NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1313

Sky Effect on Solar Cells Calibrated at 80,000 Feet

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Abstract

The use of high-altitude balloon flights for the calibration of standard solar cells has been proven to be a reliable method of obtaining space-calibrated solar cells for terrestrial and laboratory measurements. A technique is presented to help further refine these methods by determining the percentage of sky radiation incident on solar cells during the balloon cell calibration. It was found that the contributions of sky radiation to the output of solar cells at 80,000 feet were less than 0.5%.

Sky Effect on Solar Cells Calibrated at 80,000 Feet

I. Introduction

A method has been developed for the extrapolation of terrestrial solar cell short-circuit current measurements to earth space conditions by the use of high-altitude research balloons (Refs. 1 and 2). In this development program, fourteen balloons have been successfully launched to altitudes of approximately 80,000 ft to obtain calibration data on the short-circuit current of silicon solar cells. The experimental balloon flights have proven the feasibility of obtaining space-calibrated solar cells with calibration errors of less than $\pm 0.6\%$ and repeatable over a period of years to within better than $\pm 0.5\%$. An air-mass-zero extrapolation technique for terrestrial solar cell measurements using the balloon calibrated solar cell has been accomplished with errors less than 2%.

Although at 80,000 ft 97% of the atmosphere is below the solar cells being calibrated, considerable interest is directed to the remaining 3% of atmosphere and to its influence on the solar cell short-circuit current output. The effects of ozone in the Chappius band have been calculated in the spectral response region of the solar cell, and the resulting short-circuit current attenuation is considered negligible (Ref. 2). The contribution of light other than that coming directly from the sun illuminating a solar cell at 80,000 feet would result in producing a different output of the cell relative to its output in space. An experiment was performed at 80,000 ft to measure this contribution of sky radiation to the solar cell short-circuit current output. Details of this experiment are presented in this report.

II. Methods Used in Terrestrial Sky Radiation Measurements

Several methods are employed in the terrestrial measurement of solar arrays for the determination of direct solar illumination and total solar illumination. In one method, a collimating tube is mounted and dismounted from the solar cell under test, and the short-circuit current output is recorded in each mode.

The difference in short-circuit current values is attributed to sky radiation. Sky radiation is considered to be the nondirect or diffuse illumination caused by scattering or by dust particle and water vapor reflections. The accepted collimation system (Ref. 3) used in solar cell measurements has a slope angle of not less than 1 deg and not more than 2 deg and a ratio of distance between the receiver and limiting aperture to radius of receiver equal to or greater than 15 (see Fig. 1). Under these conditions, the opening angle (i.e., the half angle) will not be greater than 4 deg. The formula for determining the percent sky radiation using this system is[1]

$$R_s = \frac{I_{sc_1} - I_{sc_2}}{I_{sc_2}} \times 100 \qquad (1)$$

where

R_s = sky radiation, %

I_{sc_1} = uncollimated solar cell short-circuit current

I_{sc_2} = collimated solar cell short-circuit current

In a slight modification of this system, two solar cells (one collimated, the other uncollimated) are measured simultaneously. The two solar cells are matched in output and spectral response. This system is usually employed in automated data acquisition systems. The calculation of the percentage of sky radiation is the same as that illustrated in Eq. (1). In another method, the short circuit current of a single cell is measured under total hemispherical illumination; the direct incident energy is then shaded to the desired half angle and the short-circuit current is remeasured. The current generated by the cell in this mode is generated by the indirect, or sky, radiation. The percentage of sky radiation as measured by this method is determined by

$$R_s = \frac{I_{sc_3}}{I_{sc_4} - I_{sc_3}} \times 100 \qquad (2)$$

[1]The reader should be aware that "sky radiation" has been defined by others (Ref. 4) as $R_s = (I_{sc_1} - I_{sc_2})/I_{sc_1} \times 100$. For the magnitude of sky radiation considered in this paper, the difference is trivial.

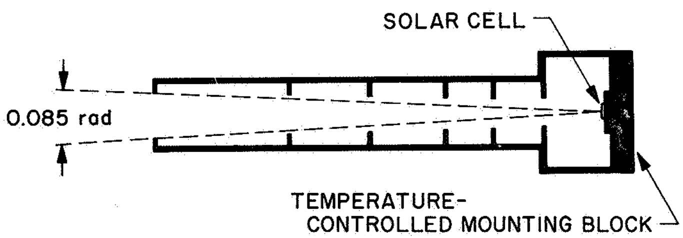

Fig. 1. Solar cell collimating tube

where

R_s = sky radiation, %

I_{sc_3} = shaded solar cell short-circuit current

I_{sc_4} = illuminated solar cell short-circuit current

III. Description of Sky Radiation Measurement Device

The balloon system used for high-altitude solar cell calibrations uses an apex-mounted tracking system. A balloon can support more weight attached to the bottom than to the top. There are, however, disadvantages in mounting solar cells on the bottom of a balloon. One is that a bottom-mounted payload is subject to pendulum and torsional motion, making the tracking of the sun for solar cell illumination more difficult. Secondly, when positioned at the bottom of the balloon, solar cells are exposed to sunlight reflected from the main body of the balloon. Although a lighter payload must be carried on the top of a balloon than on the bottom, the problems of reflections from the balloon and solar-tracker instability are minimized by the apex-mounted tracking system. The complete balloon system is discussed in Refs. 1 and 2. The apex-mounted payload is limited to those pieces of equipment which are light in weight and necessary to the sun-tracker system operation. Because of schedules and weight limitations, a modified method of the shading technique previously discussed was employed as a sky radiation measuring detector in the 1965 balloon flight calibration program.

The sky radiation detector used in this experiment was assembled specifically for the balloon solar cell calibration system. The unit was fabricated with spectrally matched solar cells and assembled into the standard type of module used on the solar cell balloon calibration flights (Fig. 2). The two solar cells were mounted such that one would receive total solar illumination and the other, with a shading device, would receive only nondirect, or diffuse, energy from the sun. The shading device was designed to restrict the total illumination on the solar cell to a half-angle of 8 deg. This value is higher than the standard collimating system half-angle. The increased half-angle on the balloon system is due to the desire to maintain full solar cell shading with the maximum solar tracker on-sun tolerances (approximately 3 deg, Ref. 2).

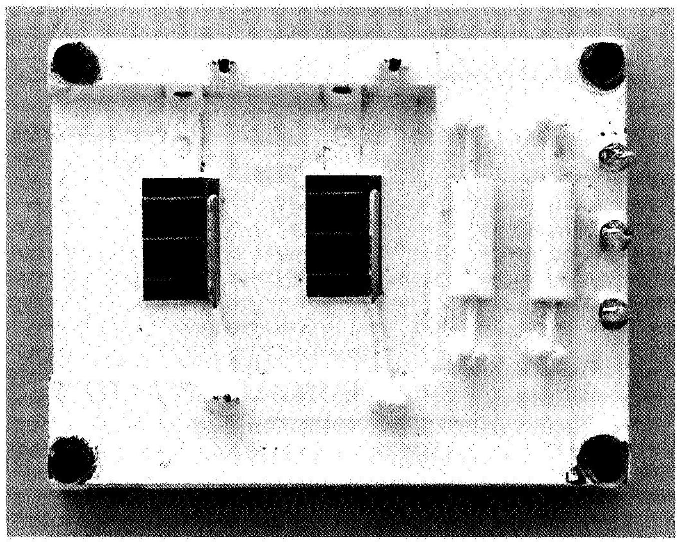

Fig. 2. Sky radiation detector module (without shade)

The two solar cells used on each detector are 0.5 × 0.5-cm, unfiltered, p-n silicon cells. The shading unit was fabricated using fiberboard impregnated with steel wire and glass. The fiberboard and wire were coated with flat black enamel. The dimensions of the shade are 0.765 × 0.913 in., and it is located 3.175 in. directly above the solar cell (see Fig. 3).

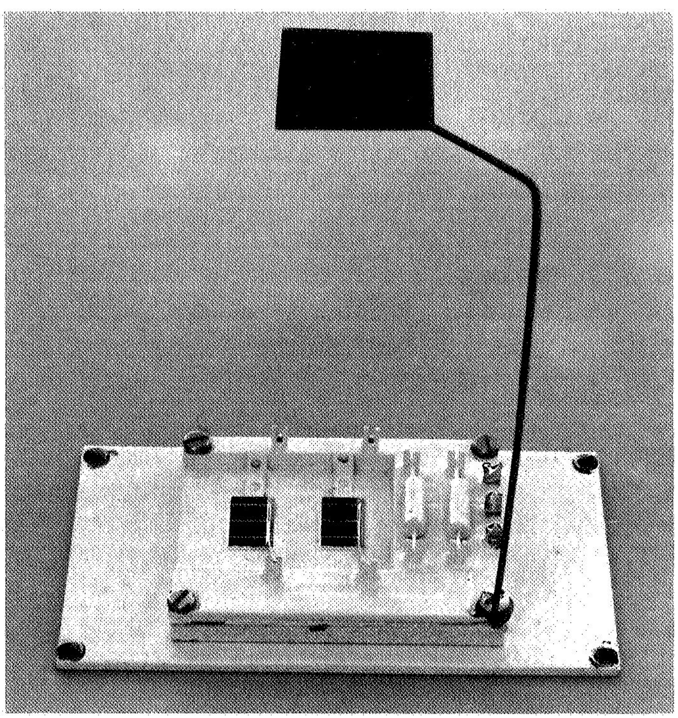

Fig. 3. Sky radiation detector module

IV. Calibration of Sky Radiation Device

The solar cells used in the fabrication of the sky radiation detector were measured under three different color temperature light sources (earth–sun, tungsten, xenon) and matched for short-circuit current output. The solar cells that exhibited less than 3% change of current in relation to each other under the three light sources were selected as detectors for the experiment. The cells were assumed to have a matched spectral response because of the relatively small change in the relative short-circuit current outputs when exposed to the three spectrally different sources of illumination.

On June 17, 1965, two matched sets of the selected solar cells were calibrated at Table Mountain, California. The calibration procedure details are described elsewhere (Ref. 5) and will only be summarized here. A group of solar cells are mounted in standard holders and compared against a primary balloon standard cell in terrestrial sunlight at Table Mountain. The spectral response of the primary standard cell is closely matched to those solar cells under calibration. The solar cells are maintained at 28°C and at normal incidence to the solar illumination by means of an equatorial tracking system. A quantity of data points are accumulated for each solar cell output and correlated with the nearly simultaneous measurement of a balloon-flight-calibrated solar cell output to establish a mean deviation. The objective in using this particular technique for calibration was twofold: to determine how closely the two solar cells on the detector would track each other over a wide range of air mass for verification of spectral matching, and to determine the difference in the short-circuit current values of each cell in order to establish a factor (K) to make these values equal. The established factors for the sky radiation detector cells are: Detector 1, $K_1 = 1.0256 \pm 0.487\%$; Detector 2, $K_2 = 0.9859 \pm 0.343\%$. To calculate the percentage of sky radiation from the measurements of these detectors the following formula is used:

$$R_s = \frac{I_{sc_3}}{(I_{sc_4} \times K_1) - I_{sc_3}} \times 100 \tag{3}$$

where

R_s = sky radiation, %

I_{sc_3} = shaded solar cell short-circuit current

I_{sc_4} = illuminated solar cell short-circuit current

K_1 = factor to equalize illuminated short-circuit currents

V. Terrestrial Comparison Measurements in Sunlight

The shading type of detector was compared with terrestrial measurements of the standard collimating system to determine the amount of error caused by the different view angles of the two systems. It was expected that the shading-type system would indicate lower sky radiation values because of the larger percentage of sky directly around the sun being directly shaded (Fig. 4), whereas the collimating system is influenced by the area in the immediate proximity of the sun. However, actual measurements showed that the sky radiation as indicated by the balloon calibration experiment was consistently higher (Table 1). One explanation for the higher sky radiation values as indicated by the shading system is the proximity of the shading device and the nonshaded cell. The shading device provides the required shaded view angle of the sun for the shaded cell. However, it also provides a geometric blocking of the total hemispheric atmosphere for the solar cell which is supposedly measuring the total sky. The fact that the cell is not measuring the total hemispheric sky results in a lower short-circuit current output of the solar cell. Because it is used to determine the sun output of the shaded cell, the lower output of this cell would influence the calculated value of sky radiation of the detector. This would account for the higher indicated sky radiation measurements obtained in the correlation tests.

VI. Performance of Balloon Flight 3031

On August 28, 1965, the fourth balloon flight (3031) in a series of four scheduled for 1965 was successfully launched from New Brighton, Minnesota, under JPL Contract 951247. The balloon was launched at 0851 CDT and reached a float altitude of 78,500 ft at 1030 CDT and remained at this altitude for 4½ h. During the float period the short-circuit currents of 14 solar cells were measured in addition to temperature measurements and inflight calibration voltages. The balloon descent was initiated at 1500 CDT and impacted at 1730 CDT, about 250 miles southeast of the launching site. The complete solar cell payload assembly was recovered without incident or apparent damage.

The balloon flight system used for flight 3031 is essentially as described in detail in Ref. 2. The full-scale volt-

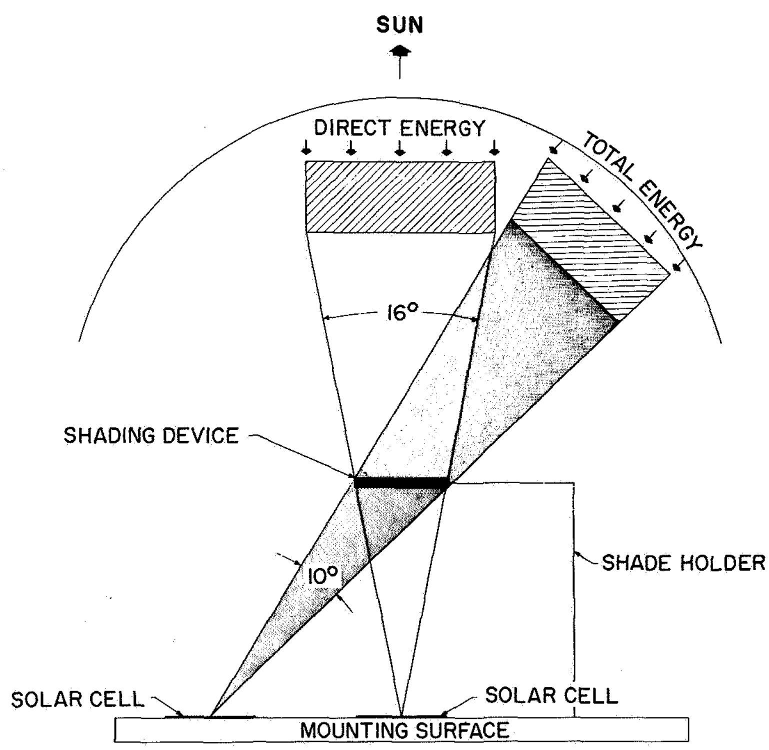

Fig. 4. Solar cell look angle

Table 1. Comparison of collimation method and shading method for sky radiation measurements (Sep 23, 1965)

Time, PDT	Collimated system, %	Shaded detector system, %
1148	8.22	8.50
1152	8.09	8.44
1155	7.84	8.37
1158	7.96	8.39
1200	7.81	8.33
1202	7.68	8.33
1204	7.49	8.23
1206	7.64	8.14
1208	7.77	8.17
1210	7.07	8.15
1239	7.13	7.80
1240	7.02	7.83
1244	7.11	7.78
1246	7.03	7.80
1248	7.60	7.82
1250	7.19	7.86
1252	7.14	7.90
1254	7.08	7.92
1256	7.20	8.00

age readout of the voltage-controlled oscillator (VCO) was modified from a 100- to a 20-mV full-scale system. The in-flight voltage calibration system was also modified to be compatible with modifications of the VCO. The VCO frequency is nearly linear as a function of voltage at its input terminals. The VCO frequency for this flight measured 7885 Hz for a zero volt input, and lowered to a frequency of 6834 Hz for an input signal of 20 mV. This resulting frequency change corresponds to 52.5 Hz/mV. In-flight voltage calibrations are maintained by using temperature-compensated zener diodes selected for precise voltages and very low temperature coefficients. Prior to flight, in-flight calibration voltages are adjusted to within ±0.01% of their calibration value. The standard voltage circuit is temperature-controlled to stay within 30 to 40°C during flight. In this temperature range, the standard voltages can be maintained to an accuracy of ±0.1%. The temperature of the main VCO is maintained within 35 to 40°C during flight, thereby controlling frequency drift. The standard voltages on the balloon provide a highly accurate data system even in the event of frequency drift in the VCO.

VII. Data Obtained on Sky Radiation Detectors on Balloon Flight 3031

Balloon flight 3031 launched on August 28, 1965, carried aloft as a portion of its solar cell calibration payload two sky radiation detectors (Fig. 5). At float altitude and after temperature stabilization, approximately 30 data points were obtained on the short-circuit currents of each of the four solar cells contained on the two detectors. Table 2 is a tabulation of these data points. The value of sky radiation is calculated by Eq. (3) and is presented in Table 3. The two detectors limited in total look angles by the antireflection shields mounted on the solar tracker (Fig. 5) have differing total look angles with respect to each other because of their physical mounting location. Despite this fact, the detectors exhibited good agreement in their measurement of sky radiation.

In evaluating the accuracy of the short-circuit current values in Table 3, several sources of error must be considered. The random errors are those which vary over a given series of measurements. These errors are noticeable from the fluctuation in the data points. For a statistically significant set of data, the random error may be taken as the rms deviation of the individual values. The following are possible sources of random errors:

(1) Sun tracker misorientation ($\Delta\theta$) was observed to be less than 3 deg because of the absence of the off-sun indicator during the sampling periods. Therefore, Eq. (4) gives the maximum error from this source, using a cosine law correction:

$$\frac{\Delta I_{sc}}{I_{sc}}\left[1-\cos(\Delta\theta)\right] = -0.00137 = -0.137\% \tag{4}$$

(2) The readout error in the telemetry counter-printer system is ±0.019 mA. Using 17.0 mA as a typical value for short-circuit current, Eq. (5) gives the error from this source:

$$\frac{\Delta I_{sc}}{I_{sc}} = \frac{0.019}{17.0} = \pm 0.00112 = \pm 0.112\% \tag{5}$$

(3) The measured temperatures are taken as being known to ±1°C. Using typical temperature coefficients of silicon solar cells this amounts to an error of less than ±0.1%. Thus the total random errors of the system are a maximum of $^{-0.349}_{+0.212}$ %.

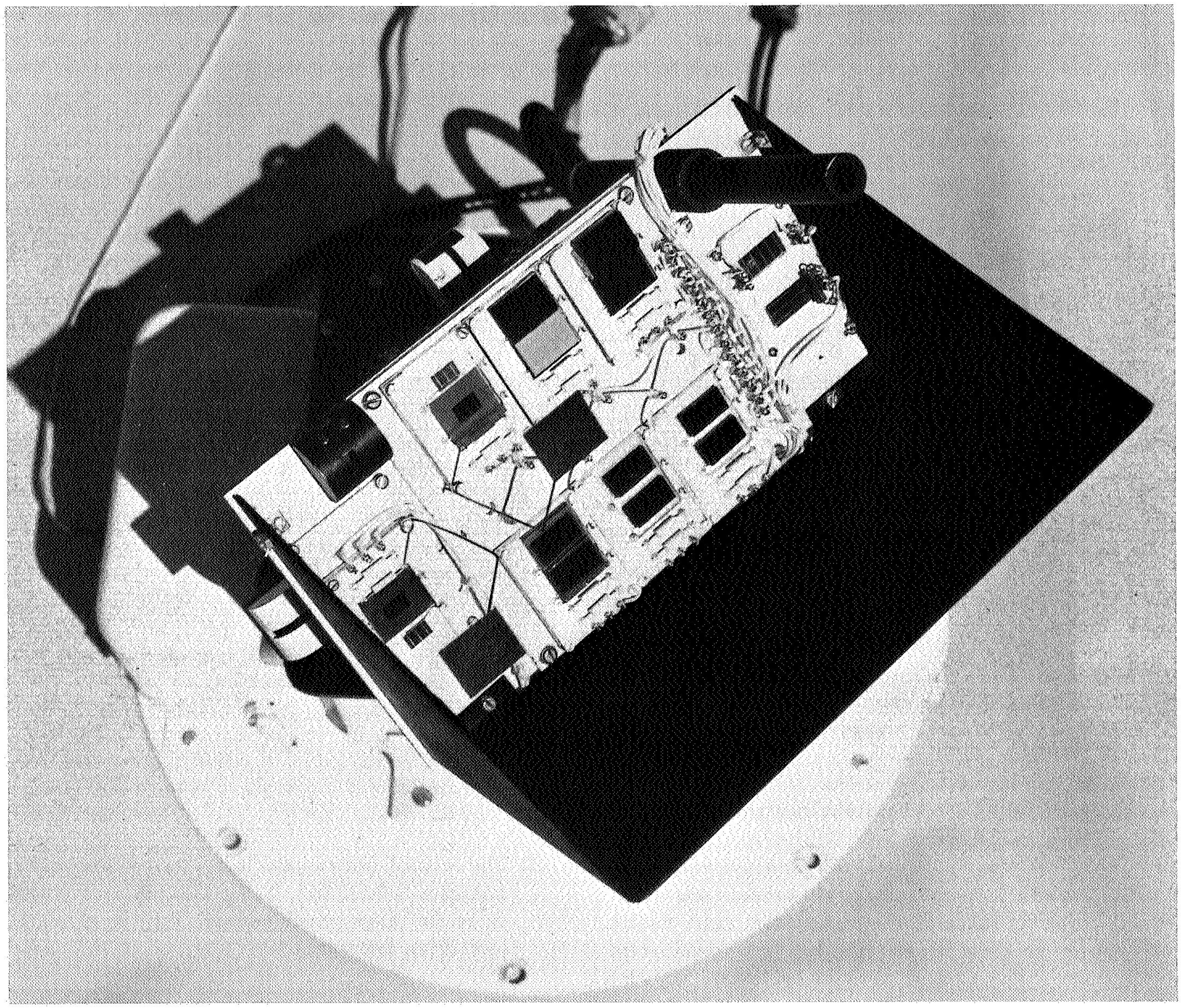

Fig. 5. Balloon flight tracking system and solar cell flight package

Table 2. Balloon flight data

Time, CDT	Detector 1, mA		Detector 2, mA	
	Shaded, I_{sc_3}	Illuminated, I_{sc_4}	Shaded, I_{sc_3}	Illuminated, I_{sc_4}
1200	0.076	17.23	0.057	17.94
1206	0.095	17.25	0.095	17.94
1212	0.095	17.25	0.076	17.94
1218	0.076	17.23	0.095	17.96
1224	0.095	17.27	0.076	17.96
1230	0.095	17.27	0.076	17.96
1236	0.057	17.25	0.095	17.97
1242	0.076	17.29	0.114	17.99
1248	0.057	17.27	0.095	17.99
1254	0.057	17.27	0.076	17.97
1300	0.038	17.25	0.057	17.96
1306	0.114	17.35	0.095	17.97
1312	0.076	17.27	0.076	17.97
1318	0.057	17.29	0.095	17.99
1324	0.076	17.31	0.076	17.99
1330	0.076	17.33	0.076	17.99
1336	0.095	17.35	0.076	17.99
1342	0.076	17.31	0.076	17.99
1348	0.057	17.29	0.076	17.97
1354	0.095	17.33	0.095	17.99
1400	0.076	17.31	0.076	17.97
1406	0.095	17.35	0.076	17.97
1412	0.057	17.31	0.076	17.99
1418	0.038	17.29	0.076	17.99
1424	0.095	17.31	0.076	17.97
1430	0.076	17.31	0.076	17.96
1436	0.076	17.29	0.076	17.96
1442	0.057	17.27	0.076	17.96
1448	0.076	17.27	0.057	17.96
1454	0.076	17.31	0.076	17.97
1500	0.076	17.27	0.095	17.96
Mean average	0.075	17.29	0.080	17.97

The systematic errors are those that remain constant over a series of measurements, thereby acting as a bias in the system. These errors are not evident from the data and can only be evaluated from the sources. These systematic errors are explained in Ref. 2 and constitute an error of +0.2% of the measured voltage.

Table 3. Tabulation of sky radiation as measured by balloon flight detectors

Time, CDT	Detector 1, %	Detector 2, %
1200	0.432	0.323
1206	0.539	0.539
1212	0.539	0.431
1218	0.432	0.539
1224	0.539	0.431
1230	0.539	0.431
1236	0.323	0.538
1242	0.430	0.646
1248	0.322	0.538
1254	0.322	0.430
1300	0.215	0.322
1306	0.644	0.538
1312	0.431	0.430
1318	0.322	0.538
1329	0.430	0.430
1330	0.429	0.430
1336	0.536	0.430
1342	0.430	0.430
1348	0.322	0.430
1354	0.537	0.538
1400	0.430	0.430
1406	0.536	0.430
1412	0.322	0.430
1418	0.214	0.430
1429	0.537	0.430
1430	0.430	0.431
1436	0.430	0.431
1442	0.322	0.431
1448	0.431	0.322
1454	0.430	0.430
1500	0.431	0.539
Mean average	0.427	0.455

Since the random error for each set of data points is actually observed as the rms deviation, the total error, random plus systematic, may be calculated for each set of data.

The mean value of sky radiation as measured by each detector is: Detector 1, 0.427%; Detector 2, 0.455%.

VIII. Conclusions

The method presented in this report for the measurement of sky radiation at 80,000 ft was employed in the JPL 1965 balloon flights series. This technique was preflight-tested and correlated to terrestrial measurements. The sky radiation contribution to the solar output at 80,000 ft as measured by this method was found to be less than 0.5%. The data indicates that a correction factor of −0.45% should be applied to the short-circuit current of balloon-calibrated solar cells to account for sky radiation at 80,000 ft.

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