NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1575

Results of the 1970 Balloon Flight Solar Cell Standardization Program

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Preface

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

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Abstract

For the eighth consecutive year, high-altitude calibration of solar cells was accomplished during July and August of 1970 with the aid of free-flight balloons. Flights were conducted to an altitude of 36,576 m (120,000 ft), which is above 99.5% of the Earth's atmosphere where all water vapor levels and significant ozone bands are absent. Solar cells calibrated in this manner are recovered and used as intensity references in solar simulators and in terrestrial sunlight. Balloon-calibrated solar cells were made available by JPL to NASA centers and other government agencies through a cooperative effort. An attempt to fly radiometers to measure the solar constant was aborted because of a balloon failure at launch. This report discusses the method employed for high-altitude balloon flight solar cell calibration. Also presented are the data collected on 52 standard solar cells on two flights conducted in 1970. Solar cells flown repeatedly on successive flights have shown correlation of better than $\pm 1.0\%$.

Results of the 1970 Balloon Flight Solar Cell Standardization Program

I. Summary

This report describes the methods used in calibrating standard solar cells on high-altitude balloon flights for the solar cell standardization program. The objectives of the program are:

(1) To provide Earth space calibrated standard solar cells for use with artificial light sources and in terrestrial sunlight for use by NASA centers and government agencies.

(2) To provide secondary standard solar cells (also referred to as NASA standard solar cells) for use by NASA centers and government agencies.

(3) To provide a means to evaluate the spectral quality of light sources through specially filtered solar cells or total energy measuring radiometers in conjunction with band-pass filters.

The work was done to fill the need for standard solar cells which are a tool used to evaluate production solar cells and spacecraft solar arrays. The standard solar cells, calibrated on high-altitude balloons, have proven to be a reliable and accurate device for solar cell and solar array evaluation.

It is recommended that the solar cell standardization program be continued and that calibration of standard solar cells on high-altitude balloon flights be performed on an annual or bi-annual basis as the need arises.

At the present time, the solar cell standardization program is the only proven method to obtain air mass zero (AM0) calibrated standard solar cells in a reliable and economical manner.

II. Introduction

One of the principal sources of electrical power for unmanned spacecraft comes from the direct conversion of solar energy through the use of solar cells. It is essential to the design of an array capable of meeting spacecraft requirements that the in-flight power output of these cells be accurately predictable from terrestrial sunlight measurements. The solar cell standardization program at JPL is satisfying this need through calibration of solar cells on high-altitude balloon flights.

The altitude selected for the 1970 series of balloon flights was 36,576 m (120,000 ft). The higher altitude (24,384 m previously) was again chosen to eliminate, as much as possible, the effects of solar energy absorption by the Earth's atmosphere. Solar cell measurements made on the 1970 flights were to within 0.46% of air mass zero as determined by a ratio of the atmospheric pressure at 36,576 m to that at sea level given in the Air Research and Development Command (ARDC) model atmosphere (Ref. 1). When the spectral response of a solar cell (0.4 to 1.2 μm) is taken into consideration, the solar irradiation at 36,576 m is essentially that of space sunlight (Table 1).

This report describes the balloon flight system and the results of three balloon flights conducted during July and August 1970 in the vicinity of Minneapolis, Minnesota.

III. Balloon Flight System

The main components of the balloon flight system are a helium-filled balloon, a Sun tracker, a telemetry system, and a battery power supply as shown in Fig. 1. The solar cells, which have been assembled into modular form in accordance with JPL Procedure No. EP504443A (Ref. 3), are mounted on the face of the Sun tracker. Dow Corning No. 340 silicone heat sink compound is applied at the interface of the solar cell module and the Sun tracker mounting plate to minimize thermal gradients between these surfaces and to ensure the best possible uniform temperature on all solar cells comprising the payload. Wires soldered to the terminals of the solar cell modules electrically connect the solar cells to a 36-position stepping switch.

The Sun tracker with the solar cell payload is mounted on the balloon apex. The telemetry system, battery power supply, and several instruments for measuring altitude are suspended beneath the balloon. An electrical cable, incorporated into the balloon during manufacture, connects the top and bottom payloads. A parachute is provided in the event of balloon failure.

The Sun tracker is used to position the solar cell payload toward the Sun, independent of balloon movements. The tracker is capable of movement in both elevation and azimuth to maintain an "on-Sun" condition within ±2 deg. A reflection shield attached to the Sun tracker prevents unwanted reflected light from reaching the solar cell payload.

The tracker and associated electronics are mounted on stand-offs above a plywood disk 1.83 m (6 ft) in diameter, which, in turn, is bolted to the balloon top end fitting and radio-controlled helium valve. The stand-offs provide clearance for the outlet of the helium valve, which is used as an alternate method of controlling balloon descent rate. The plywood disk permits the tracker to "float" atop the helium bubble and minimizes billowing of balloon material around the top payload. The weight of the entire top payload is approximately 24.95 kg (55 lb).

The balloon used for the 36,576-m (120,000-ft) altitude flights is 65.23 m (214 ft) in diameter when fully inflated and has a calculated volume of 97,987 m^3 (3,460,000 ft^3). The balloon material is polyethylene film designed specially for balloon use. The balloon material thickness for flight 70-1 was 25.4 μm (0.001 in.) (the balloon material thickness for the 1969 flights was 17.78 μm (0.0007 in.)

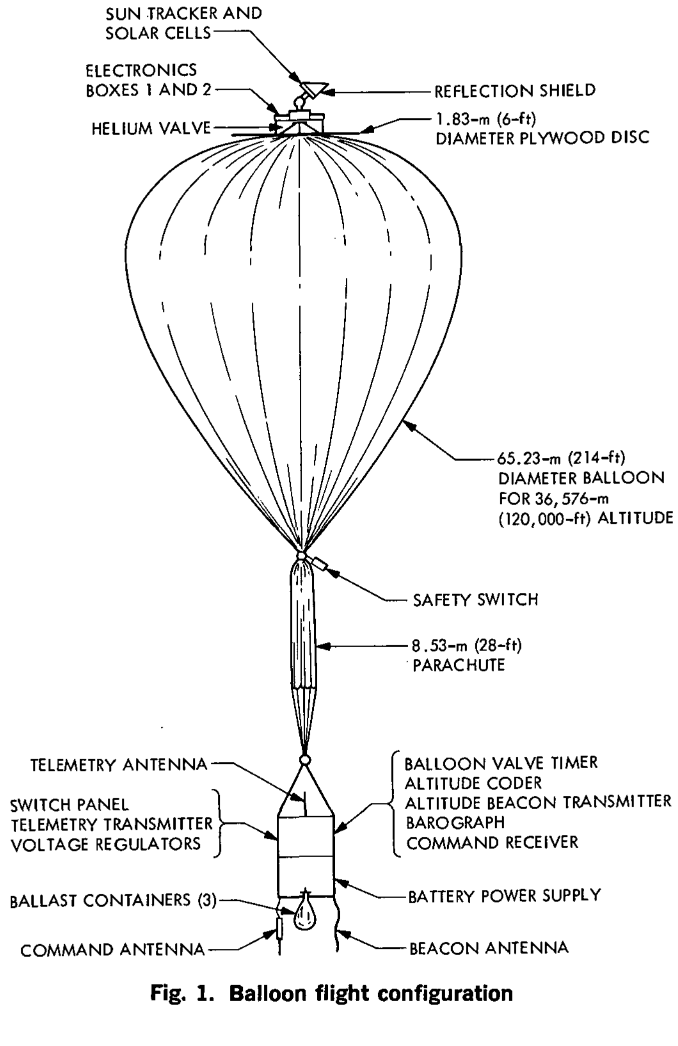

Fig. 1. Balloon flight configuration

Table 1. Attenuation of solar radiation by the Earth's atmosphere (Ref. 2)

Pressure, mbar	Altitude: Miles	Altitude: Thousand feet	Altitude: Kilometers	Wavelength regions: 0.12 to 0.20 μm	0.20 to 0.29 μm	0.29 to 0.32 μm	0.32 to 0.35 μm	0.35 to 0.55 μm	0.55 to 0.9 μm	0.9 to 2.5 μm	2.5 to 7 μm	7 to 20 μm	Altitude	IUGC
0.2	37	200	60	O_2 Absorbs almost completely	Solar irradiation intensity approximates extra atmospheric. Attenuation by scattering increases markedly toward shorter wavelengths.								Above 60 km	110 km CHEMO-SPHERE
7.5	20	108	33		(0.20 to 0.21 μm Absorption by O_2) Absorption by O_3 appreciable	O_3 absorption not important					Energy small	Energy very small	60 km to 33 km	
227	6.8	36	11		No radiation penetrates below about 11 km	O_3 absorption attenuates more than loss by scattering	O_3 absorption significantly attenuates radiation	Irradiation diminished mostly by scattering by permanent gases in atmosphere	H_2O responsible for major absorption; CO_2 absorbs slightly at 2 μm. Water vapor (or ice crystals) is found up to about 70,000 feet.			Strong O_3 absorption at 9.6 μm. Strong CO_2 absorption 12-17 μm	33 km to 11 km	20 km STRATO-SPHERE 11 km
795	1.2	6.6	2				Highly variable dust, haze (H_2O) (and smoke) responsible for attenuation in regions 0.32 to 0.7 μm		Energy transmitted with small loss down to 2 km	Energy penetrates to sea level only through "windows" at approximately 1.2, 1.6 and 2.2 μm	No significant penetration below 2 km except in "windows" at approximately 3.8 and 4.9 μm	Energy transmitted with moderate loss. Many absorption bands due to atmospheric gases	11 km to 2 km	TROPO-SPHERE
1013	Sea level					Appreciable penetration through "clear" atmosphere to sea level About 7% / About 30%	Penetration through "clear" atmosphere to sea level about 40%	Dust may rise to more than 4 km					2 km to sea level	0 km

and caused the average balloon weight (including the electrical cable) to increase to 364.2 kg (803 lb). This weight increase had a negligible effect on its ability to attain an altitude of 36,576 m (120,000 ft) with a total design payload of 170.1 kg (375 lb), and theoretically increased the chances of balloon survival under adverse handling, launch, and environmental conditions. Additional balloon specifications are listed in Table 2.

During inflation, the helium is confined to the upper portion of the balloon to reduce problems associated with surface winds (Fig. 2). The remainder of the balloon, protected by a polyethylene sheath, extends along the ground from the balloon launcher to a launch truck. The lower payload, containing batteries, timers, radio equipment, ballast containers, antennas, and a switch panel, is attached to the launch truck with an explosive bolt. Balloon launch is achieved by first releasing the upper portion, or bubble, of the balloon, held in position by the balloon launcher. Then, as the balloon rises, the launch truck is driven downwind to position the lower payload directly beneath the balloon. At this time, the explosive bolt is fired by push-button control within the launch truck, and the balloon is allowed to ascend (Fig. 3).

Table 2. Parameters for ST-213.94-100-NS-03 balloon

Payload (design)	170 kg (375 lb) to 36,576 m (120,000 ft)
Material (balloon wall and duct)	25.4 μm (1.0 mil) S.F. polyethylene
Volume (calculated)	97,987 m³ (3,460,000 ft³)
Surface area (estimated)	10,799 m² (116,242 ft²)
Inflated height	42.06 m (138 ft)
Inflated diameter	65.23 m (214 ft)
Deflated length (gore length)	86.26 m (283 ft)
Load tapes	90.72 kg (200 lb)
Fittings:	
Top (plate hoop and ring)	68.58 cm (27 in.) outer diameter
Bottom (wedge and collar)	12.70 cm (5 in.) outer diameter
Number of ducts	Two: 2.32 m² (25 ft²) each
Location of duct:	
Lo-duct	38.40 m (126 ft) from base
Hi-duct	75.59 m (248 ft) from base
Inflation tubes (2)	32.39 cm (12.75 in.) diam × 76.2 μm (3 mil) × 30.48 m (100 ft) long
Inflation attachment	9.14 m (30 ft) from top apex
Destruction device	Rip panel
Descent valves	Three gasports in hi-duct
Gasport location:	
Number 1	76.80 m (251 ft 10 in.) from base
Number 2	53.03 m (173 ft 10 in.) from base
Number 3	43.89 m (143 ft 10 in.) from base
Gasport size:	
Number 1	11.25-cm (4.500-in.) diameter
Number 2	14.92-cm (5.875-in.) diameter
Number 3	14.92-cm (5.875-in.) diameter
Estimated balloon weight (including cable)	364.24 kg (803 lb)
Engineering specification sheet	CO 9393
Manufacturer	Winzen Research, Inc., Minneapolis, Minn.

As the flight progresses, several functions are performed by pressure-sensitive switches and timing devices. At an altitude of 1524 m (5000 ft), a pressure switch activates a system deploying the long wire beacon antenna. When an altitude of 18,288 m (60,000 ft) is attained, another pressure-sensitive switch activates the Sun tracker, permitting it to lock on the Sun. At the completion of the float period, a preset timer opens several valves in the side of the balloon, allowing helium to escape at a controlled rate and causing the balloon and its associated equipment to descend to the earth. In the event the descent rate is insufficient, the radio-controlled helium valve can be activated.

During the period that the Sun tracker is locked on the Sun, solar cell voltages, interspersed with reference voltages and thermistor voltages, are fed into a voltage-controlled oscillator (VCO). The voltages are converted to frequencies and are transmitted to a ground station with a 5-W FM transmitter recently modified to operate on a new assigned frequency of 217.5 MHz. At the ground station, the data are recorded in digital form on printed paper tape and in analog form on a strip chart recorder (Fig. 4). The data are then transferred from the printed tape to punch cards compatible with a JPL computer program.

The battery power supply provides adequate power for a normal flight while keeping weight to a minimum. Aircraft-type lead-acid batteries are used to provide main power for the telemetry transmitter, the stepping switch, several temperature-controlling heaters, and other electronic equipment. The solar tracker is electrically isolated from the main batteries and is powered by a separate alkaline-type dry battery. The total weight of the battery power supply is 35.38 kg (78 lb).

Accuracy of the balloon flight system has been determined by Zoutendyk (Ref. 4) to be ±0.73%. Since

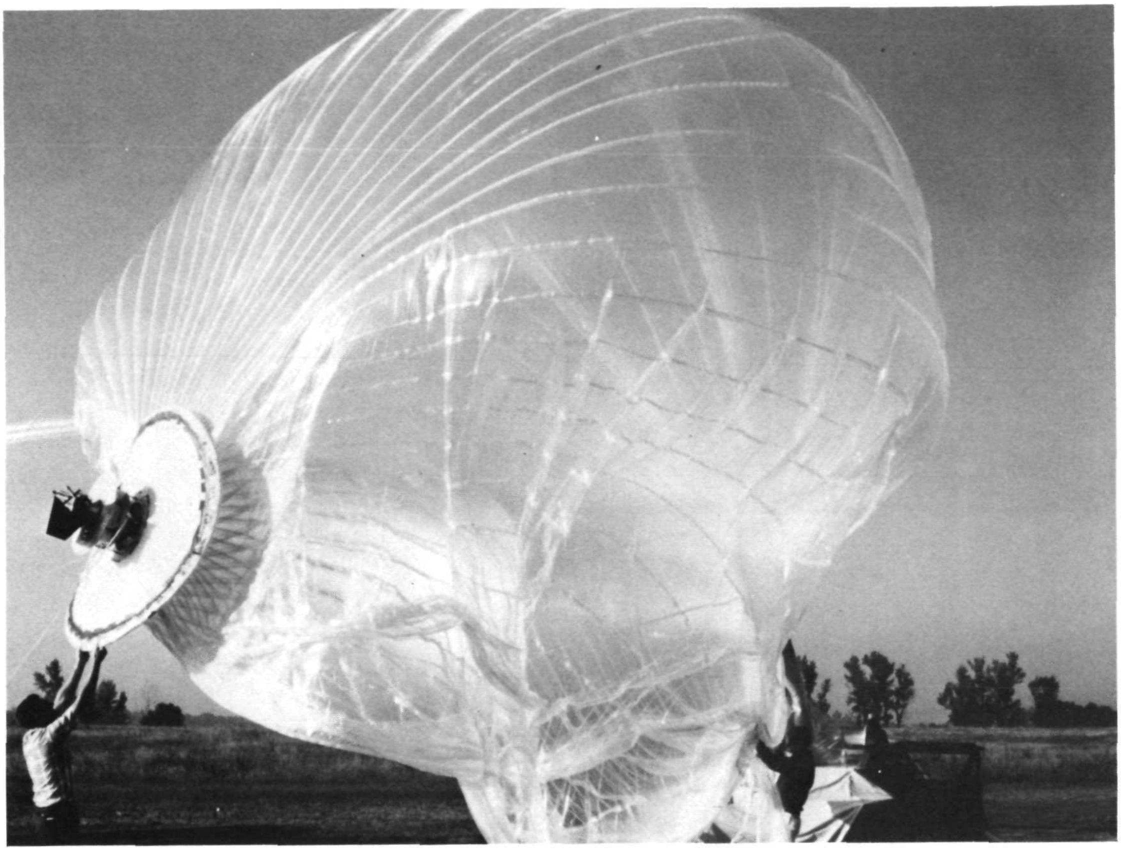

Fig. 2. Balloon inflation

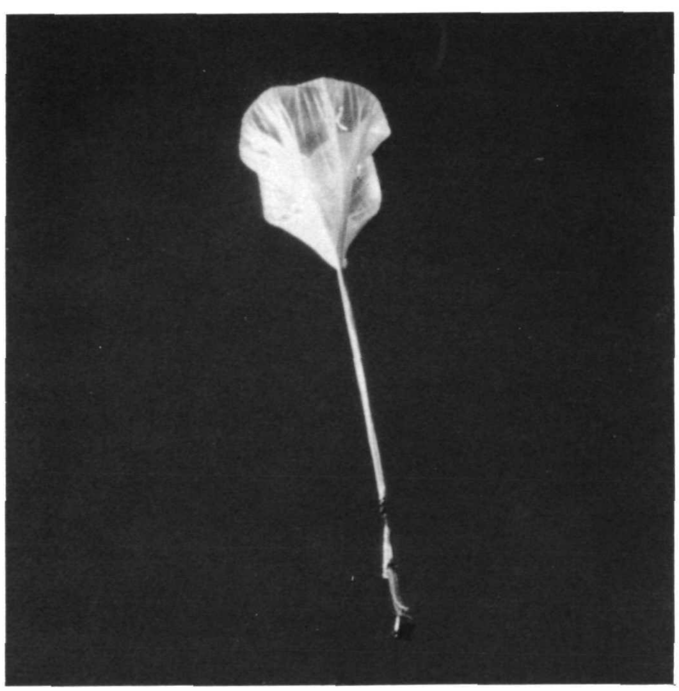

Fig. 3. Balloon system following launch

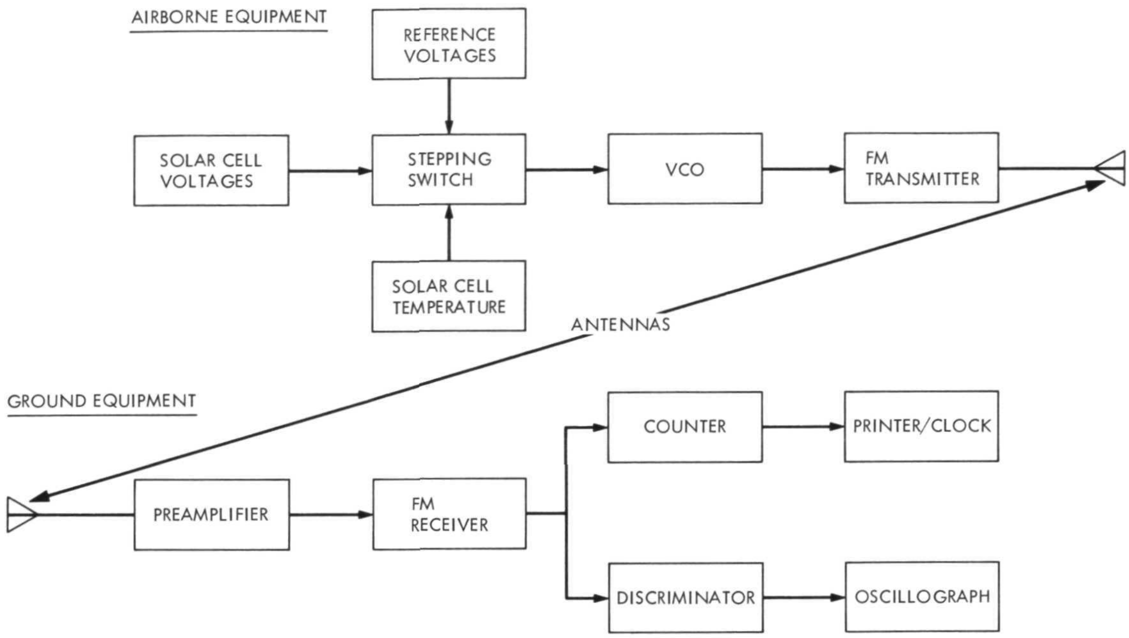

Fig. 4. Balloon telemetry system block diagram

that time, many small improvements were made to the solar tracker. This has narrowed the pointing accuracy from ±4.3 to ±2.0 deg. No other significant improvements have been made, but the tracking improvement brings the overall system accuracy to ±0.49%.

IV. Balloon Flight Payloads

Payloads for the 1970 balloon flight series were comprised of many types and configurations of solar cell modules. One of the payloads was made up of two active cavity radiometers.

The solar cell modules were supplied by six different NASA centers and government agencies. In order to insure compatibility with mechanical and electrical requirements of the balloon flight system, all modules were fabricated in accordance with the JPL Procedure for Balloon Flight Solar Cell Modules (Ref. 3). This procedure delineates physical size, mounting hole dimensions, and load resistor values in addition to material selection and assembly techniques.

The modules were shipped to JPL to permit inspection for workmanship and mechanical tolerances and were then given a pre-flight calibration in the JPL X-25L Spectrolab Solar Simulator. This calibration serves to correlate the solar simulator data supplied by the various organizations.

In general, correlations between test results obtained in the solar simulators of the different organizations and the JPL Solar Simulator have held within ±2.0%. However, solar cells other than silicon (e.g., cadmium sulphide), which have different spectral response bandwidths, or silicon solar cells covered with special band-pass filters, have exhibited differences of as high as 13.7% (Table 3).

Differences in test results obtained by various organizations are attributed to the use of different light sources, different standard solar cells used to set the intensity of the light sources, and measurement error. The Jet Propulsion Laboratory employs a filtered xenon light source which closely approximates space sunlight. Most NASA agencies now employ this same type of light source although, in the past, carbon arc light sources have been used and are in use today in some government agencies. A comparison of the filtered xenon light source with the NRL space sunlight curve is shown in Fig. 5. Figure 6 compares the spectral distribution of the carbon arc light source with the NRL space sunlight curve.

In summary, the problems which exist in the correlation of standard solar cells are:

(1) Solar simulators do not exactly duplicate the Sun's spectral distribution.

Table 3. Correlations between solar simulators of different organizations

Module No.	Cell Type	Manu-facturer	Agency	Agency source	Agency calib	JPL[a] calib	Deviation from JPL calib, %
GSF-701	N-P	HEK	Goddard	X-25	69.6	70.4	−1.14
GSF-702	N-P	HEK	Goddard	X-25	68.7	69.5	−1.15
GSF-703	N-P	HEK	Goddard	X-25	71.2	72.7	−2.06
GSF-704	N-P	HEK	Goddard	X-25	66.9	67.7	−1.18
GSF-705	N-P	SIE	Goddard	X-25	71.1	71.4	−0.42
GSF-706	N-P	AEG	Goddard	X-25	71.0	71.2	−0.28
LRC-003A	N-P	HEK	Langley	X-25	67.16	67.4	−0.36
LRC-003B	N-P	HEK	Langley	X-25	66.50	66.6	−0.15
LRC-004A	N-P	CRL	Langley	X-25	69.20	69.3	−0.14
LRC-004B	N-P	CRL	Langley	X-25	68.87	68.7	+0.25
IPC-701	N-P	IPC	AFAPL	X-25L	67.0	66.1	+1.36
IPC-703	N-P	IPC	AFAPL	X-25L	66.0	65.5	+0.76
IPC-704	N-P	IPC	AFAPL	X-25L	66.0	65.6	+0.61
MSF-8003	N-P	CRL	Marshall	X-25	59.21	58.0	+2.09
MSF-8004	N-P	CRL	Marshall	X-25	60.97	59.2	+2.99
APL-I[b]	N-P	HEK	APL	OCLI-31	88.0	80.5	+9.32
APL-II[b]	N-P	HEK	APL	OCLI-31	80.0	82.6	−3.15
APL-III[b]	N-P	HEK	APL	OCLI-31	71.6	83.0	−13.73
APL-IV[b]	N-P	HEK	APL	OCLI-31	72.9	72.8	+0.14
APL-V[b]	N-P	HEK	APL	OCLI-31	81.1	83.5	−2.87

[a]JPL calibration using Spectrosun X-25L Solar Simulator, 1-AU sunlight equivalent, 301.15 K (28°C).

[b]Set of solar cells each covered with a different band-pass filter.

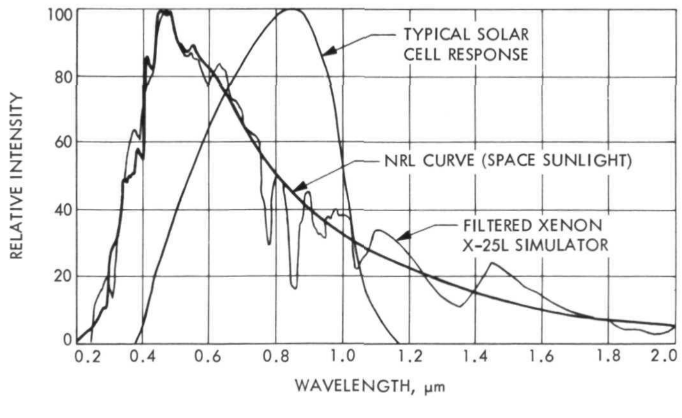

Fig. 5. Comparison of filtered xenon light source (X-25L) with space sunlight

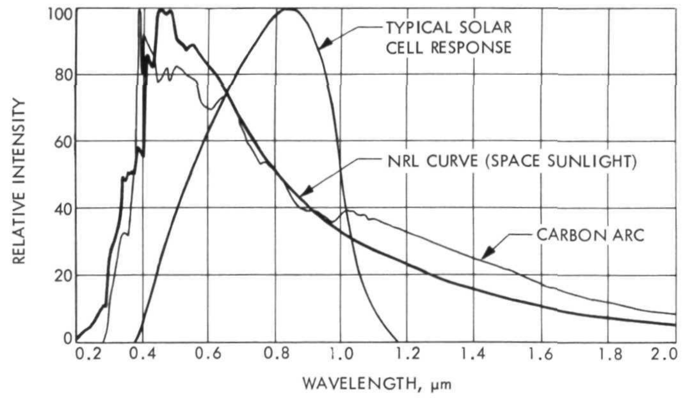

Fig. 6. Comparison of carbon arc light source with space sunlight

(2) There are differences in the spectral distribution among solar simulators. These differences exist due to:

   (a) Design

   (b) Degree of spectral filtering

   (c) Type of lamp

   (d) Lamp aging

   (e) Lamp current

   (f) Condition of optical surfaces

(3) Solar cells have different spectral responses due to type and diffusion depth.

(4) Filters placed on a solar cell effectively alter the spectral response.

(5) Inaccuracy of simulator intensity setting.

(6) Instability of simulator intensity setting.

(7) Non-uniformity of the beam pattern.

Correlation to space conditions as well as among solar simulators can be achieved to within a $\pm 2.0\%$ tolerance providing that:

(1) The spectral distribution of the solar simulator closely matches the spectral distribution of the Sun (Johnson's curve).

(2) A standard solar cell is employed which matches the spectral response of the cell or cells to be measured.

(3) The optical surfaces of the simulator are kept clean and in good condition.

(4) Lamp stability and beam uniformity are within the manufacturer's tolerance.

(5) A means is employed to ensure that the spectral distribution is maintained within established limits.

Organizations that supplied solar cell modules as part of a cooperative solar cell calibration effort are listed as follows:

(1) NASA Langley Research Center.

(2) NASA Goddard Space Flight Center.

(3) NASA Marshall Space Flight Center.

(4) Air Force Aero Propulsion Laboratory.

(5) Johns Hopkins University, Applied Physics Laboratory.

(6) California Institute of Technology, Jet Propulsion Laboratory.

The first flight of the 1970 series had a payload of two radiometers. These total radiation detection devices were designed and built by the Instrumentation Section of JPL (Ref. 5). The purpose of the radiometer flight was to obtain data on the solar constant and to provide correlation with a similar instrument, the temperature control flux monitor (TCFM) flown on the Mariner Mars 1969 spacecraft. The radiometers also have application in the laboratory for measuring the total incident radiation from artificial light sources. Although not planned for on this flight, the radiometers can be coupled with special bandpass filters so that a bandwidth-by-bandwidth comparative analysis can be made between space sunlight and solar simulators (Ref. 6).

The solar cell modules were divided into payloads for the remaining two flights. Figure 7 depicts the module mounting arrangement for the second flight, and Fig. 8 is the photograph of the payload for the second flight. Figure 9 shows the module mounting arrangement for the third flight, while Fig. 10 is the photograph of the third flight solar cell payload.

V. Balloon Flight Performance

A. Flight 70-1

A launch was attempted for balloon flight 70-1 on July 16, 1970 at 08:10 CDT. Unfortunately, the slack-chute-line holding the safety parachute in a tightened launch position was stressed and snapped. Breakage of this line was no serious matter, but its sudden release resulted in separation of a quick-release connector in the electrical cable powering the top payload. The cable was securely reconnected, and the launch sequence was resumed. At this time, a lack of lift was noted, and, as expected, the lower payload settled back to the ground moments after release. The top payload was steadied as it slowly sank to the ground and a long vertical rip was observed in the bubble area of the balloon.

The Sun tracker, radiometer payload, and all other system components, with the exception of the balloon, were

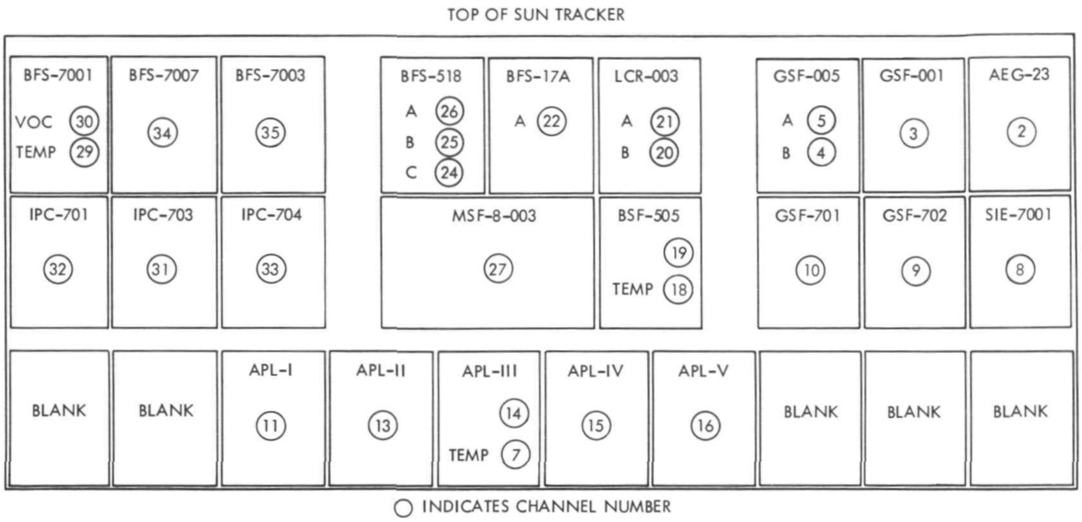

Fig. 7. Cell placement for flight 70-2 (July 28, 1970)

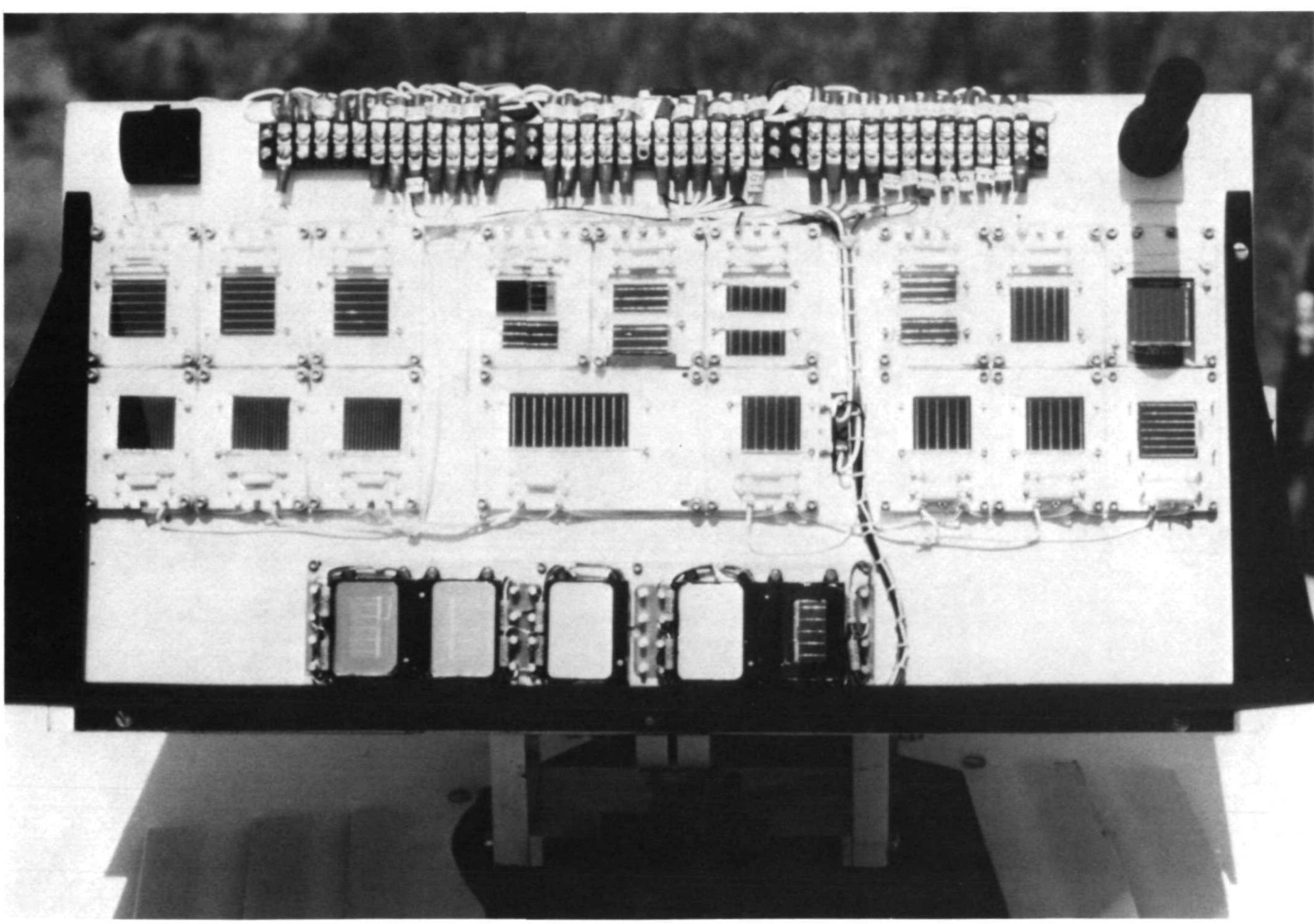

Fig. 8. Solar cell payload for flight 70-2

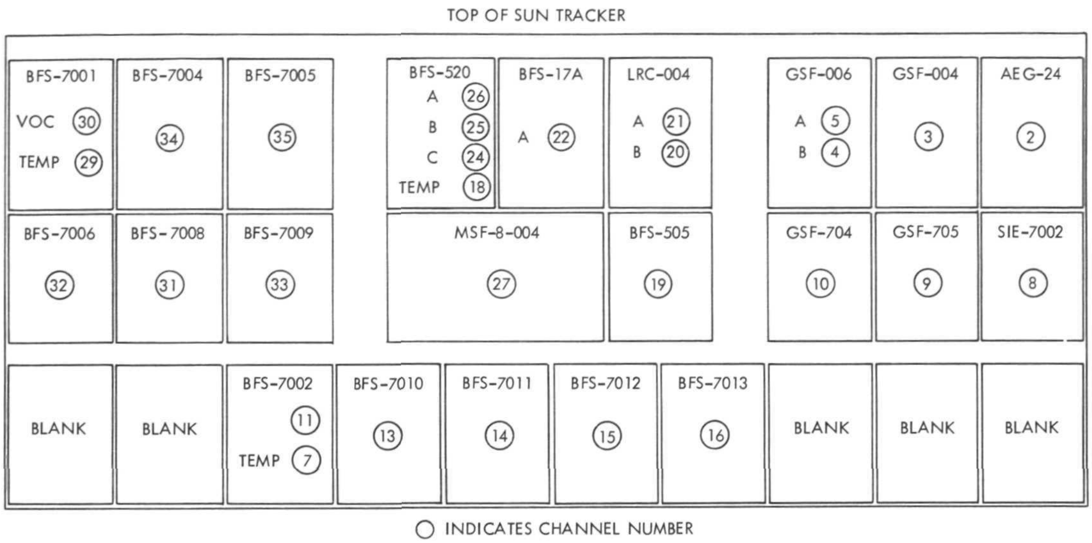

Fig. 9. Cell placement for flight 70-3 (August 5, 1970)

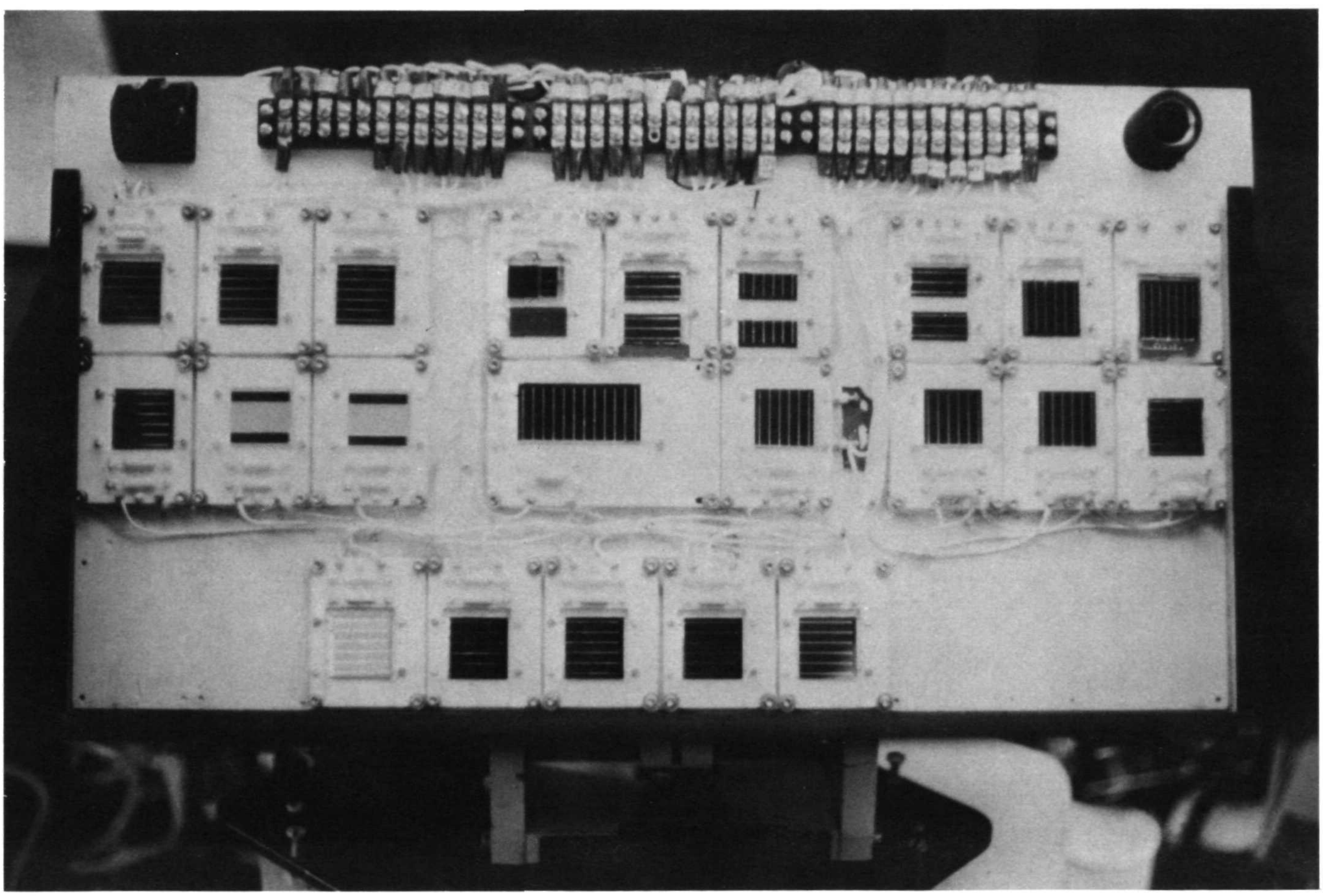

Fig. 10. Solar cell payload for flight 70-3

recovered without damage. Evidently, the balloon did not ascend properly because a balloon seam was severely weakened during previous launch attempts in 1969 and subsequent repairs (Ref. 7). Apparently, the seam gave way during the initial shock associated with release of the bubble or during the period when the balloon was restrained for cable reconnection, or when the lower payload was released.

B. Flight 70-2

Prior to launch, some of the system components were rewired to accommodate a solar cell payload. The flight was launched on July 28, 1970 at 08:14 CDT and reached a peak float altitude of 36,820 m (120,800 ft) at 11:01 CDT and remained above 35,570 m (116,700 ft) throughout the float period.

Although sizing and placement of the descent gasports had been improved on this balloon to provide a more adequate descent rate, the initial descent rate was only 72.5 m/min (238 ft/min). The radio-controlled helium valve was actuated to increase the descent rate and ensure against activation of the safety switch which separates the balloon and lower payload just prior to darkness. This method of payload separation is necessary to clear airlanes during the night hours. With time to spare, the entire system reached the earth at 18:30 CDT near Claremont, South Dakota, without damage to the Sun tracker or the solar cell payload.

C. Flight 70-3

This flight also carried a solar cell payload and was launched on August 5, 1970 at 08:28 CDT. The balloon reached a peak float altitude of 36,759 m (120,600 ft) at 10:46 CDT and remained above 35,753 m (117,300 ft) during the required 4-h float period. The balloon system was again returned to Earth in excellent condition near Doland, South Dakota at 19:02 CDT. Although the descent took longer than the previous flight, it was apparent that the balloon system would reach the Earth before payload separation. For this reason the radio-controlled helium valve was not used on descent but was opened immediately prior to Earth impact to aid balloon deflation.

VI. Discussion of Balloon Flight Data

A. Flight 70-1 Data

Due to the balloon failure at launch of flight 70-1, no data was obtained from the radiometer payload.

B. Flight 70-2 Data

Data from the solar cell payload were continuously recorded from the time the solar tracker was activated by pressure switch at 18,288 m (60,000 ft) until the end of the data recording period on descent. Data taken prior to and following the float period are normally not used since solar cell temperatures are changing rapidly, and the solar tracker has difficulty maintaining "on-Sun lock" due to a higher degree of balloon rotation during ascent and descent. Data recorded from the second flight were of high quality in that they were stable and exhibited a minimum of radio interference. The radio interference was evident to Channel 26 only when the beacon transmitter was on. Data recorded during interference periods were eliminated.

The voltage-controlled oscillator (VCO) reference frequencies remained stable throughout the flight with only a variation of 3 Hz, significantly better than the average 8-Hz reference frequency variation experienced on previous flights. This condition indicated that the thermostat controlling the temperature of the VCO to 60°C was functioning properly. It should be mentioned at this point that, even though the reference frequencies should drift during the flight, the computer program will compensate for the error using the on-board calibration voltages, interspersed with solar cell data, as references.

Data points recorded between 12:29 and 15:00 CDT while the balloon was at float altitude were selected for processing. These points were chosen because temperature variations were at a minimum during the float period. Figure 11 shows a typical temperature profile for a normal 36,576-m (120,000-ft) balloon flight. A computer program corrects for solar intensity and solar cell temperature so that the calibrated value of the standard solar cell is given at one solar constant or one astronomical unit (AU) and at a temperature of 301.15 K (28°C).

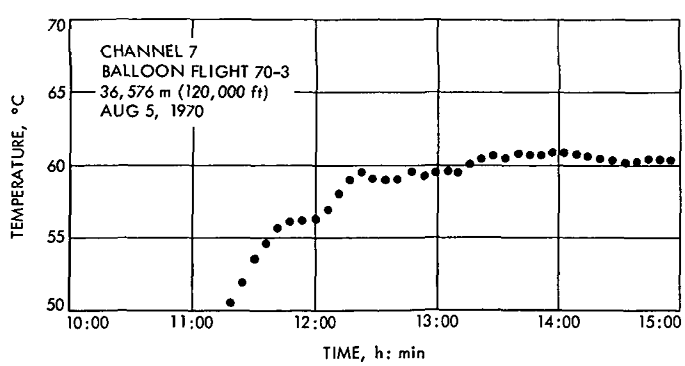

Fig. 11. Typical balloon flight solar cell temperature profile

Corrections for solar intensity must be made because of the constantly changing Earth–Sun distance over the course of a year.

For the heliocentric range considered, and for the type of silicon solar cells being tested, it has been shown that the short-circuit current (Isc) of a solar cell at a constant temperature varies directly with solar intensity. It also has been shown that for the heliocentric range considered, the solar intensity varies inversely with the square of the distance from the Sun. It follows, therefore, that the short-circuit current of a solar cell at near-Earth space conditions varies inversely with the square of the distance from the Sun:

$$\frac{\text{Isc } 2}{\text{Isc } 1} = \frac{1}{(\text{AU})^2}$$

or

$$\text{Isc } 1 = \text{Isc } 2\,(\text{AU})^2$$

where

Isc 1 = Isc at 1 AU

Isc 2 = measured value from balloon flight

AU = Earth–Sun distance

The Earth–Sun distance (AU) is given for any particular day of a year in regularly published ephemeris tables as the radius vector (Ref. 8). On July 28, 1970, the Earth–Sun distance was given as 1.0155 AU according to Ref. 8. This means that the short-circuit current of each standard solar cell on the balloon flight for the above date may be corrected to its standard Isc output at 1 AU by applying the above equation. For example, standard cell BFS-17A had an average Isc of 59.72 mA while at float altitude on July 28, 1970. Substituting in the equation:

$$\text{Isc } 1 = 59.72 \text{ mA } (1.0155)^2 = 61.59 \text{ mA}$$

Therefore, the corrected value to 1 AU for standard solar cell BFS-17A is 61.59 mA. In a like manner, the Isc of each standard solar cell on the balloon flight for that date (July 28, 1970) may be corrected to its Isc output at 1 AU.

It should be emphasized that the calibration value of a standard solar cell is a function of the mean Earth–Sun distance and the inverse square law for luminous flux. The calibration value does not depend on measured values of the solar intensity.

Corrections for temperature effects on solar cells are made to a standard temperature for ease in data comparison. The temperature of 301.15 K (28°C) came into use since it was an easily obtainable temperature for laboratory measurement of solar cells. To correct the output of a solar cell for temperature effects, the temperature coefficient must be known and is obtained experimentally from laboratory measurements for each cell.

A resistor must be used to load the solar cell near its short-circuit current point. The load resistor value is usually one ohm or less but can be higher depending upon the cell size and filter cover used. It is the voltage drop across the load resistor which is actually measured; therefore, the cell output is in millivolts and the temperature coefficient is in millivolts per kelvin even though it still relates to the short-circuit current.

Solar cell data for the second flight are presented in Table 4. The calibration data, or the cell output, have been corrected to the solar intensity at 1 AU and to a temperature of 301.15 K (28°C).

C. Flight 70-3 Data

Data from the third flight of the 1970 series were also of high quality, although the VCO did not exhibit as high a degree of stability because the temperature control thermostat apparently froze in the "on" position for a short period between 12:06 and 12:23 CDT. This caused a reference frequency variation of 6 Hz. Data taken during this period was eliminated, thus reducing the frequency variation to 3 Hz, equivalent to the excellent stability obtained on the previous flight. Operation of the beacon transmitter caused no radio interference to the solar cell data on this flight.

Solar cell data recorded between 12:23 and 14:56 CDT were selected and processed to provide 27 data points at float altitude. The maximum module temperature during the float period was 334.3 K (61.2°C), and the average temperature during the same period was 333.4 K (60.3° C).

Table 4. Flight 70-2 standard cell data summary[a]

Standard cell number	Manu-facturer	Type	Material	Cell dimensions, cm	Base resistivity, ohm-cm	Filter data	Temperature coefficient, mV/K	Calibration data at 1 AU, 301.15 K, mV
AEG-23	AEG[b]	N-P	Silicon	2 × 2 × 0.030	10	Suprasil cover	0.019	67.09
APL[c]-I	HEK[d]			1 × 2 × 0.036		0.405-0.695 μm	−0.066	81.73
APL-II				1 × 2 × 0.036		0.695-0.740 μm	−0.055	74.86
APL-III				1 × 2 × 0.036		0.740-0.810 μm	−0.023	75.27
APL-IV				1 × 2 × 0.036		0.810-1.06 μm	0.121	71.80
APL-V		N-P		1 × 2 × 0.036	10	F. silica cover	0.027	80.32
BFS[e]-17A		P-N		1 × 2 × 0.046	1	0.41-μm 0211	0.036	60.42
BFS-505		N-P		2 × 2 × 0.046		0.41-μm 7940	0.050	65.87
BFS-518A				0.6 × 1 × 0.046		Red 7-69	0.000	23.19
BFS-518B				0.6 × 1 × 0.046		Blue 1-57	−0.042	24.08
BFS-518C				1 × 2 ×0.046		0.41-μm 0211	0.021	66.38
BFS-7001				2 × 2 × 0.046		0.41-μm 7940	−0.227	58.82
BFS-7003	HEK	N-P		2 × 2 × 0.046			0.021	67.79
BFS-7007	CRL[f]	P-N		2 × 2 × 0.046	1		−0.071	80.15
GSF[g]-001	HEK	N-P		2 × 2 × 0.036	10		0.034	68.60
GSF-005A				1 × 2 × 0.036			0.017	71.15
GSF-005B				1 × 2 × 0.036			0.032	69.95
GSF-701				2 × 2 ×0.033			0.055	69.30
GSF-702	HEK			2 × 2 ×0.033			0.055	68.72
IPC-701	IPC[h]			2 × 2 × 0.036			0.049	65.02
IPC-703	IPC			2 × 2 × 0.036			0.049	64.40
IPC-704	IPC			2 × 2 × 0.036	10		0.049	64.71
LRC-003A	HEK			1 × 2 × 0.030	1		0.035	66.09
LRC[i]-003B	HEK			1 × 2 × 0.030	1	0.41-μm 7940	0.035	65.66
MSF[j]-8003	CRL			2 × 4 × 0.036	1	0.41-μm Microsht	0.027	57.54
SIE-7001	SIE[k]	N-P	Silicon	2 × 2 × 0.030	1	0.40-μm Suprasil	0.040	65.89

[a]Flight date: July 28, 1970; altitude: 36,576 m (120,000 ft); adjusted data: 1 AU, 301.15 K.
[b]AEG Telefunken.
[c]Applied Physics Laboratory.
[d]Heliotek, a division of Textron, Inc.
[e]Balloon flight standard.
[f]Centralab, Globe-Union, Inc.
[f]Goddard Space Flight Center.
[h]Ion Physics Corp.
[i]Langley Research Center.
[j]Marshall Space Flight Center.
[k]Siemens Aktiengesellschaft.

Table 5. Flight 70-3 standard cell data summary[a]

Standard cell number	Manu-facturer	Type	Material	Cell dimensions, cm	Base resistivity, ohm-cm	Filter data	Temperature coefficient, mV/K	Calibration data at 1 AU, 301.15 K, mV
AEG-24	AEG[b]	N-P	Silicon	2 × 2 × 0.030	1	Suprasil cover	0.047	66.96
BFS[c]-17A	HEK[d]	P-N		1 × 2 × 0.046		0.41-μm 0211	0.036	60.32
BFS-505		N-P		2 × 2 × 0.046		0.41-μm 7940	0.050	65.60
BFS-520A				0.6 × 1 × 0.046		Red 7-69	0.000	24.07
BFS-520B				0.6 × 1 × 0.046		Blue 1-57	−0.042	24.86
BFS-520C				1 × 2 × 0.046		Neutral density	−0.007	17.41
BFS-7001				2 × 2 × 0.046		0.41-μm 7940	−0.227	59.89
BFS-7002				2 × 2 × 0.046		0.41-μm 7940	0.028	66.33
BFS-7004	HEK			2 × 2 × 0.046		None	0.056	67.72
BFS-7005	CRL[e]	N-P		2 × 2 × 0.046		None	0.047	70.13
BFS-7006		P-N		2 × 2 × 0.046		None	−0.007	81.41
BFS-7008		N-P		2 × 2 × 0.046		None	0.009	27.21
BFS-7009				2 × 2 × 0.046	1	0.41-μm 7940	0.000	29.02
BFS-7010				2 × 2 × 0.046	10	None	0.034	72.21
BFS-7011				2 × 2 × 0.046		0.41-μm 7940	0.029	71.79
BFS-7012				2 × 2 × 0.046		None	0.042	74.16
BFS-7013				2 × 2 × 0.046		0.41-μm 7940	0.019	72.71
GSF[f]-004	CRL			2 × 2 × 0.036			0.031	70.79
GSF-006A	HEK			1 × 2 × 0.036			0.063	54.18
GSF-006B	HEK			1 × 2 × 0.036			0.082	52.79
GSF-704	HEK			2 × 2 × 0.033			0.055	66.55
GSF-705	HEK			2 × 2 × 0.033			0.055	69.72
LRC[g]-004A	CRL			1 × 2 × 0.030			0.048	68.46
LRC-004B	CRL			1 × 2 × 0.030	10	0.41-μm 7940	0.047	68.08
MSF[h]-8004	CRL			2 × 4 × 0.036	1	0.41-μm Microsht	0.027	59.30
SIE-7002	SIE[i]	N-P	Silicon	2 × 2 × 0.030	1	0.40-μm Suprasil	0.046	65.95

[a]Flight date: Aug. 5, 1970; altitude: 36,576 m (120,000 ft); adjusted data: 1 AU, 301.15 K.
[b]AEG Telefunken.
[c]Balloon flight standard.
[d]Heliotek, a division of Textron, Inc.
[e]Centralab, Globe-Union, Inc.
[f]Goddard Space Flight Center.
[g]Langley Research Center.
[h]Marshall Space Flight Center.
[i]Siemens Aktiengesellschaft.

The solar cell data for the third flight were reduced by computer in the same manner as described for the second flight and are listed in Table 5.

VII. Contents of Data Package

Following the final balloon flight and after the raw data had been reduced by computer, the standard solar cell calibration data were delivered to the several organizations participating in the standardization effort.

The data consisted of a copy of the computer printout sheet and an analog plot which gave solar cell data points in millivolts as a function of time and temperature. The computer printout sheet gives the final corrected calibration data for each cell which is also given in Tables 4 and 5 in this report. A final item included in the calibration data package was a diagram showing standard cell placement on the solar track similar to Figs. 7 and 9 in this report.

The calibrated standard solar cells were returned to the respective organizations along with the above described calibration data package so that the standard cells could be used immediately.

VIII. Use of Standard Solar Cells

Standard solar cells, calibrated by means of high-altitude balloon flights, are maintained by JPL for flight and advanced development programs. The standards can be used in either of two ways.

(1) When used with artificial light sources, the standard cell is placed in the light beam and the intensity is adjusted until the output of the standard cell is equivalent to the 1 AU calibrated value or to any desired ratio of the calibrated value. The temperature of the standard cell is held constant at the standard temperature of 301.15 K (28°C). Once the intensity of the artificial light source has been set, test solar cells can be placed in the light beam and their parameters measured.

(2) When used in terrestrial sunlight, the standard cell is placed in the same field of view as the solar cells or solar array being measured. Provisions should be made to maintain the standard cell at the standard temperature. If this is not practical, then the temperature of the standard must be measured and the output value corrected through application of the temperature coefficient. The output value of the standard solar cell is used to determine the incident solar radiation on the photovoltaic devices under test by direct ratio.

IX. Future Plans

Flights were not scheduled for the summer of 1971 because of budget limitations, combined with a standard cell inventory which could meet most of the needs for fiscal year 1972. A continuing program for calibrating standard solar cells is necessary to aid in the evaluation of new types of solar cells as they are developed.

Future needs for standard solar cells can probably be met with fewer balloon flights than were conducted in previous years; therefore, it is planned to conduct balloon flights for solar cell standardization every two or three years as the need arises. Communication with NASA centers and government agencies will be maintained so that plans can be made to fill anticipated standard solar cell requirements.

Flights will normally be made to a 36,576-m (120,000-ft) altitude to minimize the effects of atmospheric energy absorption. When the manned orbiting laboratory and the space shuttle become a reality, a perfect opportunity will exist to calibrate standard solar cells in space.

X. Conclusions

Table 6 lists data gathered on one particular standard solar cell (BFS-17A) over an 8-yr period. This cell was used as a reference on nearly every balloon flight and has repeated its mean calibration value in each instance to within 1%. From this data, two conclusions can be

Table 6. Repeatability of standard solar cell BFS-17A for 20 flights over an 8-yr period

Flight date	Output,[a] mA
9/5/63	60.07
8/3/64	60.43
8/8/64	60.17
7/28/65	59.90
8/9/65	59.90
8/13/65	59.93
7/29/66	60.67
8/4/66	60.25
8/12/66	60.15
8/26/66	60.02
7/14/67	60.06
7/25/67	60.02
8/4/67	59.83
8/10/67	60.02
7/19/68	60.31
7/29/68	60.20
8/26/69	60.37
9/8/69	60.17
7/28/70	60.42
8/5/70	60.32
Mean	60.16 mA
Maximum deviation from mean	0.85%
RMS deviation from mean	0.35%

[a]Each data point is an average of 20–30 data points from each flight. All data are normalized to 1 AU sunlight equivalent, 301.15 K (28°C)

stated: (1) That the balloon flight system has maintained excellent stability over the years, and (2) that silicon solar cells are reliable as standards over a long term if properly maintained.

Because of the balloon failure at launch of the first flight, it is concluded that repaired balloons, as in this instance, are not reliable, and it is recommended that no attempt be made to repair a flight-line damaged balloon should such a condition arise in the future.

The solar cell standardization program is a continuing program designed to fill the need for standard solar cells. The use of high-altitude balloons has proven to be feasible, reliable, and an economical method to obtain the needed standards.

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15. Supplementary Notes

16. Abstract

For the eighth consecutive year, high-altitude calibration of solar cells was accomplished during July and August of 1970 with the aid of free-flight balloons. Flights were conducted to an altitude of 36,576 m (120,000 ft), which is above 99.5% of the Earth's atmosphere where all water vapor levels and significant ozone bands are absent. Solar cells calibrated in this manner are recovered and used as intensity references in solar simulators and in terrestrial sunlight. Balloon-calibrated solar cells were made available by JPL to NASA centers and other government agencies through a cooperative effort. An attempt to fly radiometers to measure the solar constant was aborted because of a balloon failure at launch. This report discusses the method employed for high-altitude balloon flight solar cell calibration. Also presented are the data collected on 52 standard solar cells on two flights conducted in 1970. Solar cells flown repeatedly on successive flights have shown correlation of better than ± 1.0%.

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