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Results of the 1981 NASA/JPL Balloon Flight Solar Cell Calibration Program

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

PREFACE

The work described in this report was performed by the Control and Energy Conversion Division of the Jet Propulsion Laboratory. The flight was conducted with the cooperation of the National Scientific Balloon Facility, located in Palestine, Texas.

ABSTRACT

After an aborted launch on July 23 due to balloon failure during inflation, the 1981 solar cell calibration balloon flight was successfully completed on July 25, meeting all objectives of the program. Twenty-seven modules were carried to an altitude of 35.4 kilometers. The calibrated cells can now be used as reference standards in simulator testing of cells and arrays.

ACKNOWLEDGMENT

The authors wish to extend appreciation for the cooperation and support provided by the entire staff of the National Scientific Balloon Facility. Gratitude is also extended to assisting JPL personnel, especially B. E. Anspaugh, for providing cell spectral response information and data reduction assistance. The cooperation and patience extended by all participating organizations are greatly appreciated.

CONTENTS

SECTION I

INTRODUCTION

The primary source of electrical power for unmanned space vehicles is the direct conversion of solar energy through the use of solar cells. As advancing cell technology continues to modify the spectral response of solar cells to utilize more of the sun's spectrum, designers of solar arrays must have information detailing the impact of these modifications on cell conversion efficiency to be able to confidently minimize the active cell area required and, hence, the mass of the array structure.

Since laboratory simulation of extra-atmospheric solar radiation has not been accomplished on a practical scale with sufficient fidelity, high altitude exposure must be taken as the best representation of space itself. While a theoretical prediction (Reference 1) and experimental evidence have suggested that an altitude greater than 30 kilometers is sufficient to give space equivalent calibration, the final decision as to an adequate altitude must await the results of the space shuttle solar cell calibration experiment scheduled for December 1982.

To reach and maintain the chosen altitude of 36 kilometers, the calibration program makes use of balloons provided and launched by the National Scientific Balloon Facility, Palestine, Texas.

SECTION II

PROCEDURE

To insure electrical and mechanical compatibility with other components of the flight system, the cells are mounted by the participants on JPL-supplied standard modules according to directions in Reference 2, which details materials, techniques, and workmanship standards for assembly. The JPL standard module is a machined copper block 3.7 cm x 4.8 cm x 0.3 cm thick, rimmed by 0.3 cm thick fiberglass, painted a high reflectance white, with insulated solder posts and is permanently provided with a precision (0.1 percent, 20 ppm/^{o}C) load resistor appropriate for scaling the cell output to the telemetry constraints. This load resistor, 0.5 ohm for a 2 cm x 2 cm cell, for example, also loads the cell in its short circuit current condition.

The mounted cells are then subjected to preflight measurements in the JPL X25L solar simulator. This measurement, when compared to a postflight measurement under the same conditions, may be used to detect cell damage or instabilities.

Prior to shipment to the launch facility, the modules are mounted on the sun tracker bed plate (Figure 1).

Upon arrival at the Palestine Facility, the tracker and module payload are checked for proper operation, the data acquisition and Pulse Code Modulation telemetry systems are calibrated. Mounting of the assembly onto the balloon is then accomplished (Figure 2).

At operating altitude the sun tracker bed plate is held pointed at the sun to within ± 1 deg. The response of each module, temperatures of representative modules, sun lock information, and system calibration voltages are sampled twice each second and telemetered to the ground station where they are presented in teletype form for real-time assessment and are also recorded on magnetic tape for later processing. Float altitude information is obtained from data supplied by the balloon facility. A plot of altitude in kilometers versus Central Daylight Time for the 1981 flight is shown in Figure 3.

SECTION III

SYSTEM DESCRIPTION

A solar tracker mounted in a frame on top of the balloon carries the module payload, while the transmitter of the data link is located in the lower gondola along with batteries for power and ballast for balloon control. At completion of the experiment, the upper payload and lower gondola are returned by parachutes and recovered. A more complete description of the system, including the sun tracker, can be found in Reference 3.

SECTION IV

DATA REDUCTION

The raw data as taken from the magnetic tape is corrected for temperature and sun-Earth distance according to the formula (Reference 4):

$$V_{28,1} = V_{T,R}(R^2) - \alpha(T-28)$$

where

$V_{T,R}$ = measured module output voltage at temperature T and distance R

R = sun-Earth distance in astronomical units

α = module output temperature coefficient (supplied by participant)

T = module temperature in $^{\circ}C$

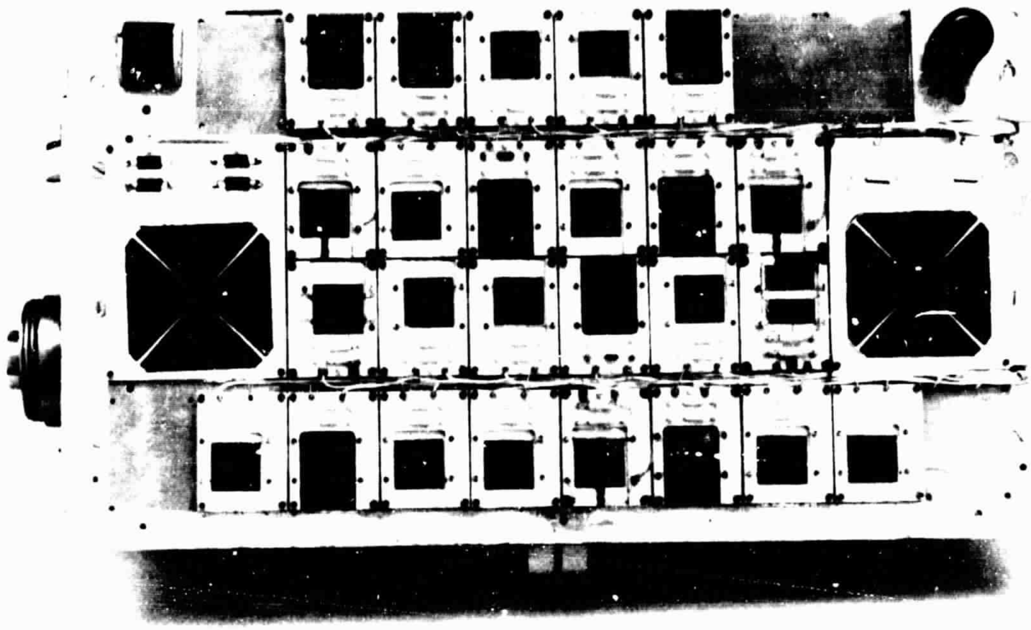

Figure 1. 1981 Solar Module Payload

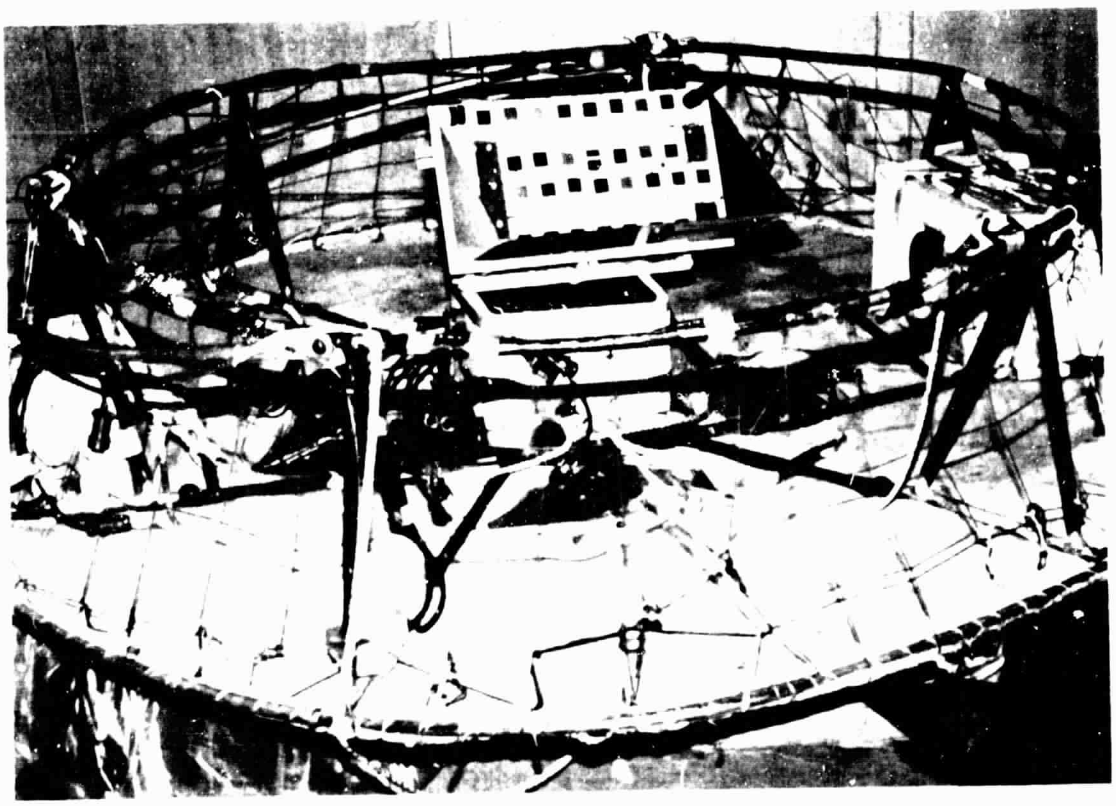

Figure 2. Balloon Mount

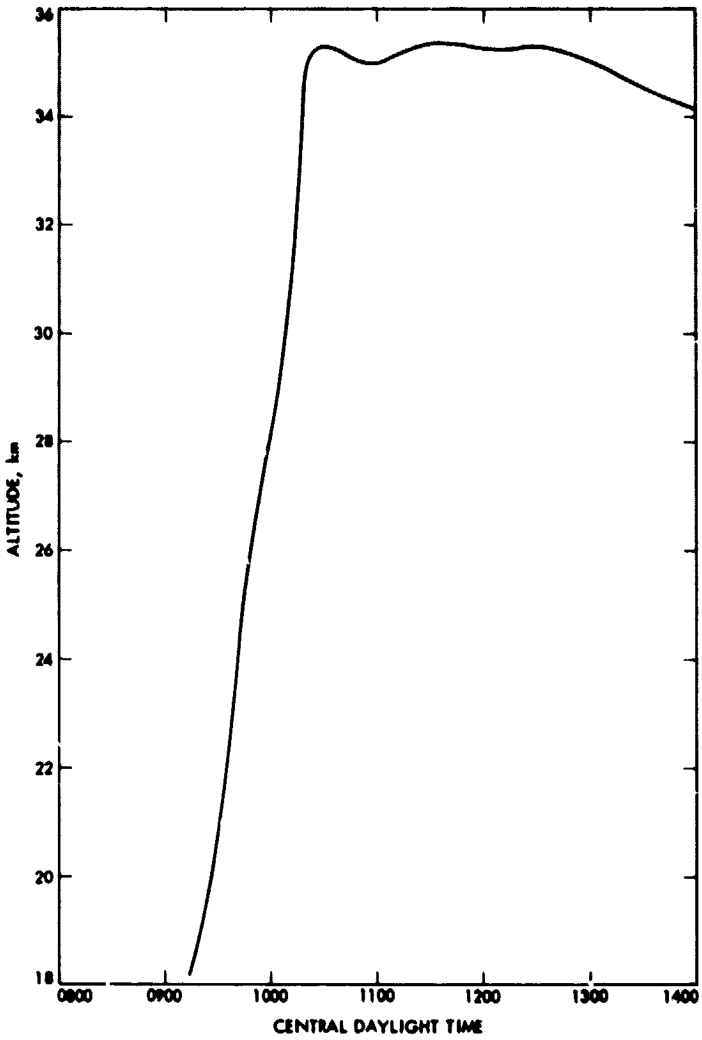

Figure 3. Flight 1981 Altitude Versus Time

The calibration value is taken to be the average of 200 consecutive data points taken around the time of solar noon after indicated temperature stability.

The flight data were thus reduced, and modules with their data and calibration values were returned to the participants. This information is collected in Table 1. The placement of modules on the field of the tracker bed for the 1981 flight is shown in Figure 4.

A detailed discussion of data reduction and an analysis of system error may be found in Reference 3.

The error in the calibration values due to radiation absorption and scattering by the residual atmosphere at float altitude is estimated to be less than 0.2 percent (Reference 1).

Table 1. Cell Calibration Data

BALLOON FLIGHT 81-1 DATE 7-25-81 ALTITUDE 35.40 KM RV=1.01565

CHANNEL NUMBER	MODULE NUMBER	ORGANIZATION CODE	TEMP. INTENSITY ADJ. AVERAGE	STANDARD DEVIATION	AMO, SOLAR SIM., 1 AU, 28 DEG.C PRE-FLT	POS-FLT	COMPARISON, SOLAR SIMULATOR & FLT PRE-FLT VS. POS-FLT (PERCENT)	FLIGHT VS. PRE-FLT (PERCENT)	COMMENTS
1	81-001	JPL	85.25	.06675	84.80	84.10	-.83	.53	K7 AL BGRND
2	81-130	HUGHES	70.99	.05502	69.70	69.30	-.57	1.86	K7
3	81-101	TRW	84.92	.07499	83.50	83.60	.12	1.70	BLK-01
4	81-002	JPL	87.10	.08473	86.00	85.50	-.58	1.28	K7 WH BGRND
5	81-132	HUGHES	80.42	.08223	76.40	76.40	.00	5.26	K4 3/4
6	81-143	MSFC	77.78	.08455	78.90	77.00	-2.41	-1.41	R8.063 686CM
7	76-001	JPL	67.86	.05878	68.70	68.70	.00	-1.22	
8	81-103	TRW	76.95	.08125	76.70	76.80	.13	.32	WSF-02
9	81-134	HUGHES	27.18	.07914	22.40	22.70	-.89	21.32	800NMNP RMA
10	81-104	TRW	76.53	.06818	76.40	76.60	.26	.17	BSF-03
11	81-003	JPL	75.55	.07710	76.20	75.00	-1.57	-.86	K4 3/4 R BG
12	73-182	JPL	67.96	.06172	68.40	68.60	.29	-.64	
13	81-186	MSFC	79.67	.06234	79.20	78.20	-1.26	.59	H8.063 686CM
14	74-205	JPL	89.99	.07079	87.40	87.50	.11	2.97	
15	81-105	TRW	73.54	.06961	73.40	73.40	.00	.18	BSR-02
16	81-004	JPL	77.55	.04589	77.00	76.80	-.26	.72	K4 3/4 W BG
17	81-136	HUGHES	22.38	.07100	20.90	20.90	.00	7.06	1000NMNP RMA
18	81-106	TRW	73.72	.06407	73.90	73.80	-.14	-.25	WSR-03
19	BFS-17A	JPL	60.07	.08107	60.50	60.50	.00	-.71	MONITOR
20	81-107	TRW	79.03	.08799	78.80	78.80	.00	.29	BFS/R-02
21	81-138	HUGHES	23.15	.06601	22.60	22.20	-1.77	2.45	350-750NMNP
22	81-006	JPL	72.49	.06798	72.10	72.20	.14	.54	NO BSF
23	81-108	TRW	79.11	.06492	79.00	79.00	.00	.18	BSF/R-03
24	73-183	JPL	66.83	.05610	67.70	67.70	.00	-1.29	
25	78-110	HUGHES	94.82	.05838	93.70	93.50	-.21	1.20	K7
26	81-102	TRW	85.09	.05541	83.80	84.00	.24	1.54	BLK-02
27	81-005	JPL	81.44	.08313	80.80	80.80	.00	.79	I-BTE BSF
39	100-MV		103.25*	.05065	.00	.00	.00	.00	
40	80-MV		82.92*	.06657	.00	.00	.00	.00	
41	50-MV		51.90*	.06494	.00	.00	.00	.00	
42	0-MV		.00*	.00000	.00	.00	.00	.00	

* INDICATES CHANNEL FOR WHICH NO TEMPERATURE COEFFICIENT WAS PROVIDED.

AVERAGE TEMPERATURE (DEG.C) AT FLOAT ALTITUDE = 52.01

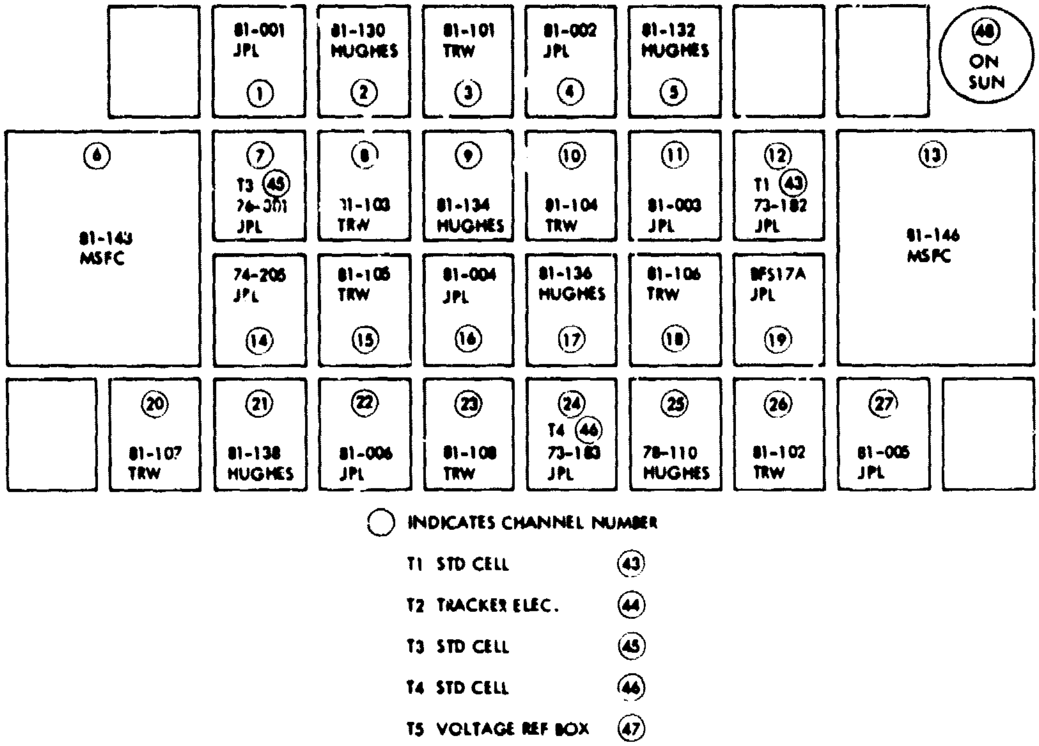

Figure 4. 1981 Module Location Chart

SECTION V

FILTERED CELLS

The relationship of the spectral irradiance of simulated sunlight sources to the AMO solar spectral irradiance is an important factor in the design and fabrication of cells and panels, since it directly impacts the predictions of performance in the space environment.

To facilitate the monitoring of the spectral irradiance of simulators, three modules of this flight were assembled with permanently bonded band pass filters of selected center wavelengths (Reference 5). With these and similar modules from previous flights, a family of AMO calibrated spectral samplings characterizing a simulator's spectral irradiance can be quickly and easily performed.

SECTION VI

MODULE CAVITY SURFACE FINISH

Questions have recently surfaced as to the effect of reflections within the white painted module cavity on the cell calibration value and the resultant effect on the setting of a solar simulator using these cells. Would a black painted cavity be more appropriate? Experiments with several simulators of various radiation angular subtense (0.5 to 4.5 deg) have demonstrated that a cell mounted in a white painted cavity will in fact show a calibration value about 2 percent greater than a cell mounted in a black painted cavity. However, these same experiments have also shown that this measured difference is not a function of source angular subtense (at least over the angular range of 0.5 to 4.5 deg), and, hence, cells in either black or white cavities should "see" the simulators (angles of 0.5 to 4.5 deg) in the same way they "saw" the sun (angle 0.5 deg) in the original calibration. Therefore, setting of the simulator should not be dependent upon the cavity finish of the calibrated cell as long as that cavity finish is not altered from the calibration condition.

These laboratory experiments were extended by including two matched pairs of cells on this 1981 calibration flight, one of each pair being mounted in a white painted cavity, the other in a black. See Figure 5 for a representative pair.

Cells 81-001 and 81-002 are each K7, are from the same production run, and have the same absolute spectral response. Cell 81-001 is mounted in a black painted cavity, cell 81-002 in a white.

Cells 81-003 and 81-004 are each K4-3/4, are from the same production run, and have the same absolute spectral response. Cell 81-003 is mounted in a black painted cavity, cell 81-004 in a white.

The flight calibration values are:

81-002 = 87.10 mV
81-001 = 85.25 mV

81-004 = 77.55 mV
81-003 = 75.55 mV

The ratios of the flight calibration values are:

81-002/81-001 = 1.022
81-004/81-003 = 1.027

These cell pairs were then measured in four simulators (LAPSS, ACC302, X25, and X25L of angular subtense 0.5, 1.5, 4.0, and 4.5 deg, respectively)* according to the following scheme. Each simulator was adjusted to the calibration value of one cell of a pair (say, the white painted one), and the output of the second of that pair was then measured. The results, shown as ratios, and the percent difference from the solar calibration ratios are given in Table 2.

These results are in agreement with the previous experiments demonstrating the validity of either cavity condition for a standard cell.

*Large Area Pulsed Solar Simulator (LAPSS), X25, and X25L, Spectrolab, Inc; ACC302, Aerospace Control Corporation.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Table 2. White-Black Ratio Versus Source

Cell Pair	X25	X25L	ACC302	LAPSS	Sun (CALIB)
81-002 / 81-001	1.022	1.021	1.024	1.021	1.022
Δ% vs Sun	0	-0.10	+0.20	-0.10	-
81-004 / 81-003	1.029	1.024	1.027	1.028	1.027
Δ% vs Sun	+0.19	-0.29	0	+0.10	-

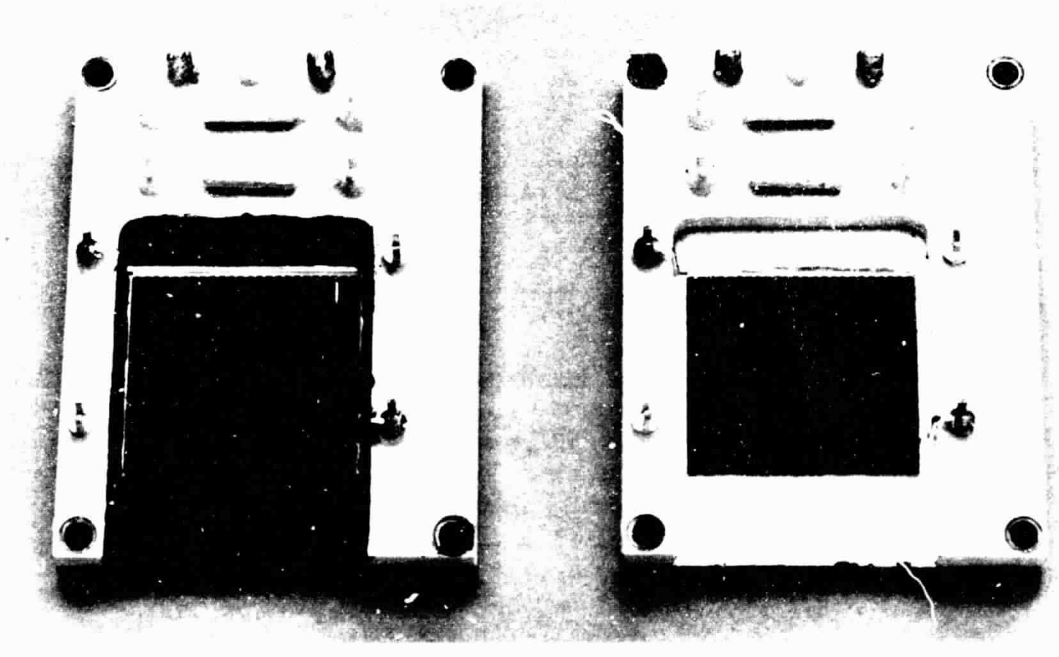

Figure 5. Black and White Cavity Modules

SECTION VII

MONITOR CELLS

Several standard modules have been flown repeatedly over the 19-year period of calibration flights. The record of the one with the longest history, BFS-17A, appears in Table 3. This data shows a standard deviation of 0.39 percent and a maximum deviation of 0.92 percent from the mean.

In addition, the uniformity of the solar irradiance (i.e., no spurious reflections, shadowing) over the field of the modules has been demonstrated since the location of this module was changed in that field from flight to flight.

SECTION VIII

CONCLUSIONS

As emphasized by the history of repeatability of cell BFS-17A, viz, ±1 percent (see Table 3), silicon cells, when properly cared for, are stable for long periods of time and may be used as standards with confidence.

It has been demonstrated that the cell mounting cavity may be either black or white with equal validity in setting solar simulators.

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3. Yasui, R. K., and Greenwood, R. F., Results of the 1973 NASA/JPL Balloon Flight Solar Cell Calibration Program, Technical Report 32-1600, Jet Propulsion Laboratory, Pasadena, CA, November 1, 1975.

4. Solar Cell Array Design Handbook, JPL SP 43-38, Vol. 1, p. 3.6-2, Jet Propulsion Laboratory, Pasadena, CA, 1976.

5. Goodelle, G.S., et al., Simulator Spectral Characterization Using Balloon Calibrated Solar Cells with Narrow Band Pass Filters, Proceedings Fifteenth IEEE Photovoltaic Specialists Conference, 1981.

Table 3. Repeatability of Standard Solar Cell BFS-17A
(33 Flights over a 19-Year Period)

Flight date	Output, mV	Flight data	Output, mV
9/5/63	60.07	8/5/70	60.32
8/3/64	60.43	4/5/74	60.37
8/8/64	60.17	4/23/74	60.37
7/28/65	59.90	5/8/74	60.36
8/9/65	59.90	10/12/74	60.80
8/13/65	59.93	10/24/74	60.56
7/29/65	60.67	6/6/75	60.20
8/4/66	60.25	6/27/75	60.21
8/12/66	60.15	6/10/77	60.35
8/26/66	60.02	8/11/77	60.46
7/14/67	60.06	7/20/78	60.49
7/25/67	60.02	8/8/79	60.14
8/4/67	59.83	7/24/80	60.05
8/10/67	60.02	7/25/81	60.07
7/19/68	60.31		
7/29/68	60.20		
8/26/69	60.37	Mean	60.25
9/8/69	60.17	Std. Deviation	0.24
7/28/70	60.42	Maximum deviation	0.55

Each data point is an average of 20 to 30 points per flight for period 9/5/63 to 8/5/70.

For flights on 4/5/74 through 7/1/75 each data point is an average of 100 or more flight data points.

For flights starting in September 1975, each data point is an average of 200 data points.