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# THE PINHOLE/OCCULTER FACILITY

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# THE PINHOLE/OCCULTER FACILITY

By H. S. Hudson, J. L. Kohl, R. P. Lin,
R. M. MacQueen, E. Tandberg-Hanssen,
and J. R. Dabbs



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**16. ABSTRACT**


A large occulting system in space can be used for high-resolution X-ray observations and for large-aperture coronagraphic observations in visible and UV light. The X-ray observations will combine high angular resolution in hard (>10 keV) X-radiation with the high sensitivity of a multiple-pinhole camera, and will permit sensitive observations of bremsstrahlung from nonthermal particles in the corona. The large-aperture coronagraphs have two major advantages: high angular resolution and good photon collection. This will permit observations of small-scale structures in the corona for the first time and will give sufficient counting rates above the coronal background rates for sensitive diagnostic analysis of intensities and line profiles for coronal structures in the solar wind acceleration region.

This document describes the technical basis for performing observations with a large occulting system in these three wavelength ranges. A preliminary description of a Pinhole/Occulter Facility presently being considered for Spacelab is given together with some indications about future developments.


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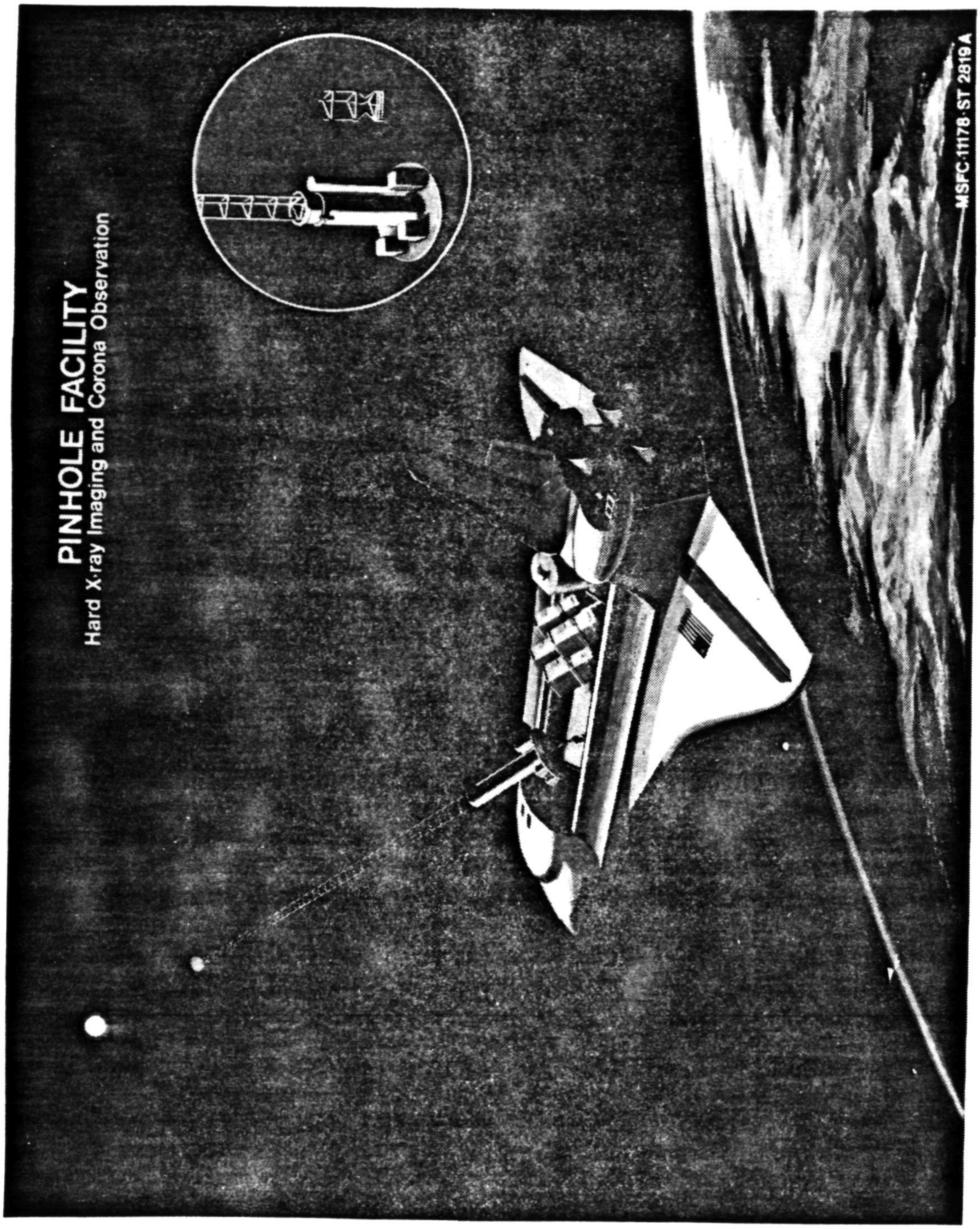

PINHOLE FACILITY
Hard X-ray Imaging and Corona Observation
MSFC-11178-ST 2819 A

TECHNICAL MEMORANDUM

# THE PINHOLE/OCCULTER FACILITY

## I. INTRODUCTION

The "pinhole facility" concept originated in a NASA study committee, the Hard X-Ray Imaging Facility Definition Team [1,2]; and in 1977 Marshall Space Flight Center (MSFC) conducted a preliminary technical assessment of the pinhole satellite concept. In 1978, the concept evolved to embrace a joint experiment that would include the X-ray pinhole aspect as well as a long focal length coronagraph, using the X-ray pinhole mask as a coronagraph occulting disk. Then with the dissolution of the Hard X-Ray Imaging Facility Definition Team, an ad hoc committee was formed in association with the continuing study effort at Marshall Space Flight Center. This group, consisting of the present authors, met during 1979 and provided the initial science definition to steer the ongoing engineering feasibility study. During the early phase Max Nein provided the liaison with MSFC's Program Development Directorate; later Joe Dabbs took over that role. In 1979, contracts were issued to Sperry Support Services, Huntsville, Alabama, and to Visidyne, Inc., Burlington, Massachusetts, to investigate boom dynamics with thermal and control analyses and the combined concept of X-ray pinhole experiment and coronagraph mounted on a boom from the Space Shuttle, respectively.

During the winter 1979-80, the definition study broadened, and for the mid-term status report review of the contracts the ad hoc committee was augmented by R. Blake, E. Fenimore, G. Fishman and N. Sheeley.

Finally, during the spring of 1980, the science definition had evolved to a stage at which NASA Headquarters considered it appropriate to constitute officially a Pinhole/Occulter Facility Science Working Group (P/OFSWG). With this group functioning, the ad hoc committee ceased to exist, and this document is the committee's report on which the P/OFSWG will continue to build.

Sections II through V set forth the scientific objectives of the pinhole/occulter facility, describe the basic concepts and their implementations, and present one possible strawman configuration of instruments. Section VI presents results of the initial feasibility studies and parts of the contract reports that are deemed particularly valuable in assessing the merits of the pinhole/occulter facility concept.

## II. SCIENCE RATIONALE

### A. Background

Observations from space over the past solar cycle have greatly altered our understanding of the various forms of solar activity. Plasma processes in high-temperature coronal regions, intimately connected with nonthermal, explosive plasma instabilities, appear to predominate in solar flares. The hard X-radiation (>10 keV) produced by the bremsstrahlung of energetic electrons appears to give our most direct observational access to these basic instabilities.

The solar corona appears to be far more inhomogeneous and transient than suspected earlier. Observations of the coronal base, especially from Skylab, demonstrated the ubiquity of closed loops of magnetically confined hot plasma as the basic structural component of solar activity; coronal transients also frequently display this form.

Combined visible and ultraviolet coronagraphic observations have recently demonstrated new plasma-diagnostic techniques for significantly advancing empirical descriptions of coronal structures for all regions above the coronal base. Such observations should lead to an improved understanding of the physical processes responsible for solar wind acceleration; coronal heating; mass, energy, and momentum transport; particle acceleration; and variations in chemical composition.

The pinhole/occulter concept represents an appropriate step in obtaining observational material that can build upon the achievements of this earlier work. It includes capabilities for X-ray and coronagraphic observations with unprecedented angular resolution and sensitivity. In the following sections we briefly review the observational setting for the development of the Pinhole/Occulter Facility.

### B. X-Ray Observations

The first systematic observations of solar X-radiation were made in the late 1960's when the satellites of the SOLRAD, OGO, and OSO series carried X-ray photometers and broad-band spectrometers (proportional counters and scintillation counters) that responded to flux from the whole Sun. These observations showed that the predominant solar-flare effects consist of an explosive energy release, characterized by hard X-radiation extending above 100 keV, and the simultaneous appearance of a sequence of magnetic loops containing high-temperature thermal plasma. The main H-alpha phase of a flare accompanies the decay of these X-ray loops, as seen most clearly in the Skylab observations (e.g., Sturrock [3]). The hard X-ray emission of the impulsive phase is characterized by rapid time variations, with time scales extending well below 1 sec. Based upon this preparatory work, the Solar Maximum Mission (SMM) carries a hard X-ray imaging spectrometer as a part of its well-coordinated experiment list.

These imaging X-ray observations, with a maximum angular resolution of 8 arcsec, have given the first direct view of the bremsstrahlung from the energetic electrons that are accelerated during the energy release in a solar flare. Another hard X-ray imaging instrument, on the Japanese ASTRO-A satellite launched in February 1981, will provide high-sensitivity observations but with relatively poor angular resolution.

The impulsive phase, marked by intense hard X-ray and microwave emissions, occurs at the time of the most powerful energy release in a solar flare. According to one nonthermal model for the impulsive-phase sources, the 10 to 100 keV electrons, accelerated by an as-yet-unknown plasma instability, contain the bulk of the flare energy later released in other forms. Future observations must obtain the highest possible angular resolution in order to link the bremsstrahlung sources with other diagnostic information; and they must have the highest possible time resolution, or equivalently in a photon-limited regime, the highest possible sensitivity. The gradual phase consists of loops filled with hot plasma that radiate thermal bremsstrahlung; these structures show the magnetic-field pattern in the corona, so that understanding the relationships between the impulsive-phase and gradual-phase sources may help us achieve a description of the plasma instabilities that make flares. Finally, the coronal transient excited by a solar flare may also contain a large fraction of its total energy. Such transients propagate to the Earth and beyond in favorable conditions, and in their passage induce various terrestrial effects. The majority of the transients appear to have loop structure, although on a grander and more dynamic scale than the compact, stationary loops seen in soft X-radiation in the flare proper. Recently, hard X-ray observations have confirmed the radio evidence that coronal disturbances of this type may cause the efficient acceleration of particles to high energies. Thus, the coordinated observation of the corona by X-ray and coronagraphic telescope becomes a further requirement for future progress.

The Pinhole/Occulter Facility offers us a chance to observe all of these sources with unprecedented angular resolution, 0.2 arcsec in the "strawman" configuration described later. This corresponds approximately to a spatial scale of 150 km on the solar surface, a size that matches the density scale height of the coolest layers of the solar atmosphere reasonably well. At the same time, the P/OF concept will give large-area detection systems with a corresponding increase in sensitivity and effective time resolution. The ability of imaging observations to distinguish individual source regions will make it worthwhile to obtain increased sensitivity, so that the fainter sources (for example, those in the corona) can be studied, free of interference from the brighter sources. In the P/OF concept, greater sensitivity is very easy to achieve, simply by increasing the detector area. Thus, the P/OF capability for X-ray observations should greatly improve upon the present-day capability in every category.

## C. Coronagraphic Observations

The past decade has truly overturned most of our previously held ideas about coronal structure. This has resulted from observations with spaceborne coronagraphs, soft X-ray telescopes, and UV and XUV instruments (e.g., Sturrock [3]). The brightest parts of the lower corona are confined in low-lying loop structures. Instead of stationary expansion, a wide variety of transient variation occurs. Coronal holes have been identified as the source of the high-speed solar wind streams. In addition to the traditional concept of coronal heating from waves generated in the convection zone, the role of magnetic heating from dissipation of currents or magnetic-field reconnection is being investigated, the former producing quasi-stable heating and the latter being associated with more dynamic plasma instabilities [4].

A large-aperture coronagraph would represent an enormous gain in spatial resolving power as compared to previous instruments and, hence, would permit the study of small-scale phenomena throughout the inner corona. Observational clues of the existence of such structures in the corona above 1.5 solar radii have begun to emerge. Measurement of the scintillations of radio waves passing through the corona are interpreted as originating in fluctuations of density and/or magnetic field at the sub-arc-second scale [5,6,7]. In addition, detailed examination of the highest resolution coronagraphic observations of the Skylab mission indicates the presence of unresolved fine-scale structure well connected with the transport of mass in discrete coronal features and the evolutionary patterns of those features [8].) The origin of inhomogeneities in coronal processes is unclear; they may, however, prove to be direct tracers of the acceleration of the solar wind, possibly provide definite evidence for the role of turbulent convection in the low corona, or yield information regarding the possible role of magnetic reconnection as the agent of coronal heating.

Another principal motivation for large-aperture coronagraphs arises from their capabilities as superior light collectors. The recent development of a coronagraph capable of observing intensities and line profiles of ultraviolet resonance lines [9] represents an important step in our ability to interpret certain physical variables of the coronal medium. Indeed, initial considerations and measurements [10,11,12] indicate that combined measurement of profiles and intensities in the ultraviolet and the intensity of Thomson-scattered radiation in visible light can provide an important new tool for determining temperatures, densities, and flow velocities in solar coronal structures. The early instruments, however, are inevitably limited in their capabilities because of their small scale; this is the result of the small-scale occulting geometries available on ordinary space platforms.

A large-scale occulting system permitting the use of a large-aperture coronagraph would make available the light-collecting capacity required to study a diverse set of spectral lines at wavelengths throughout the ultraviolet spectral region. Spectral lines from parent ions of different masses and different masses plus different ionic charge are required to determine electron, proton, and ionic densities, mass flow and turbulent velocities, and chemical composition. Such measurements will provide a broad set of UV plasma diagnostics leading to a much more complete empirical description of coronal structures located between the coronal base and several solar radii from Sun center. Of particular interest are measurements of the electron-scattered component of the coronal HI Lyman-alpha spectral line, which is about three orders of magnitude less intense than the resonantly scattered component and, hence, can only be observed in extremely low resolution (both spatial and spectral) from a standard size coronagraph [13]. Observations at much higher spatial resolution will be possible with a large occulting system, permitting unique determinations of the electron temperature of relatively small-scale structures out to several solar radii from Sun center. Observational advances in time resolution, spatial resolution, and background suppression also exist for the observation of resonantly scattered Lyman-alpha and other spectral lines. For example, observations in Lyman-alpha out to several solar radii with 1 arcsec resolution are feasible with a large occulting system.

A total eclipse of the Sun also provides some of the same advantages. Such observations have provided a rich and varied background for the investigation of the solar atmosphere. At a typical eclipse, the visible sky brightness during totality is on the order of $10^{-9}$ $B_o$, where $B_o$ is the mean radiance of the solar disk. Under these conditions, the electron- and dust-scattered solar corona may be observed by ground observers to a number of solar radii above the solar limb. Particularly, the geometry of a solar eclipse permits observations down to the innermost solar coronal regions without spurious scattered radiation. Unfortunately, the unique circumstances of a solar eclipse are not optimum with respect to observations of small-scale coronal phenomena – the very presence of the lunar shadow sufficiently perturbs terrestrial atmospheric conditions so as to cause rather extreme turbulence. Thus, typically, it is impossible to achieve effective spatial resolution during a total eclipse in excess of approximately 5 arcsec. Further, as is obvious, the opacity of the Earth's atmosphere in the ultraviolet forbids any observations in that important spectral region, and UV observations during eclipse have extremely limiting time constraints.

## III. THE PINHOLE/OCCULTER CONCEPT

The basic idea consists of placing the occulter at a great distance from the detectors or coronagraph optics. For X-radiation, as shown later, this large separation translates directly into better angular resolution; for coronagraphs, the result is a wider umbral region in the shadow of the occulter. The separation between the parts of the telescope can be maintained by a long boom, or the occulter system and detector system can be placed on separately maneuverable subsatellites. The X-ray and coronagraphic portions of the occulter may be side-by-side; the X-ray mask may, of course, be opaque to optical and ultraviolet radiation.

The essential elements of the X-ray "optics" consist of an aperture-encoding mask with an appropriate pattern of small holes, and a position-sensitive detector array. A second mask just in front of the detector array is also necessary for some types of imaging, as described later.

## A. X-Ray Imaging

The basic technical concept involved in the Pinhole/Occulter Facility is the use of a large separation between the optical elements. For X-rays, a simple pinhole camera provides an illustration: the longer the baseline, the sharper the image becomes. The ultimate limitation for X-rays is the Fresnel diffraction limit, for which

$$\theta_f \approx \sqrt{\lambda/D} \quad ,$$

with D the separation between the mask (containing the pinhole or array of pinholes) and the detector; the latter must have position sensitivity comparable to the geometrical size of the pinhole.

An alternate X-ray imaging scheme, the modulation collimator, can give high angular resolution without requiring excellent position sensitivity within the detector. This approach [14] has recently been shown [15,16] to permit full imaging information. The use of these two approaches in a Pinhole/Occulter Facility concept is described in slightly more detail in the following subsections.

### 1. High-Resolution X-Ray Imaging

To obtain high angular resolution with a limited distance between the mask and the detector array requires the use of a second mask, as originally suggested for the "modulation collimator" by Oda [14]. Modern derivatives of the modulation collimator do not require mechanical scanning. However, to yield imaging information requires that the frontal area of the telescope be partitioned into subcollimators, each with a different pattern of slit apertures. Each subcollimator effectively modulates the source angular structure to provide a measurement of one Fourier component, just as in an interferometric radio telescope [16]. One then obtains angular data — a map — by calculating the Fourier transform of the raw data. In practical configurations it is inefficient to have more subcollimators than the structural information in the source would warrant, since the total area of the X-ray counters is divided among these subcollimators. Therefore, in general this system should be used only for the highest angular resolution. The diffraction limit corresponds to tenths of an arcsec (FWHM) for tens of meters separation.

2. Coronal X-Ray Imaging

The simple pinhole camera suffers from low throughput; therefore, it is preferable to have a multiple-pinhole array [17,18,19]. Recently an optimum configuration for the pinholes was invented [20,21] that cancels the random noise that must appear in a random pattern of holes. The resulting reconstructed image (e.g., Fenimore [22]) exhibits the desirable properties of a true imaging system in terms of its point response function.

The Pinhole/Occulter Facility will use a system of this type to obtain images of the whole Sun, with the high sensitivity given by the excellent throughput of a multiple-pinhole system, to observe coronal phenomena. Because the angular resolution is limited in this approach by the position sensitivity of the counters, an angular resolution better than a few arc seconds is unlikely for spacings of a few tens of meters.

## B. Coronagraphs

The basic advantage provided by the large separation of optical elements is the possibility of using a large aperture for the coronagraph optics. Not only is the diffraction limit improved, but also the total collecting area increases, with a subsequent improvement in the counting-statistics limit of the signal-to-noise ratio. We describe briefly the role of the occulting geometry in a coronagraph, to explain the fundamental differences between the concept proposed here and the relatively small coronagraphs that have flown on OSO's, the ATM, the P-78-1 satellite, and sounding rockets.

1. White-Light Coronagraphs

An externally occulted coronagraph effectively vignettes the incident coronal light, with the degree of vignetting depending upon the radial height in the corona. The action of the vignetting may be visualized in the following way: rays emanating in the outermost (unvignetted) coronal regions have an unimpeded path to all elements of the coronagraph objective lens, and effectively ignore the presence of the external occulting disk. However, rays arising from coronal regions closer to the solar limb only illuminate an unshielded portion of the coronagraph objective. The innermost rays that may reach the objective lens (a limit set by the occulter-objective distance and the radii of both elements) only illuminate a vanishingly thin crescent of the objective lens. The vignetting has two major consequences: first, it tends to counteract the radial decrease of coronal brightness, a useful effect; and, second, it degrades the spatial resolution in the inner corona.

External occulting is essential in spaceborne coronagraphs; otherwise the inherent body and surface scatter in objective lenses and mirrors would completely mask all but the innermost coronal regions. Present designs for spaceborne coronagraphs employ either multiple disk assemblies or a single toothed disk (the latter "apodizes" the occulter and reduces the contribution of diffracted light from its edge); the net stray radiance at their focal planes is typically several times $10^{-10}$B, adequate for observations in the range 6 to 10 solar radii. It is important to note that further reduction in the stray light is only marginally important, since the contrast of features in the outer corona is determined mainly by the background from the dust-scattered K-corona.

2. Ultraviolet Coronagraphs

Coronagraphs intended for spectroscopic work at shorter wavelengths must meet requirements for stray-light suppression, spectral resolution, and photon collection at the wavelengths of interest. The resonant-scattered component of HI Lyman-alpha tends to set the on-band stray-light requirement for the instrument because of the high intensity of the chromospheric HI Lyman-alpha relative to the coronal intensity. A stray-light signal corresponding to $10^{-8}$ of the on-band disk intensity is sufficient. The requirement for stray-light suppression at off-band wavelengths is much more severe than that of a visible-light instrument and is set at each wavelength by the low intensity of coronal lines and by the intensity of the coronal electron-scattered component of the Lyman-alpha line. The spectral resolution requirement is determined by the shape of each spectral line, which strongly depends on the mass of the parent nucleus. Spectral resolution, spatial resolution, signal-to-detector-background-count ratio and height of the observed region above the solar limb all influence the time interval required for each measurement. For the UV coronagraph, it is the photon-collection requirement that determines the utility of the instrument. Many spectral lines are unobservable in the practical sense with normal size occulting systems; for all other spectral lines, the spatial resolution element is large compared to known sizes of coronal substructures. Except for the strongest lines, the time resolution of normal size systems is inadequate for the study of transient phenomena. A Pinhole/Occulter Facility with, for example, a 50-m occulter-to-collector distance would provide a 20-fold increase in light-collection capability over the existing sounding rocket instrumentation and the UV coronagraph planned for Spacelab. For the study of transient phenomena in particular, but also for stable features, it will therefore be important to have large-collector optics for the ultraviolet region.

In the future, it may become desirable to attempt coronagraphic X-ray observations, with the occulter serving the same purpose as at longer wavelengths in reducing the effects of bright sources on the solar disk.

# IV. IMPLEMENTATION

The successful implementation of the Pinhole/Occulter Facility concept requires some means of maintaining the separation between the occulter, which contains the coronagraph occulting disk and the X-ray pinhole array, and the detector array. The actual distance between the two subsystems is of secondary importance, but the direction defined by reference marks on the occulter and detector array is crucially important. Section IV.B presents strawman data for the precision of position and knowledge of position for the occulter-detector separation vector.

Ultimately, the largest separations will require the mounting of the occulter and detector subsystems on separate free-flying vehicles. This may ease the attitude sensing and control problems because of the absence of a complex connecting structure. This, nevertheless, represents a far more elaborate approach to implementing the P/OF than a semi-rigid boom separator, if the latter can be shown to be feasible.

We, therefore, consider as an initial version of a Pinhole/Occulter Facility a boom mounting, and further assume for purposes of definition that the boom will be extended from the bay of the Space Shuttle and that it will be pointed with a pointing subsystem comparable to that of the Spacelab. In Section IV.A we briefly describe the boom-mounted P/OF concept, and then in Section IV.B consider some of the key technical areas. Figures 1 and 2 depict the facility in the stowed and deployed positions, respectively.

## A. Boom Configuration

Table 1 presents the scientific and engineering parameters of a P/OF using a 50-m semi-rigid boom, as they are best defined at present. We emphasize that this configuration is a true "strawman" concept, useful for planning and for the verification of engineering details. It is quite likely that the configuration and the instrument complement of the Pinhole/Occulter Facility will differ from the parameters given in Table 1.

## B. Technical Problem Areas

The key technical problem areas associated with the P/OF concept lie in the field of attitude sensing and control. The requirements for the boom-mounted version of the P/OF discussed here are summarized in Table 2. Again, these numbers are tentative and should not be interpreted as definitive in any sense, pending the outcome of feasibility and scientific tradeoff analyses now under way.

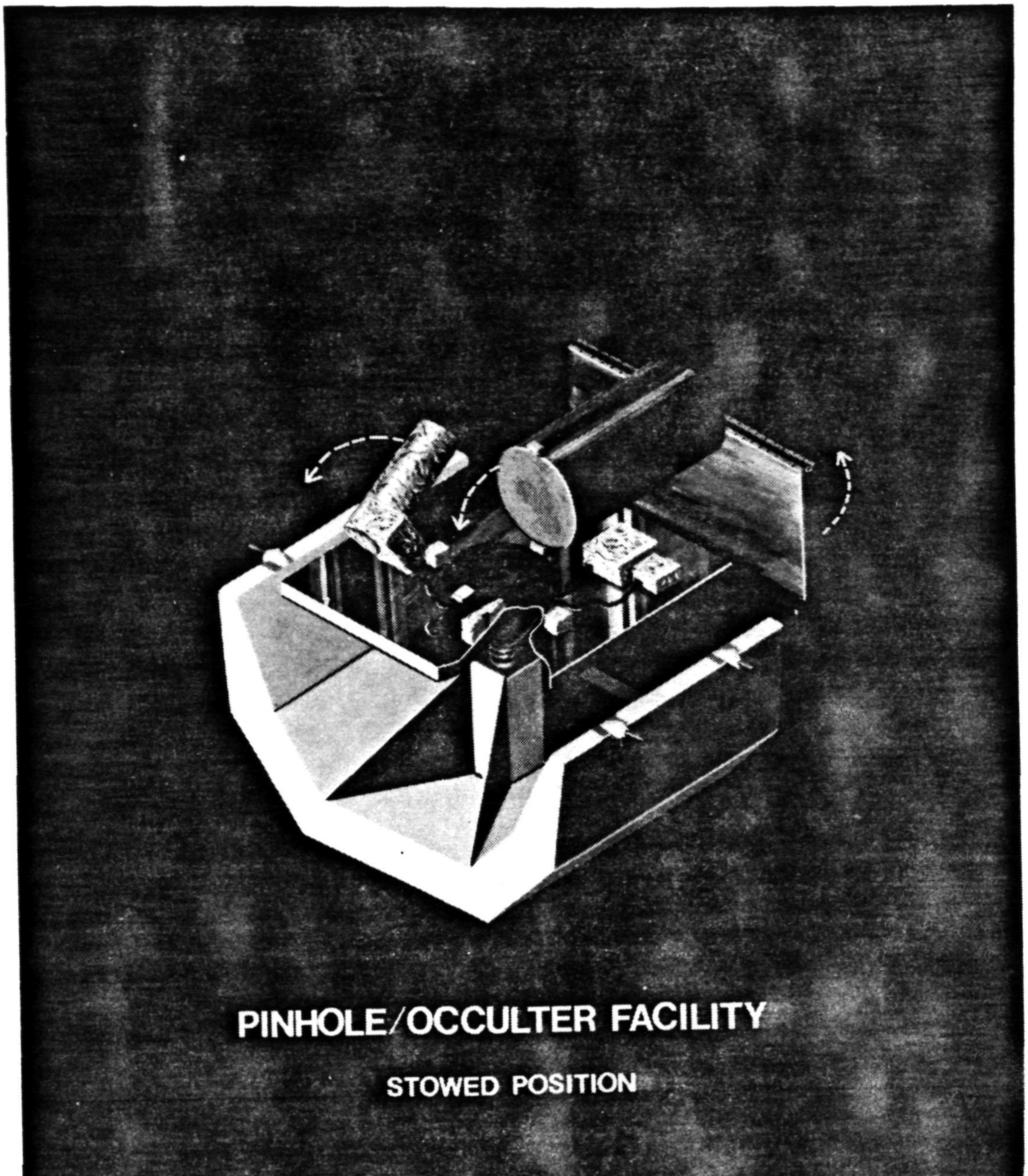



Figure 1. Pinhole/Occulter Facility in stowed position.

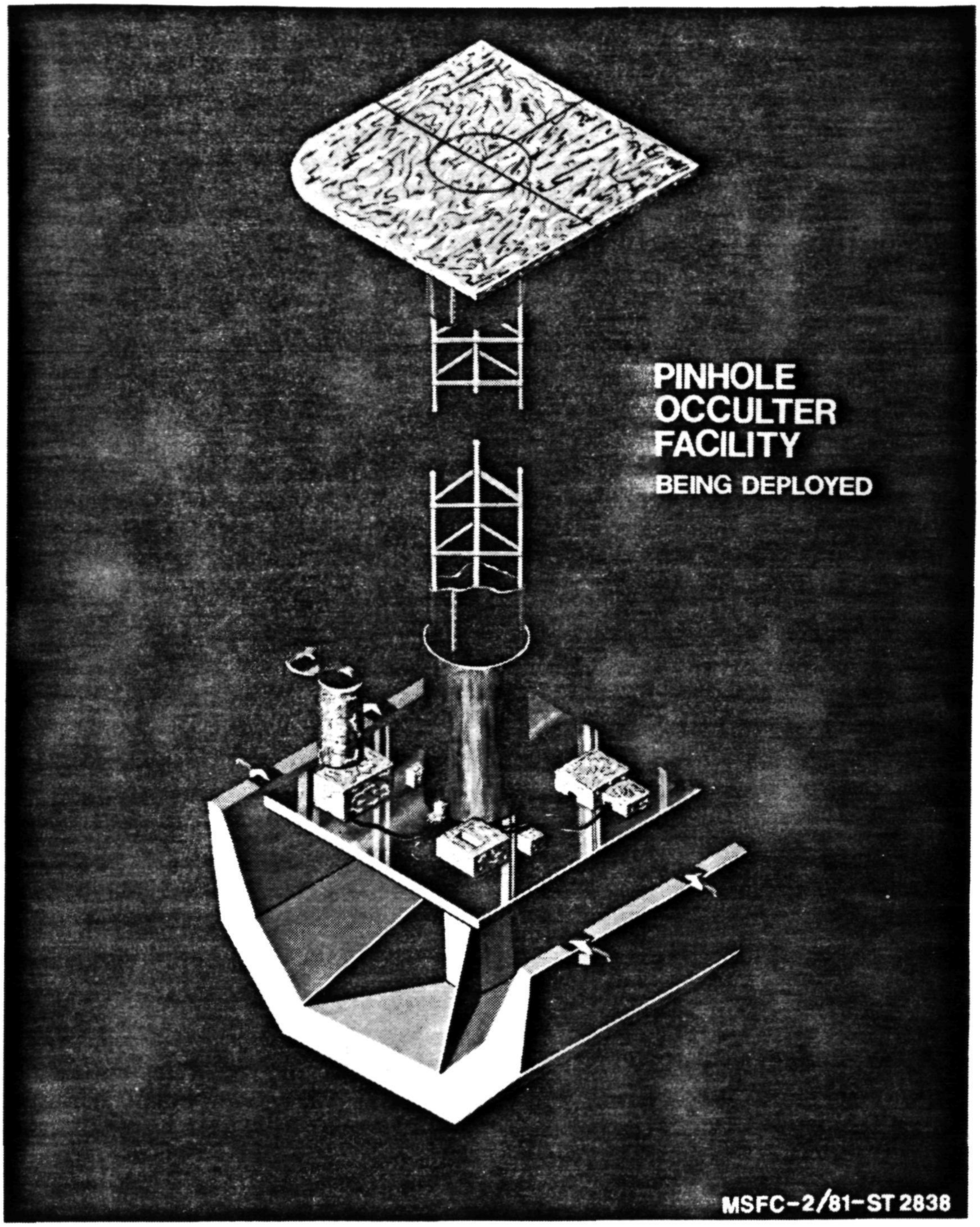



Figure 2. Pinhole/Occulter Facility in deployed position.

## TABLE 1. A TENTATIVE PINHOLE/OCCULTER FACILITY

| | |
|---|---|
| A. Instrument Complement | |
| 1. High-Resolution X-Ray Telescope | |
| a. Angular Resolution | 0.2 arcsec |
| b. Field of View | 3 arcmin |
| c. Detector Area | 3000 $cm^2$ |
| d. Optics Type | Fourier-Transform |
| 2. Wide Field X-Ray Telescope | |
| a. Angular Resolution | 20 arcsec |
| b. Field of View | 1 degree |
| c. Detector Area | 3000 $cm^2$ |
| d. Optics Type | Coded Aperture |
| 3. White-Light Coronagraph | |
| a. Aperture | 50 cm |
| b. Occulter | Semicircular |
| 4. UV Emission-Line Coronagraph | |
| a. Aperture | 50 cm |
| b. Occulter | Linear |
| B. Boom Properties | |
| 1. Length | 50 m |
| 2. Diameter | 1 m |
| 3. Tip Mass | 25 kg |
| C. Pointing Control System | To Be Determined |

## TABLE 2. POINTING REQUIREMENTS

| | Coronagraphs | X-Rays |
|---|---|---|
| Pointing Stability | 10 arcsec rms | 20 arcsec rms |
| Roll Stability | TBD | 20 arcmin rms |
| Knowledge | 0.3 arcsec absolute | 0.3 arcsec absolute<br>0.05 arcsec relative |
| Absolute Sun-Mask-Optics/sensor roll accuracy[a] | -2° | |
| Absolute Sun-Mask-Optics/sensor alignment accuracy (pitch and yaw) | ±10 arcsec | |
| Sun-Mask-Optics/sensor alignment stability (pitch and yaw) | ±4 arcsec | |
| Sun-Mask-Optics/sensor alignment knowledge (pitch and yaw) | ±4 arcsec | |
| Sun-Optics/sensor stability (pitch and yaw) | ±0.3 arcsec | |
| Sun-Optics/sensor knowledge (pitch and yaw) | ±0.3 arcsec | |

a. Roll stabilities and knowledge provided by pitch and yaw required.

1. Attitude Sensing

Knowledge of the pointing direction is the key technical problem for a high-resolution telescope. The sub-arc-sec resolution achievable by the P/OF places it in the same category as the Space Telescope and the Solar Optical Telescope (SOT), with comparable problems in obtaining knowledge of the spatial location of the field of view. The adequacy of the solar limb as a reference for aspect sensing needs to be examined. Data from the SOT may be essential in this regard.

2. Attitude Control

A boom-mounted P/OF operated from the Spacelab will use an attitude control system. This may be the Instrument Pointing Subsystem (IPS) furnished as a part of the Spacelab, or an equivalent device with comparable capability. The preliminary feasibility study carried out at MSFC has shown that the IPS is capable of meeting the requirements listed in Table 2.

## V. OPTIONS FOR THE FUTURE

The Spacelab version of the Pinhole/Occulter Facility will lead naturally into more advanced systems with new scientific objectives. In particular, the field of high-energy astrophysics can benefit from the special virtues of the remote occulter, as described briefly later. For solar purposes, the real fruition of the P/OF development can only take place when it is incorporated into an observatory configuration with the appropriate instrumentation for the comprehensive study of specific problems.

### A. X-Ray and Gamma-Ray Astronomy

The X-ray portion of the P/OF instrumentation will consist of large-area, low-background counters with high-resolution imaging capability. The angular resolution, in fact, will exceed that of any telescope presently planned for nonsolar X-ray astronomy. Numerous applications of this instrument will, therefore, be desirable. Some of these are described very briefly in this section.

1. Galactic X-Ray Astronomy

Recent observations, especially from the HEAO satellites, have shown that our galaxy contains a wide variety of X-ray sources. One of the greatest surprises has been the discovery of stellar X-ray emission from stars of many spectral and evolutionary types. This has led to new theories for the heating of stellar coronae to X-ray temperatures. Of course, the "zoo" of very peculiar objects – compact binary systems, black hole candidates, pulsars, and singular objects like SS 433 – has increased in membership.

The high angular resolution obtainable by P/OF is probably unnecessary for the observation of these essentially point-like objects. This is because the "confusion limit," defined as the angular resolution needed to avoid the chance of having more than a single source in one image element simultaneously, is very large at these photon energies. Furthermore, sub-arc-sec resolution is probably not warranted for the identification of the counterparts of the X-ray sources at other wavelengths, at least insofar as present ground-based optical astronomy is concerned. For stellar observations, then, the principal advantages are in spectral coverage and in observations of transient effects. Where imaging is needed, perhaps in crowded stellar fields, the P/OF format permits an easy means of changing the imaging parameters, since these are determined fully by the pinhole arrays.

For extended sources, however, the full resolution of the P/OF as set by the diffraction limit will be desirable. One obvious candidate for such observations is the Crab Nebula, specifically the relationship between the pulsar and the diffuse sources. The Galactic Center region also needs observation with high resolution in X-radiation.

2. Extragalactic X-Ray Astronomy

The high angular resolution achievable by the P/OF approach, as well as its capability for observations in the hard X-ray energy range, make it very suitable for the exploration of extended sources in active galaxies. These sources consist of high-energy particles normally detected by the techniques of radio astronomy, and they range in size from many degrees to the milli-arc-sec sources observed by very long baseline interferometry. In analogy with the comparable synchrotron emitters in solar flares, simultaneous radio and X-ray observations (with imaging) provide the strongest constraints upon the theories.

3. Gamma-Ray Astronomy

It is premature to discuss gamma-ray astronomy in general; observations of solar gamma-ray emission (e.g., Chupp et al. [23]) have just begun in earnest with the launch of the Solar Maximum Mission, and nonsolar gamma-ray astronomy awaits the Gamma-Ray Observatory, tentatively planned for the 1980's.

Nevertheless, it should be pointed out that the P/OF concept affords the only known practical means of imaging gamma radiation [1]. The imaging of solar sources may already be desirable, since only the gamma radiation directly gives information about the high-energy protons in solar flares.

### B. Free-Flying Platforms

A free-flying version of the P/OF has several advantages. First, any observations of solar activity will continue to provide new discoveries even after the initial operation, because of the transient nature of the phenomena. Thus, for example, it would be quite unlikely to be able to observe a white-light flare in a 2-week mission, simply because the probability of occurrence of white-light flares is relatively small even at solar maximum. Second, freedom from the constraints of the Spacelab environment offers several advantages for the extension of P/OF's capability for achieving its scientific objectives.

The Spacelab environment includes at least two possible sources of interference: (1) a presently unknown level of gas and particle contamination, potentially injurious to P/OF coronagraphic observations because of light scattering and because of the danger of contamination of the optics, and (2) mechanical disturbances – thruster firings or man motions which will perturb the attitude control system. Also, the control of a boom by the application of torques at one end, as in the Spacelab concept for P/OF, will have a practical size limit. A free flyer does not have this restriction, although of course other problems must arise. However, to achieve the ultimate angular resolution dictated by Fresnel diffraction, a long baseline is unavoidable.

Solar observations have evolved from investigations with single instruments to coordinated measurements on a broad scale, in observatories such as Skylab/ATM and the Solar Maximum Mission. This is necessary because of the structural complexity of the solar phenomena and the need for simultaneous observations of different types and in different spectral bands. Thus, the efficient extension of P/OF scientific work will, no doubt, see it included in a solar observing facility permanently stationed in orbit. The desirable accompanying instrumentation could be almost anything, but the Solar Optical Telescope with appropriate focal-plane instrumentation would probably be essential. The resources of Spacelab are not sufficient to maintain such an advanced solar observatory with multiple large instruments, so the subsequent evolutionary stages of the P/OF will surely be in such a free-flying observatory.

## VI. FEASIBILITY STUDIES AT MARSHALL SPACE FLIGHT CENTER

### A. Background

The Marshall Space Flight Center conducted a short preliminary technical assessment of the Pinhole Satellite concept in the spring of 1977. Based upon that assessment, the concept appeared feasible, but no attempt was made to address costing of the program. The assessment considered the free-flying solar mask and the free-flying detector configurations, with the other component attached to Spacelab. Both concepts appeared to have advantages. Specifically, the free-flying solar mask appears desirable in that instrument complements could be augmented by other solar-viewing experiments, and data retrieval would not require RF links. In addition, recovery of the mask/free-flyer system could be deferred by having a refueling capability and leaving the mask/free-flyer in orbit for future use.

The primary advantage of the free-flying detectors is a lower mass package and reduced RCS propellant requirements. In general, it was found that the station-keeping RCS propellant mass for a 6-day mission would equal about one-half that of the free-flyer system mass.

No considerations were given to the problems of RCS plume impingement on the field of view of other solar-viewing instruments or to the general contamination problems associated with continuously operating RCS thrusters.

The assessment did point out the possible need for development in areas such as pointing and alignment sensors, vernier thrusters, and, possibly, cold gas RCS systems.

The development of a separate free-flying subsatellite for use by the solar mask or the detectors is very costly, especially when it is necessary to start from scratch. If the Teleoperator had been developed, it might have served as a base from which to build a specialized free-flyer for the pinhole experiment. In the meantime, it became obvious that the solar mask would also be very useful for studying the solar corona, and increased interest was generated in an experiment using a mask deployed from the Orbiter by an extendable boom.

The boom-mounted configuration seemed to offer a lower cost program with possible growth into the longer baseline free-flyer program eventually. A key consideration was the stability and controllability of a long (up to 100 m) deployable boom with a heavy mask located at the tip. Subsequently, a contract was initiated with Sperry Support Services to investigate boom dynamics. This contract was a joint funding endeavor, with approximately 50 percent of the funding from the Office of Space Science (OSS) Advanced Studies program and 50 percent from the Office of Space Transportation Systems (OSTS).

## B. Sperry Study

The objective of the Sperry Support Services study (NASA, MSFC Contract NAS8-33588, August 1979 to February 1980) was twofold. The first objective was to install and check out at MSFC the Sperry Interactive Modeling System (SIMS) computer program, for use in the analysis of large, flexible space structures.

The second was to perform preliminary analysis of the Pinhole X-Ray/Coronagraph Experiment conceptual design, for the purpose of establishing feasibility of control and pointing. These analyses were to utilize the SIMS program and to illustrate its use for performing an integrated structural/thermal/control analysis.

Using SIMS, the pinhole experiment was evaluated for the structural dynamic characteristics, thermal distortion and controllability. The integrated analysis was made possible through the use of a common mathematical model, which was developed using SIMS. During the study, several parameters (which characterize the experiments and deployable boom) were varied and the resulting effect on boom dynamics evaluated.

The deployable boom concept was evaluated parametrically for lengths of 15, 30, and 50 m; tip shield mass of 6.424 to 505.7 kg (mask density = 2 $g/cm^2$ to 30 $g/cm^2$ and X-ray detector diameter 0.5 to 1.0 m); boom radius of 0.2286 to 0.9256 m; and boom bay height of 0.555 to 1.45 m. The range of mask density corresponds to X-ray and gamma-ray energies up to a few MeV. The boom was attached at the Shuttle center of gravity; and natural frequencies, mode shapes, and forced response were calculated (Figs. 3 and 4 ).

The interactive graphics program, SIMS, was used to develop the finite element models, and NASTRAN was used to perform the normal mode and the forced response analyses.

The pinhole boom finite element model is a triangular framework of bending members (longerons) and tension members (battens and diagonals). The longerons are the triangle corners and are parallel to the structure's longitudinal axis, and the battens divide the boom's length into bays. The diagonals criss-cross the faces of each bay. Because this was a parametric study, several models were generated. For clarity a typical model is shown in Figure 5. The battens and diagonals were assumed to be pinned to the longerons, and each bay's mass was concentrated at a point on the centerline and attached to the structure by massless rigid links.

The vernier thruster loads for the forced response analyses were obtained from a study by NASA/MSFC's Systems Dynamics Laboratory (ED13). A small time slice of one orbit was used to evaluate the magnitude of the disturbance of the boom tip.

Of all the parameters studied, boom length and tip shield mass had the greatest influence on the dynamic response of the boom and, therefore, on its control stability and pointing accuracy. Figure 3 illustrates the variation of the boom's first natural frequency as a function of boom length and tip mass. Only a very preliminary control analysis was conducted in this study, and its scope was limited by study resources. However, based upon the dynamics defined in this study, further effort has been undertaken to define the control requirements for a boom-mounted system. This is an ongoing study and will be discussed later. Results of the study are summarized in the final report entitled "Sperry Interactive Graphics System (SIMS) and Its Application to Control Simulation of the Pinhole X-Ray/Coronagraphic Experiment," Sperry Support Services, 13 March 1980.

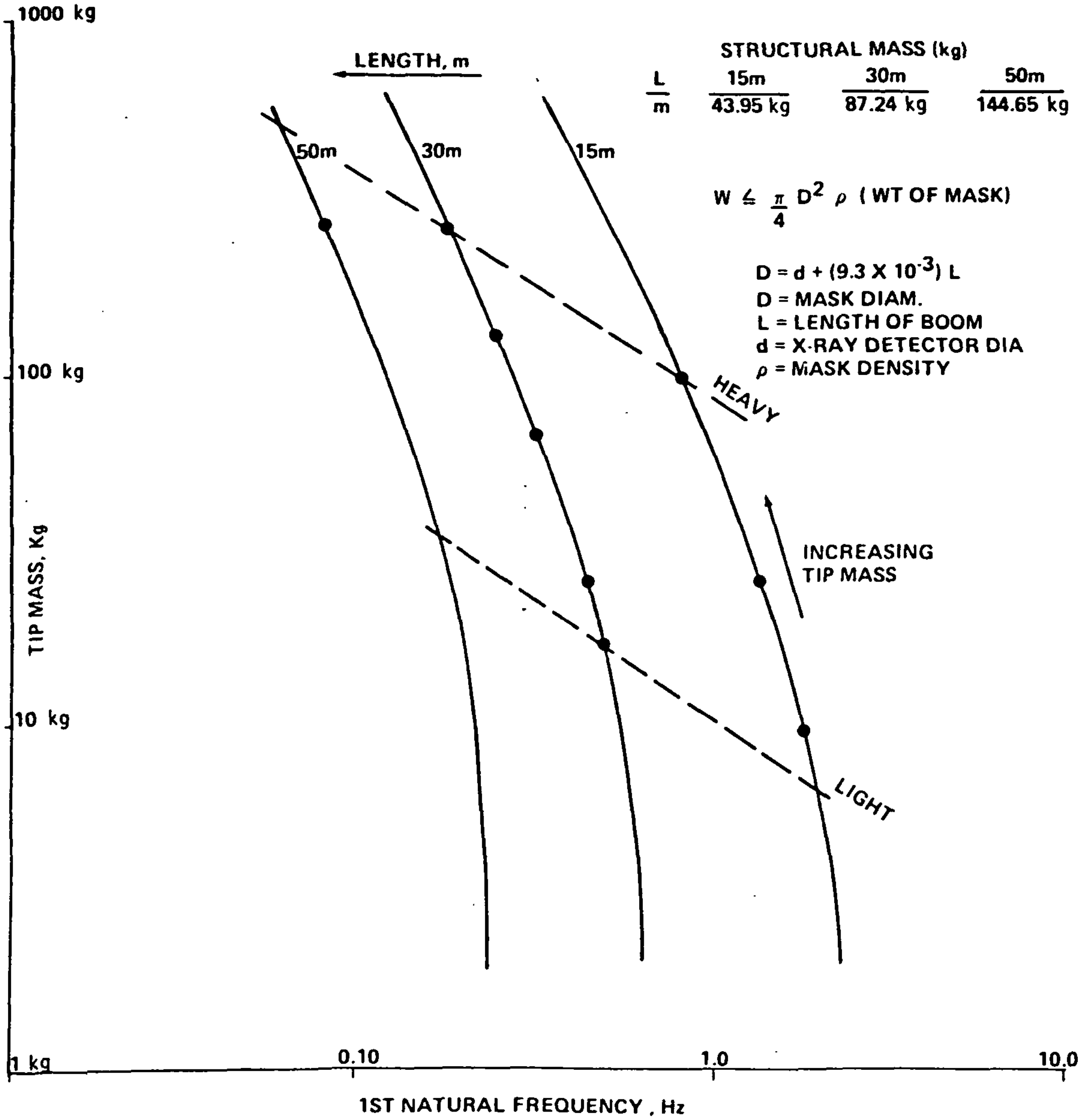



Figure 3. Boom frequency as a function of tip mass and boom length.

C. Visidyne Study

A number of problem areas were identified as being crucial to the use of the mask as a coronagraph occulter. To investigate the problems and possible trade-offs, a contract was awarded to Visidyne Corporation (NASA, MSFC Contract NAS8-33697). This study was concerned with parametric evaluation of coronagraph designs considering boom length, occulter design, camera aperture, and calculated diffracted light levels. Minimum limb observing angles and diffraction-limited spatial resolution were desired for a wide range of the preceding parameters. Families of graphs were plotted; Figure 6 is representative of this part of the study.

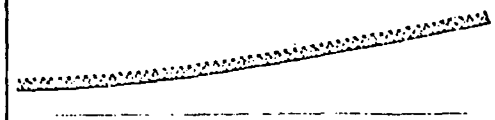
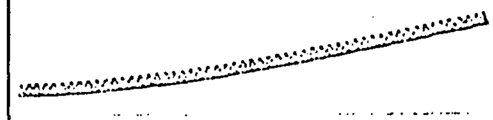
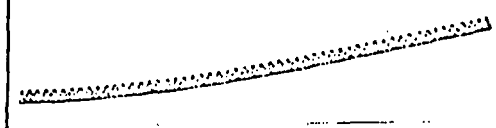
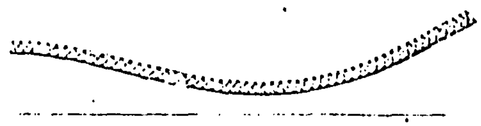
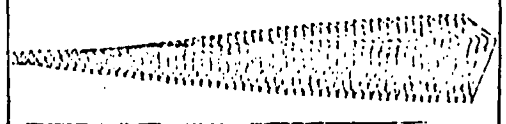
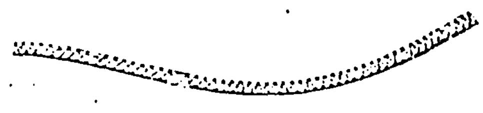
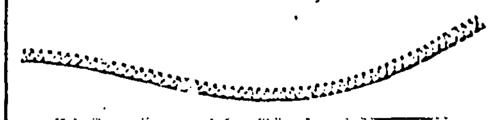
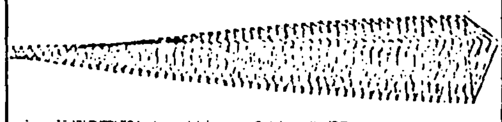
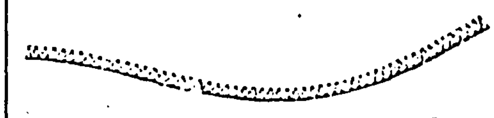
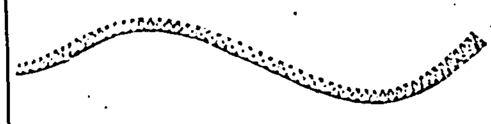
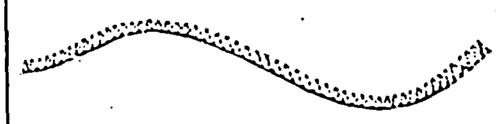
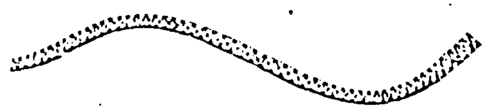
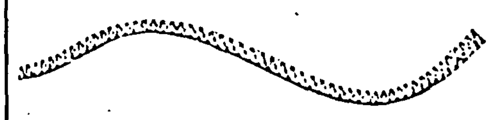
| MODE NO | L=30 METERS, TIP MASS = 249.5 KG | | L= 50 METERS, TIP MASS = 505.7KG | |
|---|---|---|---|---|
| | FREQ (HZ) | MODE SHAPE | FREQ (HZ) | MODE SHAPE |
| 1 | .18 |  | .058 |  |
| 2 | .1965 |  | .058 |  |
| 3 | 2.78 |  | .99 |  |
| 4 | 2.78 |  | 1.01 |  |
| 5 | 4.94 |  | 1.01 |  |
| 6 | 8.62 |  | 3.17 |  |
| 7 | 8.96 |  | 3.18 |  |

Figure 4. Pinhole boom frequencies and mode shapes.

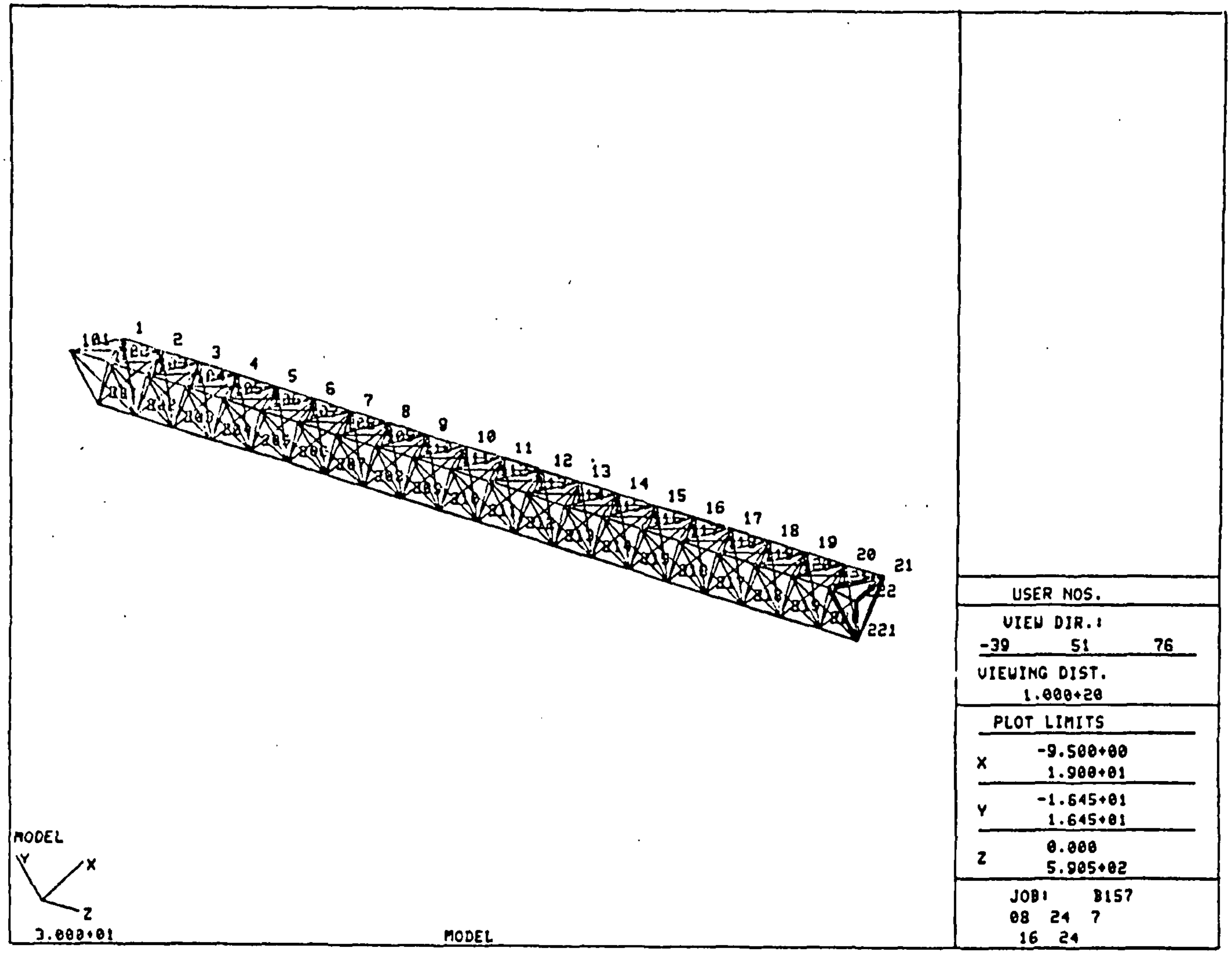



Figure 5. Typical pinhole deployable boom.

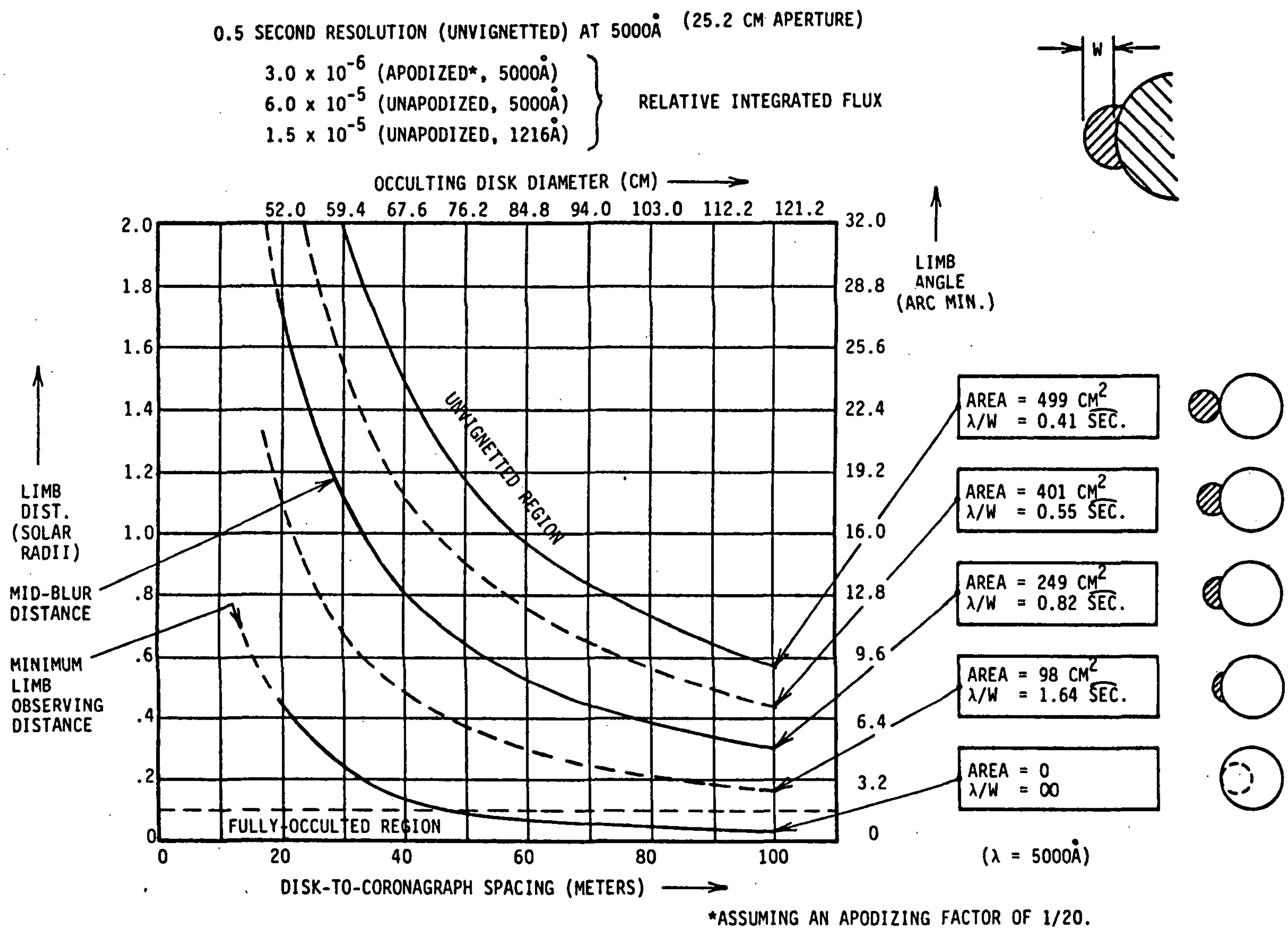



Figure 6. Parametric evaluation of coronograph designs.

Also, in this study, calculations were made of the expected stray light levels in the white light and UV coronagraphs due to solar radiation scattered along various paths involving the Earth, the Shuttle, and the rear surface of the occulter. Two general cases were considered: the backlighted case, in which radiation from the fully illuminated Earth falls on the rear surface of the occulter; and the side-lighted case, in which the spacecraft is directly above the Earth's terminator. These two cases can be considered to be at, or near, opposite extremes of the possible illumination geometries. In these calculations, a 200-n.m. orbit was assumed.

There are a number of possible techniques for suppressing the stray light illuminating the back of the occulter. The back of the occulter may simply be given a nonreflective surface, such as a diffuse black coating, or the portion of the occulter directly above the coronagraph may be formed into a concave spherical black mirror whose center of curvature coincides with the coronagraph entrance aperture. Other minimizing techniques were also considered.

Figure 7 shows the principal stray light paths into the entrance aperture of the white light coronagraph for the backlighted case (in which the Earth and Sun lines are approximately 180° apart, as seen from the Shuttle). In Path A, sunlight reflected from the Earth illuminates the back of the occulter and then passes into the coronagraph optical system. In Path B, sunlight reflected from the Earth scatters off the boom and then into the optics. In Path C, the sunlight reflects from surfaces of the Shuttle and then adds to the illumination of the back side of the occulter.

In the backlighted case, the stray light calculations for Paths A and C can conveniently be combined. This is because, as viewed from the back of the occulter, the outline of the Shuttle will fall within the illuminated disk of the Earth, and the reflectances of the Earth and the Shuttle can be considered to be comparable (on the order of 0.50). Thus, if the Shuttle were completely removed from view, the additional Earth light which had been blocked by the Shuttle will approximately compensate for the illumination previously received from the Shuttle surfaces.

Considering typical values for a 50-m boom deployed from an orbiter in a 200-mile orbit, backlighted case and with a low reflective surface on the mask (on the order of 0.03), we find stray light levels on the order of $10^{-7}$ $B_o$, which is considered satisfactory with modern low-scattering coronagraph optics. Satisfactory values were also found for the side-illuminated cases.

The third area considered by this study was aspect sensing and pointing requirements and identification of techniques to satisfy these requirements. Since the pointing, alignment and aspect requirements are currently being reviewed, a discussion of this area is deferred. The interested reader is referred to the study final report, "Pinhole X-Ray/Coronagraph Optical Systems Concept Definition Study," Visidyne Corporation, September 12, 1980.

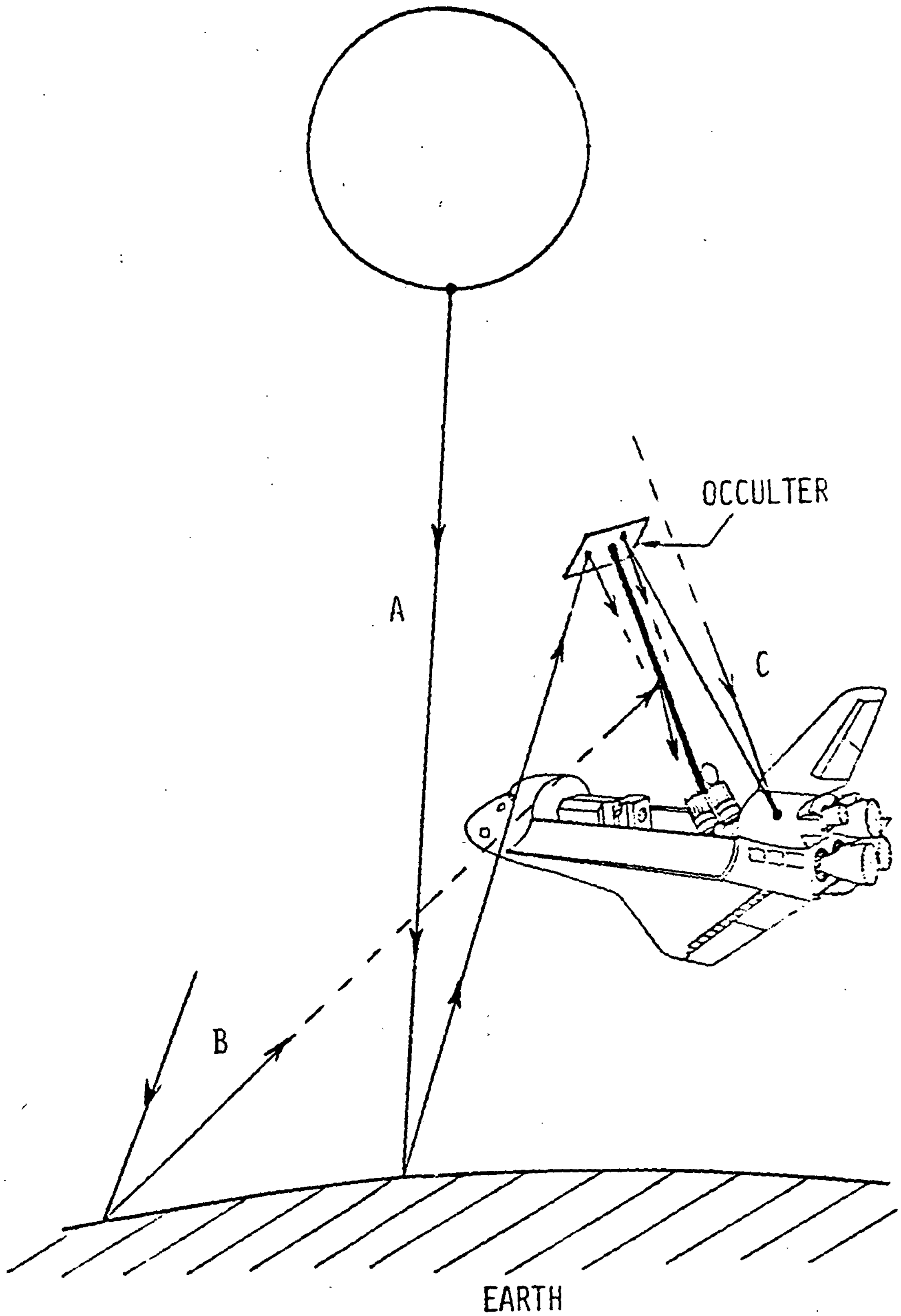



Figure 7. Stray light paths (back-lighted case).

## D. Dr. Greene's Study

As a study topic for the 1980 NASA/ASEE Summer Faculty Fellowship Program at MSFC, Dr. Michael Greene of the University of Alabama was asked to investigate the control and stability of the Pinhole-Occulter Flexible Boom Facility. A single-axis control study derived a root locus compensation scheme which was capable of stabilizing the system and pointing to within 6.5 arc-sec while the Orbiter rocks in its 0.1° dead band. The compensated system can follow step (position) inputs with zero error and ramp (velocity) inputs with a steady-state error coefficient of 4.5 arc-sec.

Based upon this study[1] a contract (NGT-01-002-099, July 1980) was awarded to allow Dr. Greene to continue, after the summer study, to work on establishing a 3-axis control scheme and simulation. The study is currently underway. The approach is to use the gimbal mounts for the base of the boom mounted at the center of mass of the Shuttle and to point the boom relative to the Shuttle. Corrections are applied to the gimbal inputs according to the relative error of the boom to the Shuttle and the error of the Shuttle to a fixed star. The corrections applied move the Shuttle in the opposite direction according to the ratio of the rotational inertias.

Optimal control is used to actively set the damping on the first four modes and to suppress the next four modes. The amount of active damping is limited only by the torque available in the gimbal motors. Optimal estimation is used to deduce the four modes from the output to feedback through the optimal controller.

[1]Dr. Green's original summer study is detailed in the final report, "On the Control and Stability of the Pinhole-Occulter Flexible Boom Facility," NASA/ASEE Summer Faculty Fellowship Program, Marshall Space Flight Center, July 15, 1980.

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# APPROVAL

## THE PINHOLE/OCCULTER FACILITY

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R. M. MacQueen, E. Tandberg-Hanssen, and J. R. Dabbs

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

Charles A. Lundquist

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Director, Space Sciences Laboratory

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