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DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

A SOLAR AUREOLE PHOTOMETER FOR USE IN MEASURING SIZE DISTRIBUTIONS OF PARTICLES IN THE ATMOSPHERE

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Wave Propagation Laboratory
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An instrument used to measure the intensity of near-forward scattered solar radiation as a function of angle is described. This instrument scans a slit-shaped field-of-view over an angular range of 16° centered on the sun's disk. The design parameters were chosen to obtain data suitable for use in deducing the size distribution of atmospheric particles which produce the solar aureole by scattering.

I. INTRODUCTION

Small particles in the atmosphere give rise to enhanced scattering in the near-forward direction. This bright region around the sun is called the circumsolar radiation or the solar aureole. The particles which cause the solar aureole can be classed as lithometeors which are solid particular matter of terrestrial origin, or hydrometeors, e.g., water droplets and ice crystals which compose clouds and precipitation. The angular scattering function for any assumed distribution of spherical particles can be computed using Mie scattering theory assuming a plane wave incident on the particles, ignoring multiple scatter. Conversely, experimental determination of the angular intensity variations allows estimation of the approximate size distribution of the particles suspended in the path (e.g., Hodkinson (1966), Deirmendjian (1970), Green et al. (1971), Post (1976) and Deepak (1977). This brief report describes the design of an instrument intended for use in obtaining suitable angular scattering data and gives sample results of the data. The details of estimating size distributions from the data is a complex question dependent upon many factors and will not be dealt with in this report except as they relate to the design of the instrument.

An attractive feature of the near-forward scattering (also called Fraunhofer scattering) for spherical particles is that the angular scattering function is almost independent of the particle refractive index and depends most heavily on particle size. Thus for monodisperse scatterers, colored Fraunhofer rings are sometimes visible. The effect of grossly nonspherical particle shapes (e.g., needle-shaped ice crystals) is to complicate the analysis and appears to have been dealt with only by approximate methods (e.g., Liou, 1972).

A circumsolar telescope with many automatic features has been described by Grether et al. (1975), and samples of data obtained from this type of instrument are given by Grether, et al. (1976). The latter instrument scans ± 3° from the sun's center and has high angular resolution, i.e., 1.5 minutes of arc out to two solar radii and 5 minutes of arc from there to 3° from sun center. The primary application of the instruments described by Grether, et al. (1975) is to obtain data on circumsolar intensity of use in prediction of performance of solar energy thermal conversion systems using focusing collectors.

The instrument described in this report was designed primarily to make measurements which could be used to infer the size distribution of particles in the atmosphere but should also yield data useful for evaluating solar energy focusing systems.

II. DESIGN CRITERIA

The following criteria were used in designing the aureole photometer:

II.1 Dynamic Range

Even casual observation convinces one that there is a large variation in intensity from viewing the solar disc (or an area very near to it) to viewing an area several degrees away from the solar direction. One of the prime requirements for a solar aureole photometer is, therefore, a dynamic range capable of handling about six decades of intensity. This is manageable using a silicon photodetector as the sensor followed by a logarithmic-response amplifier.

II.2 Relative Accuracy

The requirements on relative accuracy of measured intensities as a function of angle were somewhat arbitrarily chosen to be ± 2% or better. This appears to be attainable without the need for temperature control of the detector. Under most atmosphere conditions (particularly for clouds), variations in the spatial distribution and size distribution of the scattering particles will account for scattered intensity fluctuations of more than a few percent.

II.3 Angular Coverage

The choice of angular coverage is a compromise based on engineering design factors and an estimation of the "information content" in the forwardscatter lobe for particles in the size range of greatest interest. The prototype instrument has an angular range of ± 8° from solar center.

II.4 Angular Resolution

One of the inherent factors limiting the method is the finite angular size of the sun (i.e., diameter 0.5^o). Thus, for a small solid angle viewed near the disc of the sun, the scattered intensity observed is the result of contributions from incremental areas of the solar disc which lie at varying angles from the solid angle being viewed. In theory, it is possible to deconvolve these contributions to obtain an estimate of the scattered intensity which would be observed if the sun's light emanated from a point. The accuracy attainable in such a deconvolution will be limited in practice, and a slit 0.1^o wide was chosen as sufficiently narrow and consistent with a sampling resolution of about 0.1^o near the solar disc. If desirable, the slit width and length can be easily changed.

II.5 Spectral Response

According to Post (1976), the use of data taken at multiple wavelengths can improve deduced size distributions somewhat, particularly if the wavelengths differ considerably. The use of a silicon detector restricts the useable wavelengths to the 0.35 to 1.1 μm range. It was decided to use filters which admit the wavelength ranges 0.38-0.47, 0.48-0.56 and 0.63-1.1 μm, respectively, and an "open" filter which admits the entire 0.35-1.1 μm wavelength range.

II.6 Polarization Response

Post (1976) points out that polarization information can be used to advantage in deducing size distribution from aureole data. This has not yet been tried but could be incorporated quite easily into the instrument design.

II.7 Basic Instrument Design

A number of alternative designs for the aureole instrument were considered: These included the use of (1) in-line, integrated circuit detector arrays, (Mfd. by Reticon); (2) the use of a small moving detector in a fixed optical system; (3) scanning the entire instrument in angle; and (4) the use of a strip detector scanned by a moving aperture. The design chosen was the latter which has the advantages of simplicity and low cost with the penalty of requiring some care to obtain a normalized response with angle. The design criteria described above can be satisfied.

III. DESCRIPTION OF INSTRUMENT

III.1 Mechanical Design

Figures 1 and 2 show section drawings of the instrument. Section C of figure 2 shows the basic geometric arrangement of the scanner and detector. The disc has three slits at angular spacing of 120°. The objective lens projects an image of the sky, with the sun's image positioned to fall at the exact center of the strip detector.

Figure 3 details the intersection of a scanning disc slit and the detector area at ten-degree increments in angular position of the scanner disc. The shape of the area exposed on the strip detector (full size, 6 x 50 mm) is easily changed by masking with black tape. At angular distances greater than one or two degrees from the sun, the rate of change in intensity with angle usually decreases markedly, and the field of view can be larger without sacrificing data resolution. This fact is used to extend the overall, effective dynamic range of the instrument by increasing the detector area exposed at larger angles from the sun.

Because of the rapid change in intensity with angle near the sun, data points need to be recorded at small angular intervals as the region near the sun is scanned and can be sampled at larger intervals at angles farther from the sun, and this type of sampling variation is executed automatically as will be shown below.

Assume Θ to be the angle in the instrument field-of-view, measured from the center of the sun's image. i.e., the scattering angle. The scanner disc rotates at a constant angular rate of ω radians per sec, and the slit in the disc crosses the center of the detector at time t_o. Assume that samples are to be taken at a constant interval in time. The angular orientation of the slit, relative to that at time t_o, is $\alpha = \omega \cdot (t - t_o)$. Assume α to be within ± 60°, i.e., while this particular slit scans the detector once. The distance from the center of the scanner disc to the center of the strip detector is labeled d (figure 3). The distance from the detector center to where the slit and the detector centerline intersect is $D = d \cdot \tan(\alpha)$. For an objective lens having focal length f, the scattering angle observed (in radians) is related to the time by

$$\Theta = \arctan\left[(d/f) \cdot \tan(\omega \cdot (t - t_o))\right] \qquad (1)$$

The prototype instrument used d = 17.5 mm, $\omega = \pi/15$ rad./sec. (12 deg/sec), f = 150 mm.

III.2 Electronic System

The detector is a silicon photodiode of double-diffused structure with dimensions 6 x 50 mm. It is operated in the photovoltaic mode (unbiased) and coupled directly to the input of a logarithmic response amplifier (current

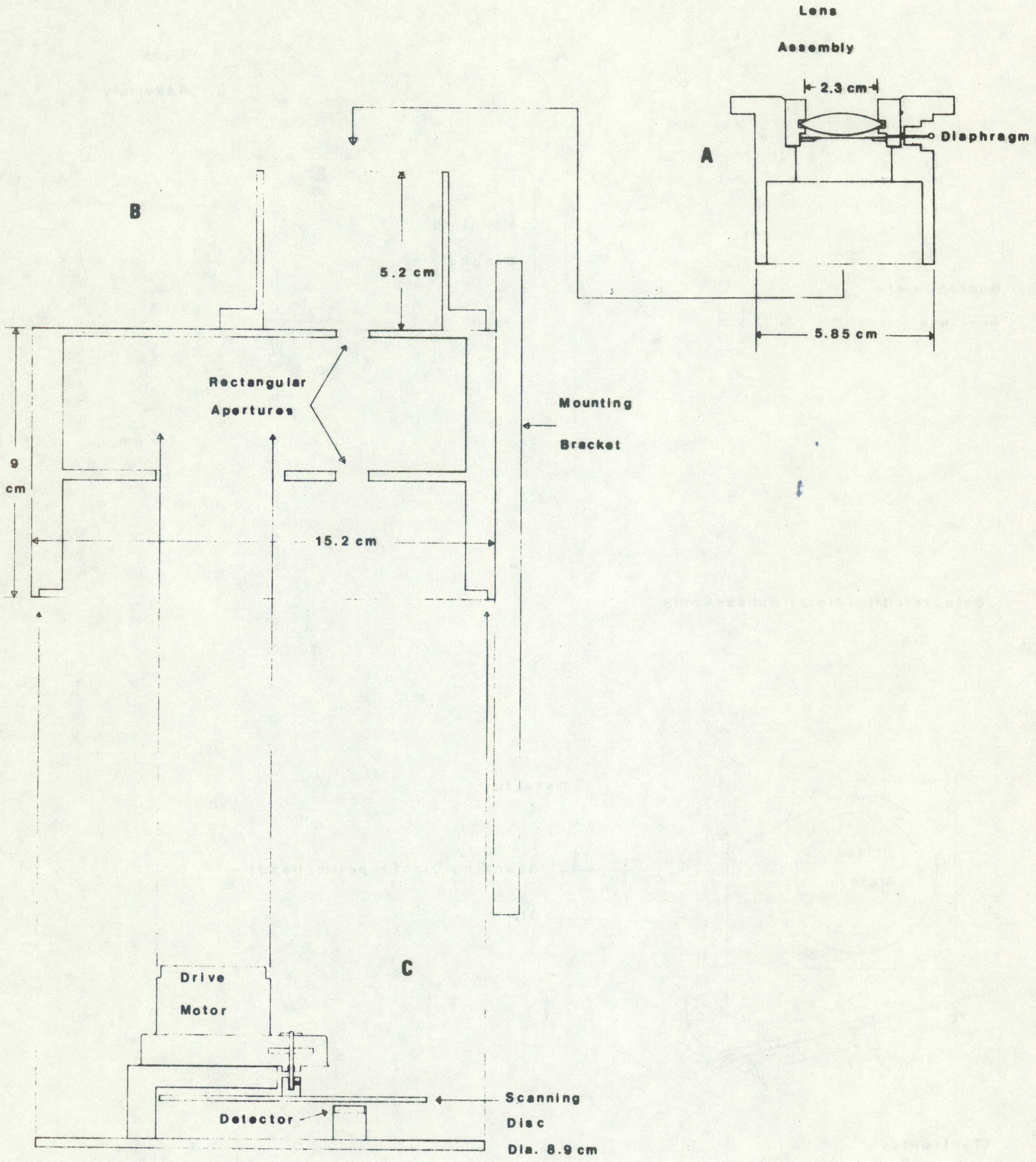


Figure 1. Section drawings of instrument. Longitudinal cut.

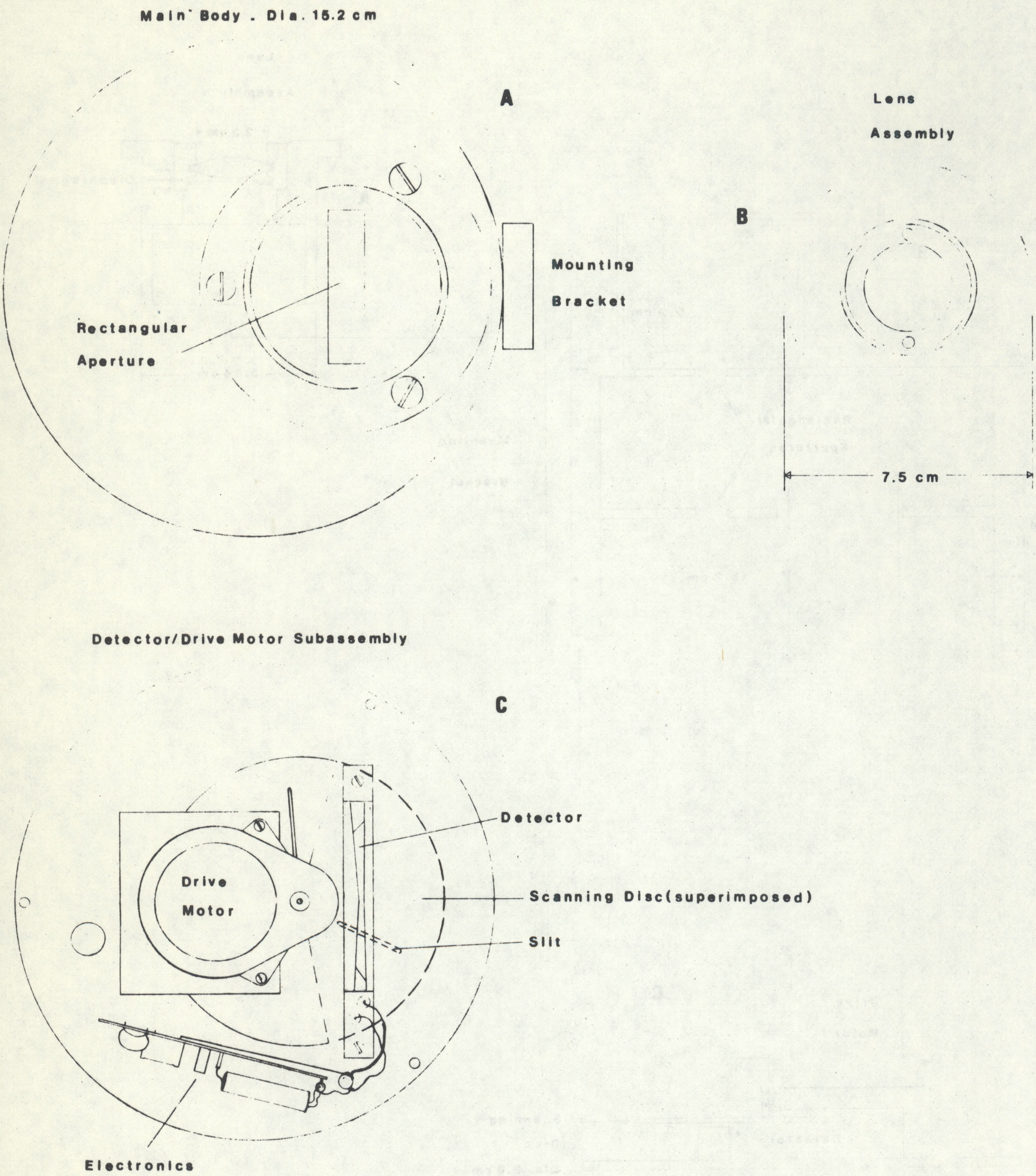


Figure 2. Section drawings of instrument. Three transverse cuts.

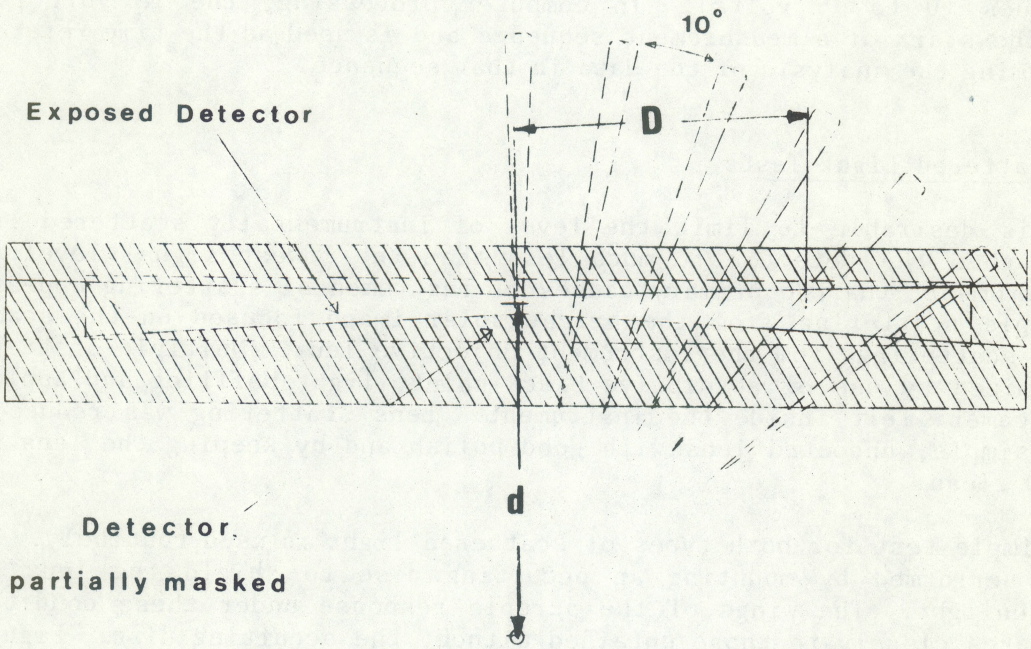


Figure 3. Detail of detector and scanning slit showing detector masking and successive positions of slit at 10° intervals in angle.

input mode). The amplifier response is periodically checked by a current-source calibrator substituted for the detector. A subminiature jack on the outside wall of the instrument enclosure conveniently allows this substitution to be made. Figure 4 shows a plot of the logarithm of input current versus amplifier output voltage.

The beginning of each aureole scan is sensed by a microswitch activated by detents in the scanning disc (3 detents at 120° angular spacing). Microswitches are also used to sense the position of the filter wheel and to advance the filter wheel by 90° (four filter positions are used) at the end of each successive aureole scan. When the filter wheel arrives at the "open" filter position, an 8-volt pulse is produced which is applied to the data channel. This pulse momentarily raises the voltage above the normal range of data values (0 to +5 volts). In computer processing, the +8 volt pulse signals the start of a measurement sequence and is used as the time reference in performing the analysis of the data in that sequence.

III.3 Scattered Light Tests

It is desirable to limit the level of instrumentally scattered light which reaches the detector to much less than the lowest signal level. In this instrument, the two primary causes of instrumental scattering appear to be multiple scattering from the bright solar image focused on the scanner disc and scattering from the instrument objective lens. Multiple scattering was minimized by use of absorptive black paint, light baffling and application of camera felt inside the instrument. Lens scattering was reduced by using a simple, uncoated lens with good polish and by keeping the lens surface very clean.

A simple test for both types of scattered light is used routinely. This test is performed by mounting an occulting disc to shield the lens from direct sunlight. The wings of the aureole response under these conditions are compared closely to those obtained without the occulting disc. Figure 5 shows the results of such a comparison. The black occulting disc decreases by about 5 orders of magnitude the received intensity along the optical axis (where the solar image is normally formed). It also greatly decreases the net amount of light striking the objective lens. The small difference in the aureole wings between the occulted and nonocculted cases is a measure of the instrumentally scattered light. Typically. this difference is not greater than 5×10^{-7} of the non-occulted peak intensity and appears to be acceptable for the smallest scattering levels normally encountered at Boulder. For very low levels of scattering, such as might be encountered at a high mountain site, this instrumental scatter might impose a limitation on the measurements.

III.4 Detector Response Correction

A strip detector inherently varies in response as a function of position along the strip. These variations are manufacturer-specified to be less than

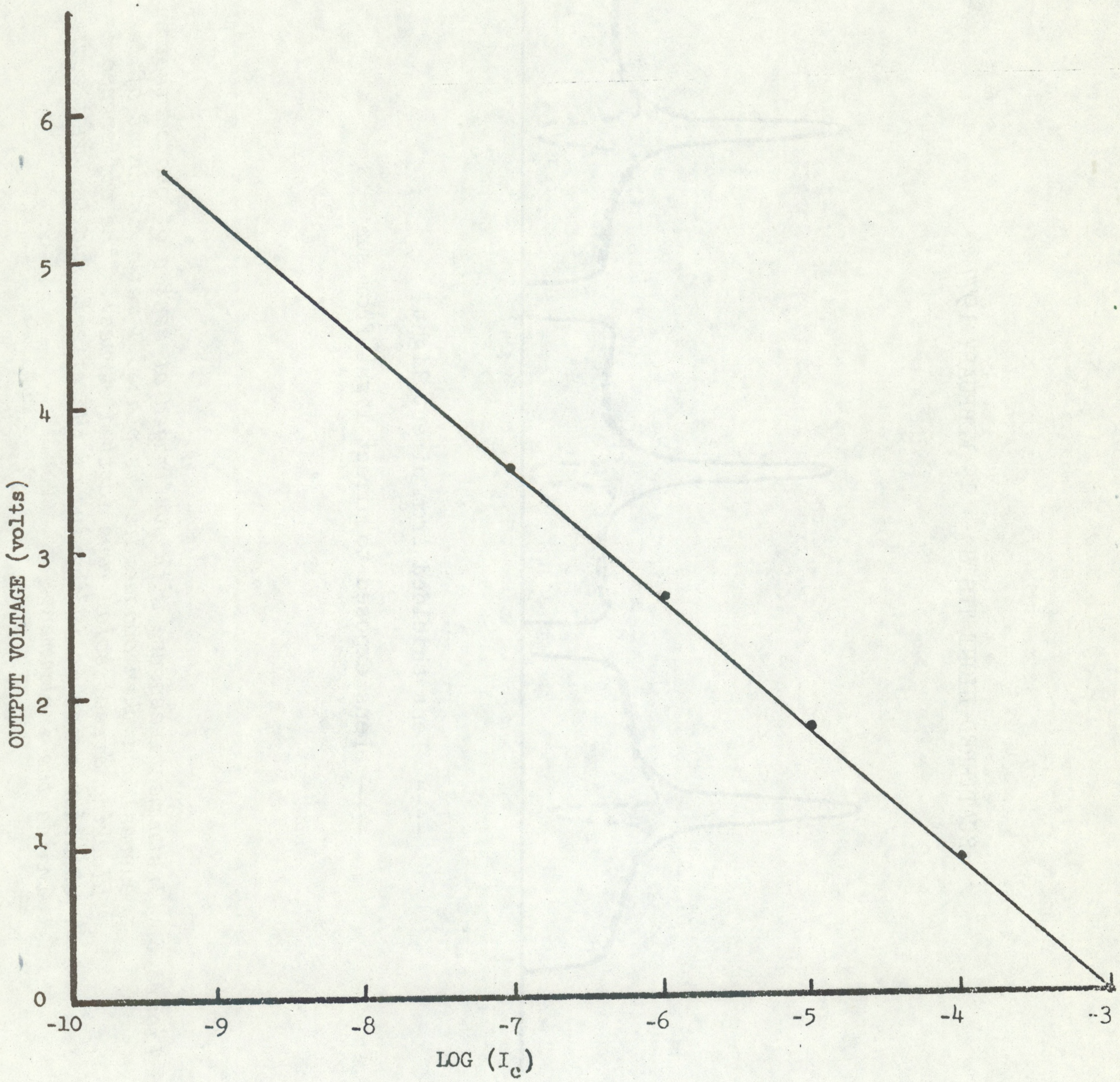


Figure 4. Plot of instrument output voltage as a function of the logarithm of current supplied by a calibrating current source.

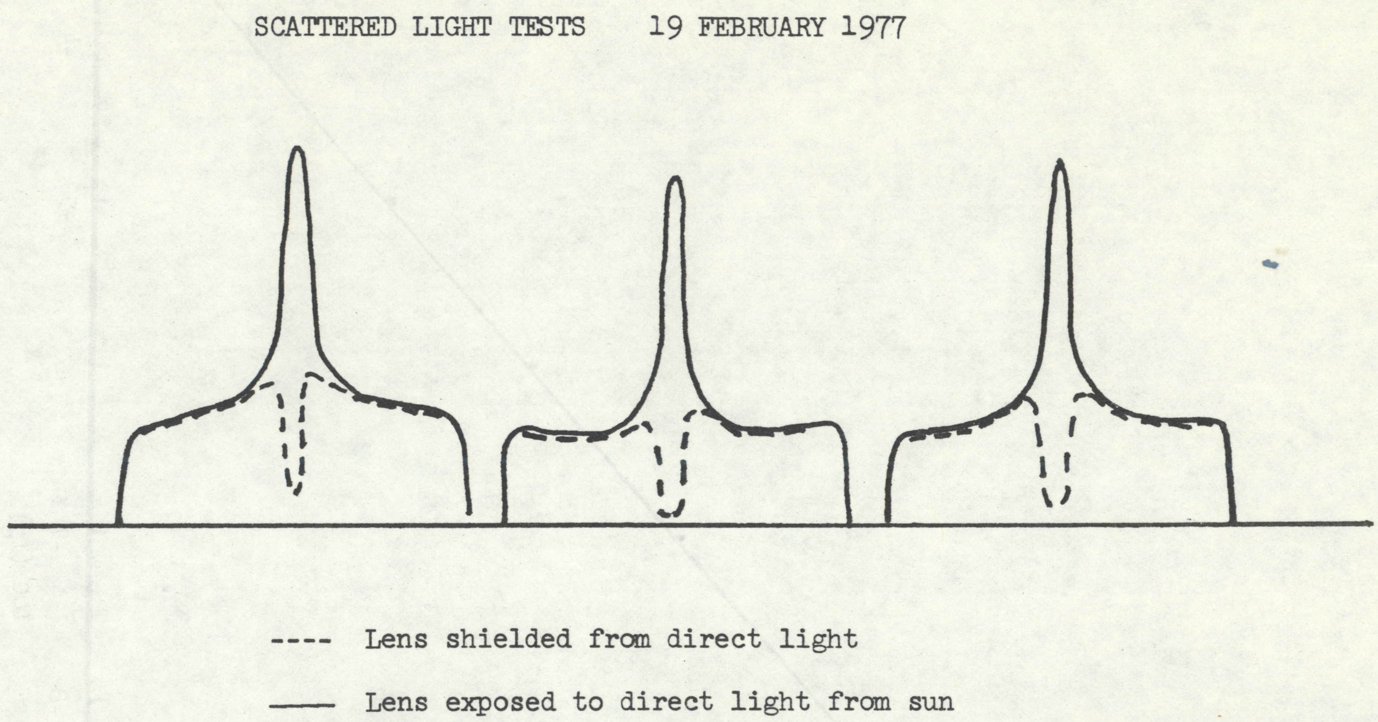


Figure 5. Instrument response with sun imaged at center of photodetector (solid curves) and when opaque disc is placed 1 meter in front of lens, blocking direct solar rays (dotted curves). The difference in the shoulder areas is indicative of the effects due to light scattered inside the instrument.

5%. Superimposed on the detector response variation is the designed-in geometric variation of exposed detector area versus scan position.

These factors are dealt with together, and a composite correction curve is obtained by directing the instrument at a smooth screen painted with omnidirectionally scattering white paint, as indicated in Figure 6. Under uniform clear-sky conditions, the screen is positioned so the sun's rays strike it almost normally. Data is recorded as usual, with the scattering screen being shifted and rotated to several positions between successive scans. By averaging, say 10 to 20 curves the effects of nonuniformities in the scattering surface (either as a function of angular or spatial position) are averaged out.

The composite correction curve, shown in Figure 7, is then applied during computer analysis to the measured aureole data. This procedure normalizes the intensity data across the angular scan range. Experience to date indicates that this correction remains constant to within one or two percent so long as the detector and its masking remain undisturbed.

III.5 Detector Dark Current Correction

The detector dark current is recorded between successive scans. The computer analysis includes subtraction of the dark current from the observed detector current for each scan. The dark current is a function of detector temperature and normally changes slowly with time.

IV. SAMPLE RESULTS

Tests were first conducted with the aureole photometer using the "open" filter, i.e., 0.3-1.0 μm and a scanner disc rotation rate of 2 rpm. An angular scan thus required 10 sec. The detector output was digitized at 10 points per second to yield 100 data points for each scan. The digital processing involves first determining the center of the solar disc by computing the mid-point between the steep sides of the curve as the instrument scans across the solar limbs (points at which the signal crosses the level 0.02 of the peak value). Next, the individual points are each adjusted by the composite correction curve as described in Section III.4.

Figure 8 shows a computer plot of the data for a single scan resulting from this procedure. Note that angular spacing between sample points varies by a factor of about three, although the time rate of sampling for these points is constant, i.e., 0.1 sec/point.

Figure 9 shows four aureole plots obtained for the types of conditions specified in the figure caption. These data were taken in winter with low solar elevations, and the strip of sky scanned was oriented approximately along a vertical plane through the sun. The larger intensity in scattering below the sun (relative to above the sun) is attributable to the greater amount of material in the path of lower elevation angle. This variation in intensity is also observable, by eye, under similar conditions. Deirmendjian (1970) shows theoretical curves which illustrate this effect.

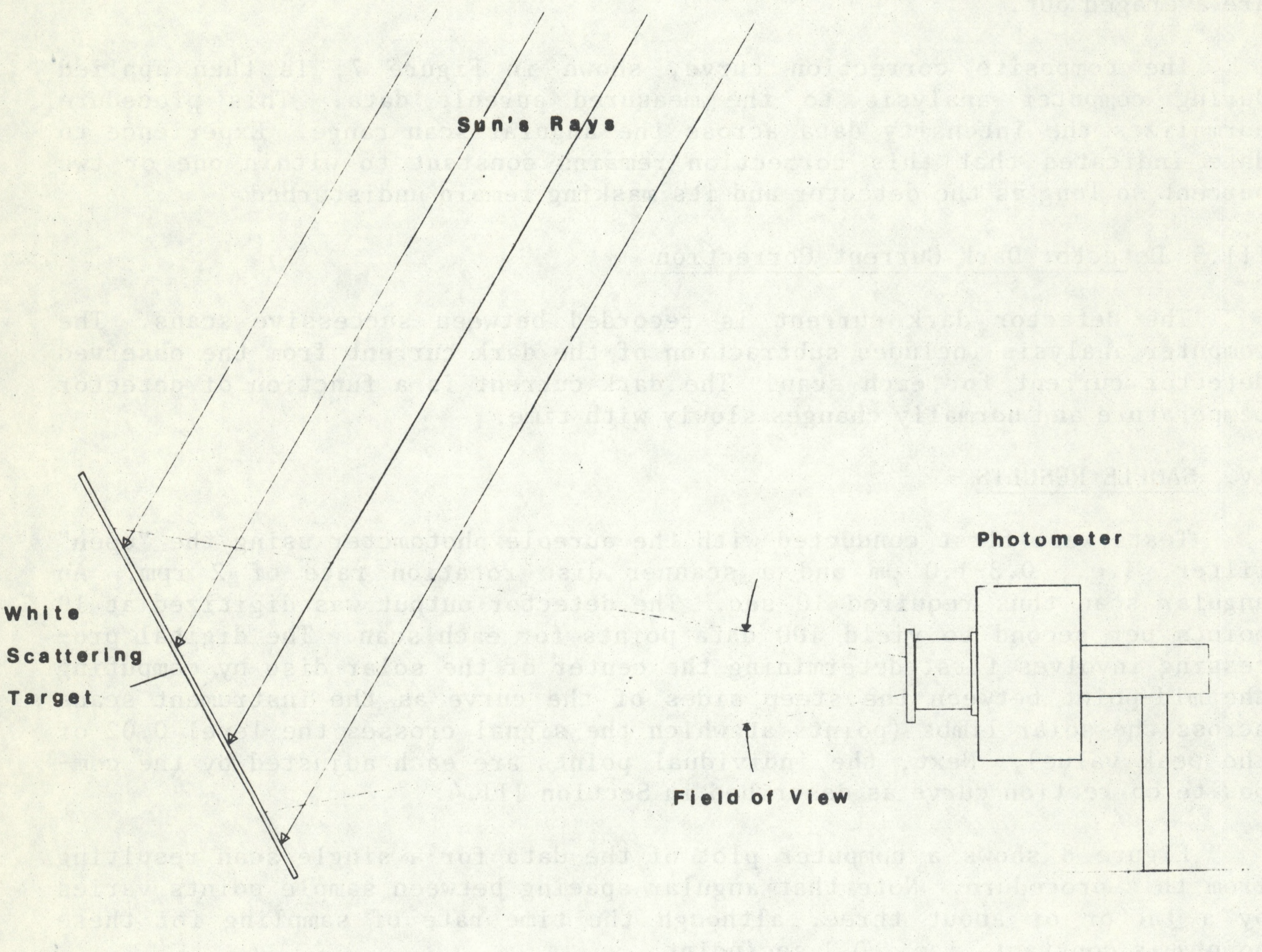


Figure 6. Pictorial diagram showing method of obtaining instrument response as function of viewing angle. The response is used to normalize the angular scattering data during computer analysis.

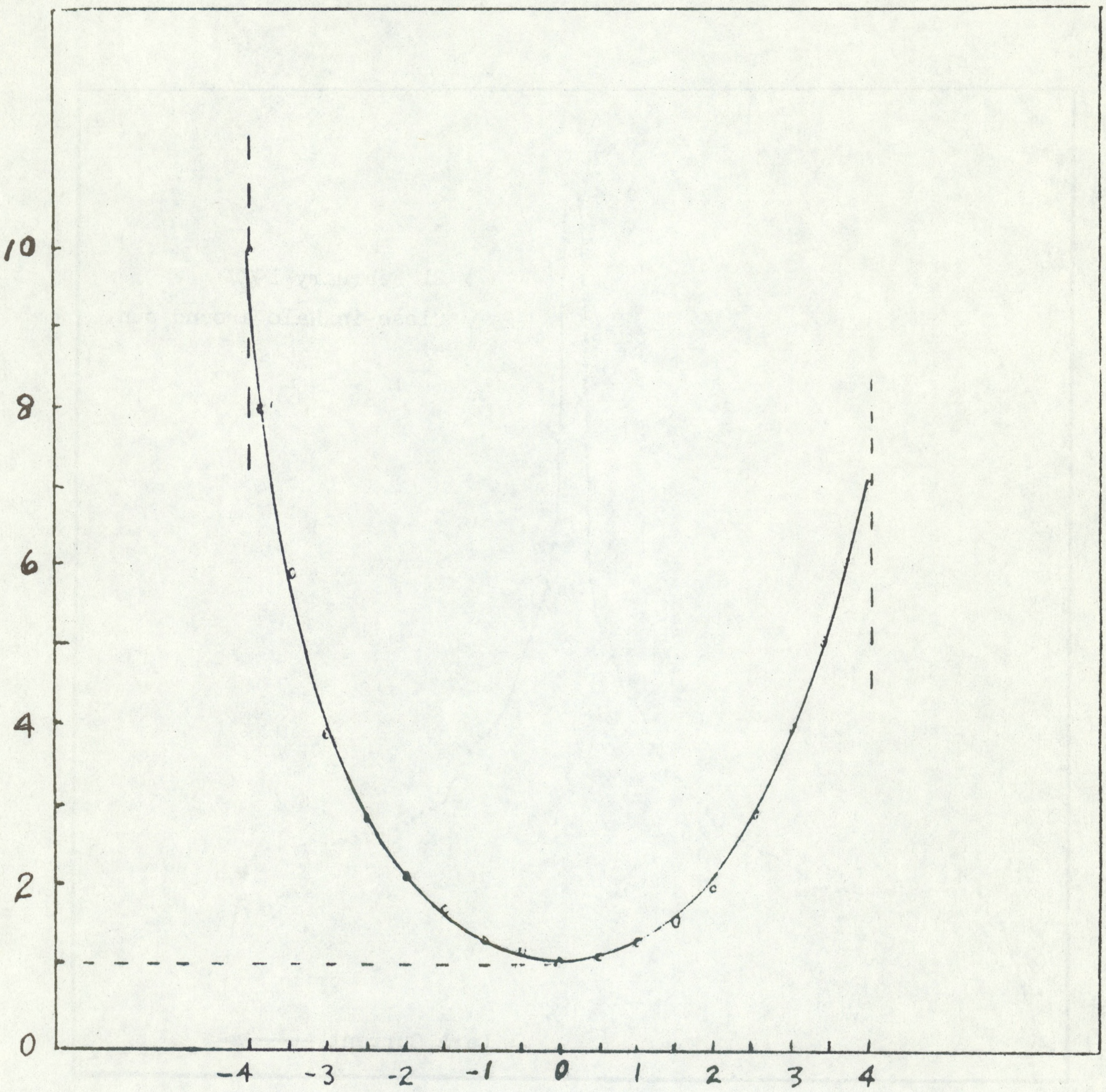


Figure 7. Measured instrument response as a function of time measured from crossing of center of detector. Note that the abscissa is proportional to scan time and is not linear with the angular position of the instrument field of view.

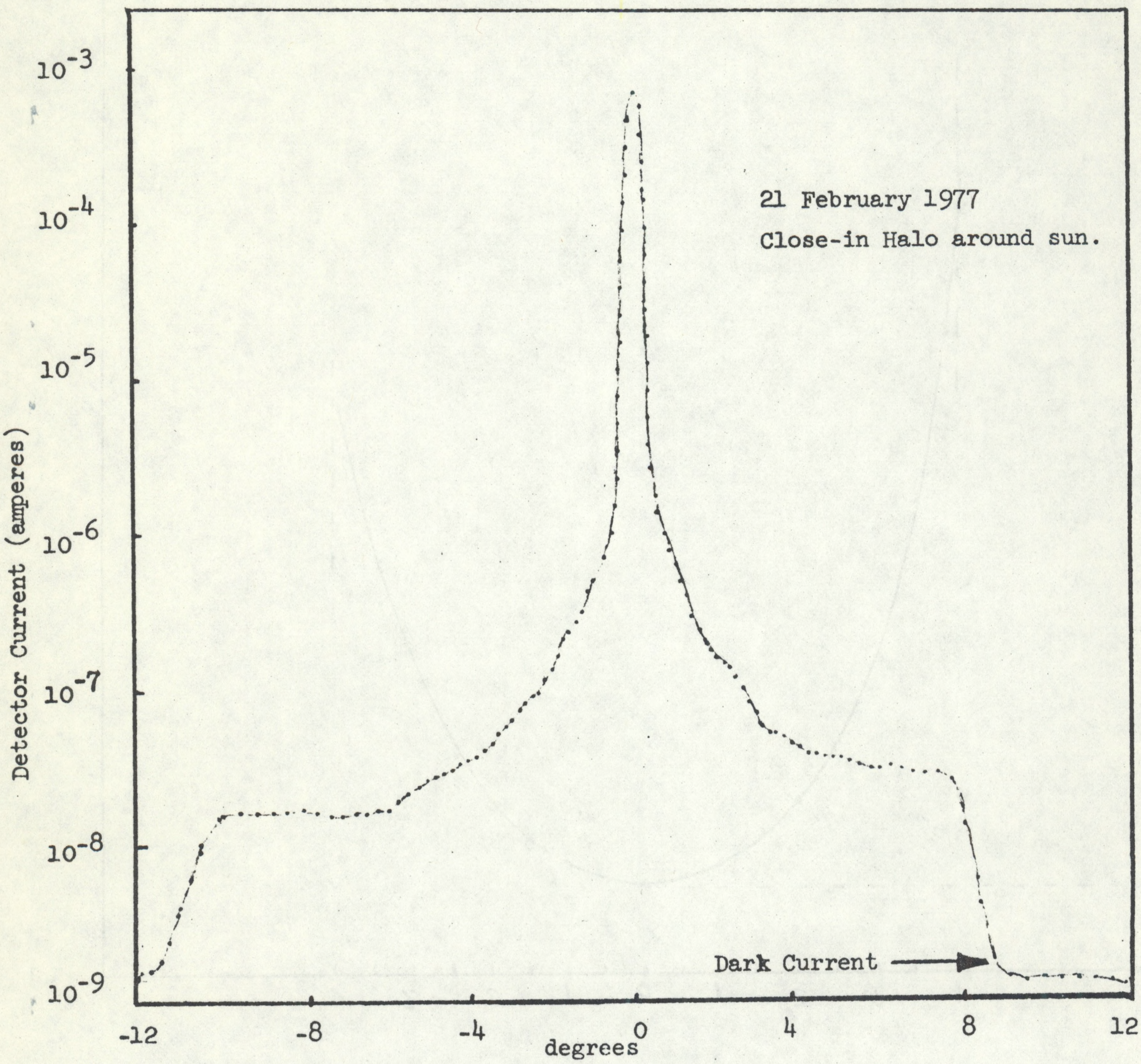
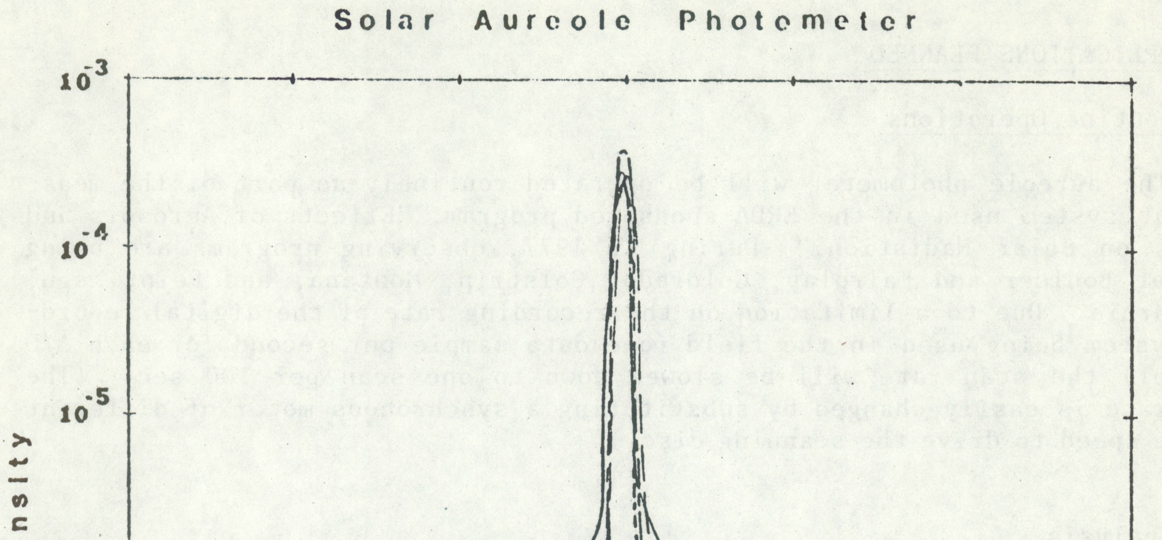


Figure 8. Plot of detector current versus scattering angle with the instrument pointed at the sun. Corrections for instrument sensitivity with respect to scattering angle have been applied.



Key:

1. Thin stratus cloud-halo around sun with red boundary at 3° radius.
2. Mostly clear sky with thin, turbulent wave cloud strands barely visible.
3. Close-in aureole just visible due to very thin stratus clouds
4. Aerosol haze seen out to several degrees.

Figure 9. Examples of angular scattering functions measured under stated conditions.

V. APPLICATIONS PLANNED

V.1 Routine Operations

The aureole photometer will be operated routinely as part of the measurement system used in the ERDA-sponsored program, "Effects of Aerosols and Clouds on Solar Radiation." During FY 1977, observing programs are being done at Boulder and Fairplay, Colorado, Colstrip, Montana, and Point Mugu, California. Due to a limitation on the recording rate of the digital recording system being used in the field (one data sample per second for each A/D channel) the scan rate will be slowed down to one scan per 100 sec. (The scan rate is easily changed by substituting a synchronous motor of different output speed to drive the scanning disc.)

V.2 Analysis

The data will be processed by computer as outlined in Section IV to obtain corrected values of intensity versus scattering angle. It will be necessary to select data suitable for use in the inversion process for size distributions, since most inversion techniques depend on uniformity of scattering material in the scanned field. This selection will be aided by aureole photographs (with the sun's disc occulted), taken once each 15 sec, and by observing the variations of the other photometric instruments which track the sun. The entire body of data should be useful for statistically defining the solar aureole. Sorting the data by type of scattering medium (e.g., aerosols, clouds of differing types, and cloud-aerosol combinations) should be of interest to solar energy systems engineers and may also be of scientific interest. The photographic aureole data will be especially useful in proper identification of cloud types and geometry.

Combined analyses of aureole data and multi-wavelength, narrow beamwidth photometric data collected simultaneously appear to offer advantages in particle size determination. This complementary relationship is due to the fact that the aureole method gives the best results for particles having large sizes compared to the measuring wavelength, while the narrow beamwidth transmission measurements have the best sensitivity when the measuring wavelength is about one-third the particle diameters. The transmission measurements are made over a wider range of wavelengths than are the aureole measurements (0.3 to 10 μm) resulting in an overlapping in the ranges of applicability of the two techniques. It is planned, therefore, to investigate the possibility of improving estimates of size distributions by combined analyses of these two techniques. Other types of data are also available (e.g., lidar and in-situ collection of particulates) and these will be used to check the validity of the particle size determinations.

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