JPL PUBLICATION 79-66

(NASA-CR-162298) RESULTS OF THE 1978 N79-32635
NASA/JPL BALLOON FLIGHT SOLAR CELL
CALIBRATION PROGRAM (Jet Propulsion Lab.)
13 p HC A02/MF A01 CSCL 10A Unclas
G3/44 35786

Results of the 1978 NASA/JPL Balloon Flight Solar Cell Calibration Program

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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. A summary of the data is presented.

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 R. G. Downing, R. L. Mueller and R. S. Weiss. The cooperation and patience extended by all participating organizations was greatly appreciated.

Abstract

The 1978 scheduled solar cell calibration balloon flight was successfully completed on July 20, 1978, meeting all the objectives of the program. Thirty-six modules were carried to an altitude of above 36 kilometers. Recovery of telemetry and flight packages was without incident. These calibrated standard cells can be used as reference standards in simulator testing of cells and arrays with similar spectral response characteristics.

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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 range 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. That representative high altitude is to be chosen to make

$$\int_{\lambda 1}^{\lambda 2} R_\lambda \; T_\lambda \; E_\lambda \; d_\lambda \geq K \int_{\lambda 1}^{\lambda 2} R_\lambda \; E_\lambda \; d_\lambda \qquad (1)$$

where R_λ = cell spectral response
E_λ = extra-atmospheric solar spectral irradiance (AMO)
T_λ = sky path spectral transmissivity
K = desired fractional fidelity to true AMO

The limits of integration, λ_1 and λ_2, in the practical case of known solar cells will be 0.30 and 1.20 μm, respectively. The values of these integrals can be evaluated to desired precision by finite summation of available data (Refs. 1 and 2). It can thus be shown that for this wavelength band, the spectral response of recent cells and K = 0.995, for example, an altitude greater than 30 kilometers is required to satisfy Eq. (1) above. This is, incidently, above the operating ceiling of the high altitude aircraft.

The factors affecting the spectral transmission of the atmosphere at various altitudes are summarized in Table 1 (Ref. 3). To reach and maintain the required altitude, the calibration program makes use of balloons provided and launched by the National Scientific Balloon Facility, Palestine, Texas.

II. PROCEDURE

To insure electrical and mechanical compatability with other components of the flight system, the cells are mounted by the participants on JPL-supplied standard modules according to directions in Ref. 4, which details materials, techniques, and workmanship standards for assembly. The JPL standard module is a machined copper block 3.7 x 4.8 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%, 20 ppm/°C) load resistor appropriate for scaling the cell output to the telemetry constraints. This load resistor, 0.5 ohm for a 2 x 2 cm cell, for example, also loads the cell in its short-circuit current condition. The mounted cells are then subjected to

Table 1. Attenuation of Solar Radiation by the Earth's Atmosphere

Pressure, mbar[b]	Altitude[a]			Wavelength regions, μm									Altitude, km	IUGG[c]
	Miles	10^3 feet	Kilometers	0.12 to 0.20	0.20 to 0.29	0.29 to 0.32	0.32 to 0.35	0.35 to 0.55	0.55 to 0.9	0.9 to 2.5	2.5 to 7	7 to 20		
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	110 km
1.5	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 to 33	CHEMOSPHERE
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) found up to about 70,000 feet.			Strong O_3 absorption at 9.6 μm. Strong CO_2 absorption 12-17 μm.	33 to 11	20 km STRATOSPHERE
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 to 2	11 km TROPOSPHERE
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 kilometers.					2 to sea level	0 km

[a] NASA/JPL balloon flight program altitude = 36.6 km (120 kft).

[b] One mbar = 100 N/m^2.

[c] Nomenclature recommended by International Union of Geodesy and Geophysics (IUGG).

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, Fig. 1. Upon arrival at the Palestine facility, the tracker and module payload are checked for proper operation, the data acquisition and Pulse Code Modulated telemetry systems are calibrated, and mounting of the assembly onto the balloon is then accomplished, (Fig. 2).

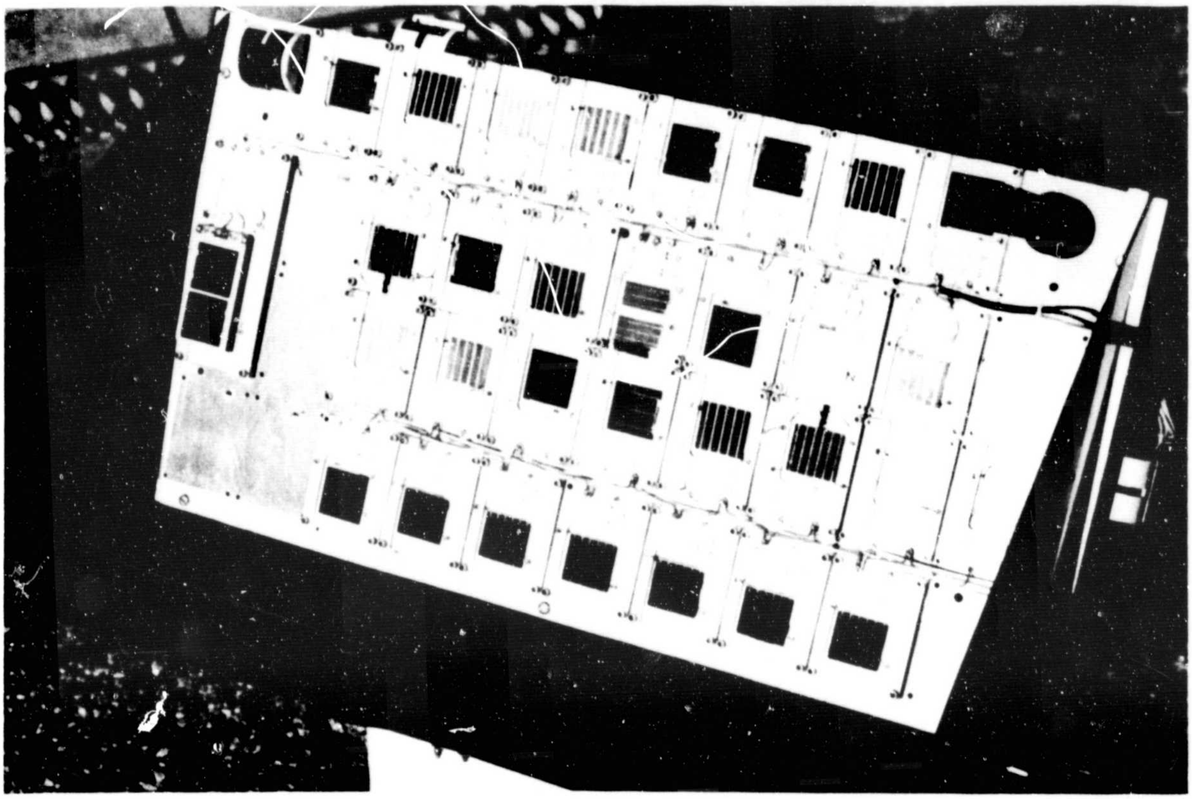

Figure 1. Solar Payload Module

At operating altitude the sun tracker bed plate is held pointed at the Sun to within ±1 degree. The response of each module, temperatures of representative models, 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.

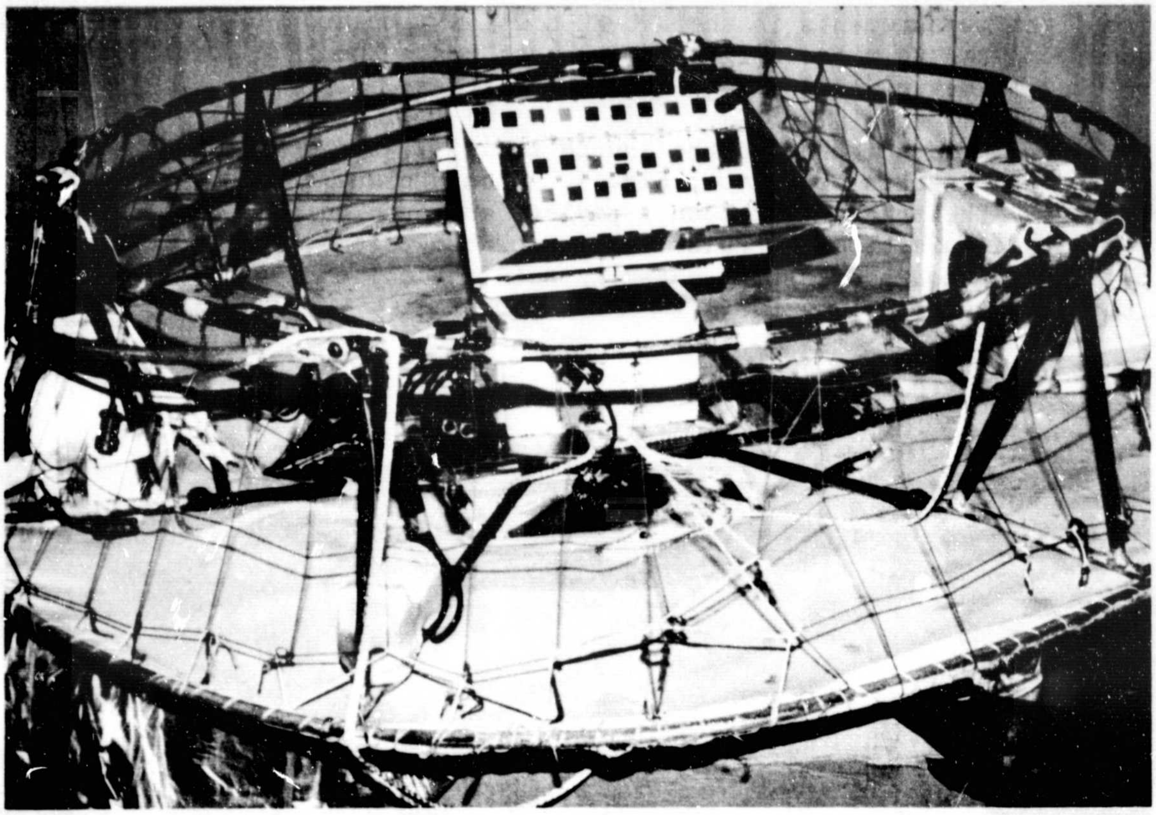

Figure 2. Balloon Mount

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 Ref. 5.

IV. DATA REDUCTION

The raw data as taken from the tape is corrected for temperature and Sun-Earth distance according to the formula (Ref. 6):

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

where

$I_{T,R}$ = measured short circuit current at temperature T and distance D.
R = Sun-Earth distance in astronomical units
α = short-circuit current temperature coefficient
T = module temperature in ^{o}C

The value of is supplied by the participant.

The calibration value is taken to be the average of 200 consecutive data points taken around the time of solar noon during indicated thermal equilibrium.

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 2. The placement of modules on the field of the tracker bed for the 1978 flight is shown in Fig. 3. A detailed discussion of data reduction and an analysis of system error may be found in Ref. 5.

Table 2. Cell Calibration Data

BALLOON FLIGHT 78-1 DATE 7-20-78 ALTITUDE 118,890 RV=1.0161039

CHANNEL NUMBER	MODULE NUMBER	ORGANIZATION CODE	TEMP. INTENSITY ADJ. AVERAGE	STANDARD DEVIATION	AMO, SOLAR SIM. 1 AU, 28 DEG.C		COMPARISON, SOLAR SIMULATOR & FLT		COMMENTS
					PRE-FLT	POS-FLT	PRE-FLT VS. POS-FLT (PERCENT)	FLIGHT VS. PRE-FLT (PERCENT)	
1	78-104	HUGHES	81.20	.04992	80.20	80.40	.25	1.24	
2	78-121	TRW	66.04•	.05149	62.40	63.10	1.12	5.84	
3	78-106	HUGHES	90.47	.03158	89.85	89.08	-.86	.69	
4	78-006	JPL	31.58	.05421	32.30	32.11	-.59	-4.94	0.5M-FILTER
5	74-205	JPL	91.39	.05149	88.50	88.33	-.19	3.26	BLACK
6	78-103	HUGHES	86.29	.02641	84.55	84.50	-.06	2.06	
7	78-126	TRW	73.06•	.04204	71.85	71.57	-.39	1.68	
8	78-101	HUGHES	95.90	.03837	93.85	93.40	-.48	2.18	
9	78-122	TRW	69.00•	.05218	64.55	65.82	1.97	6.89	
10	78-102	HUGHES	86.73	.04816	85.10	85.48	.45	1.91	
11	78-009	JPL	68.08	.09658	47.30	45.00	-4.86	43.17	0.35M FILTER
12	73-183	JPL	67.26	.04220	68.32	68.30	-.03	-1.55	TEMP 4 CELL
13	78-007	JPL	35.03	.04650	37.00	37.06	.16	-7.56	0.7M FILTER
14	6FS-17A	JPL	60.49	.02904	60.65	60.60	-.08	-.27	STANDARD
15	78-110	HUGHES	96.44	.05226	95.00	94.35	-.68	1.51	
16	78-107	HUGHES	89.52	.05147	89.40	88.80	-.67	.13	
17	78-002	JPL	75.29	.02366	75.55	75.48	-.09	-2.27	2X4 CM
18	78-001	JPL	85.92	.03647	84.60	83.95	-.77	-.20	2X4 CM
19	73-182	JPL	68.20	.02583	69.10	69.21	.16	-1.31	TEMP 1 CELL
20	78-005	JPL	79.65	.05718	80.00	80.31	.39	-.44	
21	78-123	TRW	77.37•	.04753	75.40	75.77	.49	2.61	
22	78-008	JPL	34.86	.02802	34.20	33.89	-.91	-.50	0.8M FILTER
23	78-124	TRW	83.37•	.04670	81.55	81.50	-.06	2.23	
24	78-105	HUGHES	81.75	.02455	80.90	81.00	.12	1.06	
25	78-125	TRW	90.18•	.06937	87.20	87.26	.07	3.42	
26	76-001	JPL	67.65	.05780	68.65	68.61	-.06	-1.46	TEMP 3 CELL
27	78-012	JPL	79.38	.05437	79.50	79.23	-.34	-.15	VJ (SOLAREX)
28	77-003	JPL	76.87	.04885	77.60	77.48	-.15	-.94	GREEN
29	77-005	JPL	76.31	.03175	76.00	75.68	-.42	.41	VIOLET
30	78-010	JPL	84.40	.02811	83.00	82.75	-.30	1.69	S-13
31	78-003	JPL	90.77	.05049	88.50	88.20	-.34	2.57	0.0 FILTER
32	78-004	JPL	69.99	.04867	70.15	70.68	.76	-.23	2 MIL (SLRA)
33	78-011	JPL	79.60	.04926	79.40	78.70	-.88	.25	S-11
34	77-004	JPL	77.21	.04668	77.60	77.67	.09	-.50	GREEN
35	77-006	JPL	76.70	.04772	76.20	76.12	-.10	.65	VIOLET
36	78-014	JPL	80.42	.05990	78.80	78.30	-.63	2.05	TJ (T.I.)

• INDICATES CHANNEL FOR WHICH NO TEMPERATURE COEFFICIENT WAS PROVIDED.

AVERAGE TEMPERATURE (DEG.C) AT FLOAT ALTITUDE = 54.27

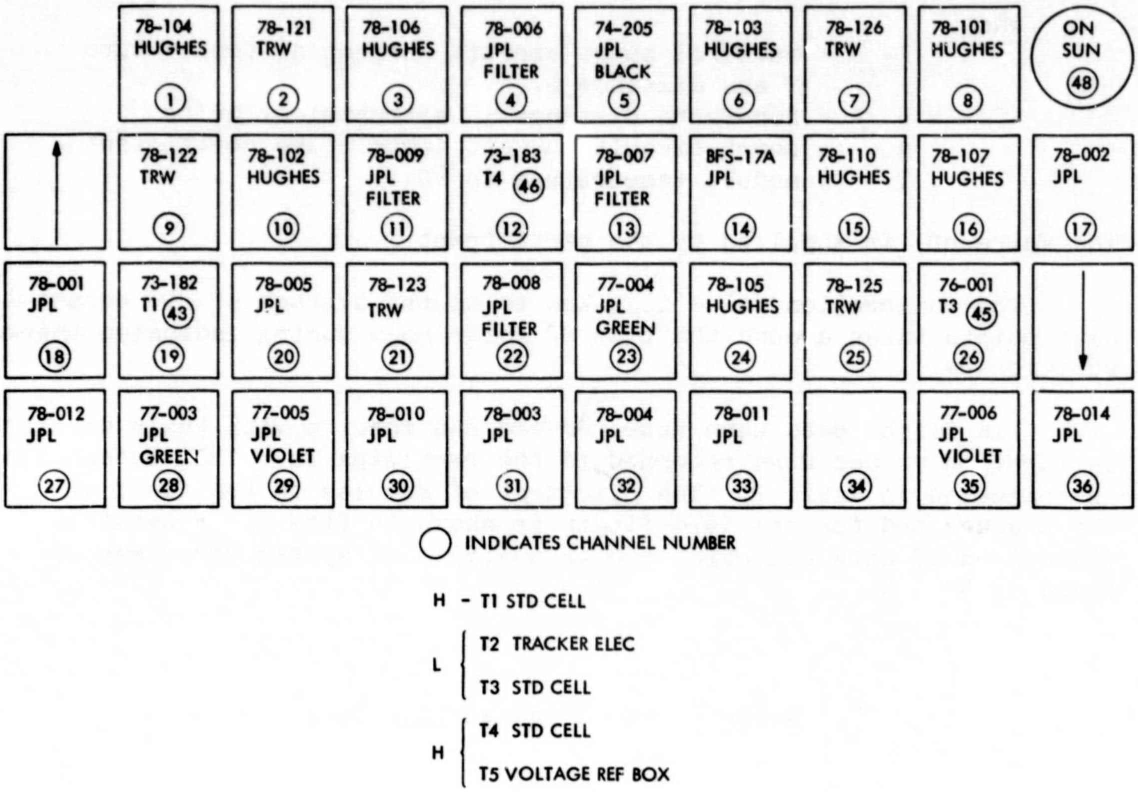

Figure 3. Module Location Chart

V. MONITOR CELLS

Several standard modules have been flown repeatedly over the 16-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% and a maximum deviation of 0.92% 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.

VI. JPL FILTERED CELLS

A group of five modules was flown in a selective filtering experiment, three of which, 78-006, 78-007 and 78-009, were filtered with 10-nanometer bandwidth interference filters centered at 500, 700 and 1035 nanometers, respectively. A fourth, 78-008, was filtered with a 780-nanometer long-pass filter. All filters were cemented permanently in place using Dow-Corning Sylgard 182. The fifth member of the group, 78-003, had no filter. This group of modules will serve to monitor the deviation from AMO in the spectral characteristics of solar simulators.

Table 3. Repeatability of Standard Solar Cell BFS-17A
for 30 Flights over a 16-Year Period

Flight date	Output, mV	Flight date	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		
8/4/67	59.83	Mean	60.25
8/10/67	60.02		
7/19/68	60.31	Deviation	0.24
7/29/68	60.20		
8/26/69	60.37	Maximum deviation	0.55
9/8/69	60.17		
7/28/70	60.42		

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.

VII. FLIGHT PERFORMANCE

The launch at 0730 hours on July 20, 1978, was uneventful as were the float and termination phases. The tracker was energized at 1023 hours at an altitude of 36.3 kilometers with sun-lock occurring within 2 minutes. The flight was terminated at 1412 hours. Recovery of payload followed.

VIII. CONCLUSIONS

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

2. To date, the only method demonstrated to be capable of obtaining AMO calibration with the accuracy required is the balloon-borne system.

3. As advancing cell technology continues to favorably modify their spectral response, continued calibration under AMO conditions is required to assure that solar panel performace with all its ramifications can be accurately predicted.

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