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Angle Sensitivity of a Silicon Cell Solar Sensor

Paul R. Spencer
College of William & Mary - Arts & Sciences

ANGLE SENSITIVITY OF A SILICON CELL SOLAR SENSOR

A Thesis

Presented to

The Faculty of the Department of Physics

The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of

Master of Arts

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APPROVAL SHEET

This thesis is submitted in partial fulfillment of

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Paul R. Spencer

Author

Approved, May 1961:

John L. McKnight

J. L. Lawrence, Jr.

Robert E. Smith

D. E. McClennan.

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TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

The angle sensitivity of a silicon cell solar sensor of original design is studied, and initial experimental results are presented. This solar sensor consists of silicon cells mounted on the lateral faces of a four-sided pyramid. An opaque shield was attached to the sensor to obtain higher angle sensitivity for small angles. The effect of varying the sensor parameters which pertain to angle sensitivity are discussed along with nonlinear characteristics of the silicon solar cells used. The effects of sensor operation in a space environment are also considered. As a result of the study presented in this thesis, it is concluded that the solar sensor discussed will be capable of reliable, long-term operation in a solar oriented space vehicle.

ANGLE SENSITIVITY OF A SILICON CELL SOLAR SENSOR

INTRODUCTION

A wide variety of future space vehicles will require orientation with respect to the sun. Some of these will be solar research projects while others will be space vehicles or satellites which utilize various solar properties.

Examples of the solar research projects include the following: studies of the solar spectrum in bands that are inaccessible below the earth's atmosphere; monitoring the solar constant to furnish the meteorologists with terrestrial-heat-balance data; a solar oriented telescope to yield information on sunspots, flares, or other aspects of the solar atmosphere.

The solar applications include on-board power supplies such as solar cell banks or parabolic energy concentrators to operate thermionic energy converters or boilers with a working fluid. The former converter ejects electrons from a solar heated emitter to deposit them on a cold cathode to produce a current through an external load. The latter converter uses conventional thermodynamic cycles to operate a heat engine. A second type of application would take advantage of the intensity and immobility of the sun for use as a beacon for space navigation. Still another solar property which may be used in space vehicle operations is the solar radiation pressure for which large, lightweight "sails" have been proposed as low thrust devices.

In order to orient a space vehicle with respect to the sun, three basic components are needed: (a) a reaction mechanism such as gas jets or flywheels to mechanically perform the required maneuver; (b) a control system to activate the reaction mechanism at the proper time for the required period to realign the vehicle; (c) a solar sensor to continually provide the control system with an electrical signal which indicates the attitude of the vehicle with respect to the sun.

If flywheels are used as the reaction mechanism, they serve to rotate the vehicle by changing their own rotation rate, employing the principle of conservation of angular momentum. If gas jets are used as the reaction mechanism, they impart a torque to the vehicle by providing thrust along some moment arm from the center of mass; the basic principle is action and reaction.

The control system may assume many different forms in the design details, but the principle of operation in broad form is the following: A signal is produced by the sensor in the form of a voltage which vanishes when the solar pointing error approaches zero, and which changes polarity when the solar pointing error changes sign. This signal is amplified and fed to a servomechanism which activates the reaction mechanism in the proper direction.

Any solar sensor to be used in the orientation of space vehicles must be capable of operation in two separate phases. The first phase called capture refers to the ability of the sensor to view the solar disk throughout a wide range of misalignment errors. The second phase called fine pointing refers to the ability of the sensor to hold the vehicle within a very narrow angular confine once capture and preliminary alignment has been attained.

Solar sensors for space applications have appeared only within the last 15 years. Perhaps the earliest, and most common of these are the sensors developed by the University of Colorado Upper Air Laboratory at Boulder, Colorado.[1] One set of these sensors, referred to as the coarse eyes, served to orient a flight package to within several degrees of the sun. When this was done, another sensor, called the fine eye, was used to maintain the solar pointing of the vehicle within narrower limits. One set of coarse eyes was used to operate the azimuth servo while another set was used for the elevation servo. The photosensitive unit for the fine eye was the 1P42 vacuum phototube. To obtain the most stable tubes the 13 best ones were selected from a group of 75. High leakage sensitivity changes and fatigue drift were the principle disadvantages of these tubes at the time. A proposal to overcome the serious drift error was to control the balance from the ground with telemetry.

The coarse sensor consisted of three eye cartridges with 925 phototubes mounted behind opal glass diffusers and infrared filters, because of the sensitization of these tubes to infrared. These cartridges were arranged to point out a triangle surrounding the solar disk; each of the outside cells were combined with the center one to produce each degree of freedom of information.

The fine eye consisted of four 1P42 phototubes lying on the bottom of a tube containing a lense to focus the solar image onto four separate quadrants containing the tubes.

A polaroid disk was used to reduce the light intensity to prevent destruction of the phototube. As solar misalignment developed, the solar image shifted off center so as to light two quadrants more intensely and hence produce an error signal to direct the control system toward alignment of both axis. The coarse eyes attained capture for the fine pointing.

The Kearfott Company has proposed a solar sensor designed to produce solar direction information to an accuracy of 0.1°.[2] This system uses silicon solar cells in a design similar to the University of Colorado's. The fine sensing was done with only three units, which required rather elaborate circuitry. A continuous balancing system was suggested. No indication was given that the sensor or any of its components had been built.

The Space Vehicles Group of the National Aeronautics and Space Administration at Langley Research Center has become interested in using a solar sensor for the orientation of large erectable aluminized Mylar parabolic solar energy collectors. In the time elapsed since the University of Colorado designed their sensor, many advances have been made in solid state devices and miniaturization. It was thought that recent technological advances could be used to arrive at a solar sensor of novel design which would satisfy present needs for many types of space missions. In particular, greater consideration needed to be given to the following points: (a) reliable operation for prolonged periods in a space environment; (b) compactness, low weight, and high strength; (c) low power consumption (ideally, no power consumption).

To begin to meet these requirements, an investigation was conducted to select the best, presently available, photosensitive element for use in a space vehicle solar orientation system. Since photosensitive elements are also used as solar energy converters, literature is abundant in this area.

Silicon solar cells appeared to be superior in many respects to competing photosensitive devices. A principal advantage of the silicon solar cell is its high conversion efficiency, which is defined as the ratio of electrical power output to luminous power incident on the cell. Pearson, of Bell Telephone Laboratories[3], has compared the conversion efficiencies of various devices for converting solar radiation directly into electrical energy. In this study, Pearson examined thermopiles, photogalvanic cells and photovoltaic cells. Thermopiles use the results of J. J. Seebeck dating back to 1823, when he discovered that an electromotive force originates from a circuit containing two dissimilar metals if one junction is held at a higher temperature than the other.

Photogalvanic cells were first described in 1839 by A. E. Becquerel in a paper entitled "On Electrical Effects Under the Influence of Solar Radiation." The device consists of two electrodes placed in an electrolyte to produce an electromotive force when light is incident upon one electrode. The barrier-layer photovoltaic cell is a true solid state device which was developed around 1876 when W. G. Adams and R. E. Day found that in certain cases a selenium cell was found to generate a current without the aid of an external battery. (Proc. Roy. Soc. Lon., 1877, 25, 113.) A more detailed history of photosensitive devices is found in reference 4.

None of these devices produced conversion efficiencies in excess of about 1 percent. In 1954, D. M. Chapin, C. S. Fuller, and G. L. Pearson, of the Bell Telephone Laboratories, succeeded in raising the efficiency of the photovoltaic cell to 6 percent. (D. M. Chapin, C. S. Fuller, and G. L. Pearson, J. Appl. Phys. 25, 676, 1954). This was about a year after the University of Colorado published its solar sensor report. At the time reference 3 was written, the highest conversion efficiency for commercially available cells was 11 percent. As of May 1961, conversion efficiencies of 13 percent are available. (Electronic Design, New Products Section, May 10, 1961, p. 48.) Other desirable characteristics of silicon solar cells from the standpoint of operation in a space environment are discussed later in this paper.

Because photovoltaic cells have made such rapid progress since the first solar sensor appeared, it seemed advisable and feasible to approach the problem of devising a new type of solar sensor with long-term reliability as the principal design approach. The conception and development of this new solar sensor is given in the next section.

CHAPTER I

EXPERIMENTAL PROCEDURE

Description of Setup

When first confronted with the problem of arranging the solar cells into a sensor, it was thought that some beam splitting technique would be advisable. This would have required optics along with the consequent bulk, weight, and support requirements. A much simpler arrangement was to utilize the cells as a comparative photometer operating by the principle shown in figure 1. The basic principle of operation is that the illumination of a flat surface is directly proportional to the cosine of the angle of incidence. The word "illumination" is used synonomously with "illuminance" to designate the luminous flux per unit area incident on a surface and is measured in lumens/ft^2 (foot candles) or in lumens/m^2 (luxes).

Arranging the cells in the manner shown produces a solar sensor that combines a recently developed device with an operating principle that is several centuries old. The variation of illumination of a flat surface was discussed qualitatively by Leonardo da Vinci in his book on painting (German edition by Ludwig, Vienna, 1882, p. 308). When Lamberts "Photometria" appeared in 1760, he presented a mathematical expression for the cosine law of variation of illuminance with angle of incidence.[5]

It may be seen from figure 1 that when the sensor is aligned toward the sun, the incident solar radiation is parallel to N_B and the cells are

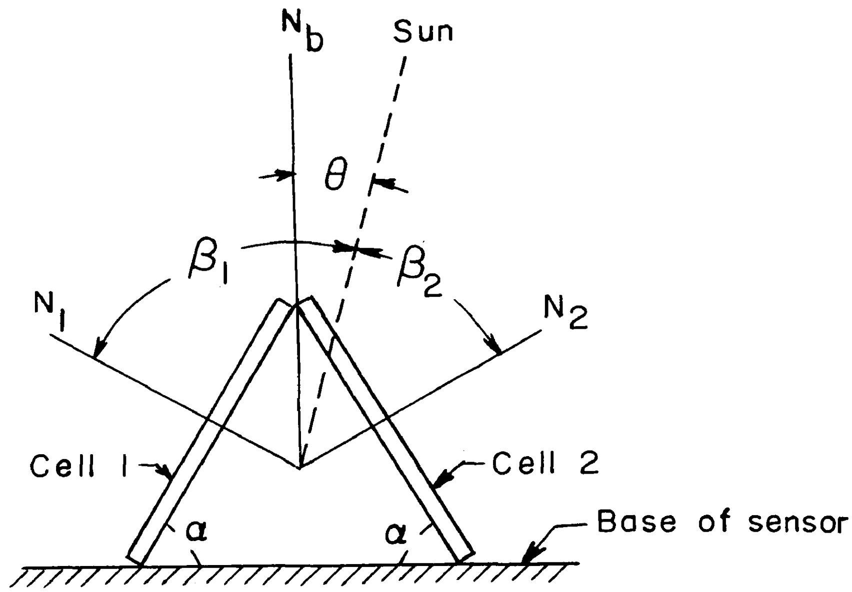


Figure 1.- Photometrical principle of operation.

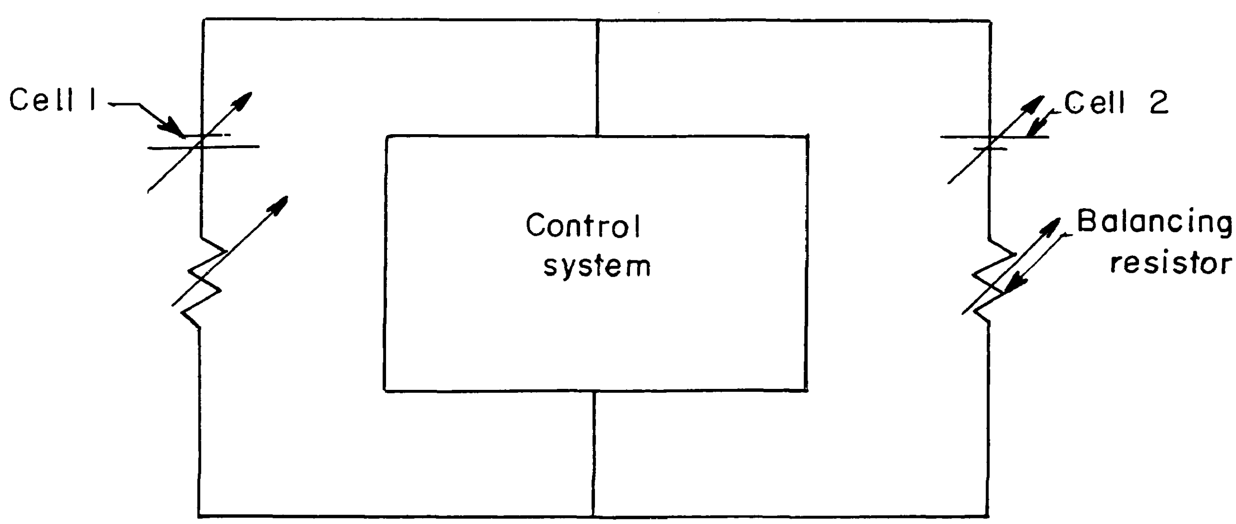


Figure 2.- Electrical principle of operation.

equally illuminated to produce equal potentials if their electrical characteristics are matched. Mismatched cells may be used by placing a resistor in series with the stronger cell. This balance resistor may also be used to point the sensor at some other desired angle to the sun.

The cells are connected in a battery-bridge circuit shown in figure 2. When the solar sensor is aligned toward the center of the solar disk, there will be no current through the center of the bridge which is actually the control system. If, however, the incident radiation forms an angle, θ, with the sensor normal N_B, then the more illuminated cell will produce an electrical signal through the center of the bridge. This signal will increase in intensity with increasing error angle, θ, because the difference in cell illumination also increases with increasing θ. The form of this increase can be seen from the geometry of figure 1. The illumination of cell 1 is given by

$$I_1 = I_{max} \cos (\alpha + \theta)$$

until cell 1 is completely shaded out. This occurs when

$$\theta = 90^\circ - \alpha$$

The illumination of cell 2 is given by

$$I_2 = I_{max} \cos (\alpha - \theta)$$

until the sun is no longer in the field of view of the sensor. This occurs when

$$\theta = 90^\circ + \alpha$$

Prior to the construction of an experimental solar sensor, two inclined silicon cells were taken on the rooftop and aligned in azimuth and vertical directions. The voltage output was recorded at various intervals along with the time of reading. The angular positions of the sun were then computed from the position and time. An increase in signal was noted as the pointing error increased. The data obtained were not taken under controlled conditions due to clouds, building reflections, changes in solar elevation with consequent change of optical depth, etc. From the general trend of the data, however, it was thought that the sensor of figure 1 could be used, at least for somewhat uncritical types of orientation applications.

In figure 1 we have only discussed single-degree-of-freedom orientation. A second axis of orientation may be obtained by adding a second set of cells rotated 90° to the first set about N_B.

A variable parameter of figure 1 that readily comes to mind is the angle of solar cell inclination to the base, α. In order to determine the influence of α upon the difference in cell illumination for various values of the pointing error, figure 3 was plotted. From this figure one may see that the steeper angles of cell inclination produce both a high small-angle sensitivity and a wide angle of solar capture capability.

The complete equations for the curves of figure 3 are as follows: when both cells are illuminated

$$\Delta I = I_{max}\left[\cos(\alpha - \theta) - \cos(\alpha + \theta)\right] \quad 0 \leq \theta < (90^\circ - \alpha)$$

when one cell only is illuminated

$$\Delta I = I_{max} \cos(\alpha - \theta) \quad (90^\circ - \alpha) < \theta < (90^\circ + \alpha)$$

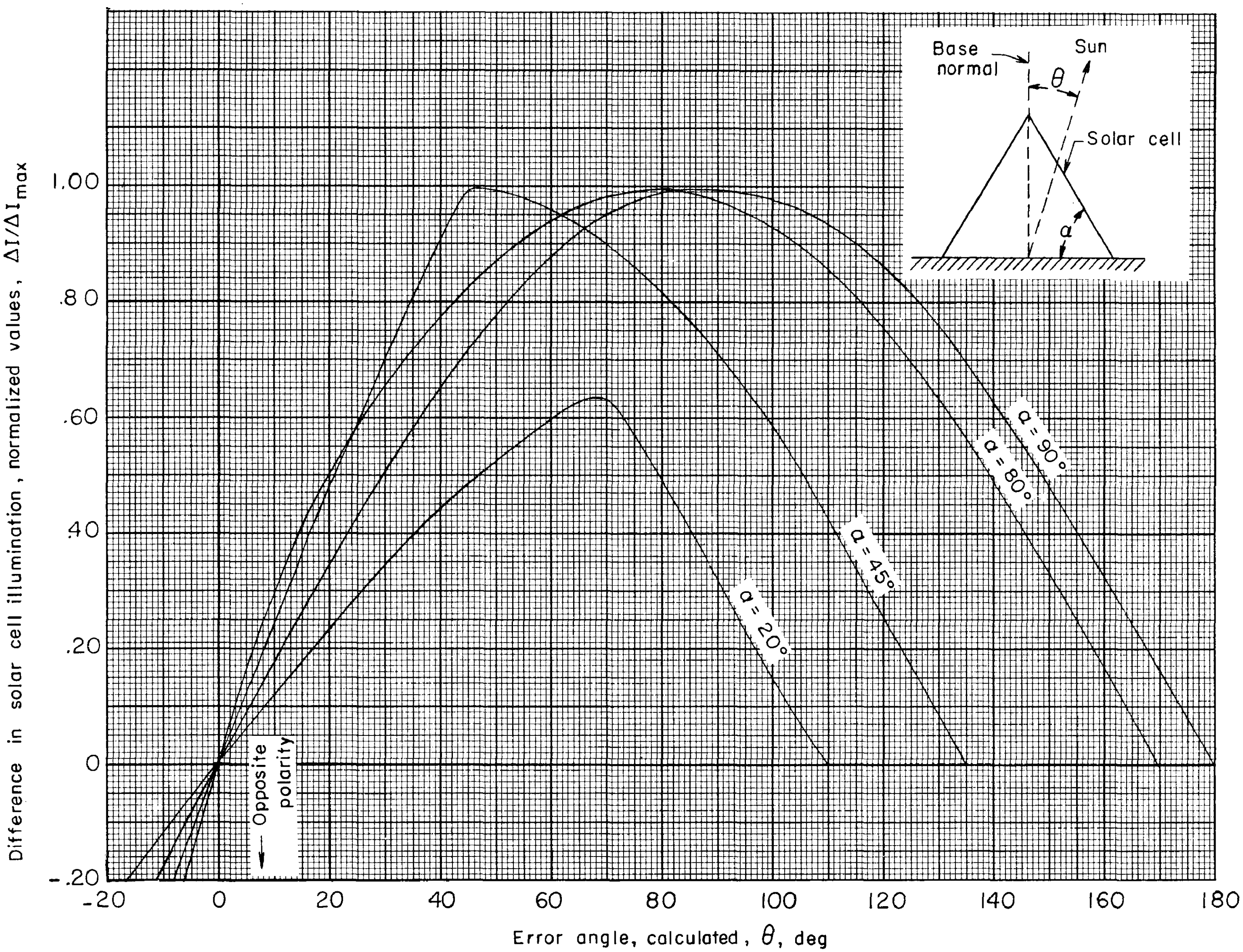


Figure 3.- Difference in illumination of coarse sensor for various angles of solar cell inclination.

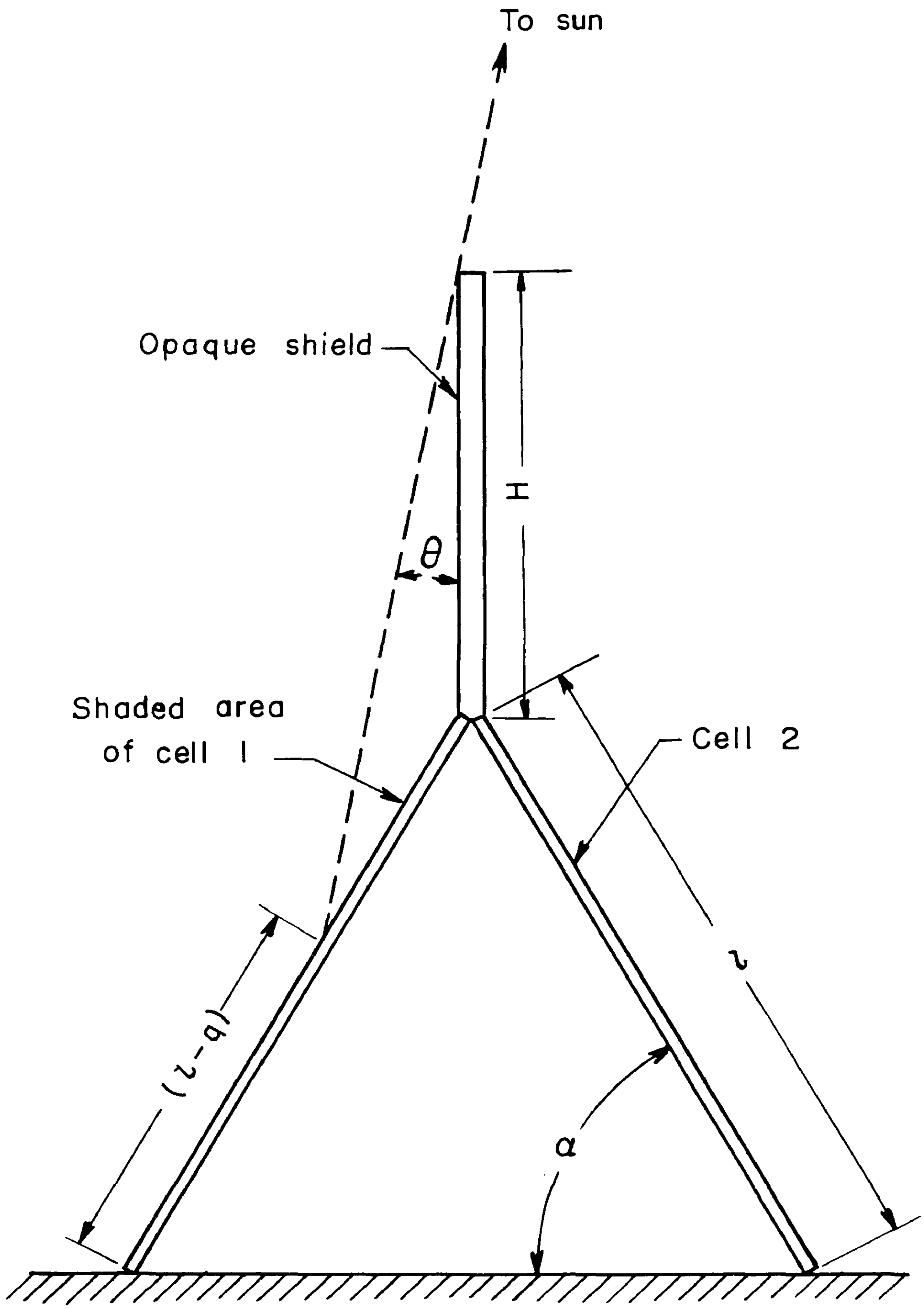


Figure 4.- Shading effect of opaque shield. Dimensions are shown for the calculations of appendix A.

and when neither cell is illuminated

$$\Delta I = 0 \qquad (90^\circ + \alpha) < \theta \leq 180^\circ$$

The other two quadrants are not necessary because of symmetry; the roles of I_1 and I_2 would simply be reversed.

Before the actual construction of an experimental version of the solar sensor, an additional technique was considered which would improve the small angle sensitivity with no loss of capture capability but with a slight increase in the dimensions of the sensor. This technique was the addition of an opaque shield at the apex of the sensor as is shown in figure 4. From this figure one may see, qualitatively at least, that the shadow cast by the shield on cell 1 will cause a greater change in sensor output for small error angles because the shadow causes the illumination of cell 1 to decrease more rapidly with increasing θ. This effect is shown graphically in figure 5 for which an inclination angle, α, of 80° was assumed. For this figure, a shield length of 5 inches was selected as a reasonable compromise between sensitivity increase and additional bulk.

The method of obtaining figure 5 is as follows:

Referring to figure 4, the illumination of either cell may be expressed as

$$I = Cw(l - q)\cos B$$

where

C illumination on a flat surface located in the vicinity of the cell and normal to the illuminating source

w width of cell

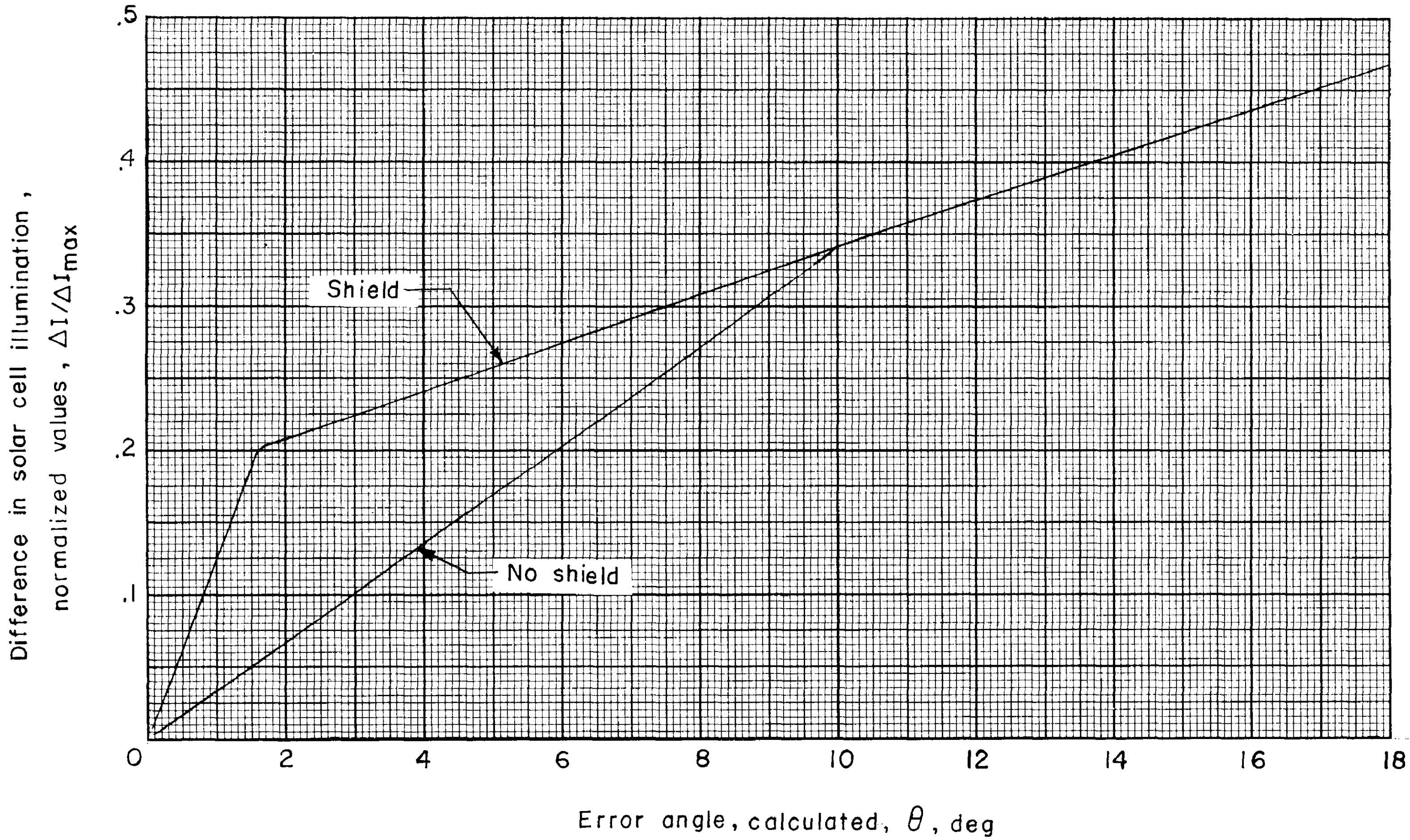


Figure 5.- Effect of shield. $\alpha = 80^{\circ}$; shield length, 5 inches; solar cells, 1 inch square.

l length of cell

q amount of cell's length shaded by shield

B angle of incidence

The area of cell 1 under illumination is

$$S_1 = w(l - q)$$

From the geometry of figure 4

$$q = \frac{H \sin \theta}{\cos(\alpha + \theta)}$$

so that

$$S_1 = w\left[l - \frac{H \sin \theta}{\cos(\alpha + \theta)}\right]$$

Since the illumination of cell 1 diminishes as the cosine of the angle of incidence, this illumination is

$$I_1 = Cw \cos(\alpha + \theta)\left[l - \frac{H \sin \theta}{\cos(\alpha + \theta)}\right]$$

Similarly for cell 2

$$I_2 = Cwl \cos(\alpha - \theta)$$

Subtraction yields

$$I_2 - I_1 = \Delta I = Cw\left[l \cos(\alpha - \theta) - l \cos(\alpha + \theta) + H \sin \theta\right]$$

for the condition

$$0 \leqq \theta \leqq \theta_{crit}$$

where θ_{crit} is the value of θ for which cell 1 becomes completely shaded and is given by

$$\theta_{crit} = \tan^{-1} \frac{\cos \alpha}{H + \sin \alpha}$$

For larger values of θ

$$\Delta I = Cwl \cos(\alpha - \theta)$$

It may be noted that the special case of the equation which occurs when $H = 0$ is that used previously for the coarse sensor.

The effect of changing the length of the opaque shield for small error angles is given when $\theta < \theta_{crit}$. From the relationship of H and ΔI, it is seen that the optimum length of the shield is a more or less arbitrary parameter which can be decided upon only after consideration is given to structural factors, mission requirements, and space available for the sensor.

Still another quantity subject to change is the geometric shape of the cell which may be used to a limited extent to control the slope of the curve in figure 5 for $\theta < \theta_{crit}$. For most purposes a smooth maximum slope is desired, which led to the use of rectangular cells in this discussion.

The calculations showing the effect of the shield have a slight error since they do not take account of the penumbra due to the finite angle (about 32 min.) subtended by the solar disk. Furthermore it must be noted that figure 3 and figure 5 do not precisely describe the solar sensor output principally because of the nonlinear characteristics of photovoltaic cells such as the silicon solar cells.

It is thought, however, that these figures serve as a rough guide to indicate the general effects of changing various parameters, such as the angle of inclination to the base, the length of the opaque shield, and the maximum value of the illumination. The effects of these factors are described more realistically in the "Conclusions" section of this paper.

Apparatus

The experimental version of the solar sensor presented in figure 6 was constructed for use on the single-degree-of-freedom platform shown in figure 7 which is mounted on the air bearing shown in figure 8 and oriented toward a light source simulating the sun.

The sensor of figure 6 uses four 0.5-inch by 1-inch rectangular cells connected in series to produce two 0.5-inch by 1-inch rectangular units on each face, which is inclined at an angle of 80° to the base of the sensor. The opaque shield was 5 inches in length with a 1.5-inch square cross section. The center of the bridge circuit was a 1,000-ohm precision resistor (1 percent) to simulate the control system impedance. The circular cells recessed in the opaque shield were used to provide an independent error angle signal which provided rate information for damping of the platform.

Figure 7 shows an early version of the test platform used as a breadboard version of the solar sensor, control system, and reaction jets. At the top of the photograph is a makeshift solar sensor used while awaiting construction of the version shown in figure 6. At the left of the photograph in figure 7, the solenoid valves and torque-producing jets may be seen. The compressed nitrogen storage bottle

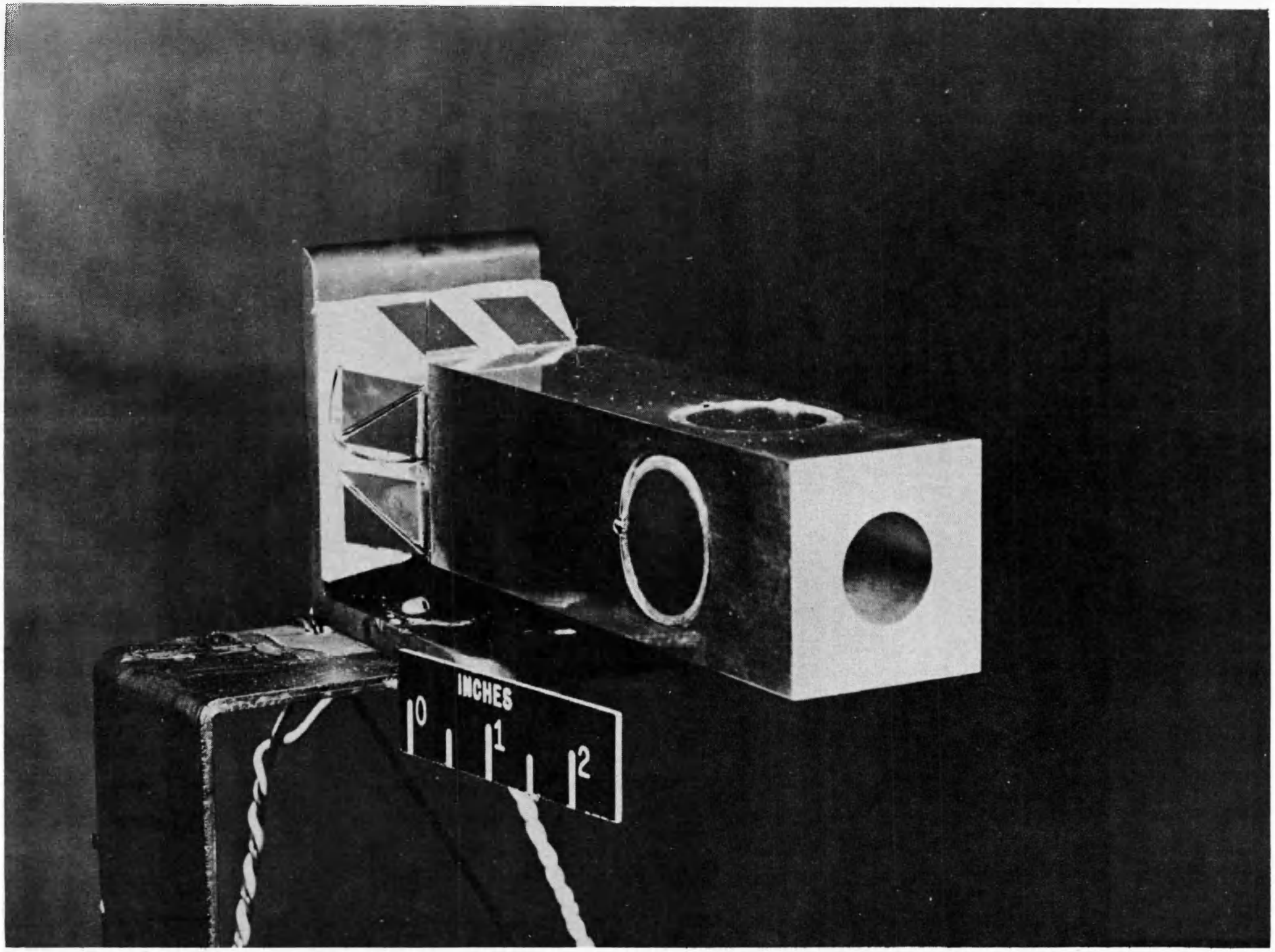


Figure 6.- Experimental version of solar sensor. L-60-4611

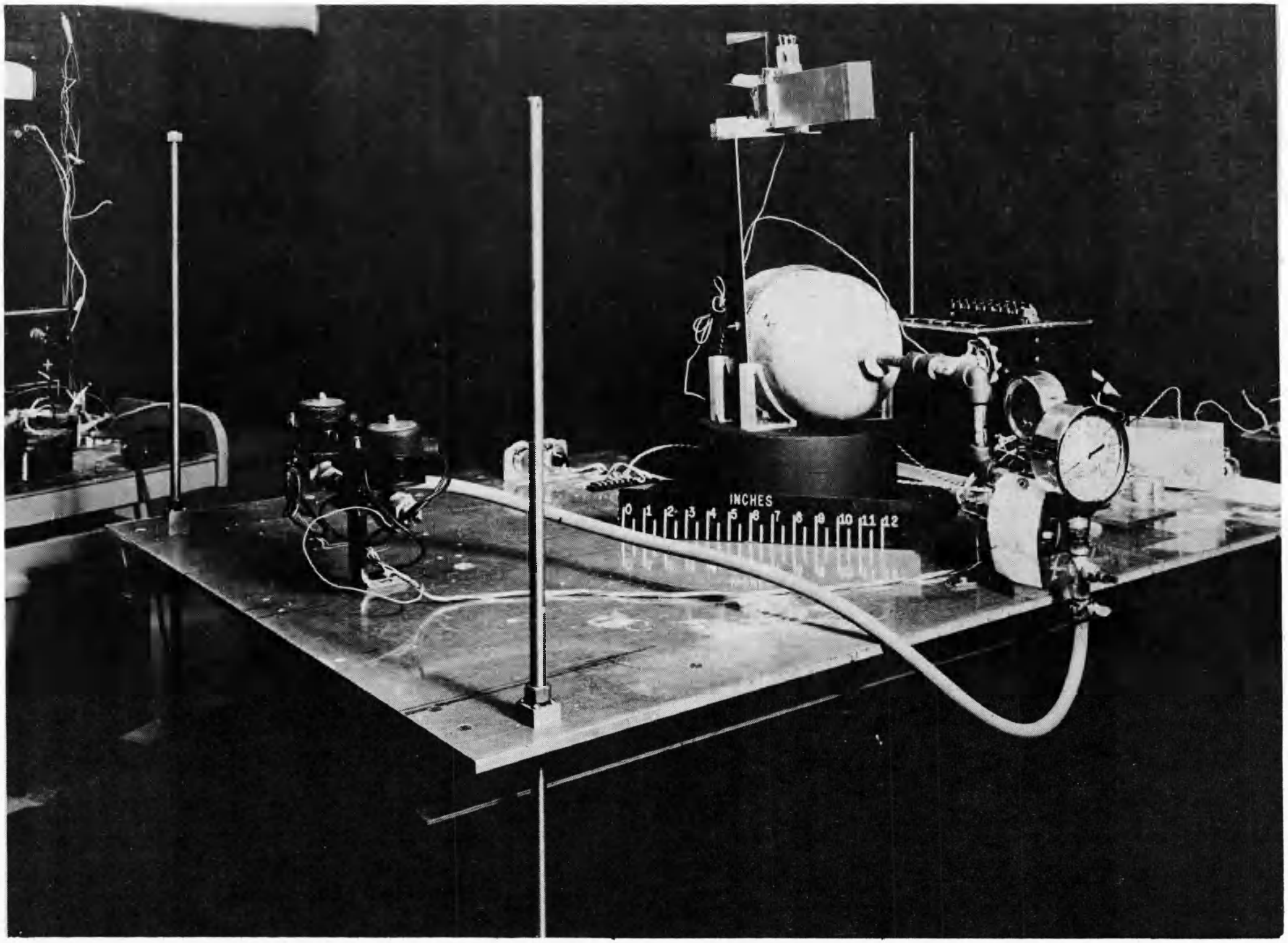


Figure 7.- Test platform for complete solar orientation system. L-60-2019

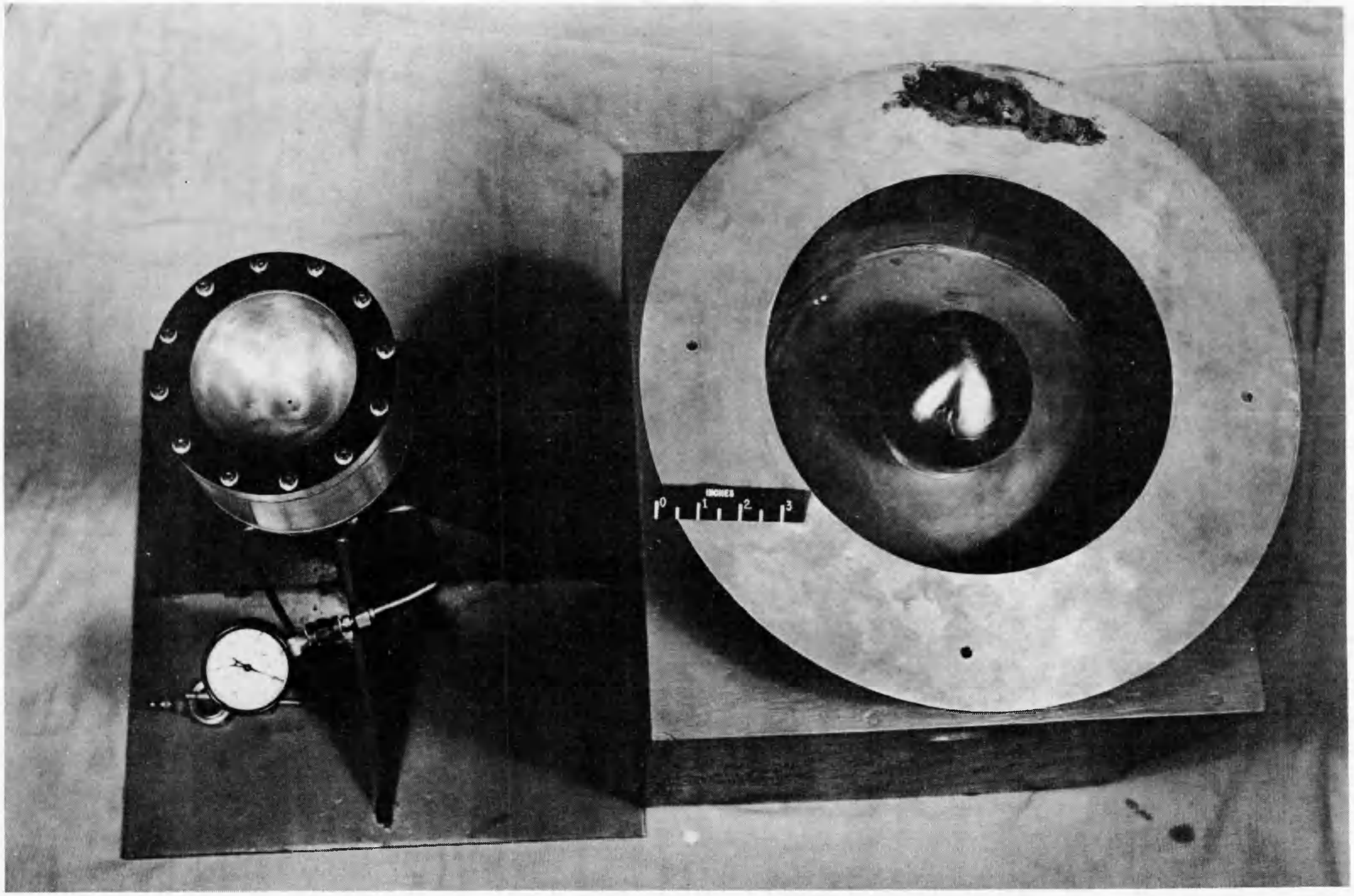


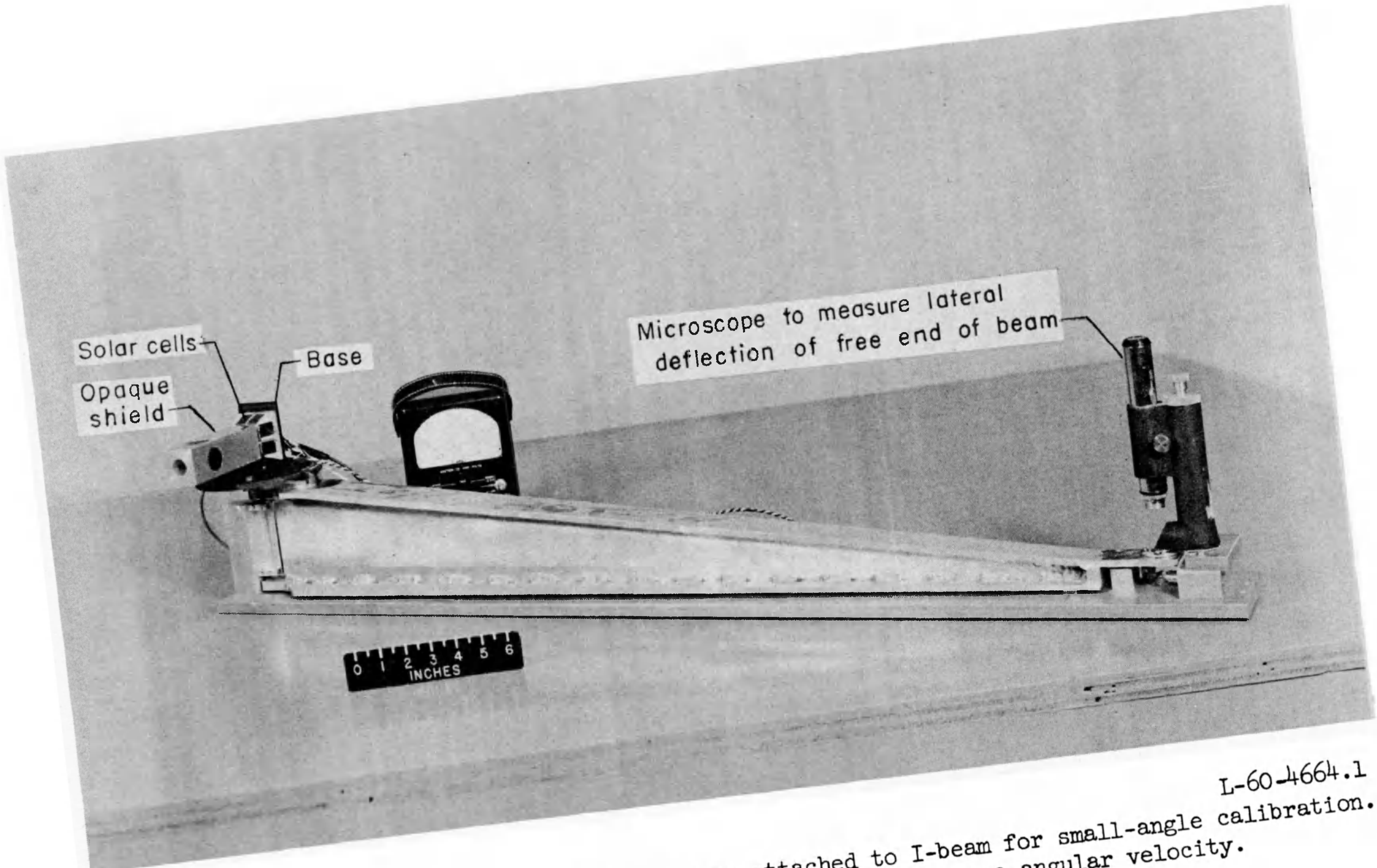
Figure 8.- Air bearing support for test platform. L-59-5365

appears near the center, and the plumbing and circuitry are to the right of the bottle and behind it. The long vertical bars are used to suspend and adjust weights to position the center of mass of the platform.

This platform was mounted on the air bearing shown in figure 8. The female portion of this bearing shown on the left consists of a hemispherical socket with an air orifice at the center and 32 other orifices distributed along the lower portion. Pressurized air flowing through these orifices provide the male portion of the bearing (shown in its inverted position on the right half of the photograph) with a cushion of air upon which to "ride." This bearing allowed the test platform to rotate with very little retardation.

The bearing and platform described were used to test the integrated solar orientation system. The equipment used to calibrate the solar sensor separately is shown in figures 9 and 10.

Figure 9 shows the experimental solar sensor mounted on a protractor head (left end of photograph) clamped to the end of the I-beam. To obtain angle sensitivity data for large angles (capture phase), the protractor head was unclamped from the I-beam and rotated through a complete circle while being illuminated by a fixed light source. The I-beam apparatus was used to obtain fine-pointing angle sensitivity data. The beam itself is 41 inches in length and is supported on one end (left side of photograph) by a vertical torsion bar while the unsupported end (right side of photograph) was moved in a horizontal direction by a micrometer drive screw to rotate the beam through very small angles.



L-60-4664.1

Figure 9.- Experimental version of solar sensor attached to I-beam for small-angle calibration. Circular cells in shield provide a separate signal to sense angular velocity.

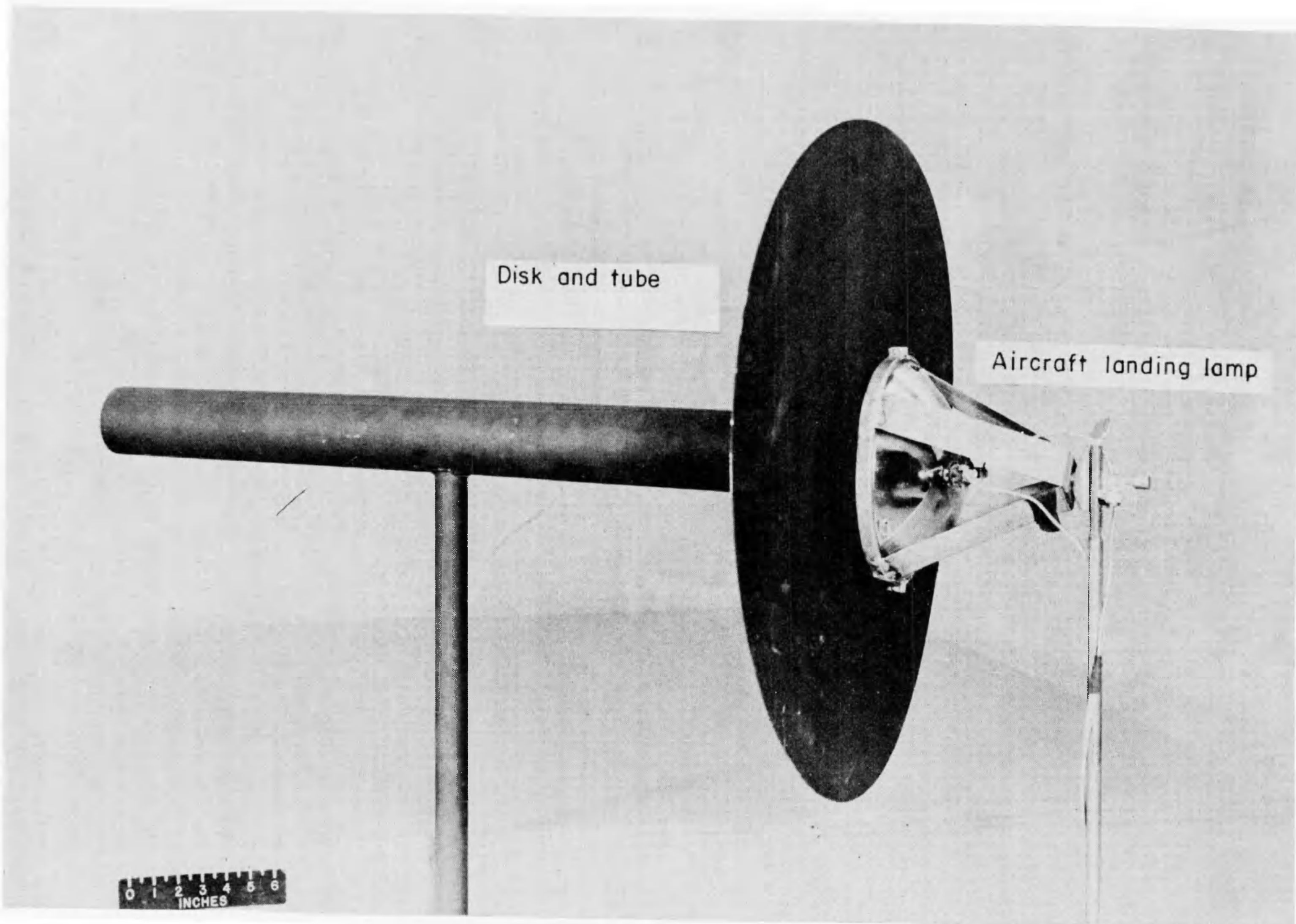


Figure 10.- Light source for solar sensor calibration. L-60-4663.1

The reason for the torsion bar pivot is to eliminate lateral displacements of the pivot end of the beam which would result from bearing tolerances or eccentricity if a conventional bearing support had been used. Due to the extremely high ratio of I-beam flexural rigidity to torsion-bar torsional rigidity, the I-beam flexural rigidity introduces virtually no error. Any lateral motions of the supported end which may have occurred could not be detected with a microscope.

The small displacements of the free end produced by the micrometer drive screw were read on a microscope reticle attached to the free end. This reticle consisted of 100 lines per millimeter, and could be read to the nearest half line. This corresponds to an angular reading accuracy of 1 second of arc rotation of the sensor.

The light source used in conjunction with the angle sensitivity measurement apparatus is shown in figure 10. This consists of an aircraft landing lamp (left side of photograph), Westinghouse number 4559, 600 watts, operated by a Tabtron DC power supply producing 28 volts. At 1 inch in front of the aircraft landing lamp is placed a circular tube and disk (left and center of photograph). The disk and tube were painted flat black to prevent stray light reflections and to limit the size of the beam. The tube was 36 inches long with a 2-3/4 inch inside diameter. The solar sensor was placed 60 inches from the closest end of the tube. At this location the light source delivered 1,200-foot candles as measured by a Wollensak Fastax Foot Candle Meter.

This amount of illuminance is about 9 percent of that produced by the sun at one astronomical unit outside of the earth's atmosphere.[6] The spectrum of the aircraft landing lamp is of course shifted toward the infrared as compared with the sun. Figure 11 shows the spectrum of an aircraft landing lamp, the sun, and the response of a silicon solar cell superimposed.[7] From this figure it is seen that the solar sensor response curve peaks in the red region of the solar radiation and in the blue region of the aircraft landing lamp spectrum so as to obtain roughly similar amounts of energy from each of these sources.

As the sensor was rotated in the beam of light from the lamp, output voltages across the load resistor were read with a Hewlett Packard Model 425A DC Micro volt-ampere meter. This meter has an accuracy of within ±3 percent of end scale, and an input impedance of the order of 1 megohm. When the small angle sensitivity readings were taken, room vibrations caused some difficulty in reading the meter since the needle executed small vibrations in a random fashion. These variations were carefully watched and average readings were taken for each data point.

Environmental

A solar sensor must be capable of reliable, prolonged operation in the environment of space. Among the hazards likely to be encountered are severe particle and electromagnetic radiation, vacuum, and micrometeor bombardment.

Silicon cells have proven capable of reliable operation in a space environment by the satellite, 1958 Beta, whose cells have been operating for an extended period. Some laboratory tests on the effects of radiation on silicon cells have been performed,[8] and they have been found to withstand ultraviolet, X-rays, gamma rays, electrons, protons, and alpha

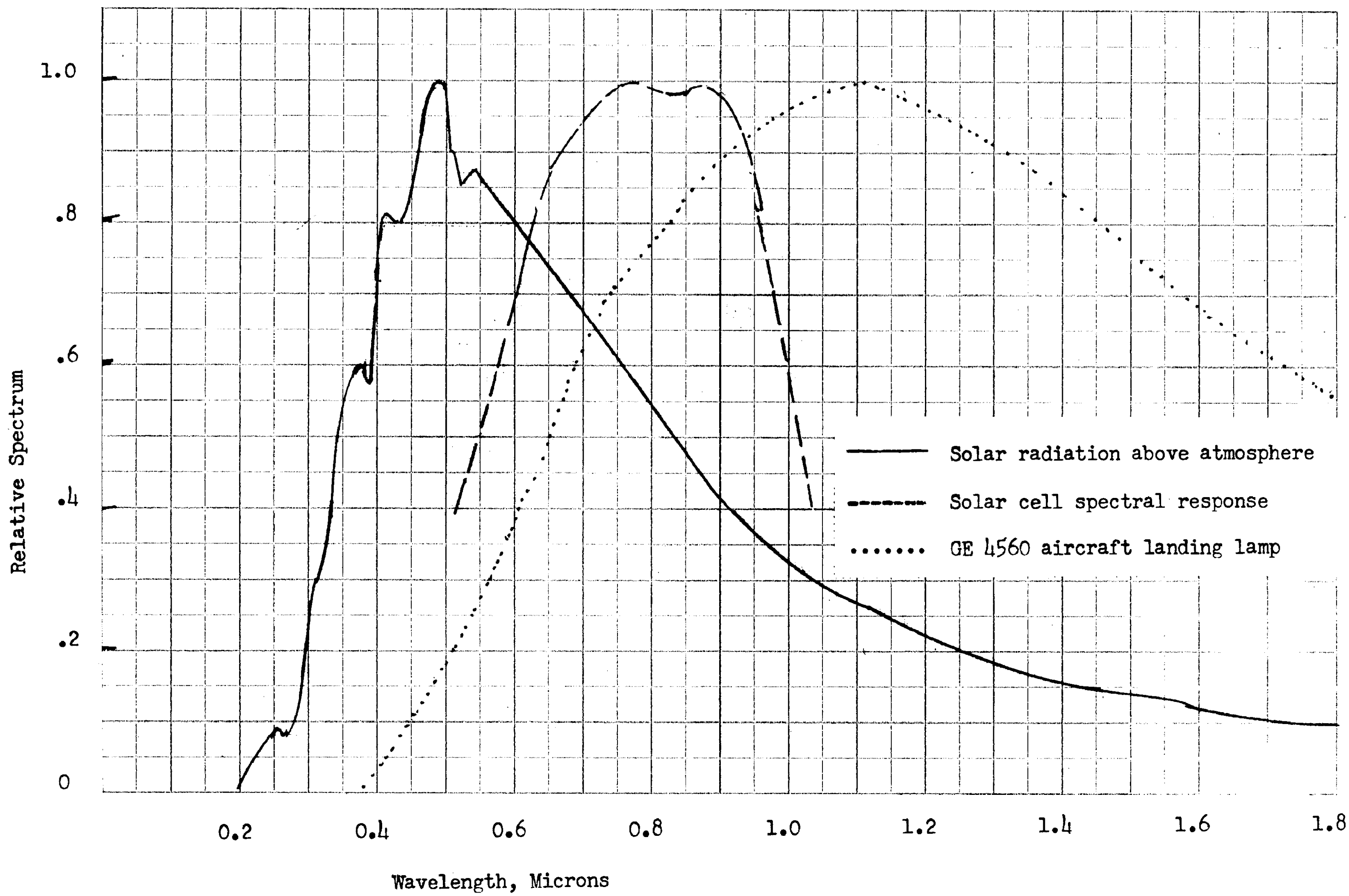


Figure 11.- Spectra of solar radiation and aircraft landing lamp, and solar cell response. (From ref. 8.)

particles of moderate energy. The results of these tests indicate that silicon solar cells decrease their output to 75 percent their original value in about 14 years. Hence the solar sensor sensitivity would have a similar decrease. It must be realized, however, that these values are extremely rough, and better estimates must await more complete data concerning the nature of the Van Allen belt and other deleterious phenomena such as solar proton streams.

Another hazard to the solar sensor is the damage which might be caused by micrometeorite erosion and puncture. However, present data indicate that this problem is less serious than is radiation damage.[9] In order to protect the silicon cells from the sandblasting effects of micrometeorites, windows of highly resistant fused silica may be provided.

Although these have favorable mechanical properties, up to 20 percent of the transmitted energy may still be lost by the sandblasting effects.[10] This indicates that the sensitivity would eventually be reduced by about 20 percent due to micrometeorites if windows of fused silica were used to cover the sensor.

Another environmental effect on the solar sensor sensitivity is temperature. The temperature coefficient of conversion efficiency is -0.5 percent per degree centigrade for the range between $+20^{\circ}$ C and $+175^{\circ}$ C (Hoffman Electronics Corporation, Technical Information Bulletin number TIB 32-58). A 10° temperature rise in this range would therefore lower the sensitivity by 5 percent. It is believed that this would not present a serious problem because of advances made in the thermal control of space vehicles, and because of recent knowledge of the probable thermal environment of a satellite (ref. 11, for example).

CHAPTER II

EXPERIMENTAL RESULTS

Data

The wide angle calibration curve of figure 12 was obtained by rotating the solar sensor at various angles to the beam emitted from the aircraft landing lamp. From this curve, one may see the high angle sensitivity of the solar sensor for small angles. This portion of the curve will be shown later in greater detail. The slight asymmetry results from the initial mismatch of the characteristics of the silicon cells used, since no balance resistors were employed in the experimental solar sensor. Another factor contributing to the asymmetry is the failure to determine the precise null position for the wide angle curve. A large portion of the wide capture capability is also shown here. A conspicuous feature of this wide angle curve is the sharp knee which appears just beyond the steep linear portion of the curve. A nonlinear characteristic of the silicon solar cell is responsible for this.

The nonlinear characteristic accounting for the sharp knee appearing in figure 12 is that the solar cells attained rapid saturation as may be seen from the saturation curve of figure 13. This curve was obtained by varying the operating voltage of the aircraft landing lamp to reduce the illumination on one face of the solar sensor situated normal to the light source. Measurements were again taken with the foot candle meter

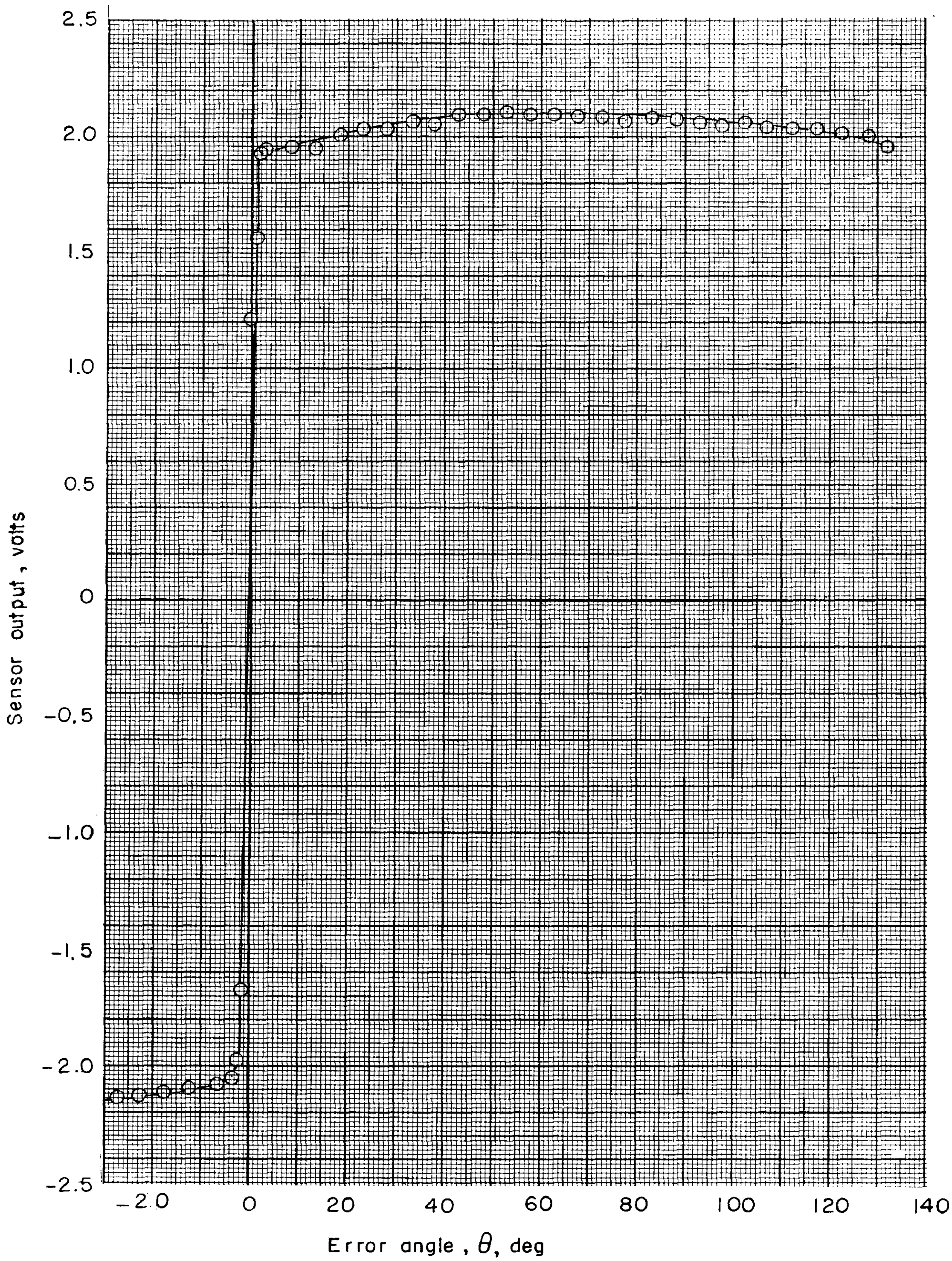


Figure 12.- Large-angle performance of experimental solar sensor.

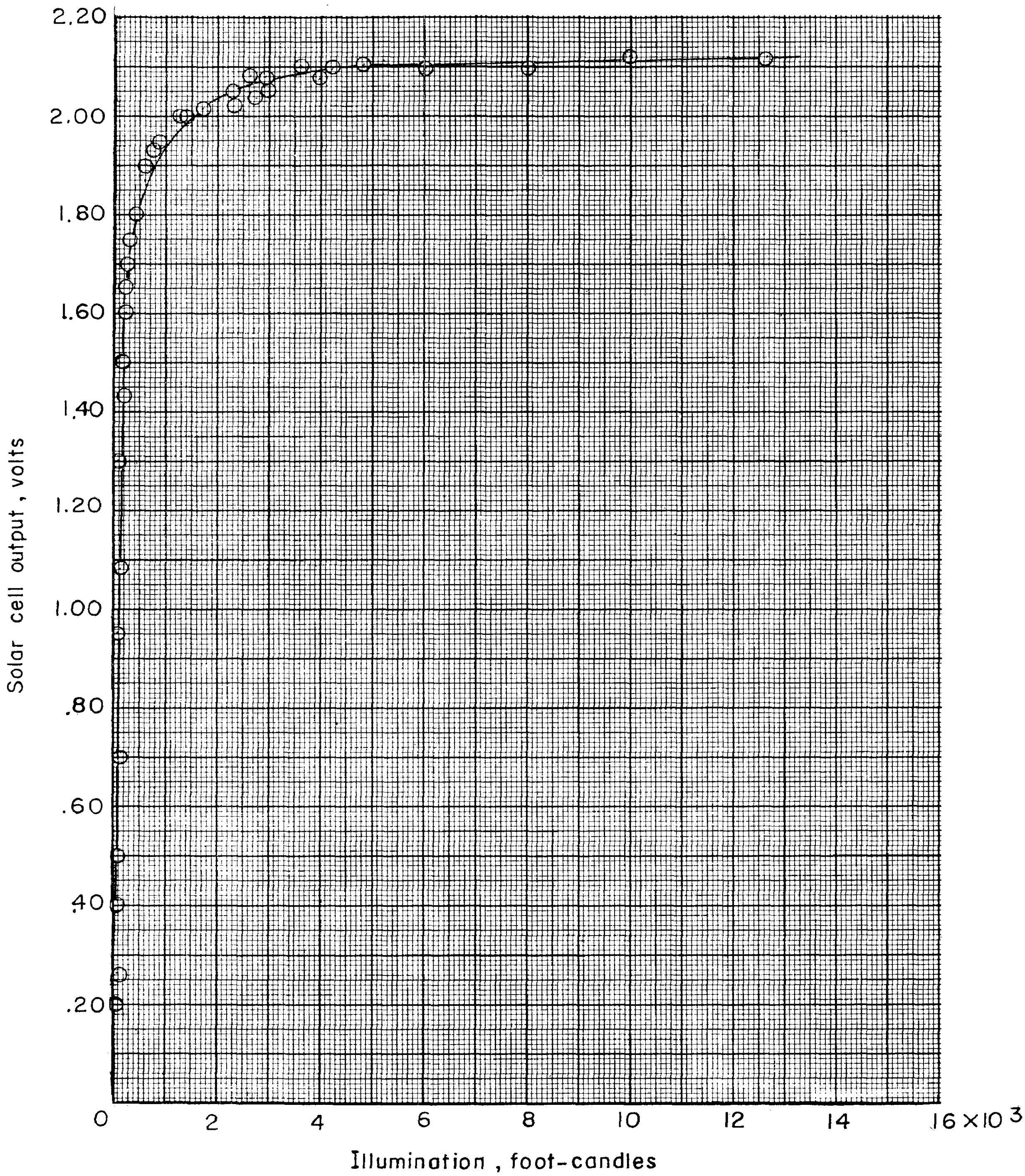


Figure 13.- Light saturation curve for one face of solar sensor. Load resistance, 1,000 ohms.

realizing some inaccuracies may have been introduced by a spectrum shift toward the red when the temperature of the tungsten filament decreased.

Characteristic curves for silicon cells may be found in reference 12. These curves indicate that for high values of load resistance and illumination, the product of the current and load resistance becomes constant.

The fine-pointing angle sensitivity curve is shown in figure 14. This curve was obtained with the method and apparatus described in an earlier section of this paper. The solar sensor had a load resistance of 1,000 ohms and an illumination of 1,200 foot candles. The linearity of the curve in the region shown is desirable for processing the electrical signal. The fine-angle sensitivity is obtained from the slope of the curve. This slope produces a sensor output of 1.2 millivolts per second of arc.

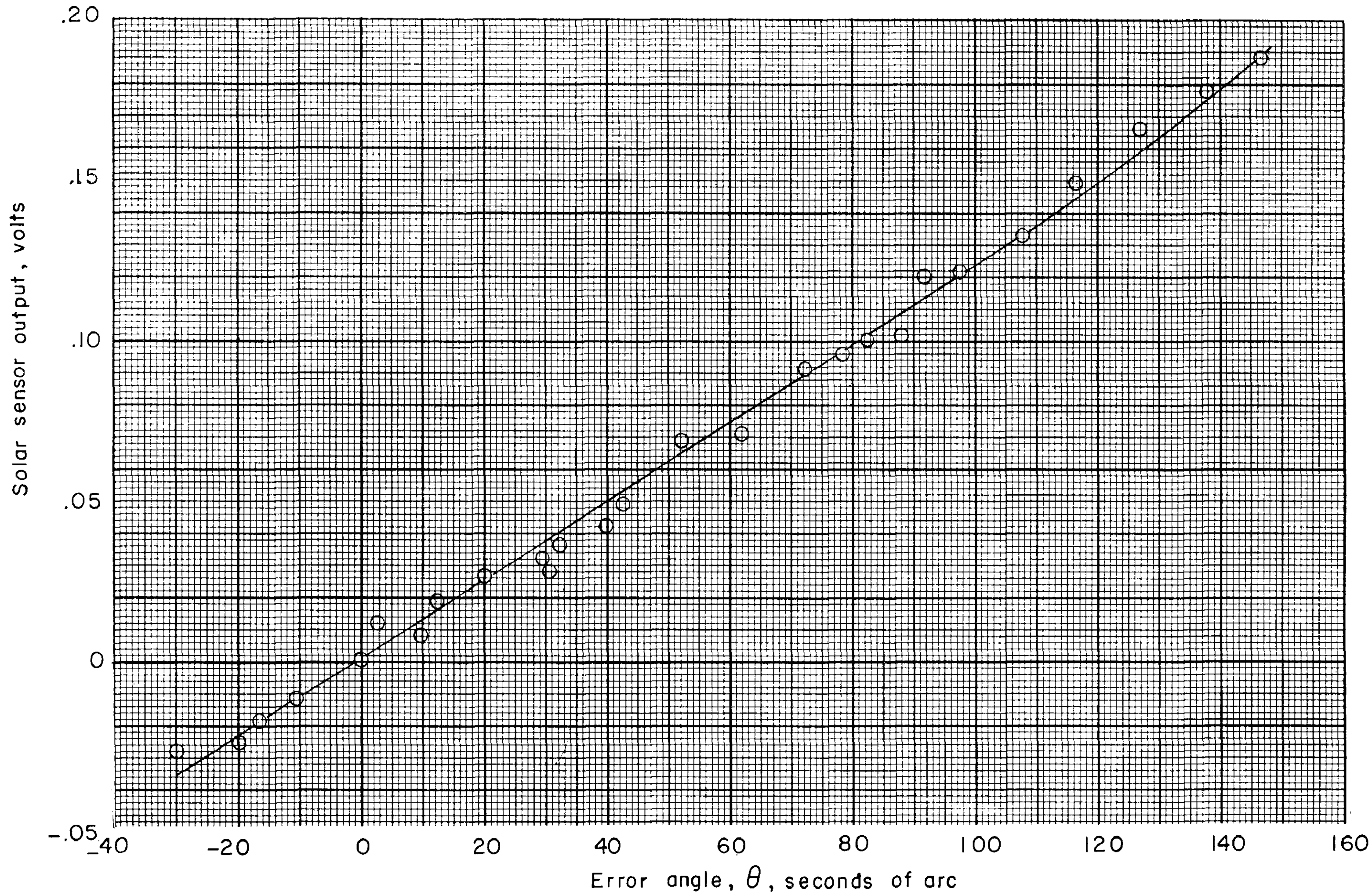


Figure 14.- Small-angle performance of experimental solar sensor. Source of illumination, 1,200-foot-candle aircraft landing lamp.

CHAPTER III

CONCLUSIONS

The preliminary research presented in this paper indicates the feasibility of the configuration studied. Previous sensors have had more inherent disadvantages, particularly in regard to continuous, accurate solar orientation of a space vehicle. The two basic factors contributing to the advantages of the sensor presented are simplicity of design and the use of silicon solar cells as the photosensitive elements.

Specific factors contributing to the reliability of the sensor studied in this paper are as follows:

1. The sensor is able to withstand the deleterious effects of a space environment. Silicon cells have already performed for prolonged periods of space.

2. The solar sensor consumes no power. Previous sensors used phototubes which require external power for their operation. Silicon cells, however, are self-powering and have a high conversion efficiency.

3. No optical components are needed. The operating principal is photometric. Nothing is needed to focus the beam or protect the silicon cells from optical destruction. Previous sensors employing phototubes required care to prevent "burning."

4. The sensor has no moving parts to cause failure or frictional wear.

5. For many applications, such as the orientation of silicon cell banks to power a satellite, only one unit is required to perform the separate functions of initial acquisition of the solar disk and fine pointing to hold the solar pointing error within narrow limits for long periods of operation. Previous sensors used separate units to perform the operations of initial and final orientation.

6. The sensor is light in weight due to the small number of parts needed.

7. The sensor has sufficient mechanical strength because it has no delicate parts.

8. The size of the sensor is reasonable. Without an opaque shield the solar sensor occupies about a cubic inch. The addition of a shield will add only several inches to the sensor's length, but this may be compensated for by producing greater angle sensitivity for small angles with no resulting loss of field of view.

9. The sensor is easily and cheaply constructed because of the simplicity of its component parts. Alignment of cells on the sensor is not extremely critical since final alignment may be accomplished with the balance resistors shown in figure 2.

10. The electrical drift of the sensor is very slight. Silicon solar cells exhibit very little optical fatigue, and will operate as stable reference standards for long periods even under full sunlight. The drift problem was especially acute for previous solar sensors.

11. The electrical signal produced by the solar sensor is easy to process. The output consists of a voltage increasing with error angle and reversing polarity as the error angle passes through and beyond the null. Two-degree-of-freedom orientation uses two independent output voltages.

12. The experimental sensor verified many aspects of the theoretical feasibility studies.

13. The experimental sensor proved that by using the configuration presented, it is possible to obtain an angle sensitivity of at least 1.2 millivolts per second of arc through a control system with a resistance of 1000 ohms.

14. The sensor presented is capable of orienting a space vehicle to at least 17 seconds of arc. The experimental sensor shown in figure 6 has been ground tested on an air-bearing-supported platform in conjunction with an on-off control system and nitrogen gas jets. This platform has been able to capture and hold a test light source with a final pointing error of 17 seconds of arc from an initially pointing error of greater than 90°. This is thought to be still a couple orders of magnitude from the inherent capabilities of the sensor, and reflects merely the state of development of the control system used.

It has also been found that in order to more closely predict the output of the sensor at various inclination angles between the cells and the base, it is necessary to consider the nonlinear voltage output characteristic as the illumination on a cell is varied. This characteristic was shown in figure 13 for a particular load resistance and light source.

Further research is being conducted to optimize the sensor for use with various types of control systems. Future experiments with the solar sensor will use a mercury-xenon vapor lamp to more closely duplicate the solar intensity and spectrum.

Future experimentation with the solar sensor presented in this thesis includes a four-stage vertical probe which is now being prepared to test the complete solar orientation system at an altitude of several hundred miles.

REFERENCES

1. Department of Physics, University of Colorado Upper Air Laboratory: Special Report No. 7, Contract No. W19-122AC-9, May 31, 1953.
2. The Kearfott Company, Inc.: Solid State Sun-Tracker, Technical Proposal ETO-426, April 2, 1959.
3. Pearson, G. L.: Electricity From the Sun. Proc. World Symposium on Applied Solar Energy (Phoenix, Arix.), Nov. 1-5, 1955, pp. 281-288.
4. Summer, W.: Photosensitors, Macmillan, 1958.
5. Mach, Ernst: The Principles of Physical Optics, translated by John S. Anderson and A. F. Young, Dover Publications, 1926, pp. 14-15.
6. Ehricke, Kraft A.: Space Flight, vol. 1, Environment and Celestial Mechanics. D. Van Nostrand Company, Inc., April 1960, p. 140.
7. Niebaur, K. L.: High Altitude Performance of Silicon Solar Cells. AIEE Conference Paper No. CP 58-914, May 6, 1958.
8. Loferski, J. J., and Rappaport, P.: The Effect of Radiation on Silicon Solar-Energy Converters. RCA Review, vol. XIX, no. 4, Dec. 1958, pp. 536-554.
9. Whipple, Fred L.: The Meteoric Risk to Space Vehicles. (Preprint) 499-57, Am. Rocket Soc., Oct. 1957.

10. Zahl, Harold A., and Ziegler, Hans K.: Power Sources for Satellites and Space Vehicles. Solar Energy, vol. IV, no. 1, Jan. 1960, pp. 32-38.

11. Wood, George P., and Carter, Arlen F.: Predicted Characteristics of an Inflatable Aluminized-Plastic Spherical Earth Satellite With Regard to Temperature, Visibility, Reflection of Radar Waves, and Protection From Ultraviolet Radiation. NASA TN D-115, 1959.

12. Sasuga, John: Solar Cell and Photocell Handbook, International Rectifier Corporation. November 1960, pp. 19-24.

VITA

Paul R. Spencer

The author was born in Bangor, Maine, on April 8, 1934. His primary education was received in Brewer, Maine, and Old Town, Maine. Secondary education was obtained at Old Town High School, from which the author graduated in June 1951. He then returned to high school for an additional year to take science and mathematics courses because he felt inadequately prepared for college training in these fields.

In May 1952, the author enlisted in the United States Air Force where he attended Control Tower School and Aircraft Landing Control Operator School for a period of 6 months. The author served the rest of his 4-year enlistment period as a ground controlled approach (GCA) radar operator. During the period spent in military service, the author obtained college credit equivalent to about three semesters by taking evening, correspondence, residence, and summer courses from Baylor University, the University of Chicago, the United States Armed Forces Institute, and the University of Maine.

After military service, the author attended the University of Maine for 2-1/2 years to obtain the Bachelor of Science degree with a major in Engineering Physics in June 1958. The summer of 1957 was spent at the Naval Research Laboratory in Washington, D. C., as a student trainee.

The author has been employed by the National Aeronautics and Space Administration since July 1958. He is presently an Aerospace Technologist with the Space Vehicles Group of the Langley Research Center.