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Solar Cell Calibration Facility Validation of Balloon Flight Data

A Comparison of Shuttle and Balloon Flight Results

B. E. Anspaugh
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October 15, 1985

National Aeronautics and
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Jet Propulsion Laboratory
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16. Abstract

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ABSTRACT

The Solar Cell Calibration Facility (SCCF) experiment was designed and built to evaluate the effect of the earth's upper atmosphere on the calibration of solar cell standards. During execution of the experiment, a collection of carefully selected solar cells was flown on the shuttle, and reflown on a high-altitude balloon, then their outputs were compared. After correction to standard temperature and intensity values of 28 deg C and an earth-sun distance of 1 AU, the solar cell outputs during the two flights were found to be identical. The conclusion is therefore that the high-altitude balloon flights are very good vehicles for calibrating solar cells for use as space flight reference standards.

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What goes up must come down, but don't expect it
to come down where you can find it -- Lily Tomlin

SECTION 1

INTRODUCTION

The Solar Cell Calibration Facility (SCCF) experiment was conceived to evaluate the effect of the earth's upper atmosphere on the calibration of space solar cell standards. The concept involved flying a collection of solar cells on the shuttle, reflying them on a balloon, and then comparing their outputs. When flown on the balloon at altitudes near 120,000 ft (36 km), the cells receive sunlight only after it passes through a thin band of atmosphere. This thin band attenuates solar radiation by a small amount. The experiment was designed to determine whether this attenuation has any measurable effect on the output of solar cells. If so, calibration values that have been derived from balloon flights over the past 22 years would have to be changed. Nearly all the solar panels flown in space (during those 22 years) have been measured on ground-based solar simulators whose intensity was set using one of these balloon-flown standards, so if the effect is large, the result would be of considerable interest to the space power community.

A secondary objective of the SCCF experiment was to measure the temperature coefficients of the collection of solar cells during the shuttle flight and compare the results with measurements made in the laboratory. Solar cells produce short circuit currents that increase linearly as a function of temperature. This rate of increase, the solar cell short-circuit-current-temperature coefficient, is commonly used to correct solar cell data to some standard temperature. The use of accurate temperature coefficients is essential in many aspects of solar cell measurements and solar panel design. Their measurement in space should agree with their measurement in the laboratory.

SECTION 2

EXPERIMENT DESCRIPTION

2.1 OPERATIONAL SEQUENCE

The SCCF experiment was one of three experiments that made up a larger experimental package called the OAST-1, which flew successfully on the first flight of the Discovery shuttle (STS-41-D mission) from late August through early September 1984. The SCCF consisted of a panel of solar cells and thermistors, the mounting structure, and control electronics. An on-board data acquisition system processed the experimental data and recorded them on tape. With the exception of electrical power, which was derived from the shuttle, the SCCF was entirely self-sufficient and required no telemetry.

Operation of the SCCF experiment was initiated by switching on SCCF power, then giving a command to the shuttle's attitude control system which caused the shuttle to rotate and point its payload bay at the sun. The shuttle's celestial sensors and computers then controlled its attitude to keep the SCCF solar panel perpendicular to the sun. An on-sun indicator located on the SCCF solar panel monitored the accuracy of the alignment with the sun. If the alignment was within a 3 degree half-cone angle, data was accepted by the data acquisition system and recorded onto magnetic tape. The experiment was turned on four times during the Discovery flight and each time it was operated for the sunlit duration of an entire orbit.

At the end of the flight, the solar cells were removed from the panel and mounted on the tracker used for JPL high-altitude balloon flights. They were flown on balloon flight No. 1405P on July 12, 1985, at the National Scientific Balloon Facility (NSBF) in Palestine, Texas. After reaching a float altitude of 115,000 ft (35 km), the tracker was turned on, allowing it to lock onto the sun. During this time, the solar cell output and solar panel temperature data were radioed to Palestine by the on-board telemetry system where it was decoded and recorded on magnetic tape. The flight was terminated after recording data for a three hour period centered around solar noon. The payload came down by parachute, was recovered, and was returned to JPL.

The balloon flight data and shuttle flight data were analyzed similarly, except that temperature coefficients measured in the JPL solar simulation laboratory were used for making temperature corrections to the balloon data. The data analysis programs for these two experiments were written by different programmers and the methods of analysis were developed separately. This procedure was used to minimize the possibility of accidental agreements or disagreements between shuttle data and balloon flight data.

2.2 SOLAR CELL DESCRIPTION

Many types and sizes of solar cells were selected for this experiment. They were chosen to have wide variations in technology, size, manufacturer, and material. Cells with wide variations in spectral response were also included. If the attenuation of solar illumination was significant, the cells having high blue sensitivity would be expected to show more difference in output than those cells with a high red sensitivity. Table 1 lists the cell types flown and gives a description of the technology used to manufacture the cells. The photograph in Figure 1 shows how the cells appeared after assembly onto the shuttle flight panel. Figure 2 is a diagram of the same panel, identifying the modules as they were placed on the panel.

Table 1. Description of the Modules

Module No.	Cell Description	Size		Technology			
78-012	Vertical Junction	2x2					
81-002	Planar	2x2	10 mil	TEX	BSF	BSR	MLAR
81-143	w.a.	6x6	8 mil				
81-146	w.a.	6x6	8 mil				
STS-011	w.a.	2x4	8 mil			BSR	
STS-026T	w.a.	2x4	8 mil			BSR	
STS-012	w.a.	2x4	2 mil		BSF	BSR	MLAR
STS-027T	w.a.	2x4	2 mil		BSF	BSR	MLAR
STS-016T	w.a. Low alpha	2x2	2 mil			BSR	MLAR
STS-002	w.a. Low alpha	2x2	2 mil		BSF	BSR	MLAR
STS-003	LPE GaAs	2x2					
STS-018T	LPE GaAs	2x2					
STS-028T	LPE GaAs	2x4	12 mil				
STS-004	Hi Red	2x2	8 mil	TEX	BSF	BSR	MLAR
STS-019T	Hi Red	2x2	8 mil	TEX	BSF	BSR	MLAR
STS-005	Lo Red	2x2	4 mil			BSR	MLAR
STS-020T	Lo Red	2x2	4 mil			BSR	MLAR
STS-006	Hi Blue	2x2	8 mil			BSR	MLAR
STS-021T	Hi Blue	2x2	8 mil			BSR	MLAR
STS-007	Lo Blue Lo Red	2x2	8 mil			BSR	Ta_2O_5
STS-022T	Lo Blue Lo Red	2x2	8 mil			BSR	Ta_2O_5
STS-008	Flat SR	2x2	8 mil		BSF	BSR	Ta_2O_5
STS-023T	Flat SR	2x2	8 mil		BSF	BSR	Ta_2O_5
STS-009	Gridded back	2x2	3 mil		BBSF	BSR	MLAR
STS-024T	Gridded back	2x2	3 mil		BBSF	BSR	MLAR
STS-010		2x2	2 mil		BBSF	BSR	MLAR
STS-025T		2x2	2 mil		BBSF	BSR	MLAR

Notes: See Ref. 1 for the commonly used abbreviations in the table. Other abbreviations are as follows:

w.a.	Wraparound contacts
Low alpha	Gridded contacts, both front and back
LPE GaAs	GaAs cells made by Liquid Phase Epitaxial growth
SR	Spectral Response
Hi/Lo Blue	Cells with unusually high/low blue SR
Hi/Lo Red	Cells with unusually high/low red SR
BBSF	Boron Back Surface Field
T	Indicates modules containing a thermistor

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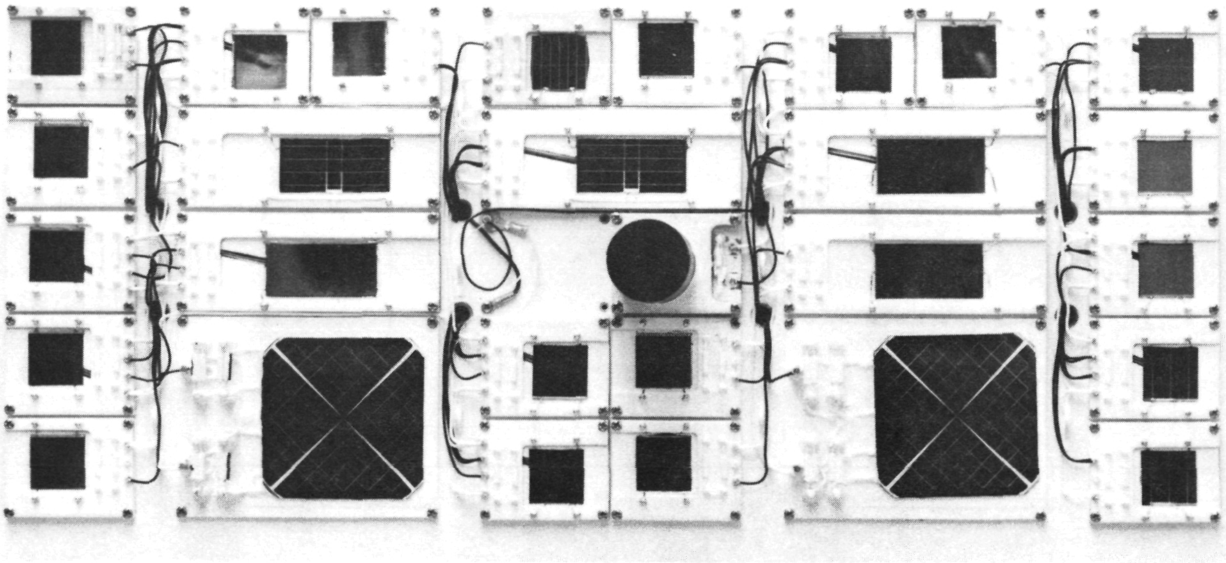

Figure 1. Photograph of the SCCF Solar Panel

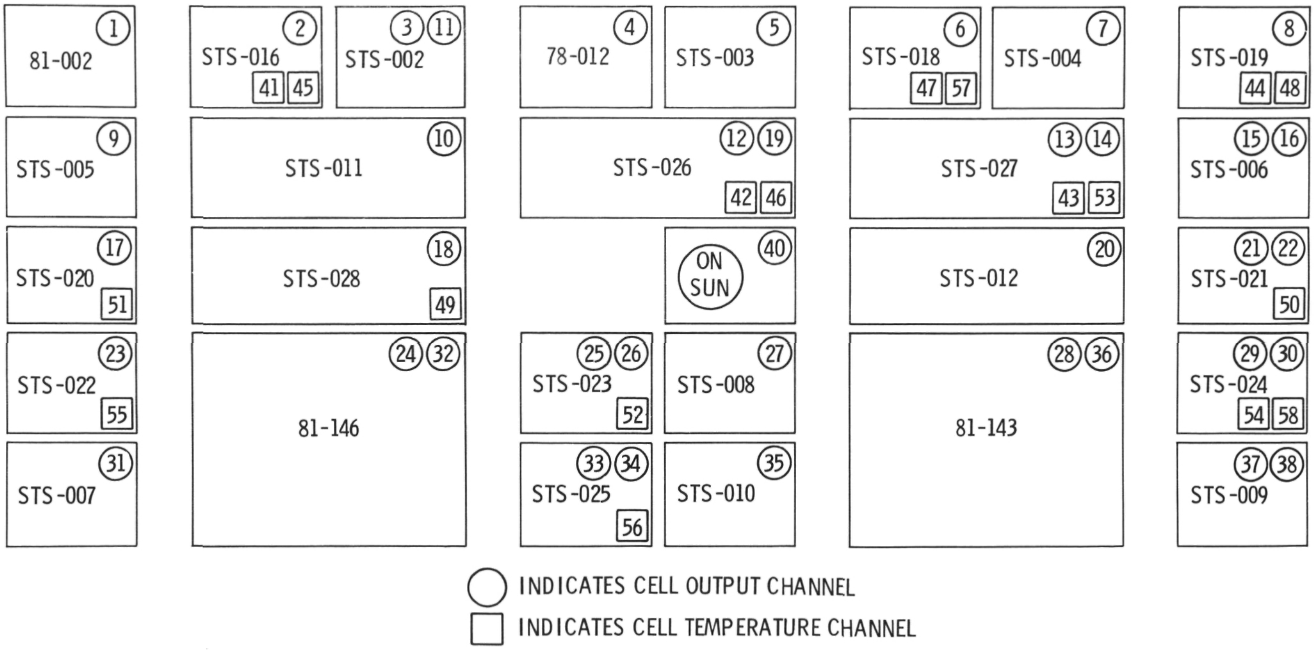

Figure 2. Schematic Layout of the SCCF Solar Panel

The cylindrical black item in the center of the panel is a collimator mounted above the on-sun indicator.

SECTION 3

SHUTTLE FLIGHT

3.1 SHUTTLE DATA ACQUISITION SYSTEM

The system for sampling, digitizing, and recording the data was built by SCI Systems, Inc., of Huntsville, Alabama. A block diagram of this Flight Data System is shown in Figure 3. Briefly, it consists of a multiplexer, a variable gain amplifier, an 8-bit analog-to-digital (A/D) converter, RAM memory, and a digital tape recorder. The solar cells, loaded with precision resistors to provide a voltage output of nearly 100 mV, were wired to channels 1 through 38 of the multiplexer; the thermistors to channels 41 through 60; the on-sun sensor to channel 40; and the calibration reference voltages to channels 61 through 64.

Automatic gain control of the A/D converter was a special feature of the shuttle data acquisition electronics. Since thermistor resistance is a nonlinear function of temperature, amplifier gain requirements necessary to give a specified temperature resolution vary strongly as the temperature changes. An analysis of the data acquisition system showed that amplifier gains of 1, 5, 10 and 20 were necessary to achieve the desired temperature resolution of 0.5 deg C. The A/D system was therefore designed so that the amplifier would change its gain as the solar panel changed temperature. The panel temperature reading for this purpose was determined by a thermistor connected to channel 59. This thermistor was connected to the top surface of the solar panel near the center. Gain changes were programmed to occur only when the multiplexer was connected to thermistor channels. When the

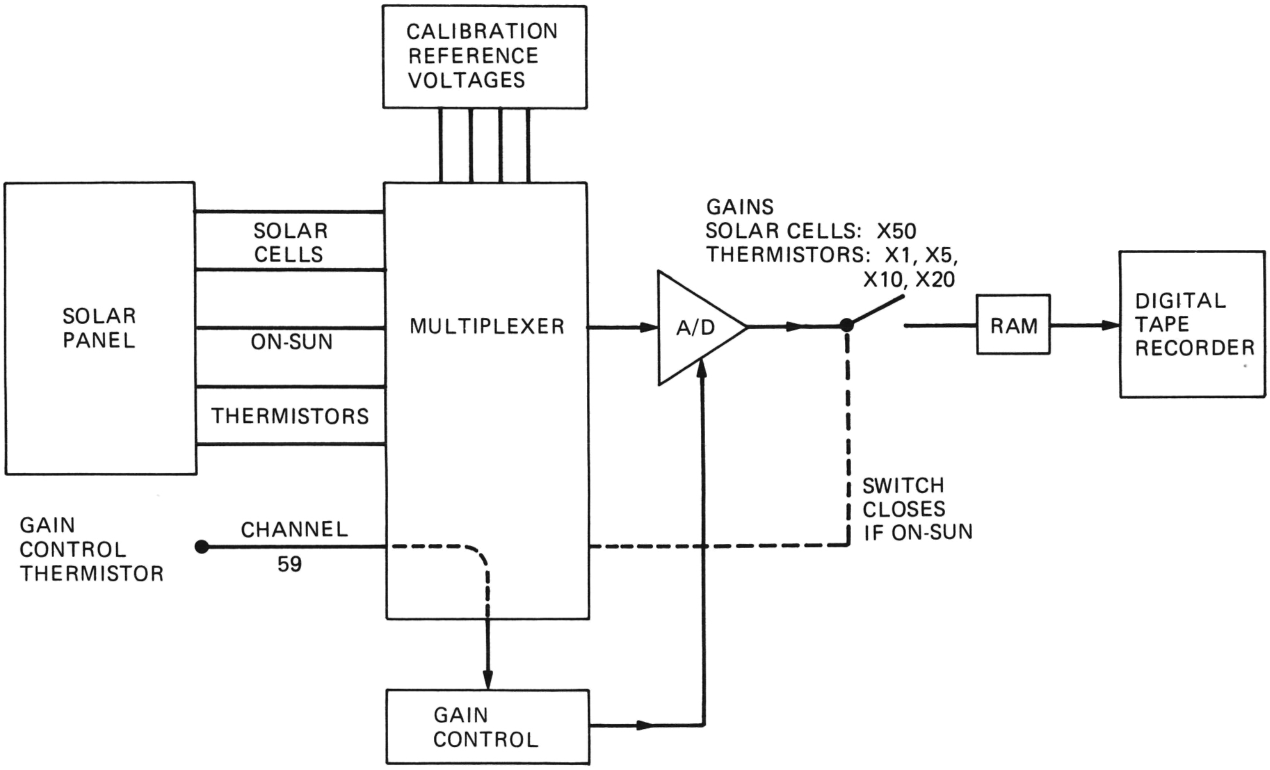

Figure 3. Block Diagram of the SCCF Flight Data System

multiplexer was reading solar cell channels, voltage reference channels, or the on-sun indicator, the amplifier gain remained at 50.

The on-sun indicator was used as a gate to determine acceptability of the data. If the panel was within ±3 deg of being perpendicular to the sun, the signal generated by the on-sun indicator was large enough to close the switch, permitting the data to flow into the buffer RAM. When the RAM was filled with a block of 60 scans (a scan is a complete sampling of all 64 channels), the data block was sent to the digital tape recorder in a burst. The process was then repeated so that the RAM was continually filled and then written onto tape. Digitizing and recording the data occurred at a rate of two scans per second.

The electronics of the Flight Data System included a power supply that produced calibration reference voltages of 0, 50, 75, and 100 mV. These voltages were connected to data channels 61 through 64. They were multiplexed and processed through the electronics and recorded, along with the solar cell voltages and temperatures, during the flight. The output of these calibration channels was examined during the data analysis phase to ensure proper operation and stability of the entire system.

3.2 SHUTTLE FLIGHT DATA ANALYSIS

The Univac 1100 computer was used to read the data tape written by the on-board tape recorder and produce a data file in 1100 format. During this step, the data was converted from 8-bit binary words to engineering units of voltage, temperature, and time of day. Data from each channel were collected and arranged in chronological order. All of the solar cell data were corrected to a standard solar intensity of 1 AU by multiplying by the square of the earth-sun distance.

The solar cell data, corrected for intensity, were next used to produce plots of output voltage vs. time for each solar cell channel. (The solar cell output voltage read by the SCCF electronics was accurately proportional to the cell short circuit current because the load resistors connected across each cell are less than 0.5 ohm). Since the solar cell short circuit increases with temperature, the plots were expected to show a monotonic increase of cell output with time as the shuttle came out of occultation and the panels warmed up under solar illumination. It was observed, however, that the modules had an anomalously high output just after coming out of occultation and again an anomalously high output just before going into occultation. This was interpreted to be an albedo effect, caused by the reflection of additional light onto the panels during those times when the SCCF panel was looking at the sun through part of the earth's atmosphere. Figure 4 shows a plot of the channel 1 current output showing this effect. From a visual examination of several plots of this nature, it was possible to select portions of each orbit where the albedo effect did not occur. The associated beginning and end times for data analysis were selected and used as input to the program. Out of the 53 minute sunlit portions of each orbit, approximately 44 minutes of data were judged to be free of the albedo effect.

Each solar cell was assigned to one or two thermistors located nearby on the panel. The computer, using this assignment, produced plots of cell temperature vs. time for each solar cell channel. Figure 5 shows the temperature data taken at the same time as the cell data plotted in Figure 4. Data in the allowable time periods were used to construct plots of cell current vs. temperature. Figure 6 is an example of a current vs. temperature plot which has been constructed by merging the data shown in

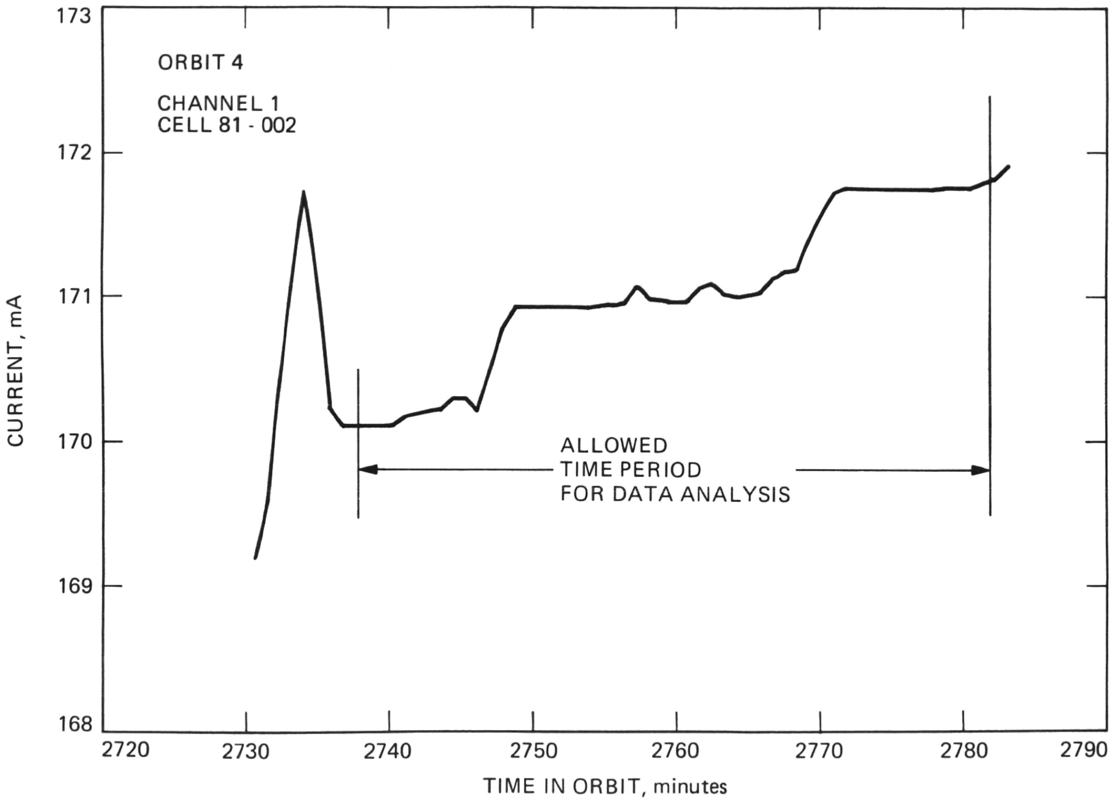

Figure 4. Plot of Channel 1 Output (Cell 81-002) vs. Time During Orbit 4

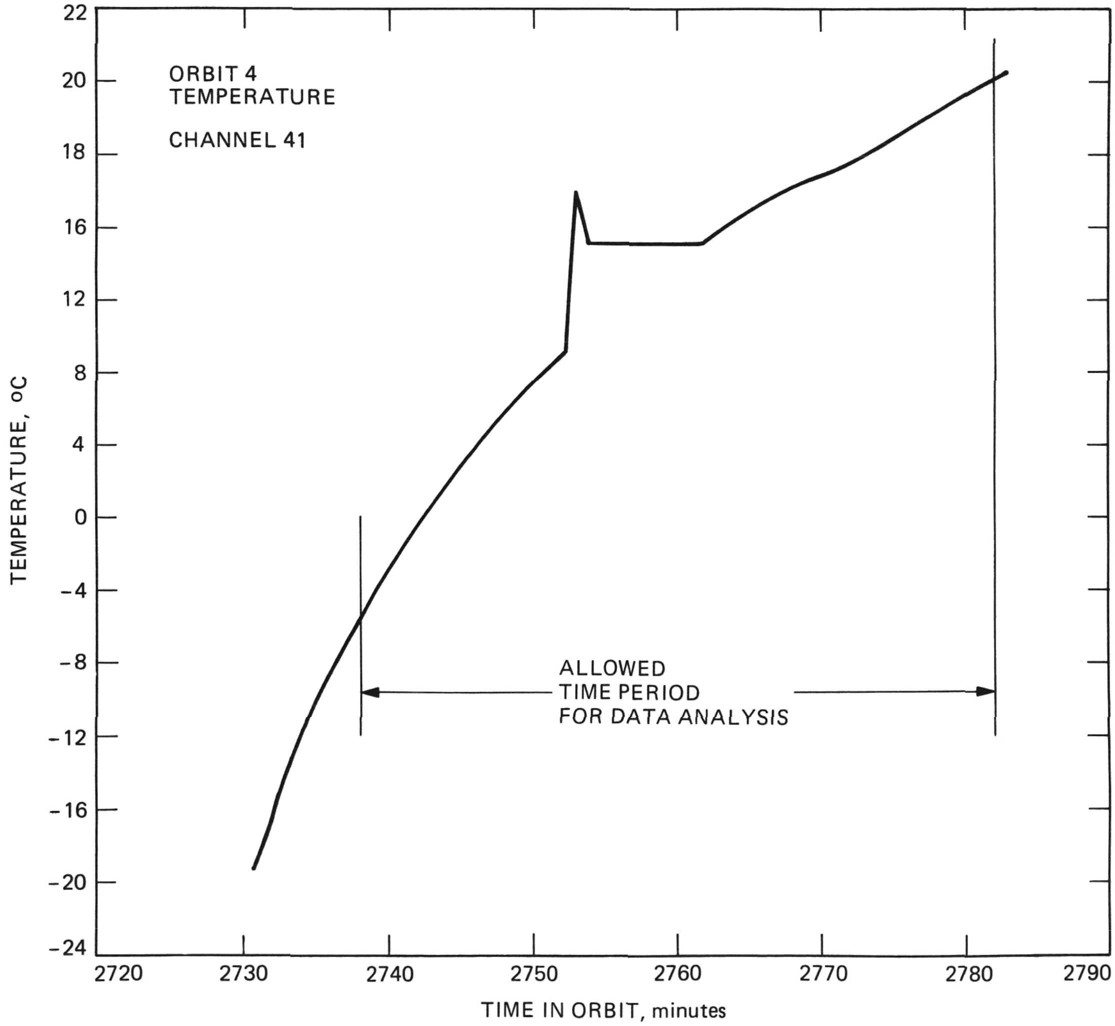

Figure 5. Plot of Temperature vs. Time for Channel 41 During Orbit 4

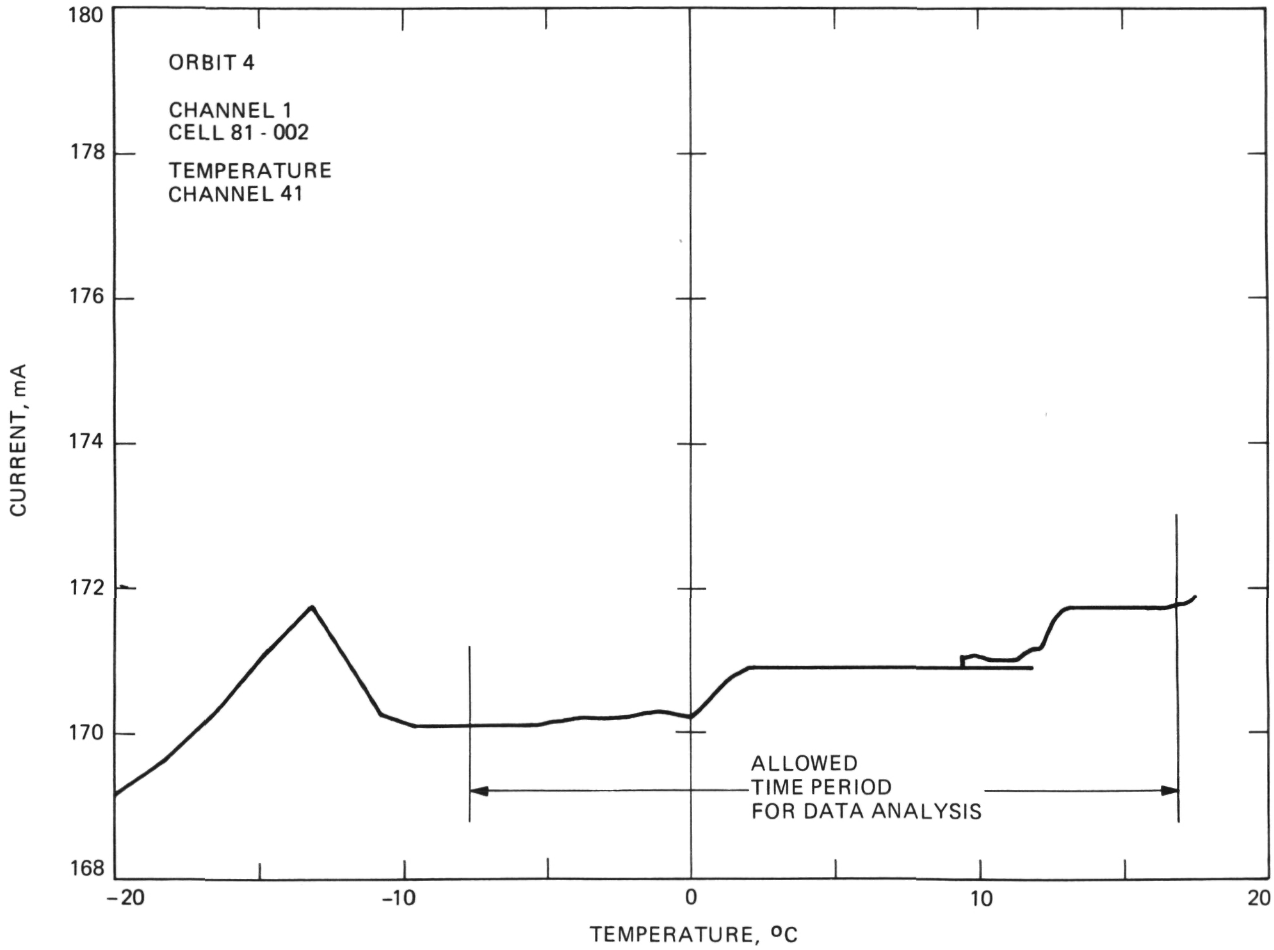

Figure 6. Plot of Channel 1 Output vs. Temperature During Orbit 4

Figures 4 and 5. Plots of this nature were constructed for each solar cell. Some 5000 data points went into each plot for each cell for each orbit. Linear regression analyses of the current vs. temperature relationships were then performed for each cell. The regression coefficients computed in this analysis are the cell output at 0 deg C and the short circuit current temperature coefficients.

An examination of the cell temperature vs. time plots revealed an additional anomaly. As the solar cell temperature increased when the shuttle came out of occultation, several discontinuities in the temperature data occurred (see Figure 5). These were found to be induced by the amplifier which changed gain as a function of the temperature of the thermistor connected to channel 59. This thermistor was attached to the top surface of the solar panel, but not connected to a solar cell module. It changed temperature at a different rate than the thermistors attached to modules, so it occasionally induced gain changes in the data amplifier at inopportune times. This resulted in saturation of the amplifier, causing the discontinuities in the temperature vs. time curves. During the design of the data analysis program, these curves were manually smoothed and used in the regression calculations to derive temperature coefficients. It was found that the correction due to smoothing caused changes of (at most) 1 part in 10,000 in calculating the temperature coefficients, so the smoothing technique was abandoned.

The four sets of regression coefficients for each cell and each orbit were next averaged together. The temperature correction of the data to +28 deg C was calculated by substituting 28 deg C for the temperature in the regression equation. The resulting calibration values, corrected for both the earth-sun distance and temperature, are reported in Table 2. Each

Table 2. SCCF Calibration Values From the Shuttle Flight

Module No.	Calibration Value (mV)	Load (ohms)	Channel No.	Thermistor Channel No.
78-012	78.985	0.5	4	47
81-002	86.298	0.5	1	41
81-143	77.991	0.063	28	54
81-146	79.864	0.063	24	56
STS-002	73.690	0.5	3	47
STS-003	59.317	0.5	5	47
STS-004	81.339	0.5	7	44
STS-005	68.071	0.5	9	51
STS-006	73.056	0.5	15	50
STS-007	69.905	0.5	31	55
STS-008	77.517	0.5	27	52
STS-009	77.295	0.5	37	58
STS-010	75.012	0.5	35	56
STS-011	76.840	0.25	10	42
STS-012	77.022	0.25	20	53
STS-016T	63.081	0.5	2	41
STS-018T	57.380	0.5	6	47
STS-019T	82.798	0.5	8	48
STS-020T	68.339	0.5	17	51
STS-021T	72.848	0.5	21	50
STS-022T	70.667	0.5	23	55
STS-023T	76.307	0.5	25	52
STS-024T	77.114	0.5	29	54
STS-025T	75.314	0.5	33	56
STS-026T	75.590	0.25	12	42
STS-027T	80.060	0.25	13	43
STS-028T	57.370	0.25	18	49

calibration value in the table is based on an analysis of approximately 20,000 data points.

SECTION 4

BALLOON FLIGHT

After the solar cells were recovered from the SCCF, they were removed from the panel and remeasured using the JPL X25 Mark II solar simulator. The cell readings were found to be the same as their pre-flight values, indicating that they sustained no damage during the flight. Temperature coefficients of the cells were measured in the laboratory, again using the X25 for the illumination source. The cells were interspersed with the normal complement of cells scheduled for the 1985 calibration flight and mounted on the balloon flight solar tracker. The photograph in Figure 7 shows the cells as they were mounted on the tracker panel, and the diagram in Figure 8 identifies the cells as they were placed on the panel. The modules drawn with dark borders identify the cells that had also been flown on the shuttle. These cells were flown on the balloon, recovered, returned to JPL, and remeasured with the X25 solar simulator. The cell readings were again found to agree with their pre-flight values.

4.1 BALLOON DATA SYSTEM

The data system for the balloon flights is described in Ref. 2. This data system consists of the following major parts on-board the balloon: (1) a solar tracker and its complement of solar cells mounted on top of the balloon, (2) a multiplexer, programmable to handle between 1 and 128 data channels, (3) a 10-bit A/D converter with an internal amplifier that produces full-scale output for an input voltage of 100 mV, (4) a data encoder and transmitter, (5) a command telemetry subsystem for receiving commands used to turn the tracker on and off, release ballast, or terminate

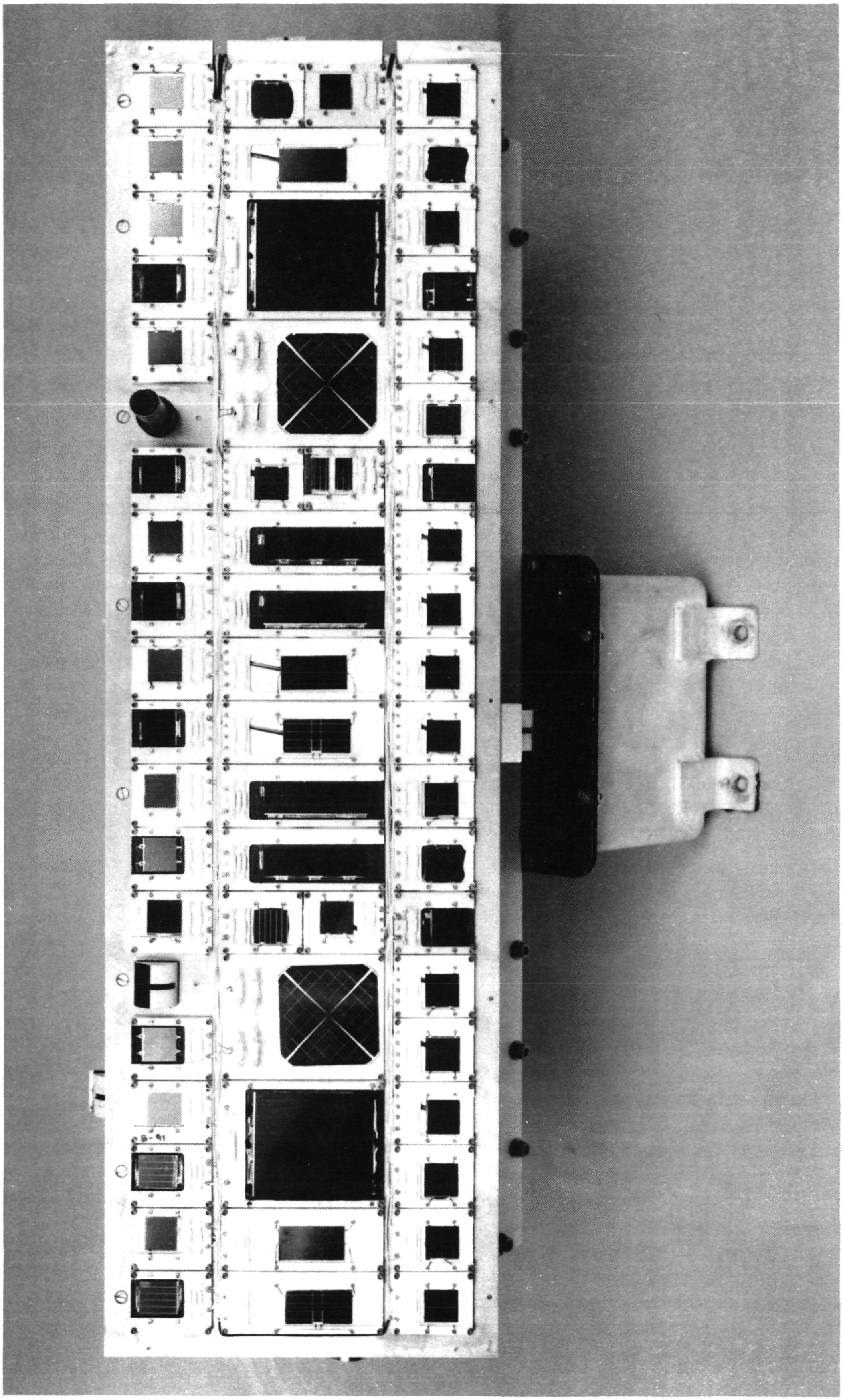

Figure 7. Photograph of the 1985 Balloon Flight Solar Panel

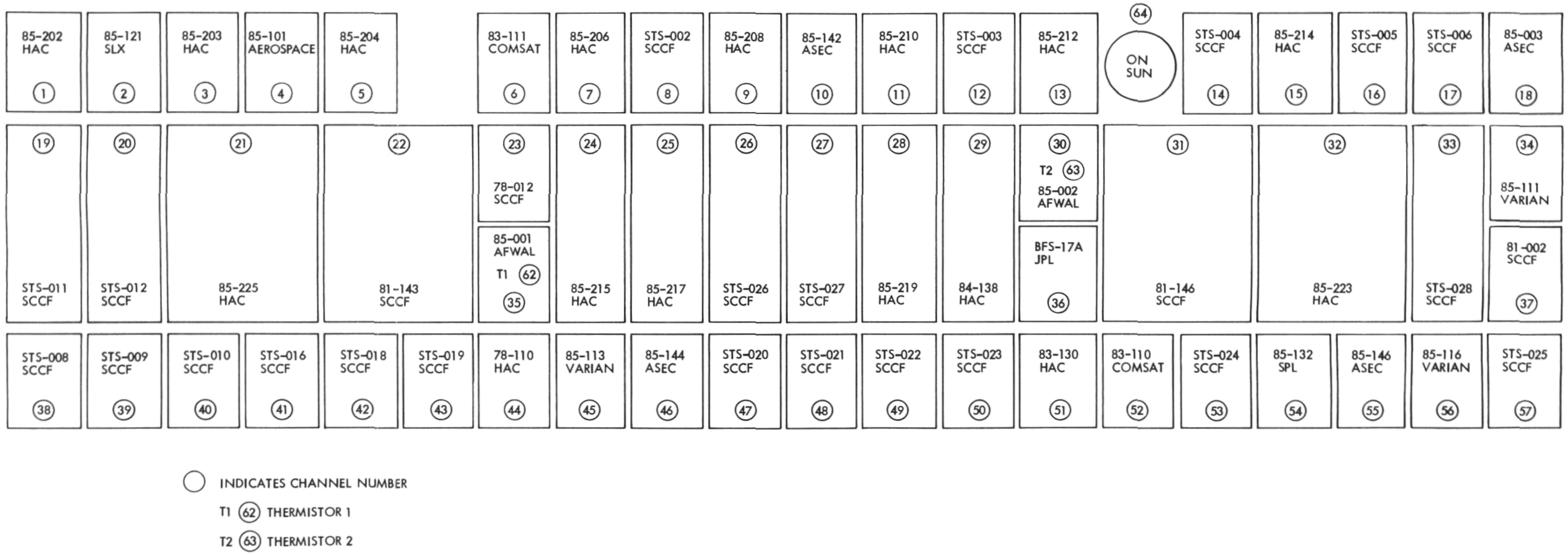

Figure 8. Diagram of the 1985 Balloon Flight Solar Panel

the flight, and (6) a complement of miscellaneous systems such as transponders, radio tracking beacons, and subsystems for encoding data such as latitude, longitude, and altitude. The ground-based part of the data system resided at the NSBF in Palestine, Texas. It consisted primarily of radio receivers and computers for demodulating, decoding, displaying, and recording all the telemetered data in real time.

As in the shuttle flight, the system aboard the balloon contained an on-sun indicator and a voltage reference box. Here, the on-sun indicator did not open or close a gate according to the suitability of the data. Its output was recorded (along with output from the other data channels), and that reading was used during analysis to determine the suitability of the data. The voltage reference box was a battery-driven power supply. It produced very stable voltages of 0, 50, 80 and 100 mV which remained constant to within ±0.1 mV over a temperature range of 20 to 70 deg C. These voltages were multiplexed with the other data, sent through the telemetry system, and recorded on tape. They were examined during the analysis phase to ensure proper operation and end-to-end stability of the balloon flight data system.

The 10-bit A/D converter aboard the balloon was capable of reading the thermistors with sufficient accuracy and resolution that a variable gain amplifier was not necessary. For instance, when the converter was reading a thermistor in the 50 to 60 deg C range, a one bit change in the A/D converter was equivalent to a temperature change of only 0.25 deg. The resolution improved rapidly at lower temperatures, becoming 0.07 deg near 28 deg C. Since the temperature corrections to the solar cell data were small (typically about 1%), additional accuracy in the temperature readings would be of little value.

During data transmission, the multiplexer stepped through the 57 solar cells, the two temperature channels, the four reference voltage channels, and the on-sun indicator channel at the same rate used on the shuttle flight, two scans per second. Data transmission occurred after the balloon had achieved its float altitude of 115,000 ft (35 km) and the tracker had been turned on. A continuous stream of data was transmitted and received over a three hour period during the flight.

4.2 BALLOON DATA ANALYSIS

The analysis of the balloon flight data is described in detail in Ref. 2. The analysis program performed several major steps:

> It selected data for analysis from the desired time period (one hour before solar noon until one hour after solar noon). The computer read data from the tape until it accumulated 200 readings for each channel (i.e., 200 scans). During accumulation, data blocks were accepted only if the on-sun indicator reading verified that the tracker was aligned properly with the sun. The data from each channel were then averaged and checked for any anomalous readings, which were eliminated and the average recomputed.
>
> A distance factor was computed to correct the solar intensity to the 1 AU standard by multiplying the average cell readings by the square of the earth-sun distance at the time of the flight.
>
> The cell data were corrected to 28 deg C using the temperature coefficients measured in the laboratory before the flight.
>
> Another block of 200 data scans was read from the tape and averaged in the above fashion. This process was repeated 19 times, then an overall average of all 4000 data points was computed to give the final calibration values.

The procedure for dealing with temperature corrections to the balloon flight data differs markedly from that used in the SCCF data analysis. In the latter case, a major part of the program was dedicated to deriving regression coefficients from the flight data. The SCCF program fit the data to a linear equation expressing cell output as a function of temperature, then used that equation to correct the data to 28 deg C. In the balloon flight analysis program, however, a temperature correction was made to each data point using the laboratory-measured temperature coefficients multiplied by the temperature difference, (28-T). During the shuttle flight, the cell temperatures rose to within a few degrees of +28 deg C; therefore the magnitude of the temperature corrections was relatively small. On the balloon flight, the panel temperatures were much higher, ranging between +57 and +61 deg C, so the applied corrections were considerably larger and in the opposite direction.

SECTION 5

COMPARISON OF SHUTTLE AND BALLOON FLIGHT RESULTS

Table 3 summarizes all the measurements and calculations for the SCCF experiment cells. It compares the calibration values derived from the shuttle data with those derived from the balloon data and also compares the temperature coefficients measured during the shuttle flight with those measured in the laboratory.

The balloon calibration values deviate at most 1.12% from the shuttle values, and the root mean square deviation is only 0.57%. An examination of the data from each module revealed that the agreement did not depend on whether the cell had a high or low spectral response in any particular wavelength region. For example, some cells with high blue responses read higher on the balloon than on the shuttle, while others with high blue responses read higher on the shuttle than they did on the balloon. The same observation was made for cells with high red responses and also for cells with relatively flat responses. This agreement shows that the balloon flights are an excellent method of calibrating solar cell standards.

The temperature coefficient results were not as consistent. Table 3 shows that the temperature coefficients computed from the shuttle data do not agree with the values measured in the laboratory. The measurement methods used in each case were similar. A series of cell output voltages were measured as a function of cell temperature, and then a linear least squares fit was performed to determine the dependence of output vs. temperature. Correlation coefficients (r^2) were computed as a measure of how well the data actually fit straight lines. The fits to the shuttle

Table 3. Comparison of Calibration Values and Temperature Coefficient Measurements, Shuttle vs. Balloon Flight

Module No.	Calibration Values			Temp. Coefficients		
	Shuttle (mV)	Balloon (mV)	Diff. (%)	Shuttle (mV/deg C)	Laboratory (mV/deg C)	Diff. (%)
78-012	78.985	79.047	0.08	0.0482	0.0379	-21.37
81-002	86.298	87.262	1.12	0.035	0.0276	-21.14
81-143	77.991	77.193	-1.02	0.0521	0.0120	-76.97
81-146	79.864	79.180	-0.86	0.0536	0.0130	-75.75
STS-002	73.690	73.603	-0.12	0.0365	0.0385	5.48
STS-003	59.317	58.964	-0.60	0.0235	0.0375	59.57
STS-004	81.339	81.294	-0.06	0.042	0.031	-26.19
STS-005	68.071	68.172	0.15	0.0395	0.041	3.80
STS-006	73.056	73.712	0.90	0.042	0.0465	10.71
STS-008	77.517	76.768	-0.97	0.0525	0.046	-12.38
STS-009	77.295	77.217	-0.10	0.0455	0.0355	-21.98
STS-010	75.012	74.614	-0.53	0.0485	0.0440	- 9.28
STS-011	76.840	76.961	0.16	0.0438	0.0430	- 1.83
STS-012	77.022	76.727	-0.38	0.0413	0.0379	- 8.23
STS-016T	63.081	63.165	0.13	0.0445	0.0430	- 3.37
STS-018T	57.380	57.130	-0.44	0.0245	0.0355	44.90
STS-019T	82.798	82.925	0.15	0.0415	0.034	-18.07
STS-020T	68.339	68.620	0.41	0.04	0.0345	-13.75
STS-021T	72.848	73.601	1.03	0.049	0.047	- 4.08
STS-022T	70.667	70.841	0.25	0.0355	0.0345	- 2.82
STS-023T	76.307	76.416	0.14	0.052	0.038	-26.92
STS-024T	77.114	77.348	0.30	0.0445	0.0385	-13.48
STS-025T	75.314	75.043	-0.36	0.0465	0.0592	27.31
STS-026T	75.590	76.007	0.55	0.0583	0.0480	-17.67
STS-027T	80.060	80.067	0.01	0.041	0.0375	- 8.54
STS-028T	57.370	56.887	-0.84	0.0275	0.040	45.45
RMS Deviation			0.569			30.65

data were rather poor, with correlation coefficients falling between 0.86 and 0.93, whereas the correlation coefficients computed for the laboratory data were between 0.97 and 0.999. These differences are primarily caused by data amplifier saturation during some of the temperature measurements and the limited resolution associated with an 8-bit A/D converter. The shuttle-based temperature coefficients were derived from data that varied over temperature ranges of only 30 deg C (typically between -6 and +20 deg C). The data did not change much over this limited temperature excursion, and when it did change, it changed in jumps of 0.4 mV because of the resolution. In contrast, the laboratory data was taken over a temperature range of 80 deg at five equally spaced temperatures. A digital voltmeter with 1 microvolt resolution was used to produce highly accurate measurements. Temperature corrections to the shuttle data using the more inaccurate temperature coefficients did not detract from the accuracy of the shuttle data because the panel temperatures were very close to the standard temperature of +28 deg C and the corrections were small.

SECTION 6

CONCLUSIONS

The SCCF experiment has shown that the method of calibrating solar cells on high-altitude balloon flights produces calibration values that are nearly identical to calibrations produced in outer space. The calibration values derived from the balloon flight agree with those derived from the shuttle flight to within 1.12%.

REFERENCES

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