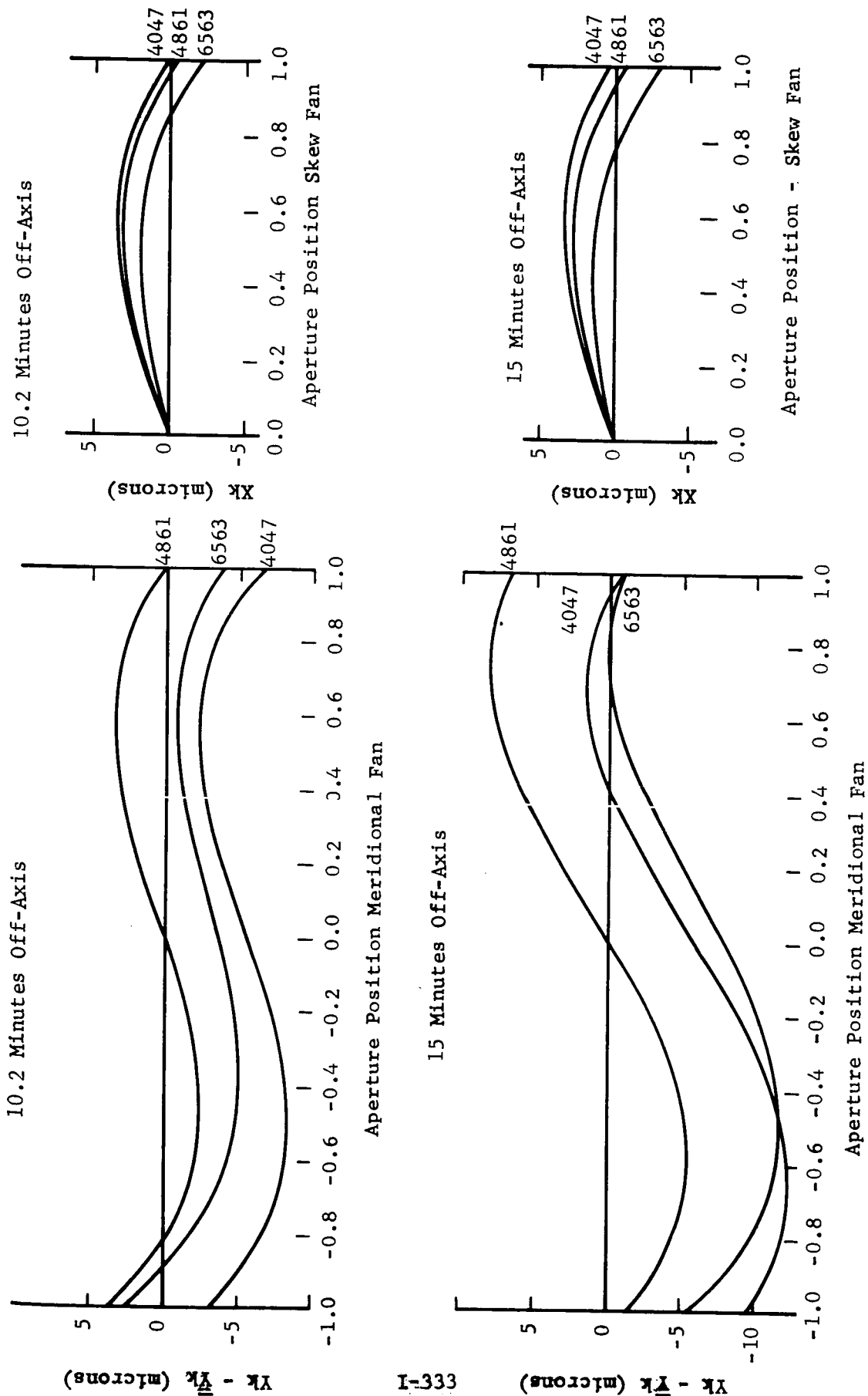


Figure 178. OTES - 2 METER TELESCOPE
Geometrical Image Size

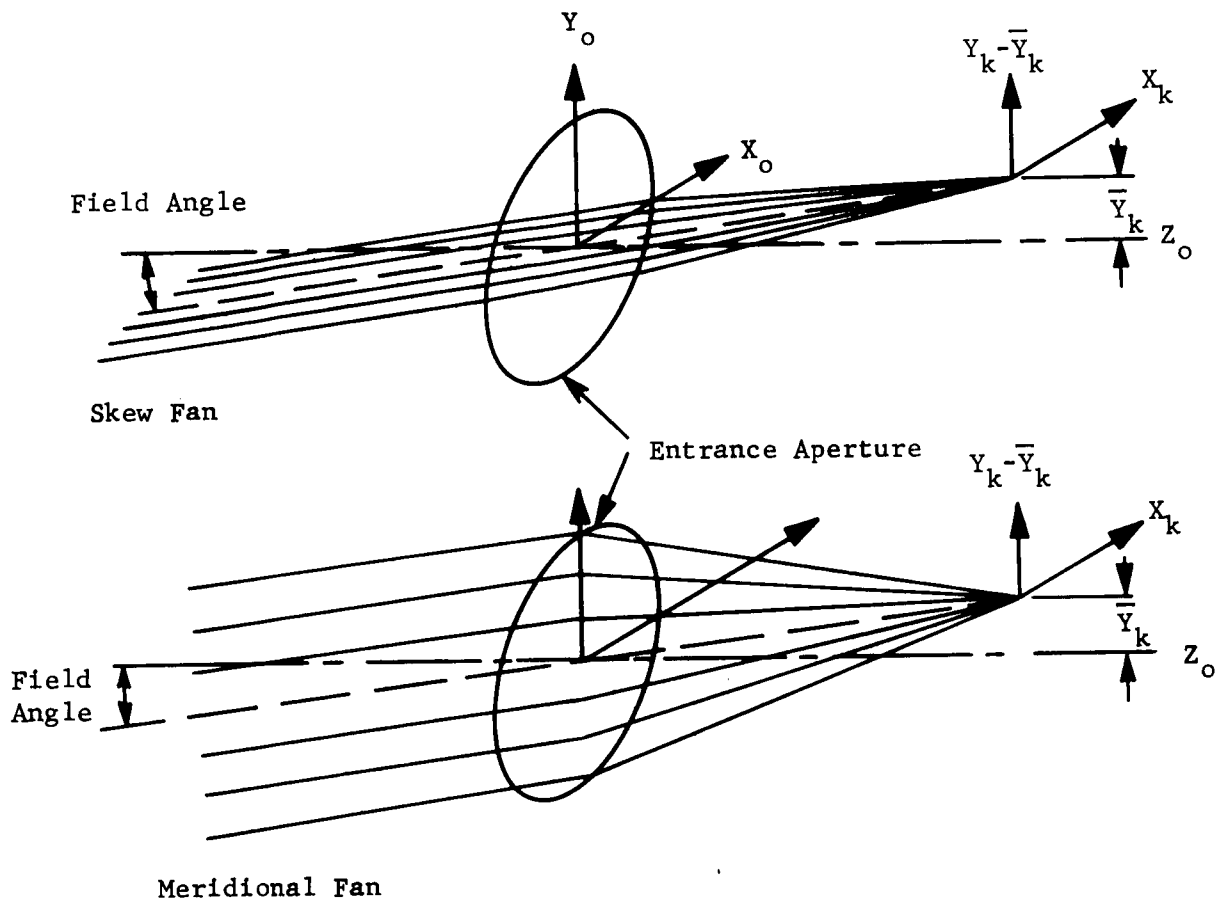


Figure 179. Meridional and Skew Ray Fans

Laser Propagation Experiments Package (Equipment Module B)

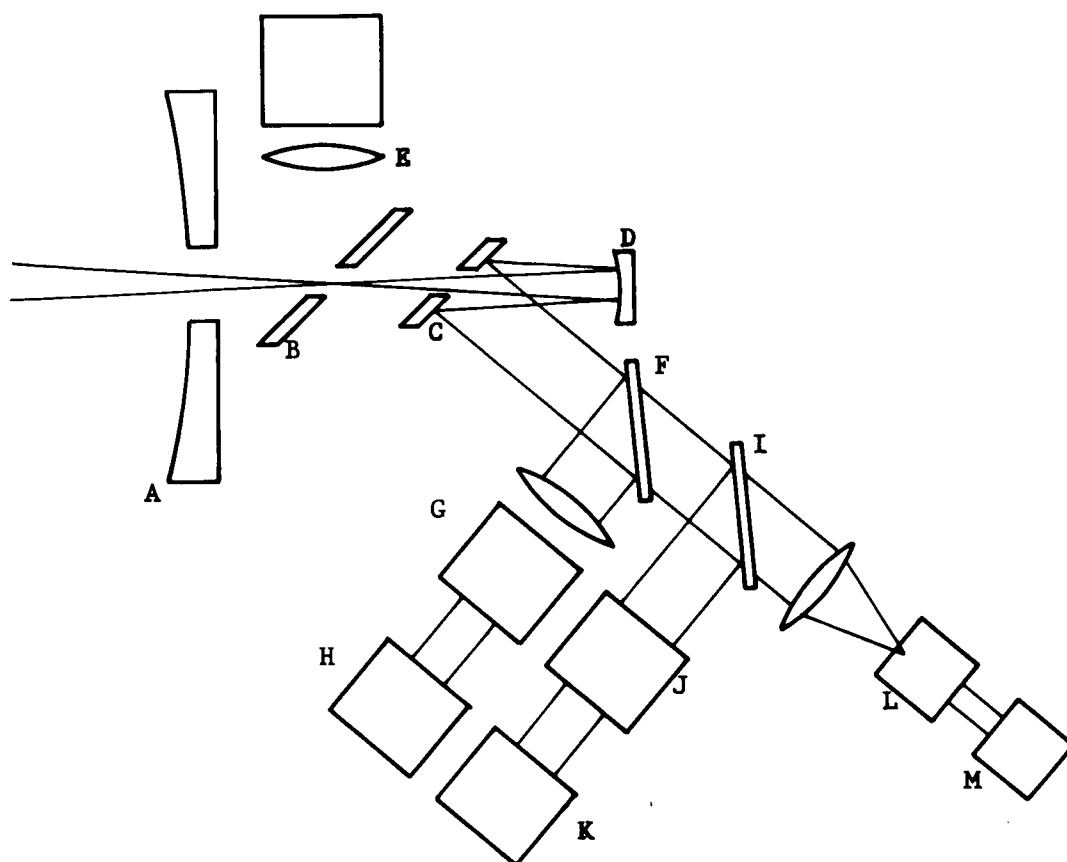
Hardware for deep space optical communications is now being developed* by Perkin-Elmer. During the first phase of the contract, the principles required for the tracking of an optical image by a system containing movable optical elements were verified. Next, these principles were used to construct a servo-controlled tracker which was used in conjunction with a 16-inch telescope to demonstrate all the tracking functions of the laser communicator. All elements were placed on a stable optical bench and no effort was extended to package these elements in a practical spacecraft volume. As a result of this phase, it became evident that no theoretical limitations existed and that the tracking-communication optics could be packaged into a small unit attached behind the mirror of the 16-inch telescope.

The block diagram of tracking optics and the CO₂ and He-Ne transmit lasers is shown in Figure 180.. The tracking and wavelength multiplexing principles developed in Phase I are being used for the present design. That is, through the use of properly aligned dichroics, the transmitted laser beam and the received Earth beacon beam are focused at conjugate focal points. By deviating a common element in the superimposed beam, it is possible to deviate both the transmitted and received beams by equal angles. The position of the deviated element is servo controlled by the output from the fine field tracker.

The functions of the laser communication package are:

- Coarse field acquisition. This subassembly finds the position of the earth beacon in the 1° coarse field of view of the telescope, and emits a signal which controls the torquers which position the telescope such that the beacon image is in the central 2 minute field of view of the telescope.
- Fine field tracking. Once the Earth beacon image is inside the central 2 minute field of view, this subassembly guarantees that the transmitted beam tracks the received beacon beam to within the diffraction-limit of the telescope.
- Point ahead. This unit inserts the correct point ahead which compensates for the angular error caused by the relative velocity between the Earth beacon station and the space station.
- Multiplexing. Wavelength multiplexing of the received beacon light and the outputs from two transmitter lasers of different output wavelengths. The present system is being designed for an argon laser Earth beacon (0.4880 micron), and transmit lasers of wavelengths 0.6328 micron (helium neon) and 10.6 micron (CO₂ laser). Present developments indicate that the 0.6328 micron laser may well be replaced by the YAlG:Nd laser/nonlinear crystal combination which will yield a 0.5300 micron output wavelength.

* Contract No. NAS8-20115, MSFC,



- | | |
|--|---|
| A - Primary Mirror | H - Helium-Neon Laser |
| B - Coarse - Fine Field Dividing Mirror | I - Dichroic - Transmits 10.6μ
Reflects $.4880\mu$ |
| C - Servo Controlled Mirror | J - Risley Prisms |
| D - Collimating Paraboloid | K - Tracking Optics |
| E - Coarse Field Acquisition Optics | L - 10.6μ Modulator |
| F - Dichroic - Transmits 10.6μ , $.4880\mu$
Reflects $.6328\mu$ | M - CO_2 Laser |
| G - $.6328\mu$ Modulator | |

Figure 180

- Optical communications. Volumes within the package are being reserved for the modulators and other communications support equipment which are needed for the prototype.

To package all of the above elements into a confined volume requires folding of the optical paths into many skew planes. A simplified schematic will be used for the discussion of the functions of the separate subassemblies. The same letters are used on both the engineering drawings (Figures 181, 182, 183 and the simplified schematic (Figure 180) for common reference.

The system has several unique features which have been newly developed especially for this application. Two of the more important changes are the introduction of an all reflective servo control transfer lens system mirror and development of infrared/visible dichroics. These changes now allow the system to operate simultaneously at a number of wavelengths. These wavelengths may range between the visible to the middle infrared. These features will now be discussed in some detail.

Coarse Acquisition

The prime focus plane of the telescope bisects the coarse/fine field separation mirror (B). During the initial stages of the acquisition the Earth beacon image will appear at the edge of the 1° field of view of the telescope. This energy is reflected by the coarse/fine field separation mirror (B) into the coarse acquisition subassembly (E). Figure 183 is a sectional view showing the coarse acquisition subassembly in detail.

The pyramid/field lens (E1) performs a dual function of a field lens and field splitter. This element serves to image the entrance pupil of the telescope--in this case the periphery of the primary mirror--onto the plane where the detector is located. The second surface of the field lens which is pyramid-shaped forms four separate images of the telescope entrance pupil in the detector plane. Each image corresponds to one quadrant of the coarse acquisition field.

The field splitter/field lens is fabricated from a special glass type that has an index of refraction of nearly 2 (SFS-1). This enables a short focal length to be achieved without having a steep lens curvature. It also has the advantage that a single anti-reflection coating of magnesium fluoride (index nearly 2) results in a negligible reflection loss at each air glass surface.

A folding prism (E2) folds the optical axis 90° and compensates for some of the aberrations introduced by the asymmetry of the pyramid/field lens. The pyramid/folding prism reduces the convergence angle of the light entering the predetection spike filter (E3). Since the bandwidth of narrow band optical filters is limited by the convergence angle of the incident radiation, the addition of the pyramid/faces and the prism allows the application of the new Fabry-Perot cavity filters developed by Perkin-Elmer.

The EMR type 573-E quadrant multiplier tube (E4) is the photodetector chosen for the coarse acquisition assembly. The quadrant multiplier phototube consists of four electrically independent cathode quadrants, followed by a common electrode chain consisting of a bias electrode, a focus electrode, and 14 dynode stages. A given quadrant is "on" when it is at the same potential as the bias electrode. The "off" condition is achieved by biasing a quadrant approximately 20 volts positive with respect to the bias electrode.

Special switching circuitry has been developed for the coarse acquisition subsystem, which biases two adjacent quadrants on, and holds the opposite half of the photocathode on. Every quarter cycle, this half on, half off, photocathode configuration is rotated by 90° . The effect is as much as if a semi-circular chopping wheel were rotating in front of the four separate photomultipliers, each of which senses one quadrant of the coarse acquisition field. It is readily established that, with reference to the chopping cycle, the in-phase and quadrature signal at the output of the detector indicate unambiguously the presence of the beacon in the respective quadrant of the coarse acquisition field.

Collimating and Transfer Lens Optics

During acquisition, the output from the coarse acquisition subsystem controls the gimbal torquer motors.* These torquers rotate the communicator structure to a position where the beacon light is centered in the prime focus plane. This light then passes through the hole in the coarse/fine field separator. The beam is then collimated by a parabolic mirror (D). The use of this technique has the additional advantage that the paraboloid compensates for some residual aberrations which result from the Ritchey-Chretien (hyperbolic primary) telescope.

The collimated beam is reflected by the servo transfer mirror (C). The optical transfer bundle is rotated in two dimensions (yaw and pitch) about its optical center.

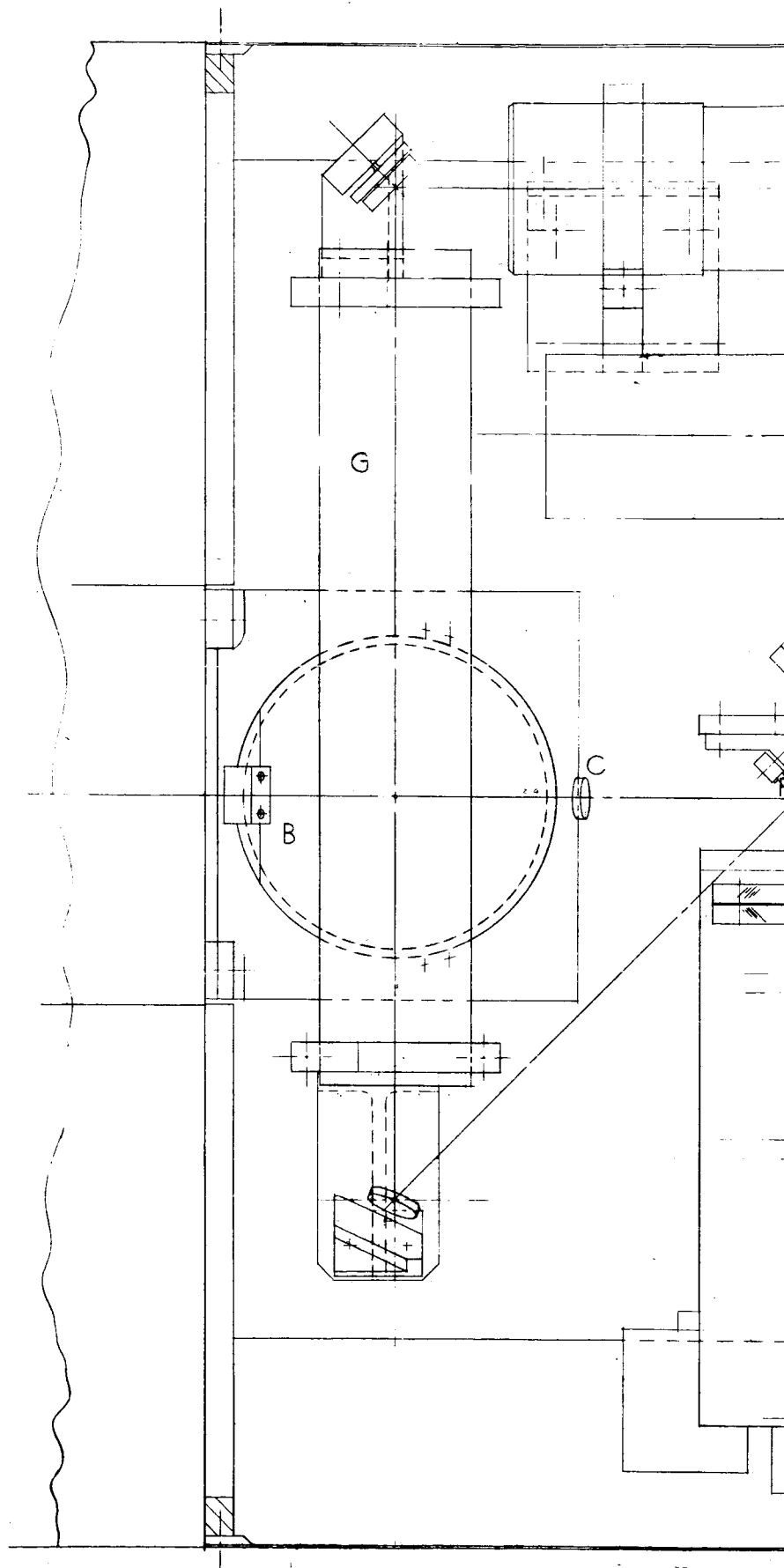
This element will introduce a small rotation of the field. This rotation is minimized by using the mirror at near-normal incidence (7.5°). Calculations show that the maximum rotation of the field (8 minutes) is within the system rotation about the line of sight tolerance for the synchronous satellite.

The exit pupil of the telescope (that is, the image of the primary mirror) is found near the servo controlled element. The advantage of this optical layout is that for small deflection angles expected there is no vignetting of either the transmitted or received beams by the mirror when the image is anywhere in the central 2-minute field of view.

The servo controlled optic is an annulus with an outside diameter of 8 mm and an inside diameter of 3.5 mm. The ratio of these values is equal to the ratio of the primary and the secondary mirrors of the telescope. Thus the annular construction of the mirror causes no additional vignetting to the system.

* Vernier Pointing Control System for ATM. This is the flexure bearing gimbal system under development by Perkin-Elmer for MSFC for ATM (Contract NAS 8-20772).

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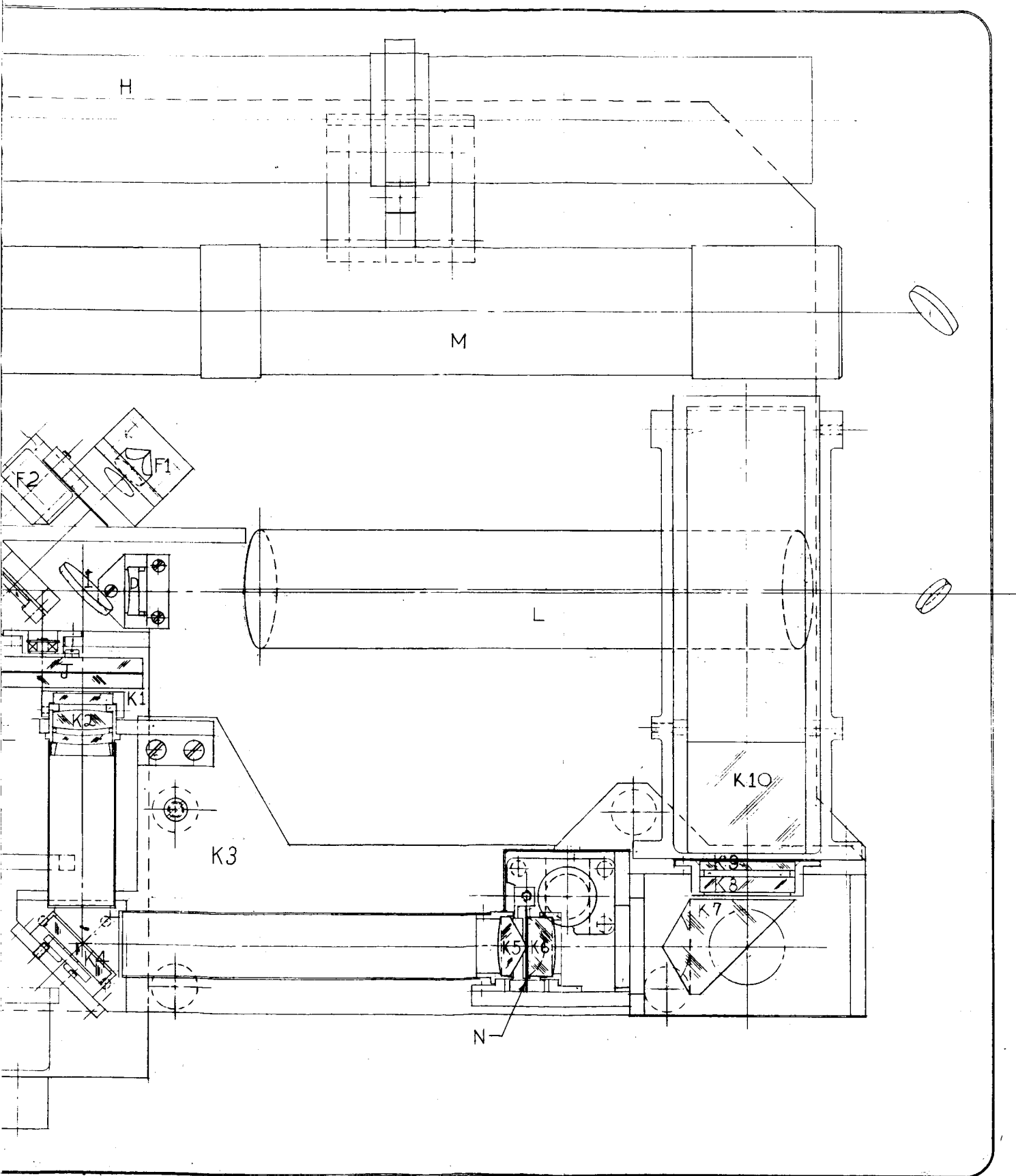


Figure 181. Laser Experiment Module (B) Layout

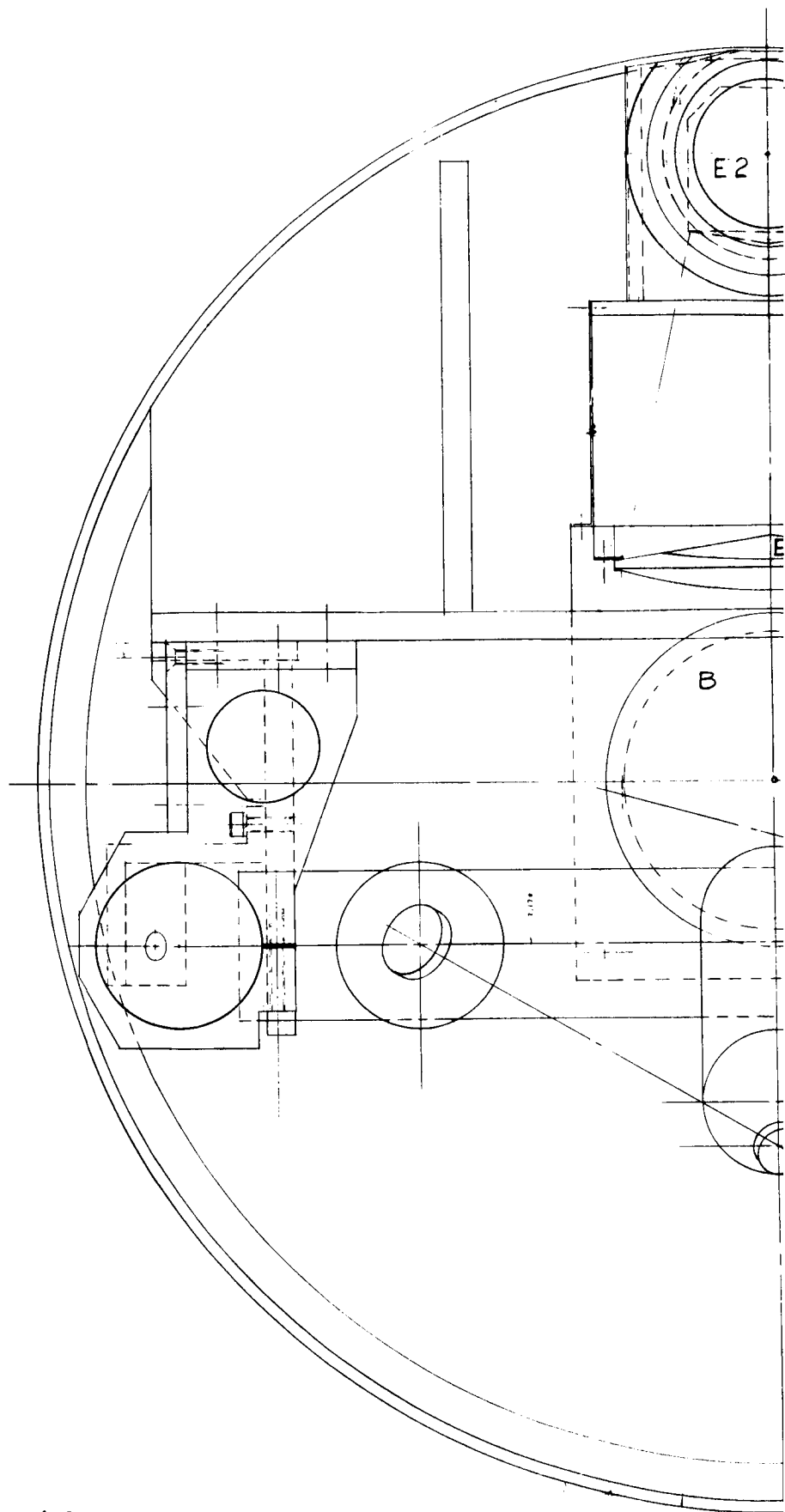
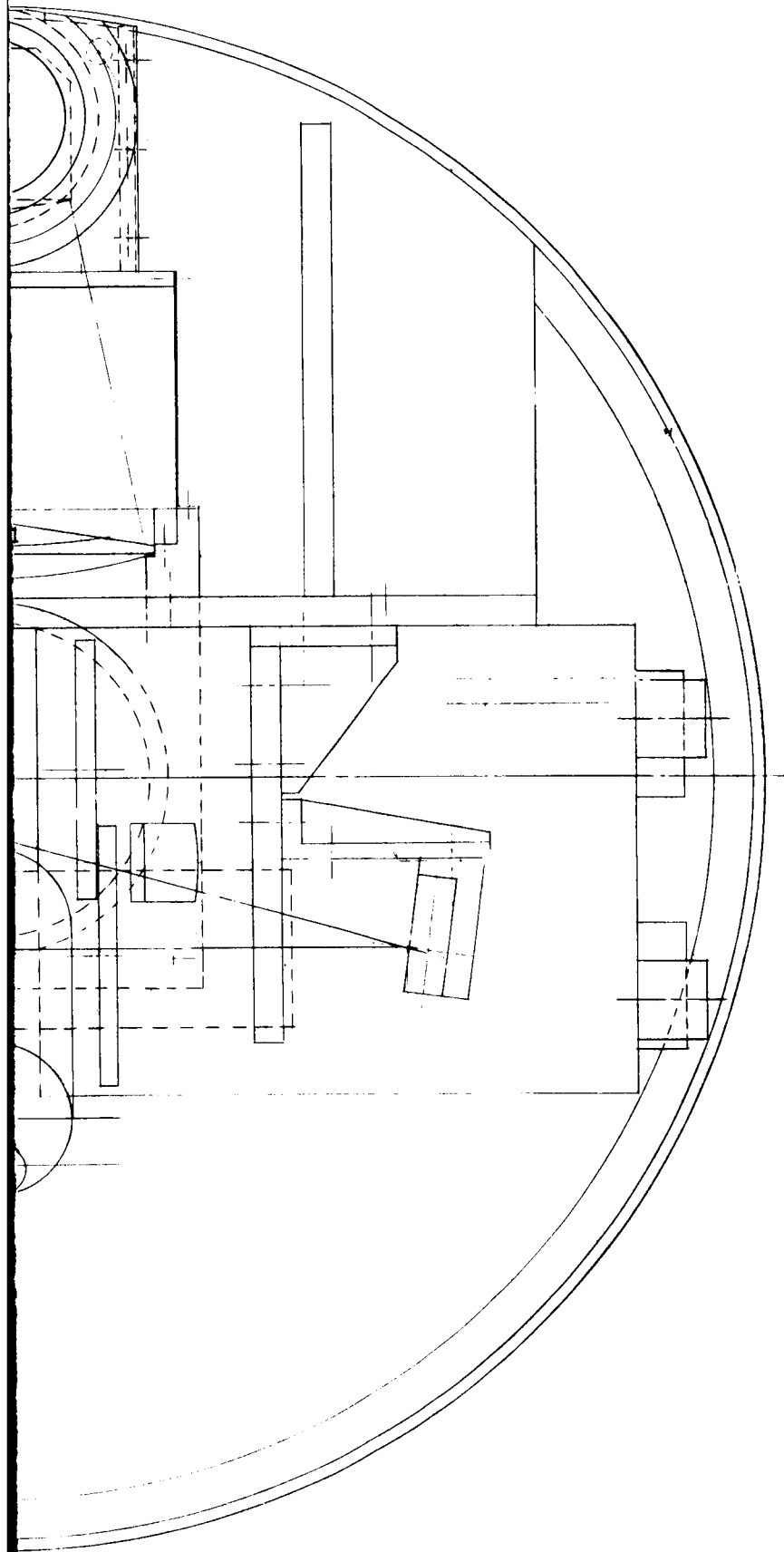
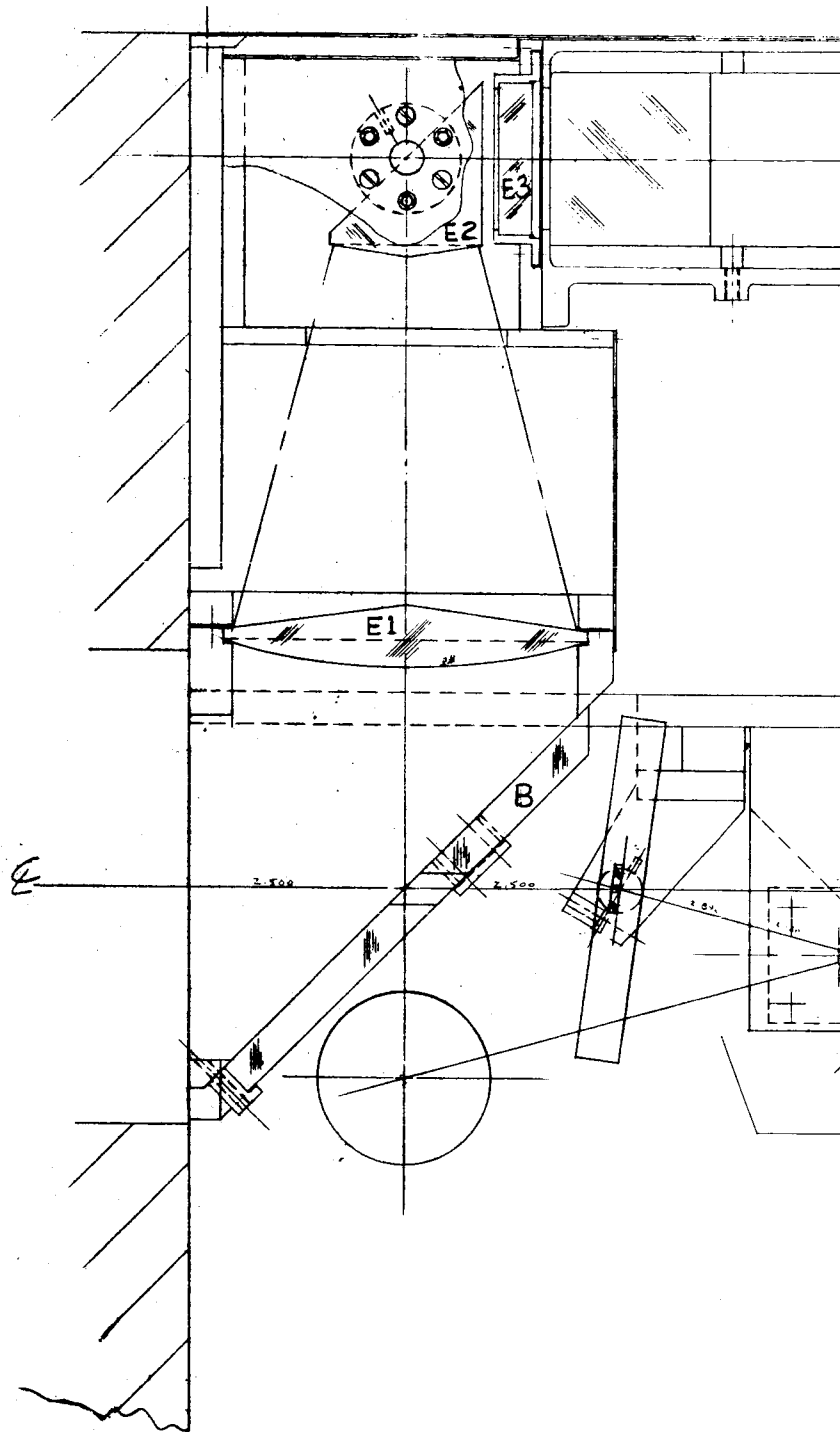


Figure 182. Laser Experiment Module (B0)
End View Layout



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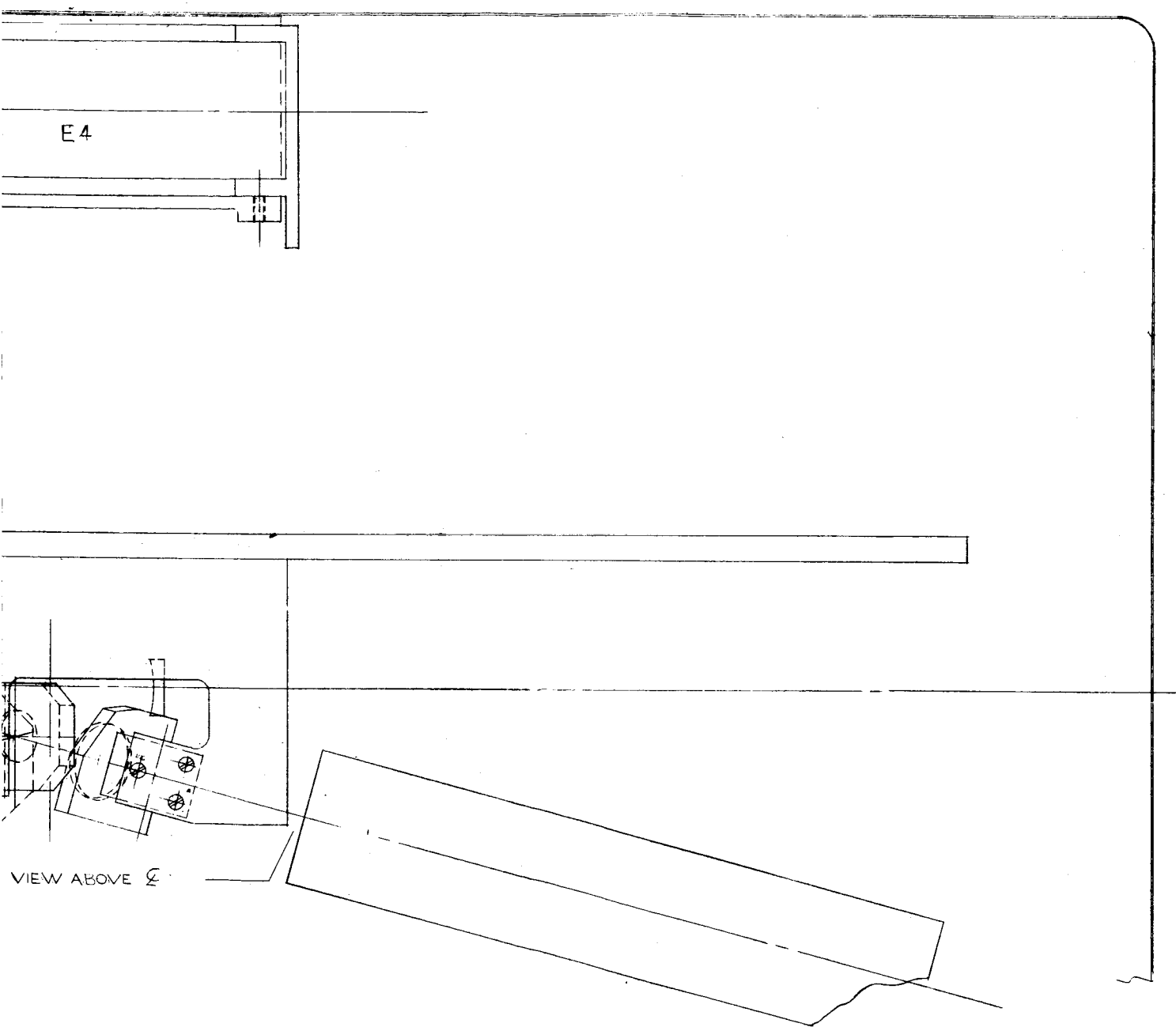


Figure 183. Laser Experiment Module (B) Layout

Tracker and Point Ahead

In general, there will always exist a finite relative transverse velocity, V , between the spaceborne laser telescope and its associated ground station. Because of this, the apparent beacon line of sight as seen by the spacecraft will differ from the correct aiming direction if the transmitted beam is to hit the ground station at or near the beacon. Assuming initial boresight alignment of the transmit and receive lines of sight, the magnitude of the offset angle (θ) away from this boresight reference is approximately $\theta = 2V/C$, where V is the velocity of light. This angle is compensated by introducing Risley prisms in either the transmit or received beams.

The previous communicator breadboard had the Risley prism (J) in the transmit channel. The addition to the present system of the capability of multiple transmit wavelength requires that a Risley prism in the transmit channel have multiwavelength capability. The design was significantly simplified by placing the Risley prisms in the tracker channel since it operates with a single wavelength of 0.4880 microns. We thus have, in fact, a "point-behind" technique where the received Earth beacon line of sight is now offset in the transmit line of sight, which is collinear with the optical axis of the telescope. The Risley prism unit developed during the preceding phase of the contract will be used in the assembly.

After the initial acquisition operations in which the tracked image becomes spatially stable, the field of view as seen by the tracker is reduced. This significantly reduces the detrimental effect of Earthshine. The adjustable field stop (M) will be an iris in the image plane which will vary the field of view between 120 arc-seconds and 2 arc-seconds. The bandwidth of the background Earthshine is determined by spike rejection filter (K1).

The received 0.4880 micron beam is decollimated by a 280 mm doublet (K2). After being reflected by the mirror, K4, an image is formed on the two crossed lens/dividing roof prisms (K4 and K5). This arrangement allows the generation of a sharp quadrant dividing edge in the focal plane. The diverging light pencils are recollimated and folded by the pyramid/folding prism (K7). The received Earth beacon light is alternately switched between right hand and left hand circularity polarization. The $\lambda/4$ plate (K8) converts these circular polarizations to plane orthogonal polarizations, only one of which is passed through the polarizer. Thus the four quadrant photomultiplier tube (K10) detects an alternately switched on-off beacon. The photodetector is identical to the EMR tube previously discussed for the coarse acquisition. All elements of the tracker are hard mounted on the basic structural carriage K3 which is designed to insure all optical elements will remain located with respect to each other. The development of a combination middle infrared and visible dichroic filter permitted the wavelength multiplexing of several transmit and received laser outputs. For example, dichroic F transmits 0.4880 micron and 10.6 micron and reflects 0.6328 micron. To guarantee that the laser and the tracker are at conjugate foci, the corner cube (F1) assembly is introduced. A small portion of light from the helium neon laser (H) is transmitted through

the dichroic (F). Under operating conditions, this light is absorbed. However, when the corner cube is inserted by the motor, F2, this light is reflected back parallel to itself and is ultimately imaged in the focal plane of the tracker. The output of the tracker photomultiplier tube is then used as a reference to reposition the dichroic, F, in the correct position.

Space is allocated for a CO₂ laser (L) and a 10.6 micron modulator (M).

The dichroics I and F will transmit a 10 micron beam of several watts intensity. Experiments at Perkin-Elmer have shown that the deformation of a visible/infrared dichroic is negligible when 1 watt of 10 micron laser radiation is transmitted through the dichroic substrate. Thus the technique of wavelength multiplexing of infrared and visible beams is feasible for the OTES experiments at synchronous orbit. For a deep space communicator, the light paths would be somewhat different depending upon the final wavelength selected.

High Resolution Imagery (Photographic) at f/10 (Equipment Module C)

As previously indicated in Table 9 and the accompanying text, the basic purpose of Equipment Module (C) is to assist in the collection of data when the OTES is stellar pointing and Experiment No. 9 is being conducted. The equipment in this module is used to establish the feasibility of future large orbiting telescopes by conducting 1/100 arc second pointing experiments during operations of the OTES (Refer to Experiment No. 26 and Experiment No. 34) attached to the Cluster and when operating autonomously. The f/10 film package can use the transfer lens technique* which was originally developed for use with Stratoscope II. Stratoscope II had a different gimbal arrangement than the proposed 2-meter OTES which uses the line of sight and cross line of sight gimbals from the ATM. Therefore, the Stratoscope II technique for correction of roll angles about the line of sight cannot be used. To prevent image smear of the stellar plates, the roll correction is provided by rotating the film/photomultiplier guidance package** to provide the necessary image motion compensation in roll.

In addition to the OTES optical technology experiments in pointing, this same equipment will be used to resolve the question of daylight astronomy for the MQAT class of space telescopes. The plan is to conduct Experiment No. 34 to provide answers to the questions of the gas scatter environment. This experiment will be conducted near the Cluster and separated by 1 mile or more in the autonomous mode. The quality of the astronomical plates obtained with this equipment module can be compared directly for the various combinations of day and night, Cluster attachment and autonomous; and if feasible, the variation in performance at both low orbit and synchronous orbit.

After the conduct of the OTES optical technology experiments, the same instrument module can be used for the conduct of more classical astronomical operations. One of the most logical tasks for a large, manned multi-purpose astronomical telescope facility is photography. Stellar photographs are firmly entrenched as a tool in many of the disciplines comprising modern astronomy. Furthermore the presence of man, even if only temporary, can greatly enhance the quality and quantity of data if film is used as the data transducer. This is partly

*The layouts which follow use the Free Float with Body Point guidance for simplicity.

**Not shown in the layouts.

because of the vastly greater data capacity of a moderate size piece of film as compared to a vidicon image tube, and partly because of the interpretive ability of man which can be applied directly and immediately towards modifying the observation program when provided with a familiar and readily comparable form of data.

The photographic instrument package design concept for OTES is in Figure 184. A special telescope correcting system for this package has not been designed since the corrector used with the f/50 vidicon imaging system could be employed. It is possible to do considerably better than the f/50 corrector design since it is not necessary to restrict the divergence angle or to leave a large space between the last corrector element and the focal plane. The possible gains to be obtained include a probable reduction in the number of elements from 4 to 3, and an extension of the corrected spectral range into the UV with fused silica, lithium fluoride, or similar optical materials which transmit in this region. The last two corrector elements, which act primarily to flatten the field, are illustrated in the side view of Figure 184.

The corrected f/10 focal plane is about 17.8 cm in diameter and situated midway between the last corrector element and a glass window. The photographic field is a 70 mm strip through the center of the corrected focal plane and from one side to the other. The film rests on a platen immediately below a focal plane shutter. Take up reels for the film and the shutter are shown in the side view.

The guidance field consists of two D shaped sections either side of the photographic field. Each "D" section contains a 4 quadrant image divider consisting of 2 prisms oriented so that the roof of one faces the roof of the other but with a 90 degree angle between the apex lines. When suitably positioned the image divider splits a guide star image into 4 separate beams which exit through a window (guidance locking plate) below the dividers. A field lens below the window of each guidance section directs the 4 separate beams onto a 4 quadrant photomultiplier from which guidance signals are derived.

The position of each guidance image divider along the X direction is determined by a screw driven fork which straddles the divider assembly. The Y direction position is controlled by a screw captured in each divider assembly which is driven back and forth by a threaded collar geared to a drive motor and encoder. The motor and encoder are fastened to the fork and travel with it along the X axis. Because it is not necessary to split both guide stars into 4 parts but only to split one into 4 and the other into 2 for roll correction, the positional accuracy required of the guidance mover mechanism is not extreme. For example, a 0.004 inch error corresponding to about a second of arc in the telescope field would serve only to decenter the actual position of the photographic field from its planned position by a comparable amount. A one second of arc offset in a 1800 by 700 second of arc field would hardly be noticeable.

Although the positional accuracy of the mover mechanism is not critical, its stability once positioned is critical. In order to keep image blur to a tenth of the image size, the relative separation between the photographic emulsion

and the image divider must be maintained to about one wavelength or 0.00004 inches. This is approximately 1.5 parts in 10^5 and is achieved with the present design despite the moderate temperature variations which are inevitable in a practical system. When the dividers are being positioned in the guidance field the locking plate is pulled away from the corrector and the divider assemblies move easily toward the new positions. Once in the new position, the dividers are clamped tightly between the locking plate and the corrector plate so that they cannot move during the exposure period. The clamping mechanism for the locking plate is shown in the side view. A spring load in each of the divider assemblies prevents the assembly from cocking and binding between the two glass surfaces when in the unclamped position and also provides a smooth transition to the clamped position and back. The glass plates on either side of the divider assemblies provide an optical path for the guidance beams, and, equally important, provide a rigid mechanical link between the guidance and imagery portions of the telescope field which is relatively immune to thermal changes. If fused silica is used ($\alpha = 5 \times 10^{-7} / ^\circ\text{C}$) then the allowable temperature change is about 13°C .

Echelle Spectrograph (Equipment Module D)

(The justification for this instrument on an OTES flight is identical to that given at the beginning of the previous section except that this instrument will use free float rather than transfer lens pointing.) The practically unlimited improvement for the ultra violet portion of the electromagnetic spectrum is possible with space systems.. A number of intriguing spectrographic observations in the far UV have already been made with small Aerobee payloads and, undoubtedly, there will be a great deal of interest in extending these measurements to fainter stars with higher spectrographic resolution. Initially at least, the greatest need will be for an instrument of moderately high spectral resolution but capable of performing a spectrographic survey of a faint stellar spectrum in a minimum length of time.

This requirement appears to be met by an Echelle spectrograph modified from the one developed by Perkin-Elmer in the Advanced Princeton Study and adapted to the OTES as shown in Figure 185.. With this arrangement the guidance system is identical to the f/10 photographic package. The spectrograph consists of two gratings ruled at right angles to each other and a folding flat located near the vidicon image surface. The first grating is spherical, operates in the first order, and yields a spectrum stretching from one side of the vidicon to the other. The second grating is flat, operates at very high orders typically between 10 and 20, and has a very high dispersion. The function of the first grating is to separate the overlapping orders of the second grating so that a nicely folded spectrum is formed at the vidicon much like the lines of type on a printed page. The vidicon axis is tilted with respect to the folded spectrograph axis in order that the astigmatic image plane containing the high dispersion focus coincides with the vidicon sensitive surface.

A redundant or a complementary Echelle spectrograph is also shown in Figure 185 on the other side of the optical axis. The curved predisperser grating and the entrance slit are common to both instruments but the Echelle gratings, the

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LEFT 'X' AXIS
MOTOR/ENCODER

LEFT 'Y' AXIS
MOTOR/ENCODER

FILM PLATEN

GUIDE
IMAGE
PRISM

GLASS GUIDANCE
LOCKING PLATE

GUIDANCE CONDENSING
LENS

I-547-1

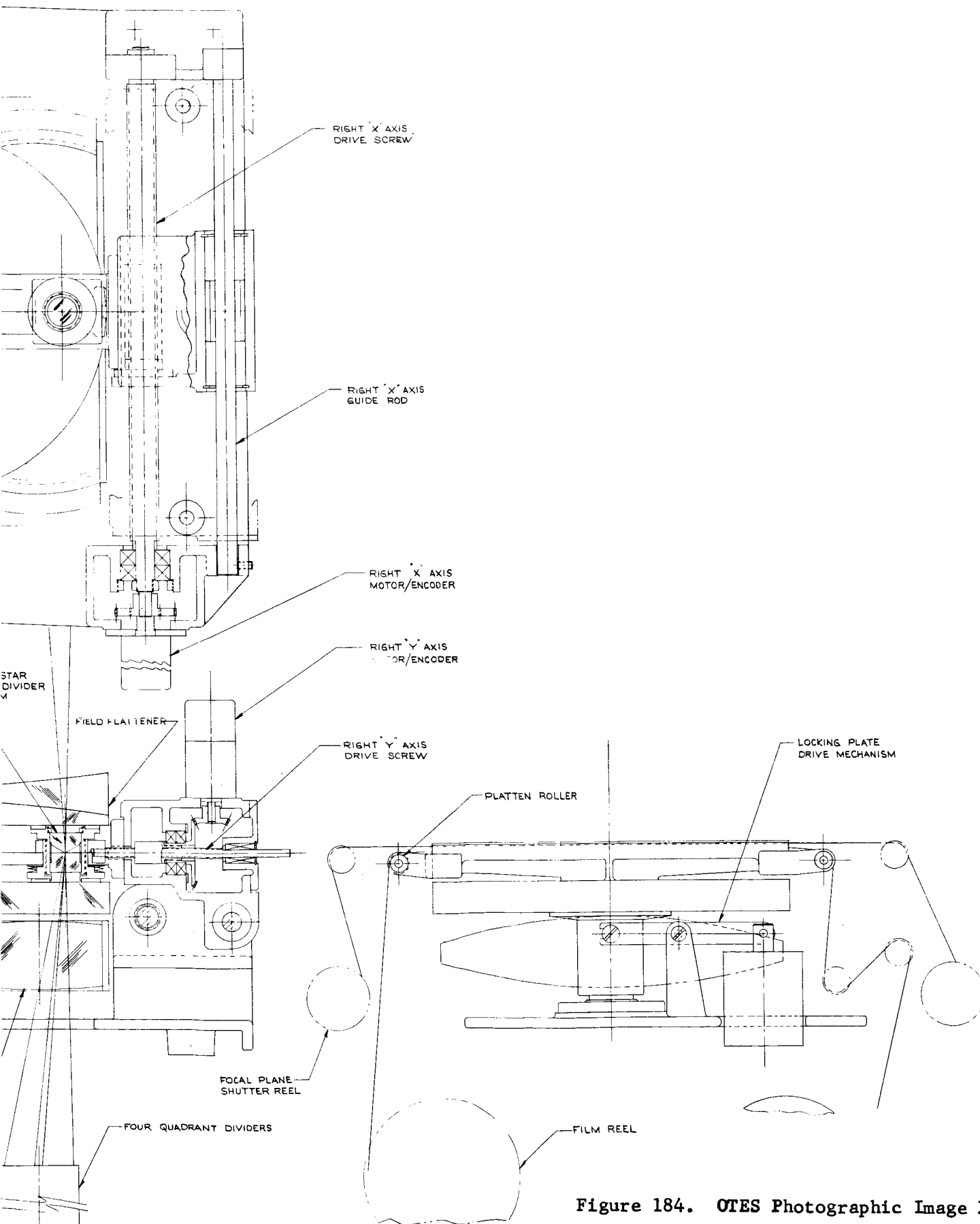


Figure 184. OTES Photographic Image Package

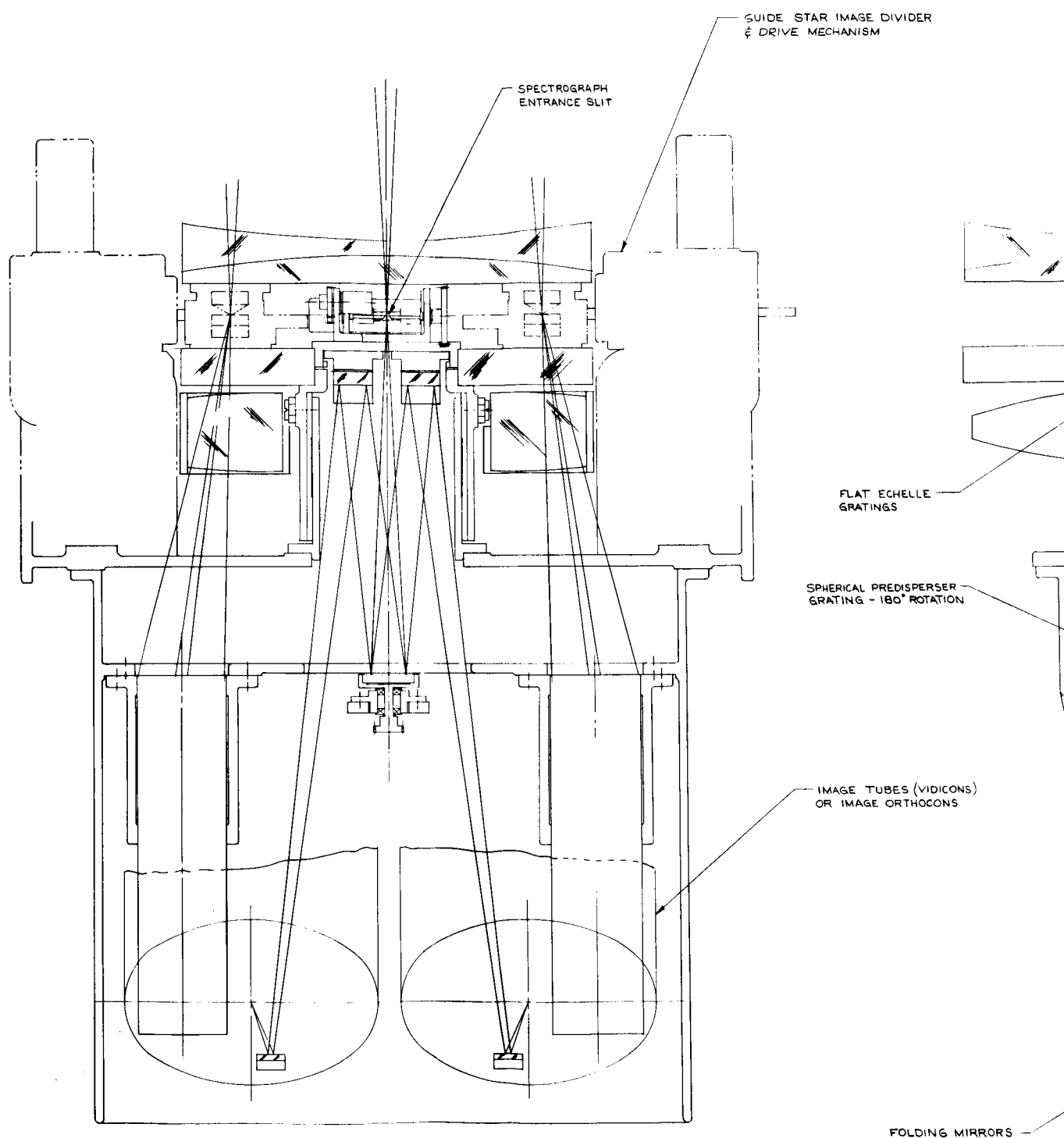
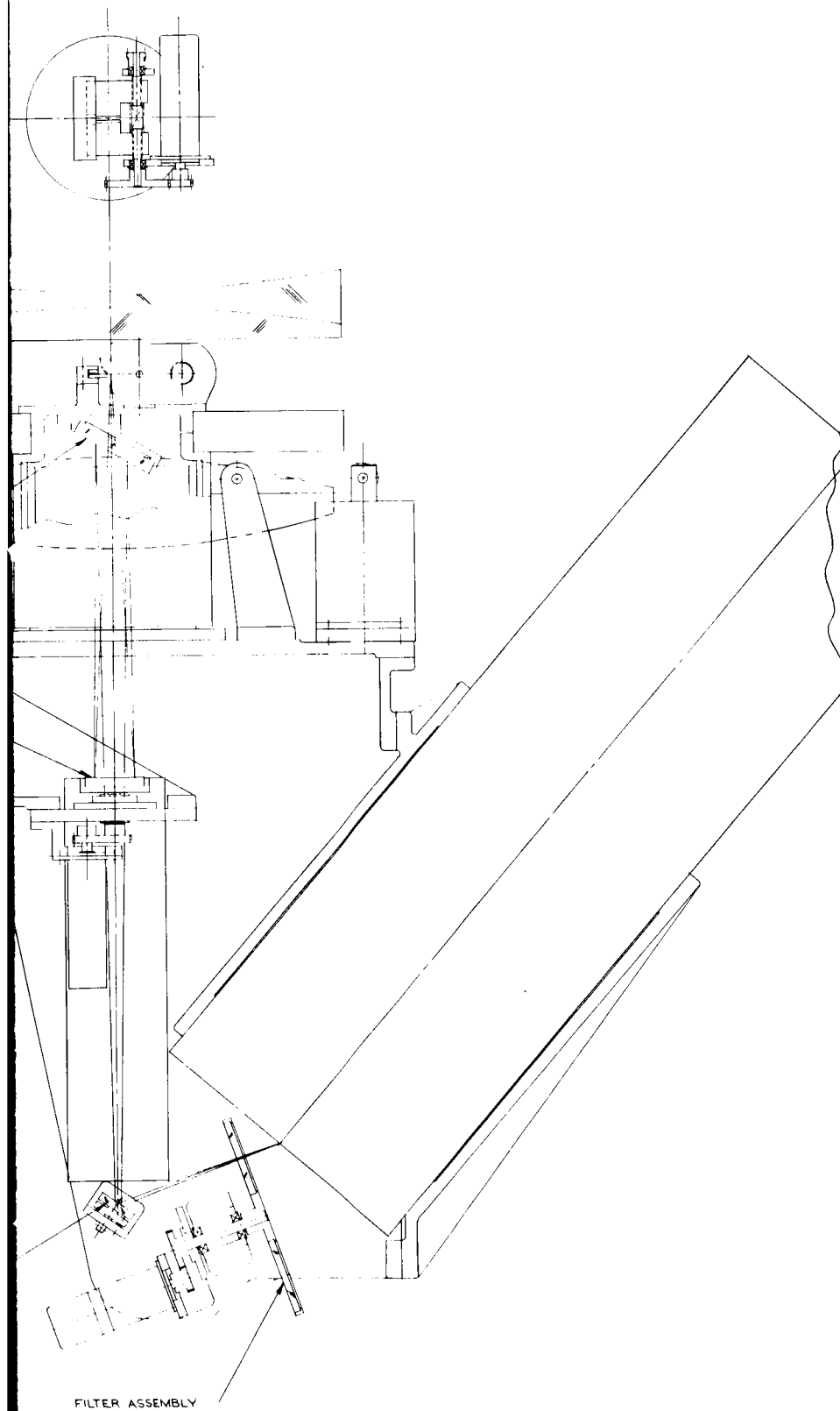


Figure 185. OTES Echelle Spectrograph Package



FILTER ASSEMBLY

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folding flats and the vidcons are duplicated. Switching from one configuration to the other is accomplished by turning the predisperser through 180° so that the blaze angle directs most of the diffracted energy to the alternate instrument section.

The vidicons are an ideal data transducer for a spectrographic survey instrument since they possess the quantum efficiency of a phototube yet have the capability of integrating the signals from a large number of resolution elements simultaneously. However, the spectral response of present tubes is limited to wavelengths longer than about 1250Å by the lithium fluoride window, the sensitivity can vary considerably from point to point on the photosensitive surface, and the size of the sensitive surface is limited to about 1.6 inches diameter for the largest. During the manned portion of the telescope operation program it may therefore be desirable to use film in the spectrograph as well as in the f/10 imagery package. This possibility is not illustrated in Figure 185, but could be incorporated in the design, probably without altering significantly the redundant vidicon arrangement shown.

The slit mechanism shown at the top of the figure allows the width of the entrance slit to be altered as desired. For stellar spectroscopy a slit is not required at all since the stellar image is extremely small (approximately 5 microns in the visible). However with large nebula or star clusters the slit serves to isolate the portion to be studied and also to determine the resolution.

Rowland Circle Spectrometer (Equipment Module E)

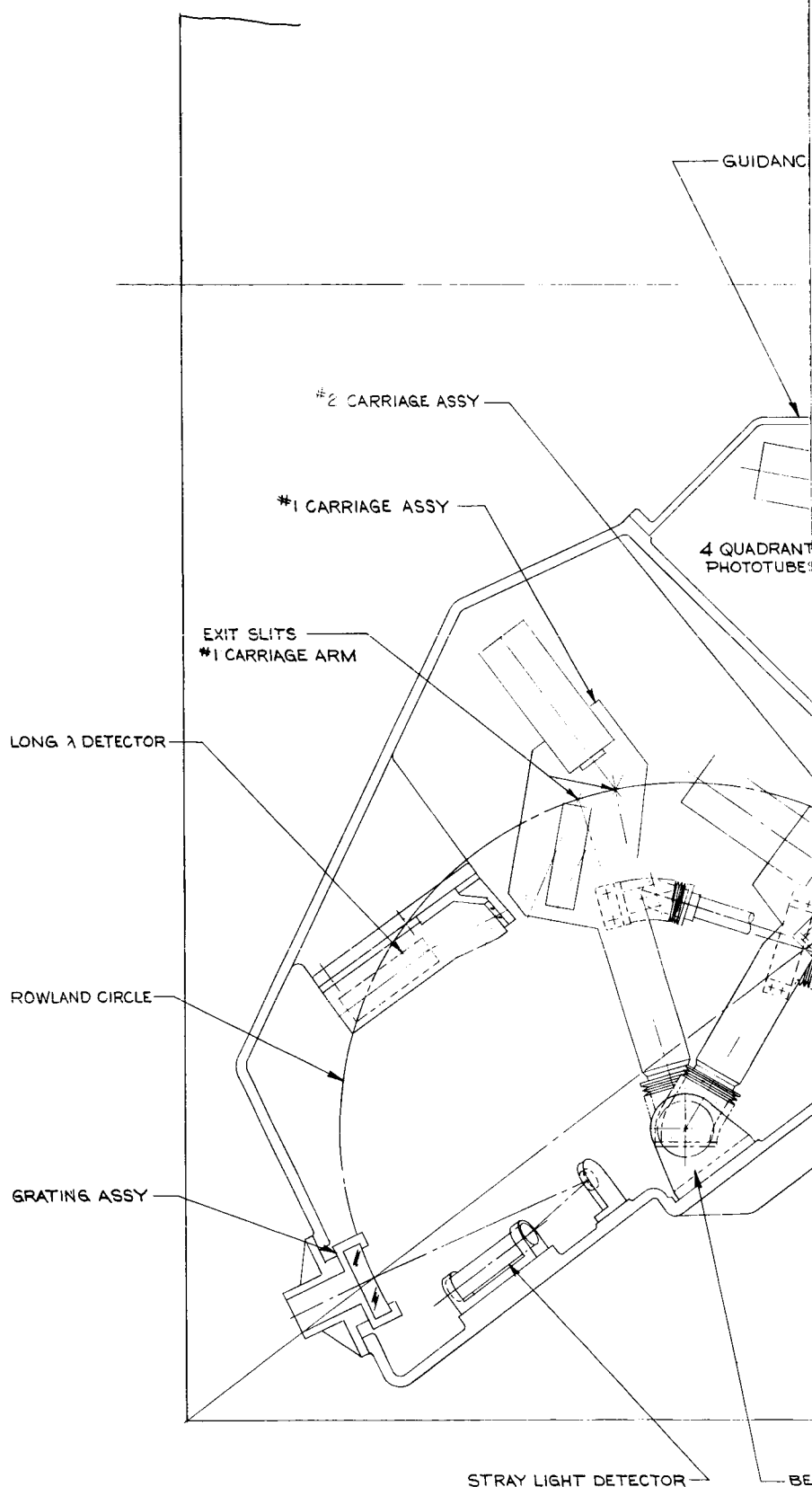
(The justification for this instrument on an OTES flight is identical to that given at the beginning of the High Resolution Imagery Section, except that this instrument will use the flexure gimbals rather than the transfer lens pointing.)

In the far UV the efficiency of the best reflective coatings is very low. At 1200Å a reflectivity of 50% is considered excellent, and below 1000Å efficiencies are somewhat less than 20%, even if platinum or rhodium coatings are used. This absorption loss is further compounded by the large scattering losses which occur at these wavelengths. Even on good surfaces, the scattered radiation generally acts to obscure the desired images. It is therefore imperative that the number of optical surfaces be kept to an absolute minimum in instruments designed to operate in this region. The Rowland Circle Spectrometer fulfills this condition and, in addition, can be designed so that the inherently lower data rate of this type of instrument is partially offset by its versatility.

A Rowland Circle Spectrometer patterned after the Perkin-Elmer designed OAO-C, the Princeton Experiment Package, is shown in Figure 186. This contains a reflective entrance slit which shears a portion of the energy from each side of the image focused upon it and directs this energy into a relay lens followed by a simple guidance system. Unlike the previous instrument packages, the Rowland Circle Spectrometer does not require two guide stars or a large telescope field, but it does require fairly bright stars since the same star is used for guidance and spectroscopy.

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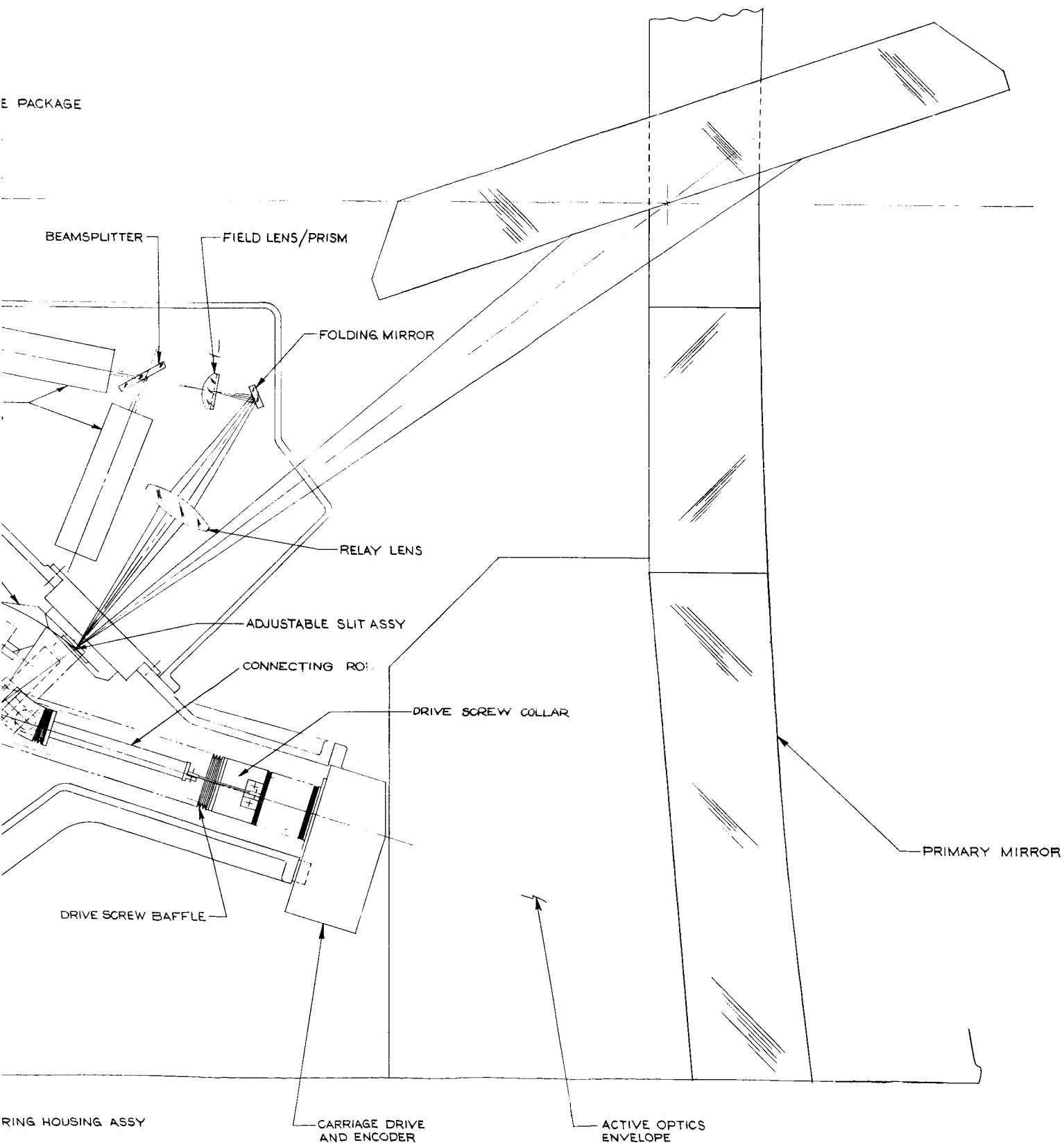


Figure 186. OTES Rowland Circle Spectrograph

The spectrum imaged along the arc joining the entrance slit and grating is scanned by two arms which pivot about the main bearing assembly. Each arm contains two exit slits, one slit for the first order spectrum in the 1600Å to 3200Å region which is detected with a conventional trialkali phototube, and the other slit for the second order spectrum in the 800Å to 1600Å region which is sensed with an open cathode type of detector. Each arm may be operated independently of the other so as to provide redundancy in the event of a failure of the detector tubes or seizure of one of the arms. Mechanical interference between the arms is avoided by folding the exit slits on arm No. 2 out of the Rowland Circle plane with a small optical flat. In this way arm No. 2 may pass in front of arm No. 1 with only a small amount of the spectrum being obscured.

Each arm is activated by a drive screw coupled to the arm by a collar and connecting rod. The main bearing, one of the connecting rod joints, and the drive screw are sealed in a bellows assembly which contains a lubricant under a low pressure inert atmosphere. As the collar is driven from one end of the lead screw to the other, the bellows on one side expand and the bellows on the other side contracts. The joint between the connecting rod and the screw collar is simply a flexible steel spring.

In the OAO-C Spectrometer the entrance slit and the exit slits on carriage No. 1 are about 25 microns wide, yielding about a 0.1Å resolution with a one meter radius grating. The slit widths on carriage No. 2 are 4 times as large, making it more useful for spectrographic survey work. In the event that the optical system should fail to produce suitably small images or if it becomes desirable to sacrifice resolution in favor of speed, then the entrance slit may be opened to match the second set of exit slits. In this case, some defocusing may also be necessary so that part of the image is returned to the guidance system. The space envelope in the OTES package requires a reduction in the size of the Rowland Circle from one meter used in OAO-C to about 60 cm diameter. This also reduces the resolution proportionality. However, it is probably preferable to suffer reduced resolution than the high absorption and scattering losses attendant with folding flats. The decrease in size, and also the thermally isolated position of the spectrometer behind the primary mirror, help to reduce the thermo-elastic deformations in the spectrometer structure, which must be kept to a very low level if the inherent resolution is to be achieved. The main sources of error are believed to be irregularities and wear in the drive screw and thermal effects from the drive motors.

The long wavelength and stray light detectors shown in Figure 186 are typical examples of peripheral instrumentation, which may be added to this type of equipment to enhance the data acquisition capability. Monitors centered on lines of astronomical interest can be used to extend the spectral coverage on either side of the nominal range covered by the spectrometer. The stray light monitor detects both the scattered radiation and the penetrating radiation components which might otherwise prove misleading. With this type of instrument it is also possible to incorporate calibration sources which can be scanned periodically to ascertain changes caused by wear or material instabilities.

The guidance sensor associated with the OTES spectrometer is very similar to one half of the guidance system employed in the f/10 imaging system (Module C) and the Echelle Spectrograph (Module D). The faces of the entrance slit are highly polished and tilted slightly with respect to each other so that they act like one of the prisms in the guidance divider assembly. If the stellar image falls on one side of the slit, it passes through the guidance system and falls on a corresponding side of a 4 quadrant image tube. A relay lens provides a second focus where a prism oriented at right angles to the slit direction splits the image into up and down directions components which also have corresponding quadrants on the image tube. The guidance electronics sequentially samples each phototube quadrant and compares opposing halves to derive the guidance signals. A beamsplitter and second phototube provide redundancy in the event of a phototube failure.

F/50 Vidicon Imaging System and Associated Image Movers (Equipment Module F)

(The justification for this instrument on an OTES flight is identical to that given at the beginning of the High Resolution Imagery Section except that this instrument will use a secondary tilting technique instead of the transfer lens pointing system.)

In the visible region the limiting spatial frequency passed by an f/10 telescope is about 200 cycles per millimeter. This is well within the resolution capability of many photographic films but exceeds by a considerable margin the resolution of present vidicons or image orthicons which are typically between ten and forty cycles per millimeter. Matching the telescope resolution to that of present phototubes would require a magnification between five and twenty. It is tempting to choose the larger magnification since it allows the widest choice of phototubes, and if it turns out to be a conservative choice it will permit the experimenter to strive for the higher resolution possible at shorter wavelengths. Unfortunately, any increase in magnification brings about a decrease in field size, and it is necessary to find a compromise. The choice is further complicated by the flight schedule of the OTES program and the rapid evolution of image tubes. Considering all the appropriate factors, it appears that the best choice is for high resolution and therefore a low magnification microscope.

The optical elements comprising the vidicon (or image orthicon) imaging system in the OTES experiment package were shown in Figure 177 on page 331. The central all-reflective portion of the telescope is re-imaged on a vidicon by a 2 mirror-5 power microscope and a folding flat. Because of the all-reflective path, the spectral range covered by the imaging system is unlimited up to the face of the vidicon. If the vidicon has a lithium fluoride window this will limit the spectral range to above 1200Å. However, even this limit might be overcome with a suitable phosphor on the front face of the vidicon window.

Sandwiched between the telescope corrector elements and the f/10 focal plane, on either side of the optical axis are two small optical relay systems called

image movers.* These are constructed in such a way that they may be oriented to move the position of a guide star from an arbitrary point in the outer portion of the telescope field to a fixed point close to the optical axis and on the uncorrected $f/10$ focal plane. In this position the guide stars are relayed by the microscope to corresponding positions either side of the vidicon where they fall in the apex of a four quadrant optical divider. A four quadrant image tube located behind the divider samples opposing quadrants so that pitch and yaw guidance signals may be derived.

The image mover optical design and mechanism shown in Figure 187 utilizes a collimated light path between the positive and negative lens groups. This is not necessary if two pivot axis rather than a pivot and a slide are used because the optical paths between all the elements remain constant. Furthermore, since the outer portion of the image mover field is used only during acquisition the only important optical aberrations that need be considered in the image mover design are spherical aberration and longitudinal color. Most of the folds in the image mover optical path have been made using internal reflections because of the much higher optical efficiency of internal as compared to front surface reflections. The number of optical surfaces has also been reduced by combining one of the positive triplet elements and a folding prism. In future design reiterations it may be possible to reduce the number of surfaces still further and thereby increase the optical efficiency.

As might be expected, a small rotation of the image mover about the telescope axis or a small shift in the position of the negative doublet with respect to the positive triplet can produce a relatively large pointing error. It is, therefore, essential that the mechanism which positions the image mover elements be designed so that such motions can be minimized during the operation of the telescope. This can probably be achieved most easily by a mechanical design which locks the elements with respect to each other and the instrument package frame once they have been positioned correctly. Small translational displacements of the entire image mover system have a negligible effect on the position of the guide star images if the f /number of the incoming and outgoing image beams are equal. In this case, the image mover system is analogous to a window in a collimated light path; it introduces an amount of parallax depending on the angular orientation, but translational motions have no effect since the optical power is unity. This advantage is utilized in the present design with the exception that the field correcting elements are assumed part of the image moving system thus yielding equal f /numbers for the uncorrected on-axis image beam and the guide star beams emerging from the image movers.

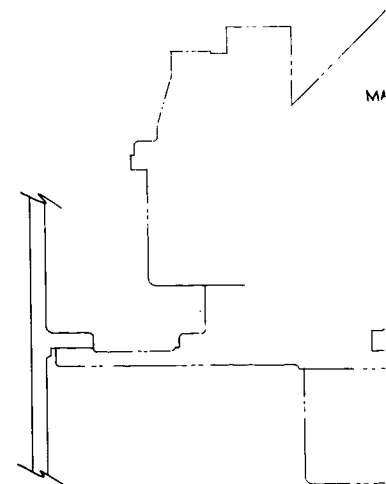
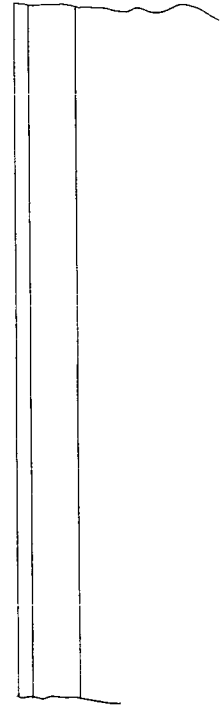
Image Movers

One of the outstanding features of the $f/50$ imagery package is a guidance system capable of providing image stability of 0.01 seconds of arc over very long time periods. The only operational system coming close to fulfilling this requirement is Stratoscope II, a 36-inch aperture balloon borne telescope designed and built for Princeton University Observatory by Perkin-Elmer. Guidance on Stratoscope II is achieved by splitting guide star images in the telescope field on the apex of prisms set to coincide with the image center. The guidance logic system

* Perkin-Elmer Report 8688 and R. Danielson Loc. Cit.

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MICROSCOPE

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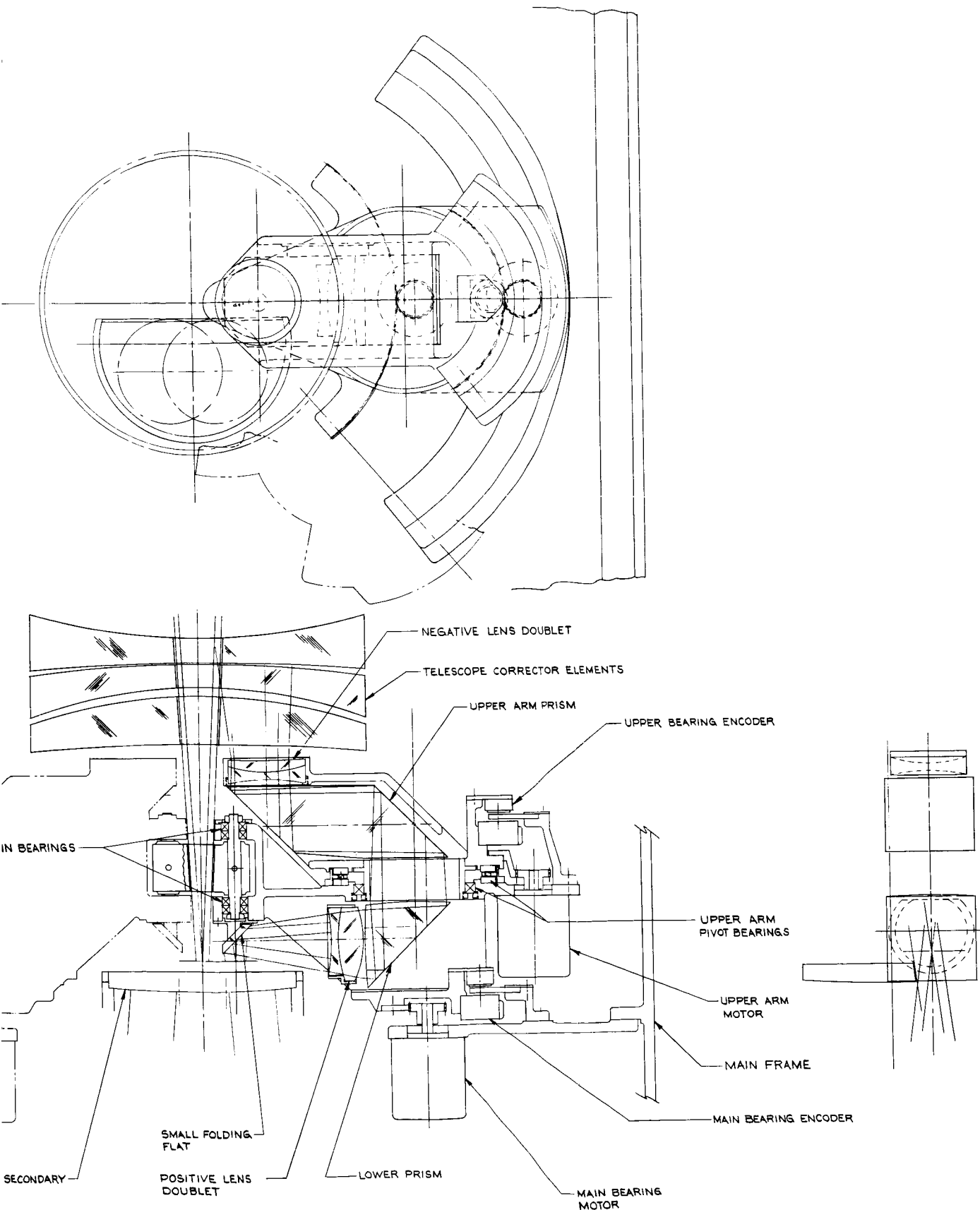


Figure 187. OTES Image Mover Mechanism

compares the intensity in each image quadrant with the intensity of the other image quadrants thereby deriving pitch, roll, and yaw guidance signals.

The principle advantage of the Stratoscope scheme is that it does not depend on the relative alignment between different optical systems. Both guidance and image systems utilize the same optical elements so that thermo-elastic deformations in the telescope structure produce identical effects in both systems. If the null seeking guidance system is operational, then image displacements due to deformations in the telescope structure are immediately compensated by changes in the pointing direction of the telescope.

The difficulty of implementing a similar scheme on a satellite borne telescope is the large volume of space required. A 30 minute of arc diameter field corresponds to a circular area 87 cm in diameter in a 2-meter, f/50 telescope. Furthermore, keeping the relay microscope field angle in bounds would probably require about 8.7 meters between focal planes.

The image mover is the ingenious scheme which retains the common telescope and microscope optics principle built into Stratoscope but also permits the size of the microscope to be reduced to a convenient, easily packaged size. The principle on which it operates was first reported by Perkin-Elmer in Report 8346 for Princeton University. Much of the description which follows is adapted from the Advanced Princeton Satellite Study Report No. 8688.

In its original form the image mover device consisted of a very simple system of lenses and mirrors which could be arranged to shift a guide star image from an arbitrary position to a fixed position. The optical arrangement required to achieve this is illustrated below.

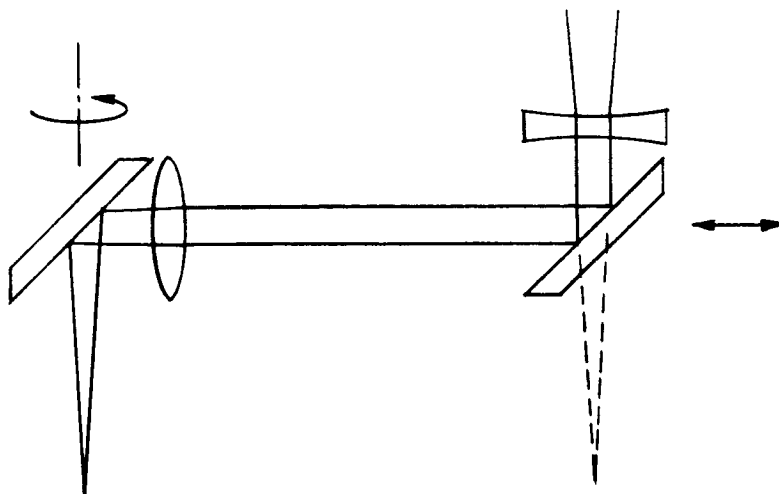


Figure 188. Image Mover Concept

A converging bundle of light from a guide star is intercepted before coming to a focus by a negative lens which renders the rays parallel. A small diagonal mirror turns the collimated beam through a right angle which intersects a positive lens. This refocuses the bundle so that after reflection from a second diagonal mirror the guide star image lies in the same focal plane as before. The image mover can be adjusted to shift guide star images from arbitrary positions by moving the negative lens and diagonal mirror horizontally toward or away from the positive lens and by rotating the entire image mover assembly about an axis through the positive lens diagonal.

The OTES image mover mechanism design concept which affords a number of advantages to the pointing system at the cost of additional optical surfaces is shown in Figure 188. There is no requirement for a sliding mechanism in the arrangement shown which uses a second pivot axis in the mechanism. Both axes are parallel to the telescope optical axis and also coincide with optical axis of the positive and negative lens groups. The main axis, about which the entire image mover rotates, passes through the small folding flat. The upper arm pivot axis, about which only the long prism and the negative doublet rotate, passes through both folding prisms. Each axis has associated with it a motor and encoder which allows the image movers to be positioned with respect to the telescope axis in analogous fashion to the known position of the guide stars and image field center.

An important advantage of the two axis OTES design shown in Figure 187 is that it provides coverage over a large portion of the telescope field and a large acquisition zone around the nominal position of the guide star image. The size of the acquisition zone required by the telescope is determined by the angular position and velocity errors expected from the course guidance system. A 2 minute of arc diameter acquisition zone, which is provided in the present design, is similar to the small star trackers in the OAO series of satellites. In the event that course guidance is markedly better in the OTES package, then the acquisition zone may be reduced with a corresponding beneficial reduction in background illumination. The portion of the telescope field which can be covered by the image movers is shown in Figure 189, along with the various orientations of the image mover mechanism required to cover the field extremities. Most of central portion of the field which is not accessible would be badly vignetted by the hole of the telescope field corrector elements and would therefore not be usable anyway.

Imaging Microscope

The main purpose of the microscope is to relay the central, all reflective portion of the telescope field to the image surface of a vidicon or image orthicon. In order to match the resolution afforded by an $f/10$ telescope to that of a vidicon, a microscopic magnification of 5 was selected. This magnification is rather low and is predicated on an anticipated increase in the resolution of vidicons or image orthicons. In order to prevent slowly changing temperature distributions in the instrument package from misaligning the guidance and imaging systems, it is also necessary that the microscope relay the guide star images positioned either side of the image field. This is a more difficult requirement since the microscope must operate farther off-axis and at a much lower f /number in order

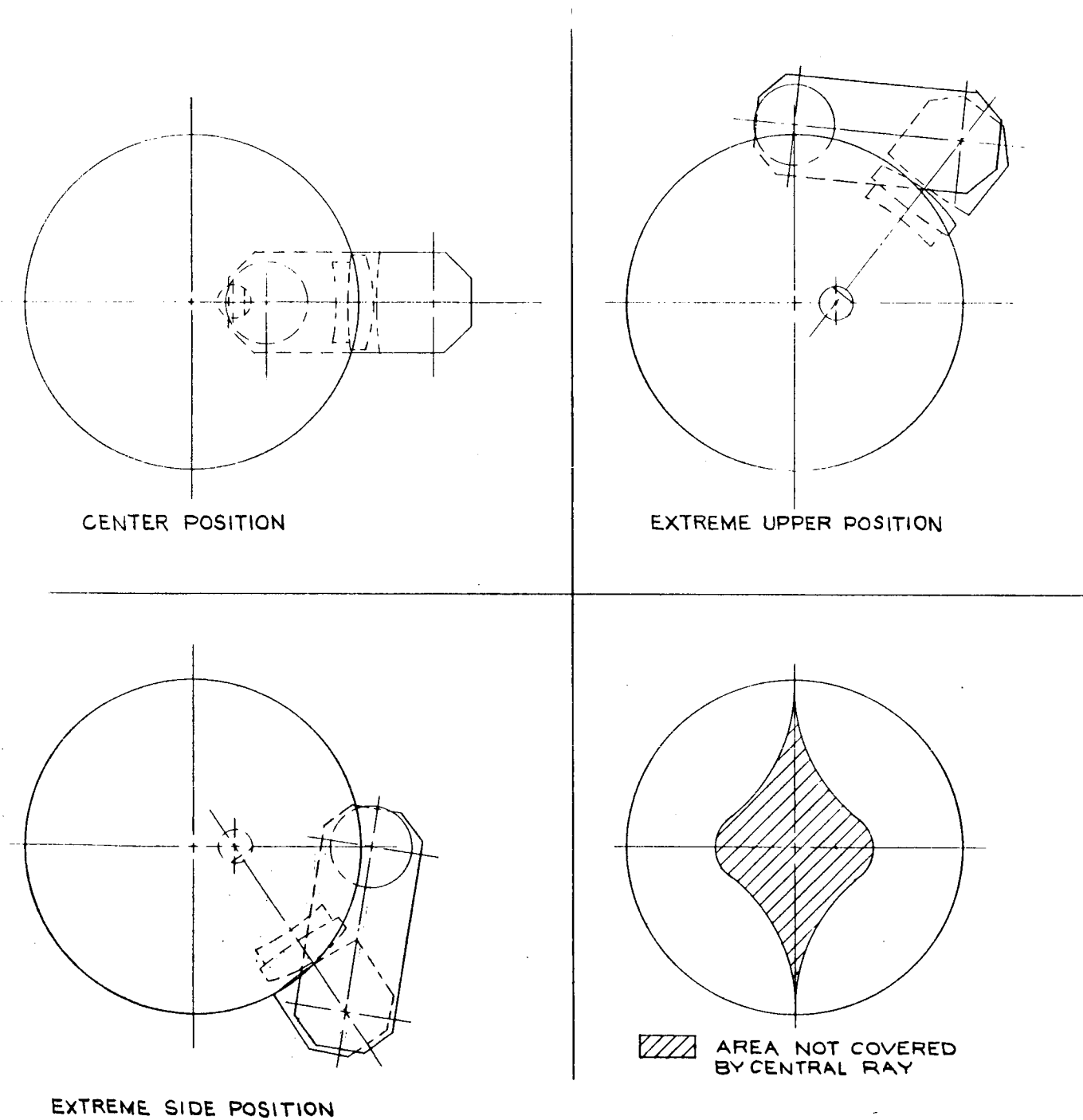


Figure 189. OTES Image Mover Field Coverage

to accomodate the tilt imparted to the guide star image beams lying on the periphery of the telescope field. The 4° - $45'$ tilt of the present corrector system increases the acceptance angle from $f/10$ and $f/3.725$.

A microscope containing refractive elements is not feasible since it would restrict the spectral range of the telescope. Furthermore the number of reflective microscope designs is extremely limited either because it is physically impossible to incorporate them into the present system, or because they suffer from a high obscuration ratio. A large obscuration would seriously compromise the overall optical performance of the telescope imaging system.

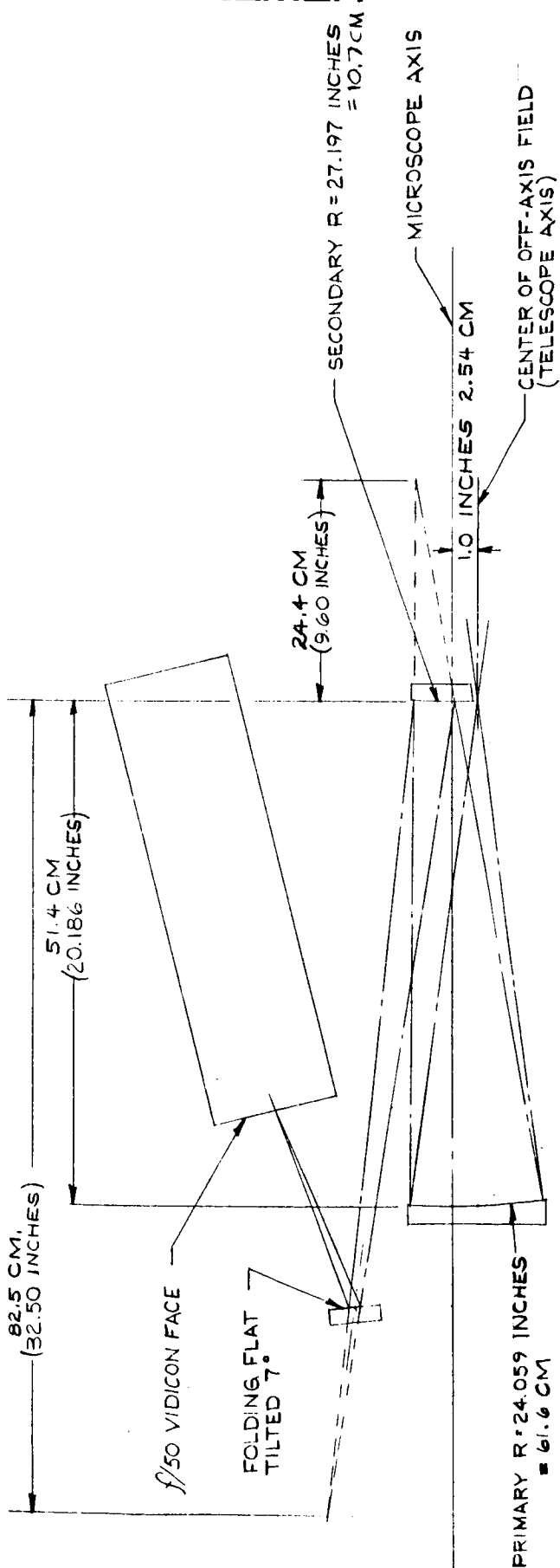
A unique Perkin-Elmer image microscope* having none of these objections is shown in Figure 190. It consists of two axially aligned surfaces of resolution. A small folding flat is also included but this has no effect on the optical performance and serves only as a packaging convenience.

Since the microscope is employed off-axis there is no obscuration. The $f/10$ focal plane of the telescope and the effective $f/3.725$ plane of the image movers is situated adjacent to the reflecting microscope secondary mirror-a position which minimizes the extent to which the telescope must operate off-axis. The vidicon or orthicon position shown in the top view of Figure 190 is folded along side the microscope. If more room were available in the instrument package, this fold might be eliminated and the overall optical efficiency in the far UV enhanced. The guide star image dividers are situated either side of the vidicon about 8 inches apart. (Bottom view of Figure 190).

It is a fortunate situation that diffraction limited performance can be achieved with two aspheric surfaces out to the edge of the field in the off-axis configuration. This is illustrated in Figure 191, which shows the geometrical image size at two field positions on a curved focal plane. The ray fans shown in Figure 191 extend over a $f/3.725$ aperture on one side and a $f/18.65$ aperture on the other side of the microscope so as to accommodate the tilt imparted to the guide star beams by the telescope corrector. In practice only about a third of the aperture is used by the $f/19$ guide star beams. This section depends on the position of the guide star in the telescope field. The on-axis telescope field which is relayed by the microscope to the vidicon or orthicon does not move around but always occupies the central third of the total aperture.

Ideally, the focal plane of the microscope would be flat, but in this particular application it is better to suffer a slight curvature of field (radius approximately 109 inches) than have the aberrations which would occur with a flat focal plane. The vidicon and image dividers occupy only a small portion of the field and may be individually adjusted to a best focus position. In fact the curved field has absolutely no effect on the image dividers which operate only on-axis during fine guidance. At the edge of the field where the image dividers are located the largest aberration is 5th order astigmatism, which amounts to 0.1 of a wavelength at $5000\text{\AA}$ for an $f/50$ image beam. This would have an imperceptable effect on image quality.

*The optical design of this imaging microscope was invented by D. Markle and L. McCarthy and is not included in this report because it is proprietary to Perkin-Elmer.



A-363

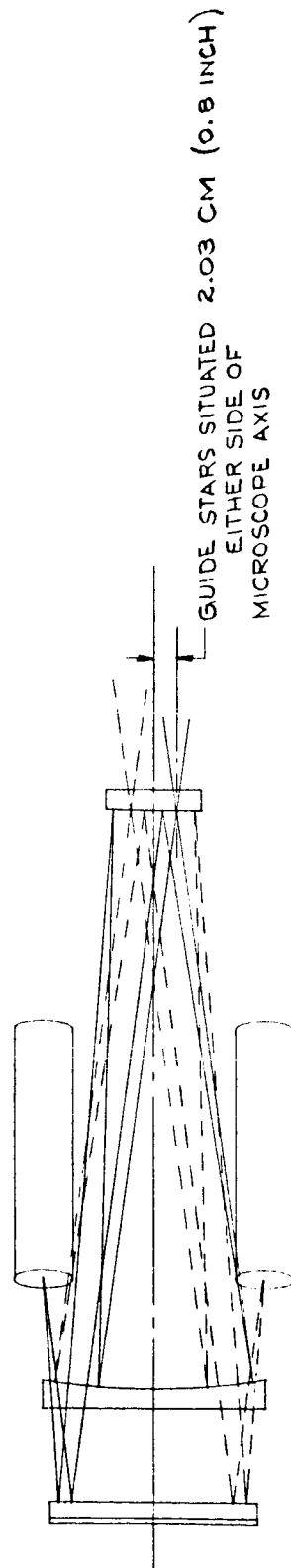
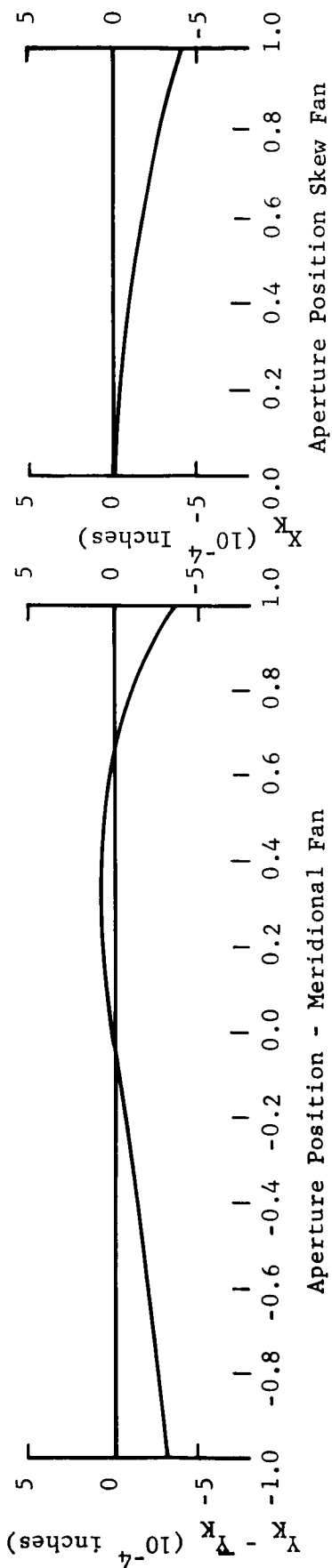
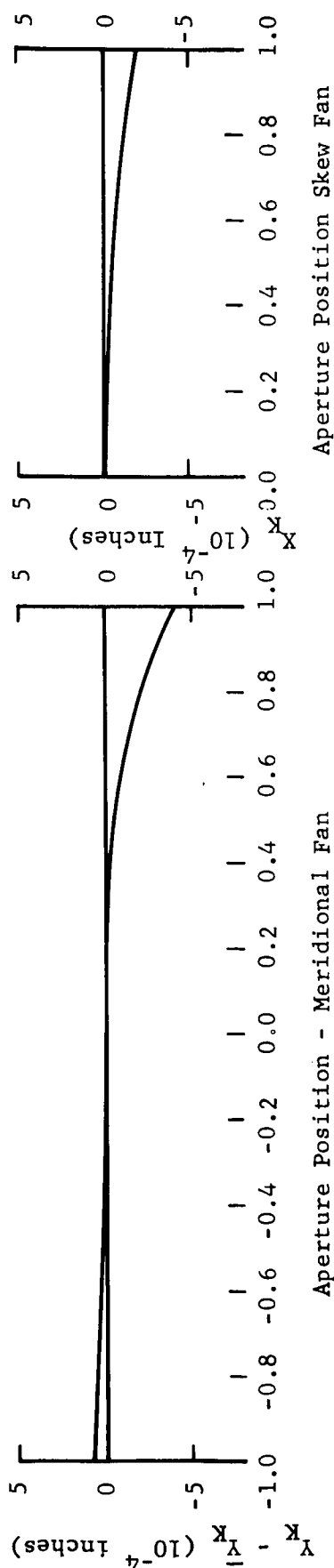


Figure 190.. OTES Reflecting Microscope



-1.28 Inches Off-Axis $f/3.723$



-9.0 Inches Off-Axis $f/3.723$

Figure 191. OTES REFLECTIVE MICROSCOPE
-20 Magnification ($f/3.723$ - $f/18.63$)

The vidicon image field also lies off-axis because of the decentration between the telescope and microscope axis. However it is not as far off-axis as the image dividers and all the aberrations, except for field curvature, are correspondingly less. Field curvature is appreciable on the top and bottom of the vidicon because the curved microscope fields cut obliquely across the center of the vidicon. Of course this could be avoided by tipping the vidicon so that it was normal to the image plane but this would introduce an undesirable amount of distortion. Assuming a sensitive surface 1.6 inches in diameter, the defocussing amounts to only 0.1 wavelengths at the very extremities of the vidicon image field.

f/50 Telescope and Microscope Combination

The overall performance of the f/50 telescope microscope combination is illustrated by the modulation transfer curves shown in Figures 192 and 193. These show the transfer functions for both radial and tangential directions in various positions of the vidicon field. The one inch decenter between the telescope and microscope axis is in the radial direction. No refractive components, which would limit the spectral response, are contained in the vidicon optical path which consists of 4 reflective surfaces up to the front surface of the vidicon. The obscuration due to the secondary and the baffles, which are necessary to shield the image and guidance fields from directly incident light, has a marked effect on the shape of the MTF curves. In the present design this obscuration would amount to about 23.1 inches out of the 78.8 inches total aperture. A central obscuration has much the same effect as optical aberrations would have on a system with a clear aperture. In both cases it is the intermediate spatial frequencies which are attenuated the most.

At the center and to each side of the 1.6 inch diameter vidicon face the MTF curves are identical to the theoretical diffraction limited response of a f/50 optical system. At the top and bottom of the vidicon field some defocussing occurs because of the curved field produced by telescope and microscope combination. The field curvature of the telescope is opposite to and slightly stronger than the curvature produced by the microscope. Because of the misalignment between the axis of the two systems their field curvatures do not cancel as well as might otherwise be expected.

The decenter between the telescope and microscope also affects the limiting frequency of the MTF curves. At the center of an f/50 system the limiting frequency would normally be $1/\lambda f = 40$ cycles/mm at a wavelength of 0.5 microns. In a decentered configuration the exit pupil is foreshortened when viewed along the telescope axis, the distance between the center of the exit pupil and the center of the field is slightly different from the nominal position, and the incidence angle of rays striking the focal plane is also altered. The effect is noticeable on the radial MTF curves and probably accounts for most of the very small difference between the top and bottom field position curves.

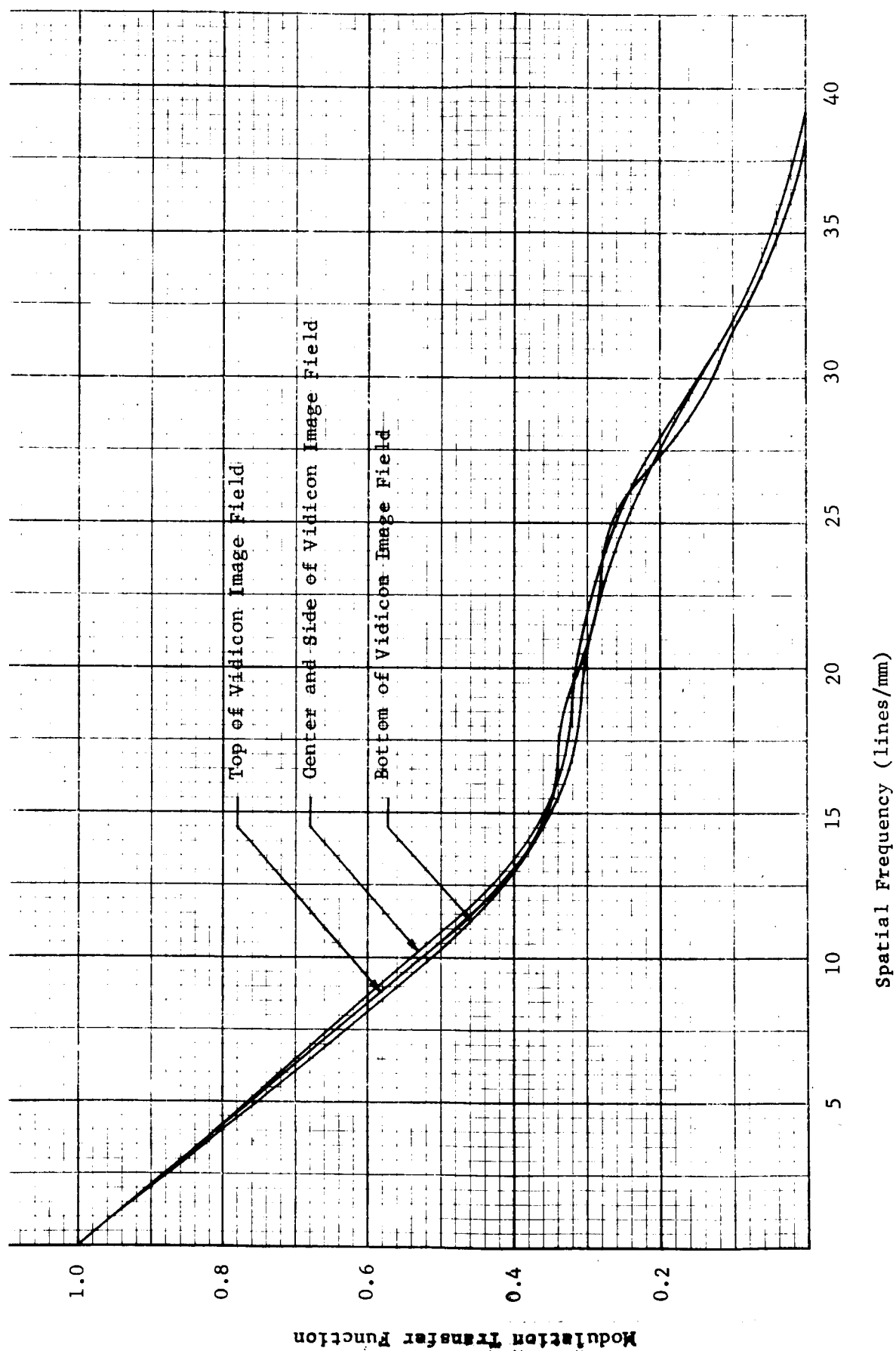


Figure 192. OTES 2-METER TELESCOPE
f/50 Vidicon Image Field M.T.F.
5000Å Radial Direction

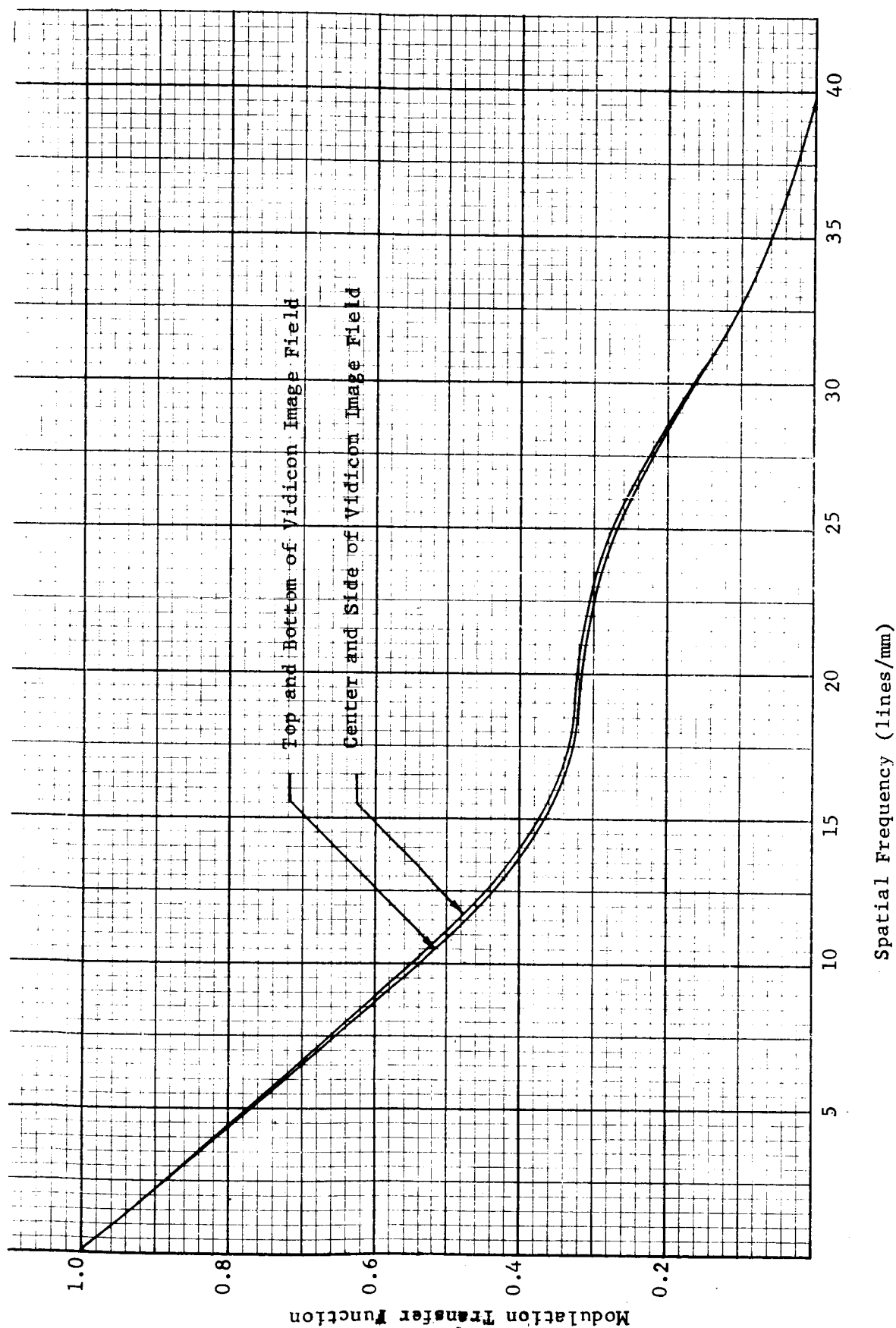


Figure 193. OTES 2-METER TELESCOPE
f/50 Vidicon Image Field M.T.F.
5000Å Tangential Direction

PERKIN-ELMER

As the wavelength decreases the effect of geometrical aberrations increases and more pronounced differences between the actual and theoretical diffraction-limited MTF's can be expected. This is illustrated in Figures 194 and 195 which show the radial and tangential MTF's at the top and center of the vidicon field for a wavelength of 0.25 microns. Even at this wavelength the optical aberrations have little effect and the design may be termed "diffraction-limited."

The transfer function at higher spatial frequencies and shorter wavelengths was not investigated since it is apparent that the resolution of the vidicon and the surface quality of the optical components will ultimately limit the resolution rather than the optical aberrations.

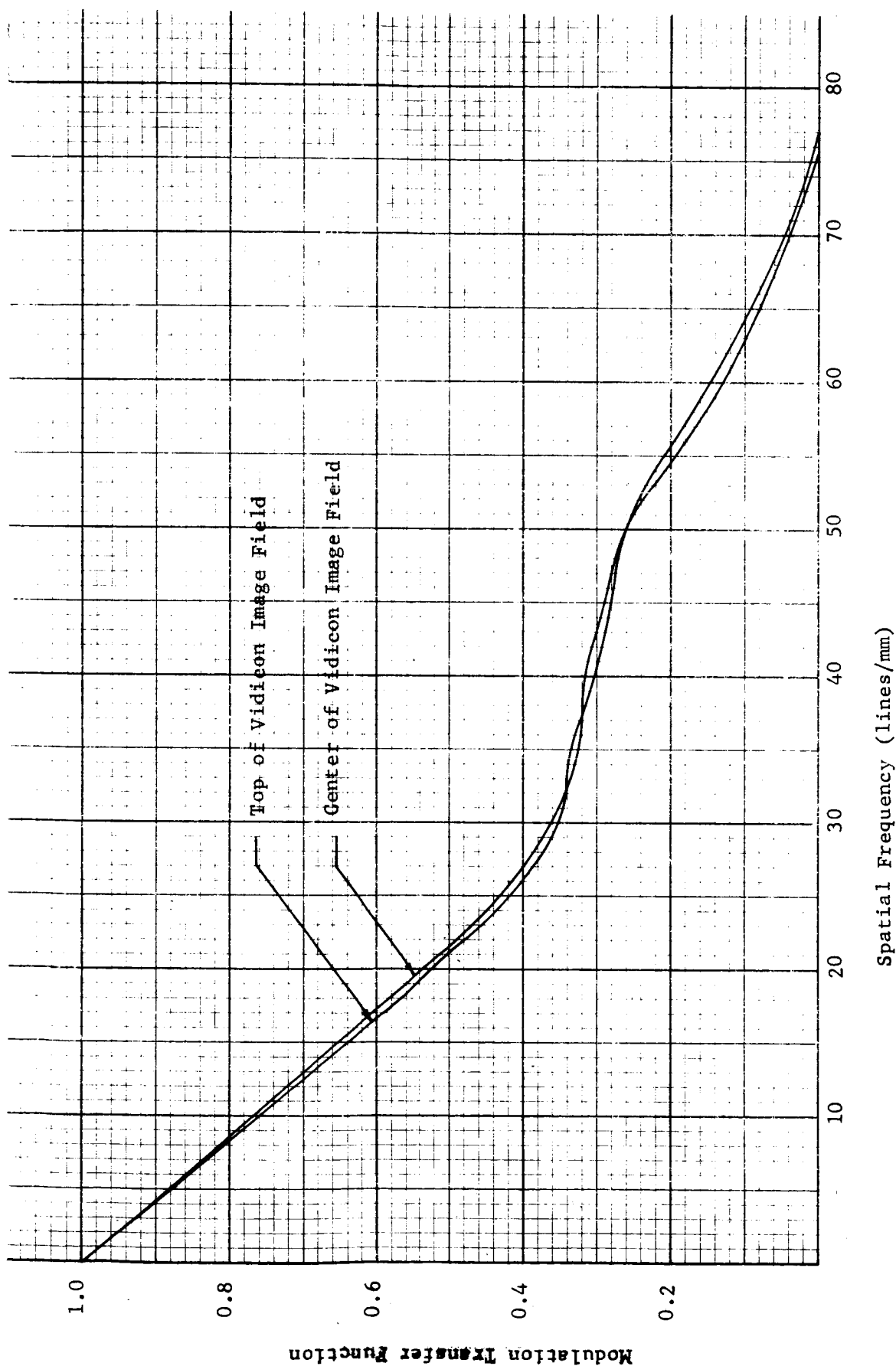


Figure 194. OTES 2-METER TELESCOPE
f/50, Vidicon Image Field M.T.F.
2500A - Radial Direction

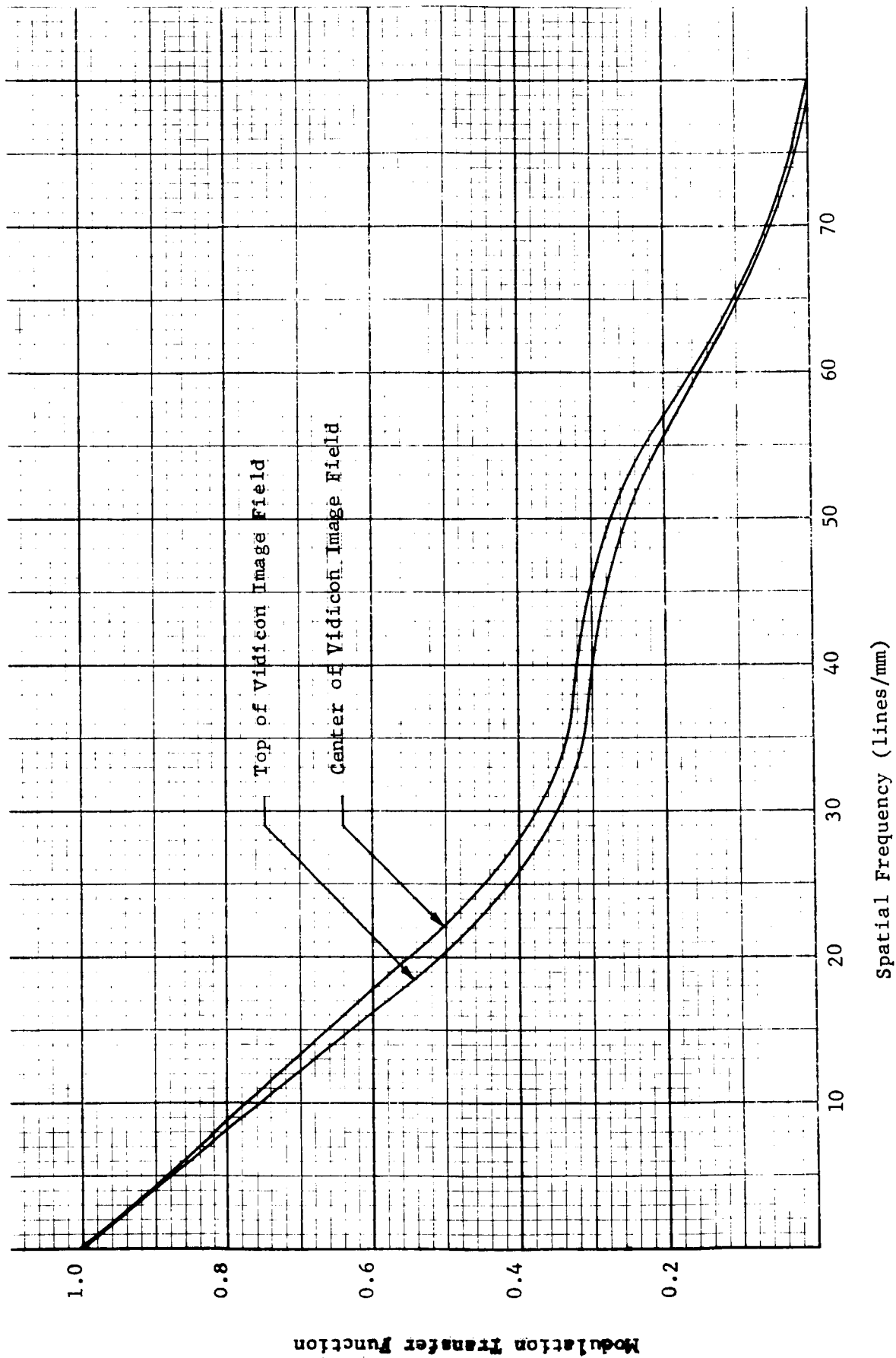


Figure 195. OTES 2-METER TELESCOPE
f/50 Vidicon Image Field M.T.F.
2500Å - Tangential Direction

CHAPTER 4 - OPTICAL COMMUNICATIONS

SUMMARY

The practical realization of a coherent oscillator in the optical part of the electromagnetic spectrum - the laser - has generated two separable breakthroughs in the art of space communication:

- The first is the high directivity or equivalent antenna gain due to the laser's spatial coherence.
- The second is that enormous bandwidths are achievable in a communications system because of the laser's temporal coherence and high carrier frequency.

The major advantage offered by optical communications in deep-space communications is the reduction of transmitter power due to the directivity of a laser communications antenna. This reduction of transmitter power permits high data rate communications at distances that are impractical with microwave systems. Deep-space laser communication systems are superior to microwave systems in the number of bits per second transmitted per watt of power required from the spacecraft.

There are several competitive techniques for space-to-Earth laser communications being evaluated by numerous investigators today. The incoherent techniques using visible or near infrared wavelength lasers such as the 5300A, helium-neon (He-Ne), argon, Neodymium doped glass or YAG, and gallium arsenide lasers, and the coherent approach using carbon dioxide (CO₂) lasers.

While it is premature to select an optimum laser for a deep space mission, the space experiments which have been analyzed in the OTES Program are common to both coherent and incoherent laser communications. The analysis which has been presented in this study assumes three missions:

- (1) a real time television link from synchronous altitude which would be an experiment of the Apollo Applications Program,
- (2) a real time television link at Martian ranges which could be an operational subsystem supporting the Voyager Probes (1973),
- (3) a 10^2 to 10^4 bit per second data link at ranges up to the radius of the solar system (before 1980).

Obviously, the designation of the modulation techniques for the third mission (and somewhat for the second mission) requires conjecture. The purpose of discussing these missions in this report is to illustrate the general feasibility and to identify and analyze space optical communication experiments which should be conducted as early as practical. Contemporary inventions and techniques are also considered even though they are not proven techniques because they may have a profound impact on the development of space laser communication technology. Because of the short time scale involved for the first mission, tighter constraints on the system design are necessary. The analysis for the synchronous altitude link must use only proven modulation techniques and use components which may be space qualified with a reasonable amount of engineering effort. For this reason, a design utilizing a helium-neon transmit laser and a PCM/PL (Pulse Code Modulation with Polarized Light) modulator are assumed for the synchronous orbit flight experiments. The physical layout and the basic design of the AAP experimental communicator have been verified in a laboratory equipment type of laser telescope system.*

To enhance the value to NASA of the synchronous altitude laser communicator experiments, numerous laser sources (such as CO₂, YAG:Nd, YAG:Nd second harmonic generation) will be considered in addition to He-Ne since their presence in the laser package will produce valuable engineering data which will speed further development of space optical communications.

Recent developments in the field of nonlinear optics have increased the efficiency of second harmonic generation (SHG) of laser light. This allows the design engineer to utilize the very efficient YAG:Nd laser (1.06 micron) and double the laser output frequency (0.53 micron) to obtain green light. There is substantial gain in the radiant output powers as well as increased photomultiplier tube efficiency.

The choice of the "optimum" optical communication system depends on many interrelated parameters, which require careful tradeoffs:

- mission characteristics
- launch ready date
- data rate
- laser state-of-the-art
- modulation technique
- photodetector quantum efficiency

* Laser/Optics Techniques, Contract NAS 8-20115.

MODULATION TECHNIQUES

As with radio frequency communication systems, optical communication systems may be broadly classified into two groups; coherent if the phase information of the optical carrier is utilized in the detection process, and incoherent if the detection process measures only the properly encoded intensity of the, received signal. The intensity detection technique avoids the wave front distortion problems introduced by the atmosphere that exist in a coherent detection technique. Coherent detection of optical radiation, as in microwave systems, requires a constant phase relationship between the radiation incident at various points in the receiver aperture. It has been shown that when a visible laser beam traverses an appreciable portion of the atmosphere, the phase coherence across the wave front is soon lost. This wave front degradation is a function of wavelength and severely limits any coherent communication link with visible light although it does not deteriorate intensity detection operations.

Thus, optical communication links utilizing visible lasers will use the incoherent, or quantum counting, detection techniques. One laser for which the coherent detection technique holds great promise is CO₂ (10.6 micron). Thus coherent detection is assumed for the CO₂ laser link and quantum counting for all visible and near infrared laser communication links in the analysis which follows.

Coherent Reception

Coherent reception, while offering a number of significant advantages to communication in the 10-micron band, does, however, imply certain specific noise conditions in the communication channel which make it worthwhile to re-examine the modulation and coding procedures used to combat the noise. Optical signaling methods have been proposed as "optimum" from various points of view, and it will now be useful to determine, in so far as is possible, the implications of coherent reception upon these optimizations.

As used in this report, the phrase Coherent Reception has two essential implications: first, the received wave front will be sufficiently undisturbed in spatial coherence that can be collected in a focused optical system of large aperture, second, the wave will also have sufficient temporal, or phase, coherence when received to permit detecting it in an "optical superheterodyne" receiver of narrow effective bandwidth (i.e., by "coherent detection" instead of simple photon-counting).

The method thus makes use of the two unique characteristics of laser radiation spatial and temporal coherence. Also, the apparent existence of a "window" in the 10-micron band is now complemented by the availability of high-powered CO₂ lasers which operate at 10.6 microns.

The two basic advantages that can be realized from coherent reception, as contrasted to simple photon-counting are:

- (1) A coherent receiver can be designed so that its effective (or noise) bandwidth is no wider than the bandwidth occupied by the signal. This increases the coherence time of the receiver above that obtainable from optical filtering, so that a bit decision can be rendered on the basis of a larger averaged photon count, with a resulting decrease in uncertainty, or noise. Oliver* shows that a simple phototube receiver having 100 percent quantum efficiency acts as though a noise spectral density of 2 hv watts/Hz were present at the input. In a coherent receiver the figure drops to hv, and, in fact, to 1/2 hv if a synchronous detector is employed and only amplitude information or phase information, but not both, is detected.
- (2) The use of a focused optical system reduces the background area viewed by the receiver to one spatial resolution element, thus excluding most extraneous background interference. This benefit is available whether or not coherent detection is employed.

Despite the advantage of coherent reception as an optical communication technique there are some fundamental difficulties which influence the type of signal to be radiated. Four major problem areas are:

- (1) Atmospheric Wave Front Distortion: This is probably the most serious barrier to optical communication to the Earth's surface, and has been discussed at length elsewhere.**
- (2) Channel Noise: The statistics of quantum noise in a coherent receiver departs significantly from the Gaussian distribution usually associated with noise in conventional radio channels due to the comparatively small number of photons received per watt of signal at optical frequencies. Noise in signal per se exerts a major influence on laser communication system design. The S/N ratio obtained from a quantum channel is quite poor by microwave standards. As a result, digital coding, such as PPM or PCM, is necessary because of its intrinsic capacity to withstand high noise levels and because of the ability of the digital format to accommodate the redundant bits used in transmitting error-correcting codes.

* Oliver, B.M.: Thermal and Quantum Noise, Proc. I.E.E.E., May 1965.

** Report No. 8500.

(3) Doppler Effect: Typifying current deep-space objectives, recent Earth-Mars and Earth-Venus trajectories involve range rates as great as 13.4 and 17.6 kilometers per second, respectively.* Superimposed on these trajectory rates is a diurnal rate variation of 4.66 km per second. These motions introduce a frequency change in the received signal which for coherent reception, must be tracked in frequency by the "local oscillator" laser for coherent reception at a constant offset, or i-f, frequency. Further, if the advantages of synchronous detection are to be realized, a final phase-lock will also be required.

At 10.6 microns, the 17.6 km/sec velocity produces a frequency shift of 1.66 GHz over a mission period of about 120 days. In addition, there is a diurnal² shift of about 42 MHz during a 6-hour track period for a single ground station.

The AFC/APC circuitry will thus be required to track a long-term shift of 1.66 GHz plus a short term shift of 42 MHz in 6 hours. The former figure will specify the dynamic range of the control loop, while the latter, having a higher rate of change, will set the loop bandwidth and thereby determine its noise characteristic. The instabilities of the laser "local oscillator" can also be expected to influence the control loop design. At 6328A, successful coherent detection at an offset, or i-f, frequency of 3 GHz has been reported.**

If the laser tuning design problems can be surmounted, and true coherent detection realized at 10.6 microns, direct digital modulation of the transmitting laser can be effected by some such means as PCM/PL, PCM/on-off or PPM/on-off as determined by considerations as discussed later in the report.

If direct coherent detection proves impractical, a sub-carrier technique may be required because of the reduced Doppler shift and Doppler rate of the sub-carrier. (A 100 MHz sub-carrier would be shifted about 6 KHz under the mission conditions assumed earlier.) Direct, photon-counting reception, followed by coherent detection of the sub-carrier, which might be frequency or amplitude-modulated, is a possibility. The modulation would probably still need to be digital because the sub-carrier channel would have a poor S/N characteristic. The literature reports successful phase-lock detection of a 78 MHz sub-carrier on a 300Å (10⁴ GC)-bandwidth source.†

In mitigation of the control-loop design problems described above, it should be stated that normal space missions are accomplished with high accuracy and predictability of trajectory and/or orbit. When this is the case, the burden on the control loop can be substantially eased by "cranking in" a programmed

* Advanced Study on Optical Communications from Deep Space, Westinghouse Defense and Space Center, Contract NAS9-3650.

** Targ, R.: Optical Heterodyne Detection of Microwave Modulated Light, Proc. I.E.E.E., July 1964.

† Ward T. H., Davison, W.F., Marcusen, E.R.: Synchronous Detection of Microwave Modulated Incoherent Optical Carriers, Proc. I.E.E.E., July 1964.

frequency correction to the local oscillator during the course of the mission. Central-loop feedback can then be required only to remove small errors and will not be used up in the major tracking task.

Another signal design problem complicated by Doppler shift is the need to provide in the transmitted message some type of synchronizing information which can be readily utilized by the ground station, since the random bit-stream of PCM does not, of itself, provide a well-defined spectral line. The added synchronizing information can be transmitted, for example, by sending an occasional extra-amplitude pulse at regular intervals, if feasible, or by a steady sub-carrier or pilot tone. Some transmitter power will have to be sacrificed to this function. The fractional amount can be small, however, in consequence of the fact that the information bandwidth required for synchronization can be made a small fraction of the information bandwidth of the channel, itself.

A more sophisticated technique which is applicable when error-correcting codes are being used is given below*. It provides synchronous information by complementing certain of the parity-check digits in the code and is therefore compatible with the objective of high-accuracy transmission in a noisy channel.

(4) Laser Spectral Purity: Coherent reception requires sufficient temporal coherence and frequency stability of the transmitted beam so that true, narrow-band operation can be realized. Early CO₂ lasers were inadequate in this respect in that their output energy was divided among a relatively large number of spectral lines of uncertain stability. Coherent detection of such radiation would be extremely difficult, as would the frequency control of such lasers in local oscillator applications. Recent laboratory development has produced a CO₂ laser at the 45-watt level having a spectral line width of less than 710 Hz, which is more than adequate for megahertz information bandwidths.** The frequency modulation capability of this unit, however, is reported to be 3 MHz total deviation, which falls far short of the Doppler-imposed requirement of 1.66 GHz mentioned earlier. Therefore, tuning problems of a local oscillator laser are still unresolved.

Noise Characteristics of 10 μ Receivers

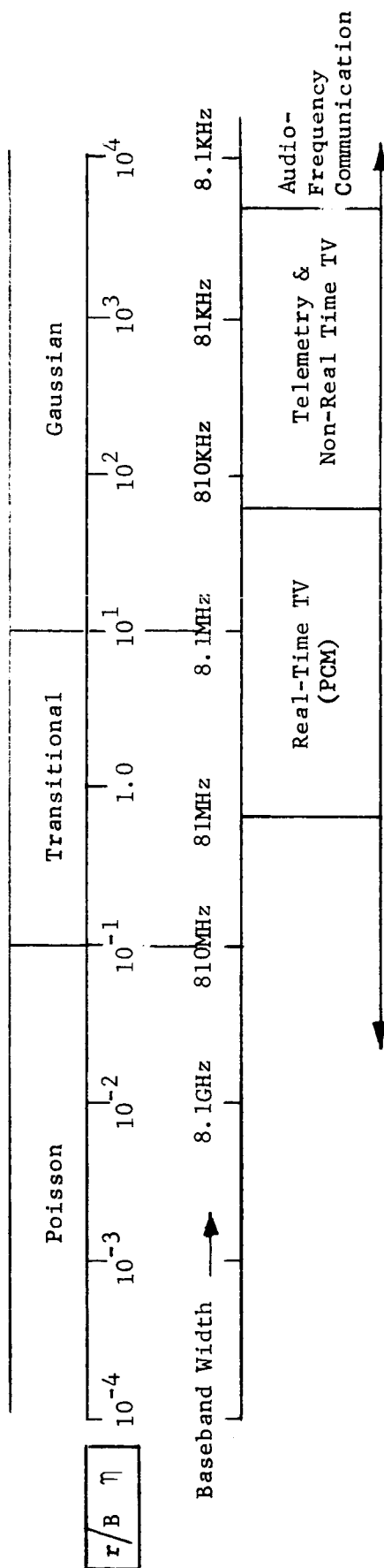
Photons reaching an optical receiver at an arrival rate of r photons per second and having an energy content of $h\nu$ joules per photon result in an energy-per-unit-time, or signal power(s) of

$$S = h\nu r$$

See Figure 196

*Levy, J.E.: Self-Synchronizing Codes Derived from Binary Cyclic Codes, I.E.E.E. Transactions IT-12, No. 3, July 1966.

**Brandwie, R.A., Haswell, W.F., Marada, R.H.: Heterodyne Detection and Line-width Measurement with High Power CO₂ Lasers, I.E.E.E. Journal of Quantum Electronics, March 1966.



Modulating Signal Bandwidths
& Corresponding Noise Characteristics
20-Watt, 10.6 Micron Source At A Range
Of 10⁸ Miles.

$$\eta_r = 1.62 (10)^8$$

Figure 196. 10 μ Signal Coherent Detection Regions

If the received signal is weak, so that the photons are, on the average, well separated in time, and if the receiver has a broad predetection bandwidth, it will respond independently to the arrival of each photon, i.e., the transient initiated by each photon will have died out before the arrival of another photon. (This will generally be the case when the predetection filter is optical, as in incoherent receivers. Even a narrow optical filter in the infrared of 0.1 microns bandwidth has a frequency bandwidth of several hundred GHz at 10 microns.) When this type of independent response prevails, the fluctuation noise will be Poisson-distributed.

The foregoing can occur in both coherent and incoherent reception. The difference lies in the fact that the coherent receiver, having a substantially smaller bandwidth, will have a Poisson-type response only to the more widely separated photons encountered in weaker signals.

A reciprocal measure of the same phenomenon is the coherence time, τ , of the receiver. It represents the minimum time separation between events to which the receiver can respond independently. It is defined as:

$$\tau = \frac{1}{B} \text{ seconds}$$

where B is the predetection bandwidth in Hertz and is the approximate time required for the transient from a single event to decay. See Figure 197.

Thus, long coherence times go with narrow bandwidths, and Poisson noise dominates when the average time separation between photons is large. In terms of the arrival rate, Poisson noise corresponds to the condition

$$r\tau n = nr/B \ll 1$$

where n is the quantum efficiency of the detector. At the other extreme, when, due to strong signals, many photons arrive during a coherence time, that is, when

$$r\tau n = nr/B \gg 1$$

the Poisson distribution degenerates into the Gaussian distribution, and the signals are detected in the Gaussian noise environment familiar to radio frequency communications and characteristic of thermal noise.

Between the extremes, when

$$r\tau n = nr/B \approx 1$$

a transitional situation exists in which the noise has a "time-varying Poisson" characteristic, a distribution not described by any of the standard statistical models.

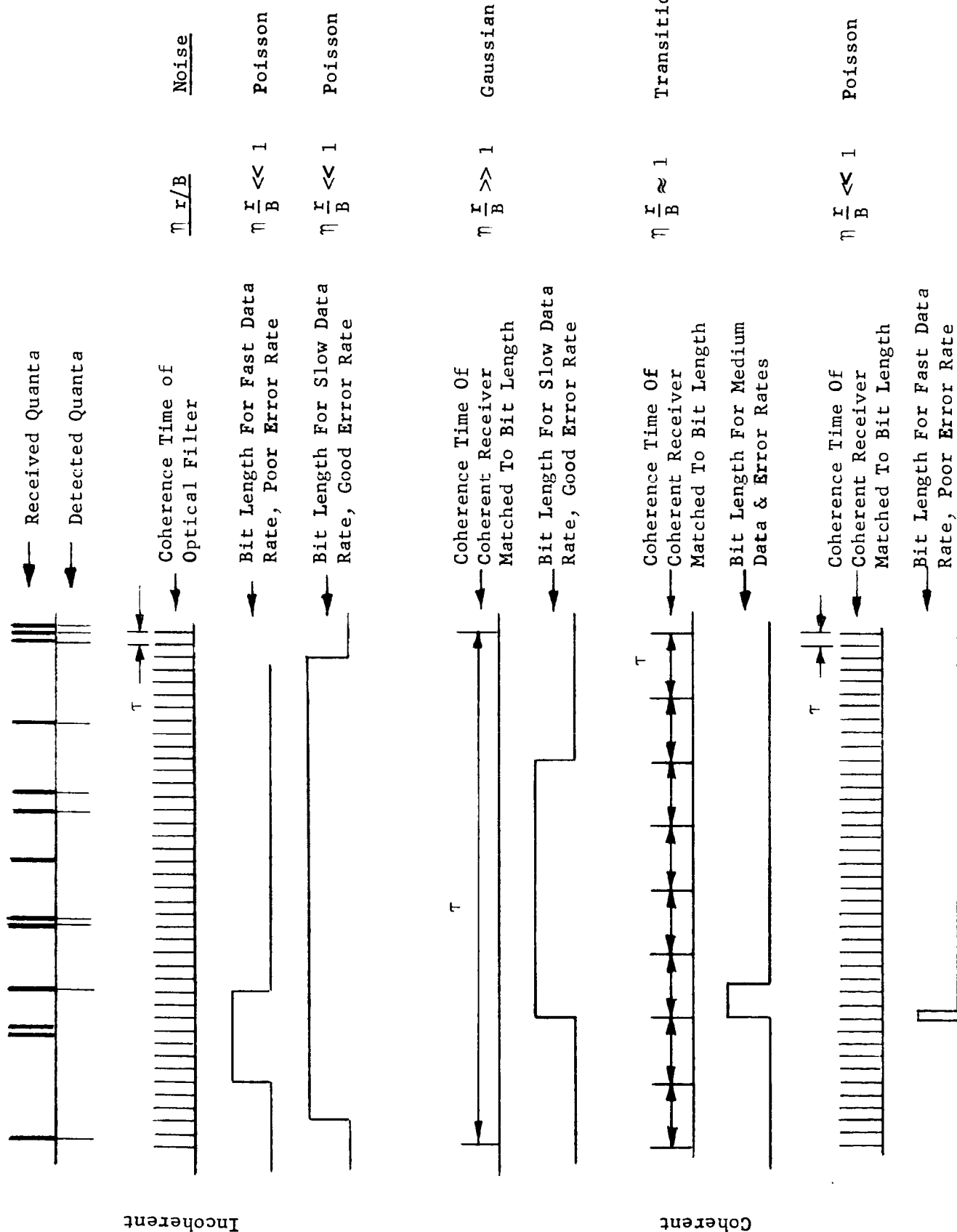


Figure 197. Representation of the Poisson, Gaussian, and Transitional Detection Regions

In the vicinity of a planet, if the interplanetary range increases, the received signal power (proportional to the arrival rate, r) decreases, and both coherent and incoherent receivers will change from a Gaussian noise characteristic through a transitional phase and into a Poisson noise region. Due to its smaller bandwidth, however, the coherent receiver will do this substantially later, i.e., at weaker received signal levels.

A useful model of this process is that of Ducot* who calculates an equivalent thermal noise input which would produce the same output noise as does the quantum effect. He shows that, at least for a-m, f-m and pulse signals, the condition $r/B \gg 1$ corresponds to a white, thermal noise level of $h\nu B/2$, while the transition to $r/B \ll 1$ is accompanied, in the case of pulse modulation, by a change to an equivalent thermal noise level of $(Sh\nu B/2)^{1/2}$, which implies that the received noise level is not additive but is a function of signal power level. This, of course, is the case for quantum noise, and corresponds to the fact that the rms deviation of the Poisson distribution is the square root of the mean value.

For the coherent detector, the signal-to-noise ratio is $(S/N) = \frac{S}{h\nu B} \eta$

From Figure 196, it is apparent that

$$(S/N) = \frac{h\nu r}{h\nu B} \eta = \frac{r}{B} \eta$$

which is the figure $(\eta r/B)$ which has been used in the previous paragraphs to establish the noise category. See Figure 198.

The diagram of Figure 196 summarizes the noise properties for the case of coherent reception and illustrates their application to the 10.6 micron communication system described in Perkin-Elmer Report No. 8500, which proposes the use of a 20-watt CO_2 laser transmitter at a range of 10^8 miles. For a fixed level of received power and a stated quantum efficiency, $\eta r/B$ is determined by the signal bandwidth, B , which is, in turn, fixed by the baseband, or modulating, signal bandwidth. For each plotted value of $\eta r/B$, therefore, a corresponding baseband width is implied by the received power level. Double sideband modulation is assumed.

Signal Design

The foregoing paragraphs argue for operation with the smallest possible bandwidth, B , to maximize the S/N ratio for any given received power level. The bandwidth, however, must be kept wide enough to admit the signal modulation. This will generally be

$$B = 2W$$

where W is the baseband width of the signal assuming that a double-sided modulation method is in use.

* Ducot, C.: A Comparison Between Thermal And Quantum Noise in Radio Reception, Philips Research Reports 17, 1962.

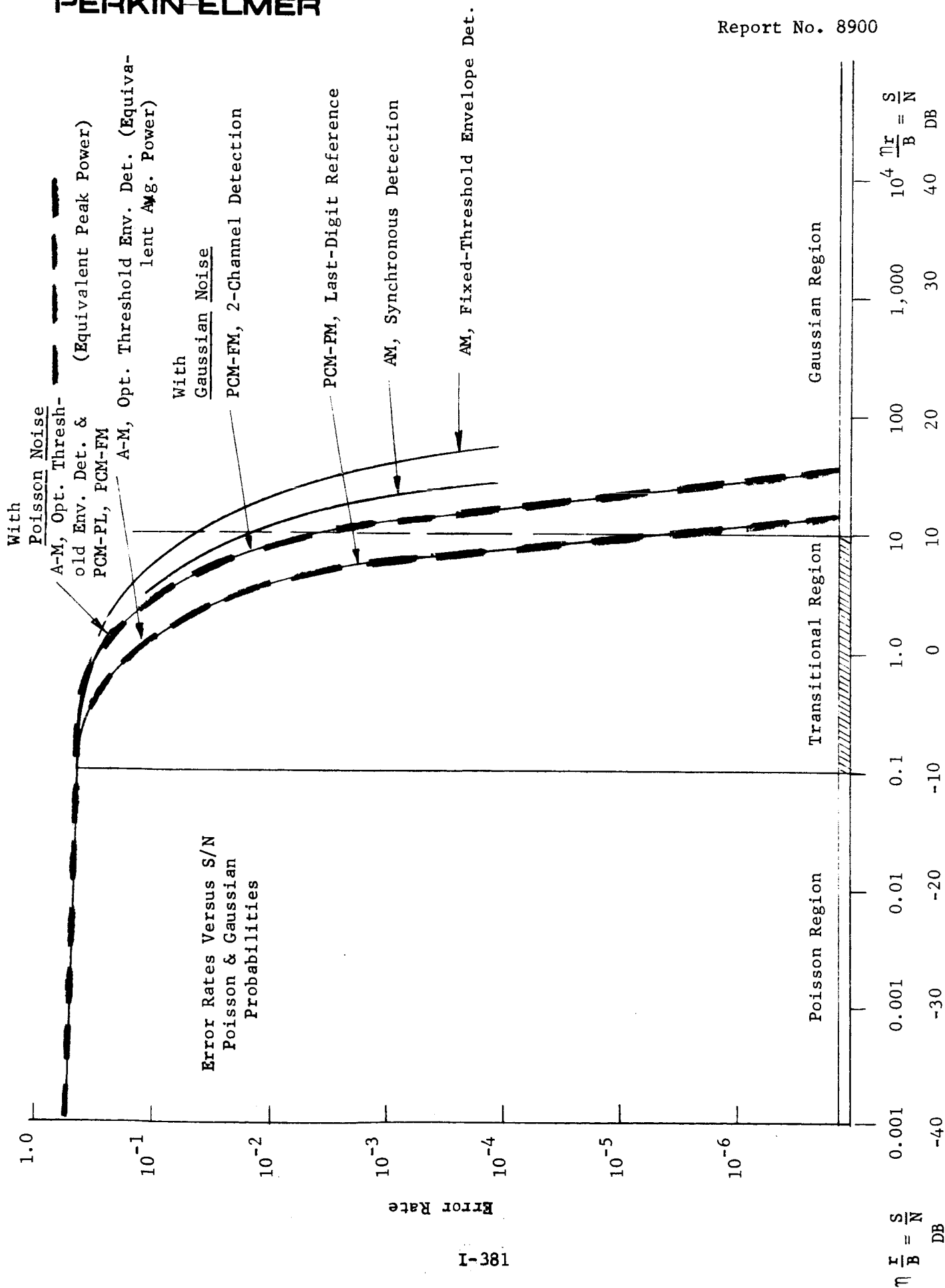


Figure 198. Coherent Detection Error Rate Curves

The usual requirement to transmit large amounts of data per unit time will result in high bit-rates and will tend to enforce a bandwidth minimum. However, as the individual bits are made shorter to accommodate the higher rates, as illustrated in Figure 197, there are fewer quanta available to define a bit, and the error rate increases.

The distinguishing feature of coherent reception, as illustrated in Figure 197, is that the coherence time of the receiver can be matched to the bit duration, which has, in turn, been made long enough to include sufficient detected quanta (perhaps 10 or more) to give low bit-error rates. The coherent receiver will, therefore, operate largely in the transitional and Gaussian noise regions because the factor $n\tau$ will generally exceed 10.

The incoherent receiver, with its optical filter, however, has such a short coherence time that Poisson noise prevails, independent of practical rates.

If a coherent optical receiving system is to operate only under conditions of strong signals or narrow bandwidths, its quantum noise will be Gaussian, as shown earlier, and coding, modulation and detection methods selected accordingly. Because of the premium placed to minimize transmitted power in deep-space applications, Gaussian statistics will not represent the worst-case situation, and channel performance will generally be predicated more upon the Poisson model since it will represent the limiting performance as the received signal grows weaker with increasing range.

However, during the early phases of a deep-space mission and also in near-space applications, the Gaussian model will be accurate and will offer the advantage of an already well developed theory. It will also be useful in interpolating performance which lies in the Transitional region between Poisson and Gaussian.

Gaussian noise is characterized by its smoothness - the very low probabilities associated with substantial departures from the mean. Gaussian noise also has the unique property of being able to distort any waveshape into any other waveshape (of equal energy) with the same probability. Hence, there is no preferred signal which looks "least like" Gaussian noise.

"Optimum" signaling in Gaussian noise is based upon a matching and averaging process in which an a-priori-known waveform is matched against a stored replica, as in cross-correlation or matched filtering, and the process averaged over a time interval. These processes give a yes/no decision as their output, not a recovered waveform, and they are optimum in the sense of yielding the minimum mean-square output error.

For purely binary communication, the combination of binary phase modulation and synchronous detection from a fixed reference is generally regarded as optimum because it achieves the lowest error rates for given S/N ratios of any of the common binary modulation methods. In practice the use of a fixed reference is usually not feasible, but a phase-lock loop reference may be derived from the signal, itself, or differentially coherent detection can be

used in which the phase reference for each bit is derived from the phase of the preceding bit. Viterbi* shows that the optimum detector for such a system consists of the linear combination of a carrier correlation detector and squared-envelope correlation detector and that the optimum signal pairs will be orthogonal for small S/N in the tracking loop, antipodal for large S/N, and that the orthogonal pair represents the best strategy for unknown S/N. Differentially coherent detection, which requires no tracking loop, is inferior to the above only when the loop S/N > 10, and is therefore attractive.

The use of coherent reception techniques makes it possible to consider these widely used phase-modulation methods for optical communication.

Although the problem of optimization has not been as thoroughly explored for the Poisson Channel, as it has for the Gaussian, a number of specific analyses do exist. Reiffen and Sherman** consider the optimum processing of a photon channel to determine which of an a-priori-known set of waveforms has been transmitted. They conclude that the optimum signal processing is cross-correlation and that an optimum, average-energy-limited signal in the presence of high background noise is on-off modulation. (This result closely resembles that for the Gaussian channel.) They also conclude that a narrow pulse is the most desirable form of "on" signal.

Error rate analyses, referenced above, also exist for polarity-keyed PCM, PPM, and symmetrical on/off keying which verify the suitability of these forms of modulation for Poisson channels. A study by ADCOM, Inc.† shows that in the presence of background noise, split-channel methods such as PCM-PL produce substantially lower error rates than on-off keying if equal peak power is assumed for the two. Under the assumption of equal average power, the situation changes, and on/off modulation is somewhat better. More to the point for coherent reception is the circumstance that, in the absence of appreciable background noise, the two systems perform nearly alike for the same peak power while on an average-power comparison, the on/off technique shows a 3-db superiority. However, since the laser sources for on/off transmitters operate CW, it is impossible to obtain this superiority.

The results for a Poisson channel for the discussion of coherent detection are chiefly of interest as limiting behavior since true Poisson behavior will be obtained only at S/N ratios so low as to be of little practical communication value.

The Poisson model becomes germane when the quantum counting visible communication links are considered.

* Viterbi, A.: Optimum Detection and Signal Selection for Partially Coherent Binary Communication, I.E.E.E. Transactions IT-11 No. 2 April 1965.

** Reiffen, B., Sherman, H.: An Optimum Demodulator for Poisson Processes: Photon Source Detectors, Proc. I.E.E.E., October 1963.

† Error Rates for Poisson Processes, Report No. G-74, ADCOM Inc, 30 October 1966. NAS8-20001

In the absence of published error-rate data for modulation and detection systems in the transitional region between Poisson and Gaussian channels, it will be useful to estimate the behavior in this region of the standard optical transmission methods and also to consider such new (to optical communications) methods as may merit attention because of the coherent receiver's ability to respond to carrier phase. In this latter category are some of the systems most used in conventional data transmission.

A basis for doing this will be found in the error-rate curves of figure 198. Insofar as the information was available, separate plots were made of the error rates for a given modulation-detection method when perturbed by Gaussian and by Poisson noise. Since the region, $0.1 < \frac{r}{b} \eta < 10$, represents a smooth transition from Poisson to Gaussian characteristics, it is reasonable to anticipate, in this region, error characteristics lying between the two.

In point of fact there are, for the cases considered, no radical separations between the corresponding curves, and, in some instances, no difference at all. For example, the error rates for PCM-FM are identical for Poisson and Gaussian noise. A-M, on the other hand, exhibits some 5 to 8 dB of difference between the optimum, variable-threshold detection assumed for the Poisson channel, and the alternative detection methods assumed, (for want of other data) of the Gaussian case. The assumption of comparable detection methods would doubtless bring the curves closer together, as does the assumption of equivalent peak power.

The interesting case of PCM-PM is presented for Gaussian noise only, there being no Poisson data available due to the fact that this form of modulation cannot be received by the incoherent receivers for which much of the published analysis has been made. This variation of digital phase modulation, in which the reference phase for decoding each bit is derived from the previous bit, promises a low error-rate, is widely used in r-f data transmission, and requires only limited temporal coherence (one bit length) in the transmission medium, for proper decoding. Similar advantages exist for PCM-FM, another phase-encoded scheme.

Conclusion

It seems reasonable to conclude that the important Transition Region introduces no radical characteristics into optical communications and will tolerate the same modulation schemes as are now prevalent elsewhere. Thus, it does not appear that any overwhelmingly optimum schemes will appear on the basis of modulation efficiency; considerations of synchronization, available modulators and other practical problems will often wield as strong an influence.

This view is supported by the finding, by Reiffen and Sherman*, of an optimum coding and detection scheme for Poisson noise. Their receiver is virtually

* Loc cit

identical, schematically, with the correlation receiver which has been long established as optimum for Gaussian noise.

Also significant is the work of Mandel,^{*} who uses autocorrelation/power spectra analysis to show that for the particular case of $\eta_r/B = 1$, simple a-m, or on/off modulation, can produce a detected S/N of 2:1 when an optical superheterodyne receiver is used, even in the presence of background radiation several times as great as the signal.

Assuming the use of focused optics to exclude effectively, all background radiation and the employment of an optical superheterodyne receiver whose bandwidth can be matched to the signal bandwidth, the limit on communication rate comes from the quantum noise intrinsic to the signal, itself. This noise can assume a Poisson, a Gaussian, or a Transitional distribution intermediate to the other two, depending on received power level and receiver bandwidth. (In this respect, the coherent technique differs from incoherent reception which is nearly always Poisson-limited because of the large bandwidth of optical filters.) In practice, only the Transitional and Gaussian distributions will be of interest because only for them does the S/N ratio become large enough for useful signaling.

By comparing error rates and system optimizations for the Poisson and Gaussian situations, it is concluded that presently used optical modulation methods will be fully useful in the Transition region, but that the ability of the coherent receiver to respond to signal phase opens the door to consideration of such phase-encoded methods as PCM-PM and PCM-FM now widely used in r-f data communications.

It should be borne in mind, that the phase modulation methods depend strongly upon the temporal coherence of the received wave, a property assumed at the beginning of this discussion. To the extent that this is not realized, due, perhaps, to atmospheric disturbances, the corresponding advantages will begin to disappear.

Quantum Counting Detection

As demonstrated in the previous section, the Poisson statistics must be used in the derivation of the bit error rates of the quantum counting (incoherent) photodetectors. The background noise bandwidth is defined by the optical filter (typically $\Delta B \cong \Delta A$ or $\Delta f > 10^{10}$ Hz), and not by the bandwidth of the signal. Thus, the background noise power is independent of the signal bandwidth. This, combined with the addition of quantum noise, forces the communication engineer to re-evaluate the optimum modulation techniques for deep-space missions.

^{*}Mandel, L.: Heterodyne Detection of a Weak Light Beam, Journal of the Optical Society of America, September, 1966.

The modulation techniques developed for radio frequency communications may be applied to optical communication systems. However, the unique characteristics of optical signals allow one to hypothesize and analyze modulation-demodulation techniques which are unique to optical communications. Only digital modulation techniques are considered for the deep-space optical communication link. The optical signals detected at the receiver of an optical communication link will be of a very low power. More exactly, the received signal will be detected as individual photons. The photon counting detection technique of optical communications systems is compatible with a digital demodulation system.

A conceivable format for a megabit communication system could include both planetary television, which requires a bit error rate of 10^{-3} , and command information which would need a bit error rate of 10^{-6} . Applying the well developed error correction coding techniques to the command information, it is possible to transmit both the TV and command information over the same link.

The data from the many data sources on the satellite must be multiplexed before transmission. Time multiplexing is compatible and relatively easy in digital communication links. Data in this format is also compatible with the digital data processing and storage facility that is available at the Earth receiver.

The disadvantages of the digital modulation techniques are increased bandwidth required, complicated transceivers, and high-speed digital logic circuits. However, the advance of both television bandwidth compression techniques and the development of thin-film technology make spaceborne digital television systems practical for the 1970 missions.

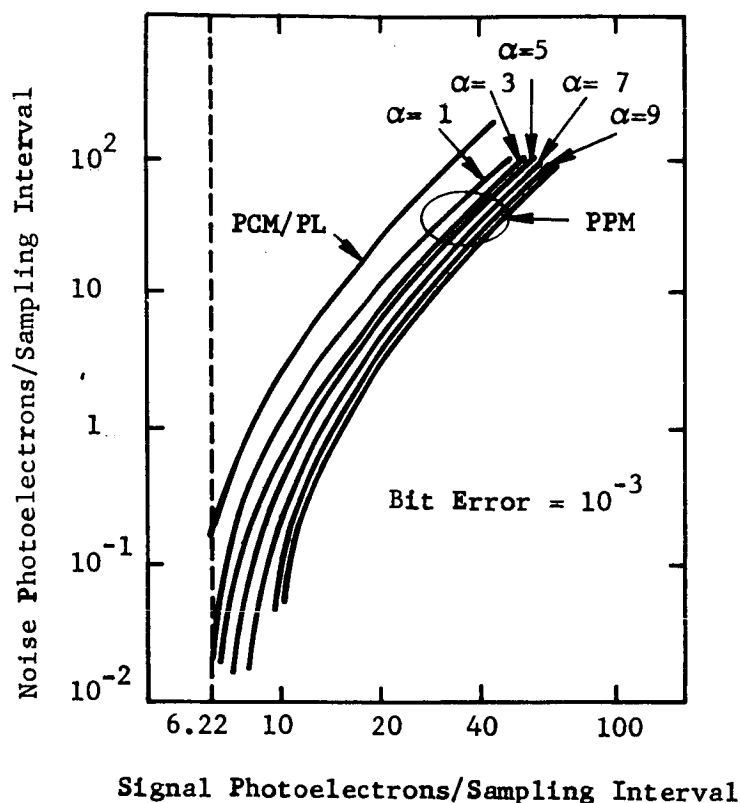
Figure 199 illustrates the modulation techniques that were considered in this comparison. To show how the information bit stream is encoded on the optical signal, consider the five bits enclosed in the bracket, namely 00100.

PCM/PL

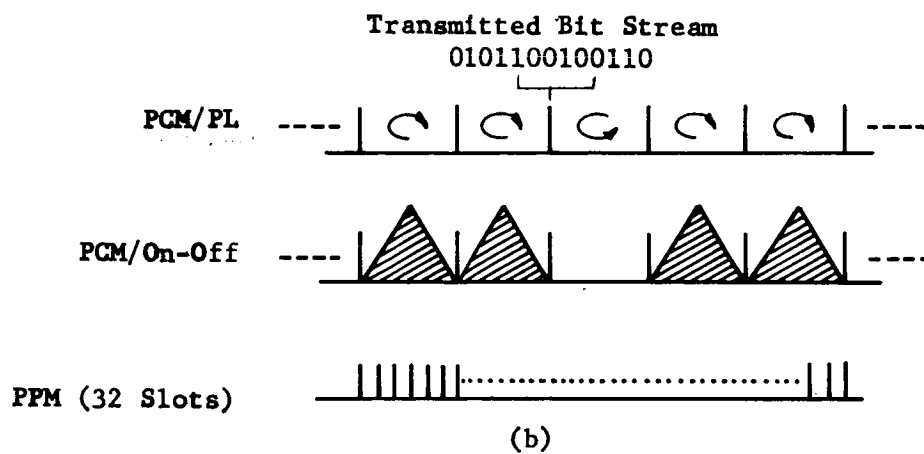
A system using Pulse Code Modulation with Polarized Light (PCM/PL) transmits one of two orthogonal polarizations for each bit. For example, consider the system that transmits right-hand circularly polarized light for the zero bit and left-hand circularly polarized light for the one bit. The first line of Figure 199b demonstrates how these five bits are encoded on the optical signal. The bit error rate equation for PCM/PL is derived in the Phase I Report, OTS Study. The results of a computer solution to the bit error rate equation are plotted in Figure 199a.

Published data demonstrates the existence of polarization errors in the atmosphere.* Other experimenters made similar measurements which did not confirm

* Fried, D.L.; Meyers, G.E.: J. Opt. Soc. Am., vol. 55, 1965 p. 740.



(a)



(b)

Figure 199. Incoherent Modulation Techniques

This figure demonstrates the method used to encode five bits of information on an optical signal.

these polarization errors.* Bit error rate equations were derived for PCM/PL under the conditions of both amplitude and phase polarization errors.** These equations show that a phase error of 30° or a reduction in amplitude of one of the component vectors of a circularly polarized beam will be corrected for by a transmitted power increase of less than 1 db. Thus, even if these phase errors do exist, there will be no significant degradation in the information transmitted. Other polarization errors have been analyzed and the resultant bit error rate curves show that only moderate increases in power are required even for quite large polarization errors.†

Log Normal Fading

Theory predicts that the fading statistics of an optical signal operated on by atmospheric turbulence is log normal††. For ground based receivers, the variance (i.e., depth of fade) of the distribution may be reduced by using larger apertures.‡ This effect is referred to as aperture averaging.

Figure 200 depicts the susceptibility of a PCM/PL channel to turbulence induced fading. Log normal statistics of intensity fluctuations for a fading optical communications channel were used to determine the relative increase in the signal power required for the system to operate at a prior error rate. The bit error rate probability for the quantum limited case ($N=0$) was integrated over the log normal probability density function.

$$P_B' = \int_0^{\infty} \frac{P_B(S, N)}{\sqrt{2\pi} \sigma_1^2 S} \exp - \left[\left(\frac{1}{2} \ln \left(\frac{S}{S_0} \right) + \sigma_1^2 \right)^2 / 2\sigma_1^2 \right] dS$$

Several values of the log amplitude variance (σ_1^2) have been used. This variance equal to zero corresponds to the no fading case and $\sigma_1^2 = 0.6$

* Adel Abdel Moneim Saleh; An Investigation of Laser Wave Depolarization by Atmospheric Transmission, Digest, 1967 Conf. on Laser Engineering and Applications.

** Peters, W.N.: Proc. of Nat. Electronics Conference, Oct. 1965.

† Peters, W.N., Arguello, R.J.: 1967 Conf. on Laser Engineering and Applications and J. of Quantum Electronics, Nov. 1967.

†† Tatarski, V.I.: Wave Propagation in a Turbulent Medium, McGraw Hill, New York, 1961

‡ Report No. 8300: Study for Optical Technology Apollo Extension System, Phase I and IA, page I-149, November, 1966.

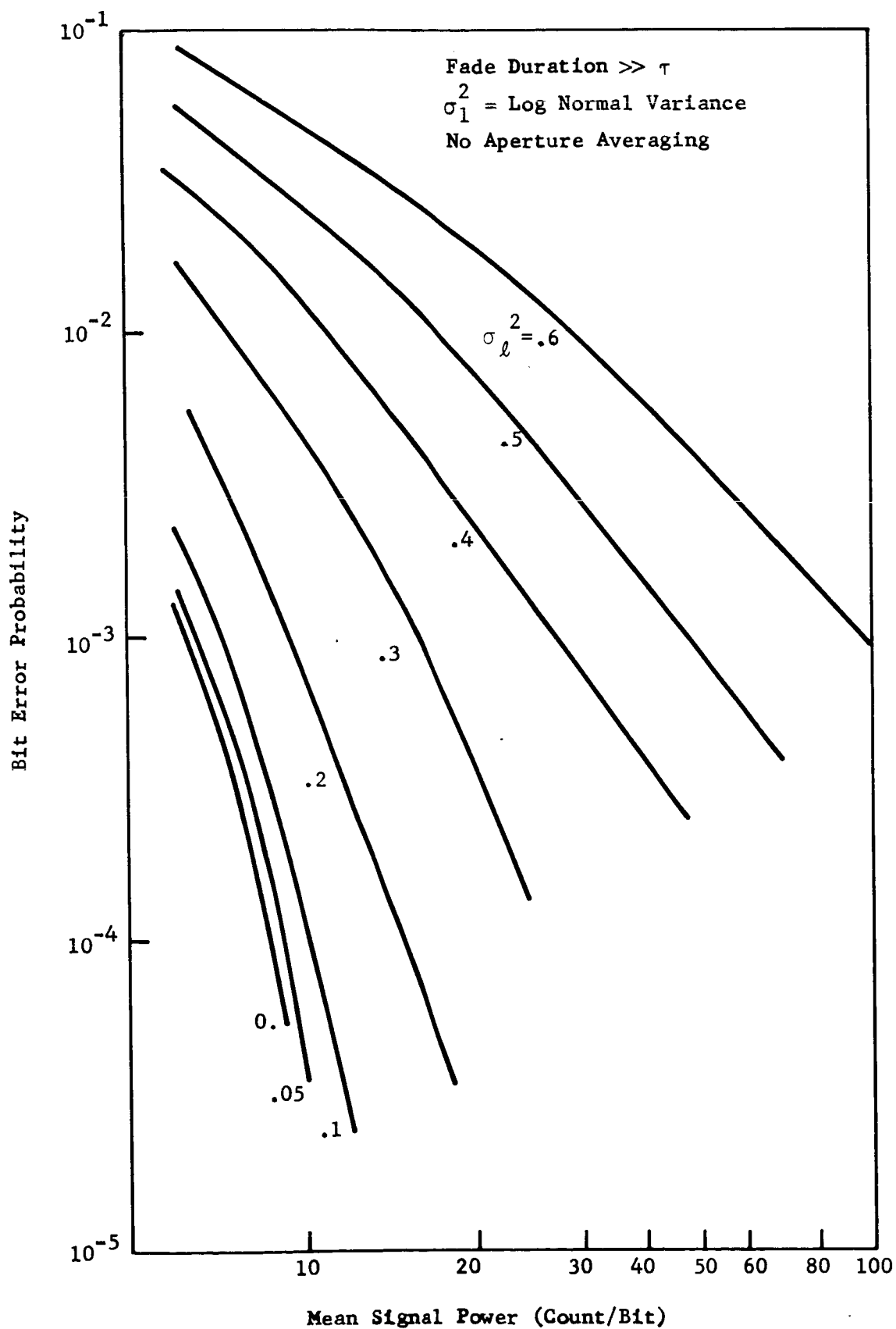


Figure 200

corresponds to strong turbulence induced fluctuations.* For the no fading case, 6.2 signal counts are required for $P_B = 0.001$. If due to strong fading, $\sigma_1^2 = 0.6$, in order to maintain $P_B = 0.001$ the signal must be increased to 100 counts per decision, or 12 db.

PCM/On-Off

The next type of modulation considered was PCM/on-off. A pulse or no-pulse is transmitted for the zero and one bits, respectively. This is demonstrated in the second line of Figure 199b.

The detector sets a threshold from prior information. This information is usually obtained from examining the signal-to-noise ratio during the previous bit intervals. The PCM/on-off detector then integrates the energy received during each of the bit intervals. Depending whether the received energy was greater than or less than the threshold, the detector assumes that a zero or a one was transmitted, respectively. This type of optical detection was analyzed by T. F. Curran, et. al.** and the extrapolated results are plotted in Figure 199a. This modulation technique has certain disadvantages; it has a relatively low detection efficiency and it requires a variable threshold if the system suffers from fading from atmospherics. Link calculations demonstrate that PCM/on-off is not an attractive modulation technique for space optical communications systems.

PPM

The next modulation technique that will be defined will be PPM (Pulse Position Modulation). The PPM transmitter defines a number of sequential time slots.

The specific example shown in Figure 199b assumes 32 time slots. The transmitter then places a pulse into only one of the 32 time slots considered. If the receiver then correctly decodes which slot contains the signal pulse, it will correctly decode $\log_2(N)$ bits where N is the total number of time slots per word. Thus by placing a pulse into one of 32 slots, the transmitter can send 5 bits of information per pulse.

*Fried, D.L., Schmeltzer, R.A.: Effect of Atmospheric Scintillation of an Optical Data Channel, p. 225 Lecture Notes compiled under contract NAS 8-18035, NASA, Huntsville, Alabama.

**Curran, T.F.; et. al.: Proc. I.E.E.E., November, 1965 pp. 1770-1711

The bit error rate equations for PPM are derived in Phase I Report, OTS Study. The results are plotted in Figure 199a for several alpha (α) levels. The alpha (α) level is the number of bits which are transmitted per pulse.

PPM is a very efficient modulation technique for two reasons. First, PPM partially suppresses the effect of quantum noise. For the sake of discussion, say that we have allocated a quantity of energy, E , for each bit to be transmitted. The receiver for the PCM/PL modulation techniques previously considered will make its decision on the basis of the received energy E . However, for the previously considered case of PPM using 32 time slots, each pulse could be allocated an amount of energy of $5E$ and the system would still require the same transmitted average power. By making a decision on the received energy of $5E$, the effective contribution of quantum noise has been reduced. The capability of suppressing quantum noise may also be deduced from Figure 199a. The vertical dashed line in Figure 199 is the quantum limit. That is, even when the background and phototube artificially approach zero, one required 6.22 signal photoelectrons per decision if the system is to operate at a bit error rate of 10^{-3} . Thus, the two PCM systems require a minimum of 6.22 detected signal photoelectrons. However, the $\alpha = 9$ PPM curve also has the same asymptotic limit. Thus, the receiver requires a minimum count of only $6.22/9 = 0.69$ detected signal photoelectrons per bit on the average.

The bandwidth of the background noise is determined by the optical filter. These filters have bandwidths of typically many kMcps. Since the optimum performance of a communication receiver occurs when the signal and noise bandwidths are equal, we see that an optical communication system operating in a high-noise background (typically the blue sky) has a severe disadvantage. Large changes in the state of the art in optical filters are not expected; however, an alternative approach to reducing the effect of high background noise is to increase the signal bandwidth such that the difference between the signal and noise bandwidths is decreased. Thus, the second advantage of PPM is its increased tolerance to high background noise. For example, the bandwidth of PCM/PL and PPM with 32 slots for a one-megabit system is about 2 Mcps and 15 Mcps, respectively. The PPM system using 9 bits per pulse has a bandwidth of over 115 Mcps.

The modulation technique of PPM has two disadvantages. Because of the increased number of time slots required for a given bit rate, the accompanying digital and laser modulating equipment are required to operate at much higher switching rates. As shown later in this section, PPM will be competitive only in the 10^3 to 10^5 bit-per-second communication system because of the increased requirements on the switching circuitry. The second disadvantage of PPM is its great susceptibility to impulse noise. Analysis of the phototube dark current measured in Earth-based experiments reveals that the noise is not uniformly distributed in the time slots, but is emitted in pulses of relatively large amplitude. The radiation environment of space will probably increase the magnitude of these impulses in a detector operating in space. The PPM detection system will not be able to differentiate between the pulses caused by the optical signal and the impulse noise pulses. The impulse noise encountered in phototubes varies in both the average number

of impulses detected in a time interval and also the average number of photoelectrons emitted per pulse. Assuming that both the impulse amplitude and impulse occurrence probabilities are Poisson distributed with expectations of A and I , respectively, the bit error rate equation for PPM may be modified to include the effect of impulse noise.* The dashed curves in Figures 201 and 202 give the obtainable bit error rate when operating in a constant noise environment of one noise photoelectron per sampling interval, on the average.

Figure 201 shows the effect on the PPM bit error rate when the average of the impulse amplitudes is changed from 0 to 40 photoelectrons per impulse. For the parameters chosen in Figure 201, note that the system may be operated at a bit error rate of 10^{-3} or greater with only a small signal power increase. However, prohibitive signal power increases are required to operate at bit error rates smaller than 10^{-3} . Figure 202 demonstrates that if more than 1 impulse occurs in 10^4 sampling intervals, a significant decrease in the detection efficiency of an $\alpha = 9$ PPM system is to be expected.

Two methods are available which reduce the effect of impulse errors. First, reduce the alphabet level. This reduces the number of time slots and subsequently reduces the effect of a given impulse when it occurs. The use of diversity in the receiver will also reduce the effect of the impulse noise. The received optical signal power is partitioned between several phototubes. Since the impulse noise in the several phototubes is uncorrelated, and the signal pulse is correlated in the outputs of all the detectors, the effects of impulse noise are reduced significantly. A block diagram of the diversity detection is shown in Figure 203.

* Peters, W.N.: Pulse Position Optical Communication System, NATCOM Proceedings, 1964.

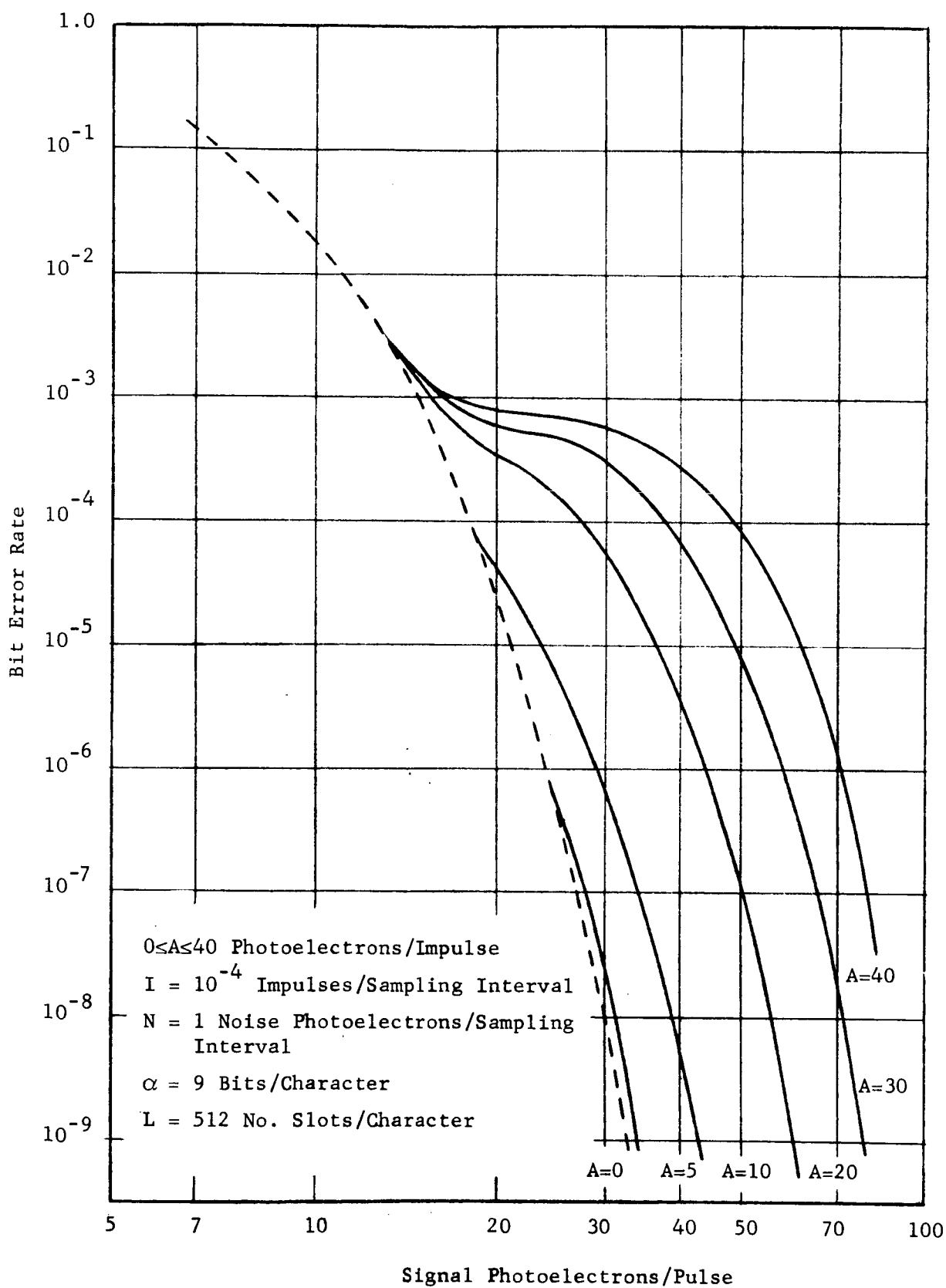


Figure 201. Effects of Various Impulse Amplitudes on a PPM System

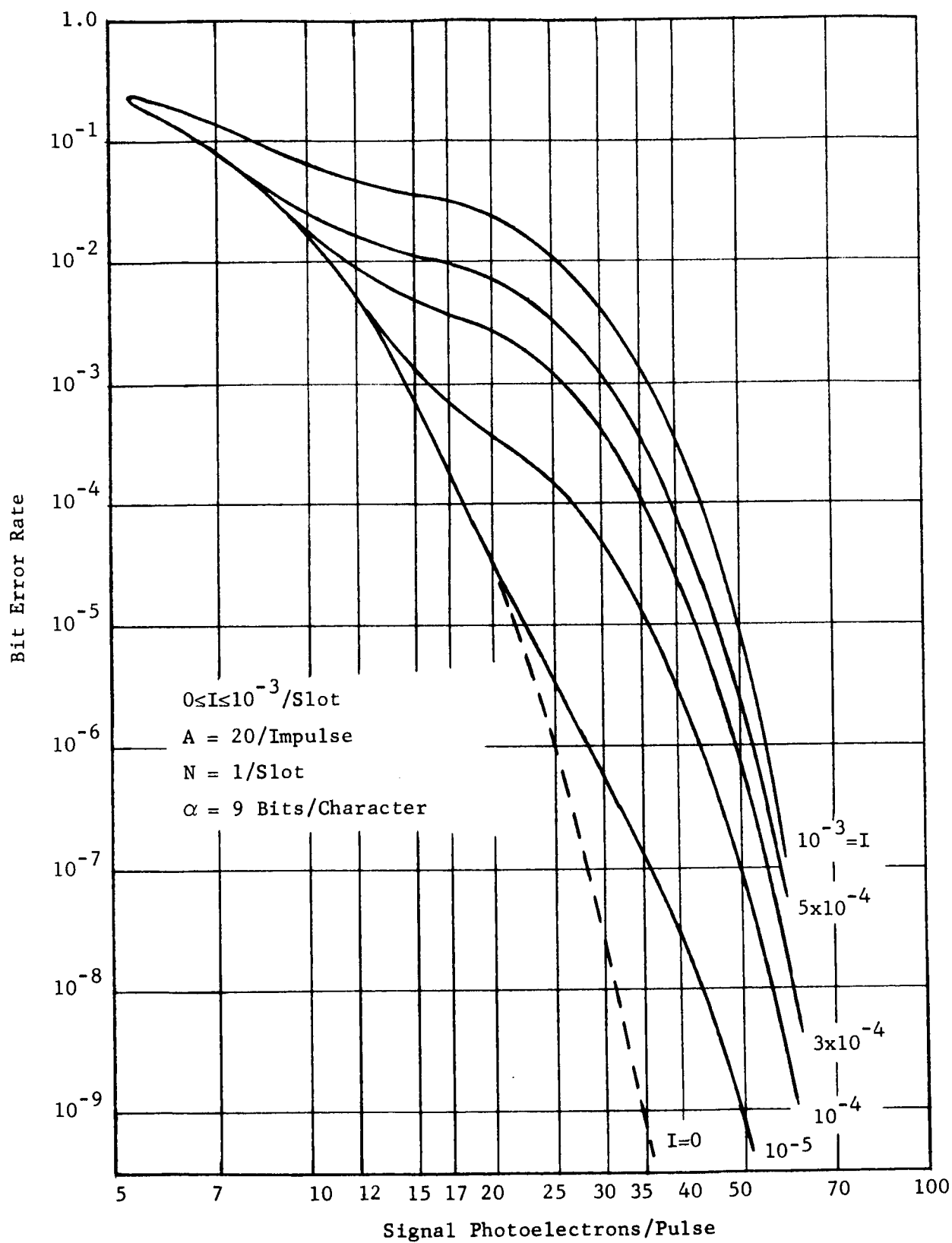


Figure 202. Effect of Impulse Occurrence (I) in a PPM System

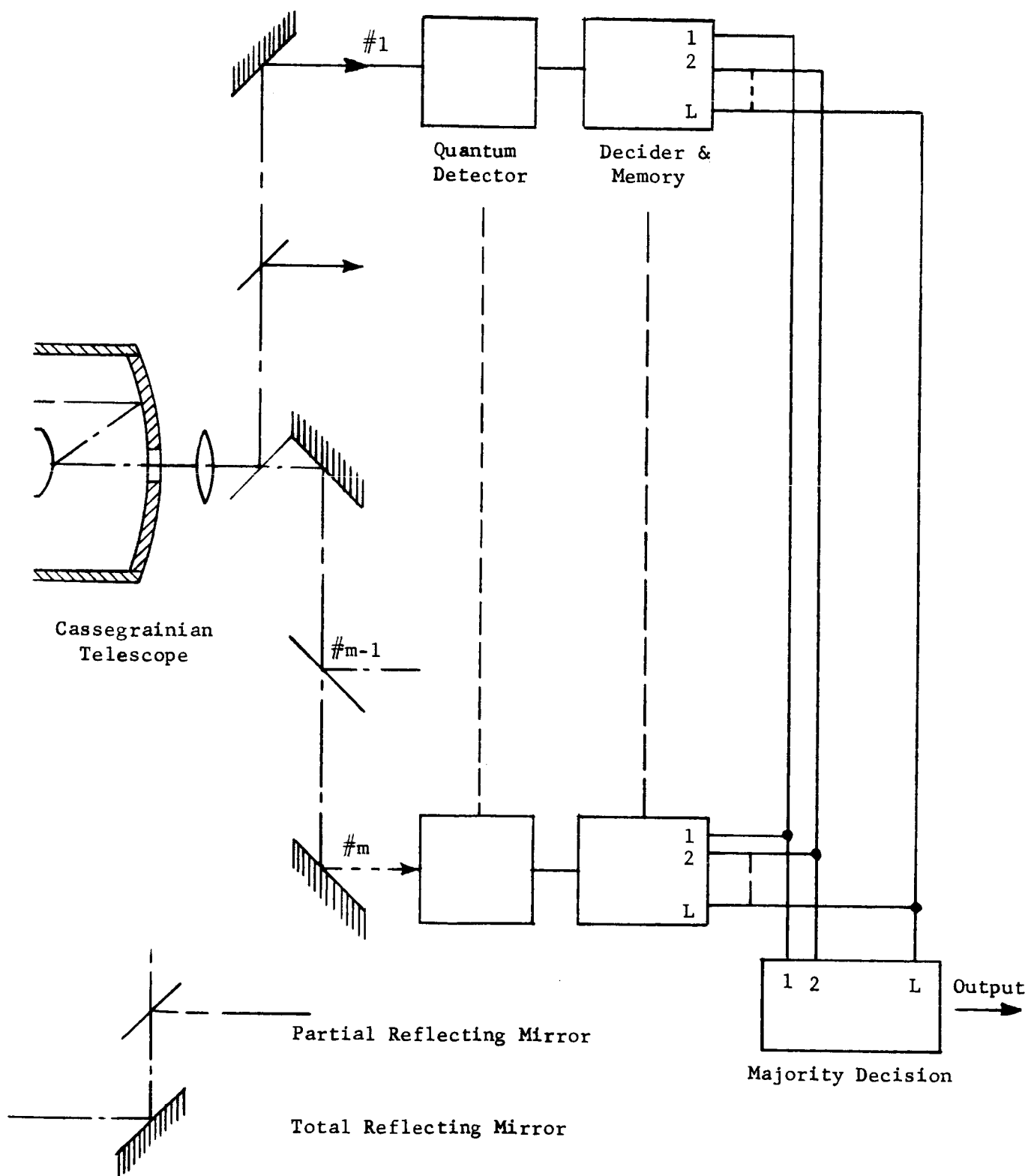


Figure 203. PPM Diversity Receiver Block Diagram

LASERS SELECTION

The selection of the laser to be used in each of the three missions previously discussed is particularly difficult because of the rapid change in laser technology. The laser recommended for the synchronous orbit mission is helium-neon ($.6328\mu$). This decision was made on the basis of several considerations:

- A space qualified helium-neon laser with sufficient power (5 milliwatts) is presently being developed for NASA*
- The laser is compatible with 21 of the 30 experiments** contemplated for the OTES (and the LCSE)
- The laser represents best choice in terms of system requirements, including: weight, power cooling, and detectability (wavelength)

The laser presently being considered for the two deep space missions is the recently developed YAlG:Nd laser (1.06μ) which has its output frequency doubled ($.53\mu$) by using a nonlinear crystal in conjunction with the doped laser crystal. Operating this laser continuously, it becomes an ideal source for a Mars 10^6 bit per second telemetry link utilizing PCM/PL.

An alternative is to consider that the laser-nonlinear crystal pair is pumped continuously, but is Q-switched to yield a pulsed output. The efficiency of the laser is reduced when it is modified to operate in the Q-switch mode. This reduction in efficiency will not be great if the lifetime of the active transition is larger than the time between pulses. For example, the lifetime of YAlG is 0.3 millisecond. Thus, solid-state lasers using continuous pumping, but operated in the multiple Q-switched mode, will be reasonably efficient for pulse repetition rates of approximately 1,000 pulses per second. Such a laser could be used as the source for a system using the PPM modulation technique. This combination of laser and modulation technique was used to analyze the possibility of communicating at distances up to the radius of the solar system.

This section will discuss in some detail the advantages and disadvantages of all candidate lasers. It was on the basis of this study that the above choice of lasers was made.

Candidates for Space Experiments

- Helium-Neon

This laser oscillates in many wavelengths; the principal ones being $6328\text{\AA}$, 1.15μ , and 3.39μ . The 1.15μ transition and the 3.39μ transition both have

* Space Qualified Laser contracted to Perkin-Elmer (NAS12-592) and Hughes Aircraft (NAS12-579); by NASA/ERC.

** Experiment Numbers 1, 4, 5, 7, 8, 12, 14, 19, 20, 21, 22, 23, 24, 25, 27, 28, 29, 30, 31, 32, 34.

higher gains than the 6328Å. However, S-20 photomultipliers operating with 6328Å offer a relatively high quantum efficiency (8 percent). For an S-1 photomultiplier operating at 1.15μ, the quantum efficiency is lower by a factor of 40 and detectors at 3.39μ are even worse. Power outputs for single frequency systems are typically 0.5 milliwatt and can be 100's of milliwatts for multifrequency, single spatial mode lasers. The output is diffraction-limited, and heterodyning experiments can be done with the laser. Since the active plasma is a low-pressure discharge, these lasers have long and stable operating lifetimes. The cooling and power requirements are modest and the laser lends itself to space qualification. Calculations have shown that this laser has sufficient power for high data rate communication from synchronous altitude, but the laser power output becomes the key limitation for deep space missions using helium-neon laser transmitters (100 to 200 milliwatts is the maximum).

- Argon

The argon laser system operates in many wavelengths also, the principal ones being 4880Å and 5145Å. The advantages of an argon laser are the high output powers (typically 1 to 10 watts) and the high quantum efficiency of detectors in this part of the spectrum (typically 20 percent). The output from this laser is diffraction-limited and operation in single spatial mode is common. The argon laser suffers from several disadvantages for use in space, which do not preclude its use as a ground-based beacon. First is its poor efficiency (at best 0.05 percent) and high threshold power requirements. Threshold input powers for typical tubes are on the order of a kilowatt. Second, the high current densities in the active region require liquid cooling for CW operation. Associated with the high current discharges are problems of gas clean up and bore erosion which limit the life of a sealed system to below 2000 hours. For these reasons, the laser is good for the Earth-based beacon which the space-borne communicator tracks.

- Carbon-Dioxide

The striking characteristics of these lasers are the very high efficiencies (up to 40 percent), and high output powers available (in excess of 100 watts CW). The radiation is at 10.6μ. There is a severe shortcoming in a 10μ laser communication system at present. The problem is the practical acquisition difficulty in a heterodyne detection mode from deep space. This is analyzed in Chapter 5 starting on page I-474.

- Gallium-Arsenide

The output frequency of this laser is a function of temperature and varies between 8400Å at 77°K and 9000Å at room temperature. Its efficiency is in excess of 50 percent and solid structure would lend itself to space qualification. There are, however, several disadvantages to the gallium-arsenide laser which make it undesirable for space communication at this time. First, at CW power levels, there is a wavelength variation due to temperature. This prohibits use of extremely narrowband optical filters. Quantum efficiency of detectors at 8400Å is only 0.4 percent. Also, the gallium-arsenide laser has

a very small rectangular radiating aperture. This would require more complex cylindrical optics for achieving diffraction-limited performance of the radiating aperture. A most attractive feature of the diode laser is the ease of modulation by modulating the diode current. However, until improvement is made in the control of wavelength, this system is not considered a sound choice for this mission.

- Ruby

Ruby crystal lasers have been operated CW with water cooling at $6940\text{\AA}$. The efficiency of the laser is very low while threshold input power levels are unusually high. Detector efficiencies at this wavelength are essentially the same as at $6328\text{\AA}$. The laser has a broad fluorescent line (at least several angstroms). For all these reasons ruby is not considered a good choice for space communications.

- Neodymium in YAlG

This solid laser has been operated CW with output powers of 200 watts. It has also been operated CW with sun pumping with an output of 1 watt. The output wavelength is 1.06μ and the best photodetectors at this wavelength have quantum efficiencies of 0.1 percent. The efficiency of this laser is about 5 percent with selective pumping and 0.01 percent when solar pumped. It requires liquid cooling and operates at room temperature.

The low quantum efficiencies of phototubes is the main limiting factor in the space application of the YAlG:Nd. A development which would neutralize this disadvantage is the avalanche photodiode. However, the noise in present photodiode severely limits single quantum counting operation. The important development of frequency doubling of 1.06μ light by the use of nonlinear crystals is discussed below.

- Second Harmonic Generation ($5300\text{\AA}$)*

The high power densities obtained with lasers allow the physicist to utilize the nonlinear characteristics of transparent dielectrics. The doubling of the frequency of light, commonly called second harmonic generation (SHG) was first done in the laboratory by a number of experimenters in 1960. Early experiments required very high power densities which were obtained only with pulsed ruby lasers. The state of the art has advanced so significantly in 1967, today it is possible to obtain CW operation of SHG with fractions of a watt of power at laser light to high electrical power input efficiencies. This laser is recommended for deep space communications.

This section will highlight the impact of the laser communication systems that can be used in deep space which can harness second harmonic generation of light ($5300\text{\AA}$).

* Non-Linear Optical Properties, J.E. Geusic, H.J. Levinstein, J.J. Rubin, S. Singh, L.G. VanUitert of Bell Telephone Laboratories (Private Communication, to be published, Fall 1967 by BTL).

The incoherent optical communication system assumed in the analysis of previous reports was a 1 megabit system using a helium-neon laser as the source and using the modulation technique of PCM/PL. This system suffered in three areas:

- (1) The low conversion efficiency from electrical power to the optical power out of the transmitter.
- (2) The wavelength was in the "wrong" part of the spectrum for the photomultiplier tubes.
- (3) The maximum single mode power available from this laser was less than 200 milliwatts.

One combination of laser source plus SHG holds outstanding promise for the types of optical communication systems considered for the OTES. It is yttrium aluminum garnet: Neodymium doped (YAlG:Nd) laser with an output frequency at 1.06 microns (near infrared) plus one of the newly developed nonlinear crystals, (NLC) such as lithium niobate (LiNbO_3). Experimenters consider an operational system of 2 watts CW optical power output with a 1 percent conversion efficiency will be available shortly, with an increase of up to 20 watts obtainable with present techniques. The second harmonic generation output frequency will occur at 0.53 micron, or just at the peak of the quantum efficiency of the available photomultiplier tubes. (See NASA CR252 report, page 7-32). The value of 25 percent photomultiplier tube quantum efficiency at 5300Å may even be increased somewhat by using the techniques of internal reflection. Thus the optical communication system using a YAG laser and a nonlinear crystal to double the frequency has significant improvements in all three areas which we previously listed as the nominal operational characteristics for the helium-neon system. That is, there is now available a communication system which has:

- (1) Electrical-to-optical conversion efficiency of 1 percent.
- (2) A wavelength at the peak of the photomultiplier tube quantum efficiency curve (25 percent at 0.53 micron).
- (3) Optical power outputs in excess of 3 watts.

5300Å Configurations

Efficiency of the nonlinear crystal used in the second harmonic generation is increased as the power density is increased. Thus it is possible to increase efficiency by placing nonlinear crystal in the cavity. However, development of second harmonic generation systems has been hindered by the unavailability of good nonlinear crystals. The best crystal based on published data is lithium niobate. However, its shortcomings of low damage threshold and index gradients limit the feasibility of SHG optical communication systems. Developments in the physics of nonlinear optics have advanced appreciably to the point where new nonlinear crystals will soon become available.*

*See footnote last page.

Three SHG systems have been hypothesized for this section. Other configurations also exist, but the three systems discussed here are representative of the generalized system design approaches. All three operate with the nonlinear crystal inside the optical cavity. We assume that the nonlinear crystal has a high damage threshold, low scattering, and high uniformity when placed in an optical cavity.

CW-SHG Laser Source

This optical communication technique is basically a PCM/PL system which is a modification of the previously considered helium-neon laser system. The nonlinear crystal is placed in the laser cavity as shown in Figure 204. We are thus faced with the problems of coupling out second harmonic at 0.53 micron. A dumping mirror with a transmission of 0.0 at 1.06 microns and a transmission near unity at 0.53 micron is one possibility. Another possibility is the insertion of a highly dispersive element in the cavity. Aligning the cavity to the fundamental frequency, the second harmonic will suffer larger deviations from the dispersive element and may be coupled out of the cavity.

All three approaches assumed may suffer from cancellation effects between the two second harmonic waves which are generated by the fundamental traveling to the right and to the left through the cavity. Such effects could limit a diffraction-limited system. One engineering solution to this problem is to construct a ring laser with an isolator in it. This forces all the second harmonic radiation to propagate around the ring laser in the same direction as the fundamental frequency. This energy may be coupled out by a 0.53 micron transparent mirror or by a dispersive element.

Q-Switched, SHG Laser Source

The Q-switched solid-state laser is used to generate the megawatt optical pulses used in research and laser radar applications. In these applications, the flash lamps pump the laser to an excited state and the Q-switch causes this energy to be dumped in a single pulse. A modification of this technique is to operate the flash lamp continuously and impress information on the optical output by Q-switching the laser cavity at predetermined instants in time (Figure 205), the position of the pulsed outputs will define the information to be transmitted. The simplest form of this modulation technique is pulse position modulation (PPM). This technique has been analyzed in sufficient detail in NASA Report CR252* and will not be elaborated on here.

The pulse repetition rate for such a system would be between 500 Hz and 10KHz. Even impressing as many as 10 bits of information on a single pulse would still permit a maximum information of only 10^5 bits per second. Since this is short of the 10^6 bit per second information rate envisioned for a Mars probe data system, this system technique will not be discussed further for this mission. However, the advantages of the Q-switched SHG system could be used in a deep space probe which has a mission profile well in excess of 10^8 mile mission assumed for a Mars probe. Such a mission would have an information rate by necessity which is limited to between 1 kilobit and 100 kilobit capacity.

*Perkin-Elmer Report 7846 (NAS8-11408)

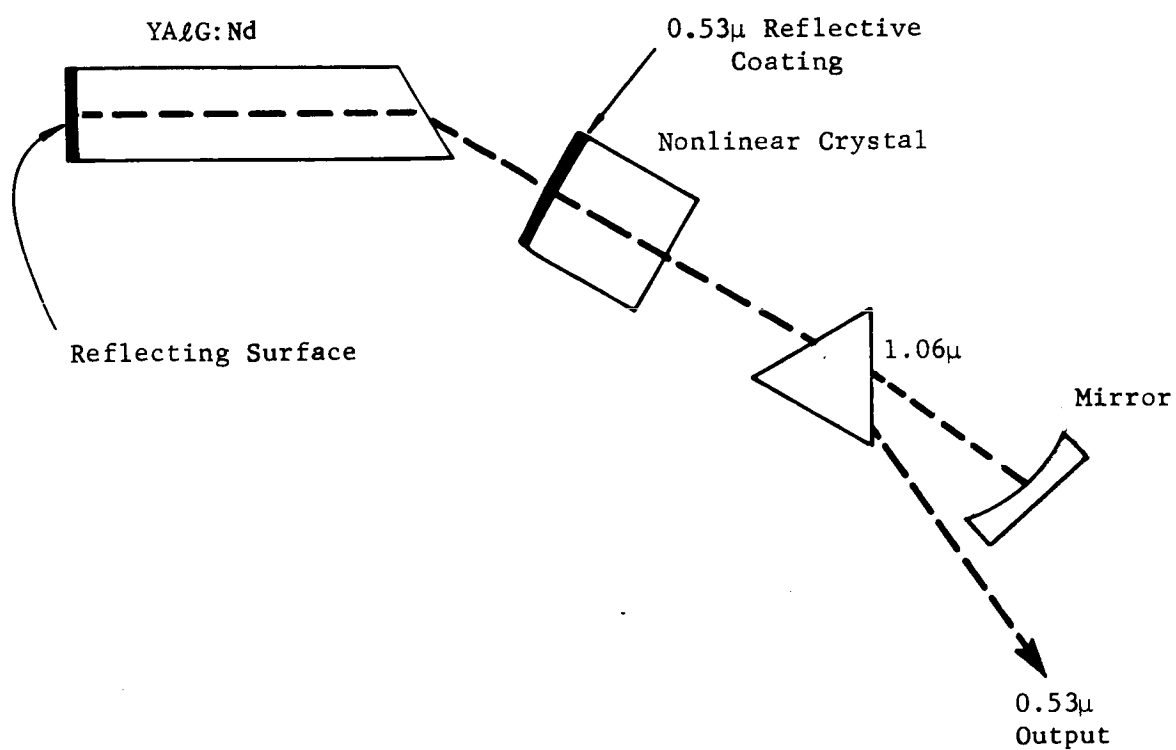


Figure 204. CW-SHG Laser Source

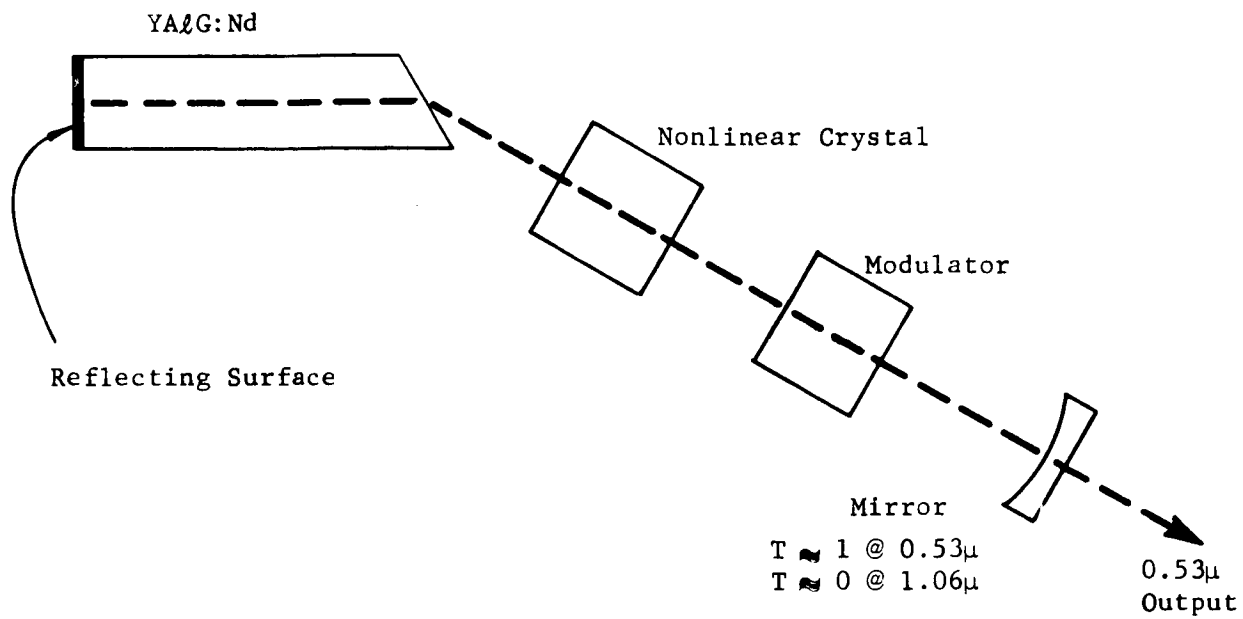


Figure 205. Q-Switched SHG Pulsed Laser Source

An interesting property of the nonlinear crystals is that they may also be used as a modulator since they show the electro-optical effect. Thus a single crystal may be used jointly to generate second harmonic and to Q-switch the laser cavity.

Mode-Locked SHG Laser Source

A second method of generating pulses is to mode lock the longitudinal modes (Figure 206).. The average power of a mode-locked laser remains constant during the mode locking, but the energy is redistributed such that a train of subnanosecond pulses is emitted with the pulse repetition rate of $C/2L$, where C is the speed of light and L is the optical length of the cavity. The peak pulse power is N times the average power of the unmode-locked laser, where N is equal to the number of longitudinal modes which are locked. This increase in the peak power will increase efficiency of second harmonic generation in a nonlinear crystal. Thus there is a definite advantage to considering this combination of a mode-locked laser and second harmonic generation. The mode locking is made possible by modulating the internal losses of the optical cavity. One modulator which has been used successfully is a fused silica block oriented at Brewster angle as shown in Figure 206..

A mode-locked SHG YAlG system has been breadboarded* and will be assumed as a typical example for the optical communication laser source. The DiDomenico laser had a cavity length of 50 cm. This yields a 300 MHz pulse repetition rate. Several modulation techniques could be used with this laser source. First, a simple switching of the polarization of each pulse would yield a 300 megabit optical communication system. This is beyond the demand of deep space optical communications. However, coding techniques could be used to increase the fidelity of real-time TV from deep space. One of the simpler techniques which could suppress background has already been described in the Phase I-IA Report for a mode-locked ground beacon. However, these results are general and may be applied to optical communication.

SHG Support Equipment Requirements

- Laser Source

The previous discussion assumed a YAlG:Nd laser crystal for the laser source. SHG has been demonstrated with a number of lasers. However, the high efficiency, room temperature operation, high reliability of the YAlG:Nd laser rod, and extensive engineering applications of this laser point to its application for space systems. The recent development of liquid lasers (e.g., solution of neodymium ions in selenium oxychloride) may yield a laser in which the laser medium itself will be the coolant. However, any consideration of a liquid laser for space application is premature at this time.

* M. DiDomenico, et al. "Generation of Ultra Short Optical Pulses by Mode Locking the YAlG:Nd Laser," Applied Physics Let., Vol. 8, April 1, 1966.

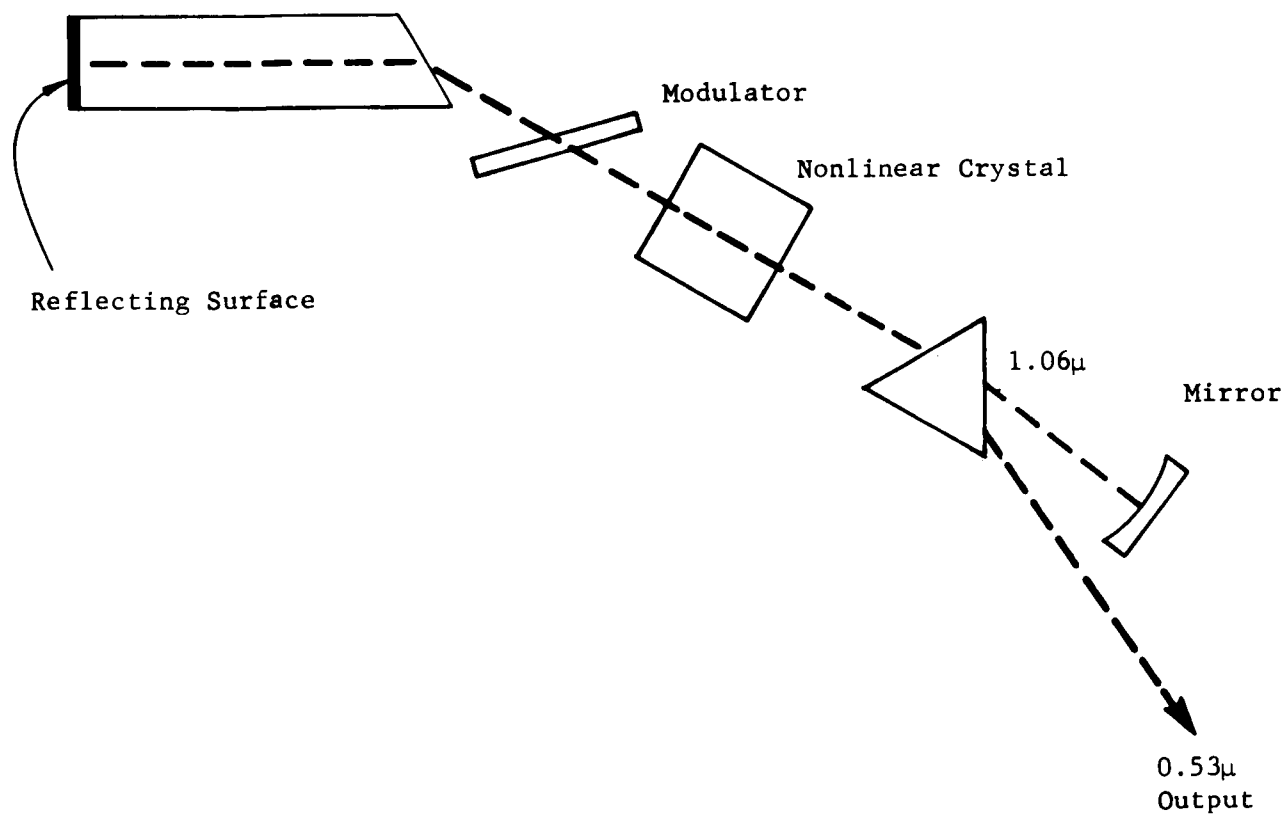


Figure 206. Mode Locked SHG Pulsed Laser Source

• Pumping

Two possible sources for pumping could be considered: (1) sun pumping and (2) high intensity CW lamp pumping. Several systems utilizing sun pump have been developed.* These systems have achieved CW operation as required by the optical communication system hypothesized. One disadvantage of the sun pumped system is evident if we assume a Mars orbiting satellite. During intersection of a Mars probe, the position of the sun and Earth is such that a sun pumped laser in an equatorial orbit is operative for less than 1/4 of the time, due to occultation of Mars satellite from the sun (laser inoperable) and from Earth (link inoperable).** The availability of the link is raised to almost 1/2 if the CW high intensity lamp pump is used.

• Cooling

Assuming a 1% efficient system, 99% of the pump energy is dissipated as heat. The presently developed sun pumped lasers use cryogenics or tap water to cool the lasers. The cooling requirement of the CW lamp pumping is less than the sun pumped laser due to the spectral matching of the pump energy to the absorption bands of the YAG laser. Independent of the pump technique, the heat will be either conducted or physically carried away by a recirculating coolant to a radiator. The radiation of the heat to space by a radiator of high emissivity then occurs. Development work is required to determine the optimum method of transferring energy to the radiator.

Communicator Optics

The modulators, tracking subsystem optics, transmitter optics, and ground station receiver optics required for the 0.53 micron link are essentially the same optics as the 0.6328 micron He-Ne laser optics which have been discussed in sufficient detail in previous reports. Thus, with the exception of the laser source and laser modulation technique, the 0.53 micron and 0.6328 micron systems are essentially identical.

The use of the shorter wavelength in the SHG system reduces the beam divergence of the transmitter optics by some 20%. However, experiments must be performed to ascertain if the output beam of an operational SHG system will have the stability required to obtain diffraction-limited performance. The solid-state lasers have traditionally had a somewhat poorer stability and spatial distribution than the gas lasers. Operational SHG systems will hopefully approach a diffraction-limited performance.

A new series of dichroics must be developed for frequency multiplexing the 0.488 micron argon beacon and 0.530 micron SHG light. These dichroics will

* The practical equipment problems of sun pumping in space make the concept less desirable than lamp pumping.

** See page I-140, Phase I and IA OTES Report.

have a frequency separation of $420\text{\AA}$ as compared with the separation of $1448\text{\AA}$ for the dichroics presently being developed for the He-Ne laser transmitter. However, dichroics capable of separating the SHG light and beacon light are feasible using the technology developed by Perkin-Elmer for NAS8-20115.

Several possible modulation techniques have been previously discussed. To be consistent with previous analyses of the helium-neon laser systems, the modulation technique of PCM/PL will be assumed for the link calculations. A final choice of modulation technique must await hardware evaluation of the competitive systems using different modulation techniques.

COMMUNICATION LINK POWER BUDGETS

In this section, calculations of the expected power requirements for the space-to-earth communication links are presented. The specifications for the various components in the optical path are listed in Table 10 along with source references, where applicable. The calculations assume worst case conditions. That is, under the expected operating environment, the average signal level will not decrease below the signal level derived in this section. The assumptions used for the worst case link included:

- Daytime operation
- Earth receiver tracking 60 degrees from the zenith
- Data rate of 10^6 bits per second (equivalent analog bandwidth of $\approx 10^5$ cps)
- Bit error rate less than 0.001
- Large atmospheric turbulence
- All components for the synchronous orbit flight are current state of the art; while for deep space, moderate extrapolation is permissible.
- Transmit power safety margin required.

Calculations indicate that all three hypothesized links, under the assumed conditions above, are feasible.

To determine the sensitivity of the maximum obtainable data rate with a variation of a given system parameter, a series of graphs are plotted with coordinates of data rate versus the system parameter being investigated. These graphs verify the importance of the 0.1 arc-second pointing requirements and the requirement of diffraction-limited optics.

The definition of the optical communicator freezes many of the system parameters. However, further analysis was required to determine some of the other parameters needed for the link calculations. This section will discuss the limiting factors which determine the value of these parameters.

Receiver Field of View, β

The value of the receiver field of view (β) will be determined by the limiting aperture in the earth-based optical system. The communicator receiver on earth will have an iris that will limit the background radiation. Ideally, the iris could be reduced to a diameter equal to the diffraction-limited spot size. However, the uncertainty caused by atmospheric and the telescope vibrations will determine a practical limitation for the field of view. As will be shown, the performance of the synchronous orbit/helium-neon laser link is limited by quantum

noise, not background noise. Being an experimental system, it is best to allow some margin in the choice of the field of view. Thus, a conservative value of 20 arc-second receiver field of view was chosen for the synchronous orbit link.

The Mars communication link utilizing an optical carrier of $.5300 \mu$ will be background noise limited. Thus, choice of the receiver field of view becomes of prime concern. The minimum field-of-view of the 10-meter dish was calculated to be 20 seconds arc.*

This value was determined primarily by the physical limitations of such a large structure. These sources of error are reduced sufficiently in the three-meter receiver such that the field of view is determined by atmospheric. Remembering that the link will be operated primarily during daytime hours when the atmospheric degradations are at its worst, a field of view of 8 seconds arc seems reasonable for a 3-meter ground aperture.

Earth Receiver Aperture

The recent introduction of the YAG:Nd/SHG laser to optical communication studies makes us re-examine the previous choice of receiver apertures. We now do not have to choose the largest feasible aperture for the ground station, but can now choose smaller apertures because of the relatively large operating margins for the link.

Quite surprisingly, $.5300 \mu$ systems using either the 3-meter or 10-meter ground apertures have almost identical performance**. This results from the penalty of a larger field of view (with the resultant increase in the background noise count per decision) when the larger aperture ground telescopes are used. Thus, an Earth receiver telescope aperture of 3-meters was tentatively chosen for the deep space missions. This structure is well within the state of the art for Earth-based telescopes.

The aperture chosen for the synchronous orbit link must be at least 24 inches because of scintillation. Even with this small aperture, there exists a most comfortable margin of 53 or 17 db.. Thus, the aperture of the ground station for the experimental synchronous orbit link was chosen at 24 inches.

Predetection Optical Bandwidth and Transmission τ_F

The optical filter preceding the PCM/PL detector in the Earth-based receiver should have, ideally, a bandwidth equal to the signal bandwidth. However, the narrowest optical filters have a bandwidth which is many orders of magnitude larger than the signal bandwidth. Ultra-narrow Lyot optical filters ($\sim 0.13\text{\AA}$) can be made, but the transmission is reduced to approximately 15 percent. Since the light input to the Lyot filter must have a single polarization, the PCM/PL receiver is required to have two Lyot-type filters for the two orthogonal polarizations. Lyot filters are sensitive to small temperature changes and, for this reason, careful thermal control of the filter is always an important requirement.

* Giant Aperture Telescope, Perkin-Elmer Corporation, for Jet Propulsion Laboratory, Contract No. NAS 7-100. Report No. 8393 and 8558.

** Daytime only, obviously at night, the 10 meter system is superior because of reduced background.

Recently, filters have been developed at Perkin-Elmer which are basically a Fabry-Perot cavity in series with a multilayer filter to suppress the unwanted modes of the cavity. Although these filters have a bandwidth somewhat larger than the Lyot filter, the increased temperature tolerance and higher transmittance of the Fabry-Perot filter makes them more suited than the Lyot filter for the proposed experiment system. The field of view requirements of the optics, limit the use of ultra-narrow interference type filters. Using the present techniques, filters of $75\text{\AA}$ bandpass and 50 percent transmission are reasonable.

The PCM/PL system will be limited by quantum noise during night operation. The only way to reduce this noise is to increase the detected power. The above values indicate that the filter transmission (i.e., detected power) increases as filters with larger bandwidths are used. Thus, during night operation, it is advantageous to have a filter with a high transmission as contrasted with a narrow spectral bandwidth.

Transmitter Optical System Transmission, τ_{OT}

Losses in the transmitter optics can be attributed to the 20 percent obscuration of the secondary mirror, several air-glass interfaces, the truncation or redistribution of the gaussian intensity distribution output from the laser, and the reflectivity of the primary and secondary mirrors. The pointing requirements of the optical communicator dictate that the output of the laser must be in the TEM₀₀ mode. Thus, the spatial intensity distribution across the laser output will be approximately gaussian.

Preliminary calculations indicate that both the central obscuration and the truncation (no redistribution) of the gaussian will introduce losses of at least 0.6. Methods are available for mapping the gaussian intensity distribution into a more optimum distribution.* Since the efficiency of the laser radiation is always of concern, the special mapping optics will be included in the optical design. Thus, the value of τ_{OT} 0.5 is a reasonable estimate of the losses in the transmitter optics. The use of antireflective coatings plus the referenced mapping techniques can increase τ_{OT} to 0.66. However, after 6 months in space there will be some degradation of the optical reflectance and the dielectric coatings. For this reason, the 0.66 value was reduced to 0.5 for the calculations.

Receiver Optical System Transmission, τ_{OR}

The wave front impinging on the earth receiver will have a uniform average intensity across the aperture.** Thus, the energy loss resulting from the secondary obscuration will be approximately 20 percent if a Cassegrain telescope is used at the receiver. The losses from the silvered mirror surfaces and the air-glass interfaces will not introduce significant additional losses. Thus, the value $\tau_{OR} = 0.75$ is reasonable for the optical losses at the receiver.

* "Laser Light Redistribution in Illuminating Optical Signal Processing Systems", J.L. Kreuzer, Optical and Electro-Optical Information Processing, MIT Press 1965.

** This statement assumes the effects of atmospheric will be small.

Diffraction Loss, τ_D

The far field pattern of an unobscured circular aperture is the classical Airy pattern. As discussed previously, both secondary obscurations and the nonuniform illumination of the transmitter aperture will distort the far field distribution on the Earth. Both effects will decrease the width of the central maximum in the far field and will increase the energy contained in the "side lobes" of the diffraction pattern. The energy contained outside the half power point of the far field pattern of the ideal uniformly illuminated aperture* is 0.4. Thus, a value of $\tau_D = 0.5$ will be expected as the loss in the far field at the optical system due to diffraction effects. No techniques are available for significantly reducing this system loss.

Synchronous Orbit - Helium-Neon Laser

Equation (1) states the average number of signal photoelectrons detected during a bit interval.

$$S = \left(\frac{d}{\alpha R} \right)^2 \times \left(\frac{\lambda P_s \eta}{hc} \right) \times \left(\tau_D \tau_A \tau_{OT} \tau_{OR} \tau_F \tau_S \right) \frac{1}{M} \text{ counts/bit} \quad (1)$$

$$= \left(\begin{array}{c} \text{ratio of receiver and} \\ \text{illuminated areas} \end{array} \right) \times \left(\begin{array}{c} \text{conversion of optical} \\ \text{power to counts/bit} \end{array} \right) \times \left(\begin{array}{c} \text{system} \\ \text{efficiencies} \end{array} \right)$$

Substituting the values of Table 10, column 3, into the above equation, the signal count is

$$S = \left(\frac{.61}{2 \times 10^{-6} \times 3.4 \times 10^7} \right)^2 \times \left(\frac{.63 \times 10^{-6} \times 3 \times 10^{-3} \times .05}{6.625 \times 10^{-34} \times 3 \times 10^8 \times 10^6} \right)$$

$$\times (.50 \times .70 \times .33 \times .75 \times .4 \times .4) \frac{1}{M}$$

$$= 530 \cdot \frac{1}{M}$$

Equation (2) states the average number of noise photoelectrons (N) detected during a bit interval.

$$N = \frac{\lambda \eta}{hc} \left\{ 2 P_P + \left(P_F \tau_A + P_B \right) \left(\frac{\pi d^2}{4} \right) \left(\frac{\pi \beta^2}{4} \right) \Delta \lambda \tau_{OR} \tau_F \right. \quad (2)$$

$$\left. + \left(P_A + P_V \right) \left(\frac{\pi d^2}{4} \right) \Delta \lambda \tau_{OR} \tau_F \tau_A \right\}$$

$$= \left(\begin{array}{c} \text{conversion to} \\ \text{counts/bit} \end{array} \right) \left[\left(\begin{array}{c} \text{noise of both phototubes+average} \\ \text{blue sky and star background} \end{array} \right) \left(\begin{array}{c} \text{Venus and Sirius A} \\ \text{"point sources"} \end{array} \right) \right]$$

*Born and Wolf, Principles of Optics, Macmillan, New York (1964) p. 398.

<u>VARIABLE</u>	<u>SYMBOL</u>	<u>VALUE</u> Synch. Orbit	<u>VALUE</u> Mars Mi
Range	R	21,500 34,060	10^8 1.61 x
Wavelength	λ	0.6328	0.53
Transmitter Optical Power	P_s	0.0030	3.0
Transmitter Beam Divergence $1.2 \lambda/D$	α	2 0.4	1.60 0.32
Diameter of Transmitter Aperture	D	16 40	16 40
Receiver Field of View	β	9.7×10^{-5} 20	4×10^{-8}
Atmospheric Transmission	τ_A	0.70	0.65
Transmitter Optical System Transmission	τ_{OT}	0.33	0.5
Receiver Optical System Transmission	τ_{OR}	0.75	0.75
Diffraction Loss	τ_D	0.5	0.5
Predetection Optical Filter Transmission	τ_F	0.40	0.5
Diameter Receiver Aperture	d	24 61	120 300
Blue Sky Background	P_B	2×10^{-3}	$4 \times 10^{-}$
Average Star Field	P_F	5×10^{-10}	$5 \times 10^{-}$
Venus	P_v	2×10^{-10}	$2 \times 10^{-}$
Scintillation	τ_s	0.4	1
Receiver PMT (RCA)	P_p	2×10^{-15}	
PMT Quantum Efficiency	η	0.05	0.25
Safety Factor	M	53	1.3
Speed of Light	c	3×10^8	
Data Rate	C	10^6	10^6
Planck's Constant	h	6.62×10^{-34}	

TABLE 10

RTH COMMUNICATION LINK

<u>E</u> mission	<u>VALUE</u> Pluto Mission	<u>UNITS</u>	<u>REFERENCE OR COMMENT</u>
10 ⁸	4×10^9 6.4×10^9	miles Km.	Receiver viewing 60° to zenith
	0.53	microns	
	3,0	watts	Measured at laser output
	1.60 0.32	μ radians arc-seconds	
	16 40	inches centimeters	
5	4×10^{-5} 8	radians arc-seconds	
	0.65	60° from zenith	Table 3-1 NASA CR-252
	0.5		
	0.75		
	0.5		
	0.5		For filter bandwidth $\Delta B = 0.75\text{\AA}$
	120 300	inches centimeters	
3	4×10^{-3}	$\frac{\text{watts}}{\text{cm}^2 \text{-ster-}\mu}$	Table 3-5 NASA CR-252
10	5×10^{-10}	$\frac{\text{watts}}{\text{cm}^2 \text{-ster-}\mu}$	Table 3-5 NASA CR-252
10	2×10^{-10}	$\frac{\text{watts}}{\text{cm}^2 \text{-}\mu}$	Figure 7-16 NASA CR-252
	1		
		watts	Radiant input power equivalent
	0.25		RCA 4526
	up to 10		
		m/sec	
	10^3 to 10^4	bits per sec	
		joule-sec	

The variables in Equations (1) and (2) are defined in Table 10.

Under normal daytime operation, the blue sky background noise power, N_D , will limit the optical communication link. Neglecting P_p , P_A , P_F , P_V , substitution of the values of Table 10, column 3, into Equation (2) yields

$$N = \frac{.6328 \times 10^{-6} \times 5 \times 10^{-2}}{6.625 \times 10^{-34} \times 3 \times 10^8 \times 10^6} \left[2 \times 10^{-3} \pi \left(\frac{61}{2} \right)^2 \left(\frac{\pi}{4} \right) \left(9.7 \times 10^{-5} \right)^2 \times 1.5 \times 10^{-4} \times 0.75 \times 0.40 \right] \quad (3)$$

$N = 3$ noise counts/bit (blue sky)

The noise count resulting from the phototube dark current, Venus at conjunction, and the star, Sirius A, will now be computed. Substitution of the values of Table 10 into Equation (2) yields the average noise count per bit listed below:

$N = 0.7$ from Sirius A

$N = 17$ from Venus at conjunction

$N \sim 0$ from phototube dark current

Noting the large safety factor for the proposed link, the optical communication system will still operate even when a star or planet is in the field of view of the receiver telescope.

Figure 207 shows the required signal count for a system with a given background noise and bit error rate. The derivation of these error rate curves for PCM/PL assume that both the signal and noise photoelectrons are Poisson distributed. Note that as the noise approaches zero, the signal count approaches a minimum. For example, this minimum is an average of 6.22 signal photoelectrons when a system operates with a bit error rate of 0.001. Thus, when one reduces the noise count much below $N = 1/2$, one can not expect a significant reduction in the signal count required by reducing the background noise.

For daylight operation ($N = 3$), Figure 207 states that the signal count required for a PCM/PL system with a bit error rate of 10^{-3} is $S = 10$. Assuming 0.003 watt of optical power transmitted from synchronous orbit, Equation (1) is satisfied when the safety factor of $M = \frac{530}{10} = 53$. That is, the system has a 17. db safety factor during daytime operation. Since the minimum average signal count allowed is 6.22 per bit, the safety factor will be increased to $M = 110 \times \frac{10}{6.22}$ or 22.5 db for quantum noise limited (night time) operation.

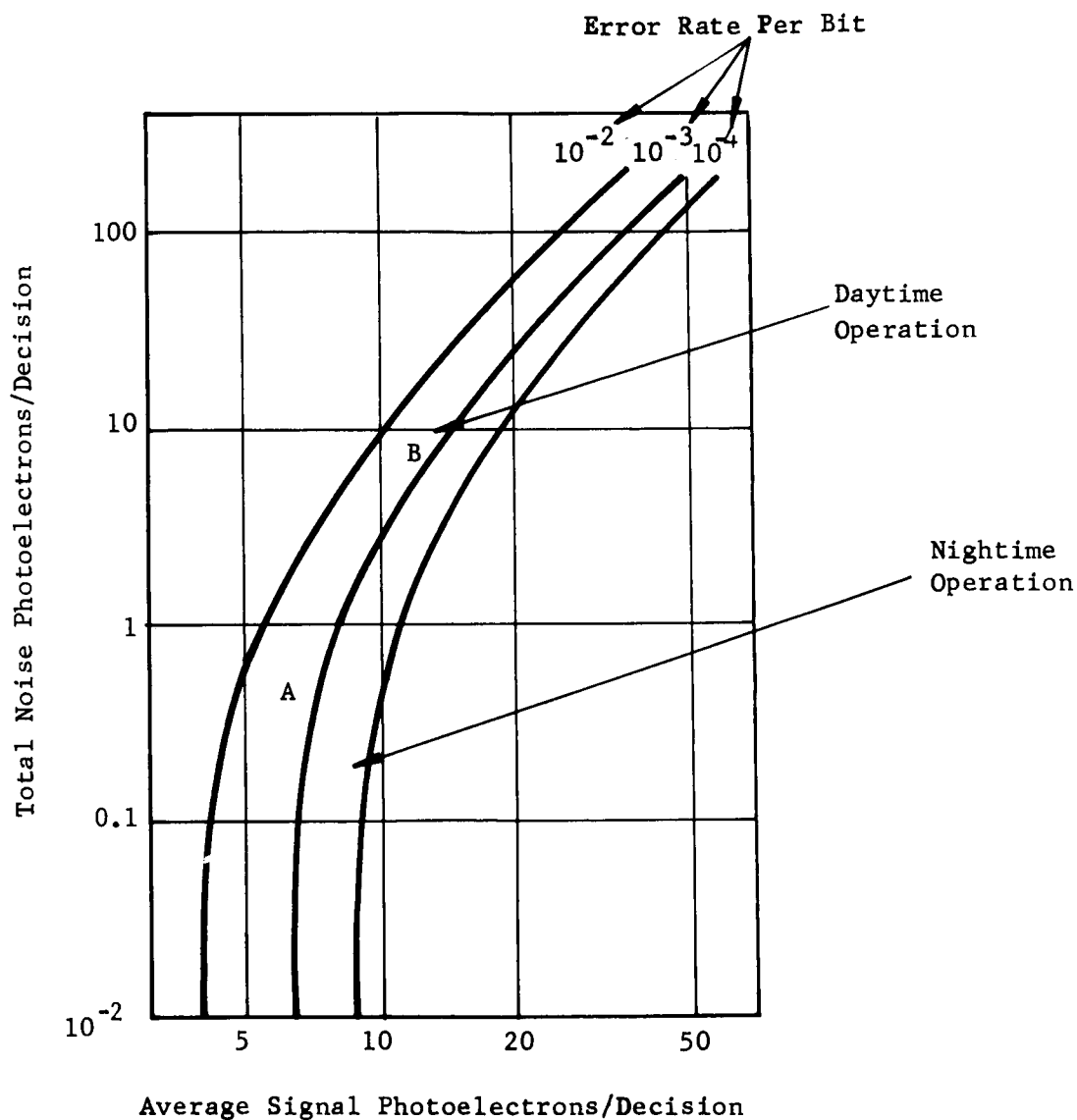


Figure 207. The Effect of Background Noise on the Number of Signal Photoelectrons Needed in a PCM/PL System for a Decision

Mars Mission - YALG: Nd/SHG

Substituting the values of Table 10, column 4, into equation (1), the detected signal count for a Mars megabit communication link is

$$S = \left[\frac{3}{1.6 \times 10^{-6} \times 1.61 \times 10^{11}} \right]^2 \times \left(\frac{.53 \times 10^{-6} \times 3 \times .25}{6.625 \times 10^{-34} \times 3 \times 10^8 \times 10^6} \right) \\ = 16.7 \times \frac{1}{M} \times (.5 \times .65 \times .5 \times .75 \times .5 \times 1.)$$

For quantum-limited operation of a PCM/PL system, the required value of S is 6.2 photoelectrons per decision. Thus the above link parameters describe a system which has a margin $M = 16.7/6.2 = 2.7$ for night operation. For daytime operation the noise count per decision ($N = 6.6$) is found by substituting the values of Table 10, column 4 into equation (2). The received signal count must be increased to 13, if the system is to operate with a 0.001 bit error rate. The day time margin is thus reduced $16.7/13 = 1.3$.

The transmitter aperture assumed in this analysis is significantly smaller than the aperture assumed in previous analyses.* Thus calculations of the beacon link follow to determine if the transmitter aperture of 0.4 meter is sufficient for the tracking subsystem of the space craft. The equation for the received beacon photoelectron count, is:

$$\eta_B = \left(\frac{D}{2R} \right)^2 \left(\frac{\lambda P_T \eta}{hc} \right) (\tau_D \tau_A \tau_{OT} \tau_{OR} \tau_F \tau_S) \quad (3)$$

The parameters are defined in Table 11. Substituting:

$$\eta_B = \left(\frac{0.4}{5 \times 10^{-5} \times 1.61 \times 10^{11}} \right)^2 \left(\frac{0.53 \times 10^{-6} \times 10^2 \times 0.13}{6.62 \times 10^{-34} \times 3 \times 10^8} \right) \\ \times (0.5 \times 0.6 \times 0.66 \times 0.75 \times 0.5 \times 1.0) \\ = 6.4 \times 10^3 \text{ photoelectrons/second}$$

The received beacon power is thus large enough for the tracking subsystem to operate properly.

Another problem area is the background noise from earthshine as seen by the space craft tracker. The recent availability of combination Fabry-Perot, dielectric-coated bandpass optical filters improves the background rejection capabilities of the tracking subsystem. The background photoelectron count per second, B, is

* Wischnia, H.F. et al: Determination of Optical Technology Experiments for a Satellite, NASA CR-252.

TABLE 11

EARTH-TO-SPACE BEACON LINK PARAMETERS

<u>Variable</u>	<u>Symbol</u>	<u>Value</u>	<u>Units</u>	<u>Reference or Comment</u>
Range	R	10^8	mile	Mars mission.
Wavelength	λ	0.4880	microns	Argon Laser
Beacon Power	P_T	100	watts	Measured at laser output
Beam Divergence of Beacon	γ	10 50	arc-sec μ -radians	Conservative Value
Satellite Field of View	β	5 1	μ -radians arc-second	
Atmospheric Transmission	τ_A	0.6	@ 60° from zenith	Table 3-1, NASA CR-252.
Beacon Optical System Transmission	τ_{OT}	0.66		
Satellite Optical System Transmission	τ_{OR}	0.75		
Diffraction Loss	τ_D	0.5		
Optical Filter Transmission	τ_F	0.50		For filter bandwidth $\Delta B = 1/2\lambda$.
Optical Filter Bandwidth	ΔB	5×10^{-5}	μ	
Satellite Aperture	D	0.4	meter	
Earthshine	W	1.6×10^{-9}	watts-in ⁻² - μ ⁻¹ /1 sec FOV	Derived from Figure 7-6, NASA CR-252.
Scintillation	τ_S			
Satellite PMT (@ 300°K)	P_P	10^{-14} $\approx 10^4$	watts electrons/sec	Radiant input power equivalent
PMT Quantum Efficiency	η	0.13		S-20 surface
Speed of Light	c	3×10^8	m/sec	
Normalized Apparent Radiance	τ_R	0.45		
Polarization Rejection Factor	τ_P	0.5		

$$B = W \pi \frac{D^2}{4} \Delta B \tau_{OR} \frac{\lambda}{hc} \tau_P \tau_R \eta \quad (4)$$

Values for these parameters are listed in Table 11.

$$B = 1.6 \times 10^{-9} \times \frac{\pi(0.4)^2}{4} \times 5 \times 10^{-5} \times \frac{0.75 \times 0.53 \times 10^{-6} \times 0.5 \times 0.45 \times 0.13}{6.6 \times 10^{-34} \times 3 \times 10^8}$$

$$= 6 \times 10^2 \text{ photoelectrons/second}$$

This value of background assumes a 1 second field of view. During acquisition, this field of view will be larger by several orders of magnitude. Thus special coding schemes will probably be employed during the initial acquisition. The optical correlation techniques presently being experimented with offer some interesting methods of suppressing background noise.* Noise reduction of 20 to 30 db is reasonable.

The fine field tracker of the spacecraft will operate with only a simple coding scheme such as chopping. Note that the background and phototube noise current are of the same magnitude as the beacon. However, by chopping the beacon light, the signal-to-noise ratio at the output of the tracker is

$$SNR = \frac{\eta_B}{\sqrt{2 \Delta f (\eta_B + B + P_p)}}$$

$$= \frac{6.4 \times 10^3}{\sqrt{2 \times 1 \times (6.4 + .6 + 10) \times 10^3}}$$

$$= 35 \text{ for } \Delta f = 1 \text{ Hz servo bandwidth}$$

The marriage of nonlinear optics to optical communication opens up several new exciting system concepts. Tentatively, the 5300Å system for a megabit Mars range system is:

- Continuous YAlG:Nd/SHG laser source (see Figure 204).
- PCM/PL modulation technique
- Margin of 1.3 in the daytime
- Laser pumped with tungsten iodine lamps.

* MacFarlane, R. et al: Prototype Optical Synchronizer/Signal Generator, Perkin-Elmer Report 8762, Contract DAA B06-67-C-0121

- Transmitter aperture of .4 meter.
- Laser output power of 3 watts at 0.53 micron.
- Argon beacon on earth for tracking.

It is emphasized that the 5300Å laser necessary to implement the above system has not been published in the technical press as of the date of this report. However, the rapid development of SHG in the laboratory indicates that the laser sources indicated will be available in the time schedule of deep space explorations.

Pluto Mission - YAlG:Nd/SHG

The increased efficiencies of the 0.5300 μ laser source opens the possibility of communicating over ranges up to the radius of the solar system. The data rate for such a hypothesized mission would be approximately 10^3 to 10^4 bits per second. Considering that the proposed *Voyager* mission to Mars has a microwave capacity of 15000 bits per second, the same kilobit capacity to Pluto is theoretically available with a laser link.

Hardware identical to that previously described for the Mars mission will be assumed for the Pluto mission. The one exception is the modulation technique utilized. A more efficient modulation technique which is easily implemented for the data rates considered is PPM (Pulse Position Modulation). The error rate curves for this technique are shown in Figures 199 through 202.

The nominal radius of the solar system is 40AU or 4×10^9 mile. Equation (1), page I-410, shows that the received signal count is inversely proportional to the square of the range. Noting that the 3 watt laser at Mars has a detection count of 16.7 the received signal count from a communicator at Pluto is

$$S = \frac{16.7}{(40)^2} = 10^{-2} \text{ per microsecond}$$

If a PPM system utilizing $R = 1,000$ pulses per second is assumed, on the average 10 signal photoelectrons will be detected on Earth for each pulsed output of the 3 watt Q-switched YAlG:Nd/SHG laser in space. Referring to Figure 199A (where α is the number of bits transmitted per pulse), the capacity of the PPM link will be αR or 10^3 to 10^4 bits per second. The maximum data rate is determined by the maximum α which is feasible. Factors that must be considered in the choice of α are background intensity, modulator and laser limitations, and stability of reference clocks in the spacecraft. These factors are discussed elsewhere and will not be enumerated in this report.

The purpose of this section is to highlight the tremendous potential of the laser communicator. The SHG laser plus the basic optical system developed for the megabit- 10^8 mile link can be used with reduced data rates at ranges up to the extent of the solar system. However, some modification of the acquisition and tracking procedure must be generated at these extended ranges.

PARAMETER TRADEOFFS

The values for the parameters listed in Tables 10 and 11 were chosen on the basis of the present state of the art and tradeoffs between the system parameters. To demonstrate the effect of varying some of the parameters, a series of graphs are derived and discussed in this section. To judge the relative effect of varying each parameter, all the graphs have Data Rate as the ordinate. The system will be background limited during daylight hours and will be quantum noise limited during night operation. That is, the system will be operating in the regions A and B (Figure 207) during nighttime and daytime, respectively. Thus, two curves are required for each graph to demonstrate background and quantum noise limited performance.

The background noise power admitted to the PCM/PL detector is independent of the data rate (information bandwidth). Thus, even with a decade increase in the data rate, the noise power admitted by the optical filter and field stops, P_B , remains constant. However, Equation (2) states that increasing the data rate, C , by a decade will reduce the average noise count per bit. As demonstrated in Figure 208 the data rate for daylight operation approaches the quantum limit (night operation) when the data rate is increased.

The reference in Figures 208 to 216 is a 10^6 bit per second PCM/PL system operating with the parameters listed in Equation (3), (worst case - daytime). For example, in Figure 208 the daytime curve crosses 10^6 bit per second when $D = 16$ inches, the value listed in Table 10.

Transmitter Aperture

The diffraction-limited 3db beamwidth from an aperture of diameter D is $\alpha = \frac{1.2}{D}\lambda$. Variation of α in Equation (1) shows that the received signal power varies proportionately with the square of the transmitter aperture. Figure 208 shows the dependence of the data rate on the transmitter aperture.

Transmitted Optical Power

The received signal power is proportional to the transmitted optical power (Equation (1)). The dependence of data rate on the signal is shown in Figure 209

Primary Mirror RMS Figure Error

In an imaging system, the intensity I at some point in the image may be expressed in the form

$$I \sim 1 - \left(\frac{2\pi}{\lambda} \right)^2 \Delta_w^2$$

where Δ_w is the rms deviation of the wave front about the spherical reference wave front.* This equation is valid only for rms deviations much less than a

* Born and Wolf, Principles of Optics, MacMillan, New York (1964)

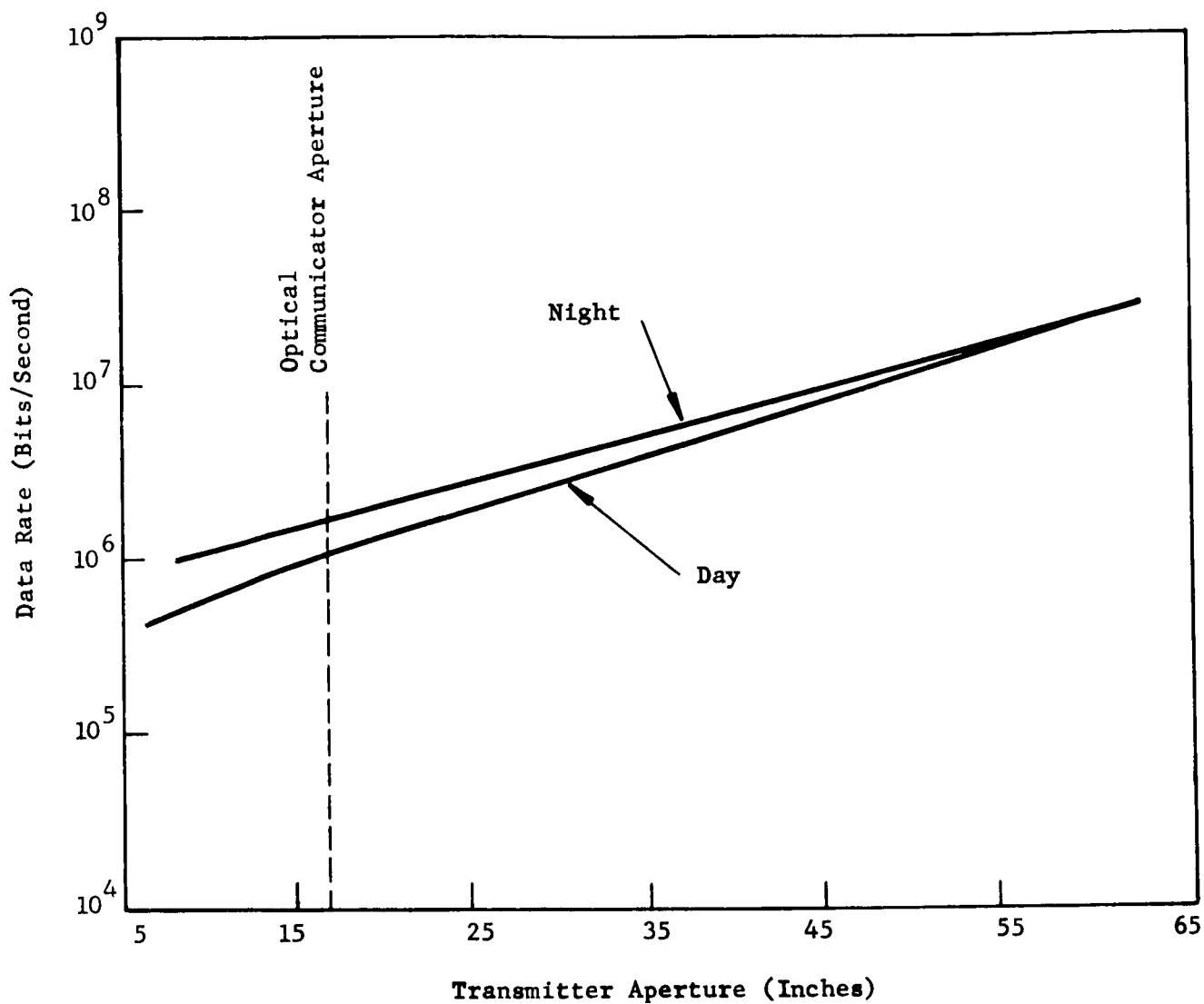


Figure 208, Transmitter Aperture Selection

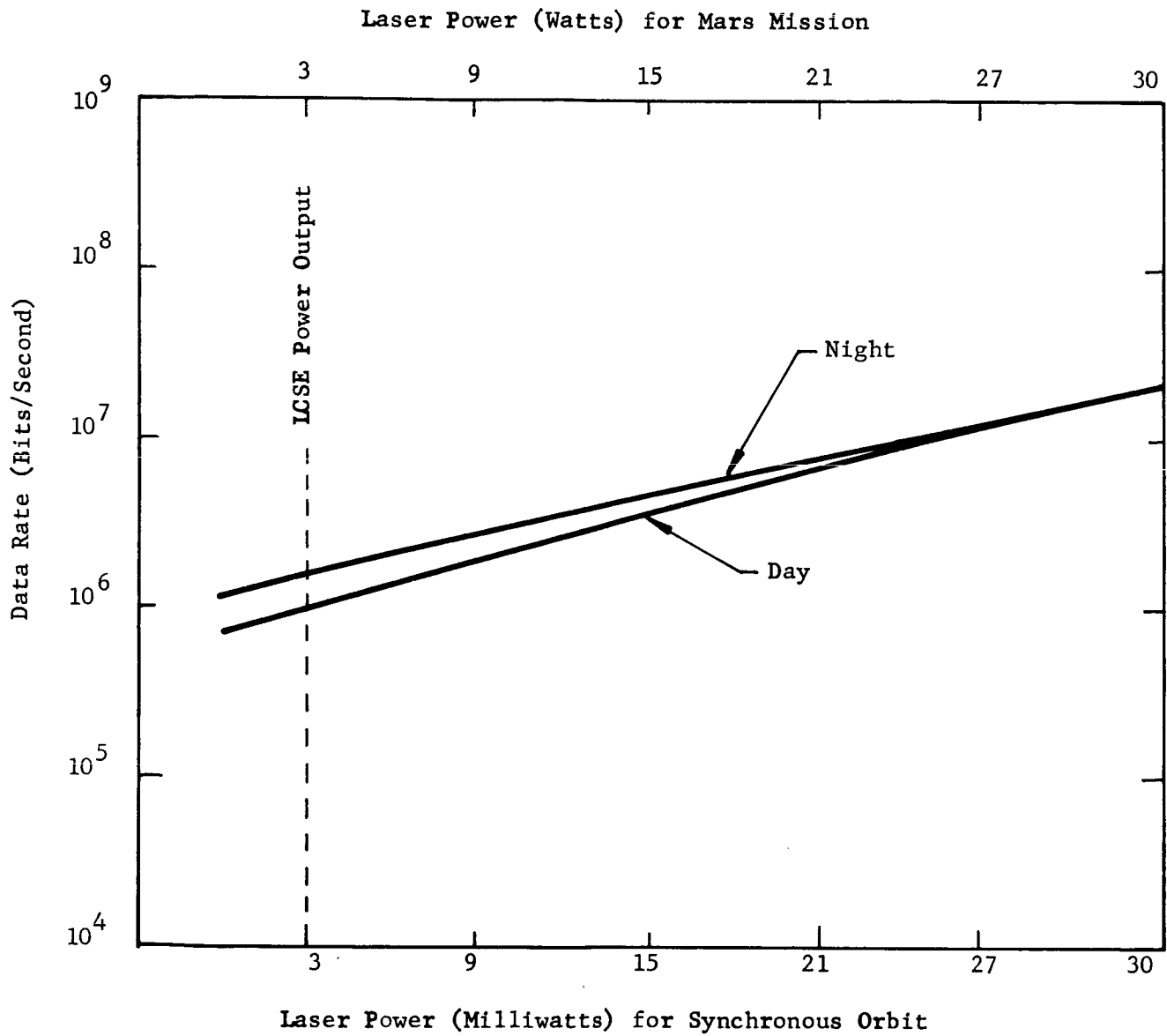


Figure 209. Laser Output Power Selection

wavelength. Since the wave front is reflected from the primary mirror, a mirror deformation of Δ_m will introduce a wave front error of $\Delta_w = 2\Delta_m$. Thus, the reduced intensity at a point in the central image is

$$I \sim 1 - \frac{16 \pi \Delta_m^2}{\lambda^2}$$

Using $\lambda/50$ as the reference for the rms mirror error, Figure 210 gives the dependence of the data rate on the rms primary figure error. In determining the specification of the primary, allowances must be made for the mirror quality required by the communicator tracking subsystem and mirror errors introduced by temperature gradients, zero gravity, and the launch environment. Thus, an rms figure error of $\lambda/40$ to $\lambda/50$ will be required to guarantee diffraction-limited performance of the telescope.

Beam Spoiling (for Synchronous Orbit Experiments Only)

A device to spoil the transmit beam was inserted in the optical communicator to insure a backup mode of operation to the fine tracking, RLOS, and point ahead subsystems. If the beam is spoiled to 4 arc-seconds, the link is operative (although at a reduced data rate in the daytime) even if the aforementioned subsystems are inoperative or only partially operative. The reduction of data rate is shown in Figure 211. Since the synchronous orbit link has a safety factor greater than 20 db, the link will support a one megabit data rate at night when the beam is spoiled to operate without the RLOS or point ahead subsystems.*

Transmitter Pointing Error

The far field pattern of the laser radiation transmitted by the optical communicator is determined by intensity and phase distribution across the telescope aperture, plus the obscuration of the central portion of the aperture by the secondary. The free space loss calculations require knowledge of the absolute energy density at the center of the far field pattern. The specifications of the pointing subsystems require knowledge of the relative change of the energy density in the far field as one introduces small angular alignments.

The light distribution across the output of a laser operating in the TEM₀₀ mode is approximately a truncated gaussian. Calculations indicate that the far field distribution near the center of the far field pattern of a telescope with a gaussian distribution across the aperture does not vary significantly** from

$$I_o \sim \left(\frac{J_1(x)}{x} \right)$$

* This statement is true only when the transmit-receive channel alignment procedure is carried out.

** Buck, Arden L: The Radiation Pattern of a Truncated Gaussian Aperture Distribution, Proc. IEEE, 55, pp. 448-450, March 1967.

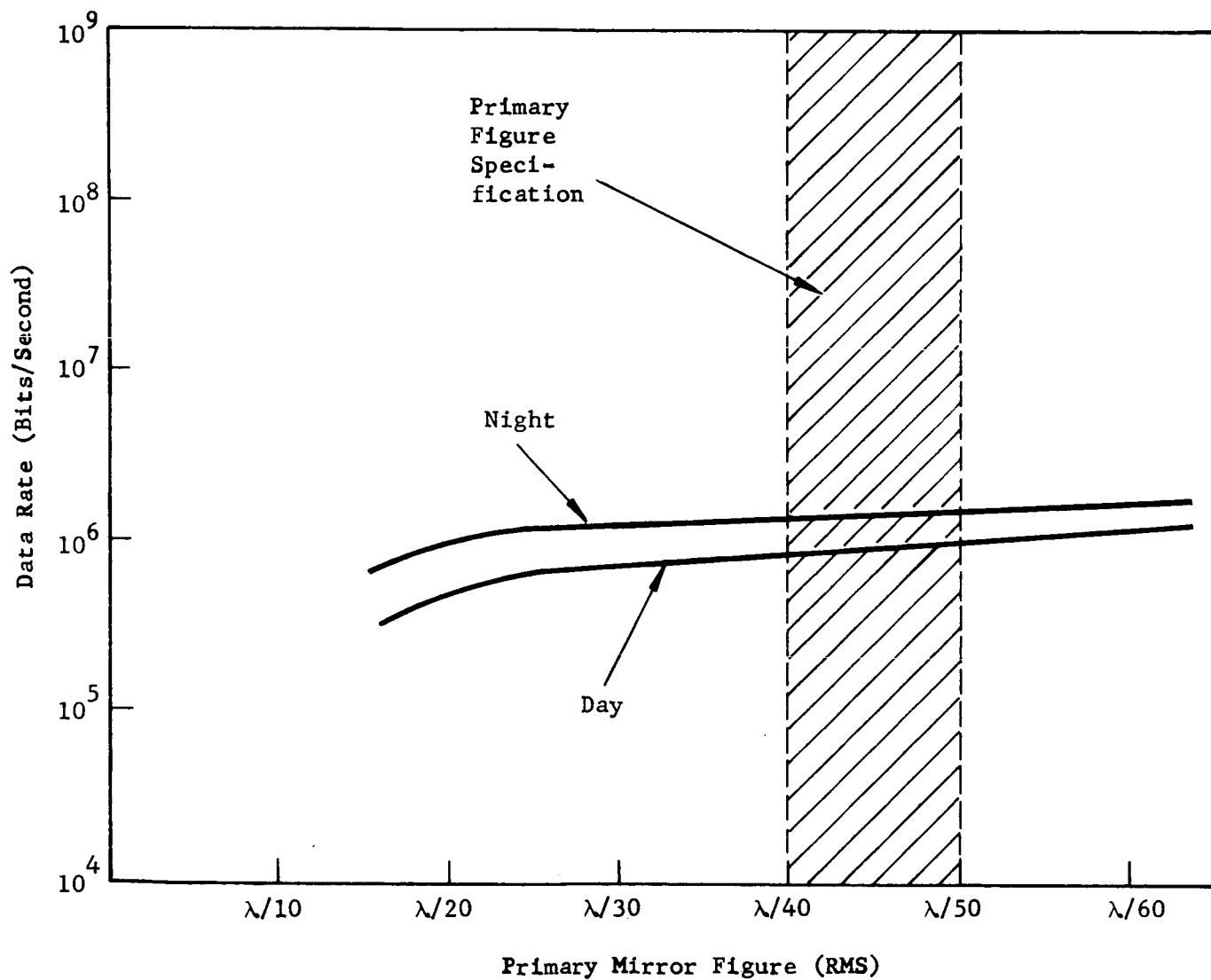


Figure 210.. Figure Error

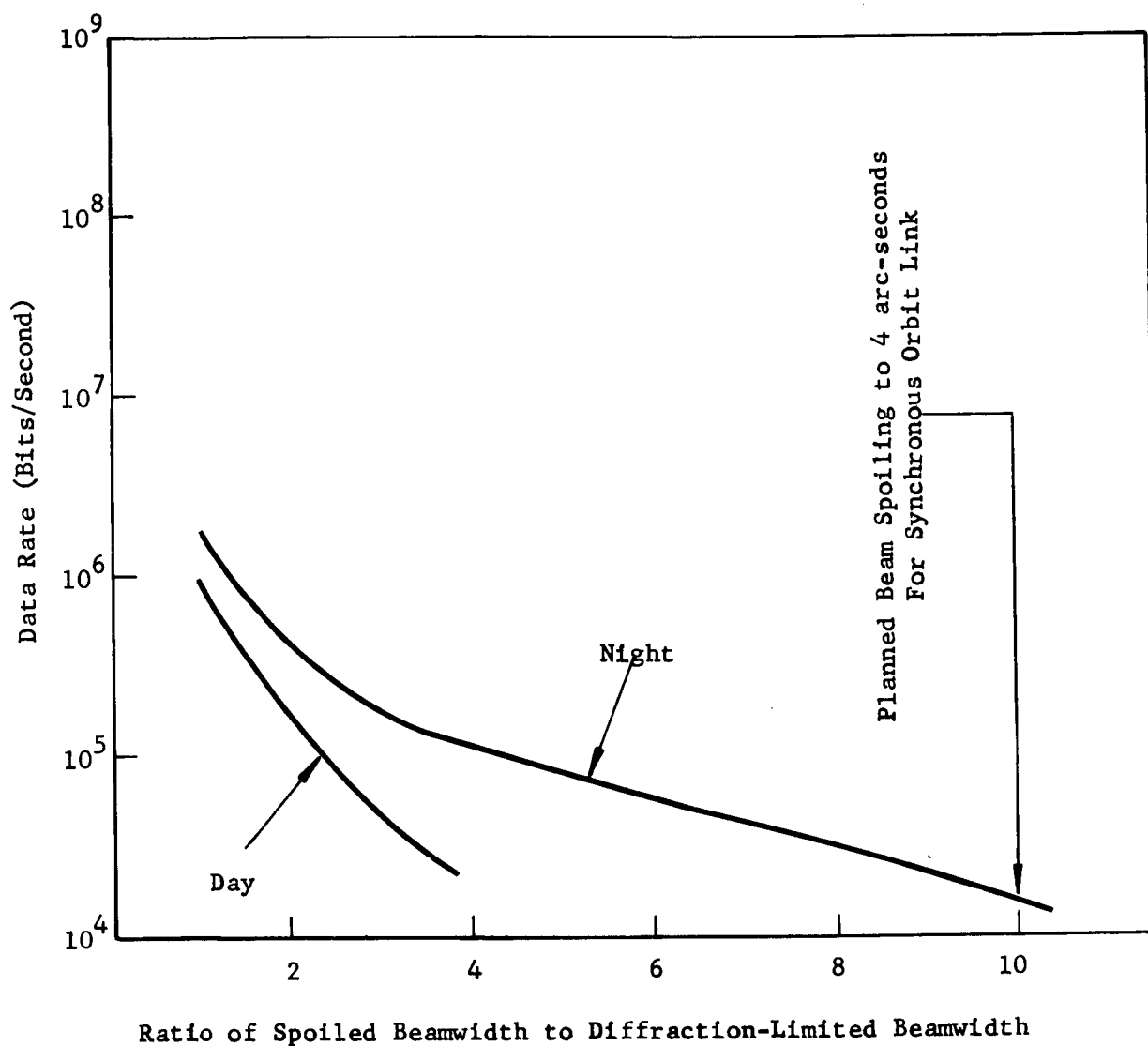


Figure 211. Beam Spoiling Selection For Synchronous Orbit Link

where I_0 is the far field distribution of a uniformly illuminated aperture with no obscuration. This idealized distribution was used to compute the variation in data rate when a pointing error is introduced (Figure 212).

Receiver Zenith Angle

The synchronous orbit satellite, as viewed from earth, will describe a tilted figure eight on the Earth surface with a period of 24 hours. The zenith angle will be determined by the location of the ground station with respect to the orbital position of the LCSE. Angles greater than 60 degrees from the zenith are not expected. Two effects reduce the data rate as the angle from the zenith is increased. First, the range increases with the corresponding increase in the free space loss. Secondly, the absorption of the atmosphere increases as the zenith angle increases.* The absorption varies approximately as the secant of the zenith angle. Both effects were considered in the plot of Figure 213. This curve is not applicable to the deep-space links.

Effect Of Scintillation On Receiver Diameter

A star viewed from the earth suffers from image dancing and blurring plus scintillation. Since the PCM/PL receiver is an energy detector (i.e., quantum counter), image dancing and blurring will not degrade the PCM/PL system as long as the received signal is incident on the photoemissive surface. The scintillation, however, will introduce fading in the received signal. Under special conditions, 100 percent amplitude modulation of a star's image has been observed. No empirical data exists to verify mathematical models of the scintillation of a monochromatic laser light beam propagating vertically through the atmosphere.

A rather complete theory of star scintillation along with confirmation data has been published by Tatarski**. The theory states that the star's detected energy, I , has time varying statistics which are log normal. The probability density function is

$$P(y) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{y^2}{2\sigma^2}\right]$$

where σ^2 = variance of logarithmic intensity scintillation

$$y = \ln \frac{I}{\bar{I}}$$

$$I = \frac{cs}{n} = \text{intensity of light wave on surface of the objective.}$$

$$\bar{I} = \frac{\overline{cs}}{n} = \text{average light intensity}$$

$$\bar{s} = \text{average signal count per decision}$$

* Table 3-1, Determination of Optical Technology Experiments for a Satellite, NASA CR-252 (NAS8-11408).

** Tatarski, V.I.: Wave Propagation in a Turbulent Medium, Chapter 13.

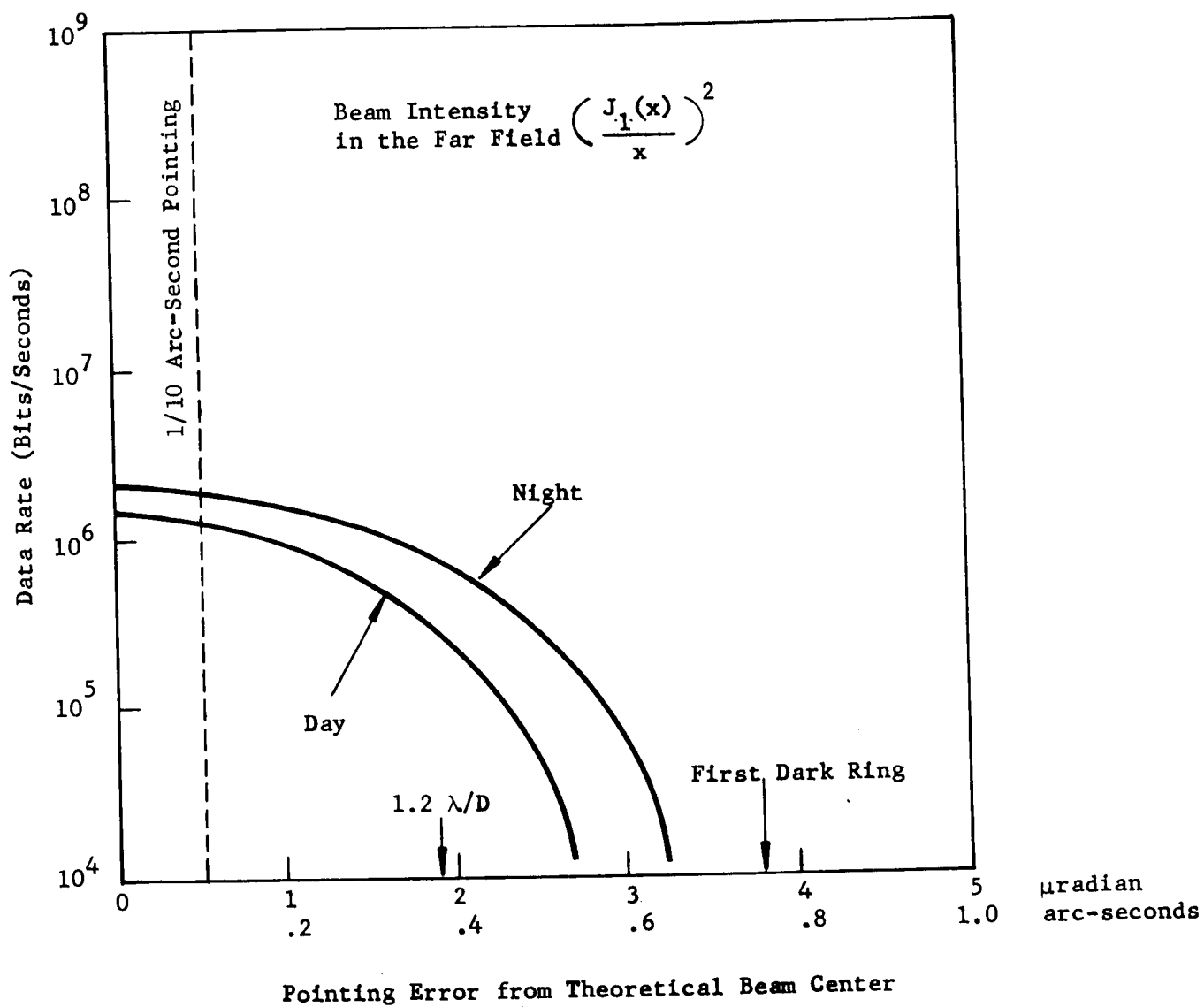


Figure 212.. Pointing Requirements

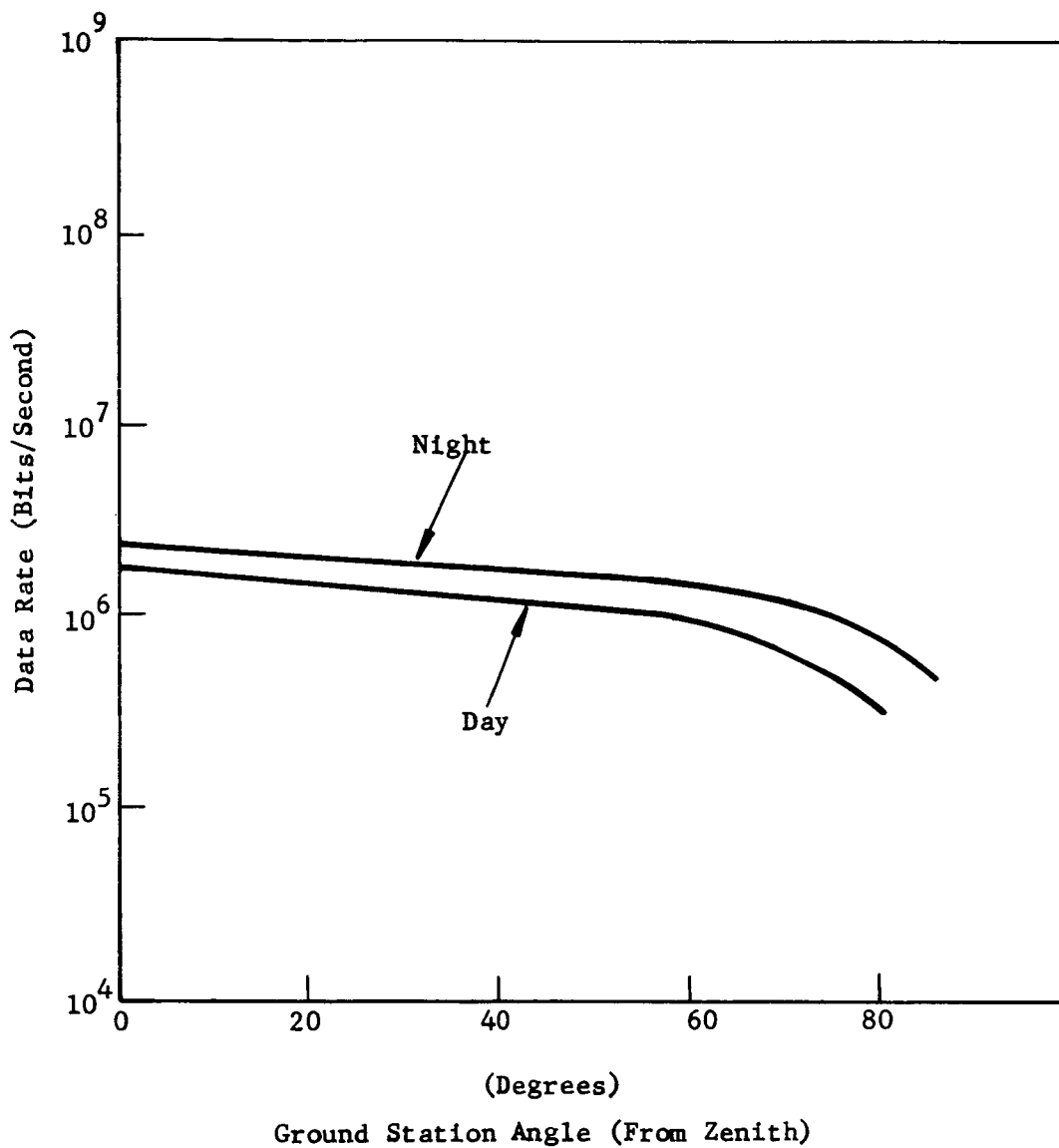


Figure 213. Up-Looking Angles Effect
(Synchronous Orbit Only)

The value of σ is greatest for viewing of stars near the horizon with a small aperture telescope. As the aperture is increased, several uncorrelated field inhomogeneities fit in the aperture. This effect (aperture averaging) reduces the scintillation by averaging the fading over several inhomogeneities.

The effect of scintillation on the error rate of the PCM/PL signal will now be discussed. Knowing the instantaneous received signal level of the time varying PCM/PL signal, the PCM/PL error rate equations* will give a corresponding bit-error rate. This method is legitimate only when the bit interval (1 microsecond) is small in comparison to the shortest period of the fading ($\approx$ 1 millisecond). Thus, stating that the instantaneous signal must be in excess of S_0 for 0.999 of the time is equivalent to stating that the bit error rate will be less than $P_B(S_0, N)$ for 0.999 of the time. Figure 207 may be used to find the relationship between S_0 and N when $P_B(S_0, N) = 10^{-3}$.

Doing the necessary transformation, the relation between the instantaneous power S_0 and the average power $\bar{S}$ is

$$\ln \frac{\bar{S}}{S_0} = \sqrt{2\sigma} \operatorname{erf}^{-1} (2 \times 0.999 - 1)$$

where $\sigma \approx 0.08$ for zenith viewing winter atmosphere 24-inch receiver

$\sigma' \approx 0.08 \sec \theta^{3/2} = 0.22$ for viewing 60 degrees from zenith

erf^{-1} = inverse error function

Substituting the above values into Equation (1) states that the power ratio $\frac{\bar{S}}{S_0}$, will be approximately 1.5 db and 4 db for zenith and 60 degrees to zenith viewing, respectively.

The value of σ increases when the aperture is reduced because the effect of aperture averaging is reduced. Figure 214 shows the dependence of the data rate on the receiver aperture. In addition to scintillation, the variation of the receiver aperture changes the value of blue sky background and the received signal power. Both of these values are proportional to the square of the aperture. The effects of all three sources of error were considered in plotting Figure 214. Note that the effects of scintillation are insignificant for the 120-inch (3-meter) ground aperture of the deep-space link.

Safety Margin

The safety margin (in db) is defined as

$$M_{db} = 10 \log_{10} \frac{\eta N_S}{CS}$$

where N_S = number of photons incident on PMT

η = PMT quantum efficiency

C = data rate

S = signal counts per decision for PCM/PL detection (See Figure 207)

* See NASA CR-252 (NAS8-11408).

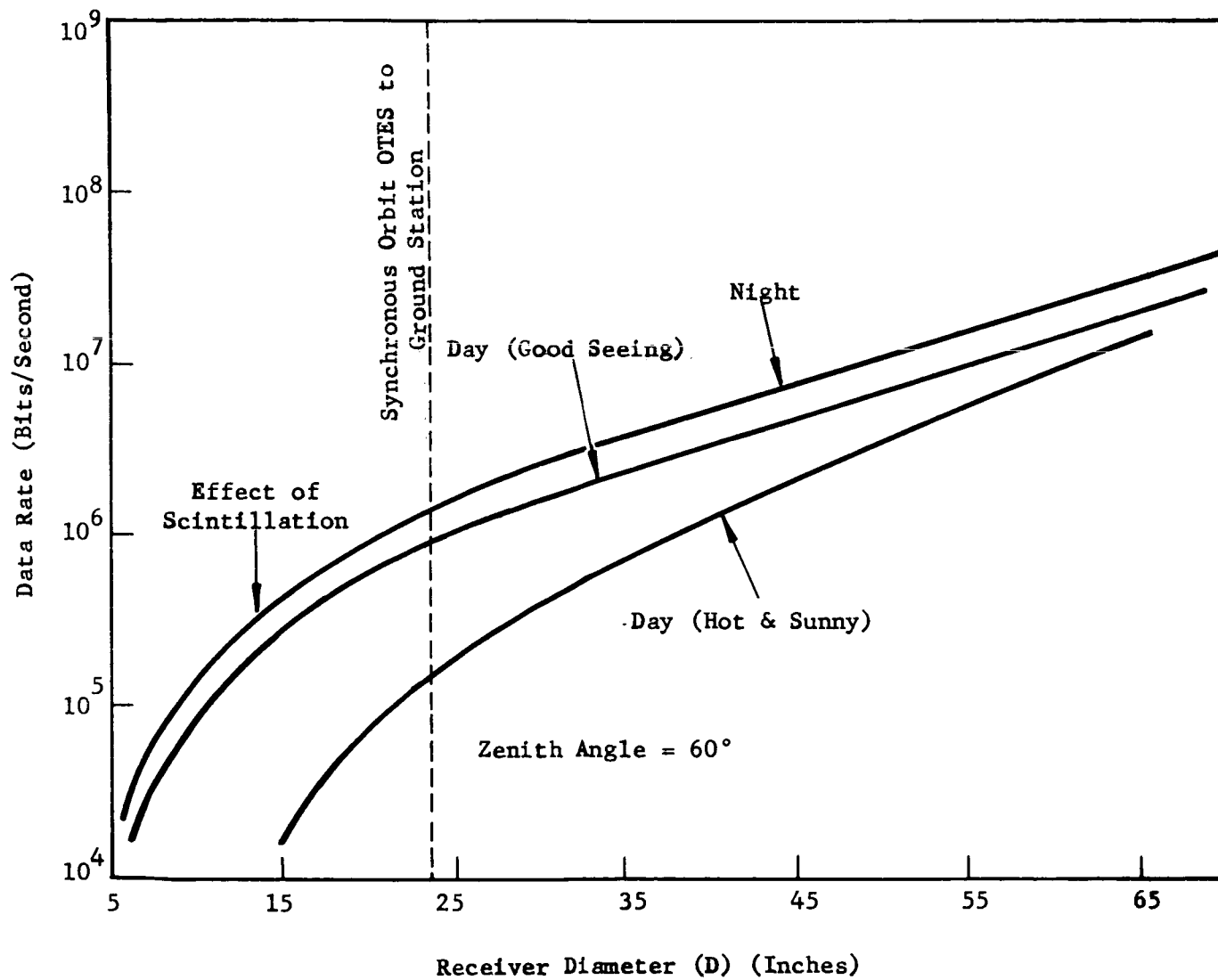


Figure 214. . Earth Receiver Aperture

A plot of data rate versus safety margin is shown in Figure 216. The synchronous orbit experiments require transmission of 10^6 bits per second. Both a pseudorandom digital sequence and slow scan video will be transmitted. Figure 216 shows safety margins of 17 db and 19 db for the worst case day and night operations, respectively. Assuming night operation, no scintillation, zenith viewing, and optimum predetection optical filter, a large safety margin (over 17 db) will be available at 10^6 bits/second and an adequate safety margin (over 10 db) at 10^7 bits/second.

Weight Minimization of Spacecraft

A trade-off between the communicator aperture and laser output exists. In the two extremes, it is possible to have a small transmitter aperture (e.g., one inch) with a correspondingly large laser (750 watt), or vice versa. Between these maxima, there exists an aperture and laser output power which yields a minimum weight. The curve of Figure 215 demonstrates that this minimum occurs near $D = 16$ inches. It is on the basis of this curve that the aperture of 16 inches (0.4 meter) was chosen for the Mars mission megabit communicator.

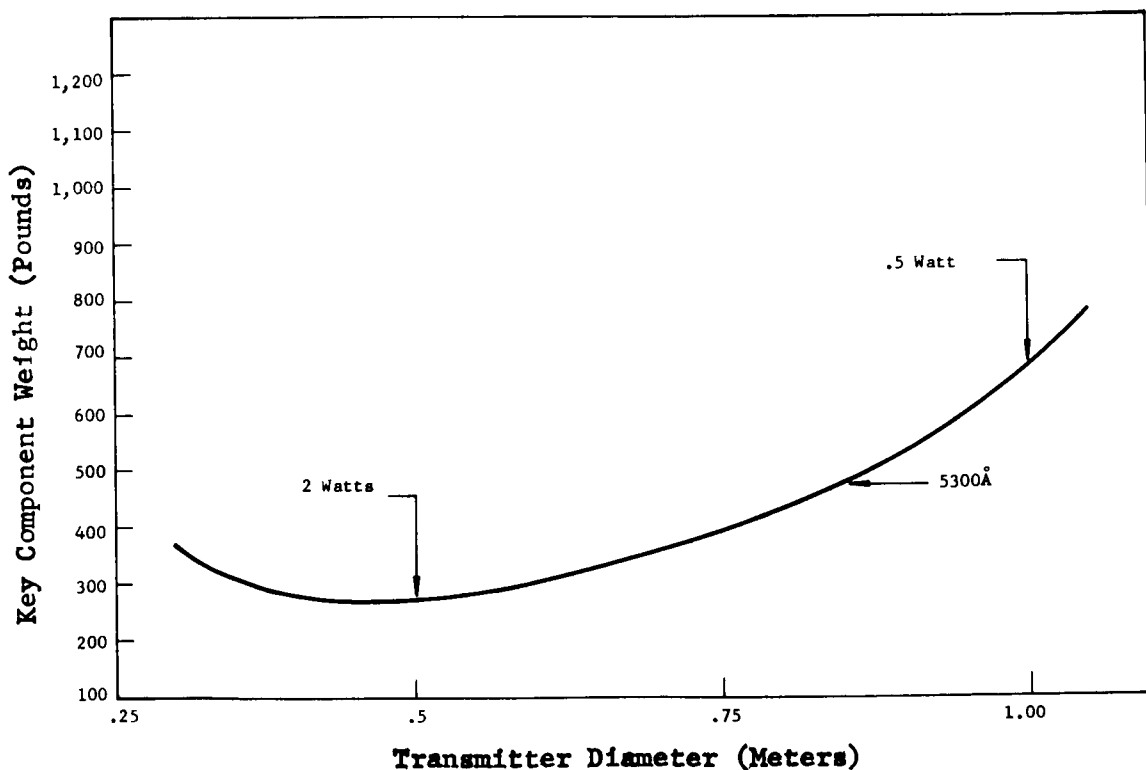


Figure 215. Weight Trade-Off for MARS Mission

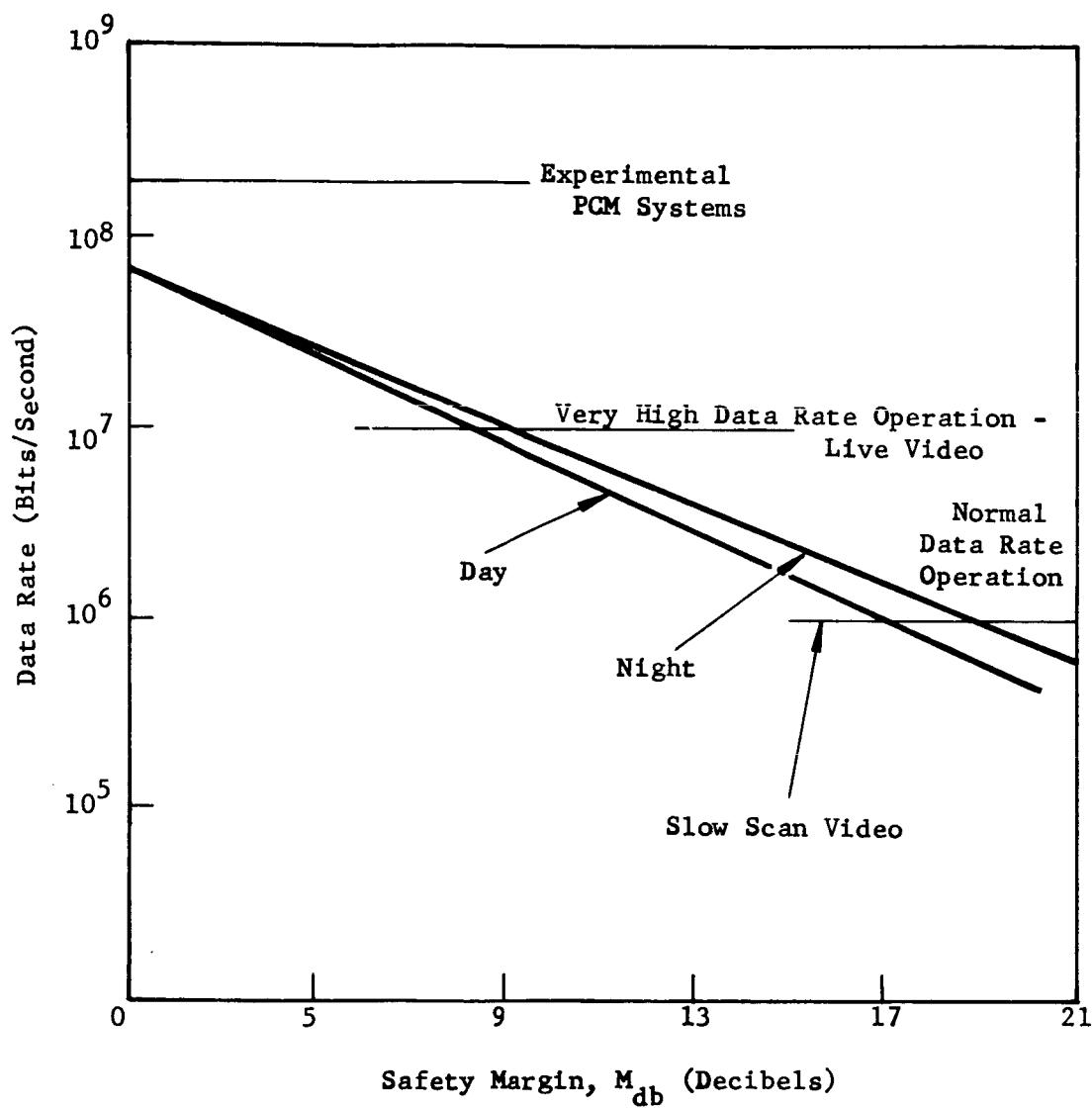


Figure 216.. Effect of Safety Margin

PERKIN-ELMER

Report No. 8900

CHAPTER 5 - GROUND STATION REQUIREMENTS FOR THE OPTICAL
TECHNOLOGY APOLLO EXTENSION SYSTEM (OTES)

GROUND STATION JUSTIFICATION

The justification for the NASA Optical Technology Test and Operations Station (OTTOS)* is to assist in the performance of those spaceborne scientific and engineering experiments of the OTES Program in optical technology. The most important experimental areas of space optical technology which require a NASA optical ground station such as OTTOS to participate in the performance of space flight experiments** are:

- large diffraction-limited mirror measurement on Earth (Experiment No. 5)
- 1/100 arc-second pointing of large-aperture telescopes (Experiment No. 9)
- 1/10 arc-second pointing of laser beams from space-to-Earth (Experiment No. 19)
- laser beam propagation through the atmosphere (Experiment No. 19-25, 27-32)
- clear air turbulence research (Experiment No. 33)

In addition to Optical Technology, a secondary objective of the OTES Program is to perform scientific experiments and/or collect data utilizing the optical and laser systems of the OTES which will further the space research efforts in areas other than optical technology. The most important area for OTTOS is scientific support of experiments in laser communication research.

Of the 30 experiments that have been recommended in the OTES Program, a uniquely instrumented ground station facility such as OTTOS is mandatory for 18 experiments. The remaining 12 experiments vary in their need for an appropriate ground facility from positions of requiring backup data collection to positions of requiring no ground facilities at all.

Location Of Site

The site should be selected for good seeing conditions with minimum cloud cover and should be located somewhere in the western United States. This area lies beneath one of two stable positions for a synchronous satellite (because of the

* Detailed work sheets on OTTOS have been prepared for MSFC in Perkin-Elmer Report 8700 dated March 31, 1967.

** Synchronous orbit required.

gravitational anomaly caused by the pear-shaped earth). The site area should be free of air traffic to eliminate contrails and the danger of airline pilots and passengers being irradiated with laser light. A special study sponsored by MSFC has been completed on this subject.*

The basic requirement for operation of the OTTOS at any time, day or night, results in site selection criteria which are quite different from those appropriate for the usual astronomical instrument. Astronomical telescopes are located on mountain tops to optimize night observing conditions despite cloudiness and convenience of access factors.

Under night conditions the ground temperature of the earth in a clear environment is significantly lower than the free air temperature. Thus radiation-chilled air tends to collect in low areas and to drain downslope. A mountain top is, therefore, the best place to be since the free (ambient) air tends to lower over the summit. This condition means that the thermal optical inhomogeneities are minimized. The astronomer must then place his telescope a sufficient height above the mountain top terrain to avoid the dynamic mixing of the surface-chilled air with the free air. Recent studies made at KPNO by Dr. C.R. Lynds indicate that this mixing has become small at a height of 100 feet.

Under day conditions the ground temperature of the earth in a clear environment is significantly higher than the free air temperature, exactly the opposite to night conditions. The surface-heated air tends to rise and a mountain upslope leads to the early onset of strong vertical convection. A site that is a good night observing station actually is likely to be a very poor daytime observing station. The combined usage of a mountain site for stellar and solar observing is usually a complicated logistics and economics compromise, and in the case of this system, these factors may be such as to further de-emphasize a mountain site.

The excellence of night seeing at a mountain site and the gains attendant with a small seeing disc for a star is a factor of dominant importance for astronomers, even though the percentage of clear sky is apt to be a minimum for the local climate. In the case of the communications receiver, the need for maximum percentage of clear sky changes the weighting factor again away from a mountain site. A mountain site generally is cloudier than nearby less mountainous terrain for two reasons: 1. the orographic effect of the mountain area tends to produce saturation of the air and localized cloudiness, and 2. the daytime convection tends to form cumulus over mountain peaks.

A site that optimizes day and night seeing would appear to be one that is above local fog or low stratus conditions (as along the Pacific Coast in the N30-40° and S30-40° latitudes) but on sufficiently gentle terrain to avoid local steep slopes on sunlit sides.

* Study on Optical Communication Experiment Facility, Sylvania Electronic Systems, NAS 8-20304.

A desert floor site, such as at Goldstone, would appear to have many factors in its favor as a compromise site of near optimum day-night criteria. For example, there are elevated slopes available to provide avoidance of chilled night air and convection day air. The percentage of clear sky is significantly larger than available on the nearby coastal mountain barrier. Dr. Meinel has pointed out that during the 200-inch site survey in the 1930's Dr. J.A. Anderson made a few tests of the seeing in the Barstow area and reported surprisingly good results. It would, therefore, appear very desirable to do some day-night seeing studies in the Goldstone area to ascertain the performance of this site, since the very important questions of logistics and peripheral facilities make this a very attractive location.

In regard to the performance of a seeing test of a Goldstone area site it is most important to make the test a valid one. A test conducted from the surface, say within the lower 10-20 feet, would not be valid due to ground effects. The execution of an optical evaluation at operating heights significant for the final site, say 50-100 feet, is expensive since the structure to support the test telescope must be sufficiently stable to wind shake to make measurements in the fractional second of arc range. One scientifically acceptable alternate to the optical evaluation test is a microthermal evaluation as used extensively in KPNO studies. In this case, a set of very short response time temperature sensors are mounted on a light scaffold tower. It is obvious that if the microthermal sensor detects blobs of air at different temperatures ($\sim 0.05^\circ\text{C}$ in ~ 0.1 sec) there will also be optical index of refraction variations that will cause wave front deformations. The advantage of the microthermal method of site investigation, even though it is an indirect measure of local optical disturbances, is that it can be done at lower cost and with relatively unsophisticated unmanned instrumentation.

In regard to high altitude seeing disturbances, these will vary only slowly from nearby geographical areas, and one needs only to take recourse to the grosser meteorological criteria as climate and large-scale orographic effects, such as the turbulence in the wake of the "Sierra wave".

If the above type of study does not show that a compromise day-night site can be found, then the possibility of requiring separate "day" and "night" installations would need to be considered.

Astronomical Utility of the OTTOS Telescopes

Although the OTTOS telescopes are basically being considered as ground receivers for space communications system experiments and for deep space communications in the future, they are very well suited for normal astronomical work and ideally suited for special applications which can make full use of their precision pointing capability and their ability to track targets on a closed-loop basis.

For routine observational astronomy the OTTOS telescopes should provide prime, Cassegrain, and Coude focal positions. Recent developments in photographic plate

technology have somewhat reduced the importance of the low f-number prime focus position and some astronomers now consider the prime focus to be superfluous. The prime focus cage is only applicable to the 120-inch, 10 meter telescopes.

The proposed design in Figure 217 has its Cassegrain focus brought out through the elevation trunnion, an advantage to astronomers who wish to use large, heavy equipment at that focus or to astronomers who are using equipment such as liquid cooled detectors that are sensitive to gravity vector changes.

The absolute pointing accuracy is advantageous to infrared astronomers making measurements on stars which are too cool to be visible.

The telescope has many advantages for experiments that require a laser transceiver capable of tracking artificial satellites. This telescope is well suited as the ground station for the lunar laser ranging experiment proposed by C.O. Alley.*

Astronomers may find that the altitude and azimuth coordinate system used by the telescope is more difficult to use than the more familiar right ascension and declination, but the availability of the computer for coordinate transformation should minimize this problem.

A more serious problem is that of rotation of the field of view in the telescope. This rotation requires that the photographic plate be rotated during the exposure. We do not consider this to be a serious drawback since the plate rotation can be easily accomplished on an open-loop basis.

Meinel** has discussed the features of alt-azimuth mounts and pointed out the advantages that they offer, especially for very large telescopes (apertures greater than 200 inches).

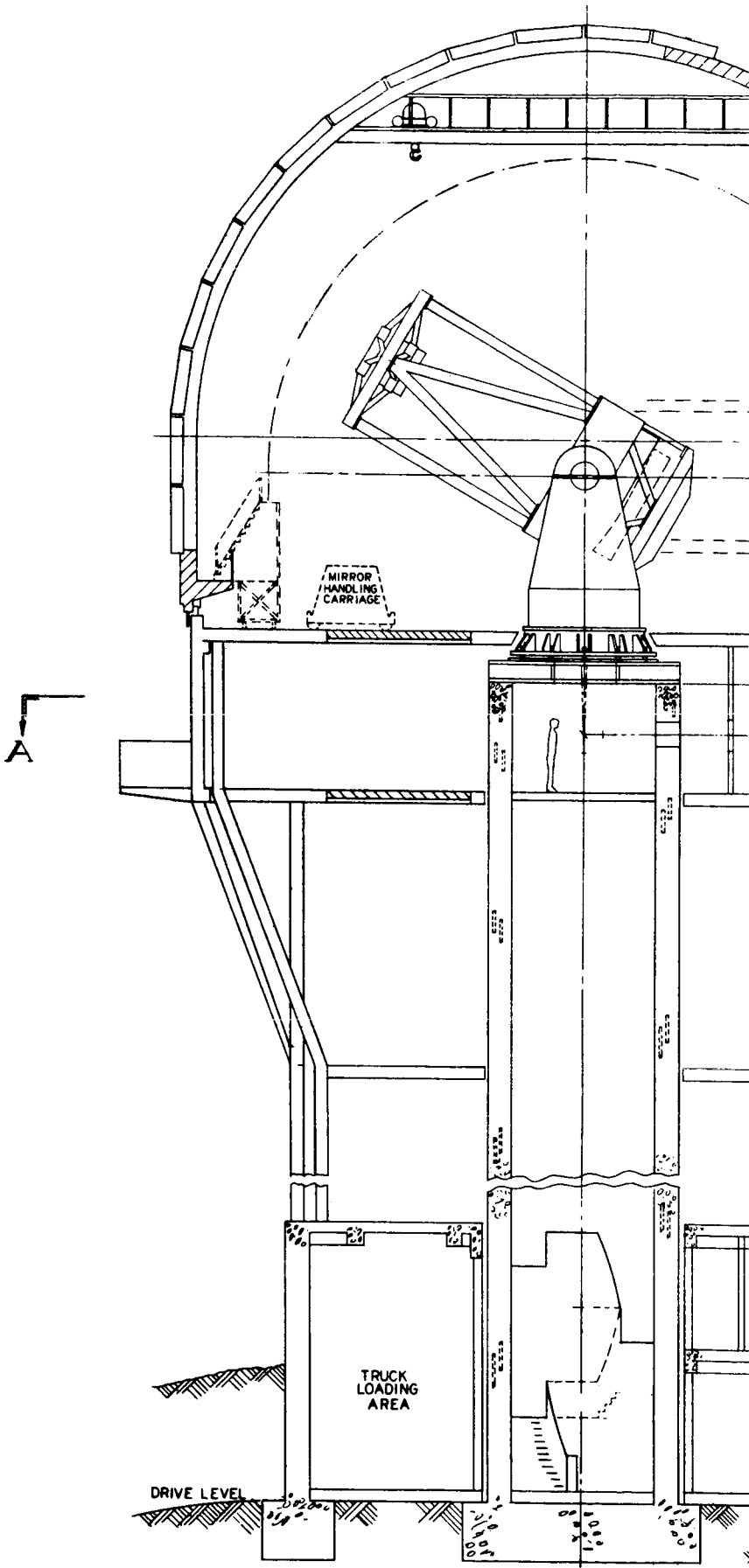
Major Instrumentation for Ground Station

The second telescope should be as large as practical and should have at least a 24-inch aperture. The telescope should have a Coude focus, use all wavelength optics (0.4μ to 10.6μ), and be mounted in an equatorial mount. A star measurement subsystem is required for star light scintillation measurements through the 24-inch telescope that is viewing the laser light. The 10-meter "photon bucket" telescope is a special case and it is not needed for the proposed OTES experiments. The 10-meter telescope which is described in a later section is used when the OTTOS site is converted to an operational receiver for receiving deep-space laser communication signals.

* Alley, C.O. et al: Optical Radar Using a Corner Reflector on the Moon, Journal of Geophysical Research, Vol. 70, No. 9, Pg. 2267, May 1, 1965.

** Meinel, A.B.: Introduction to the Design of Astronomical Telescopes, University of Arizona, 1965, Pg. 113.

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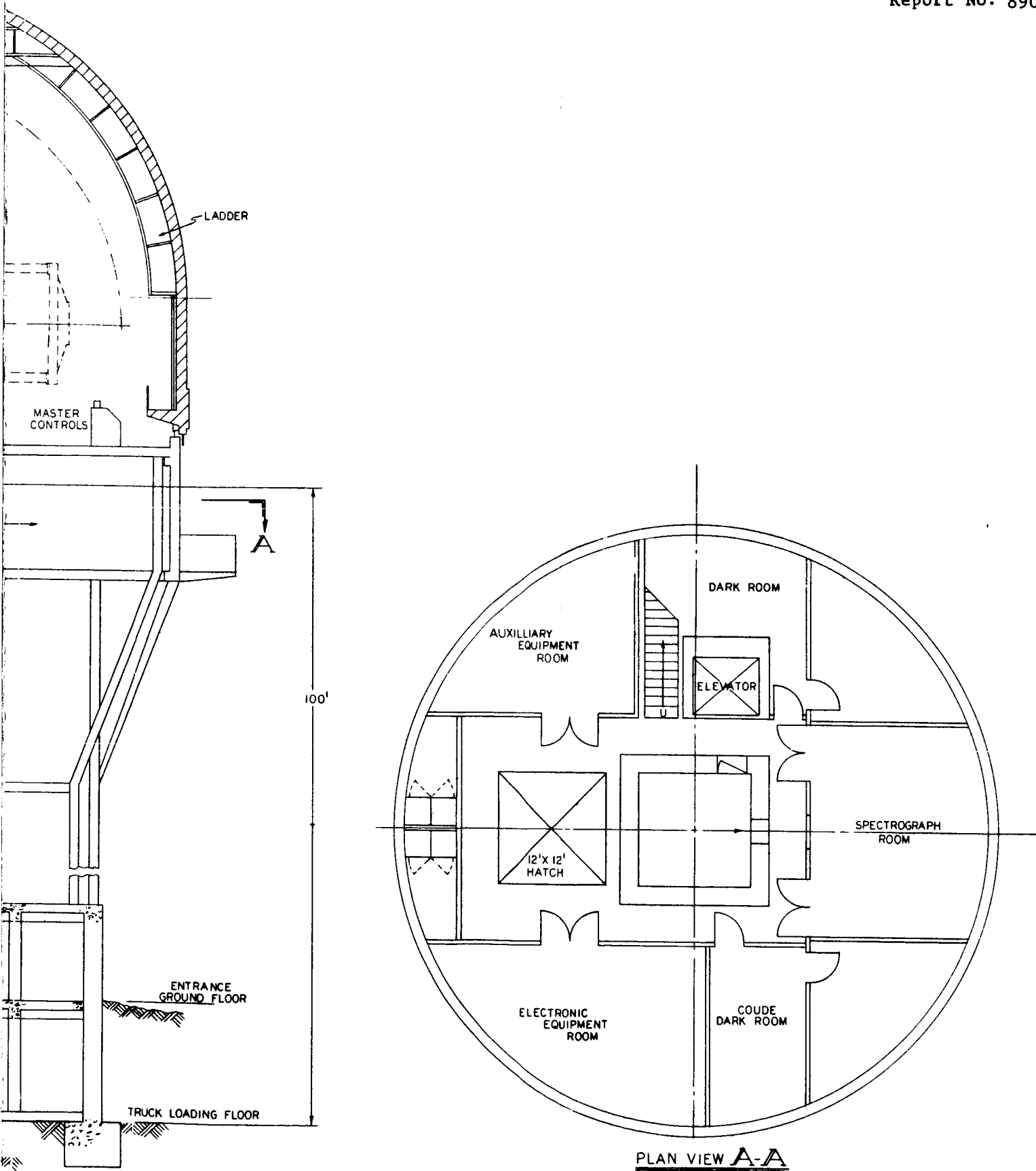


Figure 217. Building and Dome -
120-inch Aperture Azimuth
Elevation Communication Receiver

In addition, the telescope optical system for the upgoing beacon includes:

- a) Servo-controlled transfer lens
- b) Point-ahead subsystem
- c) Tunable laser system
- d) Coupling optics (to map the Gaussian distribution into a Cassegrain)
- e) Narrow band and neutral density filters
- f) PCM/PL modulator
- g) Argon beacon (1 watt, 1000 hr. lifetime, frequency controlled for OTES; 100 watts for the 10-meter telescopes)

Other basic instrumentation includes:

- a) 10.6 micron interferometer for atmospheric coherence diameter measurements
- b) Four 12-inch photoelectric laser receiver telescopes to receive the downgoing beam and assess the accuracy of the spacecraft pointing system
- c) One 2-inch aperture mobile argon beacon telescope as a backup source of a beacon light for point-ahead system measurements

Display Equipment

The display equipment required for the ground station includes:

- a) Mirror figure displays for the active optics system
- b) Equipment status displays (optical diagnostics)
- c) Spacecraft status displays
- d) Microwave link displays
- e) Astronaut activity displays

Data Processing Center

The data to be processed and correlated includes that from meteorological sensors at the ground station, scintillation data for the received beam and for starlight, and spacecraft tracking and pointing performance. A computer system is required for the computation of point-ahead data for the ground telescope and spacecraft pointing system.

Expansion Requirements

The ground station must be capable of expansion to accommodate future missions that would utilize equipment such as:

- a) A large incoherent telescope receiver (i.e., a 10-meter "Arecibo" type or a rotatable azimuth mount) for incoherent detection at visible wavelengths. (See Figures 218 and 219.)
- b) A 100-watt argon laser beacon (Mars missions).
- c) A 3 to 4-meter telescope receiver for 5300Å and/or CO₂ detection of signals from a deep-space probe. (See figure 317)*
- d) Astronomical data reduction and interpretation equipment.

General Scheduling

The schedule for the OTTOS ground station is dependent upon the pace of optical technology development adopted by NASA.. There are four OTES plans presented elsewhere in this report which require operational ground stations for the Laser Satellite Experiments by 1970, the 2-meter OTES Experiments by 1972 and the 3-meter OTES Experiments by 1976.

Ground Station Telescopes for Deep-Space Laser Communication

Sky Coverage Requirements

The configuration for the "photon bucket" type of giant aperture telescope is influenced by the regions of the sky towards which the telescope must be capable of pointing. A number of possible sky coverage requirements are possible, and the relative advantages of each must be weighed against the technical and economic feasibility of implementing the instrument required. This subject was studied by Perkin-Elmer in the JPL Contract on Giant Aperture Telescopes* and the most important points relative to the OTTOS ground station are presented in the following section.

* Giant Aperture Telescope Study, R.W. Jones, Perkin-Elmer Reports 8393, 8558 and 8691 for Jet Propulsion Laboratory, 1966 and 1967.

** Volume II, Resources Plans

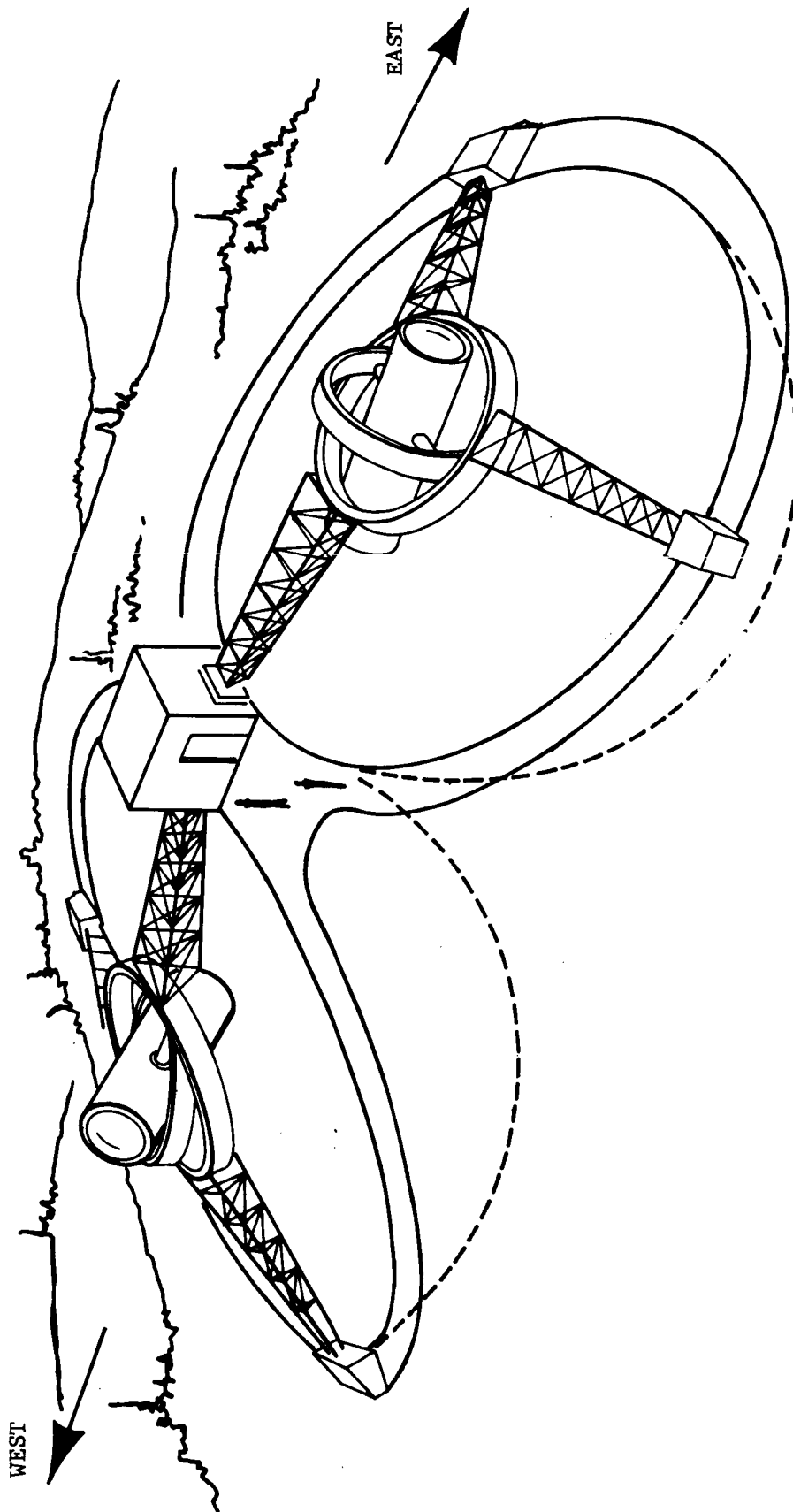


Figure 218. Laser Communication Ground Station

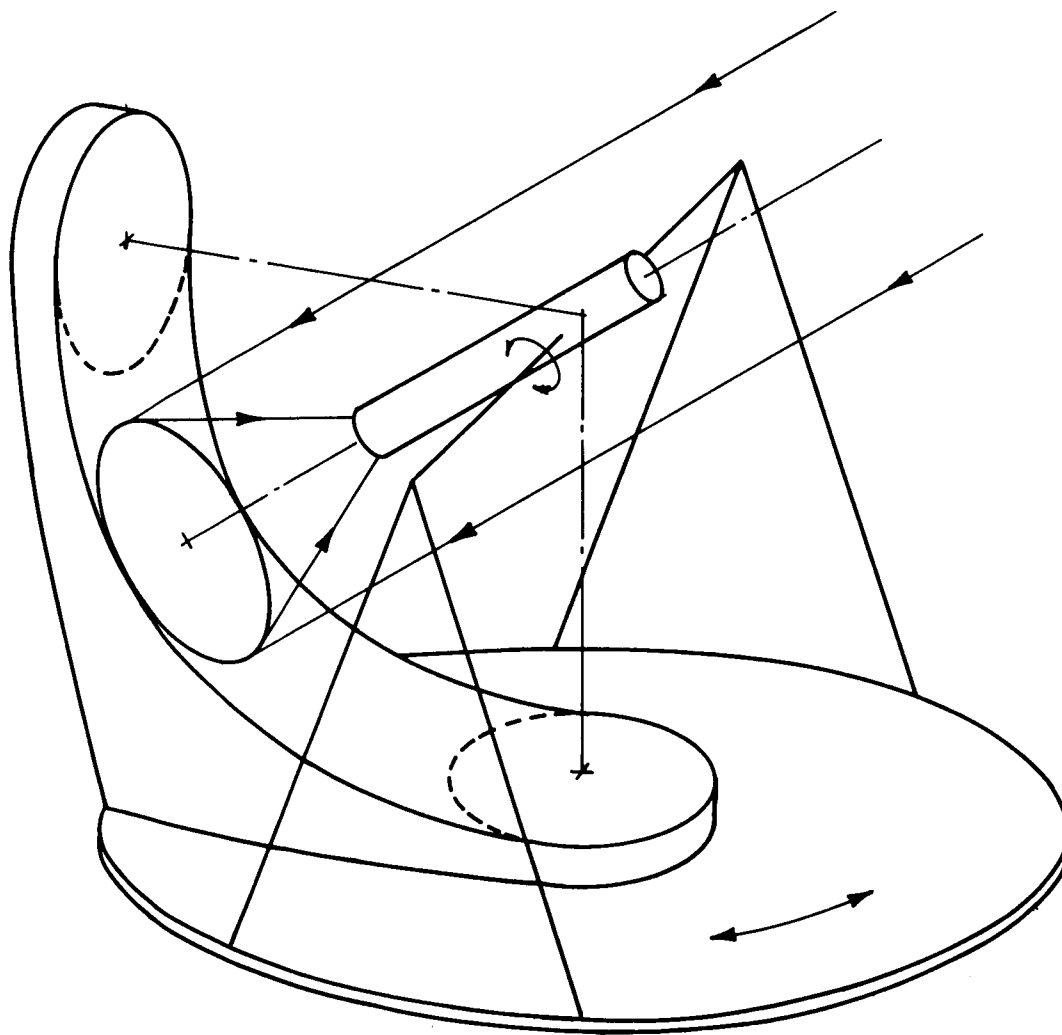


Figure 219. Schematic of Azimuth Rotating Telescope

The upper bound on sky coverage capability is, of course, the ability to look at an object anywhere in the celestial hemisphere, i.e., any object above the horizon. Coverage of the entire celestial hemisphere requires 360 degrees of azimuth angle capability and 90 degrees of elevation angle capability, and provides coverage of a solid angle subtending 2π steradians.

If the OTTOS telescope can be constrained to zodiac coverage only, that is, to communicate with vehicles traveling to the planets or otherwise in the general vicinity of the ecliptic plane, sky coverage requirements are reduced significantly.

The nature of the coverage required may be appreciated by inspection of Figure 220, which diagrams the celestial sphere as viewed by an observer at point "O" at latitude "L" in the northern hemisphere. The north celestial pole appears at an angle "L" above the northern horizon. The celestial equator is co-planar with the earth's equator, and the ecliptic plane intersects the equatorial plane along a line extending from the observer towards the vernal equinox, γ . As shown, the angle between the ecliptic and equatorial planes is $23^\circ 27'$. The entire celestial sphere rotates about the polar axis in an east-to-west direction with respect to the observer.

It is apparent that, as the celestial sphere rotates, the ecliptic plane sweeps out a band or zone $46^\circ 54'$ wide centered about the celestial equator. Consequently, if the observer wishes the capability of tracking an object anywhere in the ecliptic plane at any time that said object is above the horizon, he must be equipped to direct his instrument to any spot in the zone described.

The planets are all confined to a narrow band of sky, the zodiac, centered around the ecliptic. Hence, by reasoning similar to the above, the capability of looking at a planet at any time when it is above the horizon requires coverage of a zone of the celestial sphere centered about the celestial equator and with an angular width of $2(23^\circ 27' + i_p)$, where i_p is the maximum angular departure of the planet from the ecliptic, as seen from Earth. The illustration (Figure 221) shows this zone for an observer at a typical latitude L. Figure 222 shows the same area of the sky in a somewhat simplified diagram that also indicates some of the limiting elevation and azimuth angles. Inspection of this figure reveals that zenith pointing is required for observing latitudes $\leq (23^\circ 27' + i_p)$. Similarly, the amount of horizon coverage required increases from $4(23^\circ 27' + i_p)$ at 0° latitude to 360° at latitudes $\geq (66^\circ 33' - i_p)$.

A survey of orbital parameters for all the planets reveals that the maximum conceivable value of i_p would occur in the case of an inferior conjunction with Venus at a time when that planet is at its maximum distance from the ecliptic. Figure 223 illustrates the geometry of this situation and shows the worst-case value of i_p to be $8^\circ 46'$.

Substituting $i=8^\circ 46'$ into the expressions cited above, it is found that zenith pointing is required at latitude $\leq 32^\circ 13'$ and that the angular extent of horizon coverage required increases from $128^\circ 52'$ at equatorial observing sites to 360° at latitudes $\geq 57^\circ 47'$. Similarly, it is found that the solid angle subtended by the sky coverage described is 3.35 steradians or 53.3 percent of the celestial hemisphere.

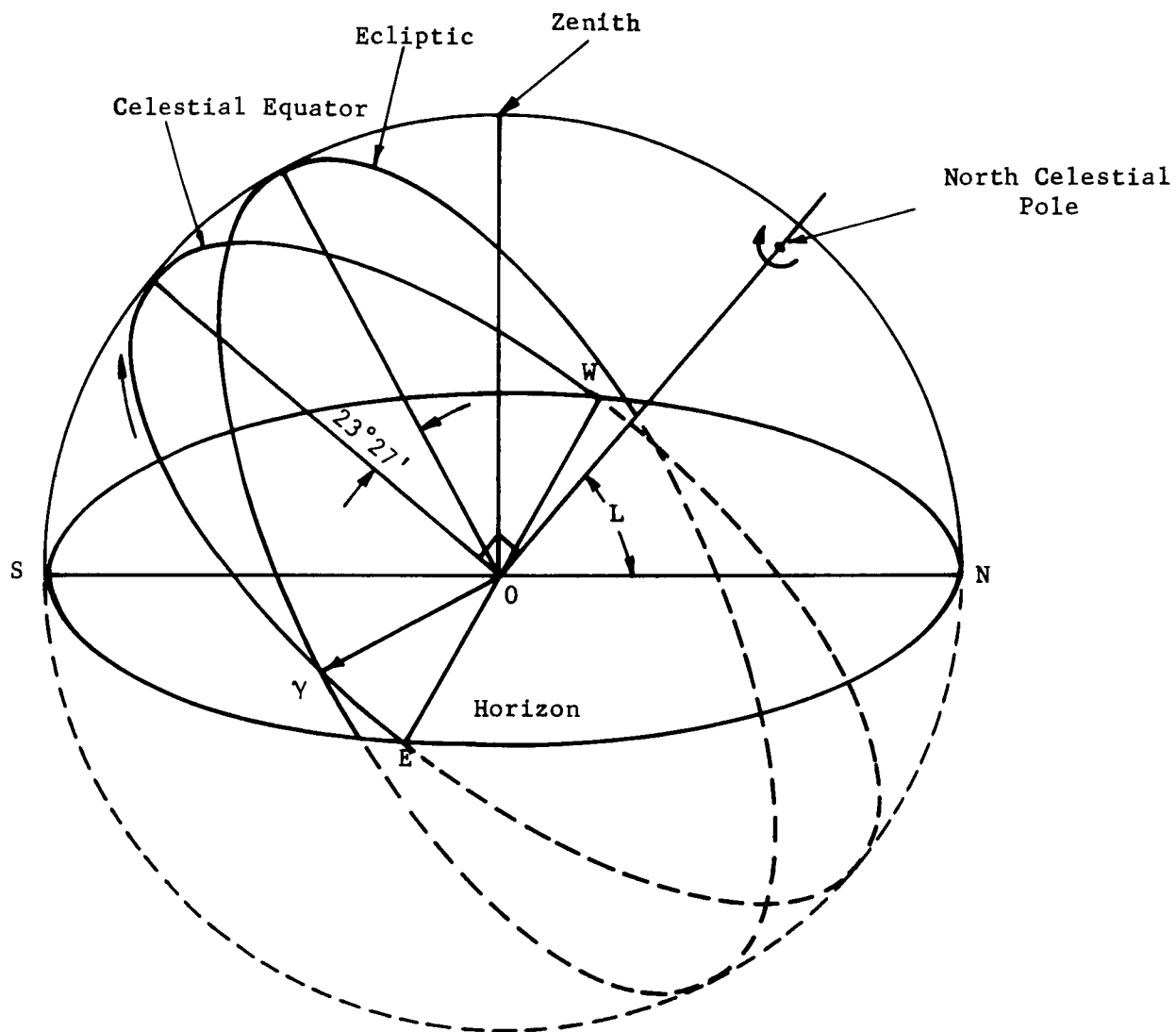


Figure 220.. The Celestial Sphere as Viewed by an Observer at Latitude L in the Northern Hemisphere

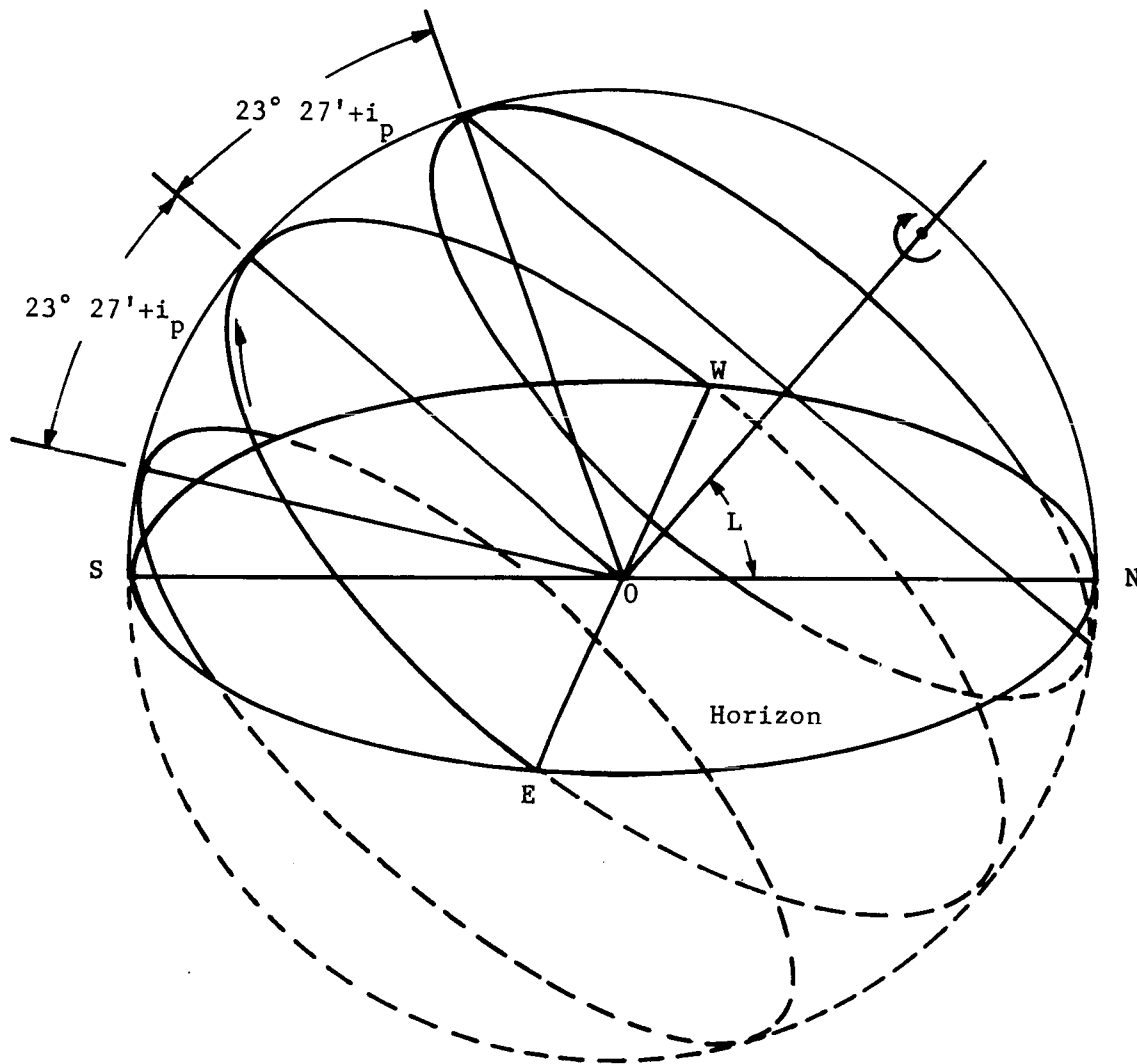
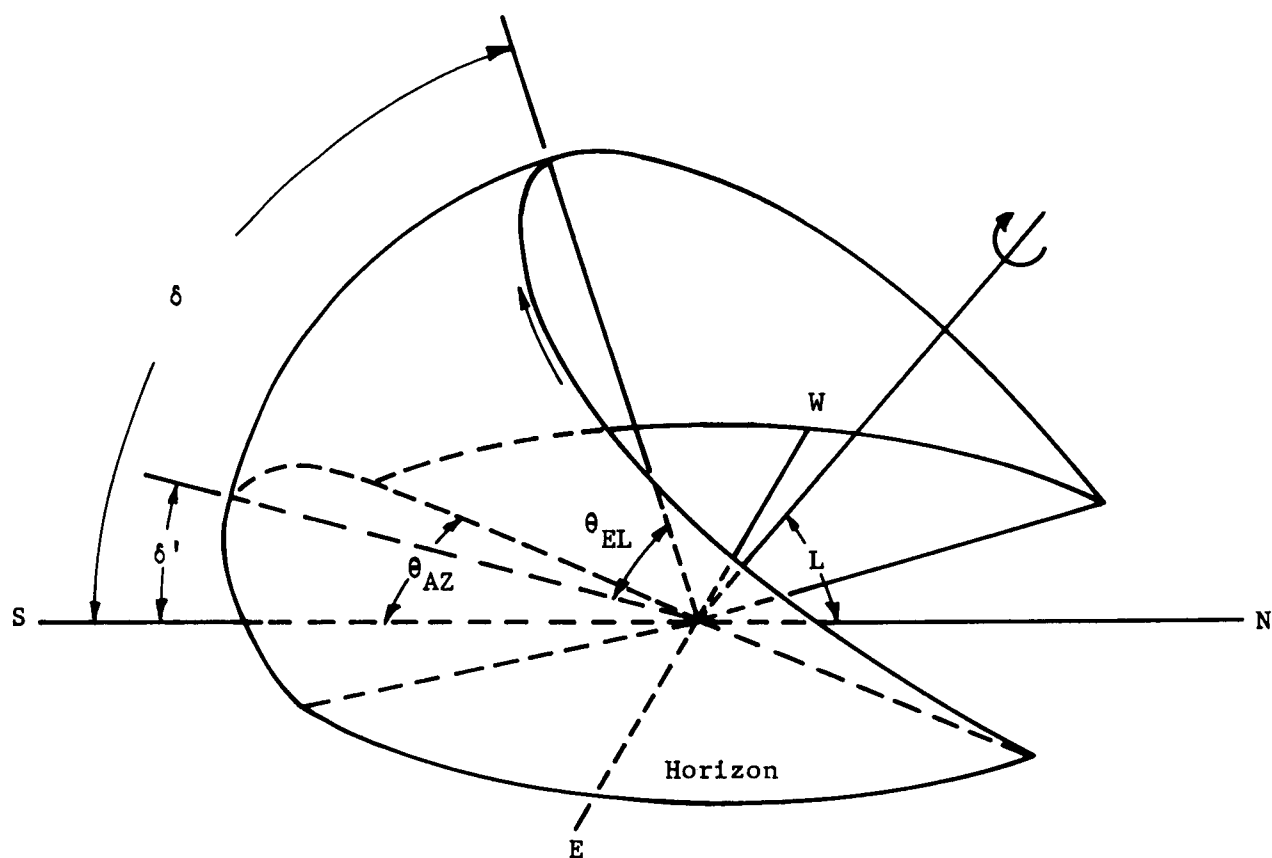


Figure 221. Sky Coverage Required to Assure Capability of Tracking an Object i_p out of Ecliptic Plane



$$\begin{aligned}\delta &= 90^\circ - L + 23^\circ 27' + i_p \\ \delta' &= 90^\circ - L - 23^\circ 27' - i_p \\ \theta_{EL} &= 46^\circ 54' + 2i_p \\ \theta_{AZ} &= \cos^{-1} \left[\frac{\sin(23^\circ 27' + i_p)}{\cos L} \right]\end{aligned}$$

Figure 222. Limiting Angles Associated with Sky Coverage Described by Figure 221

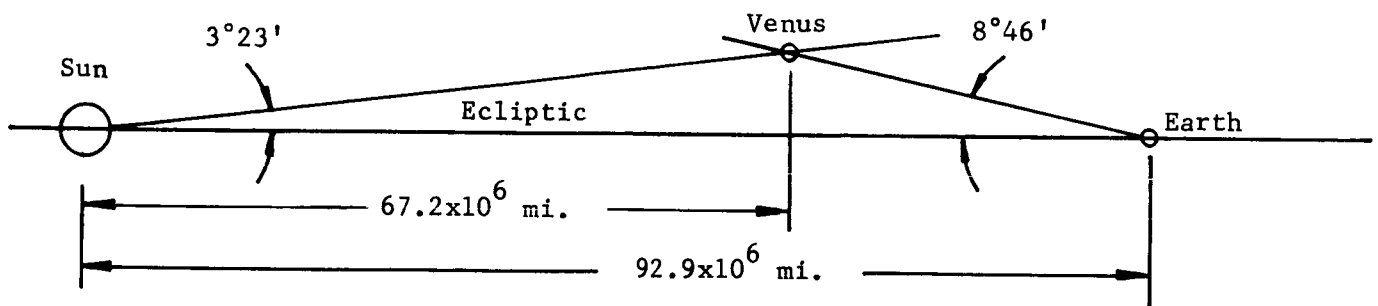


Figure 223. Worst Case Angular Departure of a Planet from the Ecliptic, as Seen from Earth

It should be noted that the situation described by Figure 223 is a relatively infrequent occurrence and that some reduction in i_p capability might be contemplated if occasional lapses of coverage were acceptable. (Inferior conjunctions of Venus occur at approximately 1.6 year intervals, with each displaced by about 218° from the preceding one.) However, the acceptable reduction for a system with a lifetime of many years would be quite small and would not significantly alter conclusions based on consideration of the worst-case condition.

Primary Mirror Area Requirements

A fundamental factor differentiating the various OTTOS telescope concepts is the area of primary mirror required. To a considerable degree, the question resolves itself to the economic trade-offs between increased mirror area and increased structural and mechanical complexity.

For aperture diameters on the order of 10 meters, it seems inescapable that the only practical approach is the use of a segmented mirror. It likewise seems apparent that the most promising method of economically fabricating a large number of similar segments, with the required degree of radius matching, is by replication.

The mirror area requirements of a number of possible configurations are indicated in the following paragraphs.

Fixed Spherical Reflector

A major problem area confronting the designer of large-aperture ground-based telescopes is the sensitivity of the primary mirror and its supporting and locating structure to the influence of gravity. This difficulty is compounded in conventional instruments by the necessity for operation in various and continually changing orientations with respect to the gravity vector.

The usual solution to this problem is an elaborate and carefully executed system of counterweights designed to balance out gravitational forces in an approximately uniform manner regardless of orientation. For single piece reflectors, this approach proves to be effective and practical.

Contemplation of apertures so large that the primary mirror must consist of a number of segments poses new aspects of the problem. While each segment might be successfully counterweighted to minimize distortions of its surface, maintenance of accurate alignment of those segments to each other requires one or more of the following alternatives:

- (1) Continuous mechanical realignment of each segment to compensate for varying gravity deflections of the support structure.
- (2) Provision of a second level of counterweights to compensate for gravity deflections of the structure, which supports and positions the counterweighted segments.

- (3) Provision of entirely separate load-bearing and positioning structures, with the latter called upon to carry no loads (even its weight would have to be transferred to the load-bearing structure).

All of these possibilities are sufficiently unattractive to encourage the search for approaches other than that typical of conventional astronomical telescopes.

One interesting concept is the complete avoidance of varying gravity deflection problems in the primary mirror by fixing that element of the system with respect to the gravity vector. Such a system might consist of a fixed spherical primary mirror in combination with a relatively small and manageable secondary optics package that, for tracking, rotates about the center of curvature of the primary. Figure 224 diagrams such a configuration.

The major advantage of this approach is the relative simplicity of the primary mirror support problem. The various segments would be rigidly and securely positioned on a massive and rigid foundation, with no concern whatever for static deflections except for possible long term thermal and soil-stability effects.

It is immediately apparent, however, that the principal penalty for avoiding the varying gravity vector in this manner is a significant increase in the reflector area required. The portion of the mirror employed at any one time is about equal in area to the aperture required, while the total mirror area needed is also a function of sky coverage desired.

If coverage of the entire celestial hemisphere is required (ignoring for the moment the problem of self-vignetting at low elevation angles), the primary mirror must itself be a complete hemisphere. It is apparent from Figure 224 that the ratio of mirror area to aperture area is simply

$$\frac{A_{\text{mirror}}}{A_{\text{aperture}}} = \frac{2\pi R^2}{\pi D^2/4} = 8 \left(\frac{R}{D} \right)^2 = 32 \left(\frac{F}{D} \right)^2 = 32 (f/\text{no.})^2$$

This relationship is plotted in Figure 225 and illustrates the urgency of employing the fastest possible primary mirror to keep the required primary mirror size within manageable bounds.

If zodiac coverage rather than hemisphere coverage is desired, the required mirror area decreases as a function of the decreased sky coverage. The surface area of such a mirror, expressed as a multiple of the aperture area, turns out to be

$$\frac{A_{\text{mirror}}}{A_{\text{aperture}}} = 32 (f/\text{no.})^2 \sin \left[23^\circ 27' + i_p + \sin^{-1} \left(\frac{1}{4 \times f/\text{no.}} \right) \right]$$

regardless of latitude. This relation also is plotted in Figure 225 for the previously discussed value of $i_p = 8^\circ 46'$. Comparison of the two solid curves in Figure 225 demonstrates that the percentage reduction in glass area requirements which results from decreasing coverage from hemisphere to zodiac, increases with $f/\text{no.}$ Reductions of 27 percent at $f/1.0$ and 42 percent at $f/4.0$ are representative.

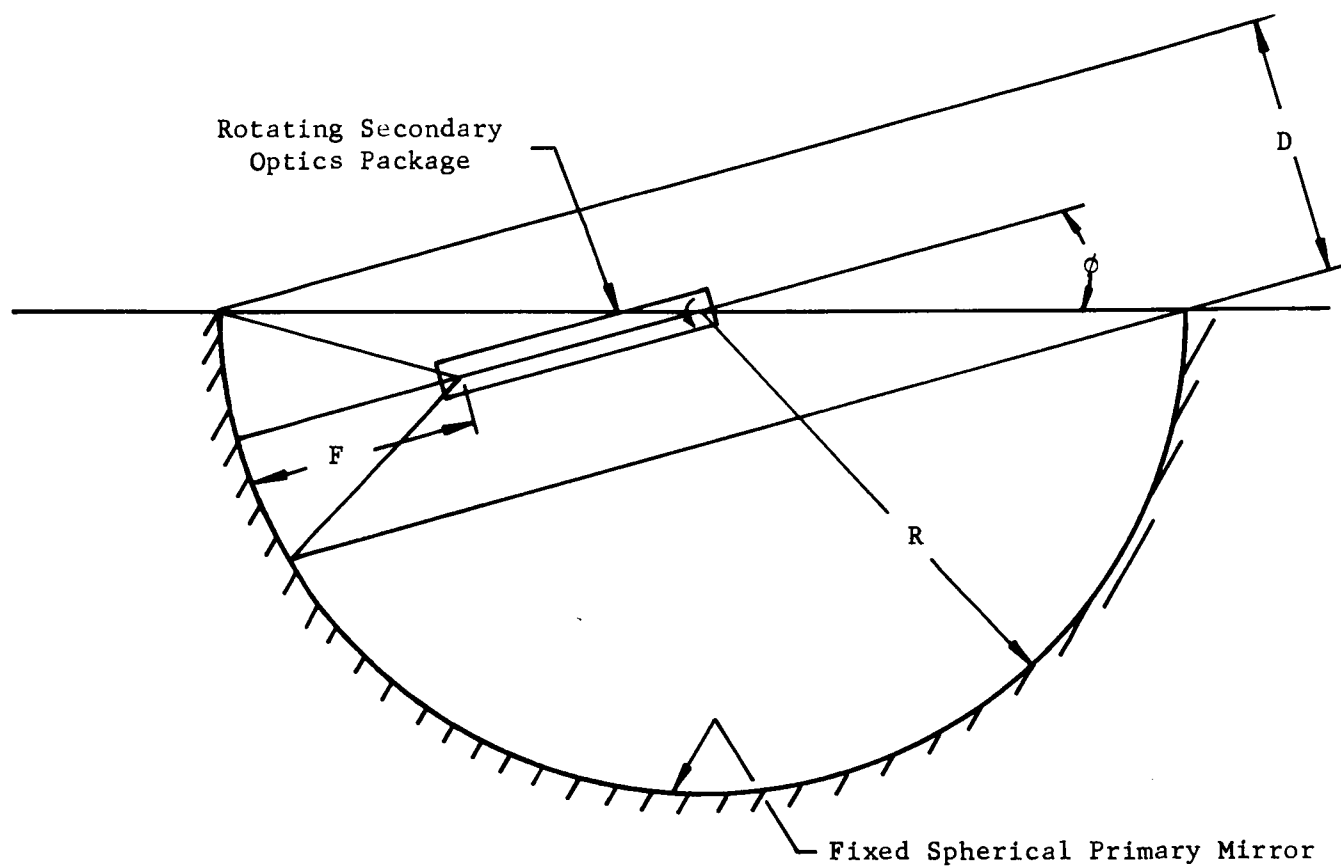


Figure 224. Telescope with Fixed Spherical Primary Mirror

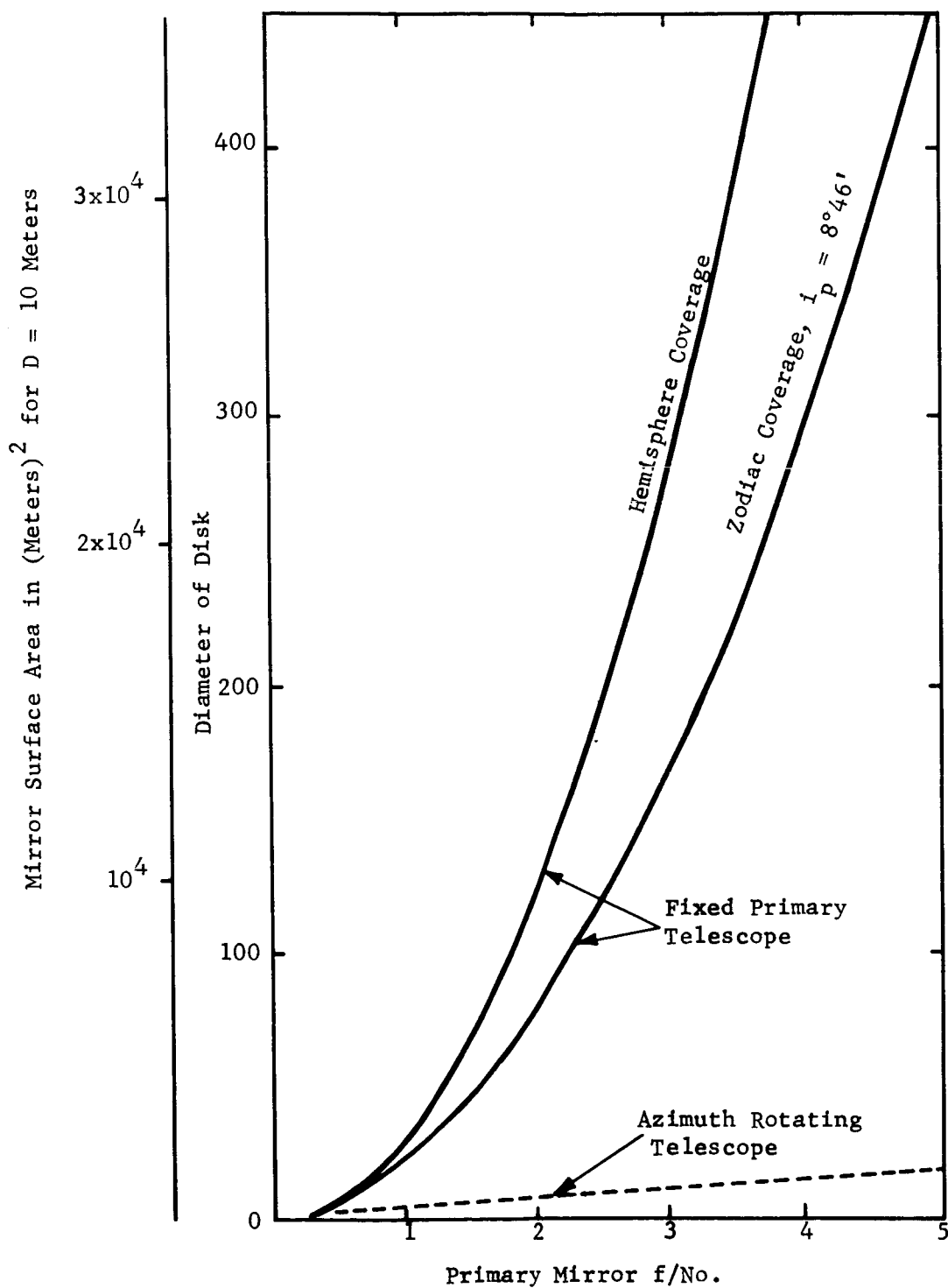


Figure 225.. Primary Mirror Surface Area vs f/No.

Table 12 summarizes representative computations of mirror area requirements for hemispheric and zodiac coverage with and without horizon capabilities.

Enclosure

It is quite clear that an enclosure or dome of some sort over the primary mirror will be mandatory. The three principal functions of such an enclosure would be:

- (1) Protection of the primary mirror from inclement weather and/or wind-borne sand and dust.
- (2) Maintenance of optimum seeing conditions for the instrument.
- (3) Minimization of direct solar thermal inputs.

The first of these items is amenable to straightforward solution, and represents no major problem. The maintenance of proper seeing conditions, however, requires detailed understanding of thermal conditions and air circulation phenomena in and around the instrument and its enclosure. This understanding must include daytime conditions of direct solar radiation, where experience with conventional astronomical instruments is of limited applicability. This is a problem of considerable proportions.

Similarly, direct solar radiation on the primary mirror and/or on the rest of the instrument would almost surely result in unacceptable thermal degradation of the mirror's figure and/or misalignments of the system. The difficulty of avoiding such effects will become acute for targets in proximity to the sun, and will certainly influence the design of the enclosure.

Pointing and Tracking Considerations

It is anticipated that the most advantageous approach to the pointing and tracking problem will prove to be an active dual-mode system composed of "coarse" and "fine" controls.

Initial pointing, acquisition, and sidereal rate tracking would be accomplished by rotation of the secondary optics package about its azimuth and elevation axes. It is probable that a relatively wide field-of-view would be employed during acquisition in order to minimize the absolute pointing accuracies required, as well as to compensate for residual uncertainties in target position and atmospheric effects.

Following acquisition of the target and initiation of nominal tracking rates by the course drive system, the field-of-view would be narrowed to an optimum value and a fine-guidance mechanism would provide active precision tracking. A likely means of implementing such a fine-guidance system is the inclusion in the optical system of a transfer lens whose lateral position is servo-controlled to maintain the target in the center of the field of view. This approach has been successfully

TABLE 12
MIRROR AREA REQUIREMENTS

	HEMISPHERE COVERAGE			ZODIAC COVERAGE				
	Excluding Horizon (Single Dish)	Including Horizon (Double Dish)	Excluding Horizon (Single Dish)	Including Horizon (Double Dish)				
				L=0°	L=20°	L= 40°		L= 60-90°
<u>Glass Area</u> <u>Aperture Area</u> f/0.5 f/1.0 f/2.0 f/4.0	8.0	13.9	7.1	12.9	13.1	13.5	15.6	
	32.0	46.7	23.3	30.6	30.9	32.0	35.6	
	128.0	159.5	81.3	91.0	91.9	93.6	102.0	
	512.0	574.7	299.0	315.0	315.0	318.0	335.0	
<u>Glass Area</u> <u>(Meter²)</u> For D=10 Meters f/0.5 f/1.0 f/2.0 f/4.0	628	1092	558	1013	1029	1060	1225	
	2513	3668	1830	2403	2427	2513	2796	
	10053	12527	6385	7147	7218	7351	8011	
	40212	45137	23483	24662	24740	24975	26311	
<u>Minimum</u> <u>Unvignetted</u> <u>Elevation</u> <u>Angle</u> f/0.5 f/1.0 f/2.0 f/4.0	30°	0° *	30°	0°	0°	0°	0°	
	14.5°	0°	14.5°	0°	0°	0°	0°	
	7.2°	0°	7.2°	0°	0°	0°	0°	
	3.6°	0°	3.6°	0°	0°	0°	0°	

*One "Blind Spot Will Exist on the Horizon
4047 M² = One Acre

employed in the Stratoscope II balloon-borne telescope. It has the attractive feature of providing fine guidance by controlling a single small element rather than attempting, in the case at hand, to move with extreme precision the massive and relatively unwieldy secondary optics package.

Utilization of the active tracking approach described, desensitizes the system to such persistent problems as varying mechanically or thermally induced deflections in the secondary optics package or its support structure and fluctuating apparent target location due to atmospheric effects.

Conventional Telescope

A possible configuration for a giant-aperture optical receiver would be a complete rotatable instrument similar in concept to conventional astronomical telescopes.

As has already been noted, an inevitable problem with such telescopes is the varying orientation of the gravity vector with respect to the primary mirror, and the consequent necessity of virtually eliminating gravity-induced deflections. A classic example of the required approach to this problem is the complex 36-point counterweight system which supports the 200-inch primary in the Palomar telescope. As has also been noted, the problem would be compounded in a very large aperture system requiring a segmented primary, inasmuch as the virtual elimination of gravity deflections must now be extended to a large positioning structure as well as to the segments themselves.

There are, however, advantages to the approach which warrant careful consideration for OTTOS. The most obvious is the relatively small glass area needed for the primary. The required area is essentially equal to the aperture area instead of 5 times as great for an $f/1.0$ azimuth-rotating system or 32 times as great for an $f/1.0$ hemispherical reflector. It is plain that elimination of that much glass could pay for a lot of counterweights and sophisticated structure.

A second attractive feature of a conventional telescope is the freedom to make the primary mirror a paraboloid or other aspheric, thus avoiding the optically awkward problem of correcting the severe spherical aberrations inherent in the use of a spherical primary.

At this stage of the OTES and OTTOS programs, existing experience with large astronomical instruments provides ample background for evaluation of various concepts. It should be apparent, however, that aperture diameters on the order of 10 meters lead inescapably to instruments of mammoth proportions. As a first estimate, a 10-meter telescope of conventional design would correspond to a 2:1 scaling of the 200-inch Palomar installation.

The present astronomical instrumentation experience is not adequate to compare the economic trades of the "photon bucket" with more classical approaches, because the JPL study concentrated on the 120-inch coherent receiver at 10.6 microns. A preliminary design study and cost estimate for the "photon bucket" is a task still to be accomplished when funds become available.

120-Inch Telescope as a Ground Receiver for Laser Communications

Figure 217 shows a prospective OTTOS 120-inch aperture-telescope on an alt-azimuth mount. The telescope is capable of complete hemispheric sky coverage about its site and may be used for normal astronomical work in addition to its intended mission as a ground receiver for a deep-space laser communication system. The entire telescope is shown mounted on a tower and enclosed by a conventional dome. All of the design features except the prime focus cage are valid for telescopes in the 80- to 120-inch aperture range. The prime focus cage is not considered to be applicable to telescopes much smaller than 120-inch because of the large amount of light blocked by a cage large enough to hold a man.

The azimuth axis of the telescope is carried by a 96-inch diameter hydrostatic oil bearing as shown in Figure 226. This was chosen for the very smooth, stiction-free, low friction, and accurate performance that these bearings are capable of providing, under the 70-ton load imposed by the telescope and yoke.

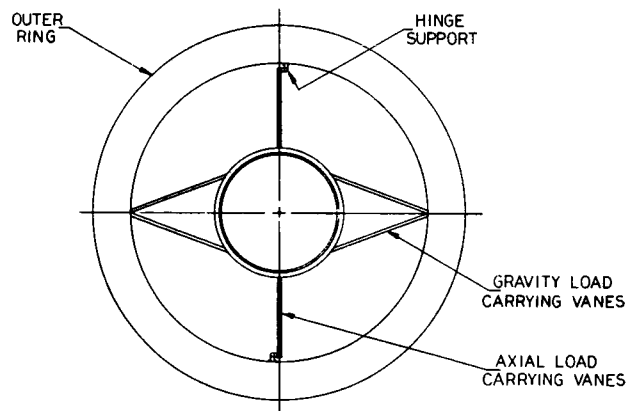
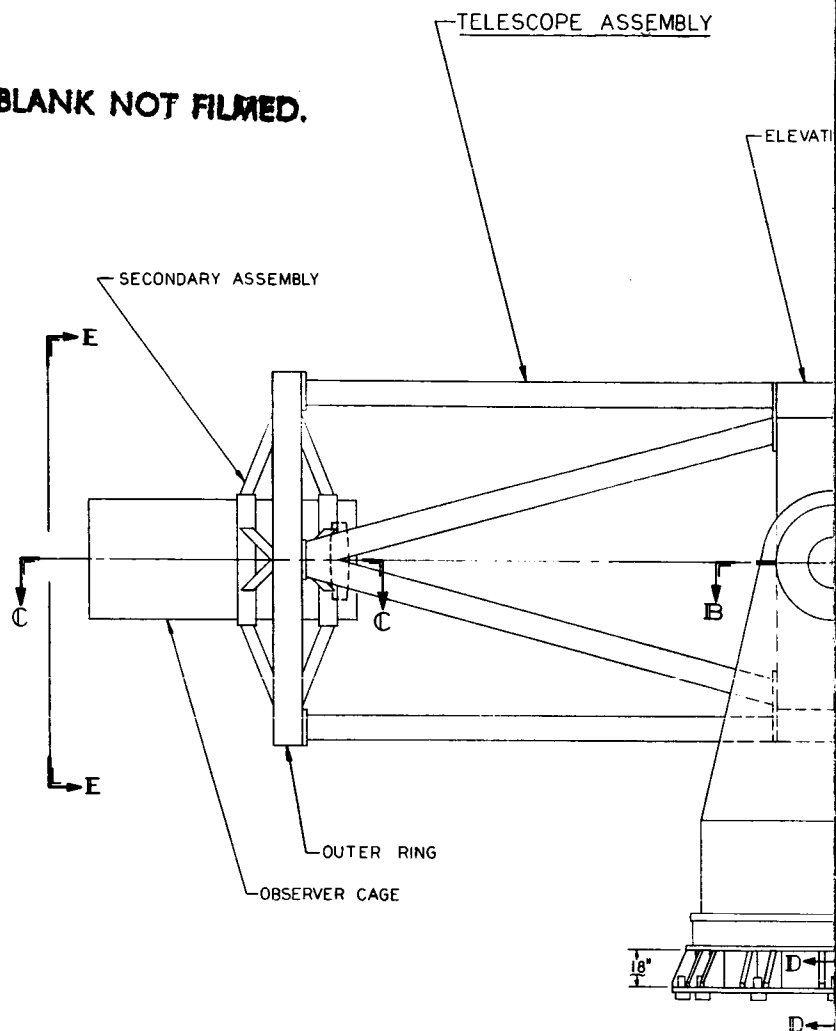
The elevation axis is carried on ball bearings of 28-inch bore diameter. Consideration was given to the use of hydrostatic bearings for this axis but ball bearings were chosen because of their simplicity and, in this size, the ability to carry the load of the telescope with sufficiently low friction torque.

Both axes are driven by direct coupled dc torquers to eliminate all effects of tooth noise and runout associated with gearing. The telescope is not capable of tracking precisely through zenith because of the infinite accelerations required with the alt-azimuth mount, but, on a conservative basis, it is capable of tracking a spacecraft that passes within 5 arc-minutes of the zenith. Since the probability of a spacecraft passing this close to zenith is quite remote, and loss-of-target in the worst-case would last less than one minute, the "blind spot" at zenith is considered to be a minor drawback.

The telescope has provision for prime, Cassegrain, and Coude focal positions when used for astronomical work. The Cassegrain focus is used for communication. A flip secondary is illustrated to change from Cassegrain to Coude focus. This mirror can be folded up when prime focus work is required. The Cassegrain focus can be used either with or without a folding mirror at the end of the elevation trunnion for astronomical work. A detachable folding mirror and mount are positioned on the fork upright at one end of the elevation axis when use of the Coude focus is required.

A digital computer control can be used to perform the computations associated with star tracking and acquisition. The computer should have available to it position and velocity parameters of the spacecraft, the site latitude and longitude, the sidereal time, and the atmospheric pressure and temperature. The computer can then solve for the proper azimuth angle, azimuth velocity, elevation angle, elevation velocity, and point-ahead angle. It is assumed that a special-purpose computer is available at the site. The availability of such a computer will eliminate the time lag inherent in serialization and transmission of data to a remote central computer facility. The presence of such a computer will also be helpful for data reduction.

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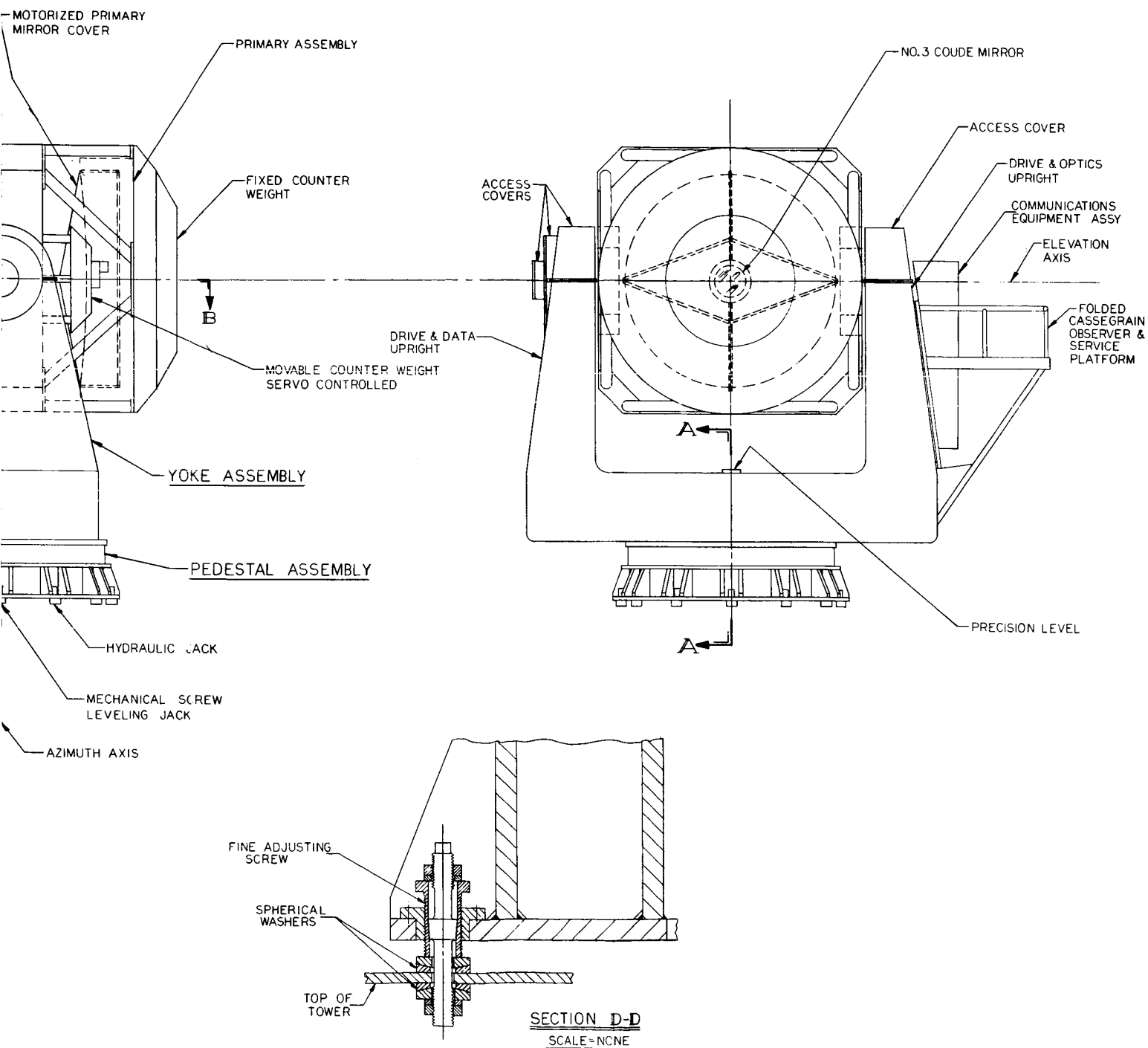


Figure 226. 120-Inch Aperture Azimuth-Elevation Communications Receiver

Both the azimuth and elevation axes of the pedestal have 21-bit digital shaft angle encoders, with the output of those encoders fed directly to the digital computer.

A dc tachometer is used to sense the shaft angular velocity of each axis. The output of the tachometer is used for servo stabilization. An analog-to-digital converter is used to transform the tachometer output into a form suitable for digital computation.

For its communication function the telescope makes use of an argon laser to provide a cooperative beacon for tracking by the spacecraft, a CO₂ laser as a local oscillator when used at 10.6 microns, a servoed fine tracking mirror to take out average wave front tilt and high frequency disturbances, and associated I.R. and visible trackers. The entire communication optics group are located in as close proximity to each other as possible, on a kinematically mounted optical bench or platform fabricated of a thermally stable material such as Invar. The close arrangement of components on the bench minimizes boresight errors that might occur as a result of thermal variations between the trackers, beacon laser, local oscillator, and detectors.

The diameter of the upgoing beacon is limited to 2 to 10 arc-seconds by the atmospheric seeing. This limitation would change when the data from the space experiments is evaluated.

The entire telescope and mount is placed atop a rigid tower of sufficient height to avoid the severe seeing degradation associated with ground-level turbulence.

The telescope is enclosed in a conventional rotating astronomical dome. The dome is supported by an enclosed structure, which surrounds the rigid tower supporting the instrument and shields it from wind loads and thermal inputs. This structure also provides ample space for auxiliary equipment and laboratories.

Sequence of Operation

Although absolute pointing accuracy is a prime objective for the proposed instrument, it is improbable that the inherent accuracy of the instrument will be sufficient to assure illumination of the spacecraft by the 2 to 10 arc-second diameter argon beacon without some external reference. The following procedure, elaborated upon in Perkin-Elmer Report 8558, utilizes the positions of known stars as reference or calibration points for the instrument:

1. The telescope is commanded to point to, acquire, and closed-loop track a known navigational reference star as close as possible to the known position of the spacecraft.
2. The encoders on the azimuth and elevation axes are interrogated, and the readings employed in conjunction with the known offset angle between reference star and spacecraft to compute encoder settings for the spacecraft coordinates.

3. The telescope is offset to the computed encoder settings and driven open loop at sidereal rate.
4. The upgoing argon beacon is turned on and the spacecraft instructed via the microwave link to initiate a search routine for the argon beacon.
5. When the spacecraft acquires the earth beacon, it turns on its 10.6 micron transmitter (for the CO₂ propagation experiments of the OTES).
6. The ground station acquires the spacecraft signal and commences closed-loop tracking thereof.
7. The spacecraft is instructed via the microwave link to begin data transmission. This transmission may continue until loss-of-signal occurs above the western horizon.

CO₂ Laser Communications System Optics

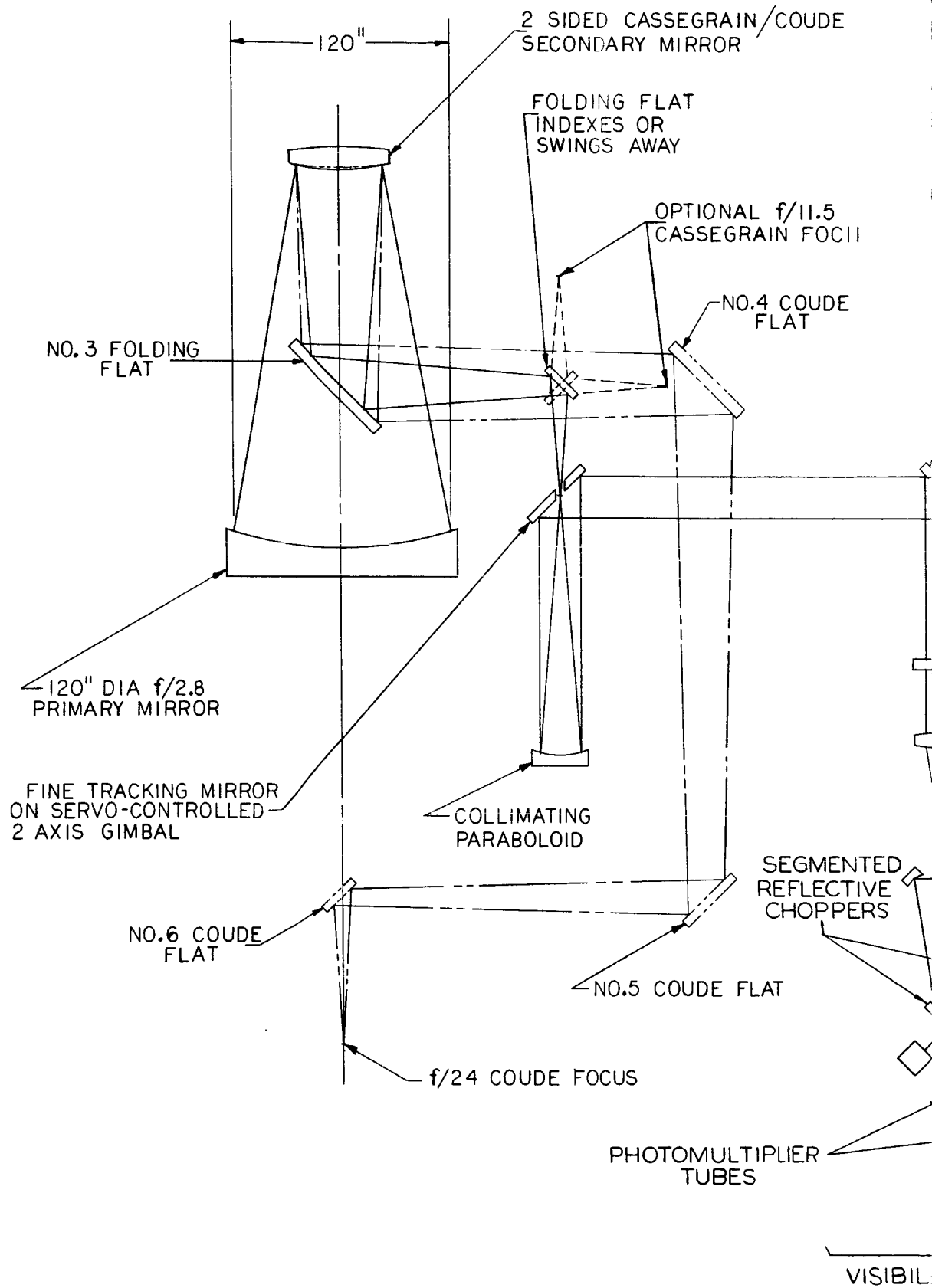
The 10.6 micron transceiver optical system for the OTTOS 120-inch telescope is shown schematically in Figure 227 and as a tentative mechanical configuration in Figure 228.

The basic telescope is the parabolic-hyperbolic Cassegrain design described in Perkin-Elmer Report 8558. A flat mirror, rigidly mounted in the telescope tube, illustrated in Figure 229, folds the downcoming f/11.5 beam of 10.6 micron light out through the elevation axis to a second smaller flat which folds the beam into a plane parallel to the exterior surface of the fork upright. This second folding flat and the rest of the communications optics are mounted on a rigid, dimensionally stable plate which, in turn, is kinematically attached to the fork upright.

The f/11.5 beam converges to a focal point and continues as a diverging f/11.5 beam to a collimating paraboloid whose focal point coincides with that of the Cassegrain telescope. The reflected collimated beam returns toward the original focal plane, where it is intercepted by a third folding flat. This flat has a central hole to permit passage of the f/11.5 beam, and is mounted on a servo-controlled two-axis gimbal, controlled in such a manner that, upon reflection from the flat, the collimated beam is propagated in a fixed direction. This gimballed mirror constitutes the fine guidance element of the system.

The next component in the system is another flat mirror, this one capable of rotating into or out of the beam in a precise manner. When this mirror is in the collimated beam, it redirects the beam through a filter and converging optics to a visible-spectrum star tracker. This tracker enables boresighting of the equipment and calibration of the encoders on stars of known position.

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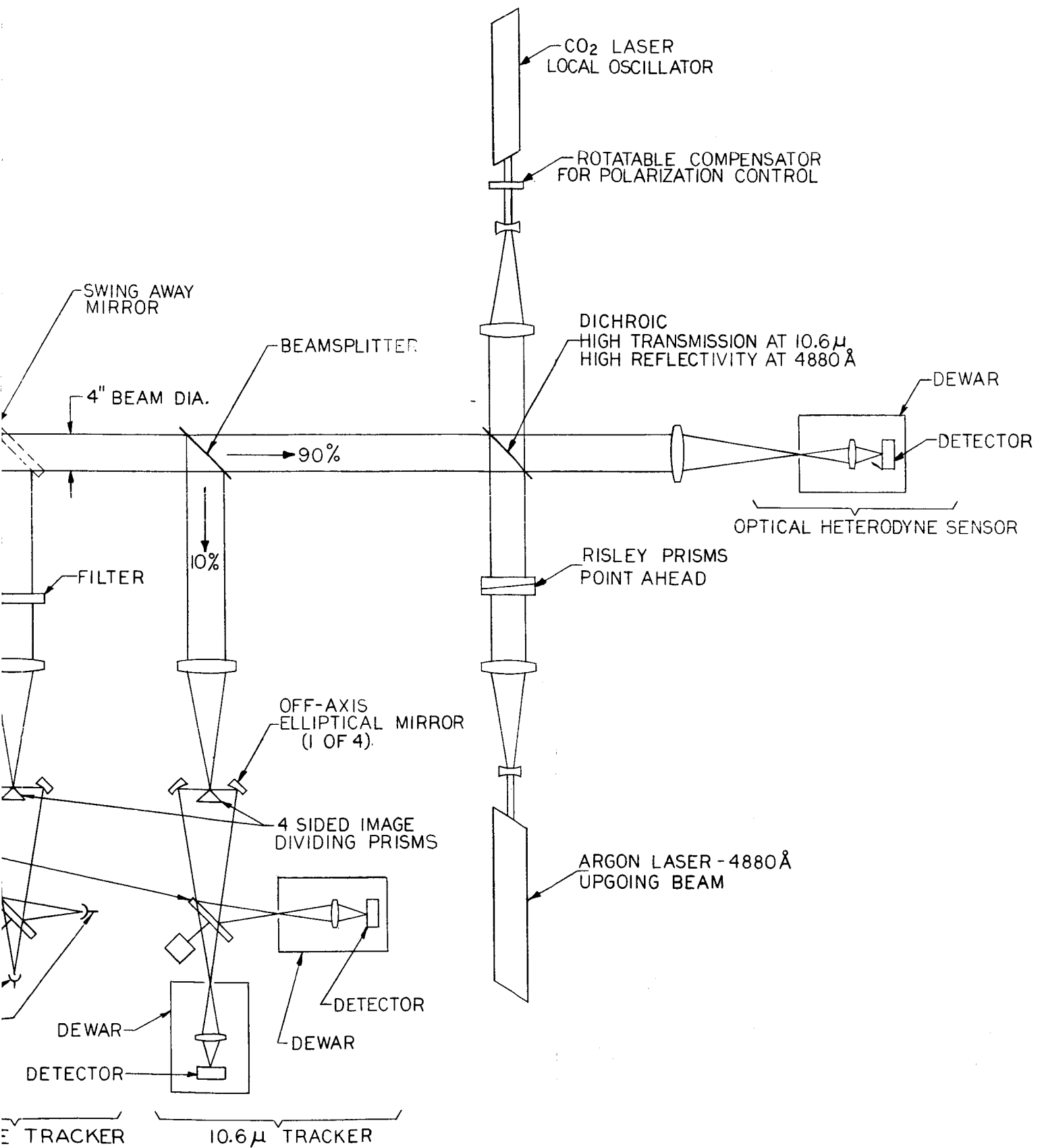


Figure 227. 120-Inch Aperture Communications Receiver
Optical Schematic

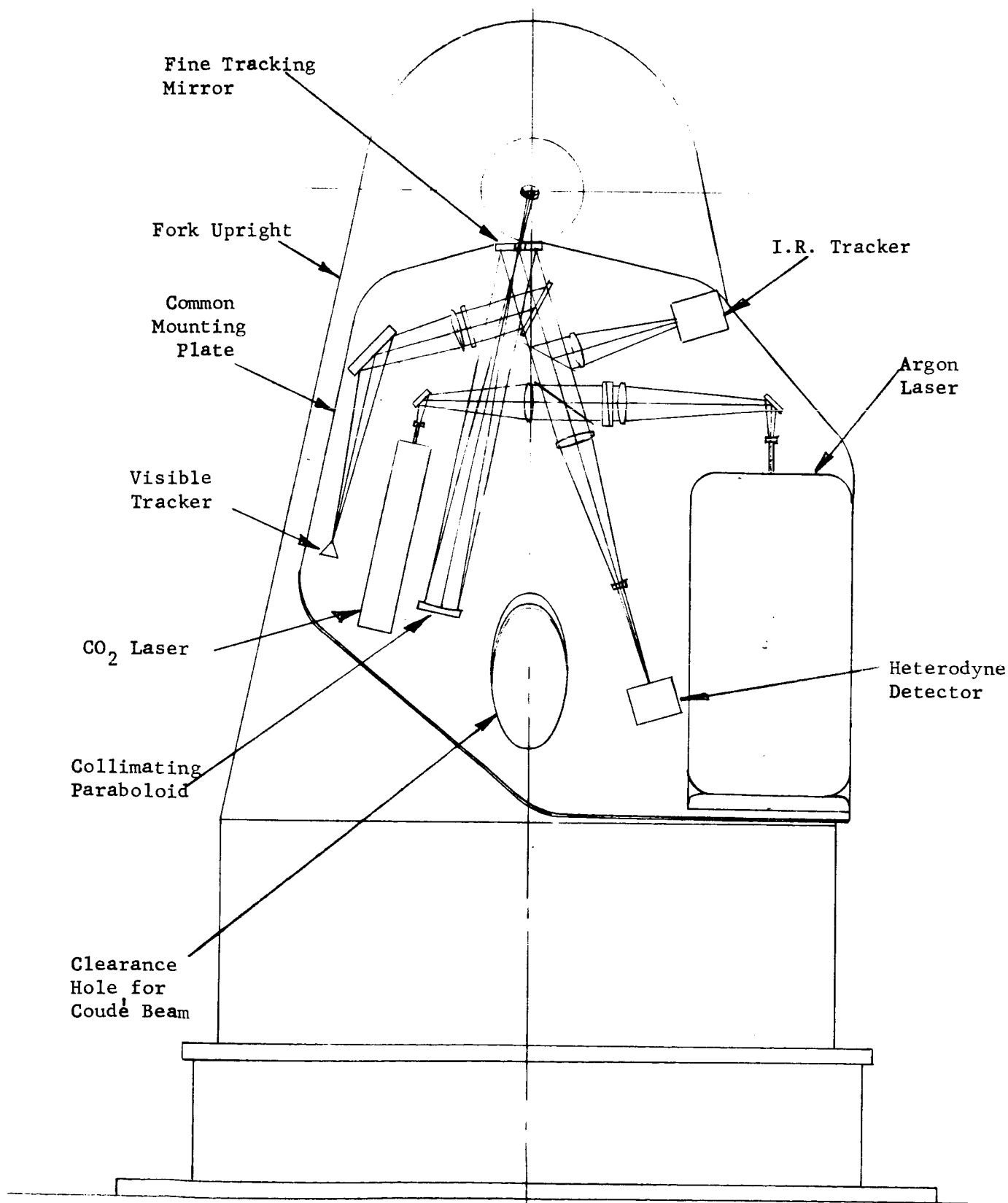
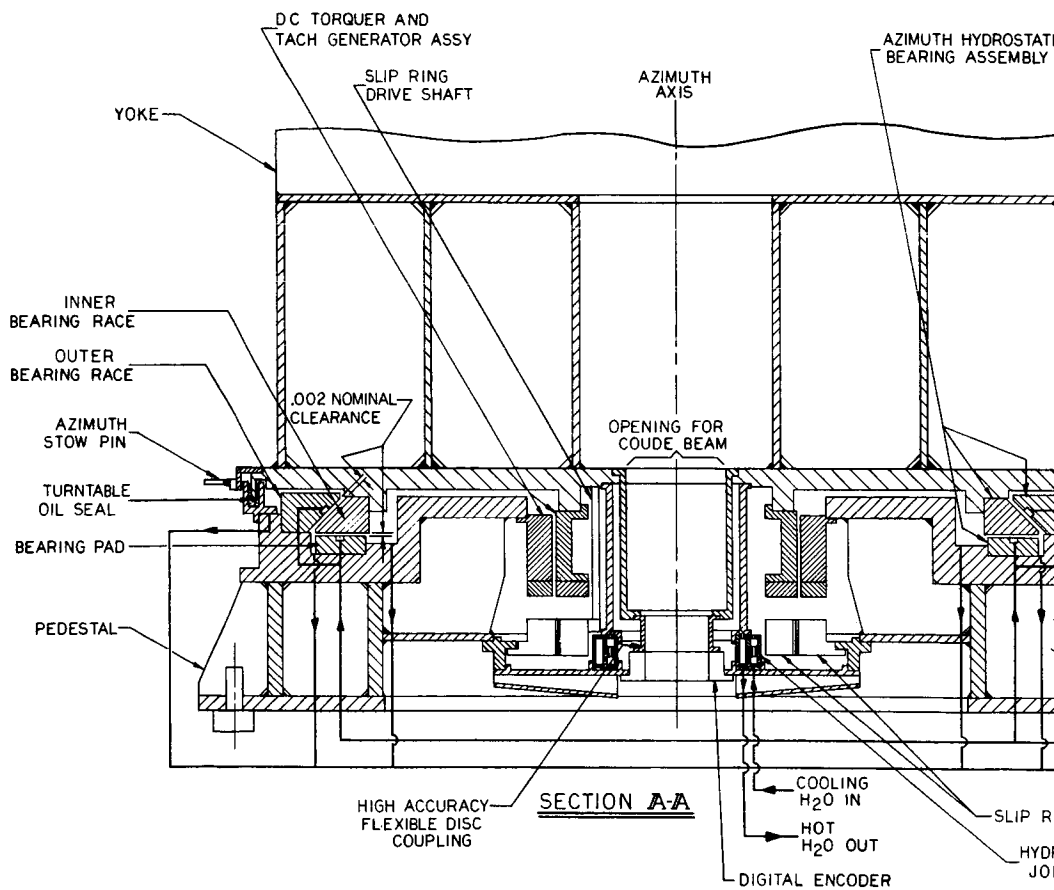
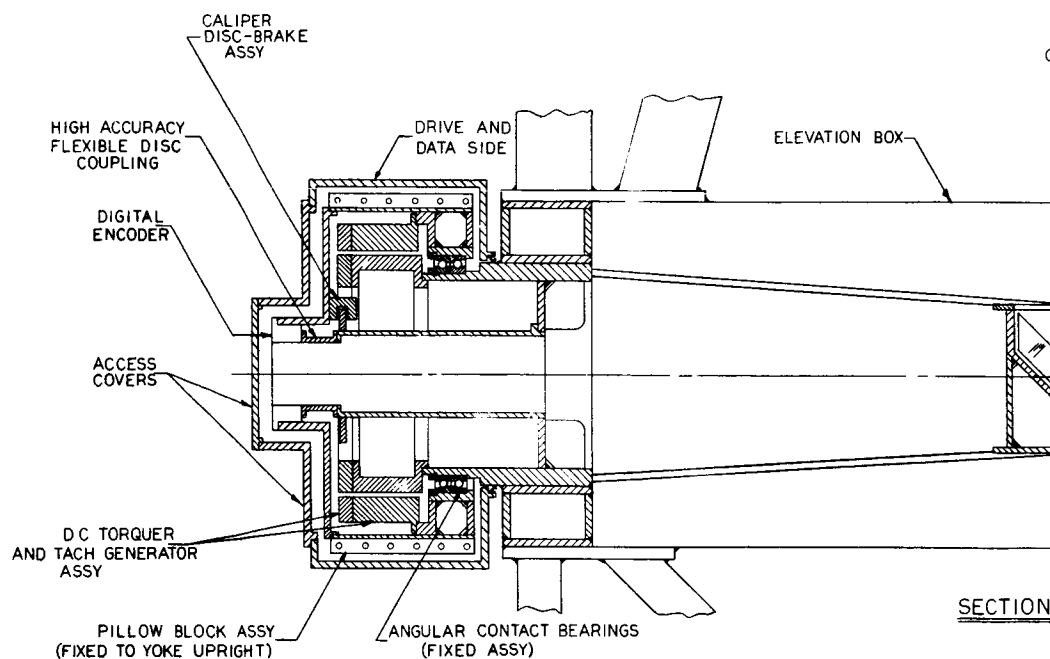


Figure 228. Tentative Mechanical Configuration of Communications Equipment



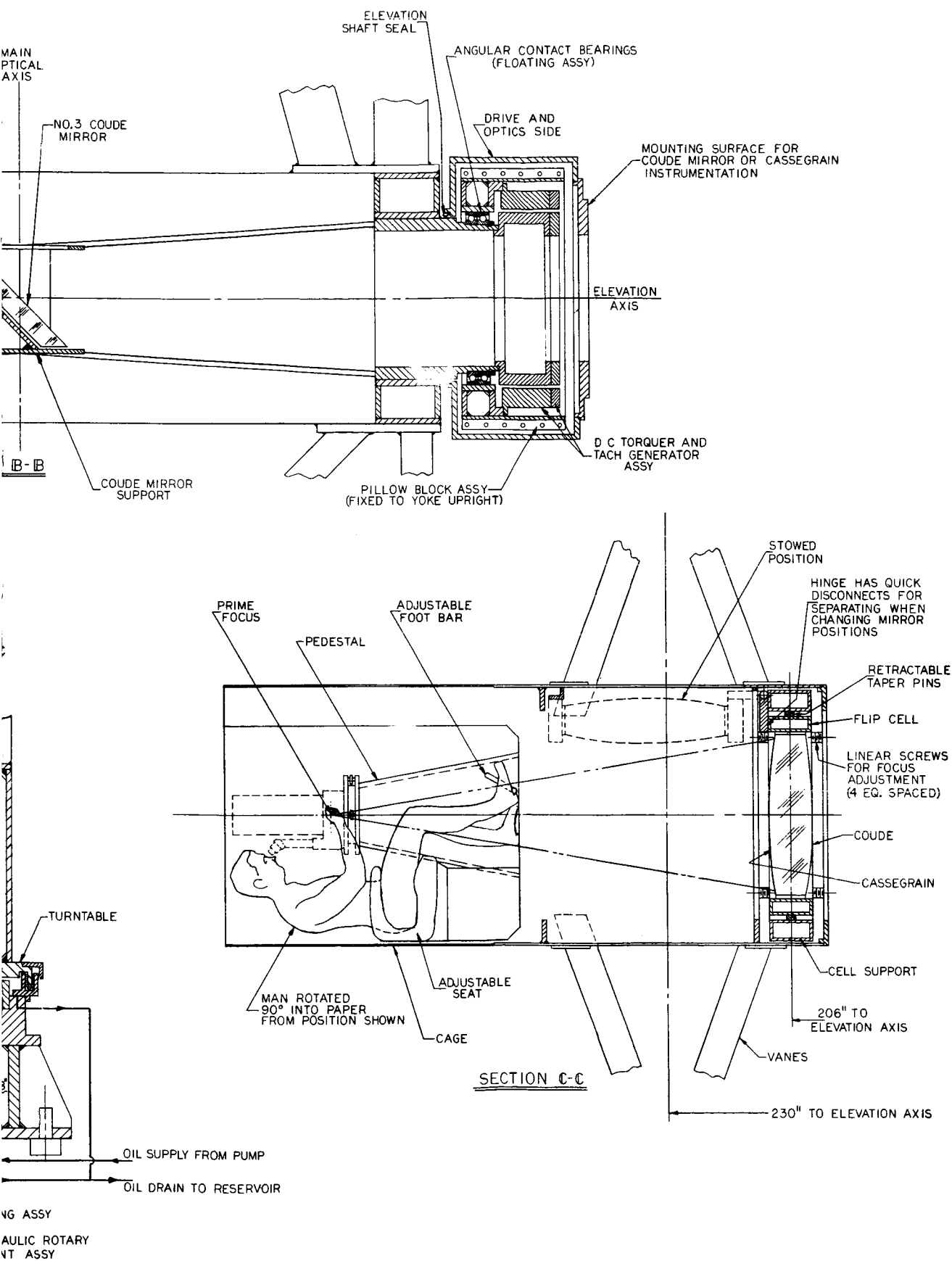


Figure 229. Details of 120-Inch Aperture Azimuth-Elevation Communications Receiver

With the rotatable mirror withdrawn from the collimated beam, the next element in the path is a beamsplitter. The design of the beamsplitter is such that 10 percent of the 10.6 micron energy is diverted through converging optics to an infrared tracker. The remainder of the energy passes through the beamsplitter, which is also designed for maximum transmission of the 4880 angstrom upgoing beacon.

The 10.6 micron beam transmitted by the first beamsplitter then encounters and is transmitted by a second specially coated dichroic beamsplitter/mirror designed for maximum transmission at 10.6 microns and maximum reflectivity at 4880Å. At this point, the beam is combined with a properly polarized local oscillator beam from a CO₂ laser, reflected from the second beamsplitter as shown. (The efficiency of this reflection is low, but available local oscillator power is more than ample.) The combined beam is then focused by converging optics onto the heterodyne detector.

The dichroic beamsplitter also serves to introduce the upgoing 4880Å beam, as illustrated. The argon laser beam passes through a beam expander, through a pair of Risley prisms which permit introduction of the required point-ahead angle, and thence off the beamsplitter and back along the same optical path employed for the downcoming 10.6 micron beam.

OTTOS Cost Study

An engineering estimate of the costs associated with the 120-inch and 24-inch instruments has been prepared. The cost study for the 10-meter "photon bucket" should be prepared when adequate funds are available from NASA.

Table 13 summarizes the estimated first-unit costs of the 120-inch installation, while Table 14 outlines some of the pertinent details. As indicated below, the costs for a number of items associated with the building, the site, and auxiliary installations have not been included. These costs are highly dependent on specific site characteristics and geographic location for the OTTOS. The costs in this section, OTTOS, are not included in the Resources Plans of Volume II.

The estimated cost for the first installation of the 120-inch telescope is \$4 million. Of this amount, it is estimated that \$1.2 million represents non-repetitive engineering and design costs. The estimated cost of additional similar installations around the world is thus \$2.8 million. The 24-inch telescope costs are estimated at \$600,000.

It is estimated that a minimum of three years would be required to complete an installation of this type. This estimate must be qualified, however, with the observation that research and development effort is required in several areas before a full-scale program can be realistically initiated. The major items in this category are:

1. Atmospheric coherence diameter studies at 10.6 microns.
2. A suitable high-power argon laser for the up-going beam which is used for spacecraft guidance.
3. A stable, tunable CO₂ laser for the local oscillator.
4. The conduct of flight experiments at 6328Å 5300 Å and 10.6 microns with the LCSE and using the 24-inch telescope.

TABLE 13

120-INCH TELESCOPE COST SUMMARY

		(\$000's)
1.0	Telescope Pedestal	371.5
2.0	Yoke	304.5
3.0	Telescope Structure	278.5
4.0	Optics	1,315.5
5.0	Transceiver	1,054.5
6.0	Auxiliary Equipment	685.0
	Grand Total	4,009.5

TABLE 14
120-INCH TELESCOPE COST DETAILS

		(000's)		
		<u>Engineering</u>	<u>Manufacturing</u>	<u>Total</u>
1.0	<u>TELESCOPE PEDESTAL</u>			
1.1	Concrete with Base Ring	5.0	1.0	
1.2	Lower Bearing Structure	30.0	25.0	
1.3	Thrust Bearing Race Assembly	12.5	10.0	
1.4	Leveling Mechanism	15.0	12.0	
1.5	Electrical Junction Terminals	7.5	5.0	
1.6	Slip Ring Stack	5.0	20.0	
1.7	Azimuth Read-out Encoders	5.0	45.0	
1.8	Hydrostatic Bearing Subsystem	45.0	30.0	
1.9	Azimuth Brakes	15.0	3.0	
1.10	Local Operator Control	15.0	5.0	
1.11	Azimuth Servo System	12.5	40.0	
1.12	Assembly	--	<u>8.0</u>	
	Subtotal	167.5	204.0	<u>371.5</u>
2.0	<u>YOKE</u>			
2.1	Yoke Weldment	40.0	60.0	
2.2	Left-hand Bearing	12.5	12.0	
2.3	Right-hand Bearing	12.5	10.0	
2.4	Observer Service Platform	12.5	4.0	
2.5	Electrical Junction Terminals	7.5	5.0	
2.6	Twist Cable	2.5	3.0	
2.7	Elevation Readout Encoders	2.5	25.0	
2.8	Elevation Servo System	12.5	30.0	
2.9	Elevation Brakes	15.0	3.0	
2.10	Assembly	--	<u>35.0</u>	
	Subtotal	117.5	187.0	<u>304.5</u>

TABLE 14 (Continued)

		(000's)		
		<u>Engineering</u>	<u>Manufacturing</u>	<u>Total</u>
3.0	<u>TELESCOPE</u>			
3.1	Structural Tube	35.0	40.0	
3.2	Secondary Structure	5.0	7.0	
3.3	Primary Structure	20.0	15.0	
3.4	Counter Weight Servo	2.5	4.0	
3.5	Counter Weight Mechanism	7.5	10.0	
3.6	Mirror Cover Mechanism	15.0	12.0	
3.7	Secondary Focus Servo	7.5	4.0	
3.8	Tube Thermal Control	15.0	10.0	
3.9	Tube Baffling	12.5	10.0	
3.10	Dew Covers and Heaters	12.5	7.0	
3.11	Boresight Telescope	5.0	10.0	
3.12	Assembly	--	<u>12.0</u>	
	Subtotal	137.5	141.0	<u>278.5</u>
4.0	<u>OPTICS</u>			
4.1	Primary	15.0	955.0	
4.2	Secondary	7.5	90.0	
4.3	No. 3 Coude Flat and Cell	5.0	62.5	
4.4	Optical Design	20.0	3.0	
4.5	Primary Cell	17.5	100.0	
4.6	Secondary Cell	<u>10.0</u>	<u>30.0</u>	
	Subtotal	75.0	1,240.5	1,315.5

TABLE 14 (Continued)

		(000's)		
		<u>Engineering</u>	<u>Manufacturing</u>	<u>Total</u>
5.0	<u>TRANSCEIVER</u>			
5.1	2-Axis Tracking Mirror Servo	15.0	10.0	
5.2	No. 4, 5, 6 Coude Flats	10.0	3.0	
5.3	Transceiver Structure and Packaging	50.0	50.0	
5.4	Collimator Parabola	5.0	1.0	
5.5	Swing-Away Mirror	2.5	1.0	
5.6	Beamsplitter	--	1.0	
5.7	Narrow Band Filters 6328Å, 5300Å Spike Pass	--	6.0	
5.8	Dichroic Pass 10.6 Reflect. 4880Å	--	3.0	
5.9	Visible Light Tracker	30.0	15.0	
5.10	10.6 Micron Tracker	45.0	35.0	
5.11	10.6 Micron Cryogenics and Detectors	17.5	15.0	
5.12	200-Watt Argon Laser System	130.0	250.0	
5.13	Risley Prism Servo Assembly	15.0	12.0	
5.14	Stable and Tunable 10.6μ local oscillator Laser with Single Side Band Shifter	37.5	20.0	
5.15	Detector Electronics	37.5	15.0	
5.16	Transmitter Modulator	2.5	10.0	
5.17	Communications Electronics	60.0	40.0	
5.18	Transceiver Assembly	<u>10.0</u>	<u>100.0</u>	
	Subtotal	467.5	587.0	1,054.5

TABLE 14 (Continued)

		(000's)		
		<u>Engineering</u>	<u>Manufacturing</u>	<u>Total</u>
6.0	<u>AUXILIARY EQUIPMENT</u>			
6.1	Pointing Control Station	15.0	20.0	
6.2	Equatorial Altitude Azimuth Converter	2.5	85.0	
6.3	Transmitter Control	5.0	10.0	
6.4	10.6 μ Control Station	5.0	10.0	
6.5	Cryogenics Control Station	12.5	10.0	
6.6	Hydraulic and Hydrostatic Control Station and P.S.	40.0	35.0	
6.7	Boresight Tower	15.0	20.0	
6.8	Boresight Tower Optics	5.0	3.0	
6.9	Boresight Tower Laser	--	7.0	
6.10	Spacecraft Station Display	20.0	10.0	
6.11	Spacecraft Status Display	50.0	30.0	
6.12	Telemetry Data Quick-Look Display	<u>75.0</u>	<u>200.0</u>	
	Subtotal	245.0	440.0	<u>685.0</u>
	120-Inch Telescope Total	<u>1,210.0</u>	<u>2,799.5</u>	<u>4,009.5</u>

THE 24-INCH TELESCOPE COST SUMMARY

(\$000's)

1.0	Equatorial Mount Telescope with Optics and with Coude Focus	\$230.0 .
2.0	Laser Transceiver	220.0
3.0	1-watt Argon Laser	30.
4.0	Foundation, Tower and Building	90.
5.0	Oversize Dome (20-1/2 feet diameter)	<u>8.</u>
	Total	\$578.

The following items have not been included in the OTTOS estimate:

- Land Costs
- Auxiliary Power Station
- Dome for the 120-Inch Telescope
- Building and Building Services
- Water Cooling System
- Air Conditioning Plant
- Transportation Costs to Site
- OTES Displays
- Spare Lasers
- Erection Costs of Site
- Local Digital Computer
- Data Tape Recording
- Site Development
- Roads
- Living Quarters

Heterodyning at the Ground Station at CO₂ Wavelengths

The development of efficient high power CO₂ lasers at 10.6 μ raises the possibility of using heterodyne techniques for wideband information transmission over very large distances ($> 10^8$ miles).

At this wavelength, the alignment between signal and local oscillator wavefronts are relaxed by a factor of 20 over operation at visible wavelengths, furthermore, the lateral coherence diameter (~ 4 meters) allows much larger coherent receiver diameters.

The fundamental problem associated with such a heterodyne scheme is that the system must track both the angle of arrival fluctuations and the frequency of the incoming signal. Spatial tracking at visible frequencies (6328Å) has been demonstrated by Read et al* using the method suggested by Fried** of utilizing a focused signal beam mixed with a plane local oscillator beam. Although this transfers the problem of angular alignment to one of positional alignment of a focused spot on a small aperture at the detector surface, this can be implemented easily by using an image dissector to provide a virtual aperture at the detector surface. The aperture position is controlled electronically and is arranged to track the incoming signal position. Unfortunately, similar image dissectors are not available at 10.6 microns.

Targ and Bush*** have demonstrated a frequency tracking heterodyne system which is capable of acquiring and tracking an incoming microwave modulated signal. The incoming signal has no alignment fluctuations and the system is operated with 6328Å light.

The practical implementation of a heterodyne system detecting light passing down through the atmosphere will require an initial acquisition system which enables the signal to be accurately aligned with the local oscillator wavefront. After spatial alignment, the ground-based local oscillator is scanned in frequency until the incoming frequency is discovered (the incoming laser signal will undergo drifting and time varying Doppler shifts which cannot be accurately predicted.) After a known heterodyne signature is detected the frequency tracking loop will maintain the fidelity of the heterodyne system. It is also possible in principle to coherently track the incoming beam angular fluctuations by wobbling the local oscillator around its optimum position.† This can only be accomplished after the initial acquisition and frequency scanning are successfully completed.

The initial acquisition may be achieved either by tracking a low-power visible wavelength laser beam which is transmitted simultaneously from the spacecraft with the CO₂ beam, or by using an incoherent acquisition system at the ground receiver. If only one detector system is used for the incoherent acquisition and the heterodyne measurements, then the detector impedance will change by many orders of magnitude when the local oscillator is turned on. To avoid the

* Read, W.S., and Turner, R.G.: Tracking Heterodyne Detection, Applied Optics, Vol. 4, No. 12, December 1965.

** Fried, D.L., and Read, W.S.: Optical Heterodyning with Non-Critical Angular Alignment, Proc. IEEE, 51, 1787, 1963.

*** Targ, R., and Bush, W.D.: Applied Optics, Vol. 4, No. 12, December 1965.

† Skolnick, M.I., Introduction to Radar Systems, page 172, McGraw-Hill 1962.

matching problem to the detector amplifier, the receiver system should consist of two channels; one to achieve initial acquisition in an incoherent fashion and the other to provide frequency lock, signal demodulation, and possibly coherent tracking.

Acquisition Considerations

It has been shown theoretically that a large aperture telescope may achieve mechanical pointing precision to an accuracy of ± 5 arc seconds.* Therefore, if the spacecraft CO² laser is boresighted with a ground beacon, the ground receiving telescope must have a field of view of 10 arc seconds to ensure that the incoming beam falls within the telescope field of view. The incoming beam, which is essentially a plane wave, will only fill one resolution element of the telescope, and will have an angular spot size of $1.22 (\lambda/D)$ at the telescope focal plane. Since $(1.22 \lambda/D) \sim 0.8$ arc seconds, then the signal beam could be in approximately one of 120 positions on the focal plane. Several methods of detecting the angular position of the focused spot are possible.

- 1) Use of a four-quadrant beam divider and four detectors.
- 2) Use of an array of detectors whose individual size corresponds to one telescope resolution element.

The second system offers a better signal to background power ratio than the four-quadrant detector for incoherent measurements, but involves many more detectors. When an incoherent acquisition system is used to view light from deep space, together with the sky background radiation, the detector impedance can be shown to limit the frequency response of the wavefront fluctuation tracking system. To illustrate this, a calculation has been made for the case of one detector (of an array) whose size corresponds to one resolution element of a 3-meter telescope.

The background power from the earth's atmosphere incident upon one resolution element of the telescope focal plane is

$$P_b = (1.22)^2 \pi^2 N \lambda^2 \Delta \lambda t_f t_r / 16 \text{ watts} \quad (1)$$

where the parameters are defined in the following table. Using these values, we obtain

$$P_b = 9.5 \times 10^{-13} \text{ watts/res. element} \quad (2)$$

at the detector (assumed to be equal to one resolution element). The received power from the spaceborne telescope can be written as

$$P_r = P_T D_R^2 D_T^2 t_a t_f t_d t_r t_s / (1.22 \lambda R)^2 \text{ watts/res. element} \quad (3)$$

and substituting values from the following table we obtain

$$P_r = 1.4 \times 10^{-11} \text{ watts} \quad (4)$$

* Perkin-Elmer Report No. 8558, Giant Aperture Telescope Study.

PARAMETERS FOR CO₂ LASER LINK TO MARS

Parameter	Symbol	Value	Comment
Transmitter Power	P_T	200 watts	
Receiver Diameter	D_R	3.0 meters	1.
Transmitter Diameter	D_T	1.5 meters	2.
Atmospheric Transmission	t_a	0.36	3.
Receiver Filter Transmission	t_f	0.6	4.
Diffraction Loss (Far Field)	t_d	0.5	
Receiver Transmission	t_r	0.5	
Transmitter Transmission	t_t	0.5	
Scintillation Factor	t_s	1.0	5.
Wavelength	λ	10.6 micron	
Range to Mars	R	2.3×10^{11} meters	
Sky Spectral Radiance	N_λ	$3.4 \text{ watts m}^{-2} \text{ st}^{-1} \text{ u}^{-1}$	6.
Filter Bandwidth	$\Delta\lambda$	0.01 micron	4.
Background power/resolution element	P_b	9.5×10^{-13} watts	
Received power/resolution element	P_y	1.4×10^{-11} watts	
Photon arrival rate	n	7×10^8 photons/sec	
Detectivity	D^*		
Noise equivalent power (optical)	NEP	3.3×10^{-15} watts	
Photon flux at detector	N	depends on $P_\#$ see fig. 230	

1. Chosen on basis of coherence diameter at 10.6 microns.
2. Perkin-Elmer Report No. 8393.
3. 30° elevation angle (Report No. 8393).
4. Spectrum Systems Inc., Waltham, Mass.
5. Chosen on basis of aperture averaging
6. Spectral Irradiance of Sky and Terrain, J.O.S.A. 50, 12.

the corresponding photon arrival rate

$$= 7 \times 10^8 \text{ photons/second} \quad (5)$$

The detector resistance, area, frequency response and system f/number can be obtained from the following considerations:

The detector impedance (R) is related to the photon flux (n) at the detector by the empirical relation

$$R = 10^{22} A/n \text{ ohms/square}$$

which from equation (5) is

$$R = 1.4 \times 10^{13} A \text{ ohms/square} \quad (6)$$

for a detector of size equal to one resolution element of the optical receiver

$$A = (1.22 \lambda f/D)^2$$

where f is the telescope focal length and D its diameter. Therefore, the detector area required to cover one resolution element can be expressed in terms of the telescope f/number (F#), i.e.:

$$A = 1.5 \times 10^{-6} (F\#)^2 \text{ cm}^2 \quad (7)$$

This enables the detector impedance, detector size $\sqrt{A}$, and detector frequency response to be expressed as

$$R = 2.1 \times 10^7 (F\#)^2 \text{ ohms/square} \quad (8)$$

$$\sqrt{A} = 1.22 \times 10^{-3} (F\#) \text{ cms} \quad (9)$$

$$f_o = 1.5 \times 10^3 / (F\#)^2 \text{ Hz} \quad (10)$$

These equations assume a value of detector and lead capacitance of 10pF, which is the average value for present-day detectors. The equations (8), (9), and (10) are shown in Figures 230, 231 and 232 as a function of the optical system f/number and illustrate that, to use reasonable size detectors (0.5 to - 1.0 mm) a large f/number system is required, which results in a large detector impedance and consequently low frequency response. Linear arrays of detectors have been produced with sizes $\sim 1 \text{ mm} \times 3 \text{ mm}$ per cell* and it is possible to combine these arrays into a two-dimensional array by optically dividing the telescope field of view into line segments. If a small f/number system is used, the increased photon flux at the detector provides an upper frequency response of several hundred cycles per second, but this requires detector sizes well below the

* Schisler, R.K., Hughes Aircraft Labs, IRIS

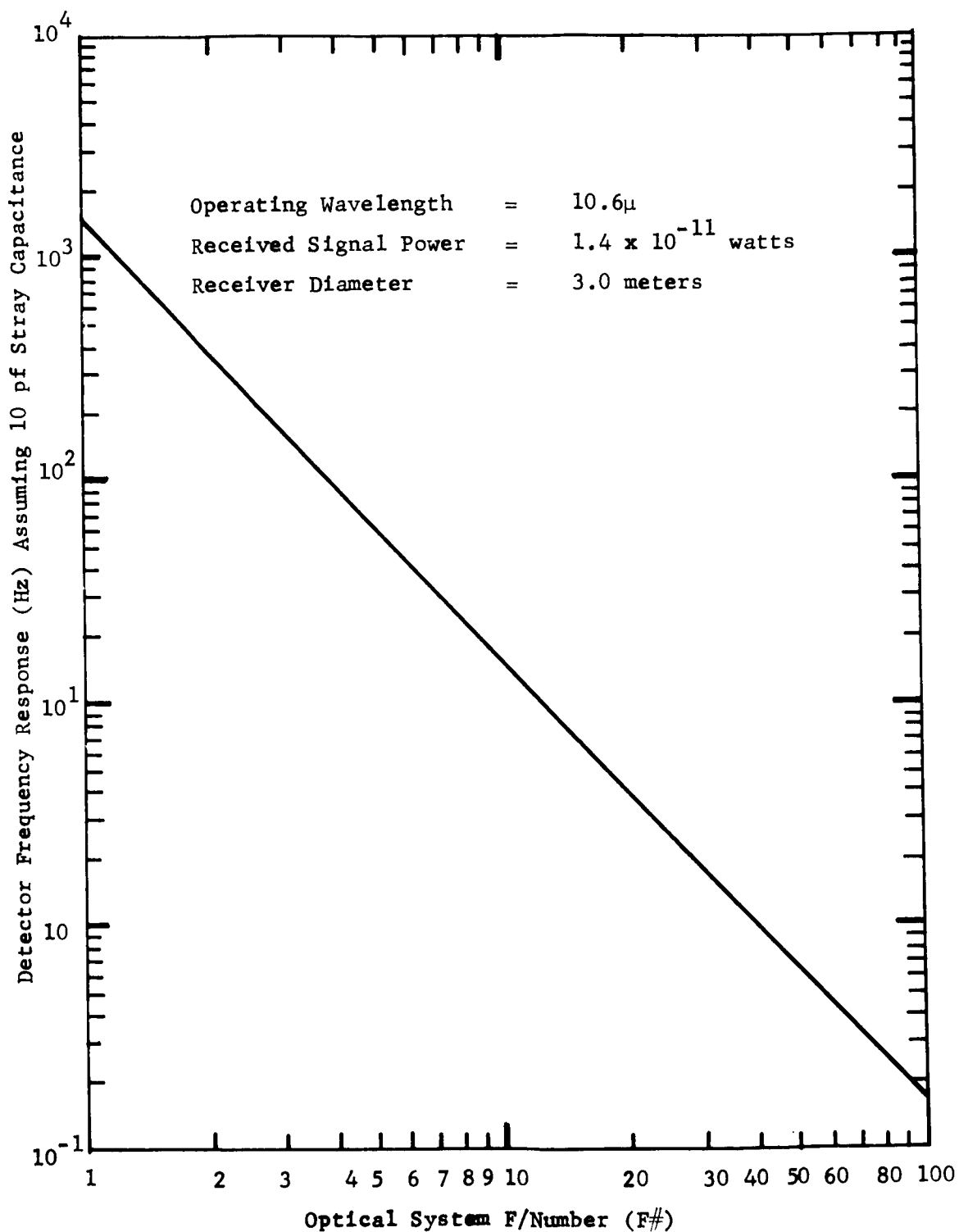


Figure 230. System Frequency Response for a Detector Filling One Resolution Element of the Receiving Telescope

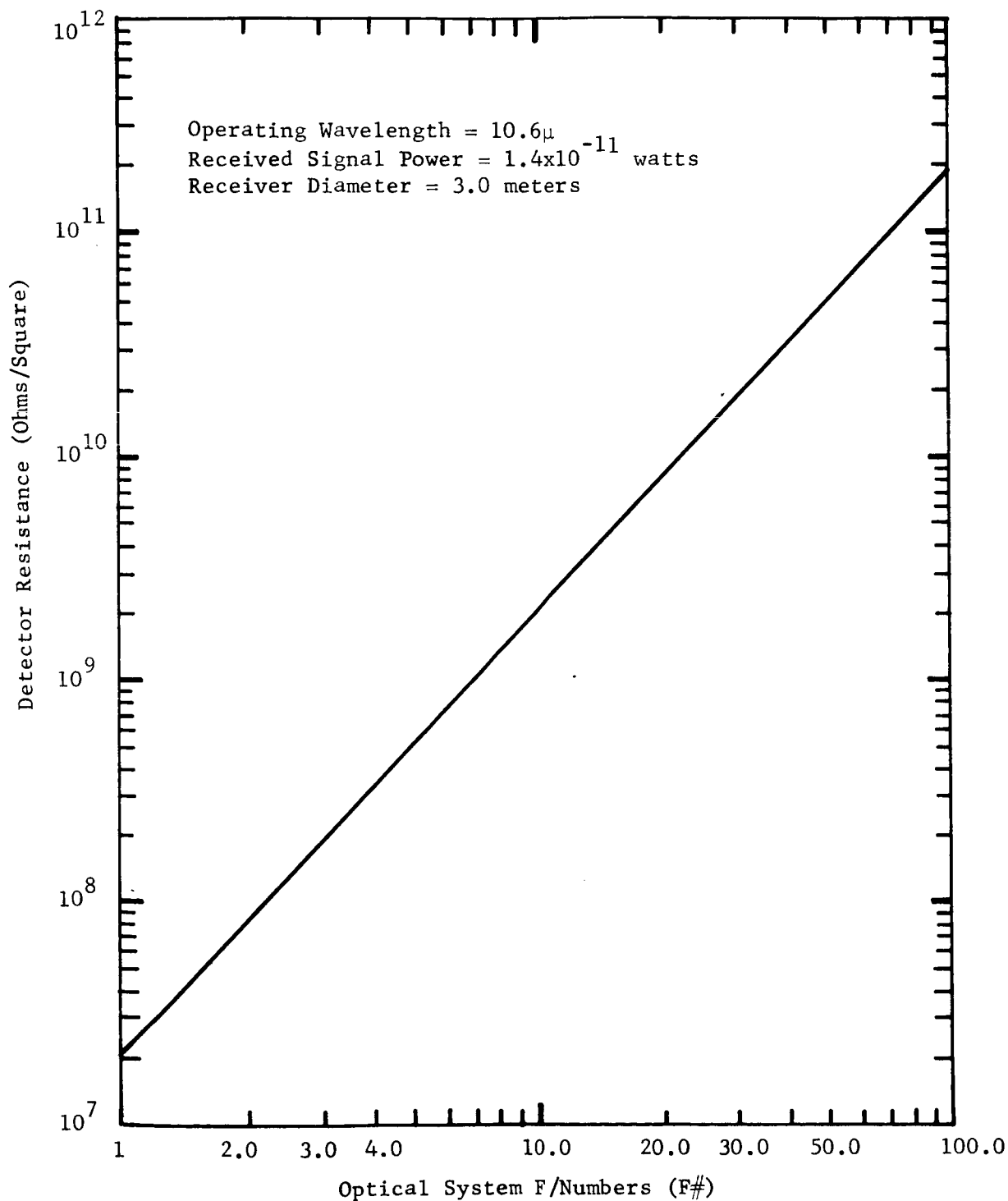


Figure 231. Impédance Level of a Detector Filling One Resolution Element of the Receiving Telescope

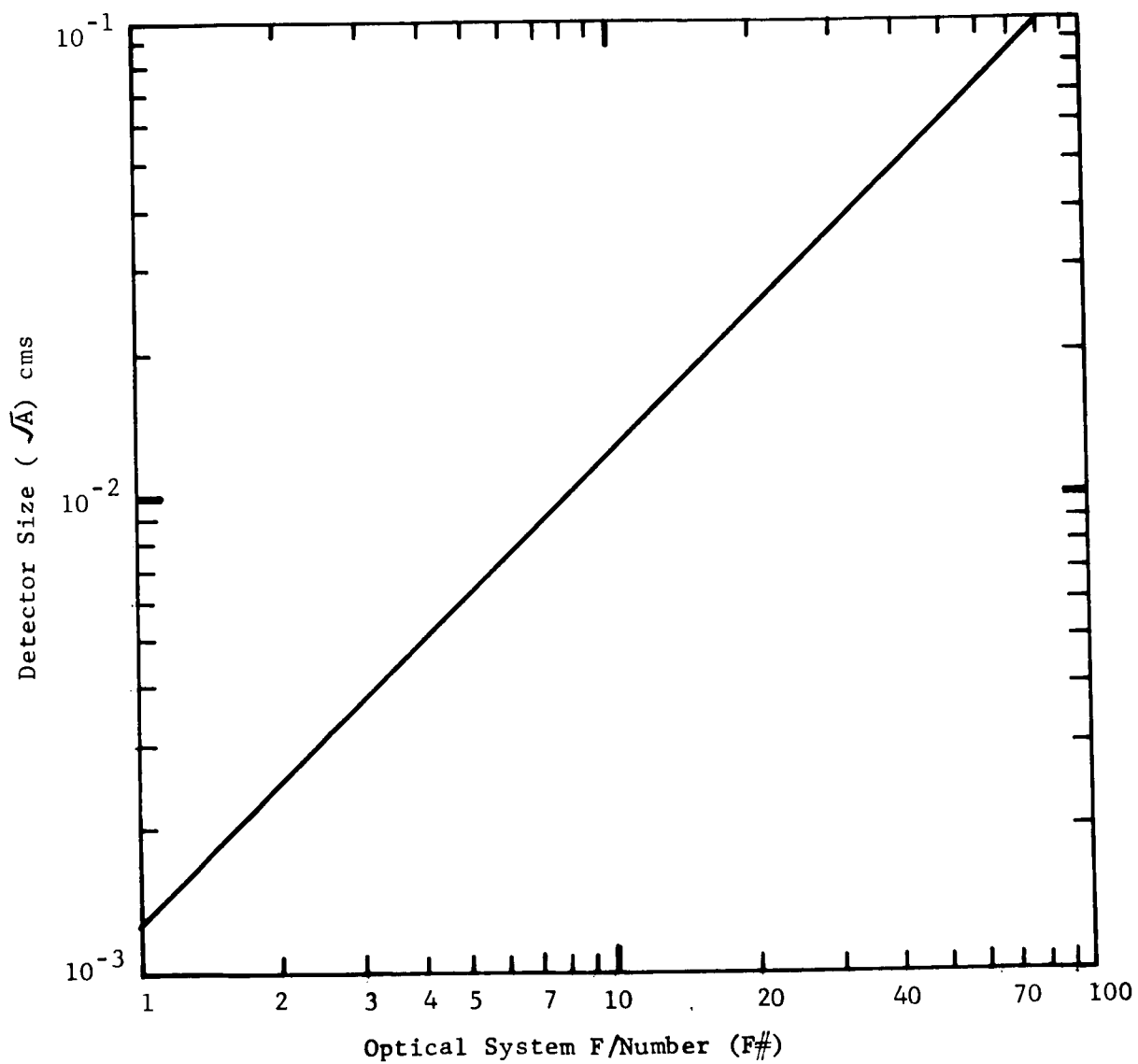


Figure 232. Detectors Size to Fill One Resolution Element of Receiving Telescope

present capabilities of detector technology. The low frequency response of individual detectors may not necessarily be a limiting factor if the frequency spectrum of the angle of arrival fluctuations is well below the detector cut-off frequency. This frequency spectrum for 10.6μ laser light propagating down through the atmosphere has not been measured at the present time. The noise present in IR detectors at low frequencies is $1/f$ noise and this predominates out to several kilocycles before the generator-recombination noise becomes comparable.

For the case of a four-quadrant detector where each detector is approximately 25 resolution elements in area, the same situation applies regarding the detector impedance since the photon arrival rate is increased by 25 times and the detector area is similarly increased. The disadvantage is that the sky background radiation is now approximately twice the signal power. The optical power signal-to-noise ratio for detectors comprising an array assuming background limited operation BLIP can be calculated as follows:

The photon flux incident upon the detector is

$$\begin{aligned} N &= \frac{n}{A} = 7 \times 10^8 / (1.22 \times 10^{-3} F\#)^2 \\ &= 4.6 \times 10^{14} / (F\#)^2 \text{ photons cm}^{-2} \text{ sec}^{-1} \end{aligned} \quad (11)$$

the detectivity can be related to the photon flux for BLIP operation by*

$$D^* = 5 \times 10^{19} / (N)^{1/2} \quad (12)$$

and by definition

$$D^* = \frac{A^{1/2} \Delta f^{1/2}}{NEP} \quad (13)$$

where NEP is the noise equivalent power (optical) of the detector. Substituting from (9), one obtains for a bandwidth (f)

$$NEP_{BLIP} = 4.5 \times 10^{-16} (\Delta f)^{1/2}$$

This parameter is the most general for BLIP-limited point detectors (one resolution element) since it is independent of the optical system parameters. This is not the case for D^*_{BLIP} for point detectors.

Therefore, the signal-to-noise ratio for BLIP operation is

$$\begin{aligned} \left(\frac{S}{N}\right)_{\text{opt pwr}} &= \left(\frac{P_r}{NEP}\right) = \frac{1.4 \times 10^{-11}}{4.5 \times 10^{-16} (\Delta f)^{1/2}} \\ &= 3.1 \times 10^4 (\Delta f)^{-1/2} \end{aligned}$$

* Bode, Op. Cit.

In practice, the BLIP condition is not realized at 10.6 microns, recent developments by Bode have shown the practical NEP values to be approximately one order of magnitude higher than the ideal case, so that in practice one may expect

$$\left(\frac{S}{N}\right)_{\text{opt power}} = 3 \times 10^3 (\Delta f)^{-1/2}$$

This is equivalent to the voltage signal to noise ratio for unit quantum efficiency. This analysis shows that the limiting parameter in an incoherent acquisition system at 10.6 microns is the presently available detector size (0.5 to 1 mm). This large size requires optical systems with large f/numbers and consequently low frequency response, for example a detector of 0.5 mm requires an f/40 system leading to a detector impedance of a 3×10^{10} r and a frequency cutoff of 10 Hz. Any wavefront fluctuations of greater frequency than 10 Hz could not be compensated for by the acquisition system and therefore angular alignment of the incoming beam and the local oscillator beam would not be maintained in an optical heterodyne receiver.