Sky Brightness Photometer

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A Sky Brightness Photometer has been developed at the National Center for Atmospheric Research to make continuous measurements of atmospherically scattered light at a position close to the edge of the solar disk. The instrument was designed for use in field operations at remote, high mountain sites where skies are exceptionally clean and the scattered light intensity is low. The photometer provides reliable, drift-free measurements for long periods of time, and requires minimal shelter and logistic support. Two prototype instruments were built and tested at NCAR; detailed test results are presented in this report.

Although the photometer was developed primarily to aid in the selection of optimal viewing sites for observations of the solar corona, other uses are possible. The design of the instrument's optical and electronics systems may be helpful to workers involved in similar developmental projects.

The photometer was developed and tested while the authors were staff members of the Program on Applications Analysis, a division of the Facilities Laboratory until 1969. The instrument is now used by the High Altitude Observatory. Minor changes in the text and in some of the calibration figures, made in consultation with the authors, reflect recent testing results.
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CONVENTIONS USED IN FIGURE LABELS

1. Prefixes to identification numbers indicate electronic component equipment type:

A - amplifier
B - plug-in circuit board
J - jack or socket
K - relay

P - plug
R - resistor
S - switch
TS - terminal switch

2. Identification numbers indicate component location within the photometer electronics system:

100-199 spar electronics
200-299 clamp and overload module
300-399 logarithmic amplifier
400-499 relay detectors and synchronization
500-599 difference amplifier and low-pass filter
600-699 power and control chassis

3. Within each signal-processing module, sockets and plug-in units are numbered from front to rear.

4. All components enclosed by a dashed line are on the same plug-in board. The following diagram illustrates circuit board B101 and its active pins.
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PART ONE

PHOTOMETER DESIGN DEVELOPMENT

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I. DESIGN OBJECTIVES

The Sky Brightness Photometer was designed to determine the ratio of scattered sky light intensity to solar disk light intensity with less than 10% measurement error. This accuracy must be maintained for ratios as low as $2 \times 10^{-6}$. To avoid the introduction of critical error levels by scattering within the instrument itself, the design required reduction of light diffracted from the entrance apertures and shielding devices to a value of less than $0.2 \times 10^{-6}$ the value of the solar intensity.

The light spectrum of greatest interest for sky-to-sun-brightness ratios lies between 4000 and 6500 Å; in this region Mie scattering contributes the variable component of light scatter. The photometer should ideally be capable of accurate measurement at selected wavelengths throughout this range.

Current knowledge of boundary-layer flow and higher altitude turbulent mixing indicates that particle concentration, and therefore scattering intensity, is highly variable with time. To provide statistically meaningful light intensity data, the photometer must therefore make rapid measurements for extended periods of continuous operation.

Simplicity of operation was the dominant design criterion. This requirement necessitated a restriction of measurement angle in the configuration which was ultimately adopted. (The prototype instrument cannot measure closer than $1.5 R_\odot$ [24 arc min] from the solar limb and still maintain low instrumental scatter. At its base alignment position the instrument measures $1.8 R_\odot$ from the limb.) The need to use the photometer at remote sites also necessitated a design allowing disassembly into loads transportable by two men over rough terrain.

The need for automatic, accurate, and continuous sun tracking required a solar guiding system capable of: (1) tracking accuracy of at least 1 arc min, (2) operation at cold temperatures, and (3) adjustable guiding alignment of the photometer spar relative to the sun. The solar guiding system used in the prototype units is one of several types available commercially.
II. DESIGN DESCRIPTION

The Sky Brightness Photometer (Fig. 1) consists of two units: an optical system and an electronics rack. The optical system and two pre-amplifiers are mounted on a commercial equatorial mount and sun tracker (spar). A separate electronics rack cabinet contains a signal-processing system, control circuits, and power supplies.

The optical system employed is the simplest design which will maintain acceptable internal scatter levels. The use of lenses has been deliberately avoided since their degree of cleanliness strongly influences light scatter, an important consideration for extended operation at remote sites.

The photometer makes comparative measurements of sky brightness and attenuated sun brightness.* Such comparative measurements eliminate errors in sky brightness readings caused by the diurnal variation in air mass, and reduce the possibility of electronic gain change and drift error inherent in absolute measurements.

The comparative sky and sun measurements are made alternately during the observation period. The light sensor is exposed to the flux from the sky, and then to the flux from the sun; the sequence is repeated 20 times/sec. This necessitates only one light-sensor- and gain-inducing-amplifier chain, and any occurrence of electronic gain change or drift is common to both measurements. The smoothed logarithmic ratio of indicated sky- and sun-brightness values is formed to cancel the effect of common error. The photometer displays output voltages proportional to this smoothed log ratio.

* All future references to sun brightness will mean attenuated sun brightness.
Fig. 1 Complete Sky Brightness Photometer assembly, with the electronics rack cabinet at left, and the commercial spar supporting the photometer optical system at right.
A. OPTICAL SYSTEM

The photometer's optical system (Figs. 2 and 3) consists of two identical 400 mm tubes, each equipped with 0.80 mm entrance and exit apertures. Internal baffles reduce tube wall reflection. This combination of aperture size and aperture separation defines a geometrical field of view $4 \times 10^{-3}$ rads diam.

The tubes are mounted rigidly on the sun-tracking spar, one above the other, with their optical axes forming an angle of $13 \times 10^{-3}$ rads. This angle must be rechecked following any lengthy transport of the instrument. When the axis of the lower (sun) tube is aligned with the center of the solar disk, the axis of the upper (sky) tube is aimed at a point $1.8 R_0$ above the solar limb. In front of the sun tube is an opal attenuating filter, and in front of the filter is a short tube that limits the filter's field of view to $10^\circ$. The path between the filter and the entrance aperture of the sun tube is enclosed to prevent light scatter into the sky tube and back-illumination of the opal.

In front of the sky tube are three knife edges positioned on the spar along the optical axis of the sky tube 99.6, 77.0, and 57.0 cm from the entrance aperture; they shield the entrance aperture of the sky tube from direct solar rays and are adjusted to minimize the amount of diffracted light falling into the entrance aperture.

Behind both tubes (Fig. 4) is a shaft driven by a synchronous motor. On the shaft is a shutter assembly with three shutters, as illustrated by the enlarged detail of Fig. 3. The top shutter provides a synchronization signal, and the lower two control the sky- and the sun-tube light paths. These last two shutters are aligned to block one tube whenever the other tube is passing light to the signal-processing system. Each light channel is sampled 20 times/sec, and both channels are blocked for $1.5 \times 10^{-3}$ sec between samples.

Behind the shutters are two fiber optic bundles, one for the flux from the sky tube, and one for the flux from the sun tube. The bundles convey the light from the shutters to a 1P21 photomultiplier (PM) tube used as the light sensor. Selective wavelength filters can be installed.
Fig. 2 Optical system and associated electronics. (Protective shroud is removed for illustration purposes.) The sun-tracking components of the support spar are indicated.
Fig. 3 Schematic representation of the optical system and associated spar-mounted electronics.
Fig. 4 Interior view of the spar-mounted housing at the rear of the optical system.
in a holder mounted along this path. A box to hold the PM tube preamplifier and the synchronization amplifier is mounted on the side of the shutter and PM tube housing.

The fiber optics bundles are flexible, but can be mounted firmly at each end; thus they greatly simplify maintenance of sky- and sun-tube alignment with the PM tube. The half-power points of angular light distribution at the entrance and exit apertures of the fibers are \( \pm 30^\circ \) from the optical axis; consequently, any light falling on the entrance aperture of the bundle will be spread angularly at the exit aperture, and will illuminate the whole photocathode of the PM tube. This function of the fibers is analogous to that of the field or Fabry lens in stellar photometers. Since the bundles are random, i.e., non-image transmitting, variations in brightness distribution over the entrance aperture will be smoothed out at the exit aperture.

B. ELECTRONICS SYSTEM

A block diagram of the photometer's complete electronics system is shown in Fig. 5. The principal components are a PM tube preamplifier, a precision dc clamp (restorer), a logarithmic amplifier, relay detectors with their associated synchronization and driver circuits, a difference amplifier, and an active low-pass filter.

The PM tube preamplifier is in a box fixed to the optical system electronics housing on the spar (Figs. 6 and 7). It is a high-quality, current-compensated operational amplifier used as a current-to-voltage transducer. In this configuration the PM tube works into the virtual ground presented by the summing point of the amplifier; i.e., the amplifier acts as a nearly perfect current sink, assuring linear PM tube operation over a wide range of light inputs. The current-to-voltage conversion is determined by a single resistor, mounted on a plug-in circuit board.

Associated with the preamplifier is another operational amplifier used as a non-inverting, unity-gain follower, and serving as a cable
Fig. 5 Block diagram of the complete electronics system with representative wave forms indicating significant test points of light-signal processing.
Fig. 6 Interior view of the spar-mounted electronics housing.
Fig. 7 Circuit diagram showing preamplifier, follower, and synchronization amplifier for the spar-mounted electronics system.
driver. The synchronization signal is derived from a silicon solar cell and amplified by a third operational amplifier, with a voltage gain of 50, mounted in the box on the optical system housing.

A rack cabinet (Fig. 8) houses the remaining electronic components. Arranged from bottom to top are units containing the high voltage supply for the PM tube, the low voltage supplies and control circuitry for automatic switching between battery and ac operation,* and the signal-processing system.

The signal-processing system is made up of four modules; the signal flows from left to right when the rack is viewed from the front. The first module contains an overload circuit and the precision dc clamp (Figs. 9 and 10). The signal from the light sensor is fed to both the overload circuit and the clamp in parallel; the overload circuit turns off the PM tube high voltage supply whenever output from the preamplifier exceeds \( \sim 10 \text{ V} \).

It will be recalled that the photometer shutter is designed to block all signals from the PM tube periodically for \( 1.5 \times 10^{-3} \text{ sec} \). The sensor output signal therefore includes voltage samples proportional to the dark current of the PM tube as well as samples proportional to sky and sun brightness. The dc clamp serves to remove the dark current voltage from the signal by clamping the signal to ground during the interval in which the dark current is sampled.

The second signal-processing module (Figs. 11 and 12) contains a logarithmic amplifier whose transfer function is

\[
E_o = K \times \log_{10} \left[ \frac{I_{\text{ref}}}{I_{\text{in}}} \right]
\]

*Battery operation is used to warm the electronics but not for actual measurements.
Fig. 8 Front view of the electronics rack showing the four modules of the signal-processing system, the low voltage supply and control circuits, and the high voltage supply unit.
Fig. 9 Interior view of the dc clamp and overload circuit module of the signal-processing system located in the electronics rack cabinet.
Fig. 10 Circuit diagram of the dc clamp and overload circuit (first module of the signal-processing system).
Fig. 11  Interior view of the logarithmic amplifier module of the signal-processing system.
Fig. 12 Circuit diagram of the logarithmic amplifier module of the signal-processing system.
where $I_{in} = E_{in}/R_{in}$. The variable $E_o$ denotes output voltage, $K$ an adjustable gain factor, $E_{in}$ and $R_{in}$ the input and resistance voltages, and $I_{ref}$ an adjustable reference current. Departures from this transfer function are $<1\%$ of its absolute value for $\sim 4\frac{1}{2}$ decades of input signal voltage ($I_{ref} = 1 \times 10^{-4}$ amp, $R_{in} = 100,000 \ \Omega$, $K = 1 \ \text{V/decade}$).

The signal from the dc clamp passes through the logarithmic amplifier to the third module, which contains relay detectors and their synchronization and switching circuits (Figs. 13 and 14). The relays are high-speed, mercury-wetted contact types with a life expectancy of at least $2 \times 10^8$ operations. Timing of the relays is adjusted so that the log voltage samples from sky measurements are passed to one output terminal of the module, and log voltage samples from the sun to a second output terminal. During the time the signal is clamped to ground, both output terminals are grounded.

The fourth module of the signal-processing system contains the difference amplifier and the active low-pass filter (Figs. 15 and 16). The two signals from the relay detectors in the third module are applied to the input terminals of the difference amplifier; its output in turn is connected to the input of the third-order Butterworth filter. The cutoff frequency of the filter is selectable from 0.15 to 10.0 Hz through the use of appropriate resistors on a plug-in circuit board.

The voltage at the non-inverting input terminal of the difference amplifier is

$$E_{sun} = K \times \log_{10} \left[ \frac{I_{ref}}{i_{sun}} \right]$$

The voltage at the inverting input terminal is

$$E_{sky} = K \times \log_{10} \left[ \frac{I_{ref}}{i_{sky}} \right]$$
Fig. 13 Interior view of the synchronization and relay detector circuits module of the signal-processing system.
Fig. 14 Circuit diagram of the synchronization and relay detectors.
Fig. 15 Interior view of the difference amplifier and low-pass filter module of the signal-processing system.
*All unspecified resistors are mounted on a single card and their respective pin numbers are circled, as

Their resistance values are determined by the desired cutoff frequency: \( \omega = \frac{1}{R} \)

Example: \( f_c = 2 \text{Hz} \)
\[
R = 79.6\text{K}\Omega, \; 2R = 159.2\text{K}\Omega, \; \frac{R}{4} = 19.9\text{K}\Omega
\]

Fig. 16 Circuit diagram of the difference amplifier and low-pass filter.
(The variables $i_{\text{sky}}$ and $i_{\text{sun}}$ denote currents at the log amplifier summing point.) The output voltage of the difference amplifier is

$$E = E_{\text{sun}} - E_{\text{sky}} = K \times \log_{10} \left[ \frac{i_{\text{sky}}}{i_{\text{sun}}} \right]$$

The low-pass filter removes any ripple from this signal and reduces output noise levels produced when optical wavelength filters, which severely limit the operation of the PM tube, are employed.
III. PERFORMANCE TESTS

The photometer's response and accuracy are directly related to four instrument characteristics:

- Optical system field of view
- Instrumental scatter or "optical noise"
- Drift and linearity
- System noise vs optical signal wavelength

Results of tests to evaluate the influence of these parameters on the performance of the prototype instrument are described in this chapter, Sects. A-D. An error analysis of the electronics system is found in Sect. E.

A. OPTICAL SYSTEM FIELD OF VIEW

The photometer's effective field of view was defined by determining the relative amounts of light transmitted through the sky- and sun-tube apertures as a function of the angle from the optical axis.

The spar was driven so that the optical axis of the aperture being tested crossed a pinhole light source (the other aperture was covered). The log amplifier was disengaged and a jumper was used to connect the dc clamp output and the relay detectors for linear operation of the electronics system. As the photometer swept across the light source, the varying voltage of system output was monitored on a strip-chart recorder.

The clock drive mechanism of the spar-guiding system directed the photometer across the light source at a known angular rate (15 arc sec/sec). Recorder chart speed was also known, and relative signal response vs aperture axis angle could be read directly from the chart. Table 1 gives typical field-of-view test results for the 0.80 mm apertures, 400 mm apart.
Table 1
PHOTOMETER FIELD OF VIEW VS MEASURED LIGHT INTENSITY

<table>
<thead>
<tr>
<th>Angular diameter of field relative to maximum light intensity viewed (min)</th>
<th>Signal output (db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>-3</td>
</tr>
<tr>
<td>6.6</td>
<td>-6</td>
</tr>
<tr>
<td>10.0</td>
<td>-16</td>
</tr>
<tr>
<td>14.75</td>
<td>-40</td>
</tr>
</tbody>
</table>

B. INSTRUMENTAL SCATTER

Using a light-scatter calibration curve derived for the prototype photometers, the three knife edges shading the sky tube were adjusted to produce minimum instrumental light scatter. Once the knife edges were positioned, tests were made to determine the relationship between instrumental scatter and the angular distance from the center of the light source to the actual point of light measurement. The sensitivity of light-scatter levels to changes in knife-edge position was also measured.

For scatter tests, a laboratory "sun" was synthesized with a ribbon filament lamp and a lens aperture system. The lamp was focused on the first knife edge* to form an image ~1 cm high and 5 cm wide at that spot. The exit aperture of the light source subtended an angle of 10 mrad when seen from the first knife-edge position. The increase in source size over true solar image size compensated for the relatively small distance between the source and the photometer. To

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*The knife edges are numbered in order of increasing distance from the light source.
facilitate aiming, four pinholes were drilled above the main source aperture. The angles between the pinholes and the center of the main source aperture (when viewed from the first knife edge) were 1.5, 2.0, 2.5, and 3.5 source radii, respectively.

The lamp was powered by an adjustable, well-filtered dc supply to eliminate ripple; a solar cell and a precision high impedance voltmeter were used to keep the light source output constant for all measurements.

During all light-scatter tests, the log amplifier was again disconnected, and a jumper placed between the dc clamp and the relay detectors. The sun-tube channel was blocked so that all measurements were made against the PM dark current. An integrator, with a time constant of \( \sim 1 \text{ V/sec} \), was connected to the system output, and was followed by an accurate voltmeter.

Calibration

The relationship between incident light and photometer output voltage was determined by making at least ten 1 min integrated output voltage measurements with each of several calibrated diffuse filters placed at the first knife-edge position in the sky channel optical path. Filter transmittances ranged from \( 10^{-4} \) to \( 10^{-6} \), and the resulting curve displaying mean output voltage as a function of filter transmittance was used to determine scattered light levels in all subsequent tests.

Knife-Edge Positioning

With all three knife edges depressed, and only the 2.0-radii pinhole aperture uncovered, the sky channel axis was adjusted until maximum voltage output was obtained. Thus the center of the area measured by the photometer sky channel was 2.0 source radii from the actual center of the light source. For the remainder of the procedure the main source aperture was uncovered and the pinholes blocked.

With the second and third knife edges depressed, the first was raised to a very high position perpendicular to the optical axis. The
optical path was completely blocked and very low system output was obtained. The knife edge was lowered, and system output voltage passed through a local maximum as the diffracting edge became centered in the field of view. As the edge was lowered further, output passed through a local minimum; the knife edge was locked in place at this position.

The same procedure was followed to position the second and third knife edges, always leaving the preceding edges in position. A series of integrated output readings was made, and the average result was compared to the calibration curve to obtain the relative light scatter for that set of knife positions.

Once the knife edges were adjusted for minimum scatter, with the sky tube measuring the intensity of light 2.0 source radii above the source center, measurements could be made to determine instrumental scatter for other angular separations. The pinholes drilled in the light source aperture cover were used to aim the photometer by the same method used for the 2.0 radii pinhole. Table 2 shows results of these measurements.

Table 2

<table>
<thead>
<tr>
<th>Angular separation measured in source radii</th>
<th>Instrumental scatter relative to incident flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>$1.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>2.0</td>
<td>$7.4 \times 10^{-6}$</td>
</tr>
<tr>
<td>2.5</td>
<td>$1.85 \times 10^{-7}$</td>
</tr>
<tr>
<td>3.5</td>
<td>$6.7 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
Other tests were made to evaluate scatter sensitivity vs knife-edge position. With the sky tube aimed 2.5 source radii above the center of the light source, each of the knife edges was raised and lowered in turn until the perturbation yielding a 10% increase in scatter was determined. While any one knife edge was being moved, the other two remained in their minimum scatter positions. Table 3 displays the results of these tests.

Table 3

<table>
<thead>
<tr>
<th>Knife edges</th>
<th>Vertical position deviation resulting in 10% scattering level increase (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>+0.0125 or -0.010</td>
</tr>
<tr>
<td>Second</td>
<td>±0.005</td>
</tr>
<tr>
<td>Third</td>
<td>±0.005</td>
</tr>
</tbody>
</table>

In another effort to reduce scatter, a fourth knife edge was installed behind the three already present. With the photometer aimed at an area 2.0 radii above light source center, the fourth knife edge reduced instrumental scatter from $7.4 \times 10^{-6}$ to $4.9 \times 10^{-6}$. The four knife edges were then adjusted to occult the measurement field 1.5 radii above the source center, and with the photometer still aimed 2.0 radii above the center a scatter level of $1.85 \times 10^{-6}$ was obtained. Neither of the procedures using four knife edges yielded satisfactory scatter levels; in fact, the perturbation sensitivity of the instrument increased.
C. DRIFT AND LINEARITY

The photometer was tested to measure errors incurred through system drift and deviation from linear response (gain change). The system was tested in normal operating mode using the sun as well as an artificial light source capable of illuminating sky- and sun-channel filters equally.

Drift is defined as any change in output voltage (and therefore in indicated sky brightness) with time. Drift incurred in the prototype unit was measured by placing calibrated opal filters (D = 11 \times 10^6 and D = 9.7 \times 10^7) in the sky channel optical path and then noting system output. Any deviation in signal during the sample period was interpreted as instrumental drift. The first filter had the same density as the reference filter in the sun channel, and yielded information on zero drift. The second filter permitted measurement of system gain changes. The maximum zero drift never exceeded 1% of absolute sky brightness. Gain drifts never exceeded 5% of absolute sky brightness, and were typically < 2%.

Measurements of the photometer’s instrumental deviation from ideal signal response were based on the equation defining ideal response:

\[
\text{output voltage} = G \times \log_{10} \left[ \frac{B_{\text{sky}}}{B_{\text{sun}}} \right]
\]

where \( G \) = system gain in voltage/decade, \( B_{\text{sky}} \) = indicated sky brightness, and \( B_{\text{sun}} \) = indicated sun brightness. Filters covering the desired light intensity measurement range were inserted in the sky channel optical path, and the output voltages for each were recorded.

Photometer output voltage should be directly proportional to \( \log_{10} \left[ \frac{B_{\text{sky}}}{B_{\text{sun}}} \right] \); any deviation from the anticipated straight-line response constitutes an error, or system noise. The relative magnitude of the error can be determined at various optical signal wavelengths by using the graph (Fig. 17) of percentage-error in relation to normalized system noise.
Fig. 17 Photometer noise-equivalent error (i.e., percentage-error in photometer output) vs normalized system noise.
The prototype photometer exhibited < 3\% deviation from linear response over the brightness ratio range $5 \times 10^{-6} < \left[ \frac{B_{\text{sky}}}{B_{\text{sun}}} \right] < 100 \times 10^{-6}$. In the range $0.9 \times 10^{-6} < \left[ \frac{B_{\text{sky}}}{B_{\text{sun}}} \right] < 500 \times 10^{-6}$, deviation was < 10\%, with the maximum error occurring at interval extremes.

D. SYSTEM NOISE VS OPTICAL SIGNAL WAVELENGTH

The percentage error due to noise was measured for various source brightnesses and signal wavelengths. The system was tested in standard operating mode in bright sunlight and calibrated in the normal manner. The output recorder was set to examine the dc and ac components of system output separately. All measurements were made with an $11 \times 10^6$ opal filter in the sky channel, and light intensity was varied by installing Wratten filters #15G, #23A, and #29; unfiltered light was also tested. Photometer output was passed through an auxiliary analog circuit with output

$$N = \left| \frac{V - \bar{V}}{\bar{V}} \right|$$

where $V$ denotes instantaneous photometer output voltage, and $\bar{V}$ photometer output averaged over 13 sec. Their absolute difference is also averaged over 13 sec. (It would be preferable to increase the latter averaging time by at least one order of magnitude, but component tolerances and amplifier drift would lead to serious error.) Values of the analog voltage, $N$, were recorded on a strip-chart recorder; the peak value during a 5 min test period was taken as the measure of system noise.

Measurement error introduced by system noise is given by the equation

$$\text{percentage error} = \frac{230.6 \times N}{G}$$
where N is measured as above, and G denotes system gain in volts per decade-change in brightness ratio. Table 4 shows the noise level associated with the peak wavelength of each intensity measured; peak light wavelength is a function of filter intensity and PM S-4 response.

Table 4

<table>
<thead>
<tr>
<th>Peak wavelength ((\mu))</th>
<th>Wratten filter</th>
<th>Maximum noise (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.400</td>
<td>none</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>0.540</td>
<td>#15G</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>0.590</td>
<td>#23A</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>0.640</td>
<td>#29</td>
<td>&gt; 2</td>
<td>insufficient signal for accurate clamping</td>
</tr>
</tbody>
</table>

*All calculations made with G = 2.2 V/decade.

E. ELECTRONICS SYSTEM ERROR ANALYSIS

The photometer's signal is not sensitive to changes in gain before it reaches the log amplifier as long as the light sensor signal remains within the linear region of the log amplifier. Since the linear region encompasses four decades of input voltage, and since the photometer operates near the middle of this range, a large change in gain must occur to introduce appreciable error.

The gain factor K introduced by the log amplifier is probably the largest single source of electronics system error. However, tests in a controlled temperature chamber show that gain variation is < 2% for temperatures between 0 and 35°C.
Gains in the difference amplifier and low-pass filter are low (five and one, respectively), and are determined by the ratios of precision resistors. The closed-loop gains are very small in comparison to even the worst open-loop gains; the resistors are not stressed and can be expected to exhibit the same percentage drift with temperature. Thus, it is unlikely that significant error will be introduced in these components.

Any occurrence of zero drift before the signal reaches the clamp (including change in PM tube dark current) will have no effect on system accuracy, but drift in the clamping level and in the amplifier associated with the logarithmic unit can be significant. This is best understood by recognizing that any offset from zero is equivalent to adding or subtracting from the signal current. Since offset is constant for both sky and sun signals, output voltage becomes

\[
E = K \times \log_{10} \left( \frac{i_{\text{sky}} + i_{\text{offset}}}{i_{\text{sun}} + i_{\text{offset}}} \right)
\]

According to this equation, offset current \(i_{\text{offset}}\) has no effect when sky and sun signals are equal, a condition occurring when the ratio of sky to solar brightness is \(\sim 10^{-5}\). Offset current error can, however, become troublesome with very dark skies. This source of error is minimized by using low-drift amplifiers for the clamp and log unit, and by determining the proper operating point for the log unit.
IV. SUMMARY OF DESIGN SPECIFICATIONS

**MEASURED AREA**

**Field of View**

Lensless aperture system. Circular field of view with geometrical limit of 14 arc min. Half-power point 5.1 arc min.

**Distance from Solar Limb**

Fixed at 24 arc min. Gradient sweeps possible to 10°, dependent upon transmission characteristics of sun-channel attenuation filter.

**OUTPUT SIGNAL**

**Analog Form**

Signal range from -10 to +10 V; dc voltage proportional to

\[ \log_{10} \left( \frac{\text{sky brightness}}{\text{solar disk brightness}} \right) \]

**Sampling Rate and Smoothing**

Selectable maximum response 10 Hz; slowest \( \sim 0.5 \text{ Hz} \) (limited by leakage resistance).

**DYNAMIC MEASUREMENT RANGE**

Four decades possible, dependent upon sun-channel filter transmittance. (With filter density 5.0, range is three decades, from \( 1 \times 10^{-6} \) to \( 1000 \times 10^{-6} \) of solar disk brightness.)

**MEASURED WAVELENGTHS**

Wavelengths from 4000 to 5900A are measured within the limits of the S-4 response curve of the 1P21 PM. Wavelength range can be selected by suitable filters.
ACCURACY

Overall system accuracy is > 10% absolute.

POWER REQUIREMENTS

115 V ac at 60 Hz. (A power system circuit diagram is shown in Fig. 18).

ACCEPTABLE OPERATING TEMPERATURE

Spar: -40 to +35°C

Electronics Package: 0 to 35°C
Fig. 18 Circuit diagram of the power chassis.
PART TWO

OPERATION MANUAL

I. INSTRUCTIONS FOR ALIGNMENT, OPERATION, AND CALIBRATION ........ 43

II. SAMPLE DATA ................................................. 55
I. INSTRUCTIONS FOR ALIGNMENT, OPERATION, AND CALIBRATION

A. ALIGNMENT

Optics

Optical alignment of the photometer (except for the aiming lens) should not be necessary unless the instrument has been severely maltreated. Should this occur, the procedures given for knife-edge alignment (Part One, Sect. III-B) may have to be employed. The aiming lens alignment should be checked periodically for wear in the lens mount seat. Lens alignment is accomplished in the following steps.

1. Remove sun-channel filter holder and tube. Cover sky channel.

2. Place pinhole light source ~10 ft from photometer, turn on electronics, and aim the sun channel at the pinhole by adjusting the position for maximum signal.

3. Place scribed aperture cap over sun channel and insert lens firmly into front knife-edge holder. Be certain that the scribed lines on the lens mounting and the knife-edge holder are aligned. Place the small mirror conveniently for viewing the front of the aperture cap.

4. Use the three setscrews in the lens mounting to adjust the lens until the source image on the aperture cap is concentric with the scribed circles. Lens alignment is now complete.

Electronics

Alignment of the electronics system involves adjusting the voltage (and the current where applicable); trimming potentiometers associated with the system amplifiers for zero output voltage (zeroing); setting the reference current and conversion gain of the log amplifier; and adjusting the relay detector timing circuits (synchronization and switching circuits). With the exception of the timing adjustment, electronics alignment is accomplished with the high voltage supply turned off. It
is recommended that the electronics system be allowed to warm up for at least 1 hr before beginning alignment.

Test card B201 can be found in the restorer signal-processing module, and is used to zero all Philbrick P65 and P85C amplifiers (Fig. 19). The special card B302, located in the log amplifier module, is used for that unit only. Given below are alignment instructions for each component of the electronics system.

Spar Electronics

1. Replace card B101 with B201 and set S201-1 (on card B201) to "V" position.
2. Connect voltmeter to jacks J201-1 and J201-2, and adjust voltage trim on A102 for null.
3. Set S201-1 to "I" position and adjust current trim pot R102-1 for null.
4. Repeat steps 2 and 3 for simultaneous voltage and current nulls.

Zeroing of amplifiers A103-1 and A103-2 is not critical; they should not need adjustment unless part replacement is required. If adjustment is necessary, the following steps should be taken.

1. Ground amplifier inputs by grounding pins 6 and 10 on card B103, and connect voltmeter to outputs (pins 12 and 15 on card B103).
2. Adjust R103-1 and R103-2 for null.

Rack Electronics

Each module in the signal-processing system has a front panel jack allowing its connection to the rest of the system while the subchassis is separated from the rack cabinet for testing; cables are provided for this connection. A switch is mounted on each subchassis; this switch should be set in the "test" position whenever the subchassis is removed for testing. It ties signal, chassis, and power grounds together. In normal operation the switch should be in the "operate" position to avoid ground loops.
Voltage Zeroing Circuit
Sensitivity: 1V/mV Offset

Current Zeroing Circuit (P85C Amplifiers Only)
Sensitivity: 1V/nA Offset

Fig. 19 Circuits used to zero photometer voltage and current (P85C amplifiers only).
Precision dc clamp

The clamp must be carefully zeroed to provide an accurate zero reference to the log amplifier. The following procedure zeros the clamp:

1. Remove cards B203 and B204. Replace B203 with test card B201. Set chassis switch to "test".
2. Set S201-1 to "V" and adjust voltage trim on P85C for null.
3. Set S201-1 to "I" and adjust R202-1 for null.
4. Repeat steps 2 and 3 for simultaneous nulls.

Logarithmic Amplifier

1. Remove SPL4-P from S303 and replace it with card B302. Set front panel rotary switch S to "zero amp."
2. Connect voltmeter to "log out" jacks on control panel.
3. Remove B302 and replace SPL4-P in S303.
4. Set log amplifier from panel switch to "I ref" and adjust I ref pot to SPL4-P for zero voltmeter reading.
5. Set switch S to "set gain" and adjust gain pot on SPL4-P for a voltmeter reading of 1 V.
6. Set switch S to "check gain." Voltmeter reading should be 4 V.
7. Set log amplifier switch to "operate" position.

Synchronization and Switching Circuits

1. Connect oscilloscope (preferably dual-channel) to test jack J401-1 on card B401. With the photometer running, adjust R401-1 for symmetrical square wave output.
2. Allow photometer to view a light source sufficiently bright to give a well-defined signal (as seen on "clamp out" jacks on control panel).
3. Connect scope to "log sun" or "log sky" jacks on control panel and adjust R403-1 and R404-1 so that the sampling period just excludes the signal "legs" (see timing diagram, Fig. 20).

Difference Amplifier and Low-pass Filter

1. Replace B502 and B201 and connect voltmeter to J201-3 and ground.

2. Connect jumpers from "Synch 1" and "Synch 2" jacks on control panel to ground.

B. OPERATION AND CALIBRATION

1. Set up the spar and align the equatorial axis. Rough axis alignment can be achieved with a compass to determine north, and with a level and protractor to set the declination. Fine adjustment can be achieved by turning on only the clock motor and observing the drift of the solar image on the guider plate at the rear of the spar. Small adjustments in declination and azimuth can minimize this drift. (In the southern hemisphere the leads to the clock motor will have to be reversed.) IMPORTANT: Use only 60 Hz, 110 V current to power the clock motor.

2. Connect the two power cords from the electronics rack to an ac power source (110 V, 55 to 65 Hz). Link the electronics rack to the photometer spar by joining the coaxial high voltage cable, and the multi-conductor control and signal cable, to the appropriate connectors on rack and spar.

3. Turn on the high voltage power supply switch, and the switch on the low voltage and control chassis panel. The high voltage switch must be in the "reset" position, and the voltage selector switches set to zero.

4. Connect a suitable recording instrument to the output jack, and turn it on for warmup. The recorder should have minimum full-scale sensitivity of ±0.5 V, and input impedance > 10,000 Ω.
NOTE: R403-1 sets interval $\tau_1$
R403-2 sets interval $\tau_2$

Fig. 20 Schematic timing diagram for the synchronization and switching circuits of the signal-processing system.
5. Photometer aiming is accomplished while the electronics are warming up. Remove the filter holder and the light-shielding tube from the sun channel. Place the scribed aperture cap over the entrance aperture of the main sun tube, and install the aiming lens on the front knife-edge holder (Figs. 21 and 22). Be certain to use the lens adjusted for the particular prototype unit being put into operation, and be certain that the scribed lines on the holder and on the lens mount are aligned. With a small mirror placed for convenient viewing of the scribed circles on the front of the aperture cap, adjust the spar-aiming controls until the solar image is concentric with the circles. Aiming is now complete; the lens and aperture caps are removed and the shielding tube and filter holder replaced.

6. Turn on the high voltage switch, and set the voltage selector switches to 750 V. The voltage should be raised gradually over a period of a few seconds.

7. Calibration is accomplished by inserting calibration filters in the sky channel (Fig. 23), and observing the output of the entire system. The photometer should be calibrated at the beginning of operation, and once every 2 to 4 hr during operation. The densities of the D and R series calibration filters correspond to sky brightnesses of $0.97 \times 10^{-6}$ and $11 \times 10^{-6}$ solar brightness, respectively. Observe and record the output of the photometer with each of these filters in place, and adjust the sensitivity and positioning controls on the recorder to yield the desired trace.

8. Remove the filter holder from the sky channel. The photometer is now in operation. NOTE: When installing and removing the sky channel filter holder, enough light may be diffracted into the sky channel to trip the overload circuit. This condition is indicated by a click from the high voltage supply overload relay and by extinction of the high voltage pilot light. The high voltage switch must now be turned to the "reset" position until the standby light comes on; the turn-on procedure (step 5 above) is then repeated.
Fig. 21 Optical system atop the sun-tracking spar, with aiming lens and aiming cap in place. (The shroud is removed for illustration purposes.)
Fig. 22 Sky and sun tubes with aperture caps used for aiming the photometer.
Fig. 23 Installation of sky-channel calibration filter.
9. The logarithmic brightness ratio corresponding to a measured photometer output signal \( E_{\text{out}} \) is calculated as follows. Let \( V_D \) be the output reading with the D-filter in place in the sky channel, and let \( V_R \) be the corresponding R-filter reading. If the filter transmittances are represented by \( B_D \) and \( B_R \), respectively, system gain \( A \) is given by the equation

\[
A = \frac{\log_{10} \left( \frac{B_R}{B_D} \right)}{V_R - V_D}
\]

in decades per volt. The log of the brightness ratio \( B_{\text{sky}}/B_R \) is then

\[
\log_{10} \left( \frac{B_{\text{sky}}}{B_R} \right) = A \times (E_{\text{out}} - V_R)
\]

or

\[
\log_{10} \left( \frac{B_{\text{sky}}}{B_{\text{sun}}} \right) = A \times (E_{\text{out}} - V_R) + \log_{10} \left( \frac{B_R}{B_{\text{sun}}} \right)
\]
II. SAMPLE DATA

Figure 24 shows chart recorder output from one prototype photometer operated on the roof of the NCAR Mesa Laboratory on 9 April 1969. Features clearly evident on the chart are the insertion of calibration filters into the sky-tube channel, the generally high level of sky brightness during the measurement period, and the point at which the signal-processing overload circuit was activated by the passage of a very bright cloud edge.

Figure 25 displays chart recorder output on both prototype photometers on 28 February 1969. The instruments were placed on the Laboratory roof ~ 12 ft apart. A striking feature of these records is the rapid variation in measured sky brightness values. Light intensity measurements in 2:1 ratios occurred frequently in periods of 1 min or less, particularly early in the day. High correlation between measurements made by the two photometers is apparent.

Visual observations during this and other measurement periods have not yet isolated conditions associated with quiet or noisy sky brightness readings. In general, days with cumuliform clouds have not been unusually noisy, and have been characterized by steep increases in brightness during cloud passage (similar to the trace shown in Fig. 24). Mean values of photometer sky brightness measurements at Boulder have shown some correlation with visual observations; days without cirroform clouds have induced lower photometer readings than days with such clouds.

With the current photometer sensitivity and at a sampling rate of at least 0.1 Hz (the rate used for testing) the two photometers can be used to determine local variability in sky brightness. If concurrent vertical wind profile information is available, spectral analysis and time lag studies can identify the altitudes of the primary scattering contributions.

The photometer may also be used to determine sky brightness gradients; Fig. 26 is a collection of such gradient curves. To obtain these graphs,
Sky Brightness Ratio = \( \frac{B_{\text{sky}}}{B_{\text{sun}}} \)

Fig. 24 Chart recorder output from a prototype photometer operating on the roof of the NCAR Mesa Laboratory 9 April 1969. The recorded voltages display the measured sky-to-sun brightness ratio.
Sky Brightness Ratio $= \frac{B_{sky}}{B_{sun}}$

Fig. 25 Chart recorder output of the two prototype photometers operating simultaneously on the NCAR Mesa Laboratory roof 28 February 1969.
Fig. 26 Sky brightness gradient curves.
the instrument was offset manually to make continuous measurements along a line extending north of the sun's edge, while the spar's clock drive continued its normal solar ascension tracking motion. Readings were made at each 16 min increment in arc (i.e., at every solar radius increment) to $10 \, R_\odot$ north of the sun, $\sim 3^\circ$ from the solar limb. Readings were taken again while the photometer returned to its fixed viewing position $1.5 \, R_\odot$ from the limb. A greater arc can be traversed for brightness gradient measurements, but the process is limited by the off-axis transmission characteristics of the sun channel's opal attenuating filter. Gradient readings over arcs $< 10^\circ$ are possible, depending upon required accuracy.
APPENDIXES

A. Optical System Reference List ................ 63
B. Photometer Component Equipment List ............. 65
APPENDIX A

OPTICAL SYSTEM REFERENCE LIST

The following drawings and parts lists are available from NCAR upon request by appropriate reference number.

1. Knife-edge assembly 327-00-100
2. Aperture and shutter assembly 327-00-200
3. Shroud assembly 327-00-400
4. Filter and aiming assembly 327-00-500
APPENDIX B

PHOTOMETER COMPONENT EQUIPMENT LIST

The complete NCAR Sky Brightness Photometer consists of the following equipment.

1. SPAR

   Base
   Three legs
   Optical system mounted on sun tracker (spar)
   Slow motion control

2. ELECTRONICS RACK

   Signal-processing modules
   Low voltage supply and control circuits
   High voltage supply
   Multiconductor cable* (blue ribbon connectors)
   High voltage cable*

3. MISCELLANEOUS

   Aiming lens
   Aiming cap
   Magnet-mounted mirror
   Sky-channel filter holder
   Two calibrated opal filters

*The multiconductor and high voltage cables are taped together; they connect spar-mounted components to the electronics rack.