SPACE ASTRONOMY

OF THE

STEWARD OBSERVATORY

THE UNIVERSITY OF ARIZONA
TUCSON, ARIZONA

LITERATURE SURVEY

FOR

SUPPRESSION OF SCATTERED LIGHT IN LARGE SPACE TELESCOPES

NASA Contract NAS8-27804

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NASA Contract NAS8-27804

Submitted by:

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SPACE ASTRONOMY GROUP

of the

STEWARD OBSERVATORY

UNIVERSITY OF ARIZONA

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LIST OF ARTICLES

CLASSIFICATION OF ABSTRACT NUMBERS

Articles which are not abstracted are given a classification number to indicate area of interest.

Within each subdivision, articles are generally listed according to date, with the earliest article first.

Meaning of Symbol Before Article

Blank -- Article Reviewed and Abstract Enclosed

N -- Article Reviewed But Not of Sufficient Interest to Abstract

NA -- Article Not Reviewed (No Copy Obtained)

D -- Duplicate Listing (Joint Authors)

Abbreviations:

Ap. Op.	Applied Optics
ARS	American Rocket Society
IEEE	Institute of Electrical and Electronic Engineers
JOSA	Journal of Optical Society of America
J	Journal
R or Rev.	Review

INTRODUCTION

The Space Astronomy Group of Steward Observatory is investigating stray light suppression techniques for space telescopes under Contract NAS8-27804. The Large Space Telescope (LST) has the design goal to observe the faintest possible stellar objects and to operate over the widest possible spatial orientation range. Stray light from the Sun, Earth, and Moon will seriously restrict the telescope operation unless an effective stray light suppression system is incorporated into the telescope design. The primary object of this study is to develop the best practical stray light suppression system for the LST.

This report is the end product of Task I of the contract, a literature survey of articles dealing with all aspects of predicting, measuring, and controlling unwanted scattered (stray) light. The survey is divided into four broad classifications: (1) existing baffle/telescope designs, (2) computer programs for the analysis/design of light suppression systems, (3) the mechanism, measurement, and control of light scattering, and (4) the advantages and problems introduced by the space environment for the operation of diffraction-limited optical systems.

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1

Wiley, R. R., Jr., "Eliminating Scattered Light in Cassegrain Telescopes", Sky and Telescope 25:232, 1963.

Discusses three methods of eliminating scattered light in cassegrain telescopes. (Reviewer's Note: Article intended for amateur telescopes of 3 to 12 inch objective size for optical viewing.) The first method is to place a stop at the Ramsden disc of each eyepiece to be used with the telescope. The diameter of the disc is obtained by dividing the diameter of the objective by the power of the telescope. The second method is similar in principle to the first, except that an errecting lens is used which can incorporate an internal stop. The third method is to use conical baffle tubes located at the primary and secondary mirrors. (Reviewer's Note: These are the "standard" primary and secondary conical baffles.)

2

Newkirk, Gordon, Jr., and Bohlin, David, "Reduction of Scattered Light in the Coronagraph", Ap.Optics 2:131-140, February 1963.

Types of coronagraphs are discussed, with emphasis on new improved types to take advantage of opportunities presented by rocket and high-altitude balloon flights, where increased reduction of unwanted scattered light is required. Ordinary, direct-optic coronagraphs are found to be unsuitable; reflecting coronagraphs with externally occulted sun shields are required. These developments result in a reduction in the scattered light by at least three orders of magnitude so that the instrumental background is similar to the skylight encountered during total eclipse.

3

Zanoni, C. A. and Hill, H. A., "Reduction of Diffracted Light for Astronomy Near the Sun", JOSA 55:1608-11, December 1965.

The problem of light diffracted by the telescope objective when astronometric measurements are made near the sun (such as with coronographs) is discussed. A technique is described which uses an apodized objective to reduce the diffracted light by four orders of magnitude below that of a circular aperture for one-half the azimuthal field for distances greater than 400 arc-seconds from the solar limb.

4

Smith, Warren J., "Glare Stops and Baffles", Modern Optical Engineering, pp. 128-32, McGraw-Hill, 1966.

Discusses the use of glare stop diaphrams and baffles in optical systems to reduce stray light reflected from walls, etc. The most effective of baffles is to arrange them so that no part of the detector can "see" a surface which is directly illuminated. States that the "ideal" baffle may be quite expensive and may not be necessary in many cases, that simple scoring or threading of offending internal surfaces may be sufficient. The use of a flat black paint is recommended, although care must be taken to insure that the paint remains matte and black at near grazing angles. The 3M black Velvet is stated to be excellent for this purpose.

5

Prescott, R., "Cassegranian Baffle Design", Ap.Optics 7:479-81, March 1968.

A straight forward graphical procedure for the design of light baffles for cassegranian systems is presented which is completely general and generates the paraxial parameters from a minimum of input data. However, this paper covers only the placement of the primary and secondary baffles and does not consider internal baffle rings, extended sunshields, or other more sophisticated baffling arrangements.

6

Gordon, William R., "Suggested Approach for Telescope Baffle Design", paper presented at 1969 Spring Meeting of Op. Soc.; Abs. in JOSA 59:486, 1969.

Traditional approaches to baffle design for telescope consider all off-axis energy impinging on the telescope barrel wall as defined by the field of view, and provide baffle cavities such that energy entering any given cavity is attenuated by a certain percentage at each surface until the reflected energy is sufficiently reduced so as to prevent excessive stray light from reaching the image plane. This traditional approach results in a baffle design calling for a series of sharp-edged concentric rings with the undersurface corresponding to the field of view. Unfortunately, the number of baffle edges is usually large, and each baffle edge contributes to the scattered light reaching the image plane.

In this paper, a design approach is revealed which has baffle edge locations which for the most part are outside the field of view. For example, a design for a 1.2m telescope is presented which has an aperture of 41cm and more than 60 baffle rings, but only 3 of the edges are within the field of view.

7

NASA Report No.s N70-36676, 83, 87, 723, 30, and 45, "Optical Telescope Technology Workshop Held at MSFC, Huntsville, April 29-August 1, 1969.

a. Star trackers for OAO Series (Joe Percell, NASA Goddard)--The star trackers can look within 16^{o} of bright earth and within 5^{o} of dark earth. (Unfortunately, no magnitude limits were given) The sun baffles for OAO B & C have truncation angles of approximately 60^{o}. These baffles were not tested under simulated space conditions while on earth.

b. One Concept of a 3-meter Space Telescope (David Bogdanoff, Boeing)--The only light shielding on the proposed telescope was a simple extendable "earth shield" added for thermal shielding.

c. A Survey of Precision Pointing Systems (Douglas Fosth, Boeing)--MOT, ATM, and ESRO will require pointing accuracies of .005 to .1 arc-seconds. Aerobee was good to 1 degree, OSO to 30 arc-seconds, OAO and ESRO are basically the same with coarse control to 1 arc-minute and fine pointing control to 0.1 arc-seconds, MOT 3-meter will be 0.01 arc-seconds. Current state-of-the-art (1969) star trackers have sensitivities from M_v6 to M_v9.

d. Materials for LST (John Schroeder, Perkin-Elmer)--Optical surfaces will need to be figured to within 1.4nm (14A). Measurements of typical optical surfaces have shown the following scattering figures at 6.8nm: Coated glass surfaces, approximately 0.05%; ULE, 0.05%; CERVIT, 0.11%, Beryllium, 0.5%. However, scattering at 0.10 nm wavelength was found to be from 60 to 200 times as high.

e. Degradation of Mirror Surfaces in a Proton Environment (E.L. Hoffman, NASA Langley)--Tests indicate that a radiation dose of 10^{16} 10 KEV protons/cm^2 will reduce the reflectivity of MgF_2 coated optical mirrors approximately 20% (from 80% to 60%) for the wavelength range from 1500A to 3000A. It is concluded, therefore, that the degradation that has been noted in space (windows, etc.) must be due to something else in place of or in addition to proton irradiation.

f. Stabilization and Control of OAO (W. K. Jenkins, G. E.)--OAO uses six star trackers to maintain 0.1 arc-second pointing accuracy. The star tracker uses a two section baffle as shown in Fig.   to permit seeing a 2M star within 32^{o} of the sun.

g. Star Tracker Systems (L. Seifert, Kollsman)--A study of star trackers for potential use on the LST. Minimum requirement is to track a $M_v7.5$ star to 0.005 arc-seconds of accuracy. The list of current star trackers includes:

Kollsman tracker used on OAO has 5 sec accuracy on an M2 star with 1°FOV.

Nortronics 121 is good to 1 sec with M3.5 star and 10 min. FOV.

Many others, such as JPL, ITT, SBRC, and Bendix, are good to approximately 0.1° for M2.5 to 3.

OAO-B good to 0.1 arc second with M2 star and 4.5 min. FOV. See Fig. 1.

Extrapolation of these figures to the LST with a 3-meter aperture indicates that tracking performance of 0.003 to 0.005 arc second with stars of M9 should be possible.

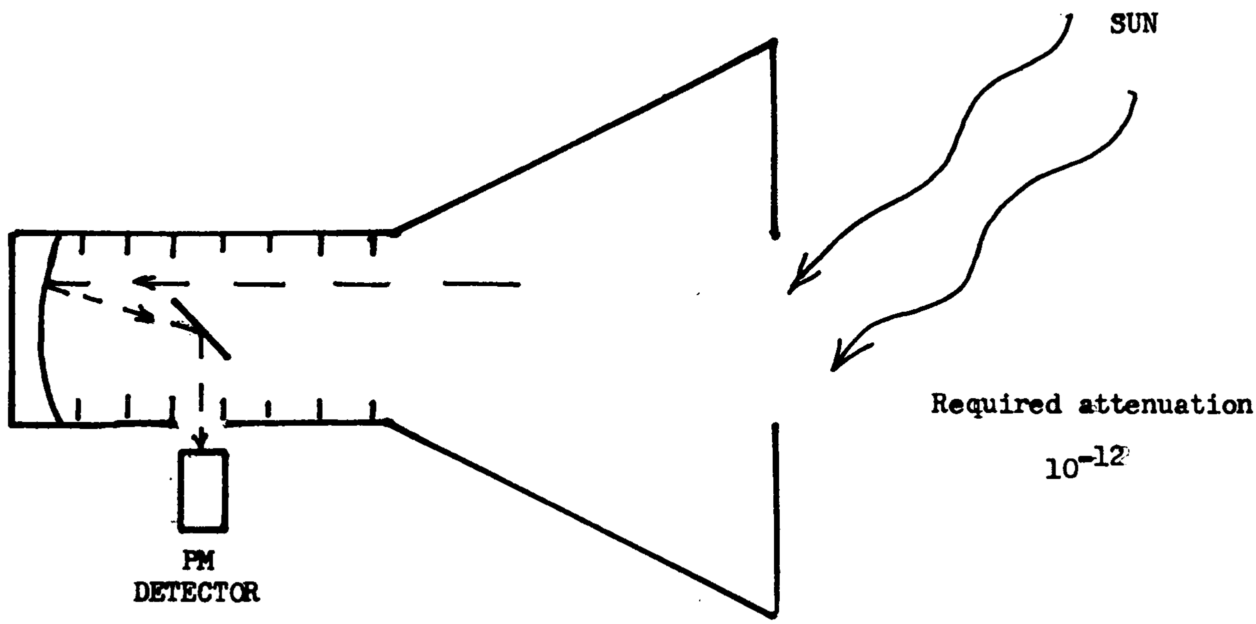
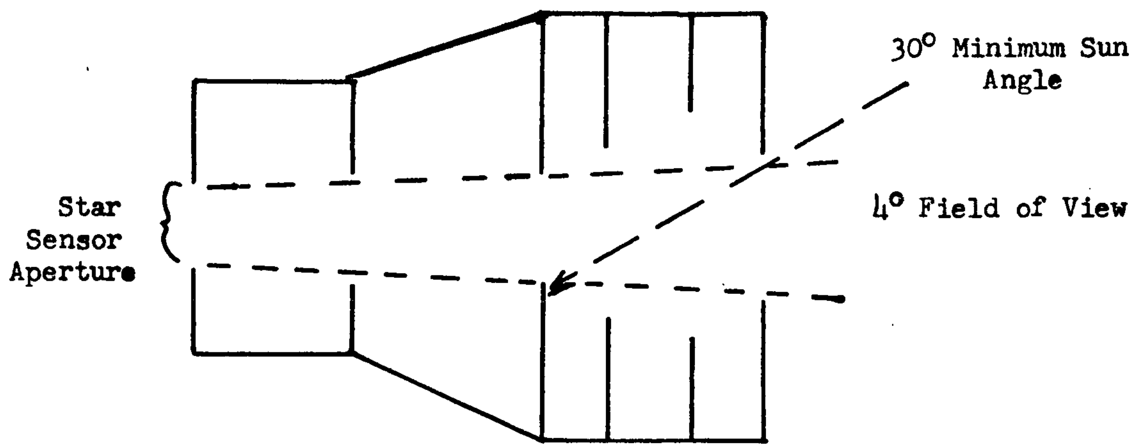


Fig. 1: OAO STAR TRACKER WITH TWO SECTION BAFFLE

8



SPARS Sunshield Design

Figure 2

Minneapolis Honneywell, "Spars Phase 1B Sunshield Development Program, Final Report", No. TM-21290-52, Oct. 23, 1970

Discusses the design of the SPARS sunshield design, which is shown in Figure 2. The star sensor has a 4° field of view; the outermost baffle just permits that field. The star sensor can see only the two inner baffles and the outermost baffle. Measurements indicate that the baffle system gives approximately 10^8 reduction in light if the sun angle does not become less than 30°. Limitations on light reduction are said to be diffraction and reflection from the outermost baffle edge for the most part. There is a complaint that the baffle system occupies considerably more volume than a simple baffle.

I

9

Leinert, Christoph, "Stray Light Suppression in Sunshield and Optical Systems", Dudley Observatory Report No. 6, 1971.

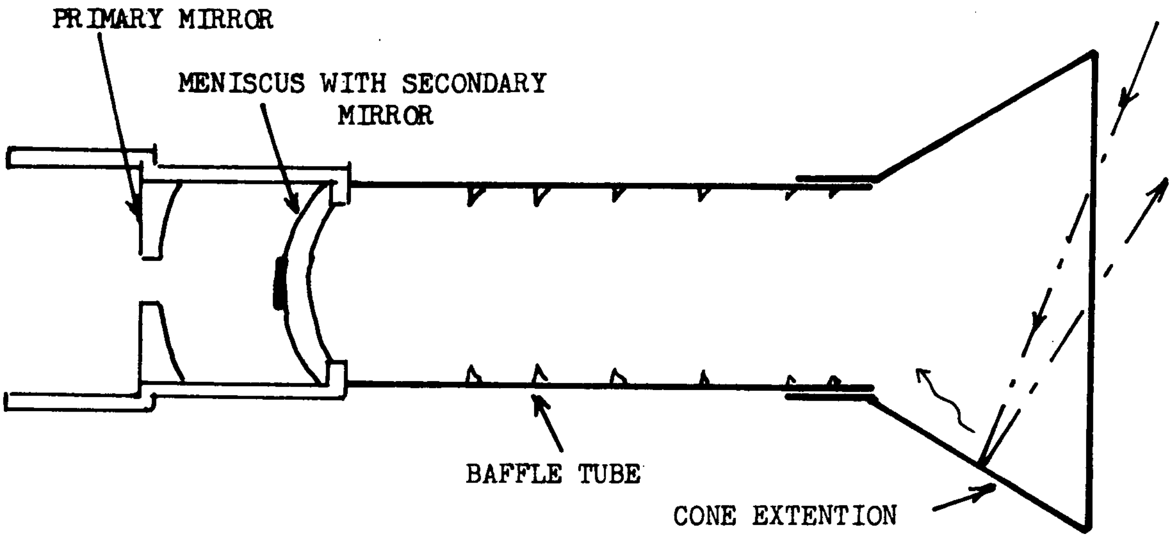
The stray light suppression of three photometric space experiments was determined by laboratory measurements. The instruments involved are the Pioneer F/G Imaging Photopolarimeter, the Skylab zodiacal light photometer, and a rocket photometer for observations of noctilucent clouds. The method and the results of the measurements are described in detail and the implications for the operation of the experiments are discussed. The stray light suppression was found to be adequate in the Imaging Photopolarimeter and for rocket photometer, whereas the Skylab photometer in its present design will have a stray light problem.

The stray light suppression measurements were broken down into two subsystems--the suppression given by the baffle system alone and that by the optical system alone. This permitted convenient measurements in the laboratory, and the product of the two measurements gives the overall stray light suppression of the experiment. (Reviewer's Note: For the purposes of this paper, only the suppression due to the baffle systems will be considered.) The light source for all measurements was a 6328A laser, with suitable optics to broaden the beam where required. The detector was an end-on type red-sensitive photocathode and a saphire window (EMR 541E-05M), operated at a gain of 10^6 (high voltage of 2.5 kv).

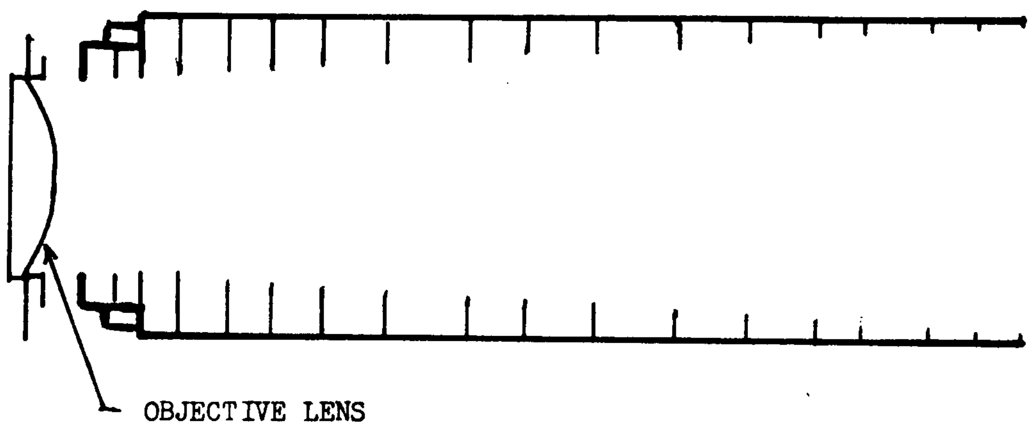
Figure 3 shows the configuration of the three baffle systems tested. Figure (a) is the Pioneer F/G Imaging Photopolarimeter (IPP) which is scheduled for launch in March, 1972, and is primarily designed to image Jupiter and its satellites while the spacecraft is passing at a distance of a few Jovian radii. The baffle system is a two stage baffle: a conventional baffle tube with knife edges, and a conical extention. The baffle tube is hot pressed beryllium and its interior is black anodized. The cone is machined from aluminum with a black reflecting finish on the inner surface. The size of the cone and its half angle of 30^o are chosen to accept all incoming light which is at least 60^o off-axis and to reflect it out of the baffle system. Under normal operating conditions, no light is permitted to directly strike any portion of the baffle tube interior. Measurements indicate that light suppression for the conical section is approximately $3(10)^3$ and for the baffle tube is approximately $3(10)^4$, so that the suppression for the compound baffle system is approximately 10^8. There are some indications that the measured figures are somewhat high, so that a "safe" figure of $2(10)^7$ is assumed.

Figure (b) shows the outline of the Skylab Photometer baffle system; this experiment is designed to map the brightness and polarization of the sky in ten colors and to investigate the contamination surrounding the spacecraft by observing the spacecraft corona, if there is any. The baffle system is machined from aluminum in eight sections and is black anodized with the Martin Marietta black process. The baffle system is a one-stage system, which means that the knife-edges may be illuminated by direct sunlight. Measurements were performed with the light source from 15^o to 82^o off-axis; stray light suppression varied from a factor of $2(10)^5$ with the light at 15^o to $5(10)^6$ with the light at 82^o. Figure (c) shows the baffle system for the camera which is mounted in tandem with the photometer. Since the camera is used primarily for photographing stars to provide supplementary directional information, it can operate at a higher light level and the baffle is not as complicated. It is considered that the light suppression for the photometer experiment is inadequate, and a redesign is in process.

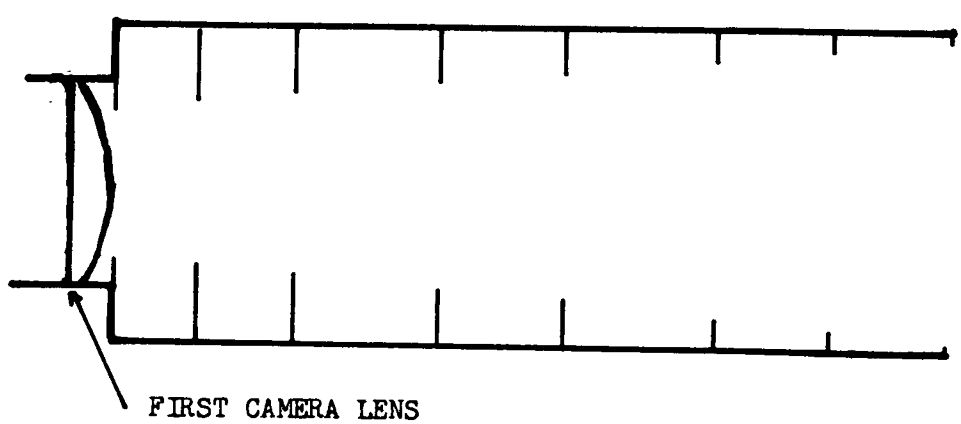
Figure (d) shows the baffle system for the Noctilucent Cloud Photometer, an experiment which was flown three times as a rocket payload in 1971. In all flights the photometer was exposed to direct sunlight. The baffle system is machined from aluminum and black anodized after assembly. It is designed for solar elevations of less than 10^o so that it operates as a two-stage baffle system; the knife edges which can be seen by the lens are not exposed to direct sunlight and are illuminated by diffuse reflection in the first baffle space only. If the solar elevation gets larger, as occurred during one flight, direct sunlight hits the knife edges and the baffle system acts as a one-stage baffle system only. Measurements taken indicate that the stray light suppression for the system was 10^8 for a 10^o illumination angle, dropped to $5(10)^5$ for an angle of 15^o (one knife edge illuminated) and to $5(10)^4$ for an illumination angle of 70^o (seven knife edges illuminated).



(a) OUTLINE OF THE IPP BAFFLE SYSTEM-- 3/4 Scale



(b) OUTLINE OF THE SKYLAB PHOTOMETER BAFFLE SYSTEM--1/2 Scale



(c) OUTLINE OF THE SKYLAB CAMERA BAFFLE SYSTEM--1/2 Scale

FIGURE 3

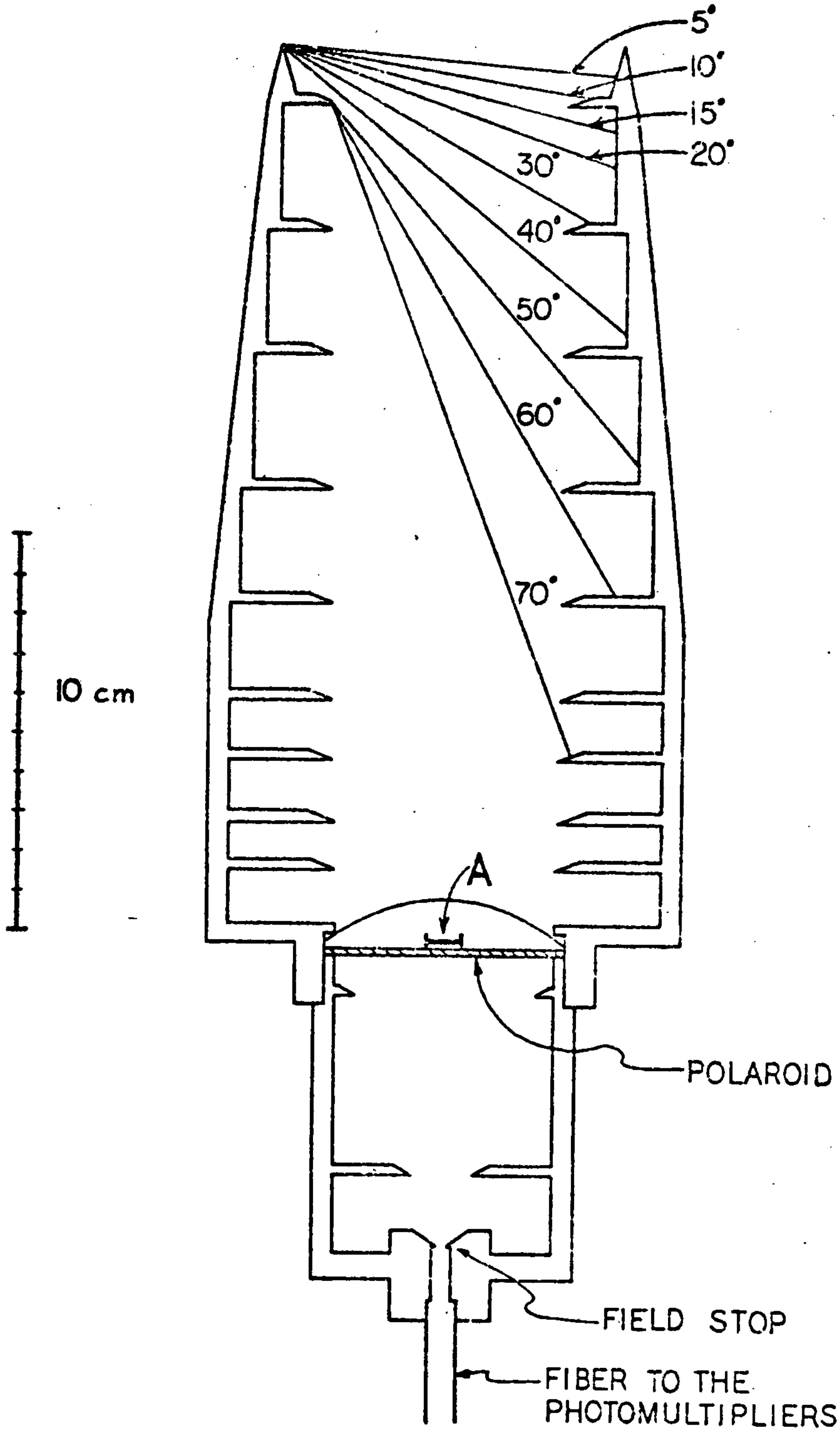


Figure (D): Baffle system and optics of the noctilucent cloud photometer

A Summary of the SAS-D Concept for Astronomical Ultraviolet Spectroscopy, Goddard Space Flight Center, March 1971.

The SAS-D experiment has a 45 cm ultraviolet telescope with the design requirement of working to a limiting magnitude of 12 when using the A resolution spectronometer for 1/2 hour exposures while operating within 40^{o} of the sun. A sun shield and baffle system has been designed based on extensive work done for ESRO in the United Kingdom for two stellar telescopes which required light reduction similar to the SAS-D. (See Figure 6)

Calculations have been made which indicate that this baffle system will be good in sunlight to m_V=16.

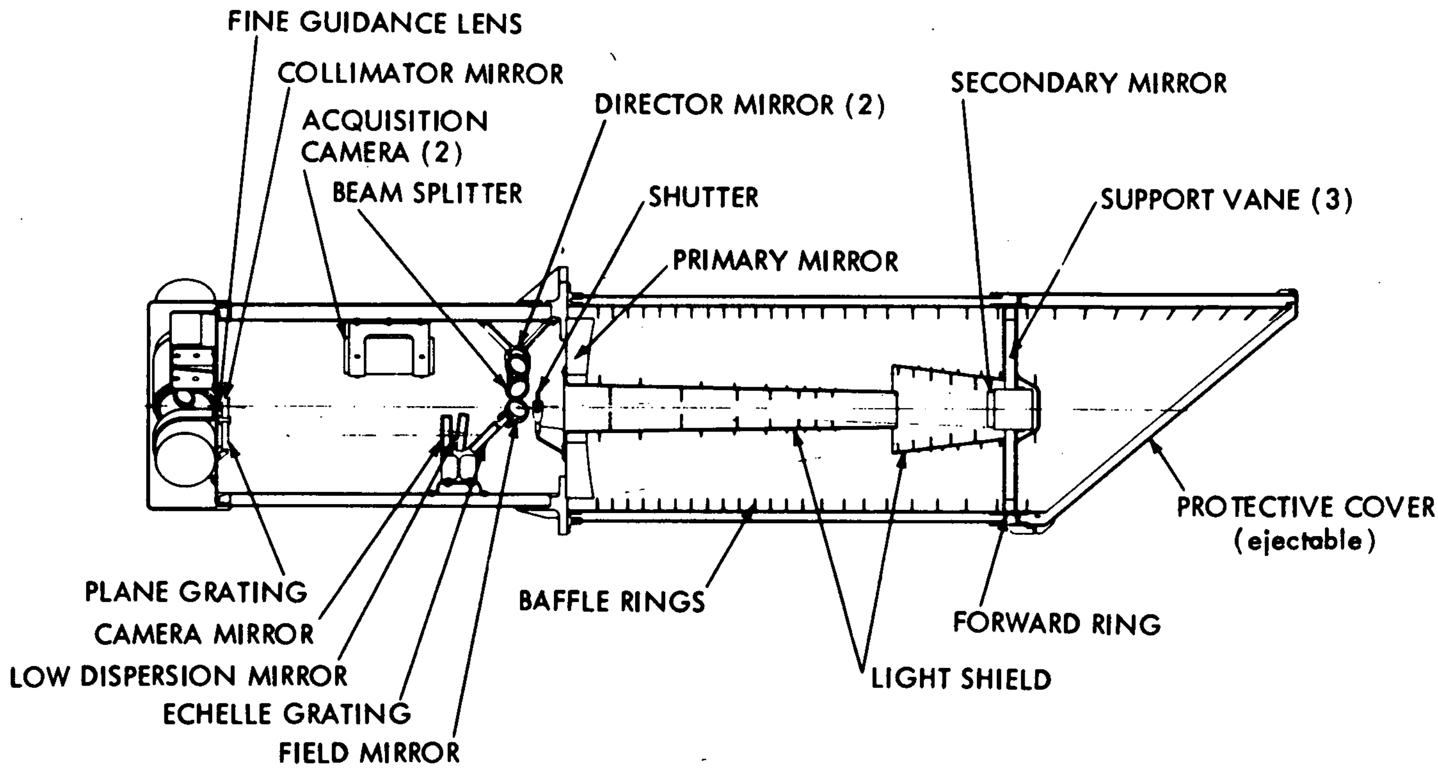


Figure4 : Cross Section of SAS-D, Showing Light Baffle System

11

NASA Report N71-15604 (JPL), "Anti-Glare Improvements for Optical Imaging Systems", Patent, January 6, 1970.

An anti-glare baffle having a specularly reflecting front surface is formed to an oblate hemispheroid. A shading flange extends inwardly from the upper edge of the hemispheroid. These surround a viewing aperture and are effective in reducing glare from light sources out of the desired field of view with minimum vignetting.

12

Wetherell, W. G., "Stray Light Suppression in the Large Space Telescope", Itek Report No. 3119.028, December, 1970.

This report discusses the results of a preliminary investigation of the stray light problem in the LST. The investigation was semi-quantitative and was intended to show the tolerable stray light levels in the image plane, the sources and magnitudes of stray light, how the stray light reaches the image plane, and what techniques can be used to reduce the stray light. Approximate calculations were made to estimate the level of stray light at the image plane for the more elementary forms of baffling. Areas where stray light suppression must be improved are defined, and possible approaches are discussed.

The report emphasizes the problems encountered when attempting to observe on the sunlit side of the earth, where the telescope is sandwiched between the bright earth and the sun. The background irradiance at the image plane of the LST due to sky background is typically 10^{-13} watts/cm^2. To achieve this level of image illumination during sunlit portions of the orbit, the stray light must be attenuated by 12 orders of magnitude between the aperture and the image plane. It is concluded that this is beyond the capabilities of conventional baffling systems. Some advanced configurations are offered for consideration.

A sunshade which is felt to offer considerable promise is shown in Fig. 5. The practical problems involved in deploying and orbiting such a large structure is formidable, however.

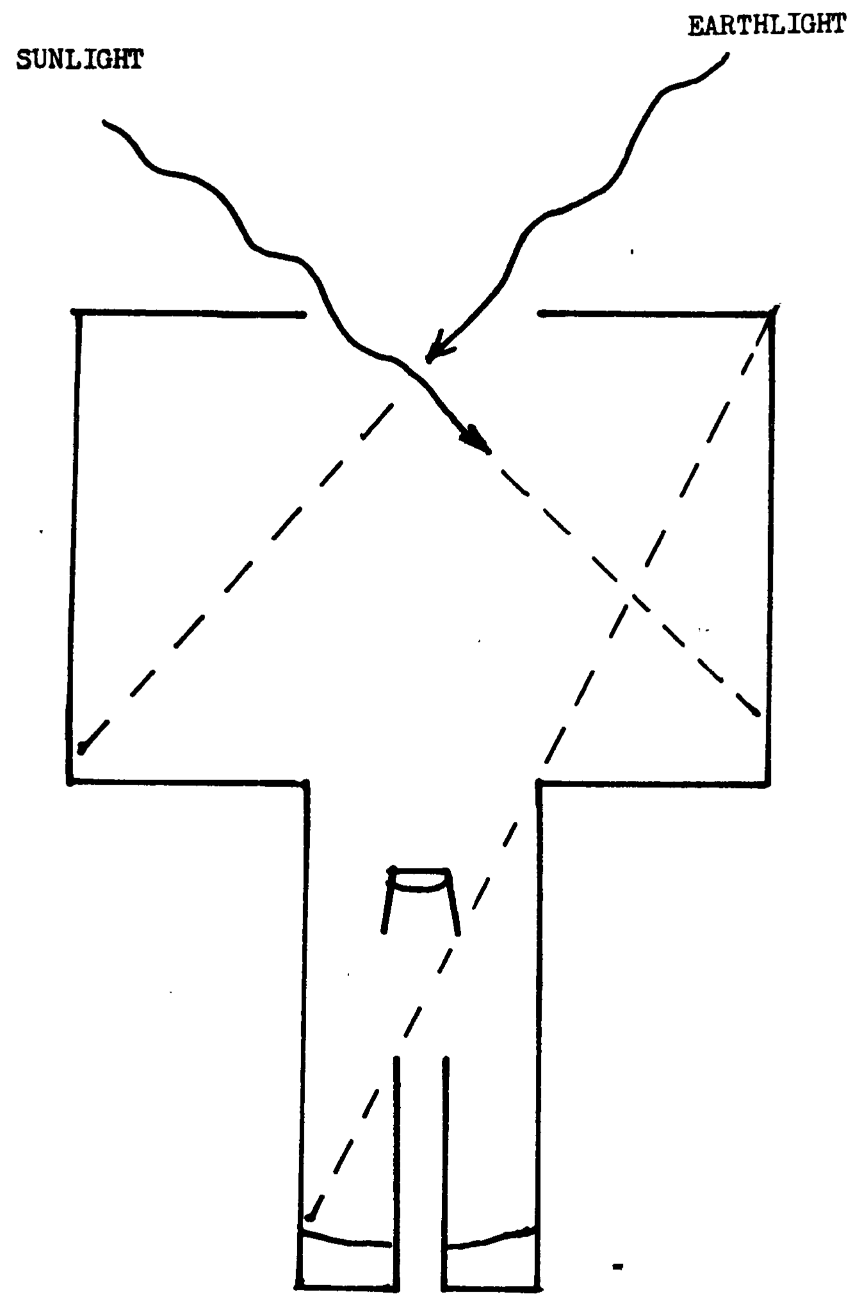


Fig. 5: LIGHT SHIELD TO PROTECT AGANIST TWO LIGHT SOURCES

13

NASA Report No. N72-15422, Schmidt, L. F., "Patent Disclosure for Star Tracker", JPL, July 22, 1970.

Describes a star tracker instrument which utilizes an image dissector tube as the detector and error sensor. No fiber optics are utilized. The light baffle is a two-stage structure; i.e., the outer section of the baffle cone has a larger angle than the inner section. The outer section has four internal ring-baffles, the inner section two additional rings. Unfortunately, no performance figures are given.

14

Schenkel, F. W., (APL), "A Self Deployable High Attenuation Light Shade for Spaceborne Astronomical Sensors", paper presented at annual meeting of SPIE, Tucson, Arizona, March 13-15, 1972.

Described a light shade designed for use with the SAS-D star seeker which is required to view M4 stars in a $5^{o}x10^{o}$ field of view to within 60^{o} of the sun. Calculations indicated that an attenuation of 10^{13} from solar level is required; a factor of 10^{3} is obtained in a filter, the rest in a baffle design. (Reviewer's Comment: What kind of filter?)

A two-stage baffle was required; the configuration shown in Fig. 3 was selected for use. No portion of the first stage is visible from the orifice of the second stage. The baffle rings have razor sharp edges, and the interior of the baffle system is coated with 3M Black Velvet. Investigations and tests were made with the solid model of Fig. 3a. Different finishes were tried, including totally reflecting outer surfaces on the baffle rings, but the performance was not improved very much. A reflective cone, with no baffle rings, for the outer baffle stage seemed to give somewhat better performance than the fabble with rings.

The space constraints for the SAS-D during launch made it necessary to develop a baffle system which could be stored in a smaller space and would self-deploy upon reaching altitude. The configuration shown in Fig. 3b was selected. This configuration approximates that of Fig. 3a. The outer walls are made of RTV 630 Silastic; it was not clear as to what material was used for the baffle rings and what internal finish was used.

Tests on the baffle (which one?) indicated that the baffle gives an attenuation of 10^{6} in the laboratory. It is thought that the low figure is due to reflections in the test chamber, etc., and that the baffle system will give the required attenuation of 10^{10} in space. (Reviewer's Comment: ??)

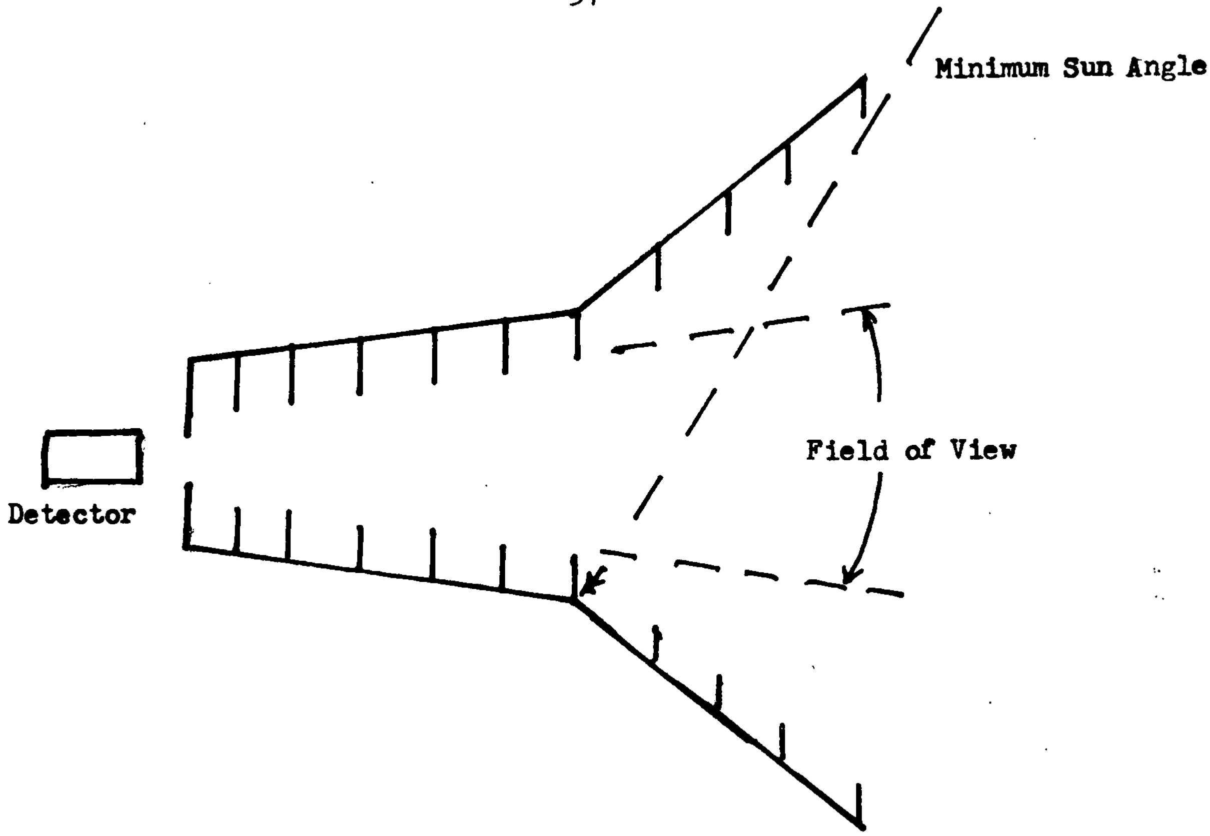


Fig. 6 a RIGID TEST MODEL OF SAS--D LIGHT SHIELD

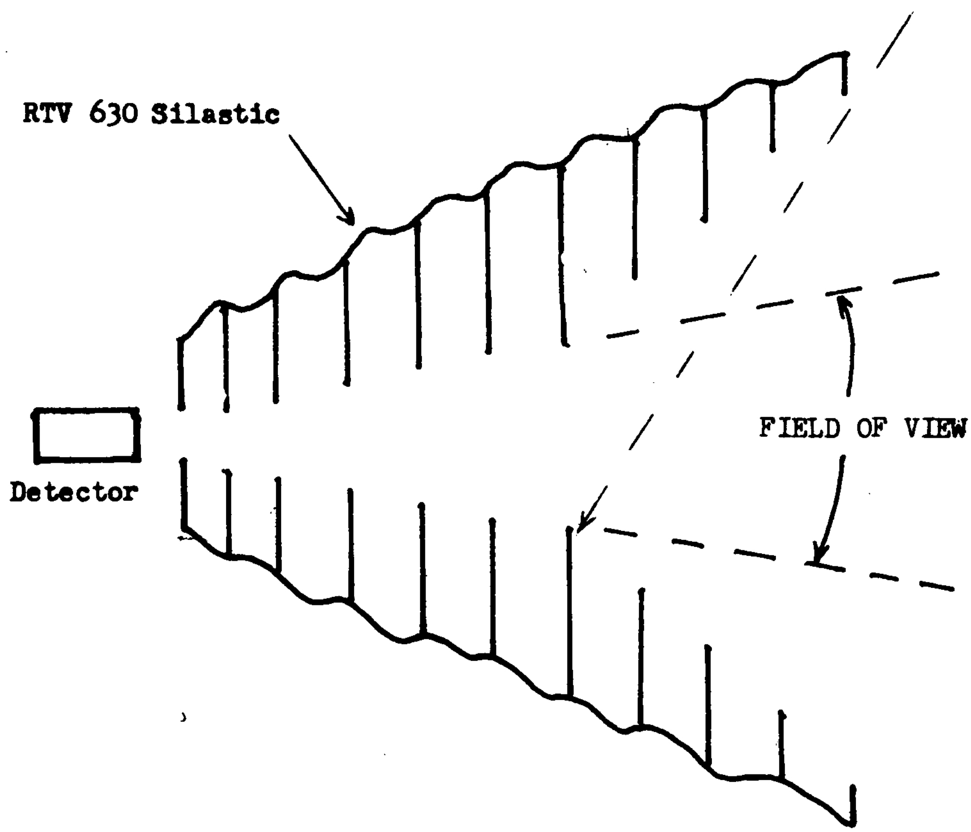


Fig. 6 b DEPLOYABLE LIGHT SHIELD FOR SAS-D STAR TRACKER

15

Lockheed, Missiles and Space Division, "Final Technical Report for Large Telescope Experiment", LSMC-A958157, 280 p., January 5, 1970.

Phase A study for LST, with preliminary design concepts, operational constraints, and areas requiring further study presented. Contains almost no information on light suppression systems, but has fairly extensive analysis of the problem of scattered light from the residual earth's atmosphere and contaminants. (Reviewer's Note: The figures listed for sunlight scattering by the residual atmosphere seem high by several orders of magnitude. Example, at 217 nautical miles, the scattering is listed as 1.3×10^{-11} of the intensity of the sun. However, the figures given are for a wavelength of 1000A; if the I_{sun} is also at that wavelength, the figures may be correct since the intensity of the sun is extremely low in that region of the spectrum.)

A good analysis of orbital parameters is given.

16

Itek, Optical Systems Division, "Final Report--Large Space Telescope", No. 71-9463-2, 282 p., September 3, 1971.

Phase A study of the LST. Extensive analysis of the optical design, alignment, and manufacturing problems, with tradeoff studies based on a "wavefrong error budget". Has the best analysis of the stray light suppression problem of any of the Phase A reports reviewed, although no conclusions are reached as to a suitable light suppression system.

17

NASA (Goddard), "Large Space Telescope (LST) Preliminary Analysis and Design Report", 540 p., December, 1971.

Phase A study of the LST, with constraints imposed by a TITAN/Shuttle launch system. Extensive consideration of optical, mechanical, electrical, and thermal subsystems, and system integration problems. Almost no analysis made of the scattered light suppression problem. Some consideration of test and manufacturing problems.

18

Martin Marietta, Denver Division, "Support Module Study for Large Space Telescope", No. S-71-46579-01, 522 p., December 15, 1971.

Phase A study of the Support Module for the LST; has excellent analysis of orbital tradeoff parameters, with expected observing times for various types of scientific instruments. No consideration given to the scattered light problem.

I

19

NASA Reports No. N71-10626 and N71-10627, "The Study of the Attitude Control of Small Satellites and Related Subsystems", AVCO, September 4, 1970.

States that the present-state-of-the-art star trackers (1970) are capable of guiding to within 0.01^{o}, and predicts that 0.005^{o} is possible. Other sensors, such as horizon sensors, solar sensors, and magnetic sensors, are approximately 1/10 as good. Present gyroscopes have stabilities to within 0.01^{o}, with predicted performances of 0.001^{o}.

20

NASA Report No. N71-24080 and 71, "Phase A Report for Small UV Astronomy; SAS-D", Goddard SFC, March, 1971.

Describes the design of SAS-D, including the sun shield and light baffling arrangements. The sunshield is truncated at a 40^{o} angle and no sunlight is permitted to enter the telescope tube. The internal ring baffles are inclined so that no first-order light hits the underside. The baffles are coated with 3M Black Velvet. (See Fig. 4 for baffle configuration)

Second diffracted sunlight is down by a factor of 10^{-7}. Moonlight is equal to $3(10)^{-6}$ of sunlight at 4500A and earthlight at synchronous orbit is 10^{-2} that of sunlight. Monte Carlo calculations show that $M_V 13$ will be just possible; however, the computer calculations are believed to be excessively conservative and operation at least to $M_V 16$ is predicted.

21

Perkin-Elmer Corp., "Three-Meter Telescope Study", 199p., May, 1971

Tradeoff studies are made for the more important parameters governing the design of a large space telescope, resulting in an "optimum" design. Considerable consideration is given to the fabrication problems involved in making "fast" primary mirrors, since the optimum system needs at least an F2 primary.

22

NASA N72-27423, "Functional Characteristics of the OGO Main Body Airglow Photometer", 24 p., May 1972

The OGO Airglow experiment uses a trialkali cathode photomultiplier to sense selected wavelengths between 2500 and 6300Å corresponding to important emission lines in the Aurora and night airglow. Two instruments, one earthbound with a 5° field of view, the other skybound with a 4° field of view, were equipped with tube-like ribbed baffles to reduce scattered sunlight. Operation is possible with the sun-line more than 60° off axis for the earth oriented instrument and 30° for the sky oriented instrument.

I-N Reports Reviewied but not of Sufficient Interest to Abstract

Itek, Optical Systems Division, "Technology Study of a Large Orbiting Telescope", Report No. 70-9443-1, May 1970

Stein, W. A., "Astronomical Infrared Telescope", Ap. Optics 10:655-9, January 1964

I-NA Reports Not Reviewed (No copy obtained)

Sauer, F., "Shield Design", Sterne Weltraun 4:14, 1966

II. COMPUTER PROGRAMS FOR ANALYSIS/DESIGN OF LIGHT SUPPRESSION SYSTEMS

1

Young, A. T., "Design of Cassegrain Light Shields", Ap. Optics 6:1063-7, June 1967.

A Fortran program has been developed which will give the "optimum" design for light shields for Cassegrain optical systems with finite fields. The problems of vignetting and obscuration are discussed. This program will, for most systems, provide a fully shielded, unvignetted field at the cost of only a few percent increase in obscuration. However, the program provides only the conventional primary and secondary shields, no internal rings or extendable sun shields are considered.

Copies of the Fortran source deck may be obtained by sending $5.00 to cover handling costs to the Astronomy Department, University of Texas, Austin, Texas. Checks should be made out to the University of Texas.

2

NASA Report N71-27643 (Rochester Univ.), "Generalized Fourier Techniques for the Theory of Light Scattering--Final Report", December, 1970.

Primarily concerned with the development of systematic techniques for determining the structure of three-dimensional transparent objects from the measurement of transmission functions of holograms.

3

Golubitskiy, B. M., and others, "The Use of the Monte Carlo Method for Calculating the Degree of Blackness of Cavities", Soviet Journal of Optics Technology 37:296-8, May 1970.

Light within the cavity is considered as individual photons; for each collision with the cavity wall, the photon has a probability distribution for its angle of reflection which is affected by the type of reflection, either directional or diffuse. Combinations of the types of reflection can be considered. By considering a sufficiently large number of individual photons, the probable performance of the cavity may be determined to any degree of certainty desired.

The results from the computer analysis agreed "well" with measured values. The comment was made that the computer program was somewhat slow and, therefore, expensive due to the lack of a more spohisticated computer.

Heinisch, R. P., and Jolliffe, C. L., "Light Baffle Attenuation Measurements in the Visible", Ap.Optics 10:2016-20, September 1971.

The SPARS program (Space Precision Attitude Reference System) requires a sunshield about a sensor to reduce stray light from the sun, earth, or moon. The system is required to detect stars of $M_V 4.0$ in the presence of sunlight. Mathematical modeling and the experimental results from laboratory tests on baffle systems is described.

The modeling was accomplished by using a Monte Carlo technique which resulted in a very complex computer program. The mathematical analysis indicated that a single stage conical baffle (as shown in figure 7a) can have a maximum attentuation of 10^{-7}, so a two stage baffle (as shown in figure 7b) was considered. If computer analysis of the two stage baffle was performed, no results were given.

Both single stage and double stage baffles were constructed and tested in the laboratory. A zircon lamp solar simulator was used as a light source and stray light detection was by photometric means. The following design guide lines were followed: (1) No optical elements were allowed to view any sunlit baffle wall or knife edge; (2) Light from within the baffles was required to experience a maximum number of reflections before entering the optical elements; (3) The knife edges were as sharp as possible--maximum edge radius was .000076 cm. (Reviewer's Note: Should be m?)

The greatest measured attenuation (for the two stage baffle with 60° incident sun angle) was only 8×10^{-5} with the interior of the baffle unpainted and 8×10^{-6} with the interior painted with 3M Black Velvet (absorptivity changed from .71 to .96?).

No explanation is offered for the poor laboratory test performance as compared with the mathematical modeling.

Reviewer's Comment: Since this article appeared, the reviewer has talked with Dr. Heinisch, who states that the program has been improved and simplified so that the accuracy of the results is greatly increased and the computer time required greatly reduced. Computer time for the analysis of a complex system is still appreciable, being approximately 15 minutes on a CDC 6600.

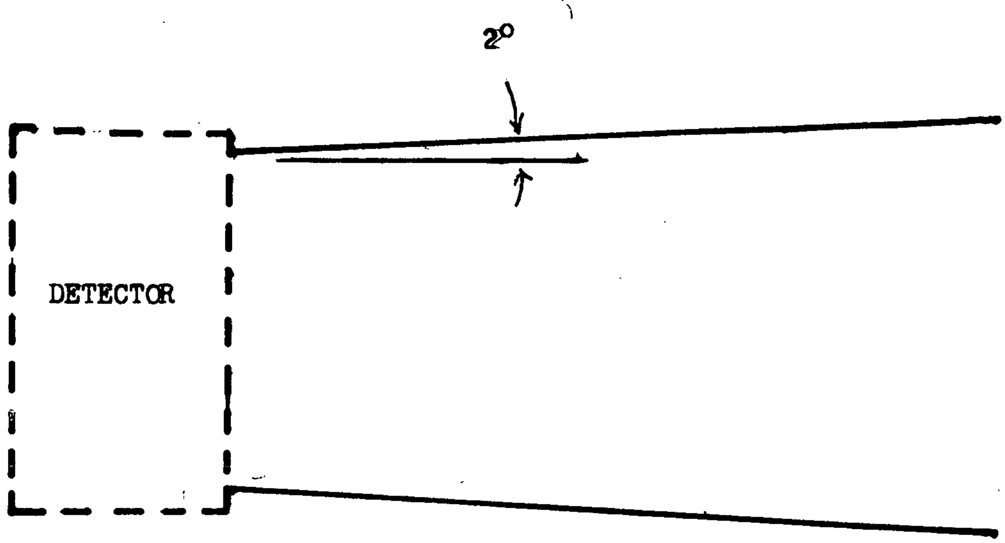


FIGURE 7a: Single Stage Baffle Tube (Full Size)

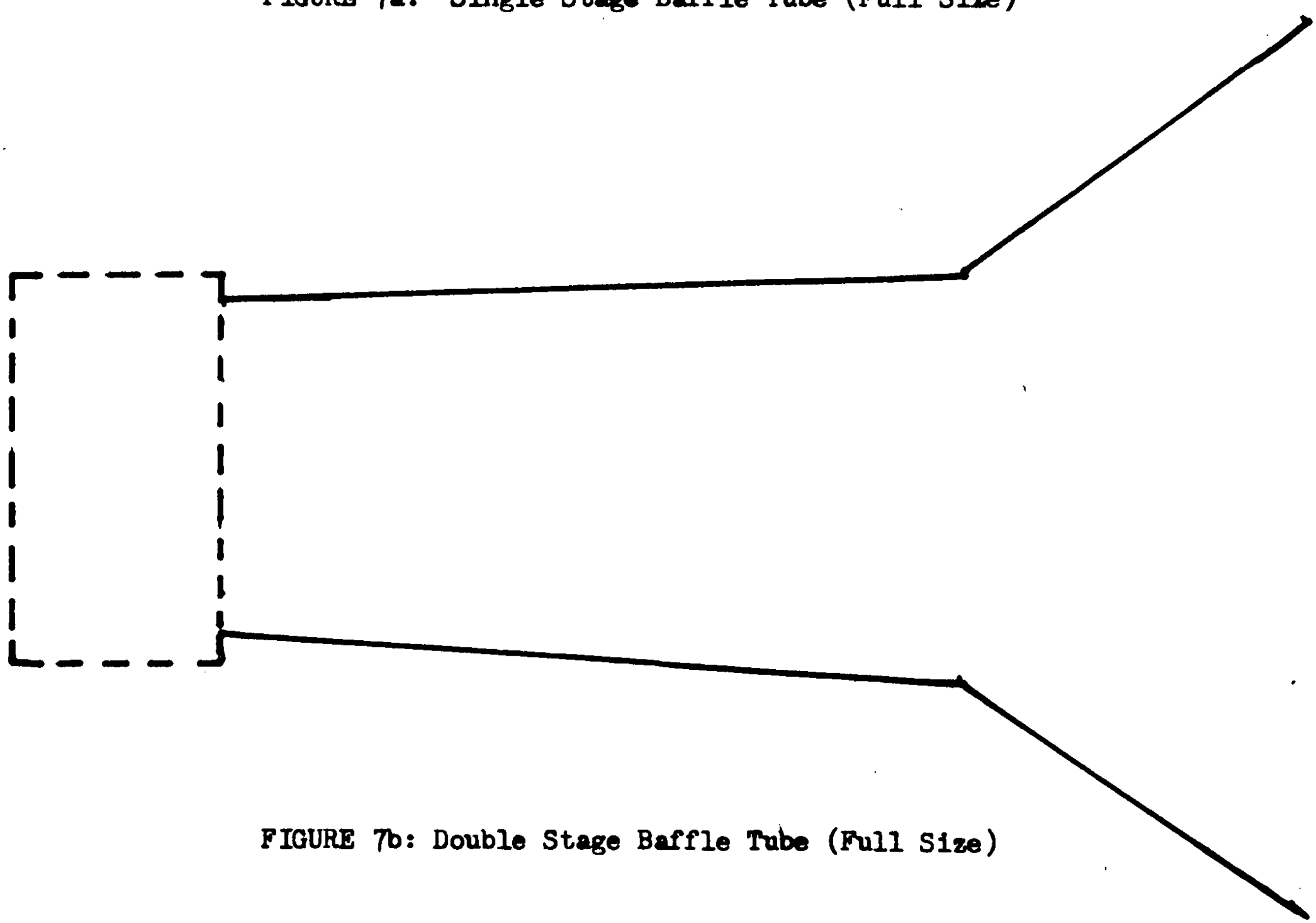


FIGURE 7b: Double Stage Baffle Tube (Full Size)

5

Goncharenko, Ye N., "Optical Design of Sun Shades", Soviet J. of Optical Tech. 38:475-7, August 1971.

The diagram for the passage of a light beam through a sunshade is discussed. A graphical method for computation of the residual light emerging from the sunshade is presented, sunshade design specifications are discussed, and sample calculations are shown and compared well with measured values.

The attenuation for a simple sunshade (conical baffle tube with six internal ring baffles) is approximately $4(10)^5$ for light entering at 45°. Attenuation of 10^6 is obtained when only the first baffle ring is illuminated (angle of 80°).

6

NASA Report N72-25763 or 25755 (Goddard), "Structural-Thermal-Optical Program (STOP)", 1972

A structural thermal analysis computer program is developed which uses a finite element approach and applies the Ritz method for solving heat transfer problems. (Reviewer's Note: It appears that this program might be extended to solving scattered light problems with a moderate amount of effort.)

The advantage of the finite element approach is that the output of one segment of the program is compatible with the input to the next. The program has principally been used to predict the effect on optical performance and alignment due to structural deformation caused by changing thermal conditions in space.

II-NA Article Not Reviewed (No Copy Obtained)

Wiener, M. M., et. al., "Radiative Interchange Factors by Monte Carlo", ASME Paper No. 65-WA/HT-51, 1965

Wolf, E. "Generalized Fourier Techniques for the Theory of Light Scattering", Final Report, 1 Jan. to 31 Dec., 1970, Rochester U., New York, Dept. of Physics and Astronomy, AD-720858, AFCRL-71-0114, Jan. 1971

SECTION III: LIGHT SCATTERING

III-A: LIGHT SCATTERING--THEORY AND CALCULATIONS

1

Tholer, F., "Die Diffuse Reflexion des Lichtes and matten Oberfluchen", Annales der Physik 11:996, (German), 1903.

One of the first technical articles on the diffuse reflection of light from a matte surface. Equations are derived (similar to the Lambertian Cosine law), measurements are described, and tables list the reflectance for various angles as a function of the angle incidence.

2

Ament, W. S., "Toward a Theory of Reflection by a Rough Surface", Proc. IRE, 41:142, 1953.

A rough, perfectly reflecting surface is first specified by the statistics of noise theory. If illuminated by a plane electromagnetic wave, such a surface will reflect statistically predictable fields. An attempt is made to formulate the problem of predicting the reflected fields in terms of the statistics of the surface. The result is a series of integral expressions in which averages of the currents induced in the surface appear as unknown functions. Owing to the mathematical complexities, these expressions are not solved for the average currents; however, a qualitative discussion is given of a known formula for the specular reflection coefficient of a gently rolling surface.

3

Born, M. and Wolf, E., Principles of Optics, Pergamon Press, Inc., New York, p. 808, 1959.

Perhaps the most classic optics text, with very comprehensive coverage of Basic Properties of Electro-Magnetic Fields, Potentials, and Polarization; Geometric Optics; Images and Aberrations; Instruments; Diffraction and Interference; and the Optical Properties of Materials.

4

Vasicek, A., Optics of Thin Films, N. Holland Pub. Co., Amsterdam, 1960.

A fairly technical text describing the action of thin films on optical surfaces. Has mathematical derrivation of the reflection and refraction of light by single films and by multiple films. Considers both dielectric films on metallic surfaces and thin metallic films on dielectric surfaces.

5

Bennett, H. E., and Porteus, J. O., "Relation Between Surface Roughness and Specular Reflectance at Normal Incidence", JOSA 51:123-9, February 1961.

Expressions relating the roughness of a plane surface to its specular reflectance at normal incidence are presented and verified experimentally. The expressions are valid for the case where the root mean square surface roughness is small compared to the wavelength of the light, in which case the decrease in measured specular reflectance due to surface roughness is a function only of the rms height of the surface irregularities. Long wavelength specular reflectance measurements thus provide a simple and sensitive method for accurate measurement of surface finish, particularly, for surface finishes too fine to be measured accurately by conventional tracing instruments. Significant changes in specular reflectance occur for surface roughness as little as 0.01 wavelength.

6

Steeffer, William, "On the Theory of Diffraction by Black Obstacles", Paper presented at 1963 Spring meeting of Op. Soc., Abs. in JOSA 53:525, 1963.

A mixed boundary condition is formulated to describe the scattering of light by black obstacles. The problem of diffraction by a black cylinder and plane are considered, and the results are compared with those obtained from other boundary conditions.

7

Beckmann, Petr, and Spizzichino, Andre', <u>The Scattering of Electromagnetic Waves from Rough Surfaces</u>, Pergamon Press, Inc., New York, p. 497, 1963.

Fairly comprehensive text on the scattering of electromagnetic waves (including light). Has two sections, one on theory in which the mechanisms and laws of scattering are derived, and the other on applications such as the scattering of sun light by the earth's surface and atmosphere.

8

Stone, M. M., <u>Radiation and Optics</u>, McGraw-Hill, New York, 1963.

Although described as an undergraduate text in the Preface, this book is a very technical treatment of theoretical optics, using such tools as vector analysis complex quantities, Maxwell's field equations, Kirchoff's Integral, Fraunhoper's and Fresnell's Diffraction theory, Fourier analysis, the Lorentz atoms, and the relationship of quanta to classical theory. There is very little geometric optics.

9

Porteus, J. O., "Relation Between the Height Distribution of a Rough Surface and the Reflectance at Normal Incidence", JOSA 53:1394-1402, December 1963.

Existing theories relating the rms roughness of a plane surface and its specular reflectance at normal incidence are extended to shorter wavelengths. The inadequacy of parameters such as the rms roughness, the rms slope, and the auto-covariance length for describing the reflectance in the shorter wavelength region is discussed. Particular attention is given to the problem of determining the distribution of heights of the surface irregularities from reflectance measurements at normal incidence.

10

Newkirk, Gordon, Jr., and Bohlin, David, "Reduction of Scattered Light in the Coronagraph", Ap.Optics 2:131-140, February 1963.

Types of coronagraphs are discussed, with emphasis on new improved types to take advantage of opportunities presented by rocket and high-altitude balloon flights, where increased reduction of unwanted scattered light is required. Ordinary, direct-optic coronagraphs are found to be unsuitable; reflecting coronagraphs with externally occulted sun shields are required. These developments result in a reduction in the scattered light by at least three orders of magnitude so that the instrumental background is similar to the skylight encountered during total eclipse.

11

Drude, P. and Dandburg, Jerome, "Determination of the Optical Constants of Metals", Annalen Der Physik (Germ.) 39:481-554, March 1963.

Describes different methods for determining the optical constants of metals, the effects of surface layers, the effects of incomplete polishing. Describes how to obtain the normal state of a metal mirror and the relationship between optical constants and temperature.

12

Mitzner, Kenneth M., "Theory of the Scattering of Electromagnetic Waves by Irregular Interfaces", Cal. Tech. Antenna Lab Report TR30, January 1964.

Problems involving electromagnetic scattering from irregular interfaces are treated. Both deterministic and statistical irregularities are considered. Interfaces with both large irregularities and small irregularities are treated. Matrix transformations are utilized to obtain rather complex solutions.

13

Nicodemus, Fred E., "Directional Reflectance and Emissivity of an Opaque Surface", Ap. Optics 4:767-773, July 1965.

Concepts, terminology, and symbols are presented for specifying and relating directional variations in reflectance and emissivity of an opaque surface element. Their relationship to more familiar concepts, including those of perfectly diffuse and specular reflectance, is given, and they are applied to illustrative examples. It is shown that, when the usual reciprocity relationship holds, the reflectance for a ray incident on an opaque surface element is related by Kirchoff's law to the emissivity of that element for a ray emitted along the same line in the opposite sense.

14

Rambauske, Werner R. and Groenzel, R. R., "Distribution of Diffuse Optical Reflection Around Some Sterometric Surfaces", JOSA 55:315-18, March 1965.

Mathematical expressions are given which permit the straight forward calculation of the optical power reflected from some simple sterometric convex bodies in all directions for different angles of parallel incident light. (The reflection is assumed to be Lambertian.) Shapes considered are spheres, cylinders, and cones.

15

McCamy, C. S., "Concepts, Terminology, and Notation for Optical Modulation", Photographic Science and Engineering 10:314-325, November-December 1966.

Reflectance, transmittance, and optical density are regarded as kinds of flux modulation factors. A coordinate system and functional notation are adopted to systematize the description of optical systems which use or measure modulation. Terms, symbols, and notation are proposed for standardization.

16

Dietz, Ralph W., and Bennett, Jean M., "Bowl Feed Technique for Producing Supersmooth Optical Surfaces", unclassified report from Naval Ordnance Test Station, China Lake, AD-644-340 (Report NOTS-TP-4224), February 1966.

A method for producing very smooth surfaces on optical materials such as fused quartz or glass is described. The material being polished is kept immersed in a slurry of polishing compound and the final polishing is done with water containing no abrasive. Surfaces as smooth as 3A rms have been produced by this method.

17

Brandenberg, W. M. and Neu, J. T., "Unidirectional Reflectance of Imperfectly Diffuse Surfaces", JOSA 56:97-103, January 1966.

The unidirectional reflection of an imperfectly diffuse surface is defined in terms of surface radiance and the equivalent hemispherical radiance of the source. Equations relating the unidirectional reflectance to the directional reflectance and the polar and azimuthal angles for indirect and reflected energy are described. A reflectometer is described for measuring the monochromatic unidirectional reflectance over the visible region of the spectrum.

18

Cox, J. T., and Hass, G., "Anti-reflective Coatings for Optical and Infrared Materials", Physics of Thin Films, Vol. II, p. 239-304, (G. Hass, Editor) Academic Press, New York and London, 1966.

Covers the theory and design principles for anti-reflective coatings for optical materials, especially for infrared materials. Considers 1, 2, 3, 4, and multi-layer (up to 39 layers) coatings. A typical example shown is that for a 20 layer coating which has approximately 100% reflectivity up to 2 microns and less than 2% reflectivity from 2 to 21 microns. Such a coating on an infrared transmitting optical material will result in an excellent filter passing only the infrared.

19

Sparrow, E. M., and Cess, R. D., Radiation Heat Transfer, Brooks-Cole, Belmont, California 1966.

Covers the application of the basic laws of thermal radiation to engineering systems, including the long neglected fields of infrared gas radiation heat transfer. The principle chapters cover Thermal Radiation, Radiation Properties of Surfaces, Radiative Interchange between Surfaces, Angle Factors for Diffuse Interchange, Effect of Specular Component of Reflection, the Application and Solution of the Equations of Radiative Interchange, Radiation Equations Controling Conduction and Radiation, and Combination Convection and Radiation.

20

Drummeter, Louis, Jr., and Hass, G. "Solar Absorptance and Thermal Emittance of Evaporated Coatings", Physics of Thin Films, Vol. II, p. 305-62, (G. Hass, Editor), Academic Press, New York and London, 1966.

Covers the theory and design of thermal control coatings for spacecraft applications, discussing the theory of emissivity and absorption, the importance of the ratio of solar absorption to thermal emissivity, and methods for measuring these quantities. Describes methods for producing thin thermal control films. Discusses in some detail the infrared "dark" mirror, which has low reflectivity in the visible range of the spectrum and high reflectivity in the infrared region.

21

Judd, Deane B., "Terms, Definitions, and Symbols in Reflectometry", JOSA 57:445-52, April, 1967.

Mr. Judd, who works for the National Bureau of Standards in Washington, proposed the adoption of standard terms and symbols for nine types of angular reflection (combinations of three types of incidence and three types of collection of reflected energy). The three types are hemispherical, conical, and directional (specular).

(Reviewer's Note: The terms and symbols for the most part seem strange and are practically unused by the optical community.)

22

Blazey, Richard, "Light Scattering by Laser Mirrors", Ap. Op. 6:831-6, May 1967.

The Beckmann theory of scattering is applied to laser mirrors. It is shown that the theory correctly predicts the wavelength dependence of scattering properly. The theory can be used to obtain numbers, σ, standard deviation, and τ, surface autocorrelation distance, for a laser mirror which describes its scattering characteristics. Scattering measurements made on eleven laser mirrors are presented which agree with the theory.

The scattering is not directly a function of wavelength, but also depends on scattering angle, σ, and τ. At some angles the scattering level may be higher for long wavelengths than for short wavelengths, particularly when σ and τ are large. It is concluded that if the parameters τ/λ and σ/λ are known, that the scattering for any wavelength and any angle of incidence may be predicted; conversely, if the scattering is measured, σ and τ may be computed.

23

Nelson, H. F., and Goulard, R., "Reflection from a Periodic Dielectric Surface", JOSA 57:769-71, June 1967.

Nelson theorizes that the deviation of diffuse reflection from Lambert's cosine law for large angles of incidence and materials with a rough surface is due to a contribution of volume scattering of refracted radiation which eventually emerges through the surface. He concludes that the magnitude of the off-specular peak is determined almost entirely by the index-of-refraction ratio of the material.

24

Fowles, G. R., Introduction to Modern Optics, Holt, Rinehart, and Winston, New York, p. 304, 1968.

Relatively modern text at the intermediate level on Optics which emphasizes the recent developments in optics (lasers, etc.). The book concentrates on physical optics, with almost no geometrical optics.

25

Beckman, P., "Scattering of Light by Rough Surfaces", Progress in Optics, Vol. VI, (E. Wolf, Editor), N. Holland Pub. Co., Amsterdam/London, 1968.

Utilizes complex mathematical analysis to predict and explain the scattering of light from rough surfaces. Considers periodic rough surfaces, random rough surfaces, and surfaces with depolarizing effects.

26

Frey, H. G., and Deavenport, R., "Scattering Properties of Random Rough Surfaces", Defense Res. Lab. of U. of Tex. Progress Report on Project SF-101-03-15, April 1968, AD-834 543L.

Describes the theoretical investigation of the scattering properties of random rough surfaces and the experimental investigations in an attempt to validate the theoretical results. The scattering coefficients of Eckart, Isakovitch, and Beckman are discussed with reference to the scattering coefficient used in processing the experimental data. A scattering cross section per unit solid angle per unit area is derived, which includes Eckart's high and low frequency theories as special cases. Only the Fraunhofer limit is discussed, which is valid only for the roughest surface.

27

Vincent, R. K., and Hunt, G. R., "Infrared Reflection from Mat Surfaces", Ap. Op. 7:53, July, 1968.

A general theory is presented which segregates the rays comprising the total reflection from a mat surface according to their dependence on the intrinsic absorption coefficient. It is compared against experimental data obtained from samples of a material (calcite and gypsum) which display a range of absorption band intensities over the 4-14 micron region. The ability of the theory to predict the different reflection behaviors of bands of various intensities is demonstrated and is considered to be important for exploring remote sensing data.

28

Hunderi, O., and Beaglehole, D., "On the Reflectivity of Rough Metal Surfaces", Phys. Letters 29:335, June 1969.

Extrapolation of the roughness induced decrease in the reflectivity of metals from above the surface plasmon cut-off frequency to lower frequency indicates that surface plasmons give a coherent contribution to the specular reflectivity. In other words, for frequencies above the plasmon cut-off frequency, the reflectivity decreases much more than is accounted for by the increase in scattered light. This article concludes that this extra absorptivity is due to a surface effect such as the trapping of light in the pits of the surface with eventual absorption.

29

Kerker, M., <u>The Scattering of Light and Other Electromagnetic Radiation</u>, Academic Press, New York, p. 666, 1969.

A recent text which extensively covers the subject of electromagnetic scattering, particularly that of light scattering, and discusses many practical applications. Emphasis is on scattering from particles or on passage through a non-homogeneous media rather than from surfaces.

30

Bell, R. J., Armstrong, K. R., Nichols, C. S., Bradley, R. W., "Generalized Laws of Refraction and Reflection", Optical Soc. of Am. Journal 59:187-9, February 1969.

The generalized laws of refraction and reflection for absorbing media are rederived, advoiding complex angles and using only definitions with measurable parameters. The results are put in a form which, by inspection, reduces to Snell's and Fresnel's equations.

31

Cheo, P. K., and Renan, J., "Wavelength Dependence of Total and Depolarized Back-Scattering of Laser Light from Rough Metallic Surfaces", Opt. Soc. of Am. Journal 59:821-6, July 1969.

The wavelength dependence of both the total back-scatter cross section and the depolarized back-scatter cross section for rough metallic surfaces of known characteristics is given for wavelengths of 0.63, 3.39, and 10.6 micron wavelengths. It is found that the metallic surfaces reflect nearly as perfect reflectors as long as the surface height imperfections do not exceed $\lambda/4$. Reflectance values for rougher surfaces at various angles of incidence are given.

32

Beaglehole, D., and Hunderi, O., "Study of the Interaction of Light with Rough Metal Surfaces", Physical Review B, 2:309-329, 15 July 1970.

Describes measurements of the reflectivity, scattering, and transmission of light by metals with rough surfaces. For surfaces whose roughness is very short ranged, the ratio of rough-surface reflectivity to smooth-surface reflectivity varies exponentially as λ^{-2} above the plasmon frequency. Below this region, for these rough surfaces, the scattered intensity follows as λ^{-4} wavelength relation. For surfaces which are more wavy, the reflectivity and scattered light vary less rapidly with wavelength.

33

Dalmas, J., "Diffusion de la Lumiere par une Demi-sphere, Posee Sur une Surface Plane, D'un Materiau de Meme Nature", Nouv. Rev. d'Optique Appliquee, 1:167-70, January 1970 (French).

Describes the problem for obtaining mathematical expressions for the diffuse reflection of light from various surfaces. Uses vector matrix algebra to obtain complex equations for the diffuse reflection of light.

34

Marathay, A. S., Heiko, L., and Zuckerman, J. L., "Study of Rough Surfaces by Light Scattering", Ap. Optics 9:2470-76, November 1970.

The problem of the scattering of radiation from rough surfaces is formulated in the language of scalar coherence theory. An experiment is analyzed to show how the intrinsic properties of the scatter can be studied quantitatively by making intensity measurements in the scattered field. It is concluded that the statistical properties of the scattered field are affected much more by a media that introduces random phase than by those that introduce random amplitude absorption.

35

Wolf, E. (Editor) Progress in Optics, Vol. I-VIII, N. Holland Pub. Co., Amsterdam/London, 1961-1970.

A series of volumes describing the latest developments in optical science. Each chapter is written by a different author; the arrangement of subject matter is almost entirely random. See Beckman (1968), Kinosita (1965), and Musset (1970) for abstracts of particular interest.

36

Arsenault, Henri H., "Roughness Determination with Laser Speckle", JOSA 61:1425-26, October 1971.

Considers the problem of the determination of surface roughness by using the speckle pattern produced when a rough surface is illuminated with a laser beam. Results are expressed in somewhat complex matrix algebra, and the author questions the validity since assumptions must be made about the distribution of the energy from the illuminating diffuser.

37

Ohidal, K. Navratil, and Lukes, F., "Reflection of Light by a System of Nonabsorbing Isotropic Film--Nonabsorbing Isotropic Substrate with Randomly Rough Boundaries", JOSA 61:1630-39, December 1971.

The reflection of light by a system consisting of a nonabsorbing isotropic film and nonabsorbing isotropic substrate with both boundaries (air-film and film-substrate) rough is considered. The scalar theory of light scattering on such a system is developed. In most studies of the optical properties of thin films it is assumed that the boundaries between the media are perfectly flat planes; this paper makes allowances for the fact that in practice it is impossible to make perfectly flat surfaces.

38

Reo, C. R., Chen, H. S., and Takashima, T., "Laboratory Determination of the Characteristic Reflection Matrices of Natural Surfaces", British Journal of Ap. Physics (D) 4:1057-62, July 1971.

A simple procedure is given for determining the elements of a 3 x 3 matrix which describes the reflection of light by natural surfaces. The procedure is based on the determination of the Stokes vector of the light reflected by the sample under different conditions of illumination, with either polarized or unpolarized light. The results account for the discrepancies which occur between the values obtained by the assumption of the Lambert law of reflection and observed values.

The analysis is made for natural soils and sands, but would appear to be equally valid for other surfaces.

III-N Article Reviewed but not of sufficient Interest to Abstract

Beckman, P., "Scattering by Composite Rough Surfaces", Proc. IEEE 53:10-12-15, 1965

Berreman, D. W., "Anomalous Reststrahl Structure From Slight Surface Roughness", Phy. Rev. 163:855-64, November 1971

Born, M., Optik, Springer-Verlag, Berlin, 1933

Brand, Kolman W. and Spagnolo, Frank A., "Lambert Diffuse Reflection from General Quadric Surfaces", JOSA 57:452-8, April 1967

Chenmoganadam, T. K., "On the Spectral Reflectance from Rough Surfaces", Phy. Rev. 13:96. January 1919

Davies, H., "The Reflection of Electromagnetic Waves from a Rough Surface", Proc. IEEE 101:209-14, July 1954

Fragstein, C. von, "Uber die Formulierung des Kirchoffschen Gesetzes und ihre Bedeutung fur eine zweekmafige Definition von Remissionszahden", OPTIK 12:60 (In German), 1955

Healy, T. J., "The Scattering of Particles from a Rough Surface", Dissertation, E. E. Dept., Univ. of Colorado, 1966

Holl, H. B., "Specular Reflection and Characteristics of Reflected Light", JOSA 57:1967-90, May 1967

Jones, J. E., "Absorption of Films at the Surface Opposite the Surface of Incidence", JOSA 59:877-9, July 1969

Keller, J. B., "Geometrical Theory of Diffraction", JOSA 52:116-30, Feb. 1962

III-A N (cont)

Kneisal, G. J. and Geist, J., "Possibility of Obtaining Highly Reflective Diffuse Coatings for the Infrared", paper pres. at Spring Meet. 1968 Op. Soc., Abstract in JOSA 58:733, 1968

Lotsch, H. K., "Reflection and Refraction of a Beam of Light at a Plane Interface", JOSA 58:551-61, April 1968

Miller, J. C., "Reflections from an Absorbing Multi-Layer System", JOSA 58: 1604-6, December 1968

Nicodemus, F. E., "Reflectance Nomenclature and Directional Reflectance and Emissivity", Ap. Optics 9:1474-5, July 1965

Pearson, J. E., "Diffraction of Gausian Laser Beams by a Semi-Infinite Plane", JOSA 59:1440-5, November 1969

Pert, G. J., "Optical Reflection at Grazing Incidence from a Shock Front", J. Ap. Physics 41:3516-20, July 1970

Schmidt, E., "Simple Method for the Determination of Optical Constants of Absorbing Materials", Ap. Optics 8:1905-8, September 1969

Spartan, T. M., "Scattering of Coherent Light From a Rough Surface", Brit. J. Ap. Physics 2:1027-34, July 1969

Twersky, V., "On Scattering and Reflection of Electromagnetic Waves by Rough Surfaces", IRE Trans. on Antennas and Propagation 5:81-90, Jan. 1957

Twersky, V., "Reflection Coefficients for Certain Rough Surfaces", J. Appl. Physics 24:629-60, May 1953

III-A NA Article Not Reviewed (No Copy Obtained)

Arnold Engineering Development Center (USAF), "Analysis of Methods for Determining Outgassing Rates", Rpt. AEDC-TDR-64-180

Anders, Hugo, Thin Films in Optics, the Focal Press, London and New York, 180 p., 1967

Hulst, H. C. van de, Light Scattering by Small Particles, Wiley, New York, 1957

Russell, D. A., "The Spectral Reflectance of Rough Surfaces in the Infrared", Masters Thesis, M. E. Dept., U of Cal., Berkeley, 1961

Shipley, E. N., "Multiple Scattering Calculations--Geometry for Spherical Atmospheres", Bellcom, Inc., Washington, D. C., NASA-CR-118662, TM-71-1011-5, April 16, 1971

III-B: INSTRUMENTATION FOR MEASURING LIGHT SCATTERING AND SURFACE PROPERTIES

1

Gorton, A. F., "Reflection From, and Transmission Through, Rough Surfaces", Phy. Rev. 7:66-78, January 1916.

One of the first American articles on the scattering of light by rough surfaces. Discusses theory of light scattering and measurements which were made to measure the scattered light from matte surfaces over the wavelength region of 0.6 to 13 microns. Polished optical surfaces were also tested--the best silvered optical surface available had reflectivity of 90% at 4 microns, approximately 100% for longer wavelengths, but only 10% at one micorn. (Reviewer's Note: There was some confusion in the article as to whether these were actually polished optical surfaces or surfaces roughened with fine emery and then silvered.)

2

McNicholas, H. J., "Absolute methods in Reflectometry", Bu. of Std. J. of Research 1:29-73, January 1928.

The theory and use of the integrating sphere for use in the measurement of reflectometry is discussed, and compared with a new absolute method of reflectometry involving no direct use of an integrating devise. Equipment is described for the measurement of reflective properties of materials under either completely diffused or undirectional illumination for various directions of observation.

3

Hunter, Richard S., "A Multipurpose Photoelectric Reflectometer", JOSA 36:536-59, November 1940.

A multipurpose reflectometer is described which may measure reflectance specular gloss, and trichromatic coefficients of surfaces. The reflectometer is primarily intended, however, for such surfaces as ceramic, paper, textile, and paint.

Aughey, W. Henry, and Baum, F. J., "Angular-Dependence Light Scattering-- A High Resolution Recording Instrument for the Angular Range 0.05-140°", JOSA 44:833-37, November 1954.

Describes a unique optical instrument for the measurement of light scattering in physically nonhomogeneous systems. The scattering data provides a basis for the size characterization of optical inhomogeneities in the radius range of 0.1 to 100 microns. The useful angular range of the instrument extends from about 0.05° to 140°, with angular resolution of 0.02° for large inhomogeneities at small angles. Scanning rates are from 0.1 to 20° per minute. Light intensities varying by a factor of 10^8 are measured through the use of an optical attenuator which facilitates use of a 1P21 multiplier phototube at a low level of illumination. Results are recorded on a pen recorder.

(Reviewer's Note: From reading the article, it is not clear how diffraction effects are eliminated at small angles--it appears that measurements at angles less than about 0.2° may be quite inaccurate.)

5

Koehler, W. F. and White, W. C., "Multiple-Beam Fringes of Equal Chromatic Order, Part VI, Method of Measuring Roughness", JOSA 45:1011, 1955.

A new method of measuring the roughness of a polished glass surface is reported. Fringes of various orders, n, are formed at the same wavelength. The measured half-width is plotted as a function of 2/n. The slope, S, of the best straight line through the experimental points is used to obtain a roughness value from an independently experimentally determined function S vs. h, where h is the rms surface roughness.

6

Bennett, H. E., and Koehler, W. F., "Precision Measurement of Absolute Specular Reflectance with Minimized Systematic Errors", JOSA 50:1-6, January 1960.

Instruments for making precision measurements of specular reflectance at essentially normal incidence in the near ultraviolet, visible, and infrared regions of the spectrum are described. The square of the absolute reflectance is measured, with a resultant increase in measuring precision, and the major sources of systematic error in making reflectance measurements have been reduced or eliminated. The difficulty in making precision reflectance measurements in the infrared, where integrating spheres cannot be used, has been overcome by a unique compensating feature in the infrared reflectometer which prevents the image of the detector from changing size or position because of a slight tilt of the sample. The measurements on high reflectance samples are believed to be good to ±0.001.

7

Candius, E. S. and Vanderschmidt, G. F., "Optical Surface Comparator", Paper presented at 1963 Spring meeting of Op. Soc., Abs. in JOSA 53:509, 1963.

An instrument making possible rapid measurement of the optical characteristics of a room temperature surface has been developed which has found wide use in the field of development of thermal-control surfaces for spacecraft. The instrument is provided with two sensor heads, one for measuring thermal emissivity and the other solar reflectivity.

8

Torrance, K. E., "Monochromatic Directional Distribution of Reflected Thermal Radiation from Roughened Dielectric Surfaces", M.S. Thesis, U. of Minn., 1964.

The directional distribution of light reflected from surfaces of varying roughness is explored experimentally. The angle of incidence was varied from 10° to 87° while the angle of reflectance extended from 0° to 89°. The roughness of test surfaces ranged from optically smooth to 5.8 microns; the test light had a wavelength of 0.5 microns. The measurements affirm that Lambert's cosine law does not hold when roughened surfaces are illuminated at moderate to large angles of incidence. Rather, it is found that a maximum in the distribution of the reflected radiance occurs at reflection angles larger than the specular ray direction.

9

Shaw, J. E., and Blevin, W. R., "Instrument for the Absolute Measurement of Direct Spectral Reflectances at Normal Incidence", JOSA 54:334-6, March 1964.

An accurate but simple reflectometer is described for measuring the spectral reflectances at normal incidence of flat, specularly reflecting surfaces. The instrument has a wavelength range of 0.2 to 2.5 microns, and with transparent samples provides for simultaneous measurement of spectral transmittances.

The light source comes from a double monochromator, giving the wide range for input wavelength. The big advantage clained for the instrument is that it permits measurement of the specular reflectance directly at normal angle of incidence, rather than at an incidence angle appreciably away from the normal as with other instruments.

10

White, John U., "New Method for Measuring Diffuse Reflectance in the Infrared", JOSA 54:1332-37, November 1964.

In this method of measuring diffuse reflectance in the infrared, the sample is irradiated from all directions with chopped light. The source and sample are placed at conjugate foci of a hemispherical mirror with the chopper between the source and mirror, making the component reflected by the sample distinguishable from the one emitted by it. Advantages of the method are that reflectance may be measured over a very wide range of sample temperatures.

The method is claimed to be quite superior to integrating spheres for measurements in the infrared.

11

Birkebak, R. C. and Eckert, E. R. G., "Effects of Roughness of Metal Surfaces on Angular Distribution of Monochromatic Reflected Radiation", J. Heat Trans. 87:85, 1965 (Ser. "C").

Describes a detailed experimental study to explore the influence of surface roughness conditions on the reflection characteristics of metal surfaces for non-thermal radiation. The test surfaces were prepared by standard optical grinding techniques using a range of grit sizes. Biangular, sphecular, and hemispherical-angular reflectance measurements are discussed in terms of the optical rms surface roughness, the wavelength of the reflected radiation, and the surface material. The results are compared with available predictions from theoretical analysis.

12

Torrance, K. E. and Sparrow, "Biangular Reflectance of an Electrical Non-conductor as a Function of Wavelength and Surface Roughness" J. Heat Trans. 88, Ser. "C", p. 283, 1965.

Describes measurements made to determine the directional reflectance characteristics of electrical non-conductors. The test material was fused polycrystallian magnesium-oxide ceramic. Measurements were made for surface roughness ranging from 0.16 to 5.8 microns over a wavelength range from 0.5 to 12 microns. The reflectance characteristics of a given surface approach a diffuse distribution at short wavelengths and/or rough surfaces, and specular distribution for long wavelengths and/or smooth surfaces. A given surface becomes effectively smoother when the illumination angle increases. For the case of incidence of 45^{o}, it was found that maxima in the biangular reflection distribution occured at angles other than the specular; within the knowledge of the authors, such off-specular peaks have not been discussed previously.

13

George, Dianne, and Limperis, T., "Sources of Experimental Errors in Spectrophotometric Measurements", DDC Report AD-481 796, Univ. of Mich. Inst. of Science and Technology, Report No. 5698-33-P-Vol 2, May 1965.

Spectrophotometric measurement of directional reflectance requires extreme care in the choice of experimental procedure and the recording of experimental parameters. Sources of error include sample transparency, the reflectance standard, sample heating by absorption of incident radiation, sample flourescence, and polarization-sensitive samples.

14

Look, D. C. J. R., "Diffuse Reflection from a Plane Surface", JOSA 55:1628-32, December 1965.

Measurements are described which determine the angular dependence of the amount of radiation scattered from plane diffuse surfaces; the results have peak levels of as much as 10% from those predicted by the use of Lambert's law of diffuse reflection. An empirical expression is derived which agrees with the measured results within 2%. The expression is believed to hold good for any diffuse reflective surface (a surface which has no large specular component of reflection).

15

Wood, B. E., "Vacuum Integrating Spheres for Measuring Cryodeposit Reflectances from 0.35 to 15 microns", Arnold Engineering Center, Arnold Air Force Station, Report No. AEDC-TR-65-176, AD-468-609, August 1965.

Two new integrating sphere systems are described. A M_gO coated integrating sphere is described for measurements in the visible region of the reflectance of CO_2 cryodeposits on a Cat-a-lac black substrate. A sulphur coated integrating sphere is described for measurements in the infrared region of the spectrum.

16

Nicholls, R. L., "Near Infrared Diffuse Reflectivities of Natural and Manmade Materials", British Journal of Ap. Physics (D) 2:201-4, February 1966.

Describes a method of measuring the reflectivity of materials by using an integrating sphere in the 0.8 to 2.5 micron band. Primarily interested in high reflectivity materials, but also tested some highly absorbing materials. Optical matte black paint was found to have 5% reflectance at 0.8 microns, increasing almost linearly to 15% at 2.5 microns. Strangely enough, dark green paint had approximately 10% constant reflectivity over the entire 0.8 to 2.5 micron range.

17

Johnson, R. G., Canfield, L. R., and Madden, R. P., "Reflective Scattering from Substrates and Evaporated Films in the Far Ultraviolet", Ap. Optics 6:719-22, April 1967.

Measurements of radiation reflectively scattered from mirror surfaces have been made at the wavelengths 1216A and 584A. Several glass and fused silica substrates with differing degrees of surface roughness were studied as well as evaporated films of aluminum and gold as a function of film thickness. A relatively small area detector was scanned in angle about the sample and the detected energy integrated over the scattering angle. The results indicate that fused silica can be polished to a smoother surface than glass and that a smooth substrate is significantly advantageous in obtaining evaporated films having surfaces with low scatter and that gold films are considerably smoother than aluminum films of equal thickness.

The amount of scattering measured is surprisingly low, running less than 1% for all cases; this is probably due to the fact that the scattered radiation was measured only for angles greater than 10^{o} from the specular direction.

18

Starner, Keith E., and Stark, Robert L., "Effects of Front Surface Roughening on Solar Absorptivity of Quartz Rear Surface Mirror Satellite Coatings", Aerospace Corp., El Secundo Rpt. No. TR-1001 (2240-10)-10, DDC No. AD-815-036, March 1967.

An experimental investigation was conducted to determine the increase of the solar absorptivity of quartz rear surface silvered mirrors due to surface roughness. It was found that solar absorptivity increased by a factor of 2.7 from a clear to an artificially roughened surface quartz mirror. It is postulated that absorptivity increase is caused by surface scattering of incoming and reflected radiation which gives rise to total multiple reflections within the quartz layer due to the critical angle effects. The data obtained are applicable to prediction of satellite temperature change caused by micrometeoroid erosion of thermal coating in a space environment.

19

Johnson, M. C., "Vacuum Ultraviolet Scattering Distributions", Ap. Optics 7:879-81, May 1968.

Measurements of reflectance and the profile of scattered intensity from rough and smooth surfaces are reported for incident radiation of 1216A for various incident angles. Black appearing surfaces are found to have reflectances higher than expected. The very black surfaces (carbon black, etc.) scattered a significant fraction of the light in all directions. The "black" surfaces absorbed only 10 times as much UV light as the surfaces which appear highly reflective in the visible region. Sandbalsting or annodizing surfaces before applying finishes did not help absorption qualities. Black epoxy had approximately 2.5% hemispherical scattering; gold-black had only 0.765% hemispherical scattering, but high specular reflectance. This indicates that combinations of specular and diffuse materials may be used to good effect.

20

Kenyon, B. A., "Instrumentation for Investigation of Proton Damage to First Surface Mirrors", paper presented at 1969 Spring Meeting of Op. Soc.; Abs. in JOSA 59:514, 1969.

An apparatus has been constructed for measuring _in situ_ the effect of proton irradiation on the specularity of selected space mirror surfaces. The equipment combines in one system a low-energy (1 to 30 KeV) proton accelerator, a vacuum ultraviolet absolute reflectometer, and a visible middle-ultraviolet scattered light monitor. This set-up permits alternate measurements of proton irradiation and reflectivity without intermediate exposure of the test specimen to light or air. Measurements are made in the 900-2500A region, with repeatability of better than 1%. Scattering changes are monitored up to 3^{o} off the specular beam.

21

Gloge, D., Chinnock, E. L., Earl, H. E., "Scattering from Dielectric Mirrors", Bell System Tech. Journal 48:511-26, March 1969.

The light scattered from high-reflecting dielectric mirrors is measured for angles between 0.01^{o} to 1^{o} from the beam axis over a wavelength range of 0.3 to 10 microns. A reasonable functional approximation for the measurements gives a scattered power density/sq. cm. at 0.1^{o} of 10^{-6} of the total power (for 1.0 microns), and the power density varies inversely as the third power of the angle and the first power of the wavelength. For example, the power density would be 10^{-10} at 1.0^{o} from a 10 micron beam.

Bennett, H. E., "Measurement of Light Scattered from Very Smooth Surfaces", JOSA 60:1577, November 1970.

The integrated flux of light scattered into various angles from surfaces as smooth as 7A rms can be measured at wavelengths in the 2500-8000A region using the instrument described. By mounting an aluminized hollow cone in front of the sample and using an adjustable diaphragm on the collecting mirror, light scattered into various angles between 1^{o} and 60^{o} to the specular direction can be measured directly. By extrapolating from 60^{o} to 90^{o}, the ratio of specular to total reflection can then be obtained.

23

Kelsall, D., "Absolute Specular Reflection Measurements of Highly Reflecting Optical Coatings at 10.6 Microns", Ap. Optics 9:85-90, January 1970.

A high precision method for measuring the specular reflectivity of mirrors at 10.6 microns with a CO_2 laser source when the reflectivity of the mirror approaches unity is described. The results of measurements on a range of evaporated thin film coatings is reported. Measurements at 6328 A with a He-Ne laser were also made and the results described.

24

Newman, B. E., and Brown, G. L., "Evaluation of Parameters Affecting Integrating Sphere Reflectivity Measurement Accuracy", paper presented at 1970 Spring Meeting of Op. Soc.; Abs. in JOSA 60:726, 1970.

Two important parameters affect integrating sphere reflection efficiency and accuracy: the sphere wall reflection characteristics and the detector directional characteristics. The reflection characteristics of MgO sphere-wall coatings were measured as a function of composition, age, and angle for wavelengths from 4000 to 25000A. The directional reflectance increased slightly with the angle of incidence, with the reflection being very non-diffuse for large angles of incidence. Degradation of reflectivity with age was found to be almost entirely a function of absorption of water moisture from the air. Pressed powder MgO, when compared to MgO smoke, is easier to prepare, more uniform, and more durable, but has lower reflectivity and ages more rapidly.

The directional characteristics of photomultiplier tube detection snesitivity was found to be very directional, unless the face plate is coated with MgO smoke, in which case the directional sensitivity follows a cosine law.

Recommendations are made for improvement in equipment design and for more efficient operation.

25

Muffoletto, C. V., and Plummer, W. T., "Method of Measuring Surface Microripple of Finished Optics to 10A Accuracy", paper presented at 1971 Spring Meeting of Op. Soc.; Abs. in JOSA 61:652, 1971.

Fizeau fringes are utilized by coating the pieces to be tested and the test galss with silver. One of the pieces must be transparent from the back and the silver must be about 2% transmittive in order to form and observe the Fizeau fringes. A filar microscope in conjunction with a telescope is used to observe these fringes from a distance of six meters. A series of measurements is made from peak to trough across a selected fringe and averaged; then the distance to the next fringe is measured. The ratio between fringe roughness and separation determines the surface microripple in fractions of a wavelength of the light used to form the fringes.

26

Sprague, R. A., "Measurement of Surface Roughness Using Speckle Patterns Found in Broad-Band Illumination", paper presented at 1972 Spring Meeting of Op. Soc.; Abs. in JOSA 62:722, 1972.

Measurements of the spectral reflectivity and power spectral density of a machine-finished surface are presently used to determine surface roughness. Unfortunately, these measurements are affected not only by the average height deviations of the surface contour (roughness) but also by the contour correlation widths. The correlation of these measurements to roughness is thus limited to a single type of finishing technique (grinding, milling, etc.) over a fixed range of roughness values. This paper proposed another technique to measure roughness involving ehe speckle pattern formed when the surface is illuminated with spatially coherent light having a broad-spectral band-width and viewed with a finite aperture optical system. Measurement of the contrast of the speckle pattern can be related to the surface roughness when the average roughness and coherence length of illumination are within the same order of magnitude. Techniques for implementing this idea are discussed and results presented that show a good correlation to roughness for a variety of surface finishes with a wide range of roughness values.

27

Sawatori, T., "Surface Flaw Detection Using Oblique Angle Illumination", Ap. Optics 11:1337-44, June 1972.

An analysis of a surface flaw detection method is presented in which oblique illumination is combined with a high pass spatial filter to detect the light scattered from surface flaws. The effect of surface finish on test samples is assessed statistically and the sensitivity of the system is calculated. Data have been calibrated on diffraction patterns and surface scratch detection for three stainless steel plates which have different surface finishes; the results agree with theoretical calculations and are quite promising.

28

Orme, Maj. Gordon R., Dissertation "Measurement of Small-Angle Scatter from Smooth Surfaces", Optical Sci. Center, U. of Arz., 1972.

Covers the theory lightly on the scattering of light from smooth optical surfaces at angles very close to the specular angle. Covers in detail a test procedure and results for measuring the amount of scattered light at these small angles. (Reviewer's Note: For a more detailed description and more complete coverage, see McKenney, Orme, etc. 1972)

III-B N Article Reviewed But Not of Sufficient Interest to Abstract

Bridgeman, T., "Reflectance and Transmission of an Anisotropically Scattering Material", JOSA 60:1265-6, September 1970

Depew, C. A., and Weir, R. D., "Surface Roughness Determination by the Measurement of Reflectance", Ap. Optics 10:969-70, April 1970

Eckert, E. R. G., "Measuring Reflexion won Warmestrahlen on Technischen Oberflachen", Forsch. Gebiete Ingenieurwesens 7:265, 1936

Fawcell, J. L. and Eastman, P. C., "Elimination of Surface Reflection Effects from Optical Absorption Measurements," R. Sci. Inst. 40:855-6, July 1969

Fischer, J. E., "Spurious Observations of Scattered Lingh in UV Instruments", Ap. Optics 7:715-6, April 1968

Harrison, J. G. W., Definition and Measurement of Gloss, Parta, England, 1945

Hass, G., and Waylonis, J. E., "Optical Constants and Reflectance and Transmittance of Evaporated Aluminum in the Visible and Ultraviolet", JOSA 51:719-22, July 1961

Heinisch, R. P., and Schmidt, R. N., "Development and Application of an Instrument for the Measurement of Directional Emittance of Blackboard Cavities", Ap. Optics 9:1920, 1970

McKeown, D., "New Method for Measuring Sputtering in the Region Near Threshold", Rev. Sci. Inst. 32:133, 1961

Milliard, J. P., "Comparison of Infrared Emittance Measuring Techniques", paper presented at the 1968 Spring Meeting of Op. Soc., Abs. in JOSA 58:733, 1968

O'Brien, P. F., "Directional Reflectances of Room Surfaces", Illum. Engi. 64:245-52, April 1969

Rogoff, G. L. "Optical System for Direct Spatially Resolved Measurement of of Radiation Emission and Self Absorption", R. Sci. Inst. 42:99-103, January 1971

Slater, John M., "A Recording Goniophotometer", JOSA 21:218-23, July 1935

III-B NA Article Not Reviewed (No Copy Obtained)

Harrison, J. W. G., Gloss, Its Definition and Measurement, Chem. Publishing Co., New York, 1949

III-C: MATERIALS AND PROCESSES FOR CONTROLLING SCATTERED LIGHT

1

Bennett, H. E., "Specular Reflectance of Aluminized Ground Glass and the Height Distribution of Surface Irregularities", JOSA 53:1389-94, December 1963.

The relative specular reflectance of various aluminized ground-glass surfaces has been measured at normal incidence. All of the samples tested had a Gaussian reflectance curve except for the most finely ground. Since the specular reflectance falls off very nearly exponentially with decreasing wavelength, the exponent being proportional to $1/\lambda^2$, reflection plates of ground glass material make excellent reflection filters with very good rejection characteristics in the unwanted (short) wavelength with little decrease in the energy passed in the desired (long) wavelength region. The limiting wavelength for appreciable specular reflection at normal incidence is roughly 1/4 of the average particle size of the grinding powder used, so that these scatter plates can be designed for use not only in the far infrared but also at shorter wavelengths nearly to the visible region of the spectrum.

2

Drummeter, L. F., Jr., and Fowler, W. B., "Angular-Reflectance Properties of Blackened Aluminum Honeycomb", paper presented at 1963 Spring meeting of Opt. Soc., Abs. in JOSA 53:511, 1963.

The reflective characteristics of a matte-black finish on sheet aluminum have been modified by placing a layer of glossy-black finished aluminum honey-comb over the matte-black surface. (The front edges of the honeycomb have a dull black finish). The result was a noticeable difference in the general relative angular reflecting of the composite surface and a considerable decrease in specular reflectance relative to the flat surface. The edge-modified honeycomb material is comparable in many respects to black velvet for various viewing angles in the plane of incidence.

3

Semplak, R. A., "0.63 Micron Scatter Measurements for Teflon and Various Metallic Surfaces", Bell System Tech. Journal, pp. 1659-74, October 1965.

Angular scatter measurements were obtained by illuminating Teflon and various metallic surfaces at normal incidence with a 0.63 micron laser beam and an optical probe utilizing a photomultiplier detector. The scatter from Teflon was found to be Lambertian to a close approximation for scattering angles out to 85^{o}. The forward scatter (by light passing through the sample) was approximately 1/10th of the back scatter (reflected light) for a 1/2 inch thick sample; the difference is attributed to absorption in the Teflon.

Metallic and glass surfaces were also tested. Scattering from these surfaces was not Lambertian except for intentionally roughened surfaces, but had high peaks near the angle of incidence.

4

Hass, G. (Editor), Physics of Thin Films, Vol. I-IV, Academic Press, New York and London, 1966.

A comprehensive set covering the design, production, and testing of thin film coatings for optical materials. Of particular interest are chapters on "Preparation and Measurement of Reflective Coatings for the Vacuum Ultraviolet" (see R. P. Madden), "Anti-reflective Coatings for Optical and Infrared Materials" (see J. T. Cox), and "Solar Absorption and Thermal Emittance of Evaporated Coatings" (see L. Drummeter).

5

Keegan, Harry J., and Weidner, V. R., "Infrared Spectral Reflection of Black Materials", Paper at Annual Meeting, 1966 of Op. Soc., JOSA 56:1453, 1966.

Measurements on the spectral reflectance of such black materials as carbon black, cupric oxide, platinum-black deposit on gold, commercial graphite, and black acetate plastic tape were measured in the 215 to 22.2 micron region of the spectrum at various temperatures and angels of incidence. The platinum-black on gold was found to be far the best, having a reflectance of less than 2% as compared to up to 40% for some of the others.

6

Harris, L., The Optical Properties of Metal Blacks and Carbon Black, The Eppley Foundation for Research Pub., Newport, R.I., 1967.

Considers films for enhancing the reflection, transmission, or absorption of radiation in the infrared region of the spectrum. Materials considered include metal-blacks (gold, gold alloys, aluminum, silver, antimony, zinc, and platinum), which are usually prepared by "burning" the metal in a controlled atmosphere and a partial vacuum, and non-metallic substances such as lamp-black, acetelene soot, and Parson's optical black lacquer.

Measurements of both diffuse and specular reflectance were made over the wavelength range from 0.254 microns to 40 microns, and the measured reflectances and absorptances compared with calculated values.

Parson's black* was found to be the best absorber (least reflectance) for the infrared range above 8 microns.

(*Eppley-Parson's Optical Black Lacquer, which consists of two coats; the first, or undercoat, is lampblack in nitrocellulose vehicle, applied with an airbrush; the second, or top coat, is aniline black in ethyl cellulose, also applied with an airbrush.)

7

Hostletter, G. R., "Measurement of Scattered Light from Mirrors and Lenses", Ap. Optics 7:1383-5, July 1968.

Measurements are made of scattered radiation from optical lenses and flat "laser-smooth" mirrors when exposed to solar radiation. Results indicate that scattering from the mirror surfaces is 10^{-6} I two spot diameters away from the solar image and approximately $0.2(10)^{-6}$ I five spot diameters away.

8

Mock, J. A., "No-Gloss Metal Finishes Tame Sun Glare", Materials Engineering 67:74-5, June 1968.

Discusses finishes for metal parts of automobiles so that the sun glare will not bother the driver. In addition to low-glare, the finishes must be extremely durable and pleasing in appearance. Discusses the effect of metal preparation; i.e., sandblasting, glass bead peening, etc., before applying low-luster finishes. The emphasis was on obtaining low glare (low specular reflection) rather than on low diffuse reflection. Most of the finishes were excessively reflecting from an optical standpoint, running from 5 to 20%, but one gray enamel finish was pictured which was very "flat" and was found to have zero per cent glare when tested by the crude ASAE (American Society of Automotive Engineers) test methods. Unfortunately, this finish was not identified by name.

9

Kinosita, K., "Surface Deterioriation of Optical Glasses", Progress in Optics, Vol. IV, (E. Wolf, Editor), N. Holland Pub. Co., Amsterdam/London, 1968.

Discusses the deterioriation of optical glass surfaces when exposed to different environments. Is mostly concerned with various solutions--acid, alkaline, salt, corrosive, etc., but also considers various vapors and gasses, including water vapor, oxygen, and nitrogen.

10

Madden, R. P., "Preparation and Measurement of Reflective Coatings for the Vacuum Ultraviolet", Physics of Thin Films, Vol. I, p. 123-86, (G. Hass, Editor), Academic Press, New York and London, 1968.

Discusses the special problems in obtaining high reflectivity in the ultraviolet, methods of preparing thin films, measurement techniques and the design of practical equipment. Covers wavelengths from 584Å to 3000Å. Aging effects (the rapid decrease in reflectivity with time) is given special consideration; gold and platinum films, which resist aging, are discussed in detail.

Stable reflectivities of approximately 25% are considered good below 1500Å, although reflectivities of 50% down to 584Å can be obtained with special aluminum films.

The advantages and techniques of overcoating, particularly for diffraction gratings, are also considered.

11

Bennett, J. M., and King, R. J., "Effect of Polishing Technique on the Roughness and Residual Surface Film on Fused Quartz Optical Flats", Ap. Optics 9:236-8 January 1970.

Various polishing techniques are discussed for obtaining extremely smooth optical surfaces. Bowl-feed polishing produced the smoothest surface, although the best surface obtained even with this technique was 8A. (Reviewer's Note: Also see Dietz, 1966.)

12

Musset, A., and Thelen, A., "Suppression of Scattered Light in Optical Systems", Progress in Optics, Vol. VIII, (E. Wolf, Editor), N. Holland Pub. Co., Amsterdam/London, 1970.

Discusses the advantages of anti-reflection coatings in multi-element optical systems in order to reduce scattered light. Points out that scattered light reaching the detection element is the result of multiple reflections, so that the reduction of surface reflection from 5% to 0.5% will reduce scattered light by a factor of at least 100.

13

Standford, J. L., et. al., "Roughness-Induced Absorption in Metallic Mirrors", paper presented at 1970 annual meeting of Op. Soc., Abs. in JOSA 60:1543, 1970.

A slight roughness on mirror surfaces coated with evaporated metallic films not only results in some diffuse scattering of the incident light, but is directly responsible for reflection-decreasing absorption, particularly in the ultraviolet. This paper reports the results of measurements on evaporated silver and aluminum films deposited both under ultraviolet vacuum and standard vacuum on a variety of mirror blanks.

The effect of natural surface tarnish and of tarnish-preventing overcoat films on scattering and absorption is also discussed.

14

Gilette, R. B., et. al., "Active Cleaning Technique for Removing Contamination from Optical Surfaces in Space", Boeing Aricraft, Report No. N72-12888, November, 1971.

Describes a method of removing contamination from optical surfaces by sputtering the surface with a plasma of O_2 ions for 50 to 150 hours. The method has been tested in a simulated space environment and works especially well on hydrocarbon contaminants, removing approximately 95% of the effects. Little discussion is given on the practical aspects of utlizing such a system in space.

15

Ardiaenes, M. R. and Feuerbacker, B., "Improved L_iF and M_gF_2 Overcoated Aluminum Mirrors for Vacuum Ultraviolet Astronomy", Ap. Op. 10:958-9, April 1971

The reflectance of aluminum surfaces overcoated with L_iF or M_gF_2 has been measured in the 1050 - 1600 Å region under ultra-high vacuum conditions and an improved process for overcoating has been developed.

Clean aluminum has the highest reflectivity in the far-ultraviolet, but overcoating is required to protect the surface from oxidizing. L_iF has a short wavelength cutoff of 1050 Å, but for is slightly hydroscopic and deterioates rapidly for ultraviolet work in a normal atmosphere. M_gF_2 is more stable but has a short wavelength cutoff of 1150 Å. A film thickness of 150 Å is found to be best. Overcoating in a super high vacuum (10^{-10} torr) enables slow evaporation rates (10 Å per second) so that careful control of coating thickness may be achieved (to within 5 Å).

Reflectivity loss of approximately 15% (from 90% to 75%) is caused by the overcoating when used at short wavelengths of less than 1350 Å. This loss can be reduced to less than 10% by annealing the deposited film coating for approximately 60 hours in a 10^{-7} torr vacuum at 300°C.

16

Schroeder, J. B., Deeselman, H. D., and Douglas, J. W., "Technical Feasibility of Figuring Optical Surfaces by Ion Polishing", Ap. Optics 10:295-9, February 1971.

Procedures are described for figuring optical surfaces by ion polishing (bombarding the surface with a beam of high-energy ions in a vacuum). Fused silica, ULE, and Cer-Vit were employed as substrate materials. The RMS surface error was reduced from 0.05 to 0.01 (at 6328A) by the ion polishing. The optical scattering after polishing was 0.06% which is comparable with conventional "good surfaces". A great advantage of ion polishing is that there is almost no chance of removing too much material and ruining the "figure", a very real problem with conventional polishing.

The samples tested were small test substrates; there are many problems in building a manufacturing facility for ion polishing medium or large scale optics. The design of such a manufacturing facility is discussed.

17

Schultz, V. K., and Crutcher, A. R., "Efficient Fabrication of Low-Scattering Optical Surfaces for Telescope Materials", paper presented at 1971 Annual Meeting of Op. Soc.; Abs. in JOSA 61:1550, 1971.

Space telescope require optical surfaces that are mechanically stable, have low scattering characteristics, and that can be produced with reasonable efficiency. It has been shown that etching silicate materials cause no remnant strains (greater than 10^{-8}) after applied shear stresses are removed--unlike the remnant strain preset in non-etched material. This presentation reports the application of etching and other techniques in the efficient fabrication of precision optical surfaces with low-scattering and high reflective characteristics. Tests were conducted in the soft X-ray and ultraviolet regions on fused silica, Cer-Vit, and Zerodur.

18

General Dynamics, Convair Division, "Composite Material Applications to Optical Components and Structures", Report No. GDC PIN 71-416A, August, 1971.

Discusses the physical properties of graphite fiber-epoxy composite materials. Of particular interest for possible LST use are two types: (1) very high-strength filaments such as Courald's HT-S, and (2) very high-modulus filaments such as Celanese GY-70, both impregnated with Convair Fiberite X-904 epoxy.

Advantageous properties of the composite materials include low weight (less than 9 pounds per cu. ft.), very high strength/weight ratio, excellent fatigue characteristics, wide temperature range (-320 to +350^{o}F), high resistence to the rigors of a space environment, and a truly sensationally low coefficient of temperature expansion (typically 0.1 $(10)^{-6}$ in/in.-F, less than 1/100th of aluminum and approximately 1/10th that of Invar). Major disadvantages include high cost (approximately \$100/lb now but expected to drop to less than \$50/lb by 1976) and lack of experience with tooling and manufacturing techniques.

The report suggests several uses for the composite material in space applications, and has a fairly extensive analysis of its use in the HEAO-C X-Ray Satellite which contains a large-area telescope of approximately 1-meter aperture and 10 meters in length. Advantages include much simpler

19

Pipher, J. L., and Houck, J. R., "Black Paints for Far Infrared Cryogenic Uses", Ap. Op. 10:567, October, 1971.

A cryogenic paint which remains absorptive throughout the infrared has been developed. The paint exhibits excellent surface stability at liquid Helium temperatures and is resistant to abrassion and flaking. Measurements with a specially constructed cryogenic integrating sphere indicate that the paint is 92-100% absorptive in the 70-130 micron range. Additional measurements at 60-130 microns, 18-25 microns, and 400-1000 microns indicate that the paint is 95% absorptive.

The paint is applied as follows: An under coat of Parson's Optical Black Undercoat and Flat Black is sprayed on a clean metal surface. A hairy flock (G. C. Electronics Felt-Kote Flock) is subsequently dusted on the painted surface while it is still tacky. A thin coat of optical black paint is then sprayed on top of the flocked surface. The resultant structure, when dry, is fibrous close to the metal surface with sharp hairs protruding from the substructure.

20

Breuch, R. A., et. al., "Evaluation of Response of Optical Materials", Lockheed LMSC Interim Report on Contract DAG-46-71-C-006 (Classified-RESTRICTED INFORMATION), AMMRC CR-71-21, 121 p., November, 1971.

Reports on the results of the investigation of the optical reflection/ absorption properties of various materials, especially with respect to the medium and long wavelength infrared. Studies were made of two physical properties of materials which affect reflectivity: (1) the loss of reflectivity of a crystalline substance on the short wavelength side of a lattice-vibration absorption band, and (2) the low reflectivity exhibited by fine powders.

Powders investigated included Alumina, Calcium Flouride, Lithium Alumina, Silicon Oxide, Magnesium Oxide, porous Vycor, and Berrylium Carbide. The reflectivity of fine powders was usually quite low, being in the order of 0.1% to 0.4% for wavelengths from 1 micron to 20 microns. This is a factor of 5 to 20 times better than 3M black Velvet over the same wavelength region. The Martin Black Annodize finish was found to be very good, being approximately the same as the powders (0.1% spectral reflectance, 1.0% total reflectance.)

The scattering properties of infrared mirrors was also investigated. Berylium mirrors were found to scatter from 10^{-3} to 10^{-4} per steradian in from 8^{o} to 30^{o}. Glossy carbon mirrors, figured and polished using standard optical techniques, gave 10 times better performance at 10.3 microns than Berylium! Such mirrors have been used for X-ray astronomy use.

21

McKenney, D. B., Orme, G. R., and Mott, L. P., "Light Scattering by Thin Film Coatings", Optical Sciences Center (U of Arizona) Report, 74 p., January, 1972.

Light scattered from thin film coated fused silica substrates has been measured for both metallic reflecting films and single- and multi-layer dielectrics. The measurements include both the integrated hemispherical diffuse reflectance and the angular distribution described by the scatter coefficients. A new type of instrument based on the use of a diffraction pattern to measure within 0.3^{o} of the specular direction is described.

The observed distribution of scattered light is found to closely approximate that which would be expected from a surface with an autocorrelation length described by a hyperbolic secant. The diffuse reflectance of multi-layer coatings was found to be strongly wavelength dependent, and is greatly affected by surface smoothness. A "fair" optical surface (180A surface smoothness) has 20 times the scattering of a "good" surface (30A) and 200 time the scattering of a "super smooth" (10A) surface. In all cases, the scattering near the specular direction was surprisingly high--the scattering 1^{o} from specular was approximately 10^{4} times the scattering 10^{o} from specular, and some 10^{6} times the scattering 60^{o} from specular.

Multi-layer thin film coatings which have thicknesses such that standing waves may be set up within the coating increase the scattering by a factor of approximately 8 over the base levels. Samples were also subjected to slightly elevated temperatures (100^{o}C) in vacuum. Most samples were damaged resulting in a scattering increase of approximately 5 owing to the formation of a number of hillocks in the coating. The hillocks were noticeably absent when the metal films were overcoated with a hard dielectric.

22

Wade, Jack F., "Martin Black Surface", Martin Marietta Denver Aerospace Division Technical Presentation, July, 1972.

Describes a process for treating metallic surfaces (principally aluminum) which provides the "blackest" (low reflectance) surface known to date for wideband usage including the long-wave infrared up to the 120 micron region. The treatment provides a reasonably rugged surface which is suitable for use in a space environment over wide temperature ranges (4^{o}K to 700^{o}K or higher), with reflectances of less than 1% in the visible region, has a peak of approximately 5% in the near IR (.75 to 1.15 microns) and at 4.5 to 6.0 microns, otherwise the reflectivity is less than 1% in the infrared region out to 33 microns, and less than 2% out to 120 microns (with suitable cooling of the surface so that the surface itself is not radiating).

Knife edges treated with the Martin process are claimed to have reflectivities of approximately 1/10th of untreated razor blade edges, which are accepted as the "standard" low-reflectance edge by many sources.

III-C N Article Reviewed But Not of Sufficient Interest to Abstract

Aronson, J. R., "Spectral Emittance and Reflection of Powders", Ap. Optics 8:1959, August 1959

Barkman, E. F., "Specular and Diffuse Reflecting Characteristics", Reynolds Metal Co., Metallurgical Res. Rep. 571-13A, April 1959

Barr, W. P., "Production of Low Scattering Dielectric Mirrors Using Rotating Vane Particle Filtration", J. Sci. Inst. 2:1112-4, Cecember 1969

Bouneuster, P., and Pincus, G., "Optical Interference Coatings", Sci. Am. 223:58-68, December 1970

Corbett, J. W., "Defects in Irradiated Silicon: II Infrared Absorption of the Si-A Center", Phys. Rev. 121:1015

Edwards, PL K., "Directional Solar Reflectance in the Space Vehicle Temperature Control Problem", ARS J. 31:1548-52, 1961

Hass, G., "Filmed Surfaces for Reflecting Optics", JOSA 45:945, November 1955

Hodgkinson, L. J., "Optical Flat Surface Roughness", Brit. J. Sci. Inst. 3:300-4, April 1970

Kaiser, W. et. al., "Infrared Properties of CaF_2, SrF_2, and BaF_2", Phy. Rev. 121:1324, 1968

Mott, L. P., "The Effect of Surface Roughness on the Optical Properties of All-Dielectric Interference Filters", MS Thesis, U of Ariz., 1971

Nelson, C. M., and Crawford, J. H., Jr., "Optical Absorption in Irradiated Quartz and Silica", J. Phys. Chem. Solids 13:296, March-April 1960

Rice, S.O., "Reflection of Electromagnetic Waves from Slightly Rough Surfaces", Symposium on the Theory of Electromagnetic Waves (Interscience Publishers, New York), 1951

Vavilov, U. S., Plotvikov, A. F., and Zakhvatin, G. V., "Infrared Absorption of High Resistivity Silicon with Radiation-Induced Defects", Soviet Physics-Solid State 1:894, June 1959

III-C NA Article Not Reviewed (No Copy Obtained)

Anders, Hugo, Thin Films in Optics, The Focal Press, London and New York, 1967

Hass, G., Mirror Coatings, Applied Optics, and Optical Engineering, R. Kingslake, Ed. (Academic Press, Inc., New York) 1965

Heavens, O. S., Optical Properties of Thin Films", Dover, New York, 261 p., 1965

Jansen, J. E., et. al., "Normal Specular Reflectance of Annodized Coatings on Aluminum, Magnesium, Titanium, and Berryllium", ASD Tech Report TR61-47, September 1961

McKeown, D., and Conlin, W. E., "Removal of Surface Contamination by Plasma Sputtering", AIAA Paper #71-475 presented at 6th Thermophysics Conf., April 1971

SECTION IV: SPACE ENVIRONMENT

IV-A: ADVANTAGES OF SPACE FOR ASTRONOMY

1

Roman, Nancy G., "Satellite Astronomical Telescope", J. Soc. Motion Picture and TV Engi. 69:35-8, January 1960.

Describes the possible applications of astronomical telescopes in satellites and some of the problems they will encounter, such as pointing accuracy requirements, telemetering, large dynamic range of light values, sensors which require greatly increased ranges of spectral response, etc.

2

Tifft, William G., "Astronomy, Space and the Moon", Astro. & Aero., December 1966.

A comprehensive article comparing the relative advantages of the four possible astronomical sites--earth-based, space telescope in low earth orbit, space telescope in high earth orbit, and a lunar-based telescope. Any space telescope has many advantages over earth-based telescopes as far as resolution, faint operating limit, and data rate are concerned. This article concludes that a lunar-based telescope is the most attractive of the alternatives--although the initial cost is high, the data-bit-per-dollar return for the moon telescope exceeds the other telescopes by a considerable margin.

3

Tifft, William G., "Theoretical Performance Capability of an Astronomical Optical Space Telescope for Photography and Photoelectric Photometry", Univ. of Arizona Space Astronomy Report No. T68-12, 10 p., November 1, 1968.

Simple arguments to show that diffraction limited space telescopes gain in photographic limiting magnitudes and photoelectric efficiency have often been used in justification for space telescope programs. To realize the potential gains offered by the darker sky and much sharper images requires consideration of telescope F ratios, integration times, detector resolutions, aperture selection, etc., which in simple arguments are often neglected or only vaguely defined. This report discusses the problems involved in achieving the theoretical gains which appear to be inherent in space operations.

Considered are the less obvious aspects involved in achieving the theoretical performance limits offered by space astronomy; it is concluded that a 120-inch diffraction limited space telescoe can indeed work to a limiting magnitude of 28 to 29 in either photographic or photoelectric modes with exposure times of approximately one day, compared with a limiting magnitude of approximately 22 for a comparable size earth-based telescope.

4

NASA Report N72-13344, "Telescope in Orbit", Translated into English from Russian, 3 p., May 21, 1971.

The advantages of extraterresterial astronomy over traditional earth-based astronomy are considered. Difficulties and problems connected with placing astronomical equipment into space are discussed. There is no mention on stray light suppression.

IV-B: OBSERVATIONS FROM PREVIOUS SPACE PROGRAMS

1

Carpenter, M. S., Keefe, J. A., and Dunkleman, L., "Visual Observation of Nighttime Glow from Manned Spacecraft", Science 138:978, 1962.

A luminous band around the horizon noted by J. Glenn in the first US manned orbital flight is attributable to airglow. The band is centered at an elevation of 91 km, with a range from 81 to 119 km. The edge-on brightness of the airglow layer was $6(10)^{-7}$ candles per square cm.

2

McKeown, D. and Fox, M. G., "Measurement of Surface Erosion Erosion from Discoverer 26", ARS J. 32:945, 1962.

Molecules of the upper atmosphere bombard satellite surfaces and slowly erode the surfaces through a mechanical process known as "sputtering". The magnitude of this problem has not been known; a direct measurement of the effect was obtained on the flight of Discoverer 26 on July 27, 1961, with a specially-designed satellite borne erosion gage developed by General Dynamics.

The erosion rate for the gold test samples was 0.2 ±0.1 A per day. This is an upper limit for an orbiting spacecraft, since the Discoverer 26 had a low perigee (230 km) where the atmosphere was relatively dense. It would, therefore, appear that sputtering will not be a serious problem for near-earth orbit.

3

Gillett, F. C., et. al., "Photographic Observation of the Airglow Layer", J. Geophys. Res. 69:2827, July 1964.

The night airglow photographs taken by Gordon Cooper during his orbital flight of May 15 and 16, 1963, are discussed. The layer is 24±3 km thick and varying in height above the earth from 77 to 110 km. (Reviewer's Note: The photographs are very poor compared with those of Hennes and Dunkleman, 1966.)

4

Hennes, J. P. and Dunkleman, L., "Photographic Observation of Night Glow from Rockets", J. Geophys. Res. 71:755, 1966.

Several very clear photographs of the earth's night airglow horizon over western Texas were obtained from an Aerobee rocket launched in December 1964. The vertical distribution of the airglow was found to have a peak at 95±4 km with 90% of the emission between 80 and 116 km. Photographs were obtained with a three second exposure using a f/1.4 camera and Tri-X film. The airglow was determined to be approximately 35 times as bright as the normal night glow, and six times as bright as the zodiacal light.

5

Ney, E. P. and Huch, W. F., "Optical Environment in Gemini Space Flights", Sciences 153:297, 1966.

In the debriefings of astronauts from the Gemini Mercury space flights, there was continued insistence by the astronauts that "stars could not be seen in the daytime". This would mean a sky background brightness of about 10^{-8} solar brightness, or 10^{5} times as bright as the night time sky. This article concludes that much of the brightness is due to window scattering, but that the spacecraft corona must be at least as much as $5(10)^{-9}$ sun brightness. Calculations are made to show that a mass ejection rate of approximately 2 pounds/hour from the spacecraft would produce this much scattered light. Discharge rates of less than an ounce/day will be required to reduce scattered light to 10^{-13} solar brightness.

6

Wolff, C., "Optical Environment of OGO-III Satellite", Science 58:1045, August 1967.

Reports on photometric measurements made from an Orbiting Geophysical Observatory (OGO-III), which sets an upper limit to the brightness of the daytime sky near a large unmanned satellite. This limit is some 30 times less than the darkest daytime yet reported by an astronaut, or less than $5(10)^{-13}$ as bright as the sun. This background light may interfere with observations of faint extended objects, such as the gegenschein, which is 10^{-13} as bright as the sun. However, some of the light came from an antenna which could not be completely shielded from a scattered light standpoint; it is estimated that the effect of the spacecraft debris cloud was to increase the scattered light by a factor of five over that seen on the dark side of the earth. (Reviewer's Note: This figure is several orders of magnitude less than encountered in manned spacecraft.)

7

Hemenway, C. L. and Hallagen, D. S., "Contamination of Optical Surfaces in Space", paper from the 124th meeting of Am. Astron. Soc., June, 1967, Abs. in Astron. J. 72:803, 1967.

During the Gemini program two experiments (S10 and S12) were flown to measure micrometeorite fluxes in the near earth vicinity. Impacts of approximately 1 per 100 sq. cm of surface per month of time of large (approximately 200 micron diameter) particles were noted, and relatively large numbers of small (approximately 1 micron) particles were noted. The small particles appeared to be rather fragile in nature, doing little damage to the optical test surfaces.

8

Nazarova, T. N., "Solid Components of Interplanetary Matter from Vehicle Observations", Space Sci. Review 7:490-533, November 1967.

Reviews the data on meteoric particles obtained by different Soviet space vehicles at distances from 100 km to 10^8 km from the earth. Very heavy concentrations of minute dust particles were observed near the earth at heights of 100-200 km. Piezoelectric "acoustical" detectors were used in most cases.

A concept of mass spectrum of meteoric particles is presented.

9

Wolstencroft, R. D., and Rose, L. J., "Observations of the Zodiacal Light from a Sounding Rocket", Ap.J. 147:271-292, January 1967.

The surface brightness and state of polarization of the zodiacal light at elongations from 30^o to 175^o have been measured from a sounding rocket. Observations were secured over a wide range of ecliptic latitude and longitude, including regions near the north ecliptic pole and the antisolar point.

Three models of the interplanetary dust cloud comprising mixtures of spherical particles composed of Fe, SiO_2, and H_2O show a measure of agreement with observation. It is shown that the presence of ice particles smaller than 100 microns within 7 a.u. of the Sun is unlikely; the two models containing ice particles are, therefore, less realistic than the model containing Fe and SiO_2 only. Some circular polarization was observed, which would require a proportion of asymmetric particles in composition or shape for the proposed model.

10

NASA Report NO. N72-10833, "Dim Sky Photography on Gemini Flight VI, VII, and IX."

Describes the results obtained from experiment S030 (Faint Sky Photography) from Gemini Flights VI, VII, and IX. The noise level (sky background) recorded on experiment D015 was 10^{-7} ft. lamberts of sky brightness. The brightness of the various phenomenon photographed on S030 was then calculated to be:

Air Glow Layer	$1(10)^{-4}$ ft. lamberts
Brightest Milky Way	$3(10)^{-5}$ ft. lamberts
Zodiacal Light	$1(10)^{-5}$ ft. lamberts
Gegenschein	$1(10)^{-6}$ ft. lamberts
Lagrangian Points	$1(10)^{-7}$ ft. lamberts

All exposures were 1/30 second.

11

Muscarri, J. A., and Cunningham, "Gemini-12 Optical Surface Contamination Study", Abs. JOSA 57:1430, November 1967.

Optical surfaces were carried on Gemini-12 to determine contamination of optical surfaces by rocket exhaust plumes, waste disposal, cabin leaks, and outgassing from spacecraft materials. The optical samples lost approximately 10% in transmission for 23 hours in orbit, 25% for launch and 43 hours of orbit. It is obvious that the launch environment is detrimental to optical surfaces and that protection should be provided during the launch period.

12

Vernov, S. N., et. al., "Radiation Belts in the Region of the South Atlantic Anomaly", Space Sci. Rev. 7:490-533, November 1967.

Reviews the studies made of the radiation belts in the region of the South Atlantic anomaly by Russian spacecraft from 1960-67. Discusses the components, variation with time, proton intensity, and behavior of the belt electrons.

13

Evans, D. C. and Dunkleman, L., "Airglow and Star Photographs in the Daytime from a Rocket", Science 164:1391-3, June 20, 1969.

Photographs of the constellation Cygnus taken in the daytime from an altitude of 100 km from an Aerobee rocket indicate that the day sky brightness in the wavelength region from 3600 to 7000 A is only slightly (a factor of 10) brighter than the night sky viewed from the ground, or about 10-12 solar brightness. There were no observable effects from a contamination cloud.

14

Rees, M. H., "Auroral Electrons", Space Sci. Rev. 10:413-41, December 1969.

Satellite and rocket measurements of auroral electrons are reviewed, and the salient characteristics of the auroral electrons are summarized. Effects of the upper atmosphere on the energy distribution of the electron fluxes are discussed. Ionization rates associated with typical fluxes are derived. Observed effects found in the atmosphere and the fate of auroral electrons are briefly discussed.

15

NASA Report No. N72-10858, Thomas G. Rogers, "Gemini Program Physical Sciences Experiment Summary", MSC, Houston, September, 1971.

a. Zodiacal Light Photography (SO 01)--Light level found to be approximately $2(10)^{-12}$ that of sunlight at 20^{o} and $2(10)^{-13}$ at 60^{o}. The Gegenschein was found to be $2(10)^{-14}$ the level of sunlight.
b. Airglow Horizon Photography (SO 11)--Top of the airglow extended to 88 ±5 km. Top of the atmosphere for star extinction is approximately 25 km.
c. Two Color Earth Limb Photography (MH 1)--Studied the scattering of sunlight by the earth's atmosphere. Scattering was fairly bad (1.5%) out to 200 km, but a large part of this is thought to be due to dirty windows. As expected, blue light scattered more than red.

16

NASA Report N72-10865, "Experiment M 411: Two Color Earth Limb Photography", September, 1971.

Sample calculations are made regarding the scattered light phenomenon of a sunlit earth limb, assuming that the light is scattered by an atmosphere irradiated by a zenith sun. Calculations are made with several different scattering coefficients for various wavelengths over the extended visual range.

NASA N72-22838, "Apollo Window Meteroid Experiment", 9p., 1972

The Apollo window experiment obtained data from crater counts and meteroid residue. A preliminary estimate of the flux for the seven Apollo spacecraft is found to be in agreement with Surveyor 3 data but is less than that given by the environmental model.

IV-B N Article Reviewed but not of Sufficient Interest to Abstract

Evans, D. C., and Dunkleman, L., "Star Sightings from Manned Spacecraft", Abs. 124 Meeting Am. Soc. Astr., 1967

NASA N72-10289, "Bibliography on Star Trackers", Laboratories de Rechercks Galestigies et Aerodynamique, Veron, France (French), April 21, 1971

NASA N72-12863 (Goddard), "Spacecraft Attitude Sensors with Emphasis on the Orbiting Astronomical Observatory", 16 p., September 1971

NASA N72-14475, "Proposed Improvements in the SDC Spacetrack Optimum Operation Based on a Study of Sky Brightness and Extinction Effects in Limiting the Baker-Nunn Camera System", 78 p., 1971

NASA N72-15743, "Space Astronomy and Upper Atmosphere Soundings--Annual Report 1969", Hubert Center for Space Research, July 1, 1971

Wallace, C., and McElroy, M. P., "The Visual Dayglow", Planet. & Space Sci. 14:677, 1966

Weinberg, J. L., "Photoelectric Polarimetry of the Zodiacal Light at 5300 Å", unpublished Ph.D. Thesis, Univ. of Chicago, 1963

IV-B NA Article Not Reviewed (No Copy Obtained)

Hering, R. G., and Smith, T. F., Progress in Astronautics and Aeronautics, Vol. 23, Thermophysics, Academic Press, 337 p., 1970

Maltby, P., "The Effect of Scattered Light on Solar Intensity Observations as Derived 9 May 1970 Mercury Transit", Solar Physics 18:3-21, May 1971

NASA N72-12861, "Attitude Stabilization of Satellites in Orbit", Adv. Group for Aerospace R & D, Paris (France), 152 p., September 1971

NASA N72-22280, "A Contamination Experiment Investigating the Failure of Nimbus 4 Wedge Spectrometer", 1972

IV-C: ENVIRONMENTAL FACTORS WHICH AFFECT OPTICAL MATERIALS/SYSTEMS

1

Johnson, F. S., "The Solar Constant", J. Meteorology 2:431, 1954.

The value of the solar constant indicated by thirty years of observations by the Smithsonian Institute is revised in light of the scale corrections announced in 1952 and new solar spectral-irradiance data for outside the earth's atmosphere obtained by National Research Laboratory. The ultraviolet and infrared corrections applied by Smithsonian are reevaluated. The accuracy of their measurement of total irradiance in the spectral range of 0.346 to 2.4 microns is generally supported, with only a 0.3% increase being indicated. The correction outside this spectral range is found to be larger. The revised value of the solar constant is 2.00 calories per sq. cm per minute, with a probable error of 2% and the solar illuminance constant is 13.67 lumens/ sq. cm (17,700 ft-candles).

2

Coulson, K. L., "Characteristics of the Radiation Emerging from the Top of a Rayleigh Atmosphere--II: Total Upward Flux and Albedo", Planet. Space Sci. 1:277-84, 1959.

Discusses a mathematical model for determining the upward flux from the earth due to reflection, absorption, and scattering in the atmosphere. (Note: the integrated reflectance with respect to wavelength is the albedo.) The contribution due to Raleigh scattering in the atmosphere is determined to be 7.6% of the albedo. This scattering is very high, as much as 50% of the incident energy, for short wavelengths (below 3200 A), as compared to approximately 1% at 7000 A.

3

Ritter, N. and Mesner, M. H., "Image Sensors and Space Environment", J. Soc. Motion Picture and TV Engi. 69:18, January 1960.

Describes the problems of using image sensors in a space environment. Environment-induced engineering modifications of a videcon are discsssed.

The problems considered include loss of atmospheric cooling; corona discharge (arc-over)--do not apply high voltages until hard vacuum is reached; possibility of explosive decompression; boiling and leakage through seals; solar radiation; solid particles (micrometeorites); disassociated gases (atmoic oxygen is available to react with heavy metals such as iron, copper, and silver); and the induced environment factors of acceleration, shock, vibration, zero gravity, and thermal conditions.

4

Clauss, F. J. (Editor), Surface Effects on Spacecraft Materials, Wiley, New York, 1960.

This is a compilation of the papers presented at the 1st Symposium on Spacecraft Materials, held at Palo Alto in 1959. Some 20 papers were presented, covering Thermal Control Surfaces for Spacecraft, the Effect of High Vacuum on Surface Materials, the Effect of Solar Ultraviolet Radiation on Spacecraft Materials, etc.

5

Reiffel, L., "Structural Damage and Other Effects of Solar Plasmas", ARS J. 30:258-61, March 1960.

For orbits or space trips that carry large area light-weight structures outside the sheltered region of space defined by the planetary magnetic fields, the damaging effects of solar plasma streams are shown to be serious and may result in low durability or high payload penalities. Substrates used as thin coats on more massive structures would be similarly affected.

The sputtering by high velocity Solar plasmas under average conditions (a density of 600 particles/cm^3 and a velocity of 1000 km/sec) is calculated to remove more than 300 A of surface per month. For intense storms (density of $10^5/cm^3$ and velocity of 1500 km/sec) the destruction of a 300 A thin film could occur in approximately 3 hours!

6

Spitzer, Lyman Jr., "Space Telescopes and Components", Astron. J. 65:242-63, 1960.

A fairly comprehensive analysis of some of the major problems in the design of a large satellite telescope for stellar observations. A 2 meter square assembly at an orbital altitude of 800 km is assumed. Included are the problems of the space environment, acquisition of targets, torquing of the spacecraft, pointing stability, maintenance of optical alignment, etc.

7

Johnson, F. S. (Editor), Satellite Environment Handbook, Stanford Univ. Press, 193p., 1961.

Considers the space environment, with chapters on Structure of the Upper Atmosphere, Structure of the Ionosphere, Penetrating Particle Radiation, Solar Radiation, Micrometeoroids, Radio Noise, Thermal Radiation from Earth, and Geomagnetism. (Reviewer's Note: This handbook is not nearly as complete as C. G. Goetzel, etc., Editors--Space Materials Handbook, 1965).

8

Roach, F. E., and Megill, L. R., "Integrated Starlight Over the Sky", Ap.J. 133:228, 1961.

Calculations are made of the total integrated starlight over the entire sky based on the star counts in Groningen Pub. No. 43. The results are given in both the photographic and the visual magnitude scales in tabular and graphical form. Other sources of night light (zodical, 5577 airglow, continuum airglow, and scattered light) are included for comparison.

9

Gulledge, Irine, et. al., "Luminance of the Night Airglow When Observed from Above the Emitting Layer", Paper presented at 1963 Spring meeting of Op. Soc., Abs. in JOSA 53:518, 1963.

The night airglow is emitted mainly from a thin atmospheric layer at an altitude near 100 km and produces a large fraction of the light in the night sky and is easily visible to the dark adapted eye. When viewed from the ground, the night airglow appears uniform across the sky, but when viewed from above, the night airglow exhibits a greatly enhanced luminance in the direction of the horizon and appears as a narrow band of light where the line of sight is tangent to the atmosphere. Carpenter saw this phenomena clearly while orbiting in a capsule in 1962; since then measurements from rockets have confirmed the situation.

10

Thompson, G. V. E., and Gatland, K. W., (Editors) Materials in Space Technology, London ILIFFE Books, Ltd., 275p., 1963.

Covers the general problems of material selection to withstand the spacecraft environment, new materials that have been developed for space use, the use of aluminum, magnesium, beryllium, high-strength steels, refractory materials, Polymers, and ablative materials.

11

Moller, F., "Optics of the Lower Atmosphere", Ap. Optics 3:157-66, February 1964.

This article gives an excellent survey of the problems of optics and atmospheric radiation arising from the influence of the lower atmosphere on the solar radiation and from emission absorption of radiation within the atmosphere. Of particular interest to the LST is the discussion of the scattering of light by air molecules (Rayleigh scattering) and by particles. The scattering coefficient for Rayleigh scattering is seen to be inversely proportional to the fourth power of the wavelength, so may become a serious problem in the far ultraviolet. Scattering by particles varies with the particle size and is a problem at all wavelengths except perhaps the far infrared. Observations made from satellites are discussed.

12

Farrell, E. J., "Information Content of Photographic Star Images", Paper presented at 1965 annual meeting of Op. Soc., Abs. in JOSA 55:1589, 1965.

The information content of a weak star image is determined by the seeing, sky background, and zodiacal light. There is an intrinsic detection limit imposed by the physical environment and the detection technique, and a limit on the accuracy with which one can locate the image of a faint star. This paper contains explicit equations for the minimum rms position error that one can achieve as a function of signal strength and background illumination.

13

Lockheed Missiles and Space Division, Space Materials Handbook, Goetzel, G. C., Rittenhouse, J. B., and Singletary, J. B., Editors, Addison-Wesley, p. 624, 1965.

A comprehensive handbook produced under sponsorship of the Air Force. Organized into four parts. The first part discusses the space environment, including launch environment, aerodynamic and vibration effects, the upper atmosphere, space conditions, solar and earth radiation, penetrating radiation, physical impact phenomena, and minor environments. Part two discusses the effect of the space environment on materials, including thermal control, optical, lubricating, adhesive, sealing, and structural materials, as well as electronic components. Part three covers materials which have been successfully used in space experiments, and has recommendations for the selection of materials for optimum performance. Part four discusses the biological interaction with spacecraft materials, i.e., the complications added by manned spacecraft.

14

Heath, D. F. and Sacher, P. A., "Space Environment Effects on Some Ultraviolet Transmitting Materials", paper presented at 1965 Annual meeting of Op. Soc., Abstract in JOSA 55:1583, 1965

The starfish explosion (1.4 Megaton) at 400 km above Johnson Island in July 1962 produced a slowly decaying artificial électron belt. The intensity of these low MeV energy electrons can cause a degradation of the transmission quality of ultraviolet transmitting materials; the exposure of some optical materials which are transparent in the 100-3000A region changed appreciably after long exposure (one year).

15

Valley, S. L. (Editor), Handbook of Geophysics and Space Environment, McGraw-Hill, New York, 1965.

Very complete treatment of Atmospheric Conditions, Electro-magnetic Propagation, Geomagnetic Winds, Ionospheric Physics, Airglow and Aurorae, Corpuscular Radiation, and Interplanetary Space (Solar Winds, etc.).

16

Doehlman, H. C., "Material Contamination of Optical Systems in a Space Environment", Abs. JOSA 57:1430, November 1967.

Tests to determine material sublimation and deposits on optical surfaces under a space environment are described. It is determined that numerious materials have severe outgassing problems under a high-vacuum condition, and that the choice of materials to be used around optical systems in a space environment is of critical importance.

17

Freden, Stanley C., "Inner-Belt Van Allen Radiation", Space Sci. Rev. 9:198-242, March 1967.

A survey of the present state of knowledge about the inner radiation zone is presented, including an historical review of emperical data and theoretical conclusions concerning electrons, protons, and heavier particles. Recent experimental results are presented and some newer theoretical ideas, such as pitch-angle scattering ahd radial diffusion, are discussed and applied to the data. Composition of the measured fluxes, spectra, and time variation are compared with theoretical calculations where possible.

Some conclusions are drawn pertaining to the sources and loss processes of the trapped particles and some comments are made regarding future measurements which should be made in the inner zone.

A complete bibliography, listing some 125 references, is included.

18

Newkirk, Gordon, Jr., "The Optical Environment of Manned Spacecraft", Planet. & Space Sci. 15:1267-85, August 1967.

The dynamics of particulate matter ejected from manned spacecraft is examined and it is found that a debris cloud up to several kilometers in diameter can be expected to surround the vehicle. The dwell time of particles is affected by atmospheric drag and by solar pressure. Molecules are swept almost immediately, larger particles have an average life time of approximately 400 seconds.

The life time of any ice particles which may form is very long, with a life time of approximately 10^6 seconds decay due to sublimation.

19

Spitzer, Lyman Jr., "Thermal Deformation in a Satellite Telescope Mirror", JOSA 57:901-13, July 1967.

Basic thermal perturbations are considered for a fused-silica primary mirror in an orbiting space telescope within 800 km of the earth's surface. In such an orbit, the change of thermal environment with pointing direction leads to an axial temperature gradient through the primary mirror with consequent deformation of the mirror. Calculations show that it is probably possible, if the telescope tube is considerably longer than the mirror diameter, to reduce temperature gradients sufficiently so that a 3-meter telescope can maintain diffraction-limited performance.

20

Dunkleman, L., "The Visible and Ultraviolet Scene from Space", Paper (FB11) presented at 1968 Spring Meeting of Op. Soc., Abs. in JOSA 58:731, 1968.

Photographic and photoelectric measurements on the luminance and ultraviolet radiance of various phenomena such as nightglow viewed edge on and nadir dynamic variance of the earth's atmosphere from space and compared with the radiance of the Milky Way, gegenschein, zodiacal light, the moon, aurora, and the hydroden lyman-alpha glow. This intercomparison is used to provide tables of luminance and ultraviolet radiance of various phenomena from the view point or a sounding rocket or a satellite.

21

Sacher, Paul A., "Effects of a Simulated Proton Space Environment on the Ultraviolet Transmittance of Optical Materials between 3000 and 1050 A", Paper presented at 1968 Spring Meeting of Op. Soc., Abs. in JOSA 58:732, 1968.

Transmittance over the wavelength range of 1050 to 3000 A of LiF, $MgF2$, Al_2O_2, fused SiO_2, ADP, calcite, and Vyar were measured after irradiation by a total dose of $8(10)^{10}$ protons/cm^2, representative of a satellite in a circular, near polar orbit at a height of 1200 km for one year. Significant changes in transmittance were noted.

22

Kovar, N. S., Kovar, R. P., and Bonnen, G. P., "Light Scattering by Manned Spacecraft Atmospheres", Planetary and Space Science 17:143-54, February 1969.

This paper discusses the problem of space contamination due to the presence of manned vehicles. The effects of a debris atmosphere on the observation of dim light sources is examined and evaluated. Such problems of contamination of exposed optical surfaces and the scattering of light by ice particles originating from leakage of cabin water vapor are considered. Numerical examples of the brightness of the debris cloud surrounding the Gemini, Apollo, and ATM spacecraft are presented and compared with the results of Newkirk (1967). If the assumptions made in this analysis are accurate, observations of such dim light phenomena as the solar corona and inner zodiacal light from Apollo and ATM vehicles will be difficult, if not impossible.

The Ney and Hutch (1966) evaluation of their zodiacal light experiment on GT-5 leads them to estimate spacecraft corona, illuminated by sunlight, to be 10^{-9} sun brightness. This limits observation of stars to m_V 2.5 or brighter.

For angles greater than 30^o from the sun, light scattering due to illumination from both sun light and earth light is estimated to be approximately 10^{-11} for GT-3, 10^{-10} for GT-11, 10^{-9} for ATM, and 10^{-10} for Apollo. Since zodiacal light ranges from 10^{-9} at 2^o to 10^{-13} at 100^o, observations of the zodiacal light will be very difficult.

23

Cordero, Don A., "Sky Brightness Factors in Space Telescope Performance", unpublished term paper for Astronomy 250, University of Arizona, 1969.

Studies the problem of faint object detection by a space telescope, with emphasis on the use of photographic film as a detector. The effect of sky brightness, other noise signals, and the granularity of the film are considered. It is concluded that it is possible to work down to m_V 27.5 for exposure times of one hour or more when using photographic detection of faint objects with a 3-meter space telescope.

24

Stein, William L., "Limitations on Photoelectric Observations", unpublished term paper for Astronomy 250, University of Arizona, 1969.

Reviews the problem of detecting faint objects by photoelectric means from a space telescope. Analyzes the effect of detector noise, background signal noise, and random fluctuations of signal photons. Concludes that a 3-meter space telescope should be able to work to m_V 30 with exposure times of approximately 4 days, to m_V 28 for exposure times of approximately 3 hours.

25

Grobman, W. D., and Buffalano, Charles, "New Conclusions Concerning the Observation of Faint Sources from a Sunlit Spacecraft", Planet. & Space Sci. 17:1089-96, June 1969.

This article concludes that the outlook for space astronomy in the sunlight is much more favorable than other estimates have indicated. The most important source of scattered light in previous estimates has been the cloud of ice crystals due to H_2O vapor leaking from the cabin of the spacecraft. This article presents a condensation model which gives an upper bound on the size of these ice crystals which is 150A (compared to 1 micron for the previous estimates), which is too small to cause significant light scattering. The estimated brightness due to scattered light is approximately 10^{-14} of solar brightness for all angles of sun illumination (Reviewer's Note: See Reid, 1970, for companion article.)

26

Hass, G., and Hunter, W. R., "Laboratory Experiments to Study Surface Contamination and Degradation of Optical Surfaces in Simulated Space Environment", Ap. Optics 9:2101-10, September 1970.

The effect of surface contamination of the reflectance (and scattering) of evaporated vacuum ultraviolet mirrors and temperature control surfaces are discussed, and data is given on the behavior of optical materials and coatings under UV, electron, and proton irradiation . Thin films of contamination, such as carbon dust or diffusion pump oil (approximately 40A thick) reduced reflectance (and therefore increased diffuse scattering??) from 90% to about 70% in the 2000 to 4000A region. However, mirror surfaces contaminated with oil tended to recover their reflectivity after exposure to vacuum for 24 hours as the oil evaporated. This recovery did <u>not</u> occur if the oil was exposed to radiation from UV or electron/proton sources.

27

Reid, N. M., Research Note "Some Findings on H_2O Vapor Nucleation in Spacecraft Debris Clouds", Planet. & Space Sci. 18:1387-89, September 1970.

Laboratory investigations tend to bear out the conclusions of Grobman and Buffalano (1969) that ice crystals will be too small to scatter much light in the vicinity of a manned spacecraft. In fact, this article estimates that the diameter of the ice crystals will be 1/30th of the diameter estimated by Grobman.

28

Silverman, S. M., "Night Airglow Phenomenology", Space Sci. Rev. 11:341-79, October 1970.

The phenomenology of the night airglow is reviewed with particular emphasis on the work of recent years. Major topics discussed include the spectrum; latitudinal dependence; diurnal variation; correlation in time and space; the effects of magnetic acitivity and the sunspot cycle and solar activity; and conjugay of the airglow.

29

NASA Report N72-15793, "Materials Problems in Space", ESRO Technical Center, 20 p., 1970.

The problem of spacecraft materials in the space environment are considered, including solar radiation effects, vacuum exposure, and thermal effects. There is little information on scattered light.

30

Nicoletta, C. H., and Eubanks, A. G., "Effects of Simulated Space Radiation on Selected Optical Materials", Ap. Optics 11:1365-70, June 1972.

The effect of simulated Nimbus spacecraft orbital (1100 km, circular, and polar) radiation on wide-bandpass glass filters, narrow-bandpass thin-film interference filters, and several types of fused silica was determined by transmission measurements over the 200-3400 nm wavelength region. No changes were observed in the filters, which were shielded with fused silica during irradiation, after one year equivalent exposure of electrons, nor for the fused silica for one year equivalent exposure to electrons and protons. Exposure to one-half year equivalent dose of solar ultraviolet radiation, however, caused a significant degradation in the transmission of the two ultraviolet-transmitting interference filters but had no effect on two colored glass filters that transmit in the visible and near-ultraviolet region. Also, as a result of the ultraviolet exposure, the fused silica samples suffered transmission losses of several percent over the 200-300 nm wavelength region.

31

NASA N72-22289, "Some Contamination Problems in the Euorpean TD Satellite", May 1972

The flux of molecules encountered by a spacecraft and subsequently reflected to its surface is investigated. The reflection occurs upon collision of outgassing molecules with ambient molecules. Relationships and graphs are developed to allow an estimate of the pressure and density at various distances from the spacecraft. Outgassing of materials is the most common source of molecules, and the rate depends on the quantity and nature of the material, the temperature, and the time of exposure.

ATM is expected to have 1/10th of the contamination of Geminii, but this is still large, with a flux of $1.9\ (10)^{14}$ molecules/cm^2/sec, due to an outgassing rate of 0.1 gm/sec.

32

NASA N72-24921, (Goddard), "Predicting Spacecraft Self-Contamination in Space and in a Test Chamber", 16 p., May 1972

Very similar in findings to NASA N72-22289 above. Concludes that ground based chamber tests can simulate the self-returning films and self-contamination for altitudes up to 400 kilometers. For greater altitudes, errors become serious.

33

NASA N72-24891, (Bochin University, W. Germany), "Zodiacal Light", 1972

The phenonomen of zodiacal light is discussed and a short summary given of the observed intensities, polarizations, and color ratios. A model of interplanetary dust composition is considered in an attempt to reproduce the phenonomen, with fair success.

34

NASA N72-10389, "Bibliography on Star Trackers", Laboratories de Rechercks Balestigies et Aerodynamique, Veron, France (In French), April 21, 1971

Studies the degree of degradation of systems for use in space environment such as mirrors, infrared filters, photographic films and plates, lenses, and transmission windows when exposed to proton and electron irradiation, with high energy radiation fluxes being used to simulate space conditions.

IV-C N Article Reviewed But Not of Sufficient Interest to Abstract

Arutunian, G., and Seppi, F. L., "The Effects of Ionizing Radiation Upon Transparrent Materials", Rpt. No. RR-1, Detroit Arsenal, Centerline, Michigan, October 1959

Beltram, A. A., and Graziano, E. E., "Radiation Effects on Solar Cells and Glass: An annotated Bibliography", Lockheed LMSC Rpt. SB-61-58, Oct. 1961

Comstock, M., and Ferriguo, P., "Effects of Radiation on Glass", BLN-6513, (Brookhaven Nat. Lab.) Upton, New York, October 1962

Gex, R. C., "Effects of Nuclear Radiation on the Optical, Electrical, and Thermophysical Properties of Solids: An Annotated Bibliography", Lockheed LMSC Report SB-61-42, August 1961

Harrison, A. W., "The Night Glow Spectrum", Planet. & Space Sci. 17, Feb. 1969

Kriedl, N. J., and Hensler, J. R., "Gamma Radiation Insensitive Optical Glasses", JOSA 47:73, January 1957

Kriedl, N. J., and Hensler, J. R., "Irradiation Damage to Glass", Bausch and Lomb Opt. Co. Report NYO-3780, Rochester, New York, November 1954

Lusk, T. E., "Infrared-Transmission Materials Would be Unaffected by Radiation in Space", Electronic Design, 74, October 1960

Martin, H. L., "Micrometeorite Distribution Near the Earth", NASA Report MTP-M-RP-61-2, MSFC, Huntsville, June 1962

Primak, W., "Fast Neutron-Induced Changes in Quartz and Viterous Silica", Phy. Rev. 110:1240, June 1958

Redus, J. R., "Sputtering of a Vehicle Surface in a Space Environment", NASA TN D-1113, MSFC, Huntsville, June 1962

Vatsia, M. L., Stich, K., and Dunlap, D., "Night Sky Radiance from 400 nm to 2000 nm", paper presented at Spring Meeting of OP. Soc., Abs. in JOSA 59:483, March 1969

IV-C NA Article Not Reviewed (No Copy Obtained)

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Ball Brothers, "ATM Contamination Study", Contract NAS wk386, 1967

Buffalano, C., "The Spacecraft Debris Cloud and Optical Environment", Bellcom, Inc., April 1968

Buffalano, C., "A Review of the Optical Environment Problem of the ATM-A Mission", Bellcom, Inc., June 1968

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Evans, G. R., and Price, W. E., "The Effects of High Energy Radiation in Infrared Optical Materials: An Annotated Bibliography", Lockheed LMSC Report SB-61-25, May 1961

Lockheed, "Contamination of Solar Cells, Lenses, and Thermal Control Surfaces by Rocket Exhaust Plumes" (SECRET), LMSC 678878, 1968

Lockheed, "IR Background from Ionospheric Radiation and Scattering", (SECRET), LMSC B230102, June 1968

Lockheed, "Optical Surface Contamination Study--Saturn AAP", LMSC A790006, October 1966

Lockheed, "Apollo Illumination Environment Simulation and Study", (Contract NAS 9-7661), by W. K. Kincair, Jr. and L. M. Glasser

NASA N72-23913, "Self Contamination and Environment of an Orbiting Spacecraft", 35 p., May 1972

Reiffel, L., "Structural Effects and Particle Content of Interplanetary Space", ARS Journal 30:654, July 1960

Royal Airforce Establishment Report TR 66290, "Determination of Gas Flow Parameters from Propane Attitude Control Jets, and Their Effect on Satellite Optical Sensors and Telescopes", September 1966