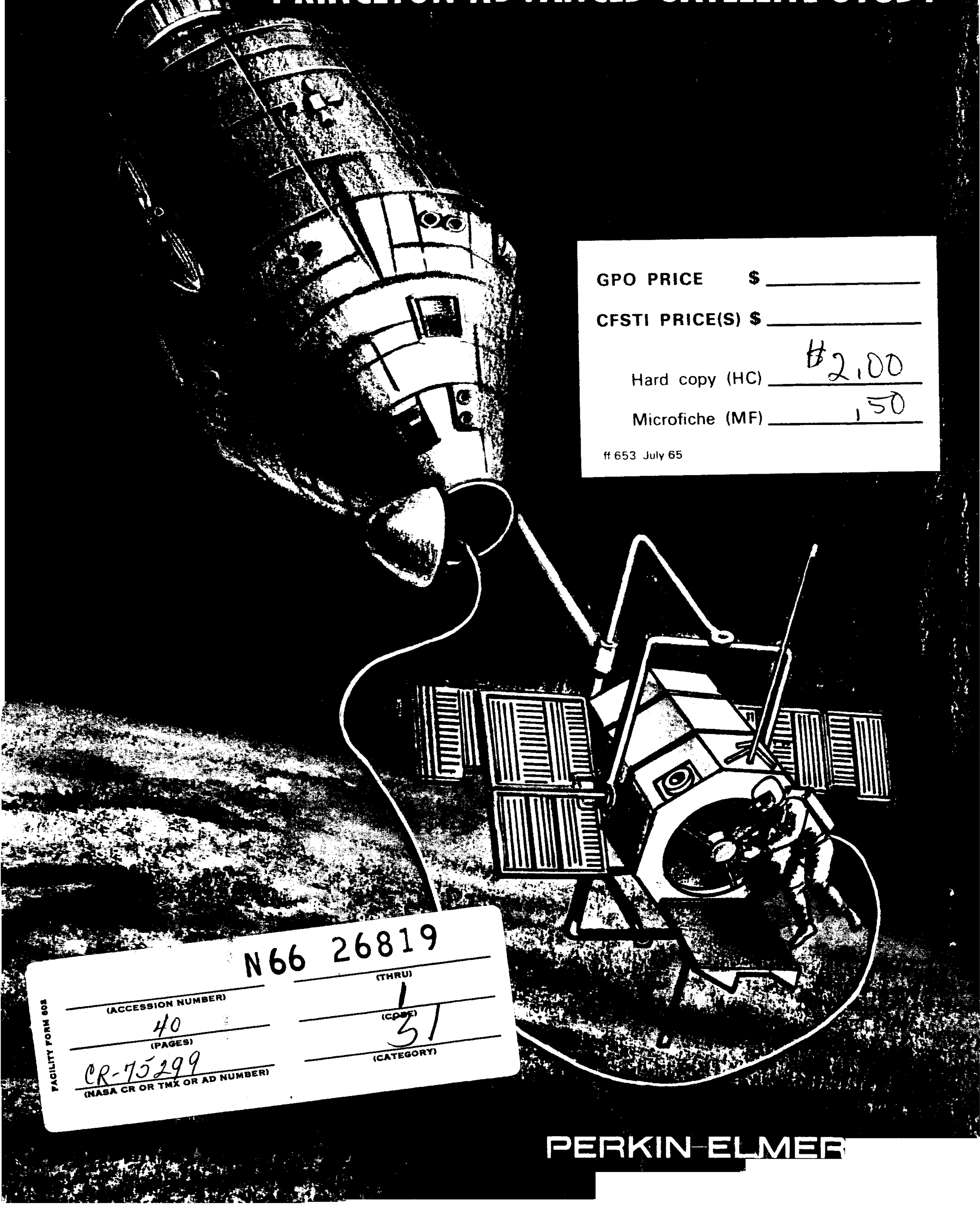
PRINCETON ADVANCED SATELLITE STUDY



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PRINCETON ADVANCED SATELLITE STUDY

FINAL REPORT

SUBCONTRACT NO. 1, NASA GRANT

NGR-31-001-044

8 MARCH 1965 TO 15 MAY 1966

PREPARED FOR:

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PERKIN-ELMER

Report No. 8346(I)

PRINCETON ADVANCED SATELLITE STUDY

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VOLUME I

PRINCETON ADVANCED SATELLITE STUDY

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PRINCETON ADVANCED SATELLITE STUDY

I. Introduction

Perkin-Elmer was awarded a feasibility study program by Princeton University Observatory on March 8, 1965 under Subcontract No. 1, NASA Grant NGR-31-001-044. The purpose of this program was to study general problems of large high resolution optical instruments with an aperture between 30" and 120" diameter in space, and the specific problems associated with a high resolution, UV spectrometer photometry, imaging telescope of 40" diameter aperture on board an OAO. Work through August 1965 resulted in a concept for a telescope magnetically suspended inside an OAO spacecraft which can be used for high resolution (0.1Å) spectral investigations down to approximately 1000Å wavelength, and high resolution star imagery with close to diffraction-limited performance. The progress of the effort through the end of August 1965 was documented in the Semi-annual Progress Report submitted to PUO.

The original scope of the study effort (Phase I) was increased on September 24, 1965 by Phase II which broadened the program to study also the merits accruing from a combined manned vehicle and astronomical package payload, specifically the use of an Apollo Extension System in combination with the OAO spacecraft equipped with the high resolution instrument. With the award of Phase II the Grumman Aircraft Engineering Corporation entered a subcontract with the Perkin-Elmer Corporation to assist in the specific aspects of associating an OAO with a manned space station, an area GAEC investigated on previous occasions.

The results of both phases of this study are included in the final report which is comprised of four volumes as defined below.

- Volume I - Summary.
- Volume II - General Problems Associated with Spaceborne Telescopes.
- Volume III - 40-inch System Description.
- Volume IV - OAO/APEP in Association with AAP.

II. General Problems Associated With Spaceborne Telescopes

The general portion of the study was directed towards exploring the factors most likely to compromise the resolution capability of a large aperture telescope. This is described in Volume II which includes a comparison of the relative susceptibility of various mirror-materials and configurations to elastic strain during test, plastic strain during launch, and thermal strain and long-term dimensional changes during operation. Also considered is the temporal variation in heat flux and the effect of this on the optical system. Finally, the theoretical pointing accuracy determined by stellar magnitude, aperture diameter, and system bandwidth is derived.

The following table and illustrations summarize the more important findings of this general portion of the study.

TABLE 1

PHYSICAL PROPERTIES OF MIRROR MATERIALS

Material	$K/C\alpha\rho$ $\frac{°C\ cm^{-2}}{sec}$	Coefficient of Expansion (α) $°C^{-1}$	E/ρ $\frac{Newton\text{-}cm}{gm}$
Fused Silica	14.50×10^3	0.55×10^{-6}	3.18×10^6
Pyrex — 7740	1.44×10^3	3.20×10^{-6}	2.89×10^6
Aluminum	38.20×10^3	23.90×10^{-6}	2.56×10^6
Beryllium	37.50×10^3	12.40×10^{-6}	15.40×10^6
Invar (36% Ni)	26.30×10^3	1.30×10^{-6}	1.85×10^6
Silicon	230.00×10^3	4.15×10^{-6}	5.56×10^6

Three figures of merit for selection of a mirror material are presented here. These are: the ratio of thermal diffusivity to coefficient of expansion, $K/c\alpha\rho$ (important in the determining temperature distribution and resulting thermal distortions), the coefficient of expansion, α (important in glasses when thermal environment determines temperature distribution), and the ratio of modulus of elasticity to density, E/ρ (important in determining deflections during working and testing in gravity environment).

Best Figure of Merit for Temperature Distribution - Silicon
Best Figure of Merit for Coefficient of Expansion - Fused Silica
Best Figure of Merit for Rigidity - Beryllium

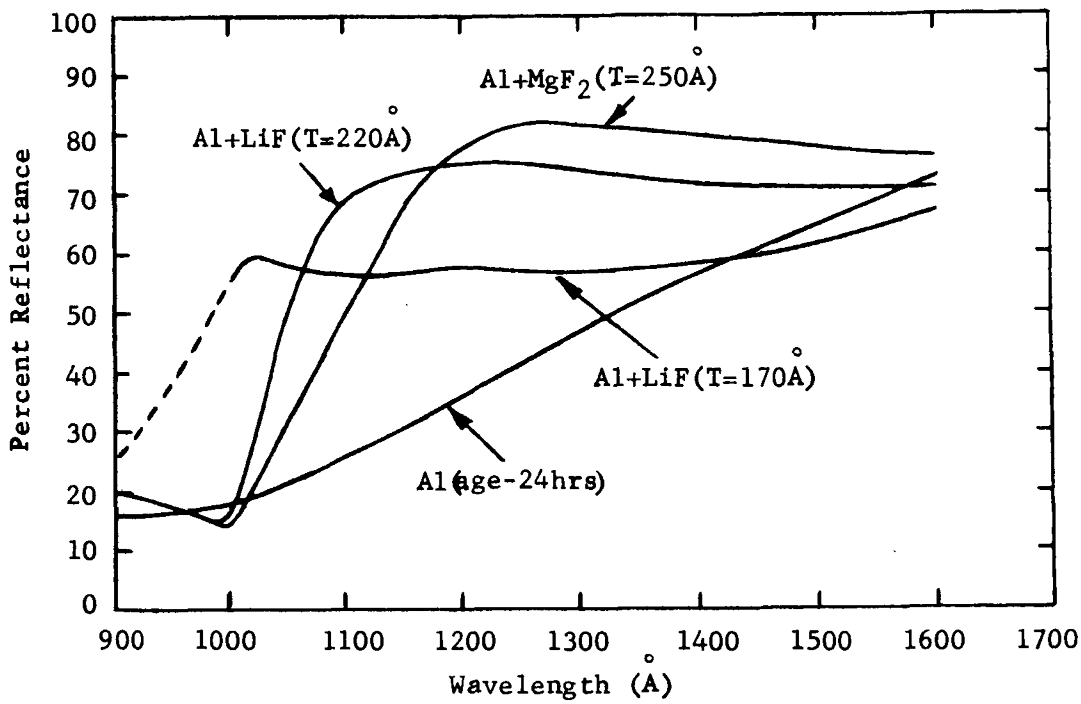

Figure 1. Reflectance of Aluminum Based Reflective Coatings

Below 1600Å, the formation of a thin oxide coating drops the reflectivity of aluminum from above 80% to very low values. LiF and MgF_2 can be used to inhibit oxide formation but also begin to absorb below 1200Å. No good reflective coating is apparent for the 900Å to 1000Å region.

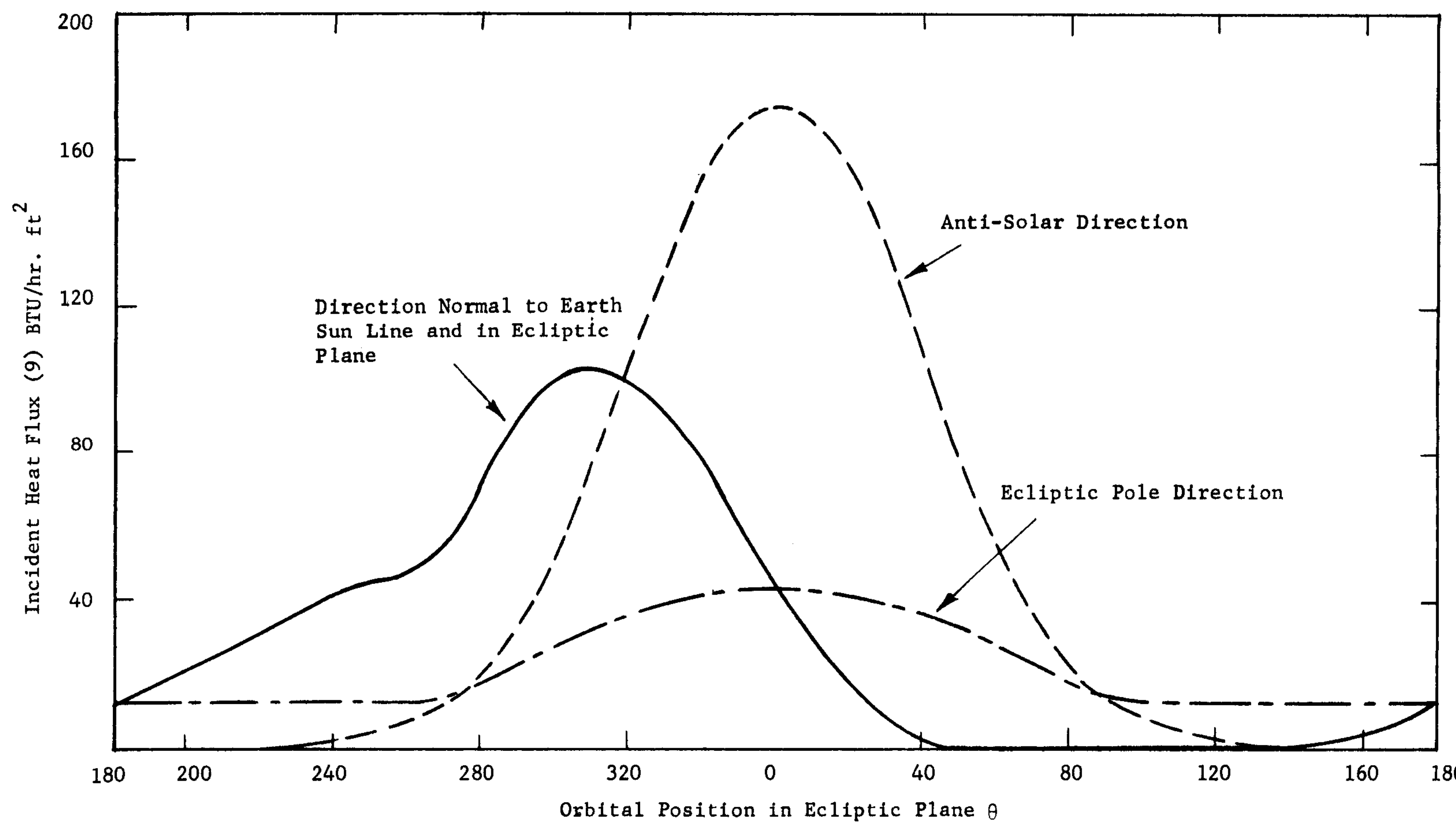

Figure 2. Orbital Variation in Total Heat Flux

The total heat flux due to earth reflected sunlight and direct earth emission is shown for three telescope pointing directions assuming a 600 n.m. orbit in the ecliptic plane. A 20% increase can be expected for the worst case anti-solar direction with a 300 n.m. orbit.

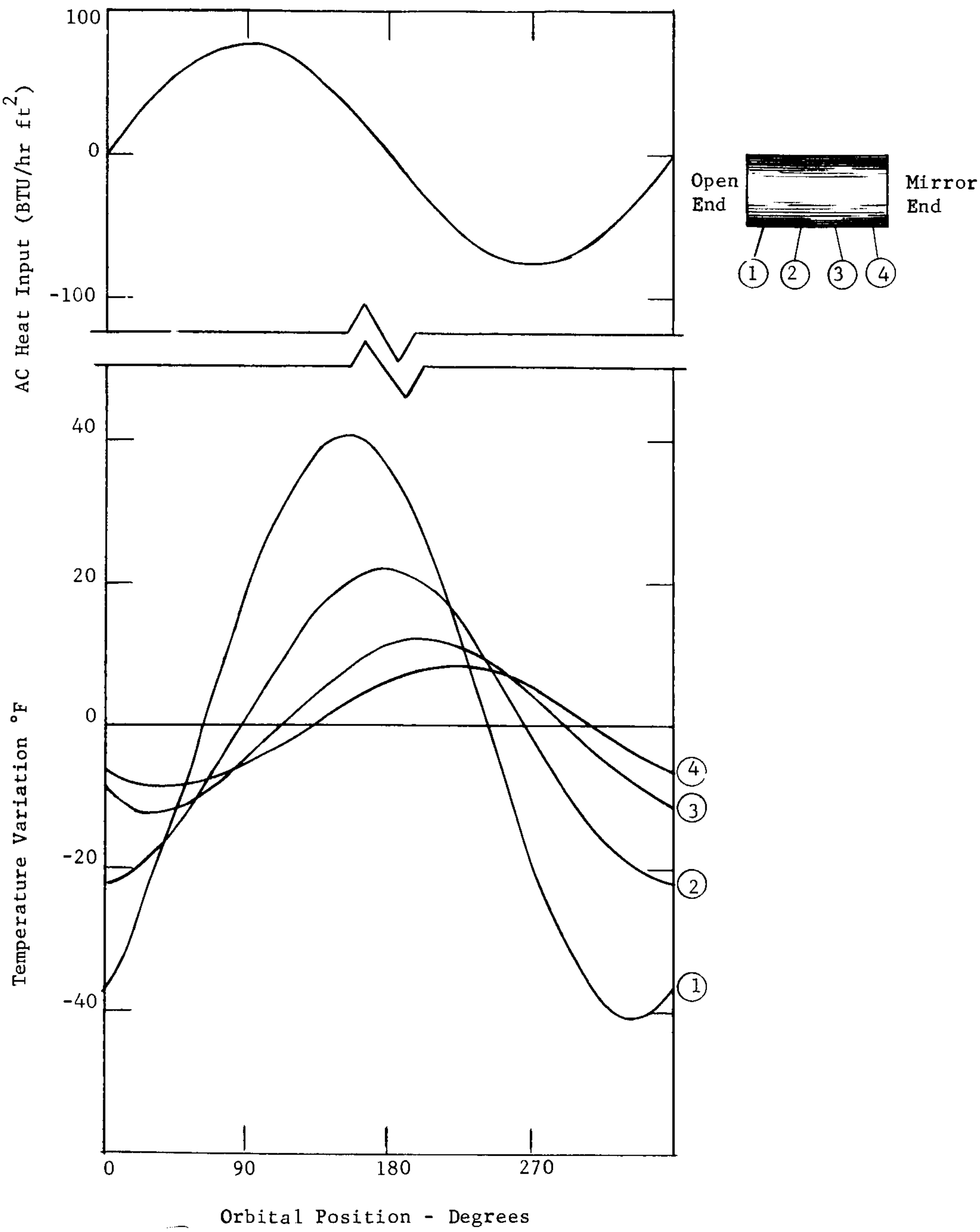

Figure 3. Thermal Behavior of a 40 Pound Aluminum Telescope Tube (40" Dia. x 80" Long)

Numbered curves show the temperature variation for various parts of the telescope tube as a function of position in the ecliptic orbital plane. A sinusoidal, isotropic heat flux is assumed to exist at the open end of the telescope tube. This is shown in the top curve.

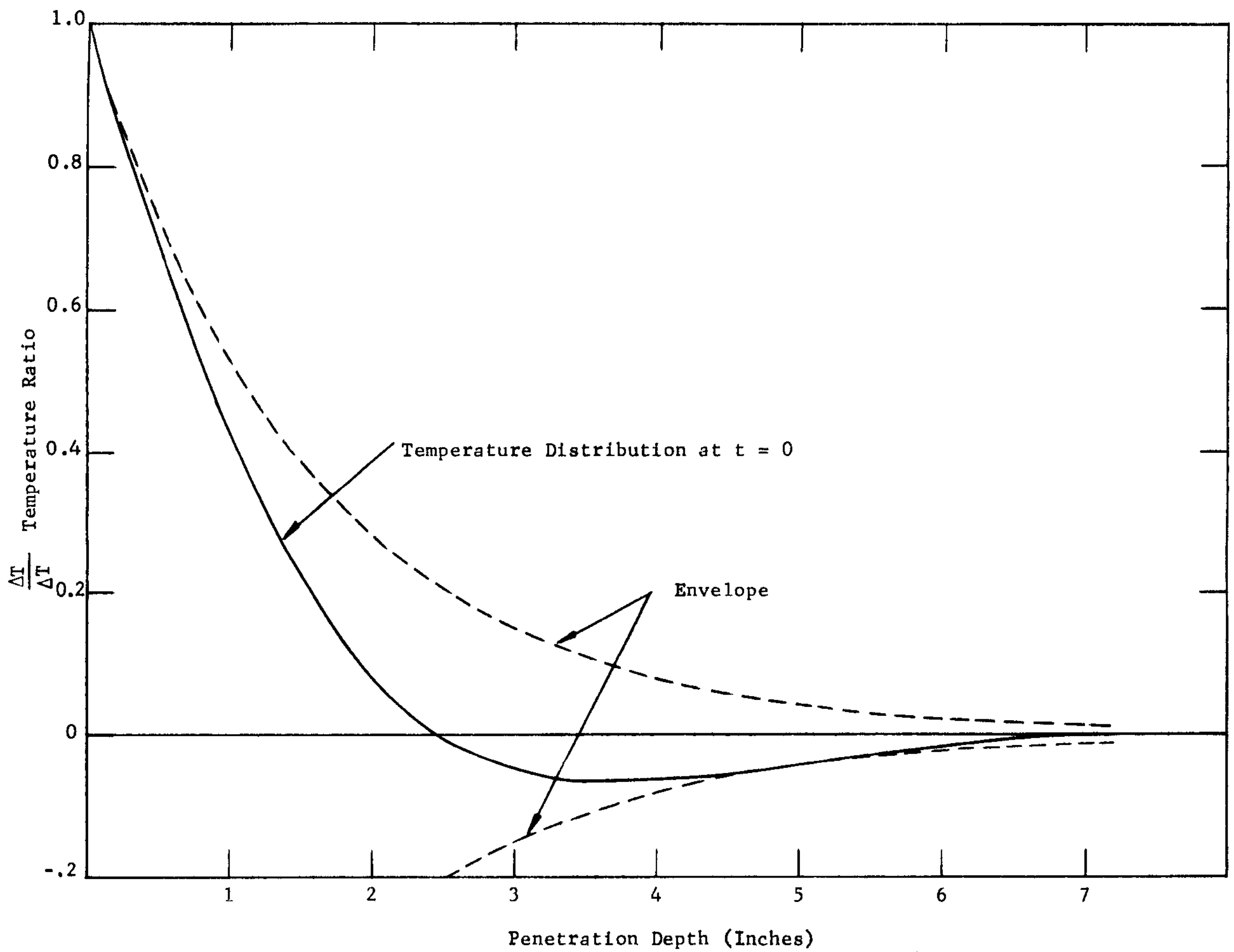

Figure 4. Instantaneous Temperature Distribution in a Semi-Infinite Fused Silica Slab (f = 0.566/Hr.)

The orbital variation in heat flux reaching the front surface of the primary mirror causes a thermal wave to propagate into the mirror material. As it propagates, the wave is attenuated logarithmetically. The figure illustrates that about 90% attenuation of an orbital period wave occurs in the first 3.5 inches of a fused silica mirror.

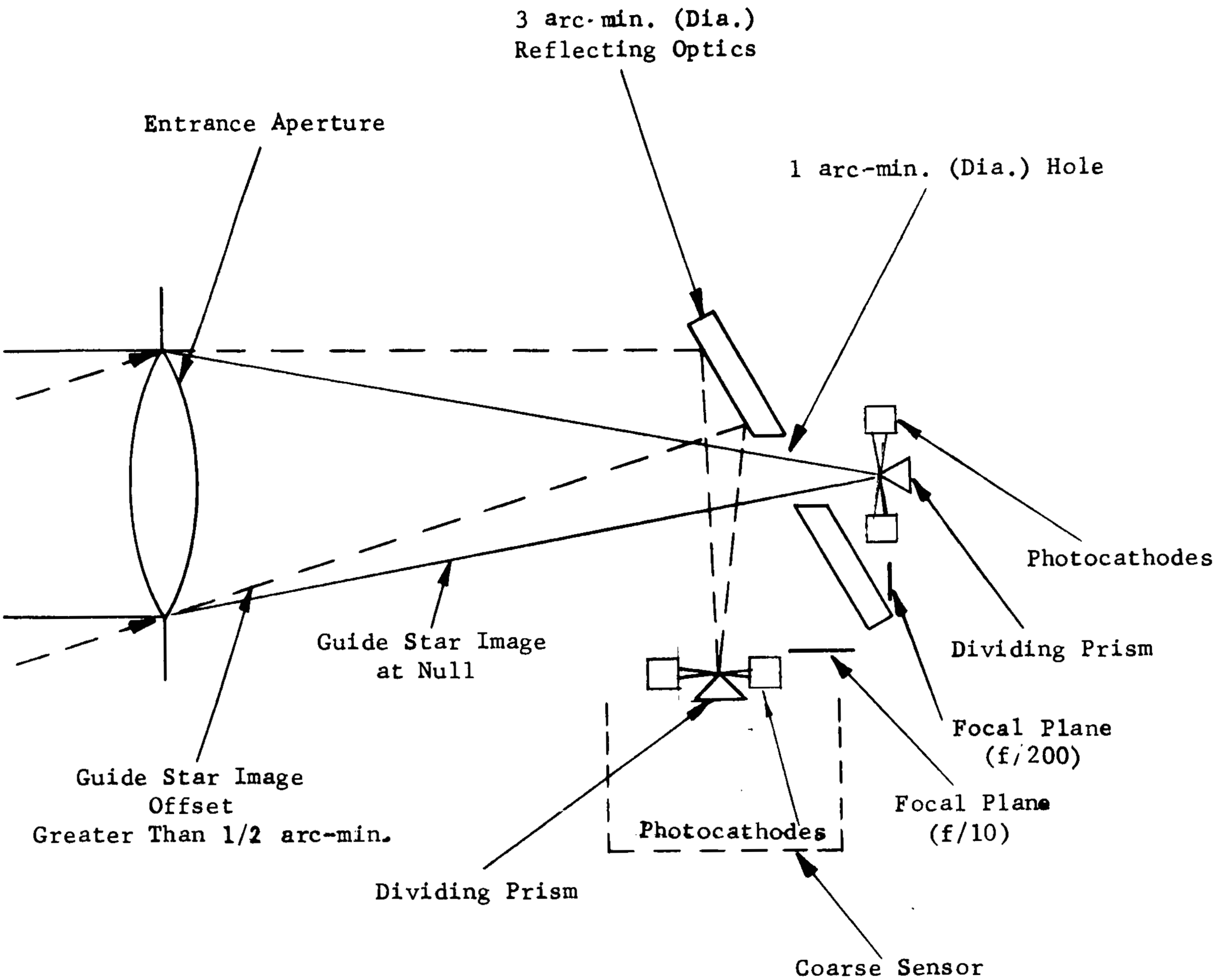

Figure 5. Guide Star Two Field-of-View Optical Sensor Principle (Single Axis-Schematic)

The telescope pointing system error analysis was based on the above optical sensor principle which operates in the following manner. For angular pointing errors greater than ±1/2 arc-minute, the star light is reflected to the coarse sensor dividing prism in the f/10 focal plane. For errors less than ±1/2 arc-minute, the light proceeds directly to the fine sensor prism in the f/200 focal plane.

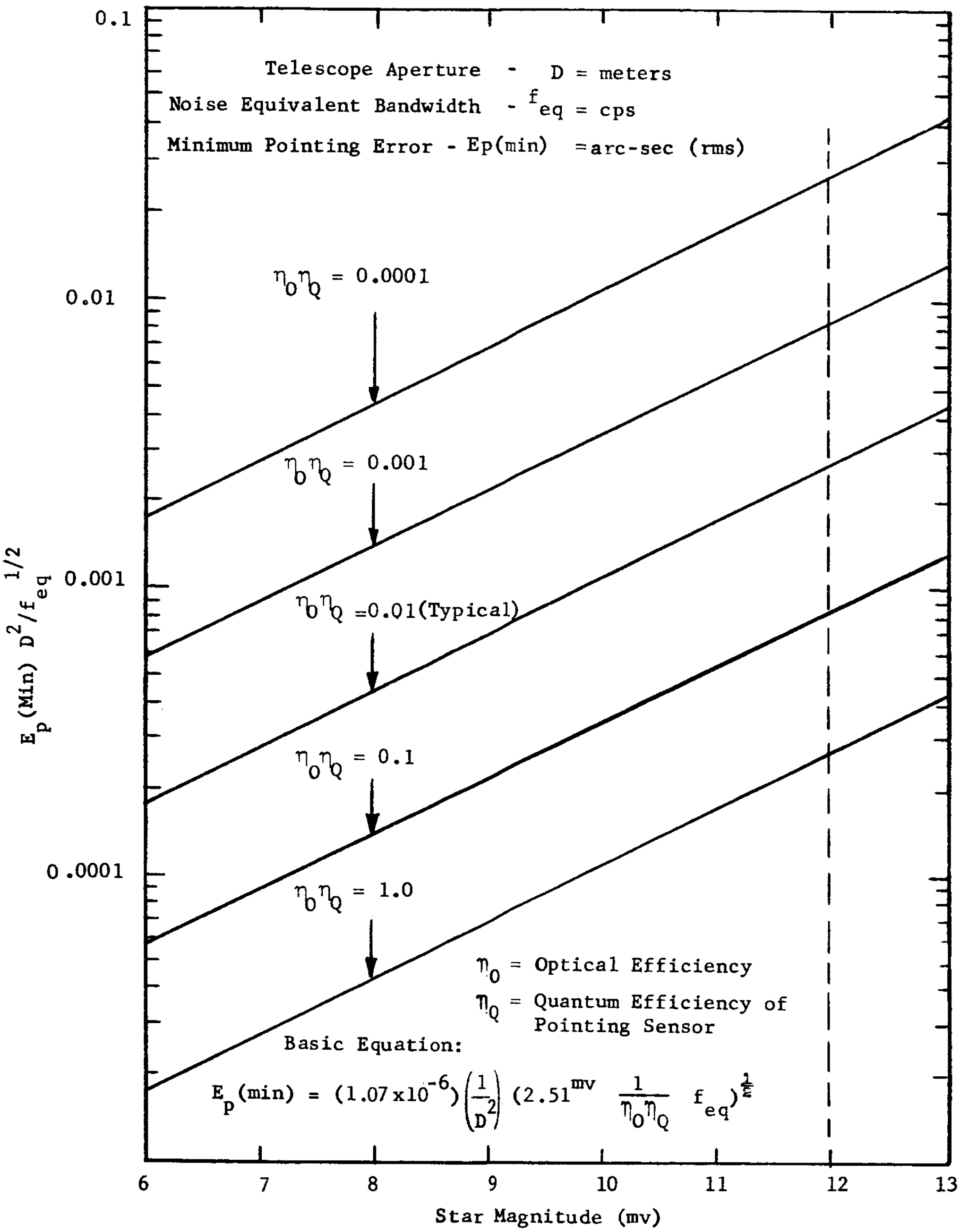

Figure 6. Minimum RMS Pointing Error (E_p) Versus Stellar Magnitude

Using the optical sensor principle of Figure 5, and zero background and dark current noise conditions, the above minimum pointing errors can be realized.

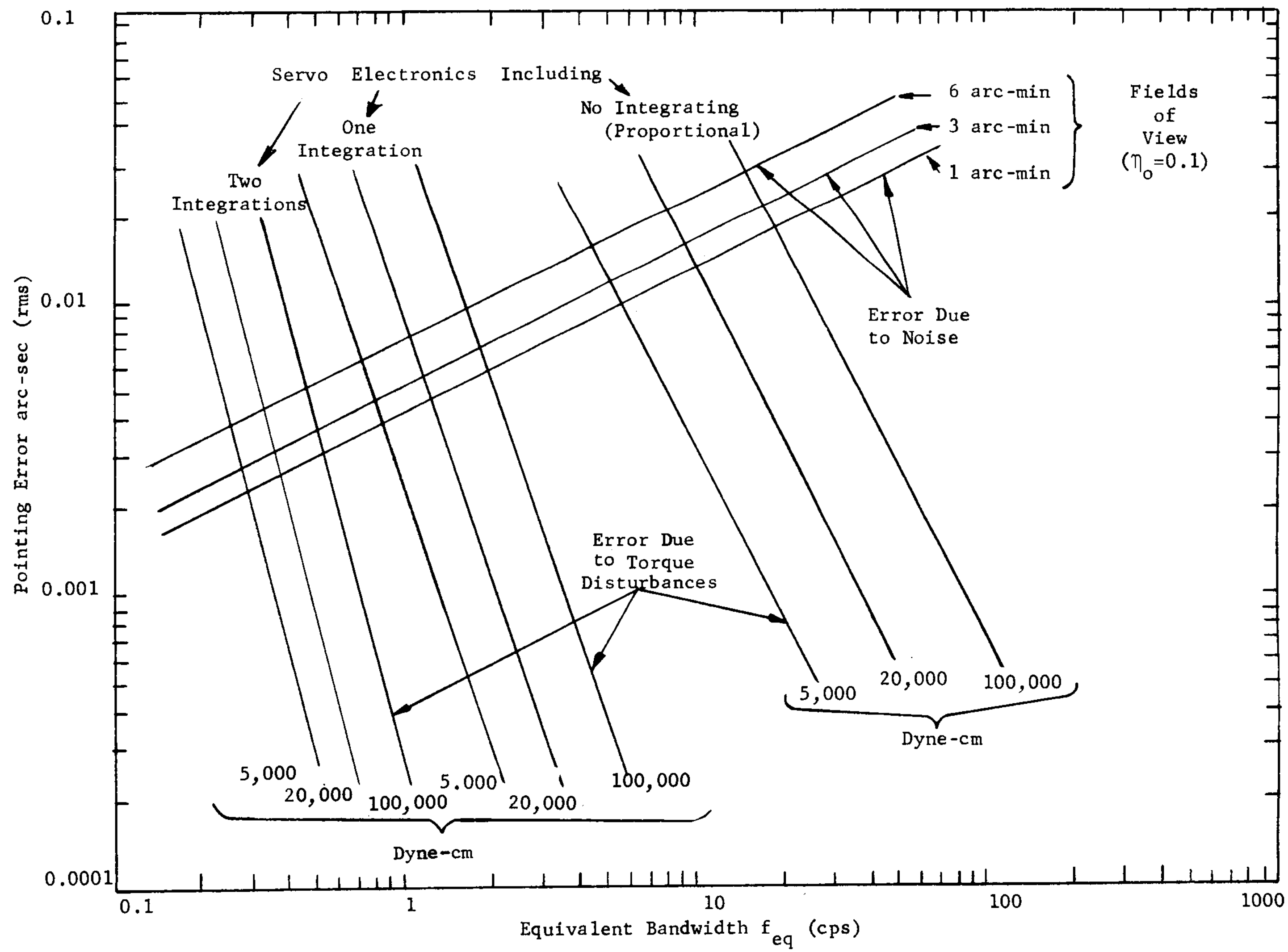

Figure 7. Tracking Error Versus Bandwidth (D = 1 Meter)

For pointing servo systems employing various levels of signal integrator, the pointing errors due to noise and the pointing errors due to disturbing torques will vary as shown as a function of equivalent bandwidths.

III. 40-Inch System Description

Volume III describes an Advanced Princeton Experiment Package (APEP) which has been tailored to fit into the same outer vehicle used for the Orbiting Astronomical Observatory (OAO) series of satellites. The experiment package contains a 40-inch diameter Cassegrain telescope which is used in conjunction with two SEC Vidicons for high-resolution spectrophotometry and diffraction-limited imagery in the visible and UV spectral regions. The optical system allows either vidicon to be used for spectrography or imagery so that failure of one vidicon does not compromise the experiment objectives.

The major innovation incorporated into the design is a suspension system which allows the experiment package to float with respect to the outer OAO vehicle. This minimizes the effect of disturbances arising from the momentum wheels and gas jets in the outer vehicle and permits the telescope to use the entire OAO vehicle as a momentum wheel. Long term pointing stability is obtained by fixing the orientation of the telescope with respect to two guide stars located within its field of view. The guidance system is designed to handle the relatively high angular displacements and displacement rates encountered during acquisition. It is also capable of minimizing high frequency disturbances due to statistical variations in photon arrival rates as well as low frequency disturbances due to magnetic and gravity gradient torques.

A detailed mechanical analysis taking into account the effect of the launch environment has not been performed on any part of the experiment package. The structures shown in many of the following figures are intended to indicate the design concept only, and are not meant to convey a completed design. Graphs are also included to depict the pointing system performance.

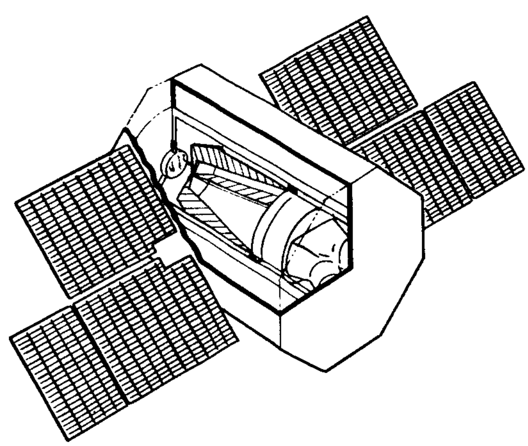

Figure 8. OAO Vehicle and Advanced Princeton Experiment Package (APEP)

During normal operation, the experiment package floats within the OAO vehicle and uses it for a momentum wheel.

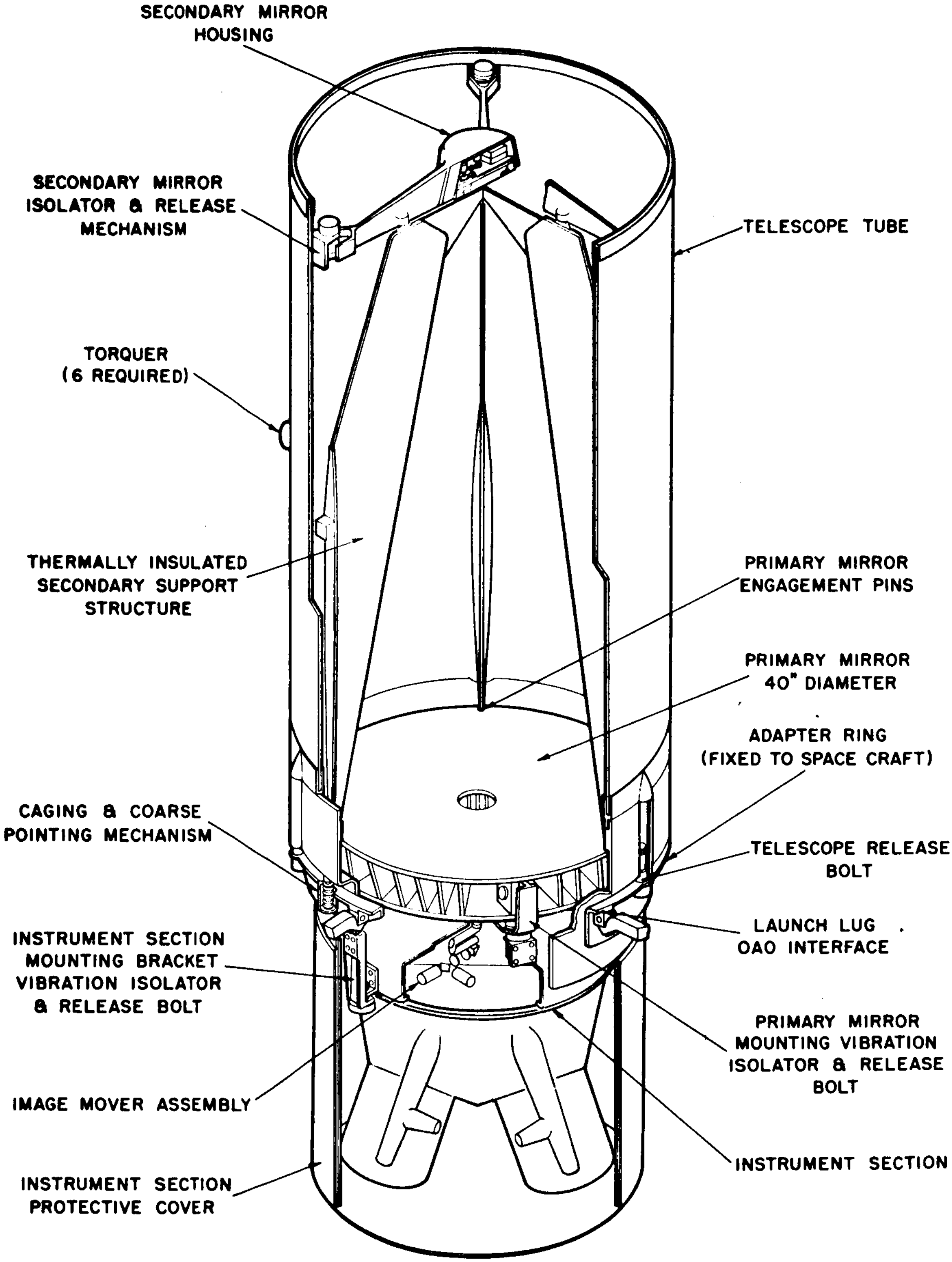

Figure 9. Optical Package

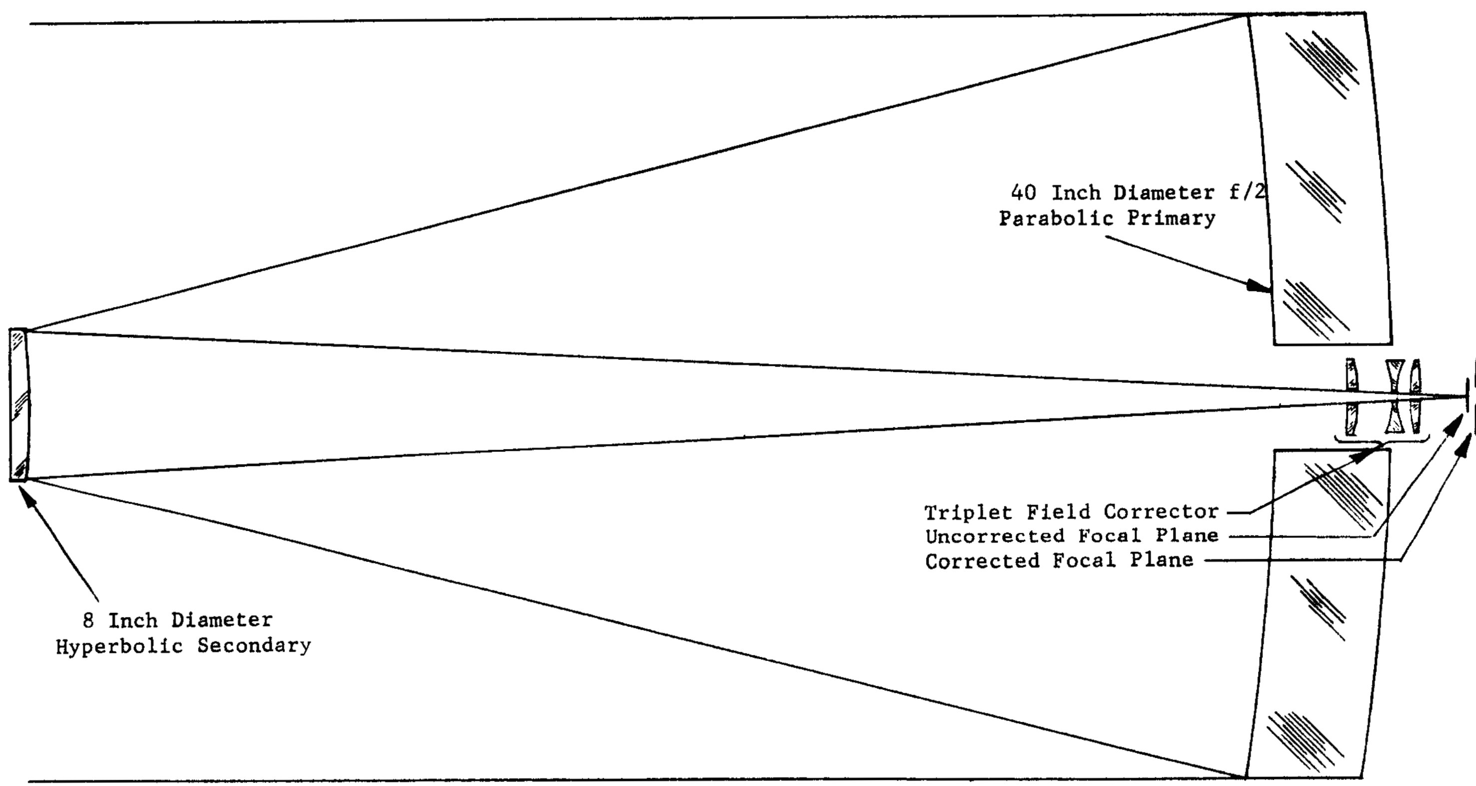

Figure 10. Cassegrain Telescope and Corrector

A fast, f/2 primary, and a secondary with 5X magnification form a f/10 optical system with only a 65" separation between them.

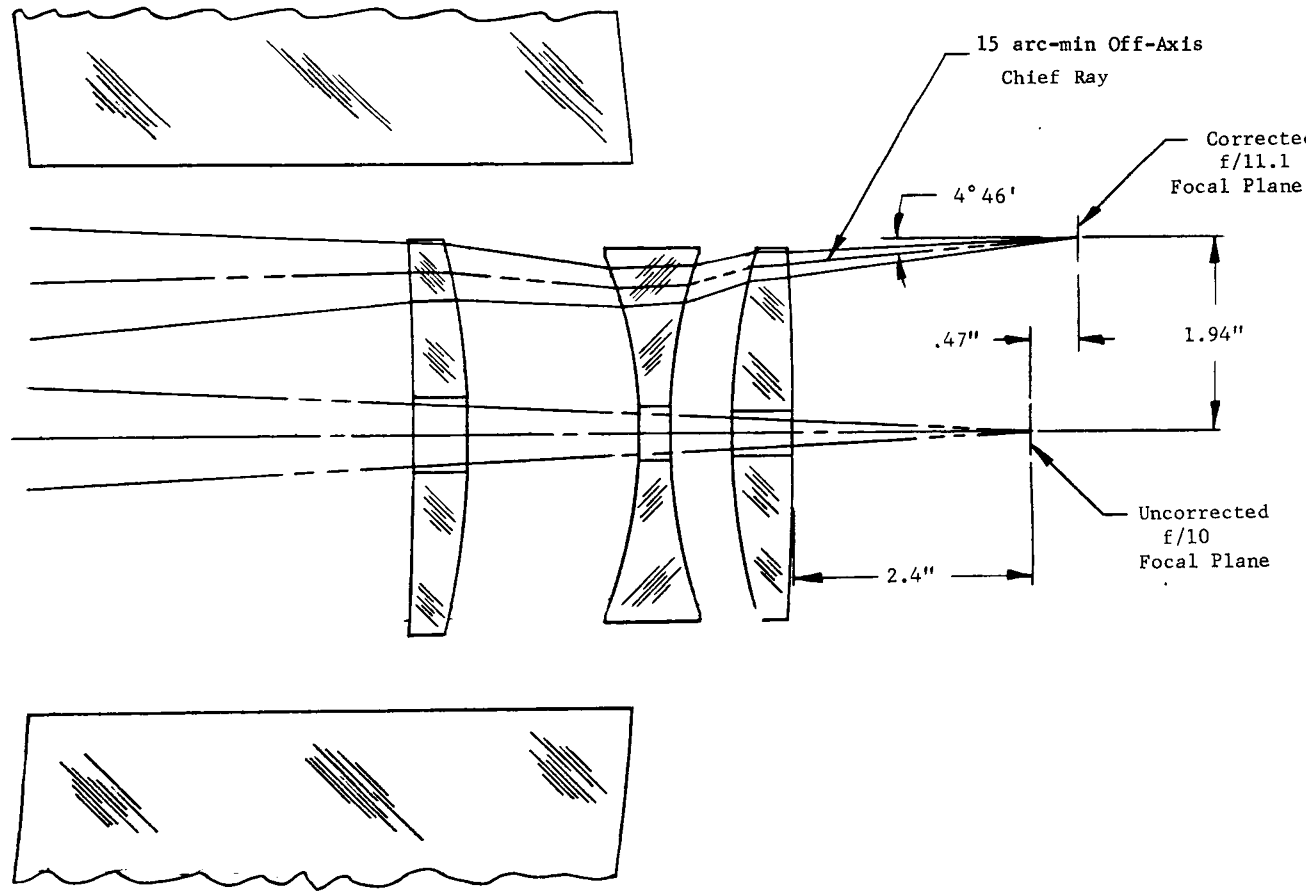

Figure 11. Telescope Field Corrector Details

The corrector provides a flat, well corrected field 30 minutes of arc in diameter at the f/11.1 focal plane. A very small field a few arc-minutes in extent and containing no refractive components is provided by a hole through each refractive component.

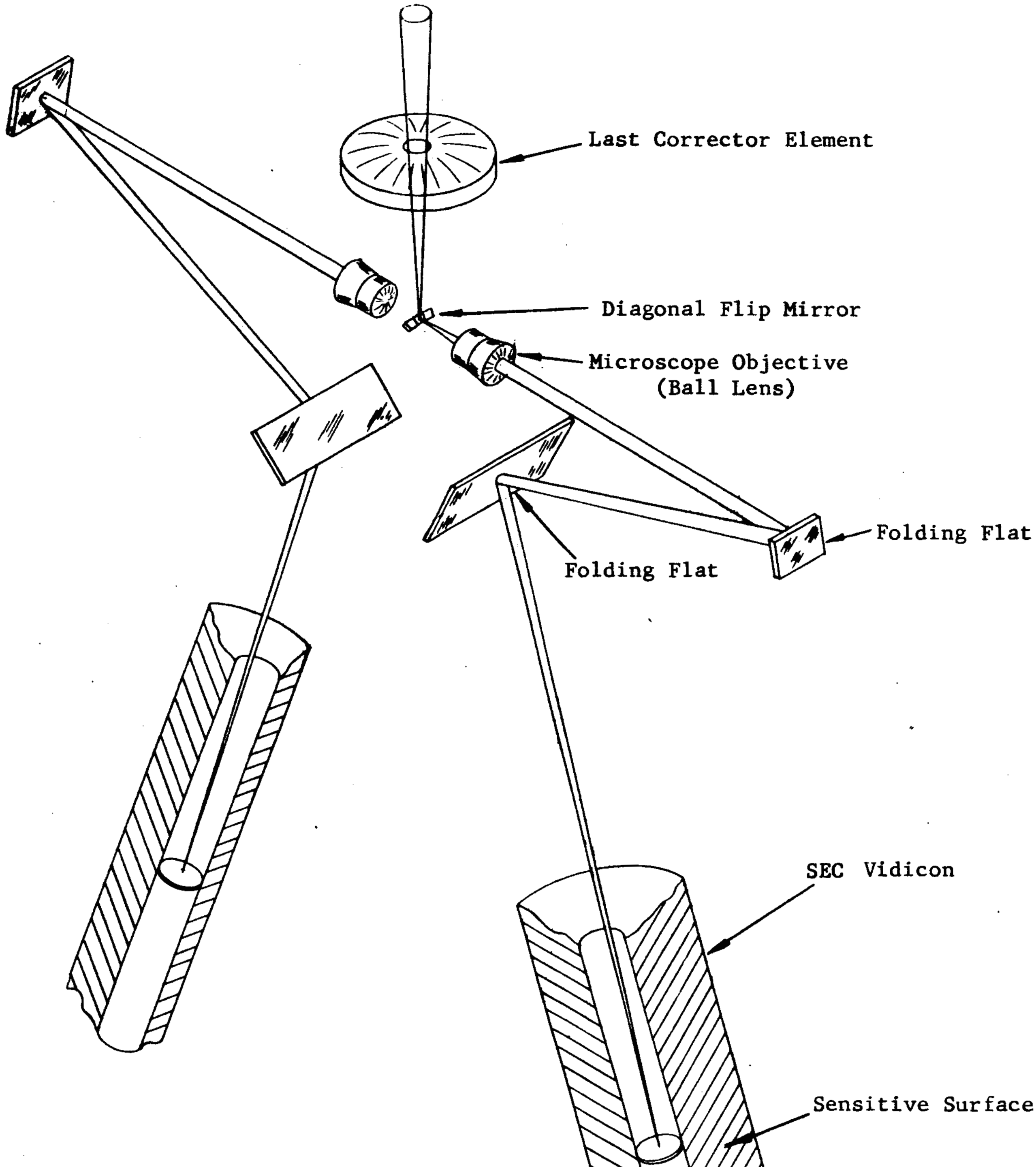

Figure 12. Imaging System

The small diagonal flip mirror situated under the last telescope field corrector and in the f/10 focal plane rotates about the optical axis to direct the image beam to one or the other identical imaging system associated with each vidicon.

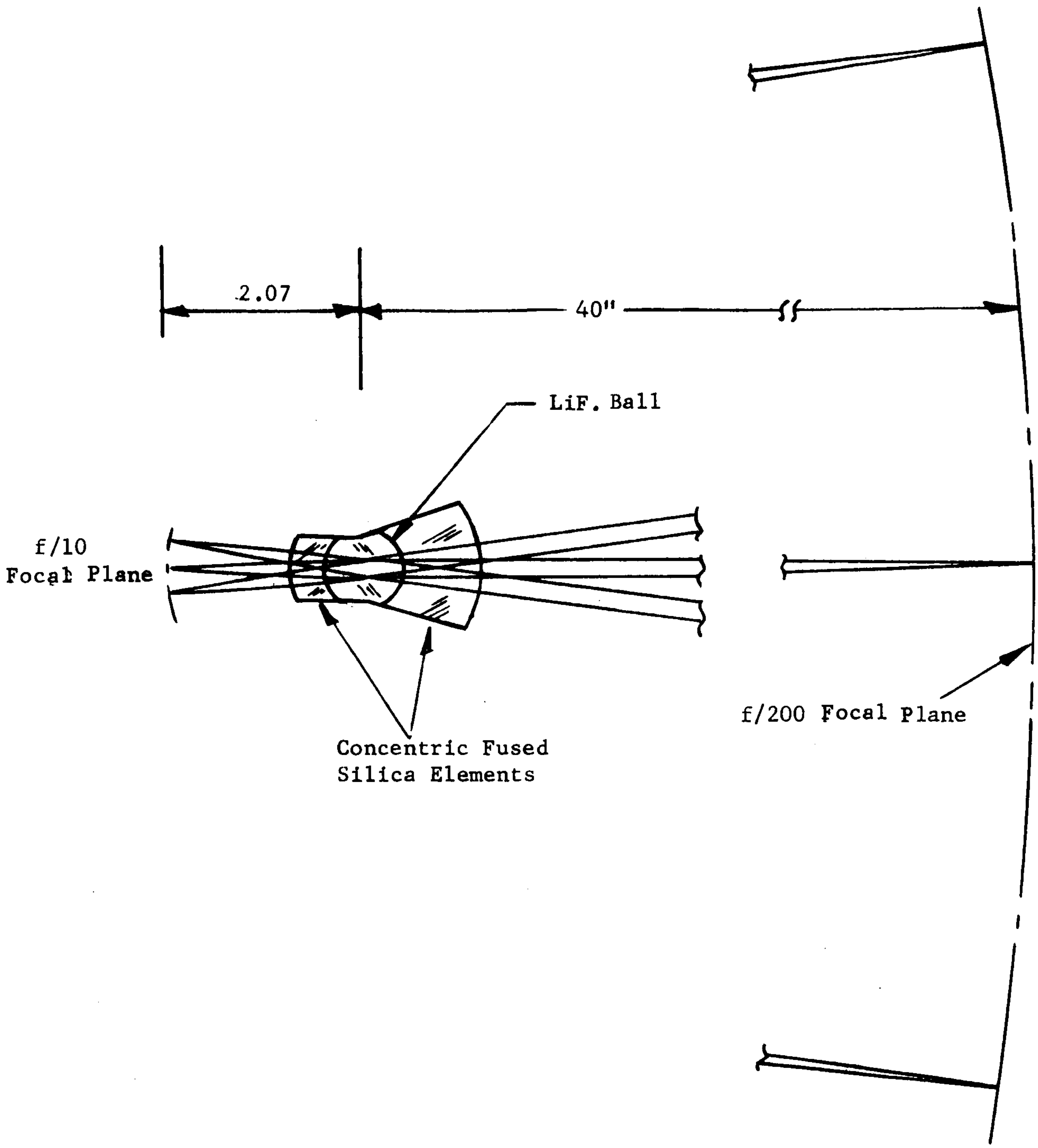

Figure 13. Wide Field Microscope Objective (f/3.7, 0.2μ - 0.6μ)

This is a "ball lens" type of design. Since all surfaces are concentric, there is no optical axis and, therefore, no off-axis aberrations which normally restrict the field of more conventional lens types.

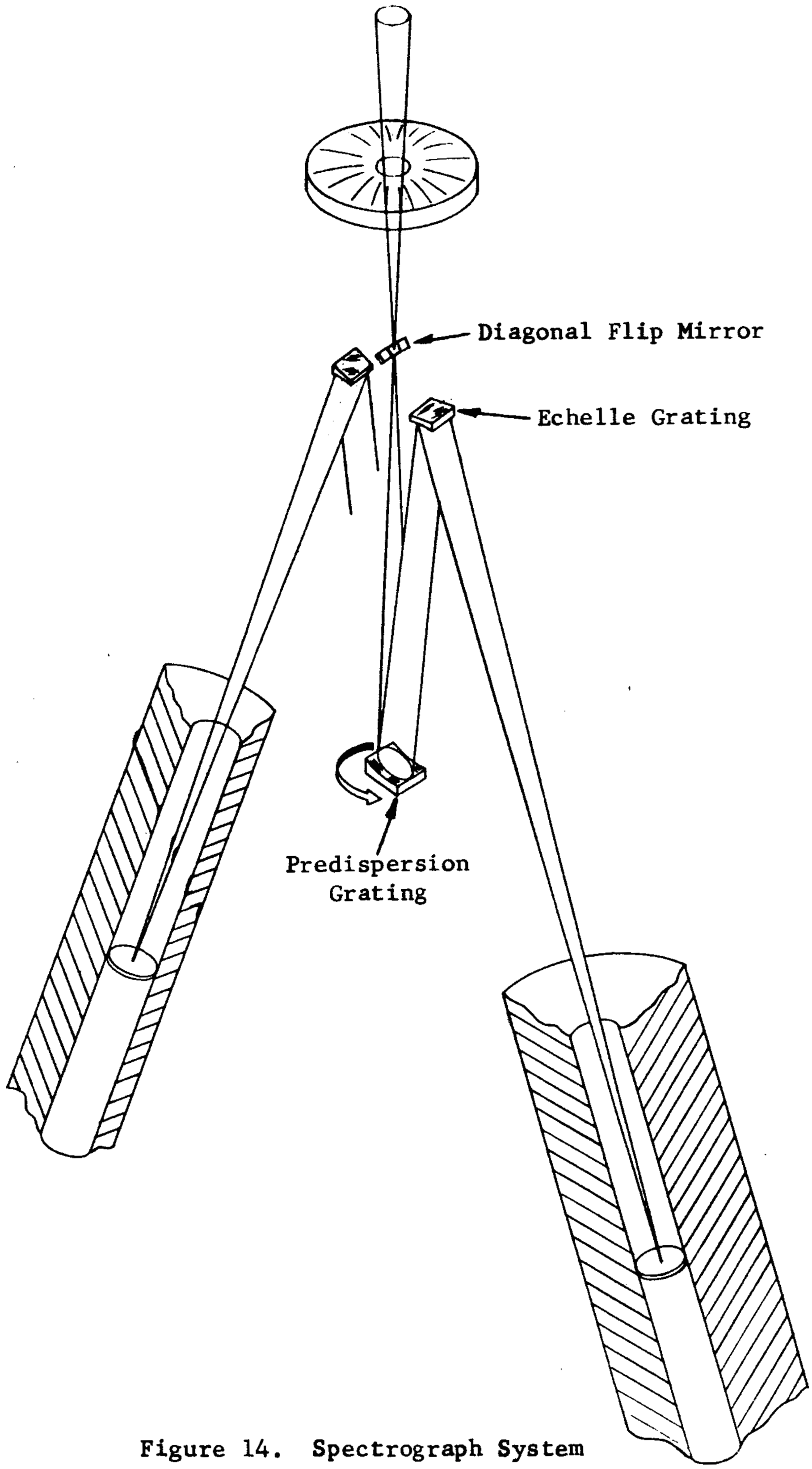

Figure 14. Spectrograph System

Energy enters the spectrograph through a small slit in the diagonal flip mirror and strikes a spherical predispersion grating. Rotation of the predispersion about the optical axis directs the energy into one or the other of a pair of echelle gratings associated with each vidicon.

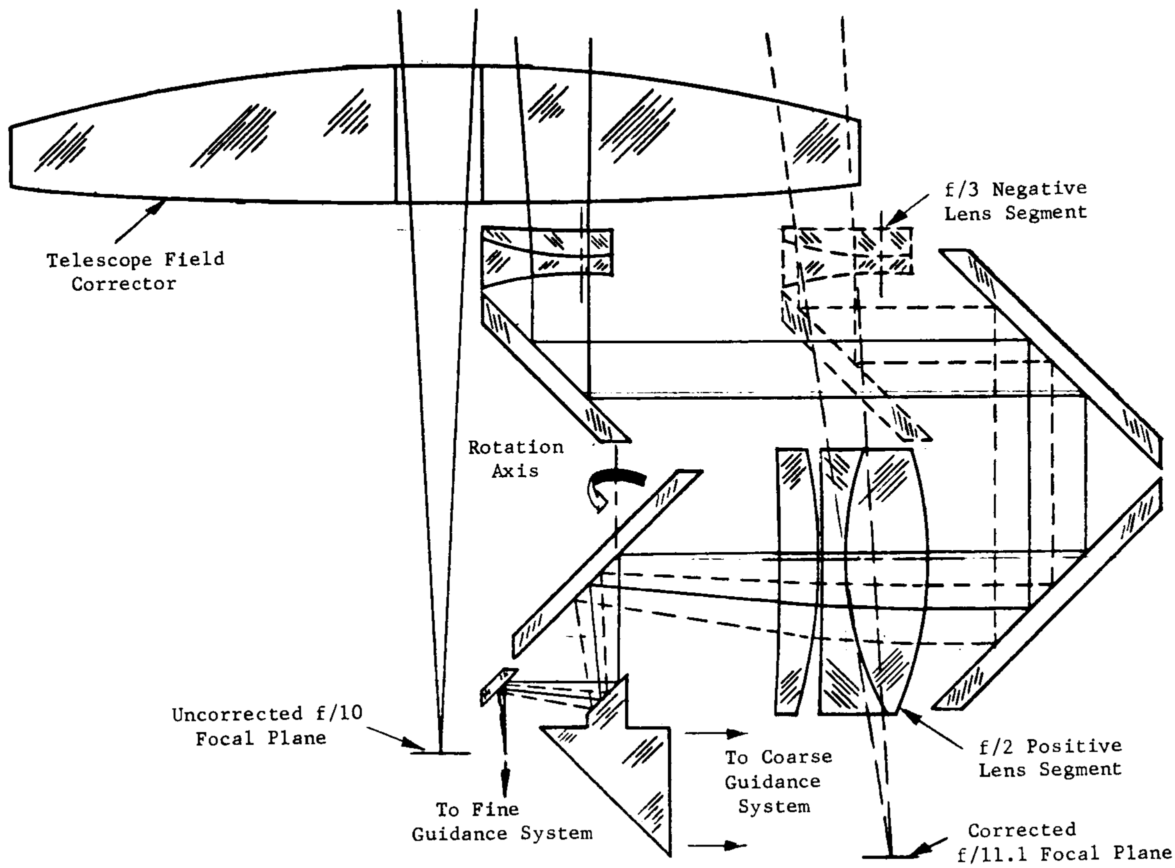

Figure 15. Image Mover Assembly

The image mover assembly relays a guide star image from its normal position in the telescope field to a position close to the telescope optical axis. The portion of the telescope field to be relayed by the image mover is selected by sliding the negative lens and diagonal mirror assembly in and out as shown by the bold and phantom views and by rotating the entire image mover assembly about an axis through the positive lens diagonal mirror. The coarse guidance prism and the small mirror immediately above the f/10 focal plane do not rotate but remain fixed.

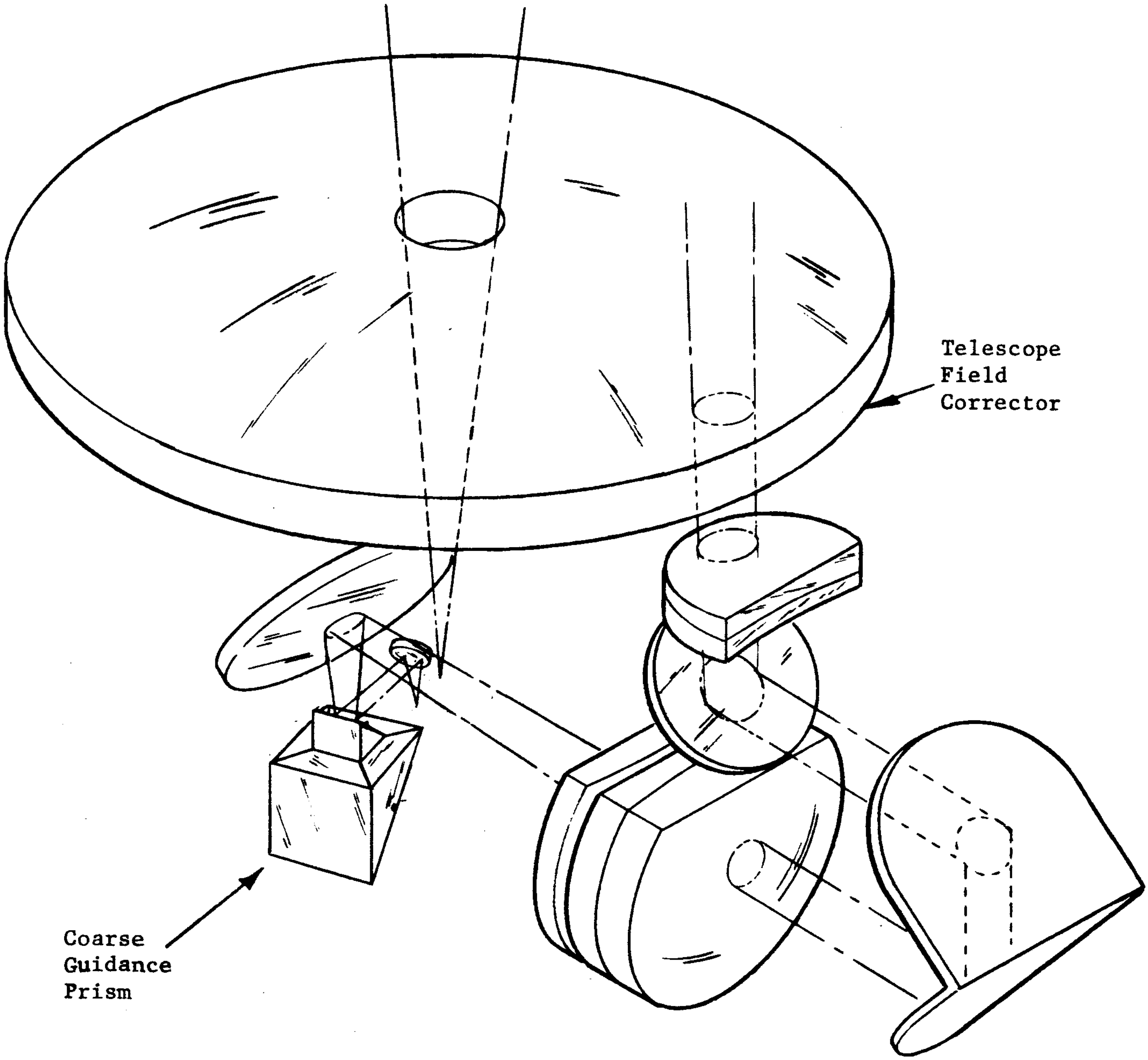

Figure 16. Image Mover in Skewed Position

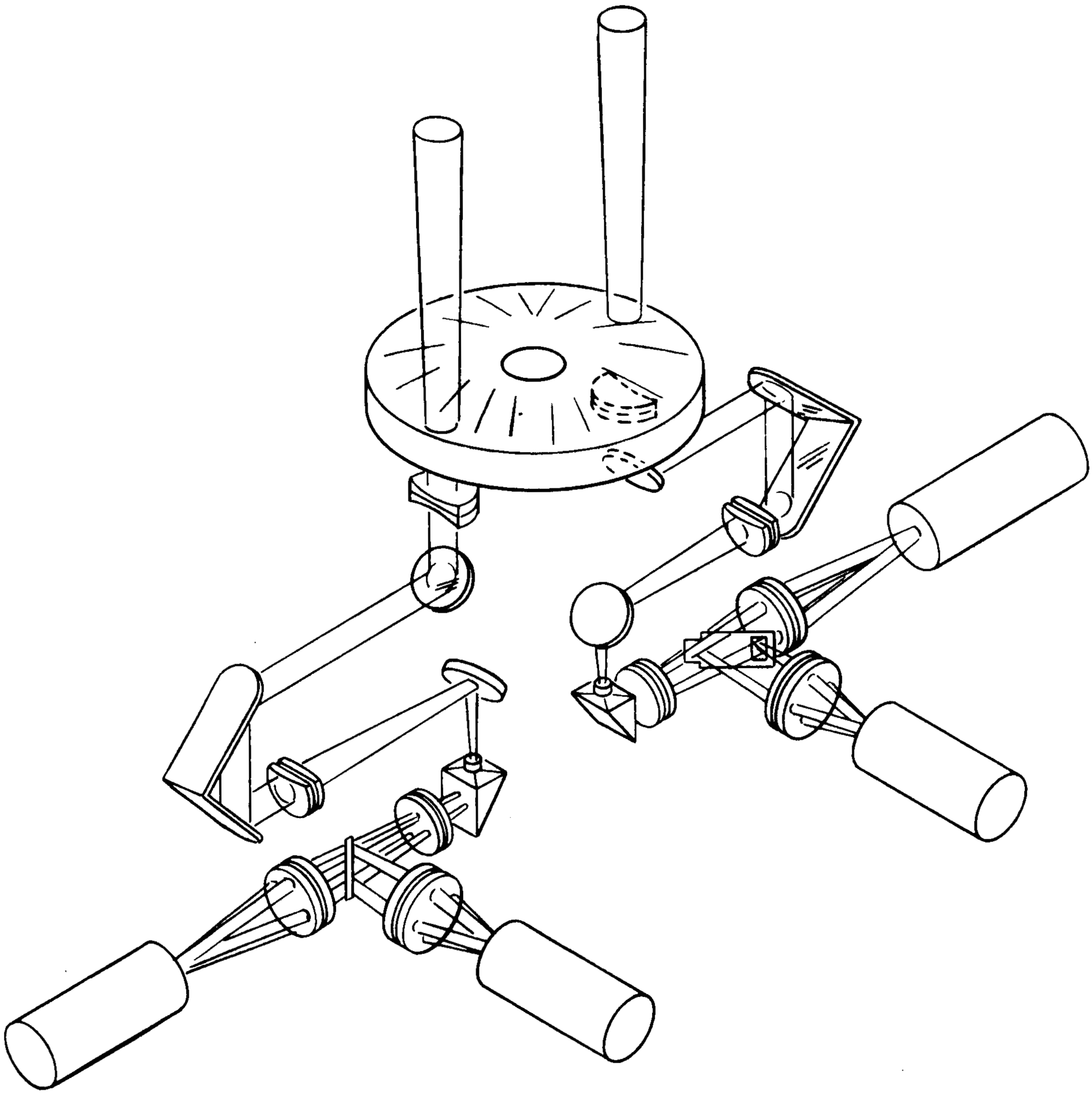

Figure 17. Coarse Pointing System

Guide star images which fall outside of the fine guidance field of view intercept the bevelled top of the coarse guidance prism. This directs the image beam to one of four positions on an optical encoder which causes the various quadrants to be seen alternately by two phototubes. The phase of the resultant signal provides guidance error signals.

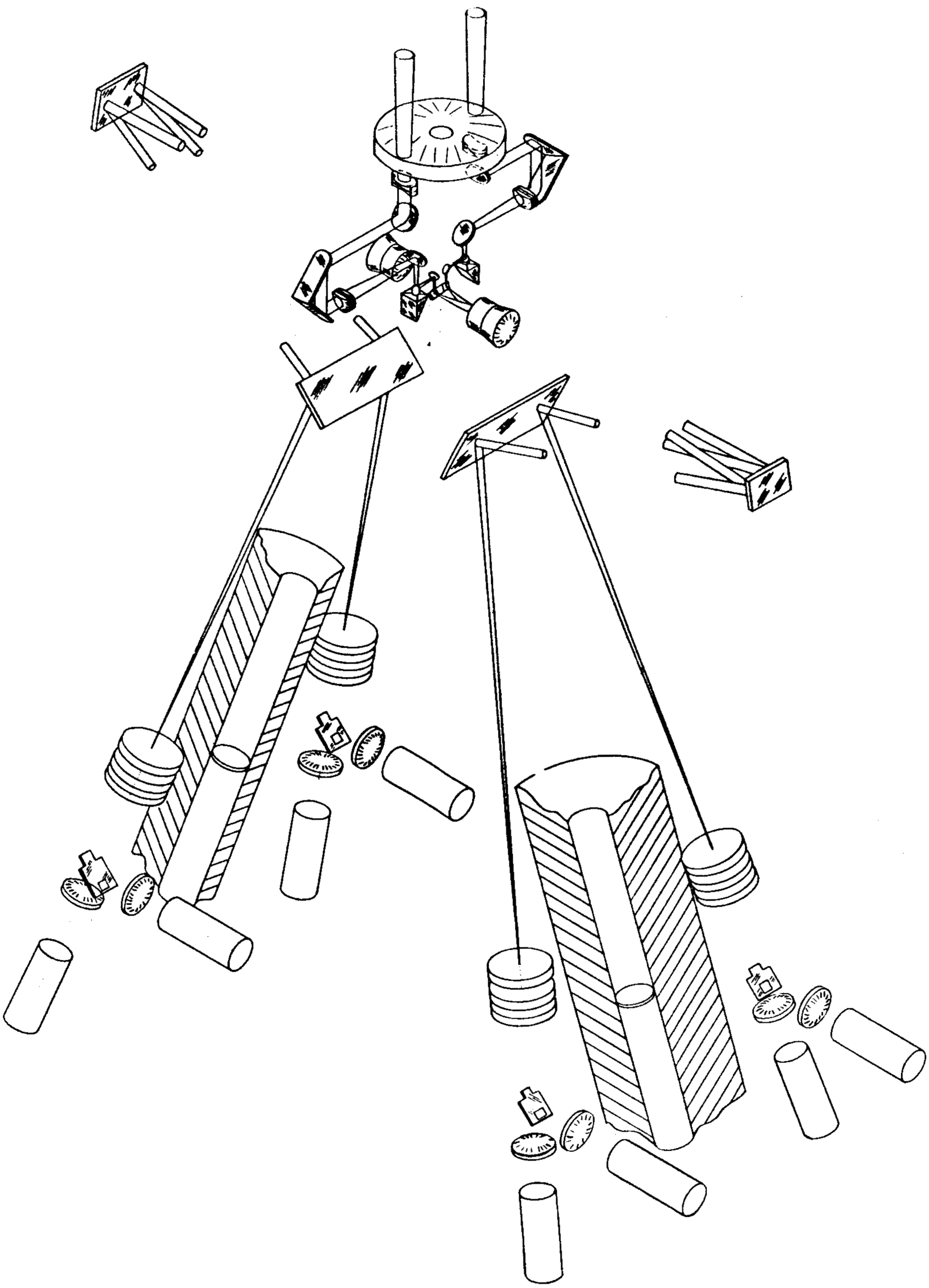

Figure 18. Fine Guidance System

Guide star images are relayed by the image movers to positions close to the optical axis. From here, they follow a path similar to the image beam until intercepting a pair of image dividers in the f/200 image plane.

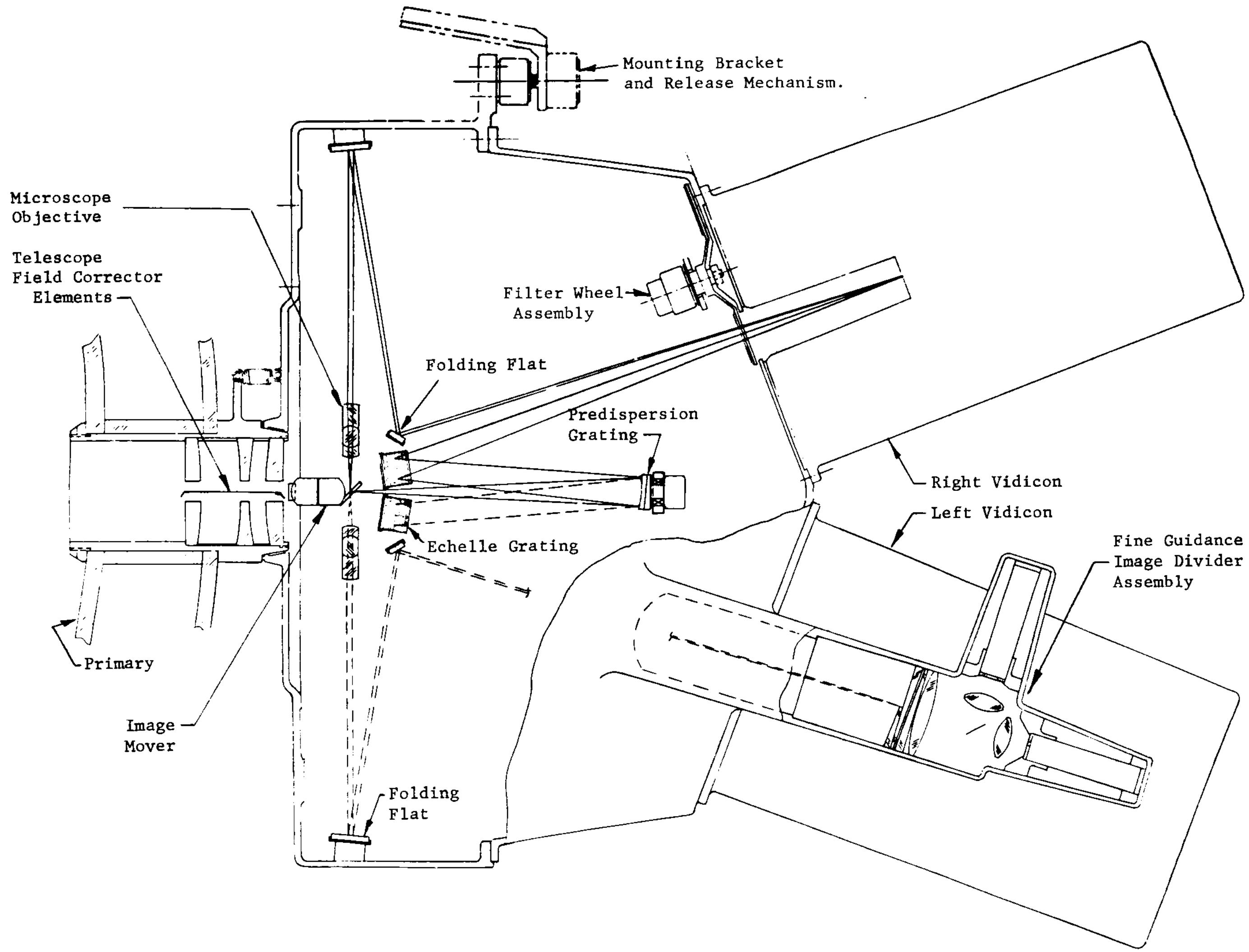

Figure 19. Instrument Package Optical Layout

The section through the fine guidance assembly is out of the plane of this main cross-section.

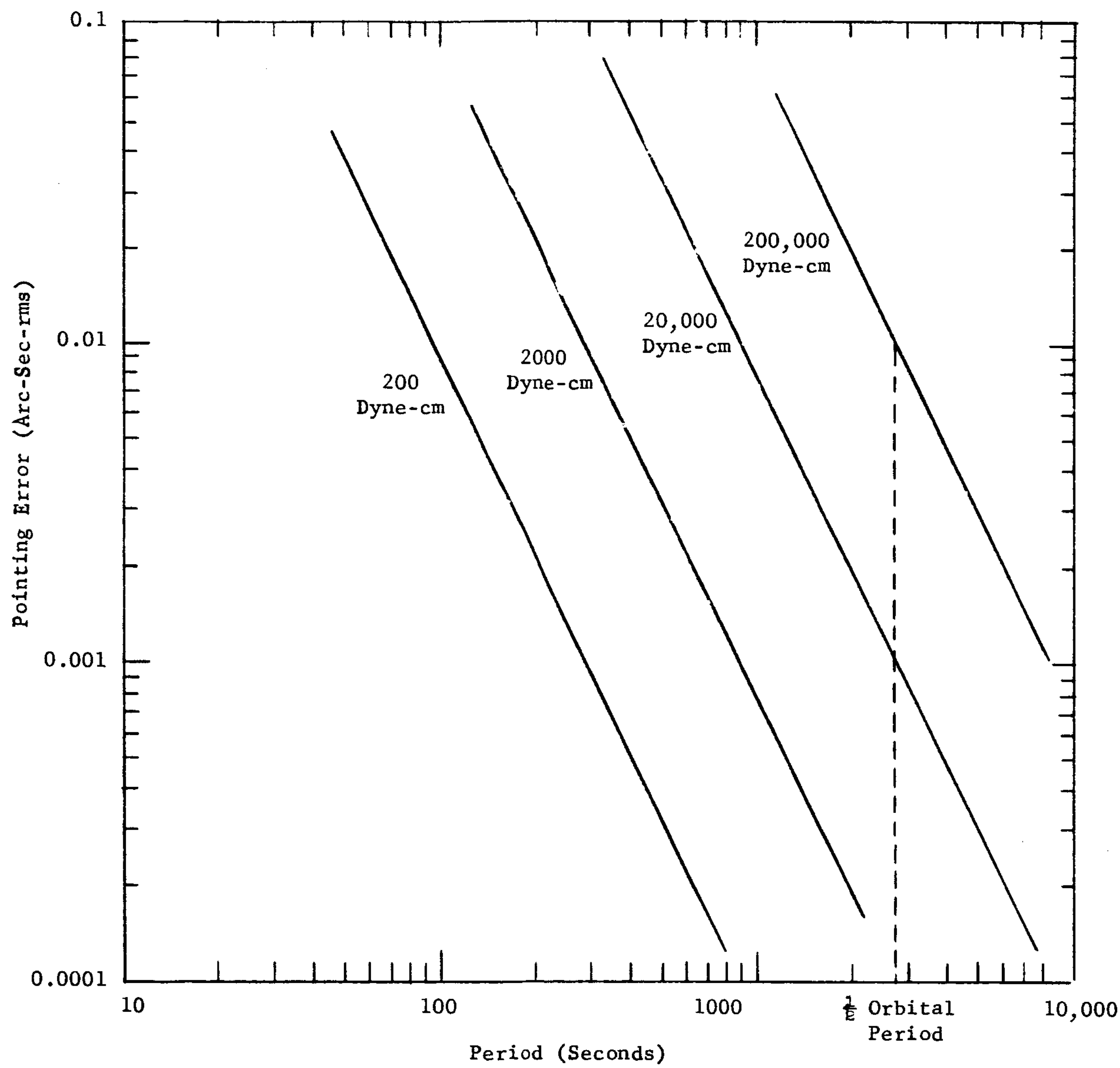

Figure 20. Pointing Errors Versus Disturbance Torques (Final Tracking Mode - Pitch and Yaw Axes)

If various magnitudes and periods of sinusoidal disturbing torques are applied to the telescope pitch and yaw axes, the resulting pointing errors occur for a servo system employing low bandpass techniques.

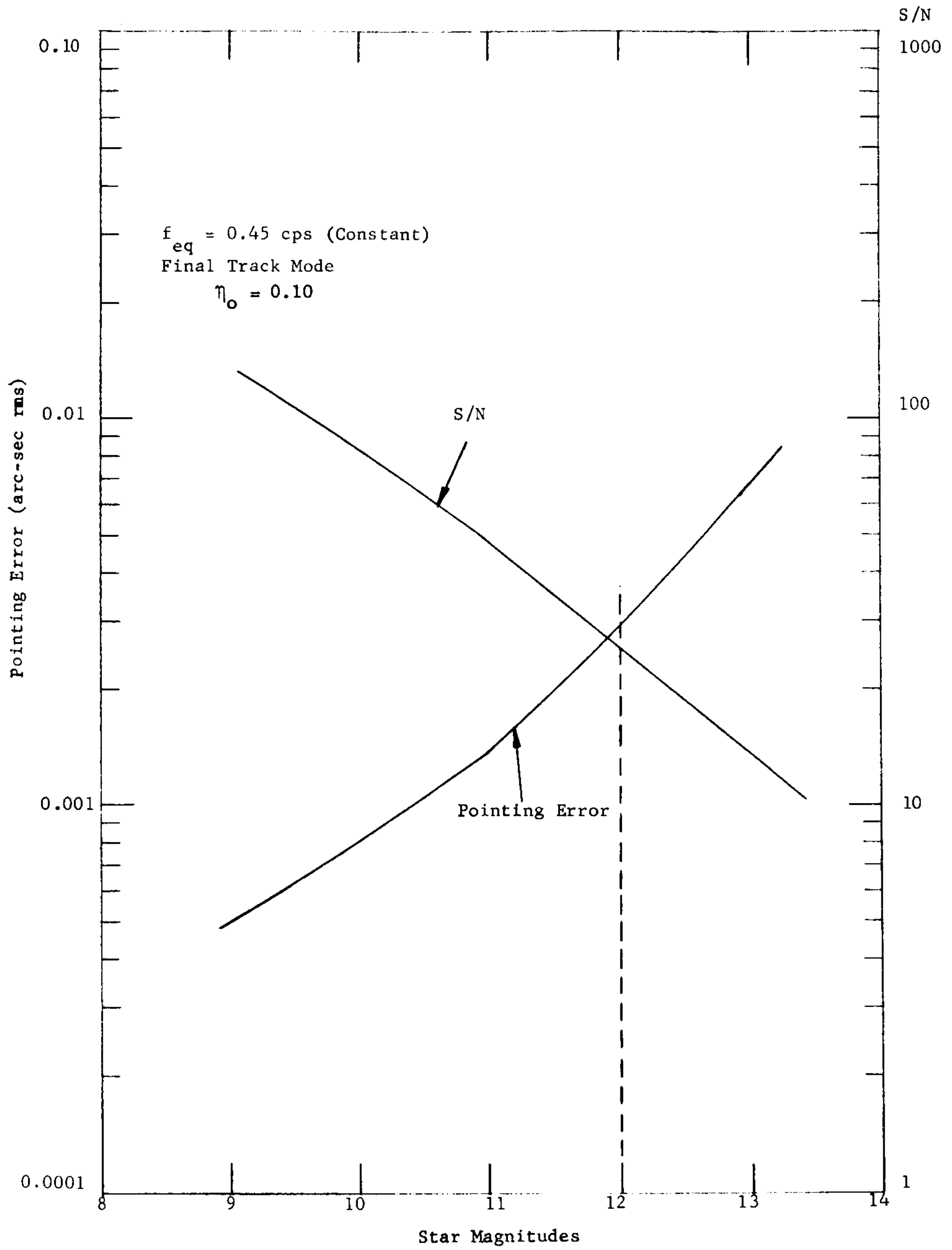

Figure 21. Pointing Error Versus Star Magnitudes (Pitch and Yaw Axes)

The telescope pointing errors due to noise (random) vary as a function of stellar magnitude as shown for a servo system with a constant bandwidth.

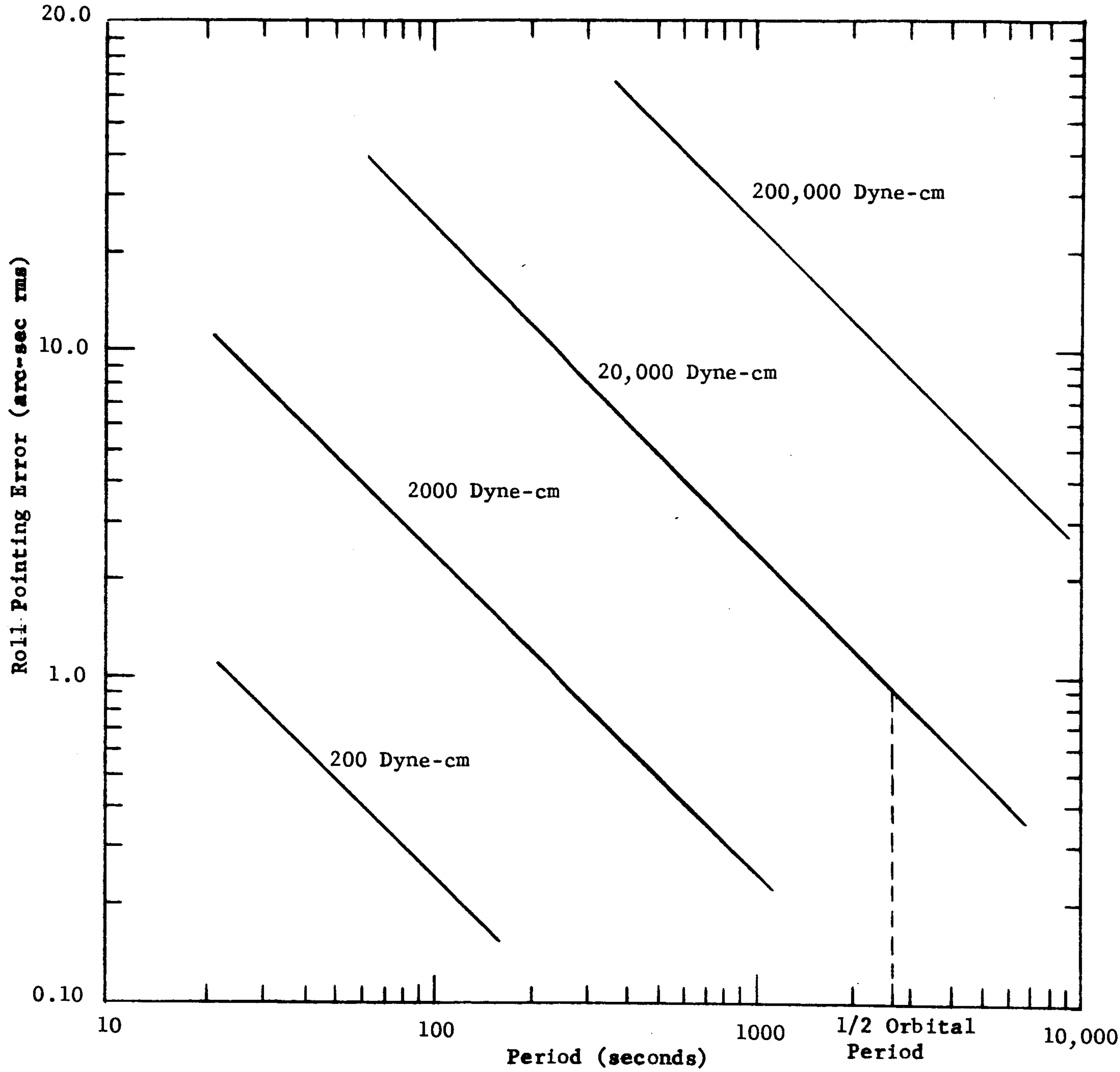

Figure 22. Roll Axis Pointing Errors Versus Disturbance Torques

If various magnitudes and periods of sinusoidal disturbing torques are applied to the telescope roll axis, the resulting pointing errors occur for a servo system employing low bandpass techniques.

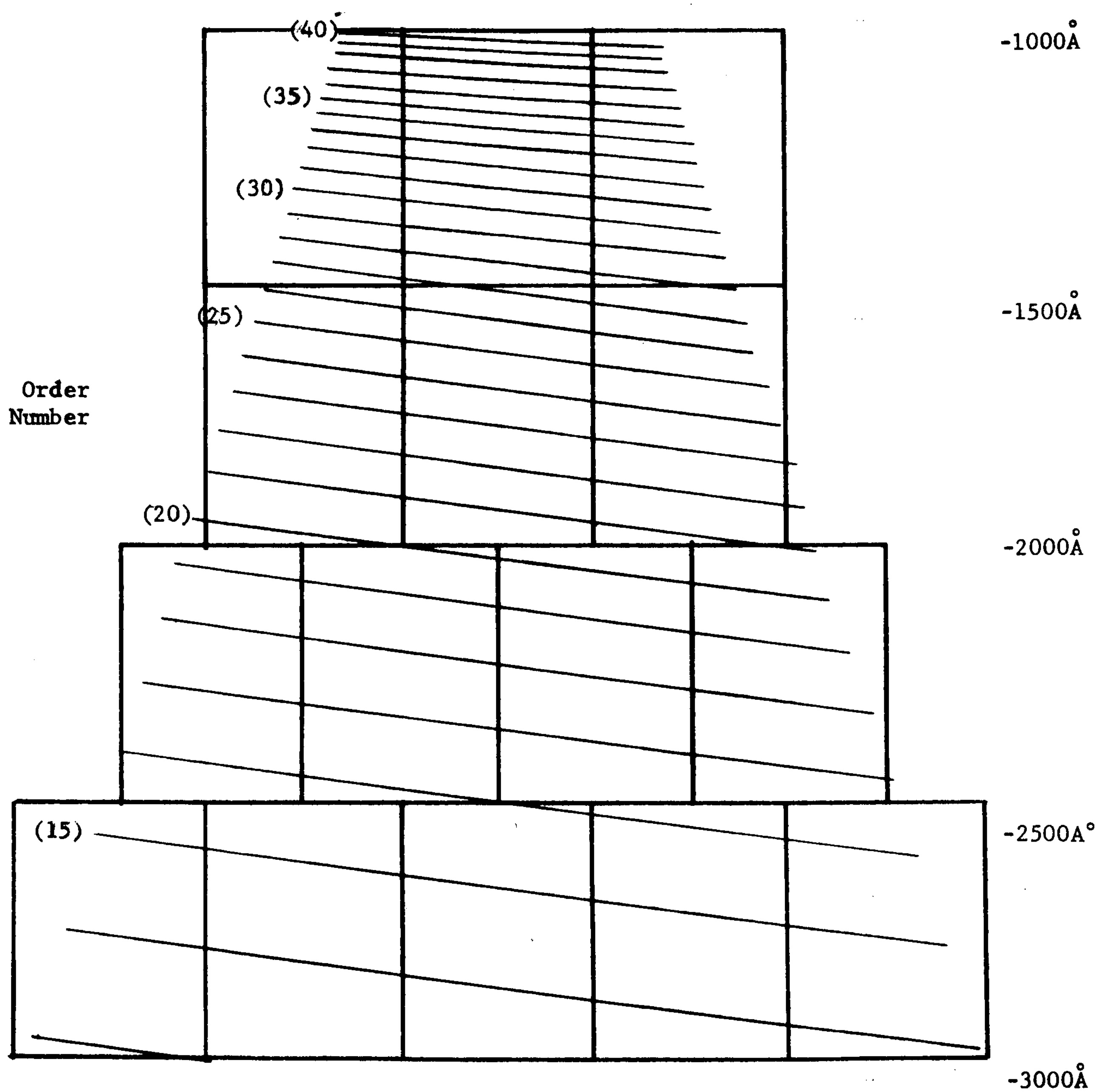

Figure 23. Echelle Spectrograph Format

Lines corresponding to longer wavelengths and lower diffraction orders become longer and the space between them increases rapidly. With a 20 x 15 mm vidicon sensitive surface, a number of steps will be required to cover the complete spectrum.

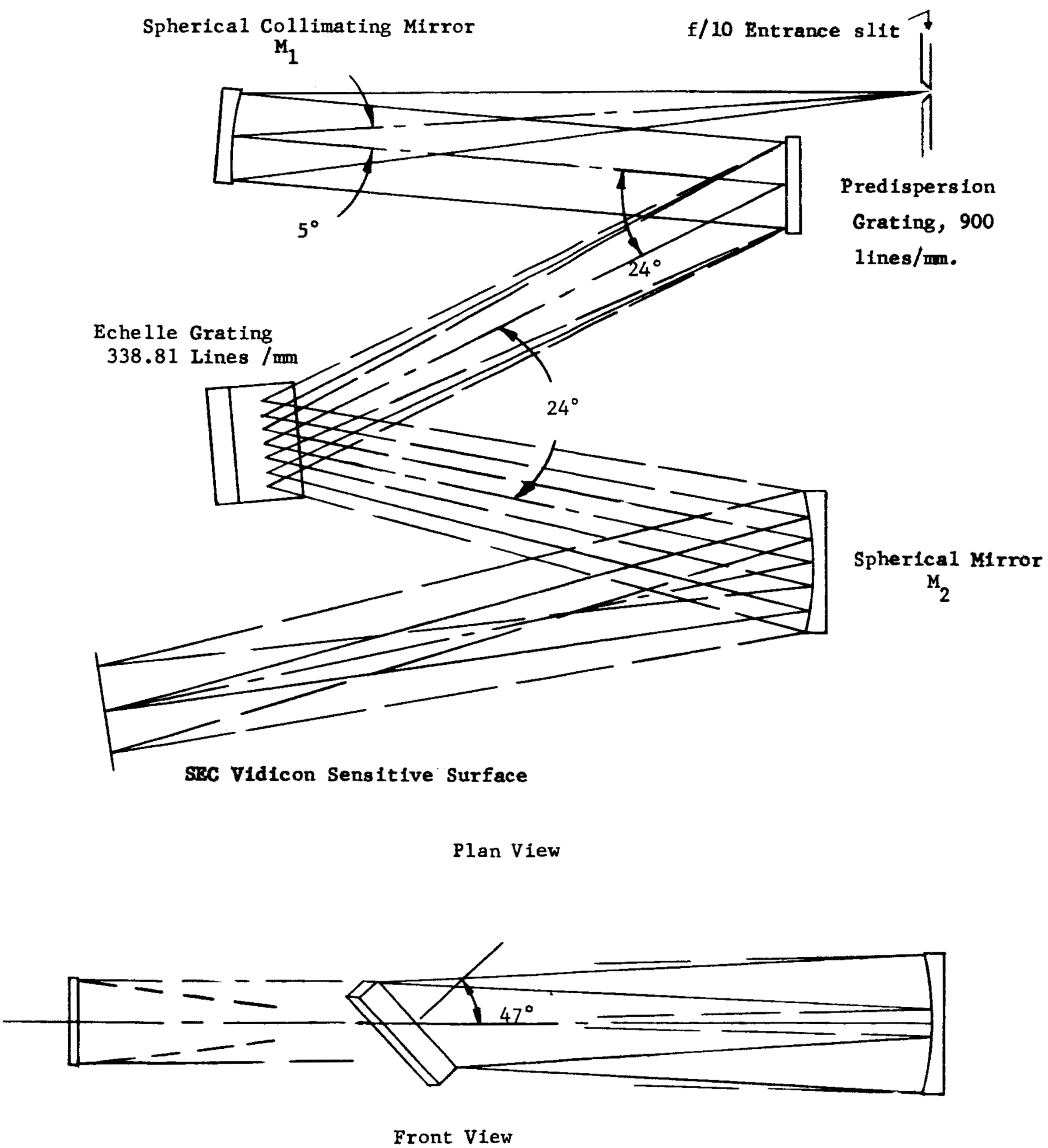

Figure 24. Four-Element Spectrograph

A spherical collimating mirror directs energy onto a flat, low dispersion, predisperser and then onto a flat high dispersion echelle grating. The predisperser and echelle gratings are arranged so that their dispersion directions are crossed. A second spherical mirror focuses the resulting two-dimensional spectrum on the sensitive surface of the vidicon.

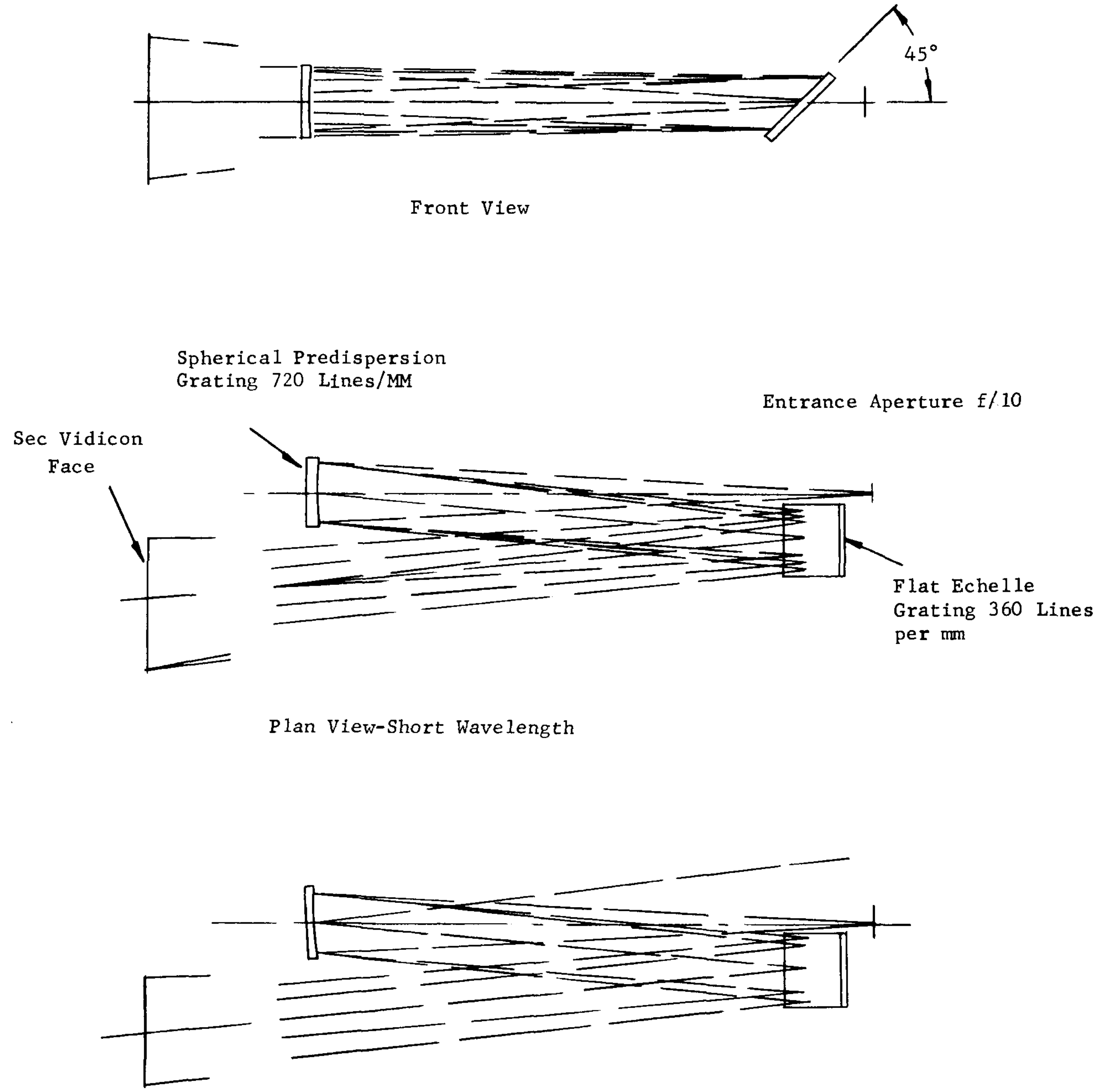

Figure 25. Two-Element Spectrograph Design

A spherical predisperser is arranged so as to direct a converging beam on a flat echelle grating which folds the beam so that it focuses on the vidicon face. The spectral region seen by the vidicon is varied by changes in the orientation of both gratings.

IV. OAO/APEP in Association with AAP

The benefits and design criteria arising from associating an advanced OAO experiment with a manned Apollo mission are explored in Volume IV. The study assumes that man-assisted operation of the OAO occurs during the first 30 days in orbit, but that the OAO is capable of remote operation during the remainder of its one year expected life. Wherever possible, existing systems and technology are contemplated in order to facilitate a 1972 launch. The results of the study indicate that a gimballed connection between the command module and OAO vehicle is feasible. A 300 mile orbit appears to be the best compromise to ensure a one-year operational life for the OAO vehicle and a tolerable radiation hazard to man. Radiation induced fogging and graininess appears to be a significant problem even with very thin photographic emulsions such as those of the Schumann type. Possible means of alleviating this problem include a heavily shielded (using low-z material) film storage container, an extra-vehicular activity (EVA) schedule which avoids photographic exposures during passage through the South Atlantic anomaly, and photographic development immediately following exposure. Limitations and considerations pertaining to the use of film by the astronauts in orbit are shown in the following table and graphs. Indications are that 100 pounds of shielding will permit film survival for eight days.

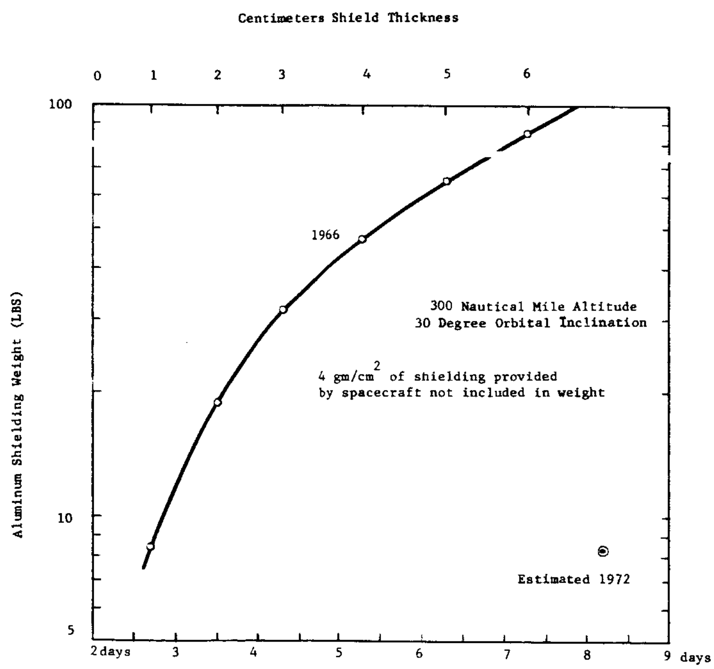

Figure 26. Shielding Weight Needed to Shield a Cylindrical Volume (8 Inch Diameter by 4 Inches) From Doses Exceeding One Radian as a Function of Days Exposure

TABLE 2

ADVANTAGES AND DISADVANTAGES OF SPECTROSCOPIC PLATES AND FILMS (103a AND IIa)

Advantages	Disadvantages
Relatively low reciprocity failure	Relatively high sensitivity to Van Allen Belt radiation.
Relatively high abrasion tolerance	Diminishing spectral sensitivity below 2500Å.
Available in quite convenient forms	Bimat processing not recommended.
Good spectral sensitivity available between 2500Å and 7000Å	Should not be in hard vacuum environment for long time periods.
Acceptable resolving power	

ADVANTAGES AND DISADVANTAGES OF UV COATED SPECTROSCOPIC PLATES AND FILMS (103a AND IIa)

Advantages	Disadvantages
Uniform spectral response possible between 800Å and 3000Å	Plates are not supplied coated. Customer must apply.
May be used in hard vacuum	Some coatings must be removed with a special solution prior to processing.
Relatively high abrasion tolerance	
Relatively low reciprocity failure	Bimat processing not recommended.
Coatings do not appreciably reduce inherent film resolving powers	Spectral sensitivity relatively low.
Available in quite convenient forms	Resolving power relatively low.

ADVANTAGES AND DISADVANTAGES OF "SCHUMANN" EMULSIONS (SWR, DC-3, SC-5, AND SC-7)

Advantages	Disadvantages
Relatively low sensitivity to Van Allen Belt radiation	Resolving power may be slightly lower than desired.
Higher tolerance to vacuum	Reciprocity failure at long exposures.
Relatively high sensitivity in UV	Very low abrasion tolerance. Handling is very difficult. Bimat processing not recommended.
	Available in very limited forms.

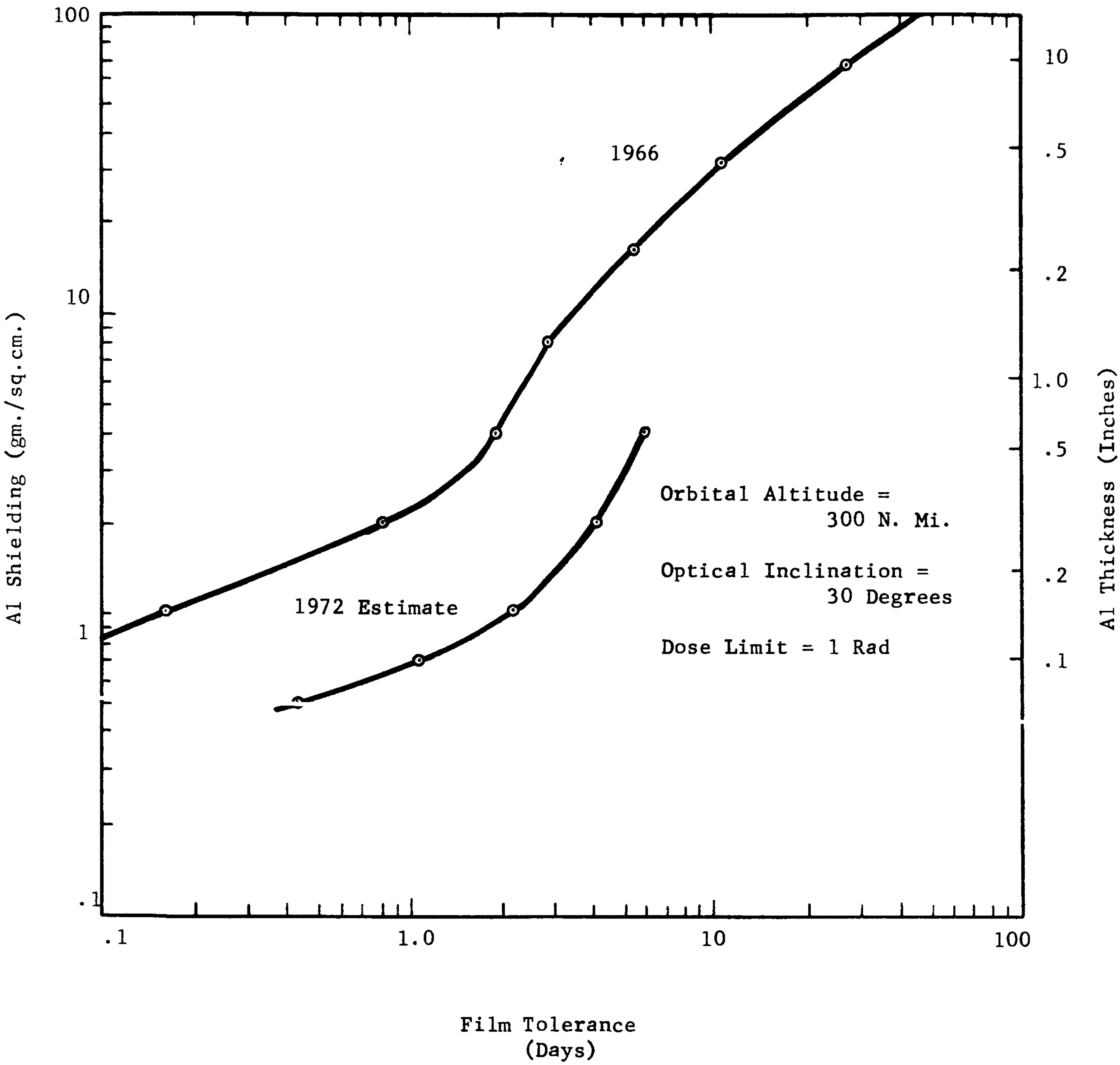

Figure 27. Shielding Requirements as a Function of Number of Days Exposure

V. Recommendations for Additional Effort

The following table lists recommendations for future effort and consideration so that the system concept developed in the study can be advanced from a general feasible approach to that of optimization:

TABLE 3

1. The possibility of silicon as a mirror material.
2. Study of radiation effects and hard vacuum on mirror materials and coatings.
3. The possibility of composite mirror structures (quartz egg-crate structure stuffed with aluminum wool).
4. Optimization of radiation coupling of optical elements.
5. Complete thermal analysis (including effect of internal heat sources).
6. Keeping full-scale mock-up current.
7. Design of a breadboard image mover.
8. Optimization of primary optics and relaying microscope design.
9. Selection of a two versus four-element spectrograph through computer analysis.
10. Completion of spectrograph optical design.
11. Further analysis of interlacing the spectrum on the vidicons.
12. Grating development and efficiency measurements of the finally selected gratings. Optical bench setup to verify spectrometer design using visual wavelength model.
13. Allocation of optical element figure tolerance.
14. Further investigation of an optical system with the exit pupil at infinity.
15. Further investigation of coma, and design of a coma detector breadboard.
16. The effect of temperature reduction on reciprocity failure of UV film (particularly on Schumann type emulsions).
17. Further study of processing UV type film in zero-g gravity.
18. Optimization of film shielding including design and configuration.
19. Multiple-axis computer simulation of pointing and magnitic centering servo system. Further study of expected torque disturbance, mechanical resonances, rigid body cross-coupling, and system simplification would compliment this simulation.
20. Further study and implementation of pulse-processing techniques to reduce cosmic ray noise.
21. Electronics systems optimization to reduce power requirements and information system (telemetry) preliminary design.
22. Study of system reliability, failure modes, and modularization for replacement by astronaut.

VI. Selected Design Parameters

Optics:	Cassegrain Telescope	
	Primary Mirror	40 Inch Dia, f/2
	Secondary Mirror	8 Inch Dia, 5X
	Field of View, Uncorrected	approx. 2 arc-minutes
	Corrected	30 arc-minutes
	Relaying Microscope	20X
	Spectrograph (Echelle Type)	f/10
	Wavelength Range	900 to 3000Å
	Resolution	10,000 (at 1000Å)
	Recording Sensor	SEC Vidicon (nominal) UV Film (during manned portion)
Guidance:	Magnetically Suspended Telescope in Spacecraft	
	Guidestar Field	30 arc-minutes
	Guidestars	1 arc-minutes
	Initial Position Error for Acquisition	
	Pitch and Yaw Axes	±1 arc-minute
	Roll	±2 degrees
	Initial Rate Error for Acquisition	1 arc-min/sec
	Acquisition Time	2 minutes
	R.M.S. Pointing Jitter (12th Magnitude Guidestar plus 11th Magnitude star/16 arc-minutes^2-background)	0.01 arc-second
Spacecraft:	Objective	High Resolution (Diffraction Limited Performance) Visual and Spectrographic Observation of Stars
	Orbital Altitude	300 naut. miles
	Lifetime	1 year
	Man's Participation OAO Gimbal-connected to AAP	
	Duration - - - - - - - - - -	approx. 30 days
	Tasks - - - - - - - - - - - -	Initial Checkout, Malfunction Correction, Photographic Operation of Telescope. Possible Rendezvous at Later Time With Gimbal Re-connection.
	Earliest Possible Launch - - - - -	1972