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A High-Precision CdS Photodetector for Sun Sensor Applications

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This report describes a new sun detector developed for the Mariner Jupiter/Saturn mission. Redundant photopotentiometers for both pitch and yaw axes, positioned below slit apertures, provide spacecraft stabilization and biased operation over + 20-deg fields of view. The biased (off-sun) operation is required for pointing the 366-cm-diameter (spacecraft-fixed) radio antenna toward Earth. Configuration and fabrication processes are presented, along with a summary of development history. Particular attention is given to the properties of cadmium sulfide as these affect adaptation to this application.

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PREFACE

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.

The S&RC Division of Honeywell, under contract to the Jet Propulsion Laboratory, developed early prototypes of the wide-angle detector. Subsequently, Honeywell contractually undertook the design, development, and flight fabrication of the detectors. Detector evaluation and sensor development are ongoing inhouse activities at JPL.

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ABSTRACT

This report describes a new sun detector developed for the Mariner Jupiter/Saturn mission. Redundant photopotentiometers for both pitch and yaw axes, positioned below slit apertures, provide spacecraft stabilization and biased operation over ±20-deg fields of view. The biased (off-sun) operation is required for pointing the 366-cm-diameter (spacecraft-fixed) radio antenna toward Earth. Configuration and fabrication processes are presented, along with a summary of development history. Particular attention is given to the properties of cadmium sulfide as these affect adaptation to this application.

I. INTRODUCTION

The sun sensor for the Mariner Jupiter/Saturn (MJS) spacecraft maintains pitch and yaw axis stabilization, and is capable of biased operation over wide fields of view. Biased operation is necessary because the high-gain antenna, 366 cm in diameter, is not separately gimballed, and, for high-rate telecommunications, the whole spacecraft must be pointed toward Earth.

Forty-degree fields of view are accommodated about the pitch and yaw axes. The sun sensor must provide stable, repeatable operation with errors on the order of 0.02 deg. Initial requirements include accommodating a change in illumination level of 100:1, with a design goal of 900:1. These requirements far exceed those imposed upon sun sensors on previous Mariner spacecraft, and necessitate an entirely new mechanization concept. A new detector has been developed to satisfy the requirements of this application.

II. MECHANIZATION CONCEPT

Figure 1 shows, conceptually, the detector's mode of function. Side by side are a film resistor, a light-responsive area of cadmium sulfide, and a conductive electrode. A line image of sunlight falls across these elements, as indicated in the figure.

A bias voltage is shown, applied to the ends of the thin-film resistor, which results in a distribution of electric potential along the resistor's length. The strip of photoconductive cadmium sulfide has a comparatively low resistance at the location of the light bar. In terms of electrical function, this serves to tie the output electrode to a particular point on the resistor. In effect, the output electrode and light bar are like the wiper in a potentiometer, and such configurations are known as "photopotentiometers."

Figure 2 is an optical schematic of the sensor and detector together as a unit. The thin-film arrays, or "detector elements," are shown along with a slit, orthogonal to the detector's elements and some height above them. Only certain light rays from the sun can reach the detector, and these form a line image which moves along the detector as the angle with the sun changes. The output signal varies over the range of bias voltage as the sun moves through the field of view from one side to the other. Two sets of these "angle detector elements" are shown, indicating redundancy. One each of the configurations shown in Fig. 2 is required for each axis, so a flight sensor would possess two slits at right angles and two detectors, as indicated in Fig. 3.

In the actual hardware implementation of this concept, each detector is a separate, hermetically sealed unit. The sensor has light baffles within its detector mounting cavities to reduce stray light and define the fields of view. A spectral filter is employed at the slit to attenuate ultraviolet radiation. The detector possesses a total of four elements. The outermost two are the angle detectors previously discussed. The two in the center are "illumination detectors"; they detect the sun as it first enters the field of view, signifying sun acquisition and enabling the "cruise" mode of attitude control.

Squarewave excitation is employed because of detector susceptibility to degradation in the unipolar mode of operation. Sensor electronics generate the appropriate squarewave bias and amplify and demodulate the outputs. Error signals are generated by comparing the output signals with dc biases from the attitude-control system for spacecraft control purposes.

III. CONFIGURATION

Figure 4 shows a complete sun detector. The package comprises a case top containing a fused silica window, a substrate on which the thin films are deposited, and a base with terminals and fill tubes installed.

The juxtaposition of the parts prior to assembly is shown in Fig. 5. The substrate is first joined to the base with a nonconductive epoxy. Terminals protrude through notches in the substrate and are connected with electrodes by means of a silver-filled conductive epoxy. Finally, the case top is placed into position, and a bead is welded around the periphery using an automated carbon dioxide laser system. The unit is filled with a gas mixture of nitrogen, oxygen, and helium and then hermetically sealed.

Figure 6 is a cross section of the thin films deposited on the substrate. The first layer, photosensitive cadmium sulfide, is deposited on the substrate in a thickness of approximately 1 μm. Doping with cadmium chloride and copper is accomplished, followed by recrystallization in a tube furnace.

Subsequently, nichrome films are deposited, fully defining the active cadmium sulfide areas. Aluminum electrodes are then deposited over the nichrome, except for those areas which are to serve as biased film resistors. Cerium fluoride is deposited over all optically active detector areas to minimize the interaction of water vapor with underlying films. Pads of aluminum and gold are deposited in areas where interfaces with the terminals via conductive epoxy are to be accomplished. A dark, multilayer "solar absorber" coating is deposited over electrodes and inactive spaces separating the various angle and illumination detectors.

Prior to being mounted on the base, the detector substrate and films are subjected to annealing in inert atmospheres for the purpose of stabilizing thin-film contact regions. Grooves are scribed in the thin films, in the inactive areas, to electrically decouple the adjacent angle and illumination detectors. Finally, after encapsulation and hermetic sealing, as described previously, the detector is exposed to a temperature of 65°C to equilibrate oxygen boundary conditions at the thin-film/gas interfaces within the detector.

Experience has shown that the temperature and gas contact history have a significant influence on detector characteristics. Far from being fully determined at the stage where doping and recrystallization are accomplished, detector performance is subject to significant modification by subsequent events. The first post-recrystallization annealing tends to increase cadmium sulfide photoconductive resistance by a factor of 5 to 10. The second annealing tends to decrease this to below the original levels. Exposure to oxygen at elevated temperatures tends to increase resistance, while withdrawal of oxygen (for example, during out-gassing of epoxies) tends to decrease it again.

Even after encapsulation in a sealed atmosphere, elevated temperatures and higher resistance are well correlated. In this connection, none of the changes appear to be permanent or irreversible. Within its range of operating temperatures, the detector's performance tends to return readily to normal following temperature excursions.

IV. DETECTOR ELECTRICAL CHARACTERISTICS

Cadmium sulfide, as processed and encapsulated in this application, has the spectral response shown in Fig. 7. Comparative tests demonstrate little variability among detectors. The photoconductive response, on the other hand, varies considerably. Typical resistance versus illumination characteristics are shown in Fig. 8 for two detectors with acceptable angle detection performance. The higher-resistance detector is not suitable for use in flight hardware because of impedance matching requirements, but its functional performance in the fundamental sense is satisfactory.

Dark resistance of the cadmium sulfide elements ranges upwards of $10^9\ \Omega$ in typical detectors. Detectors with higher resistance when illuminated generally have higher dark resistances. In Fig. 8, the increase of resistance with reduction of illumination is greater at lower levels of illumination than at higher levels. This "gain" factor usually rises above unity in the transition from 1000 $\mathrm{lm/m^2}$ down toward 100 $\mathrm{lm/m^2}$. The importance of this factor is a progressive reduction in sensitivity to stray light as the spacecraft travels farther and farther from the sun. A disadvantage is a more rapid approach to input impedance limits of buffer amplifiers in the sensor electronics.

The idealized transfer function versus an (typical) actual transfer function is shown in Fig. 9. The output, indicated in dc voltage, is intended to represent the result of synchronous demodulation of the derived squarewave signal. The deviation of the actual transfer function from a hypothetical, or idealized, one is less than 1% of maximum output signal over a ±12-deg field of view and less than 2% over the full (±20-deg) field of view. Output at the edges of the field of view exceeds 90% of the maximum applied bias voltage. These characteristics, in conjunction with 24-h repeatability to 0.02 deg, characterize the detector's short-term operating constraints.

V. PROBLEMS ENCOUNTERED

Control of resistance level and resistance uniformity has been difficult and remains a major yield factor. These problems are thought to result primarily from very high sensitivity to copper doping, which is deposited in such small quantities that process regulation is difficult. Other contributing factors may include variability of atmospheric humidity, differences in time of exposure to ambient atmosphere between vacuum depositions, and localized nonuniformities of temperatures during recrystallization and annealing processes. Although expense of implementation prohibits elimination of all such variables, process procedures already encompass a great many steps to minimize these effects.

The solar absorber coating, a multilayer of molybdenum and aluminum oxide, solved stray light masking problems that failed to yield to such approaches as paint and depositions of other materials (vanadium oxide, for one). A limiting factor in solar absorber thickness is the adherence of the underlying cerium fluoride to the next layer down. Cerium fluoride adheres well enough to aluminum, over the electrodes, but not so well to cadmium sulfide. This is the primary reason for the different thicknesses of solar absorber coating, as shown in Fig. 6.

Several types of stainless steel were tried before the right mix of weldability, solderability, corrosion resistance, and immunity to leakage of the case metal itself was found. The cases were machined from bar stock, which tends to form "stringers" of impurities at bar center, providing leakage routes for the encapsulation gas to escape through when the detector is exposed to vacuum. Deposition of metallic coatings (platinum) on the window peripheries was a problem, and certain solder fluxes tended to degrade the high-efficiency antireflection coatings during the window installation procedure (solder reflow in a peanut oil bath).

During qualification testing, it was discovered that the detectors characteristically undergo drastic loss of dark resistance as a result of prolonged dc stress. This produces, at low illumination levels of operation, the same effect as excessive stray light. Impact on angle detection repeatability was severe. The solution was redesign of the sensor to use ac bias and synchronous demodulation, as previously noted.

VI. SUMMARY

The types of developmental problems being encountered are characteristic of new technology applications, and many are solved in the normal course of instrument design. The fabrication of flight detectors is currently under way. Long-term life testing and further evaluation of qualification detectors will provide additional assurance and confidence with regard to the expectation of satisfactory flight performance.

VII. CONCLUSIONS

The wide-angle detector described in this report represents an important addition to any outer planet missions technology inventory. The basic mechanization developed for MJS can be applied to accurately pointing large antennas toward Earth without recourse to moving parts over wide fields of view, and should serve most needs of this kind for several decades to come.

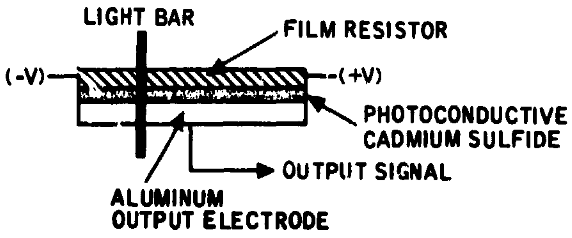

Fig. 1. Conceptual diagram of wide-angle analog sun detector

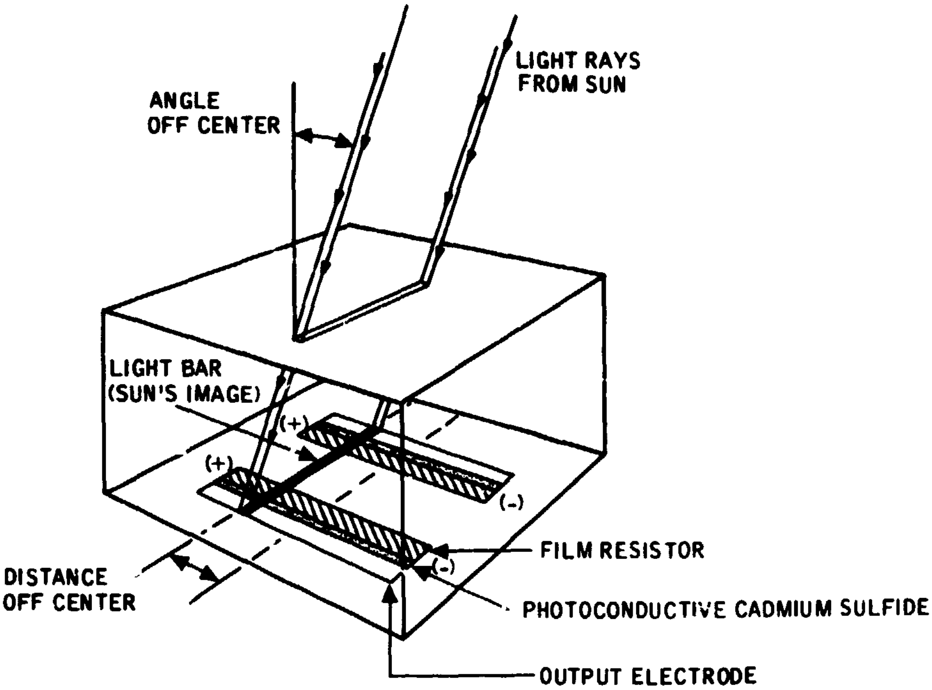

Fig. 2. Optical schematic of wide-angle analog sun detector

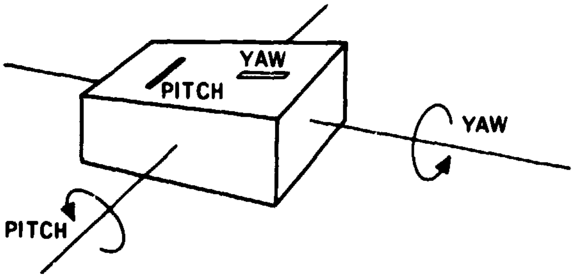

Fig. 3. Orientation of two-axis sun sensor

Fig. 4. Encapsulated detector

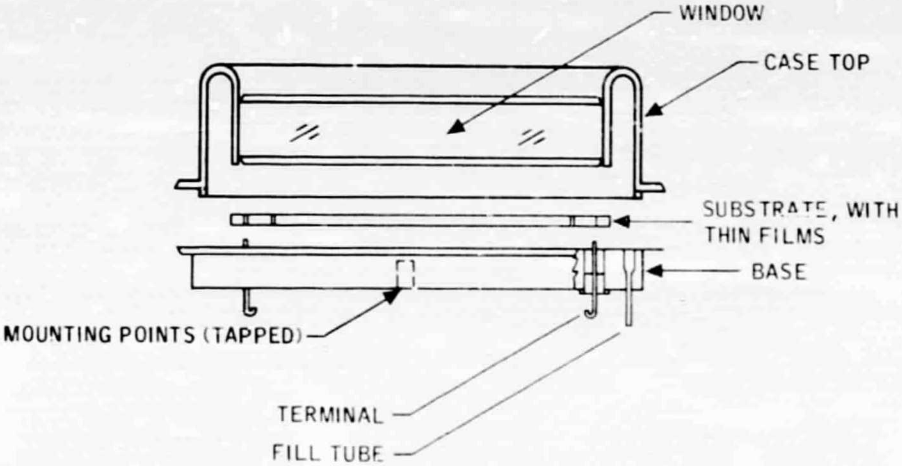

Fig. 5. Sun detector major components prior to assembly

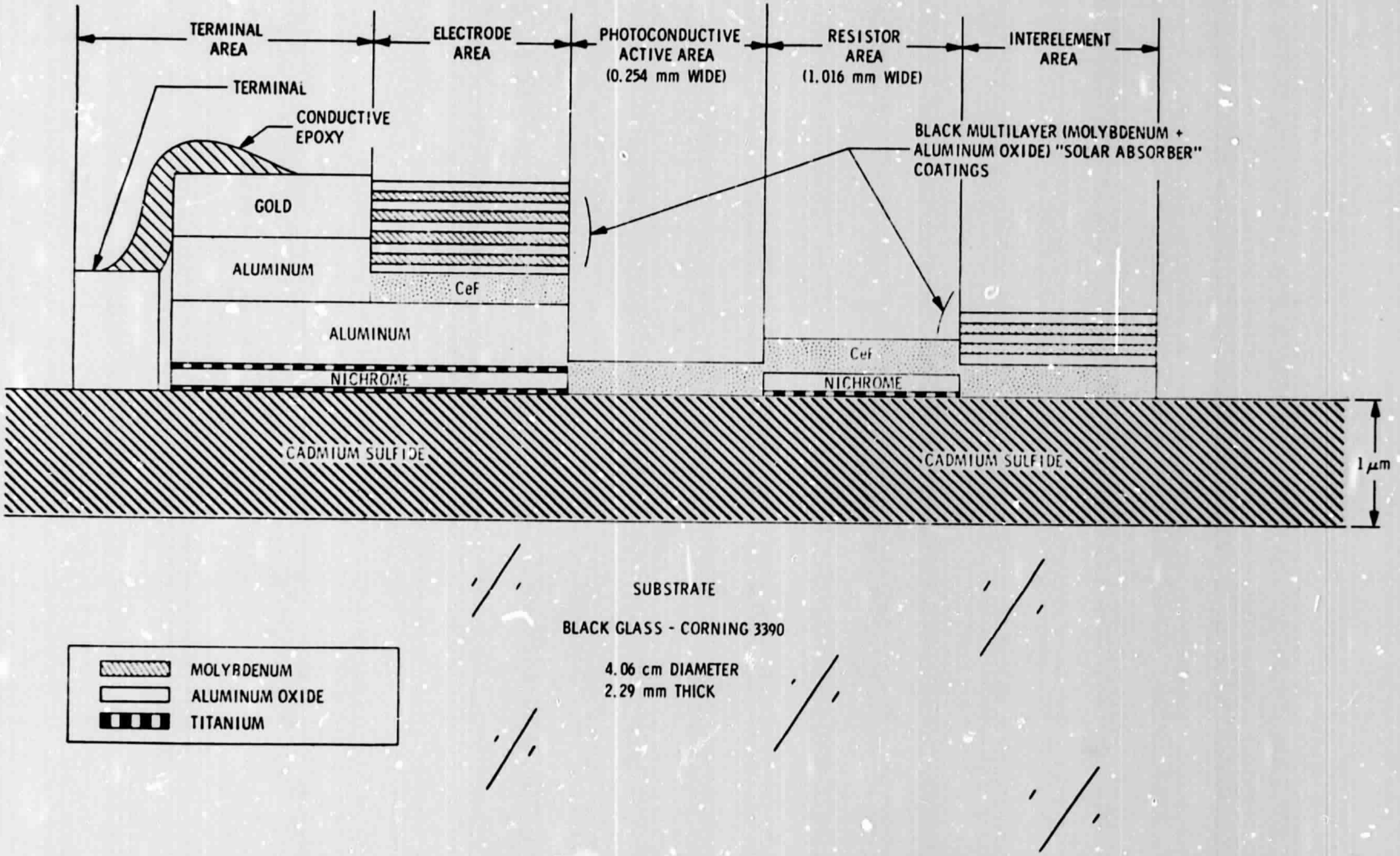

Fig. 6. Thin-film structure of wide-angle sun detector

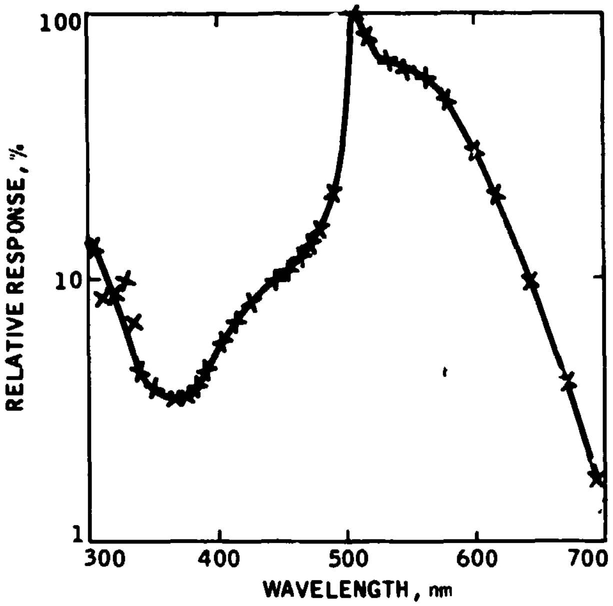

Fig. 7. Spectral response of CdS (sun detector 084)

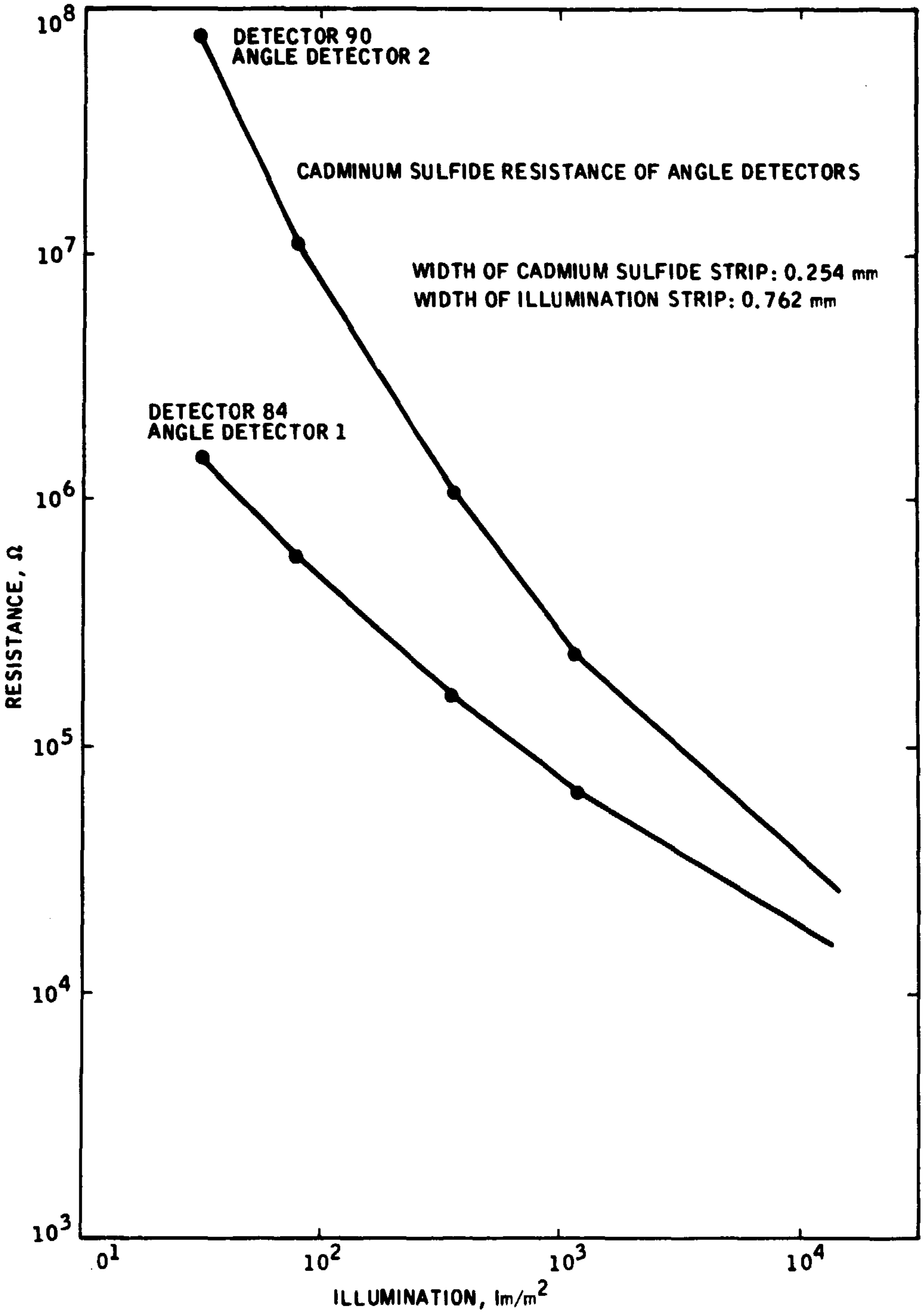

Fig. 8. Cadmium sulfide resistance of angle detectors

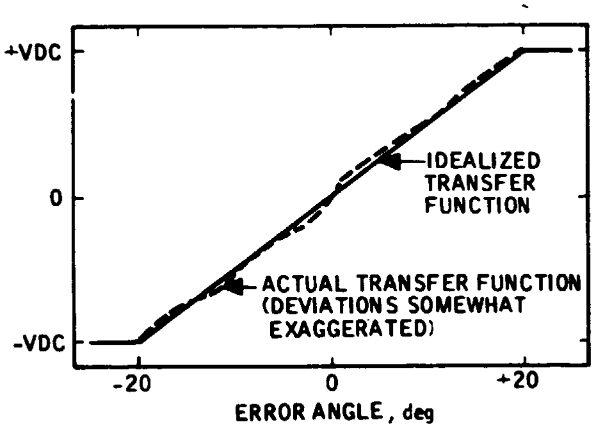

Fig. 9. Output voltage: angle detector