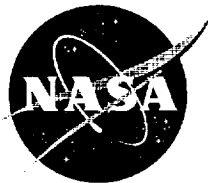


Final Report
1995

Results of the 1995 JPL Balloon Flight Solar Cell Calibration Program

B. E. Anspaugh
R. S. Weiss

December 1, 1995



National Aeronautics and
Space Administration

by

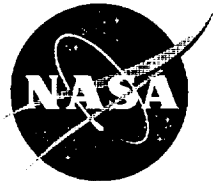
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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ABSTRACT

The 1995 solar cell calibration balloon flight was completed on August 31, 1995. All objectives of the flight program were met. Forty-six modules were carried to an altitude of 120,000 ft (36.6 km). Full I-V curves were measured on 19 of these modules, and output at a fixed load was measured on 27 modules. This data was corrected to 28°C and to 1 AU (1.496×10^8 km). The calibrated cells have been returned to the 7 participants and can now be used as reference standards in simulator testing of cells and arrays.

ACKNOWLEDGMENT

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"That, Piglet, is a *very* good idea. It is just what Eeyore wants to cheer him up. Nobody can be uncheered with a balloon."

Winnie-the-Pooh

1. INTRODUCTION AND OVERVIEW

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 cells and arrays must have the capability of measuring these cells in a light beam that is a close match to the solar spectrum. The solar spectrum has been matched very closely by laboratory solar simulators. But the design of solar cells and the sizing of solar arrays require such highly accurate measurements that the intensity of these simulators must be set very accurately. A small error in setting the simulator intensity can conceivably cause a disastrous missizing of a solar panel, causing either a premature shortfall in power or the launch of an oversized, overweight solar panel.

The Jet Propulsion Laboratory (JPL) solar cell calibration program was conceived to produce reference standards for the purpose of accurately setting solar simulator intensities. The concept was to fly solar cells on a high-altitude balloon, to measure their output at altitudes near 120,000 ft (36.6 km), to recover the cells, and to use them as reference standards. The procedure is simple. The reference cell is placed in the simulator beam, and the beam intensity is adjusted until the reference cell reads the same as it read on the balloon. As long as the reference cell has the same spectral response as the cells or panels to be measured, this is a very accurate method of setting the intensity. But as solar cell technology changes, the spectral response of the solar cells changes also, and reference standards using the new technology must be built and calibrated.

Until the summer of 1985, there had always been a question as to how much the atmosphere above the balloon modified the solar spectrum. If the modification was significant, the reference cells might not have the required accuracy. Solar cells made in recent years have increasingly higher blue responses, and if the atmosphere has any effect at all, it would be expected to modify the calibration of these newer blue cells much more so than for cells made in the past.

In late 1984, a collection of solar cells representing a wide cross section of solar cell technology was flown on the shuttle Discovery as a part of the Solar Cell Calibration Facility (SCCF) experiment. The cells were calibrated as

reference cells on this flight by using procedures similar to those used on the balloon flights. The same cells were then flown on the 1985 balloon flight and remeasured. Since the 2 sets of measurements gave nearly identical results (see reference 1), the reference standards from balloon flights may continue to be used with high confidence.

JPL has been flying calibration standards on high-altitude balloons since 1963 and continues to organize a calibration balloon flight at least once a year. The 1995 flight was the 48th flight in this series. The 1995 flight incorporated 46 solar cell modules from 7 different participants. The payload included Si, amorphous Si, GaAs, GaAs/Ge, dual junction cells, top and bottom sections of dual junction cells, and a triple junction cell.

A new data acquisition system was built for the balloon flights and flown for the first time on the 1995 flight. This system allows the measurement of current-voltage (I-V) curves for 20 modules in addition to measurement of modules with fixed loads as had been done in the past.

2. PREFLIGHT PROCEDURES

2.1 MODULE FABRICATION

The cells were mounted by the participants or by JPL on JPL-supplied standard modules according to standard procedures developed for the construction of reference cells. The JPL standard module is a machined copper block on which a fiberglass circuit board is mounted. The circuit board has insulated solder posts which are used for making electrical connections to the solar cell and to a load resistor. Of course, no resistor is included for those cells destined for I-V measurement. The circuit board can be modified to include 2 binding posts and a jumper in series with one of the leads to the resistor. After flight calibration, the jumper can be removed and replaced with current pickoff probes for use on pulsed xenon simulators that may require a current input. The assembly is painted with either high-reflectance white or low-reflectance black paint. The resistor performs 2 tasks. First, it loads the cells near short-circuit current, which is the cell parameter that varies in direct proportion to light intensity. Second, it scales the cell outputs to read near 100 mV during the flight, which matches a constraint imposed by the data acquisition electronics for the fixed load cells. Load resistance values are chosen to match the electrical characteristics of each cell flown. Nominally, the

resistors will be ≈ 0.5 ohm for a 2 x 2 cm Si cell, 0.66 ohm for a 2 x 2 cm GaAs cell, 0.25 ohm for a 2 x 4 cm Si cell, etc. The load resistors are precision resistors (0.1%, 20 ppm/ $^{\circ}$ C) and have a resistance stability equal to or better than $\pm 0.002\%$ over a 3-year period. The solar cells are permanently glued to the body of the machined copper block with RTV 560 or its equivalent. This gives a good thermal conductivity path between cell and copper block, while providing electrical insulation between the rear surface of the solar cells and the block.

2.2 CELL MEASUREMENTS

After the cells were mounted on the copper blocks, the electrical output of each cell module was measured under illumination by the JPL X25 Mark II solar simulator. For these measurements, the simulator intensity was set by using only one reference cell—no attempt was made to match the spectral response of the reference standard to the individual cell modules. The absolute accuracy of these measurements is therefore unknown, but the measurements do allow checking of the modules for any unacceptable assembly losses or instabilities. After the balloon flight, the cells were measured in exactly the same way to check for any cell damage or instabilities that may have occurred as a result of the flight.

2.3 TEMPERATURE COEFFICIENTS AND LEAST SQUARES FITS

The temperature coefficients of the mounted cells were also measured before the flight. The modules were mounted in their flight configuration on a temperature-controlled block in a vacuum chamber. For the fixed-load cells, outputs were measured at 25, 35, 45, 55, 65, and 75 $^{\circ}$ C under illumination with the X25 simulator. The temperature coefficients of the cell modules were computed by fitting the output vs temperature relationship with a linear least squares fit. The I-V cells were measured in open air at temperatures of 18, 28, 38, 48, 58, and 68 $^{\circ}$ C using the JPL Large Area Pulsed Solar Simulator (LAPSS) as the illumination source. Temperature coefficients for both short circuit current (I_{sc}) and open circuit voltage (V_{oc}) were computed using a linear least squares fit.

2.4 DATA ACQUISITION SYSTEM CHECKOUT AND CALIBRATION

A new data acquisition (DAQ) system was built and flown for the first time on the 1995 flight. The system was designed to duplicate the function of the older data encoder with regard to reading and processing the outputs of the modules with fixed-load resistors (maximum output voltage is still 100 mV). The new system has 6 dedicated

temperature measurement channels, now using platinum resistance sensors instead of thermistors. A notable feature of the new system is the capability of measuring the I-V characteristics of as many as 20 solar cells. This is done by applying 20 resistive loads to each cell and measuring the cell's output voltage and current as each load is applied. A four-wire system is used for this measurement. The resistive loads are individually chosen to generate the expected I-V characteristic of each cell and produce a large number of points near the maximum power (P_{max}) point. Sixteen resistors are available for cell loading. Selection of parallel combinations of up to 5 at a time of these resistors results in a theoretical total of 6,884 possible resistive loads available for each cell.

The heart of the DAQ is a 286-class computer on a STD bus circuit board. This computer controls the multiplexing of the cells, temperatures, calibration voltages, and power supply voltages for measurement. The computer is also used to connect each I-V cell in its turn to the measurement circuitry, and the computer also applies the unique set of load resistors across the cell under measurement. The computer is used to format the data, add clock time, synch words, and a checksum for each line, then send all this to the telemetry transmitter via an RS232 output. All of the test and measurement parameters are read out and transmitted during the course of a telemetry frame. During this time the fixed-load cells are each read 5 times, and each of the I-V cells are read once. All other engineering voltages and temperatures are also read once each frame. As presently programmed, a telemetry frame is sent every 9.5 seconds.

All measurements of electrical parameters are performed by sending the signals through suitable amplifiers, then to a 12-bit A/D converter. The fixed-load cell signals are sent through an amplifier with a gain of 49.6. The I-V cell voltage levels are sent through an amplifier with a gain of 2.001. Cell currents passed through a precision 0.1-ohm resistor. The voltage drop across this resistor was fed to a differential amplifier with a gain of 52.8. The on-sun indicator and the 7 temperature signals were each sent through individual amplifiers. All amplifiers went through an extensive calibration procedure prior to leaving JPL. Calibration voltages were available in the DAQ that could be used for monitoring the amplifiers used for voltage measurement during the flight.

The system is designed so that the output from the DAQ on the RS232 line can be fed directly to the COM input of a PC for preflight testing. During the flight, the RS232 output goes to the telemetry transmitter on the balloon, is sent to the telemetry receiver on the ground, and then to the COM input of the PC. This configuration allows a much

more thorough checkout of the system before it leaves JPL.

The PC program for receiving, converting, and storing data is written in LabVIEW, which is a graphical programming language specifically designed for making engineering-type measurements under PC control. The LabVIEW program provides for graphical display of all the fixed-load cells simultaneously. The I-V curves of any or all of the 20 I-V cells may also be displayed. The program also provides for digital readout of all the power supply voltages, calibration voltages, on-sun indicator, and temperatures. Synch status and checksum status are continuously displayed. These displays are continuously updated in real time and give an instantaneous reading on the status of the whole system.

2.5 PANEL ASSEMBLY AND CHECKOUT

After the electrical measurements of the solar cells were completed, the modules were mounted on the solar panel and connected electrically. Figure 1 is a photograph of the modules after completion of these steps, and Figure 2 is a diagram that identifies the modules in the photograph by their serial numbers. After completion of the panel assembly, the panel, tracker, and DAQ were all given complete functional tests in terrestrial sunlight. The assembled tracker and panel were placed in sunlight on a clear, bright day and checked for the tracker's ability to acquire and track the sun while each cell module was checked for electrical output. All power supply voltages and temperature readings were checked, and the calibration voltages were checked for stability and proper function. After these tests were completed satisfactorily, the assembly was shipped to the National Scientific Balloon Facility (NSBF) in Palestine, Texas, for flight.

2.6 PRELAUNCH PROCEDURES AT PALESTINE

The NSBF was established in 1963 at Palestine, Texas. This location was chosen because it has favorable weather conditions for balloon launching and a large number of clear days with light surface winds. The high-altitude winds in this part of the country take the balloons over sparsely populated areas so the descending payloads are unlikely to cause damage to persons or property. The JPL calibration flights have flown from the Palestine facility since 1973. The flights are scheduled to fly in the June-to-September time period, since the sun is high in the sky at that time of year and the sunlight passes through a minimum depth of atmosphere before reaching the solar modules.

Upon arrival at Palestine, the tracker and module payload were again checked for proper operation. This included a checkout in an environmental test chamber

wherein the tracker, calibration voltages, and the entire data acquisition system were all tested as a system. The chamber was pumped down to a pressure of ≈ 40 mb (0.4 N/cm^2) [corresponding to an altitude of 65,000 ft (19.8 km)], and cooled to -50°C . The system was tested at 10° increments during the cooldown. Then, the assembly was removed from the environmental chamber and a room-temperature, end-to-end check was performed on the payload, telemetry, receiving, and decoding systems.

After all the checkouts and calibrations were performed, the tracker was mounted onto an aluminum tubular hoop structure. This assembly was then mounted on the top portion (or apex) of the balloon. Figure 3 is a photograph of the tracker mounted on the hoop assembly. The solar panel is shown with a typical complement of calibration modules.

3. BALLOON SYSTEM

The main components of the balloon flight system were (1) the apex-mounted hoop assembly that contained the experimental package, the data encoder, the recovery system, and the camera package; (2) the balloon; and (3) the lower payload that contained the telemetry and power systems.

3.1 BALLOON DESCRIPTION

The balloon used for the JPL solar cell calibration high-altitude flights had a volume of 3.46 million ft^3 ($98,000 \text{ m}^3$). The balloon manufacturer used 0.8 mil ($20 \mu\text{m}$) polyethylene film (Stratofilm-372) designed specifically for balloon use. The balloon alone weighed 702 lb (319 kg). The balloon was designed to lift itself and a payload weight of up to 725 lb (330 kg), distributed between the bottom and top payloads, to a float altitude of 120,000 ft (36.6 km). At float altitude, the balloon had a diameter of roughly 213 ft (65 m) and a height of 146 ft (45 m). To electrically connect the top and bottom payloads, a multiconductor cable was built into the balloon during its manufacture. The balloon was built with an internal rip line designed to rip a hole in the side of the balloon for termination of the flight. A special structure was built into the top of the balloon for attaching the top payload. Two poppet valves incorporated into this mounting structure were commanded to open and release helium from the balloon at the end of the flight. The poppet valves act as a backup to the rip line.

Trying to inflate and launch a balloon with a sizable weight attached to its top is like trying to balance an apple on the horn of a nervous giraffe. A tow balloon tied to the

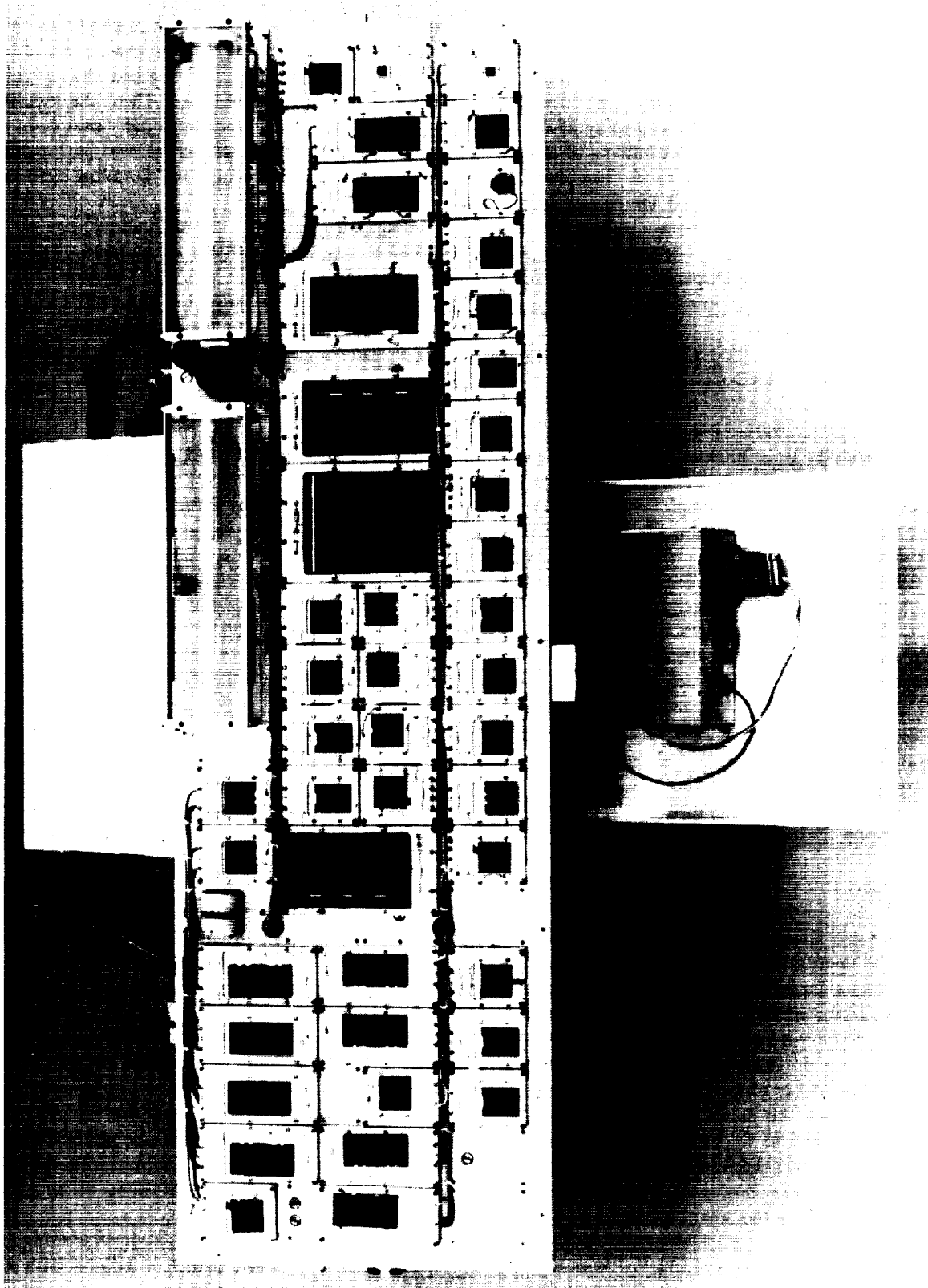
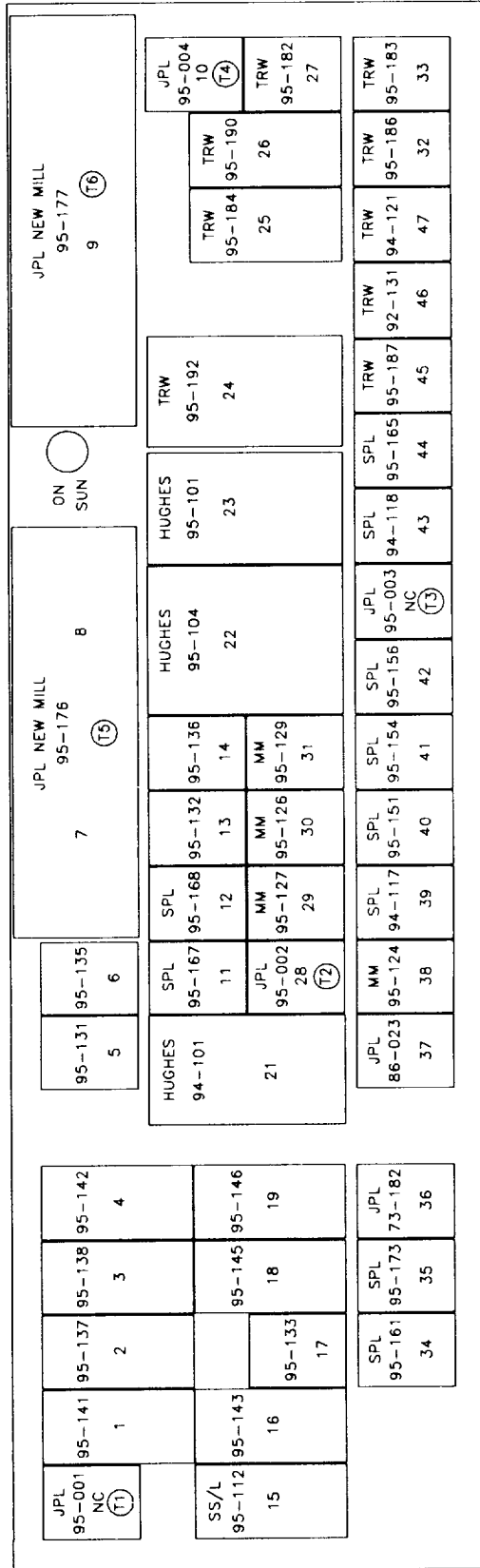


Figure 1. Photograph of the 1995 Balloon Flight Solar Panel



(T1) -- (T6) RTDs

Figure 2. 1995 Module Location Chart

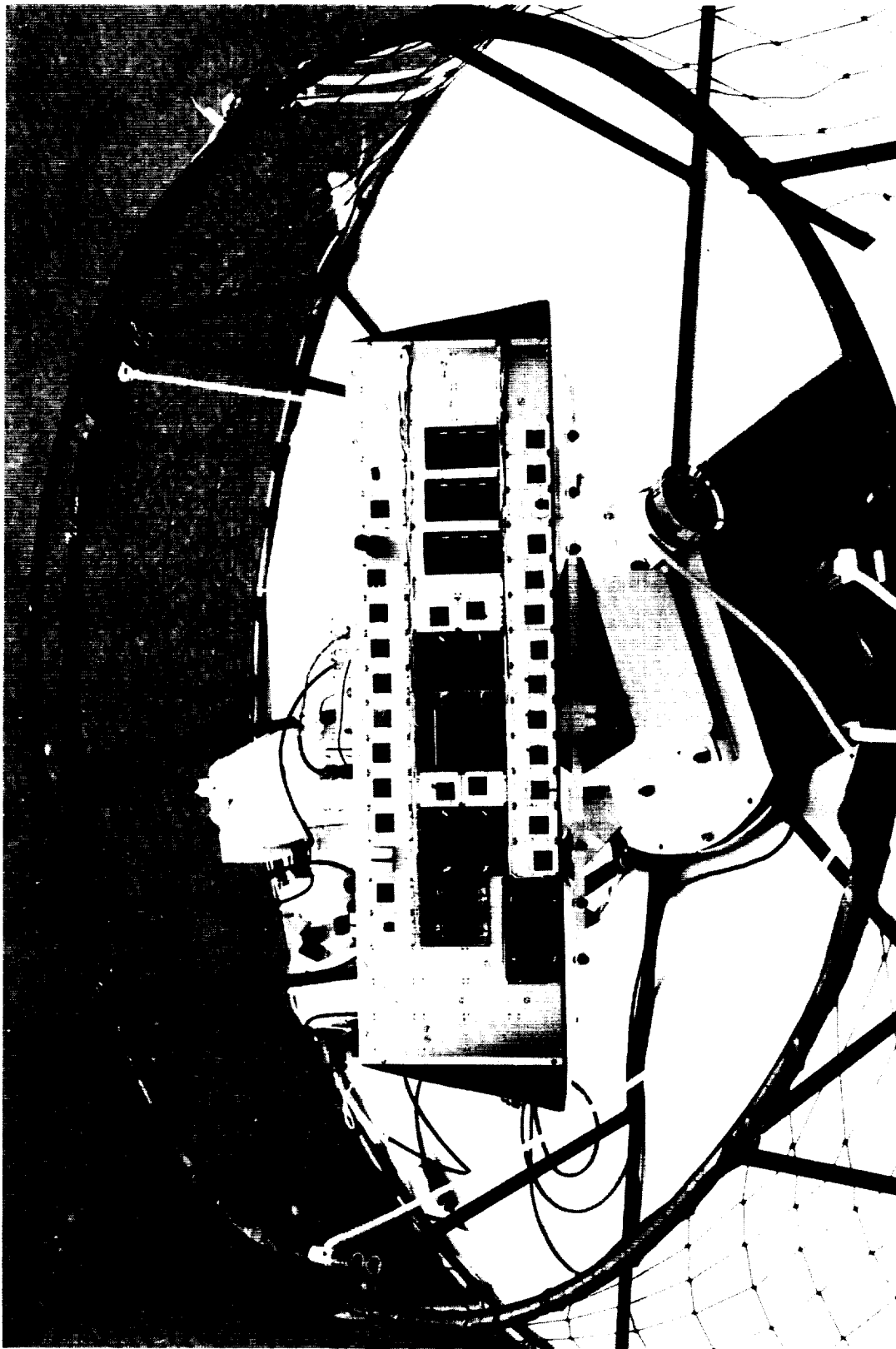


Figure 3. Tracker Mounted on Aluminum Hoop Assembly

top payload was used during the inflation and launch phases to add stability and to keep it on top. This smaller balloon, about 2,900 ft³ (82 m³), is designed to lift about 180 lb (82 kg). The tow balloon was cut loose from the top payload after the launch as soon as the main balloon stabilized and the launch-induced oscillations damped out.

3.2 TOP PAYLOAD

The top payload consisted of the tracker, solar panel, voltage reference box, multiplexer, DAQ, single-frame movie camera, clock, descent parachute, battery power supply for the tracker and data encoder, relay box, and tracking beacon. All these items were mounted to the aluminum hoop assembly shown in Figure 3. The hoop assembly served the following functions:

- (1) Permitted the top-mounted payload to "float" on top of the balloon and minimized billowing of balloon material around the top payload.
- (2) Served as the mounting surface for the balloon's top-end fitting.
- (3) Provided a convenient point for attaching the tow balloon and the descent parachute.
- (4) Acted as a shock damper to protect and minimize damage to the top payload at touchdown.

The complete apex-mounted hoop assembly, as flown, weighed \approx 130 lb (59 kg) and descended as a unit by parachute at flight termination.

The sun tracker, shown in Figure 3, is capable of orienting the solar panel toward the sun, compensating for the motion of the balloon by using two-axis tracking in both azimuth and elevation. The tracker has the capability to maintain its lock onto the sun to within ± 1 deg. To verify that the tracker was operating properly, the output of an on-sun indicator was constantly monitored during flight by feeding its output to the DAQ and entering its signal into the telemetry stream. The on-sun indicator consists of a small, circular solar cell mounted at the bottom of a collimator tube, 7 in. (17.8 cm) long, with an aperture measuring 0.315 in. (0.8 cm) in diameter. The on-sun indicator was attached to the solar panel so that it pointed at the sun when the panel was perpendicular to the sun. The output of the on-sun indicator falls off very rapidly as the collimator tube points away from the sun and provides a very sensitive indication of proper tracker operation.

A reflection shield was attached to the panel to prevent any stray reflected light from reaching any of the modules. This shield was made of sheet aluminum, painted black, and attached to three edges of the solar panel.

The solar cell modules were mounted onto the sun tracker platform with an interface of Apiezon H vacuum grease and held in place with 4 screws. The grease was used to achieve a highly conductive thermal contact between the modules and the panel and to smooth out the temperature distribution over the solar panel as much as possible.

The solar panel temperature was monitored using platinum resistance sensors (RTDs). Some of the solar cell modules were constructed with RTDs embedded in the copper substrate directly beneath the solar cell. Six of these modules were mounted on the solar panel at strategic locations so their temperature readings gave an accurate representation of panel temperature. Placement of these modules on the panel is shown in Figure 2. A seventh RTD was mounted inside the DAQ to monitor its temperature during environmental testing and during the flight.

An ultrawide-angle, single-frame movie camera mounted at the perimeter of the aluminum hoop provided visual documentation of tracker operation. A battery-powered timer activated the shutter at 10-second intervals, so that 50 ft (15.24 m) of super 8 movie film is sufficient to record the entire flight from launch to landing. A windup clock was placed in the camera's field of view for correlation of tracker operation with the telemetered data. The pictures provide a complete record of ascent, tracker operation at float altitude, descent, touchdown, and post-touchdown events.

A tracking or locator beacon was attached to the hoop assembly. This beacon, similar to those used for tracking wild animals in their natural habitat, consists of a low-wattage transmitter which sends short, 160-MHz pulses at the rate of about 1 per second. A handheld directional antenna and a battery-powered receiver are used inside the chase plane and on the ground for locating the transmitter. This beacon has been very useful in locating this very small payload in a very large open range.

3.3 BOTTOM PAYLOAD

The bottom payload was entirely furnished by the NSBF. It consisted of a battery power supply, a ballast module for balloon control, and an electronics module known as the consolidated instrument package (CIP).

Power for operating most of the electrical and electronic equipment on the balloon was supplied by a high-capacity complement of lithium batteries. This supply, furnishing 28 Vdc regulated power and 36 Vdc unregulated power, powered all the instruments in the CIP. Several other small battery sources were used at various locations on the balloon for instruments that require small amounts of power. For example, the tracker and data encoder, the tracking beacons, the voltage reference box, and the camera timer all had individual battery power supplies. All batteries were sized to supply power for at least twice the expected duration of a normal flight.

High-altitude balloons tend to lose helium slowly during the course of the flight. As a consequence, a helium balloon will tend to reach float altitude and then begin a slow descent. To counteract this tendency, a ballast system was included as part of the bottom payload. It contained ≈ 100 lb (45 kg) of ballast in the form of very fine steel shot. The shot may be released in any desired amount by radio command. By proper use of this system, float altitude may be maintained to within $\pm 2,000$ ft (± 600 m).

The telemetry system was contained in the CIP. The system sent all data transmissions concerning the flight over a common RF carrier. The CIP also contained a command system for sending commands to the balloon for controlling scientific payloads or for controlling the housekeeping functions on the balloon. Specifically, the CIP contained the following equipment:

- (1) Pressure transducers
- (2) Subcarrier oscillators, as required
- (3) L-band FM transmitter
- (4) High-frequency tracking beacon transmitter
- (5) Transponder for air traffic control tracking
- (6) Pulse Code Modulation (PCM) command receiver-decoder
- (7) 2 Global Positioning Satellite (GPS) receivers

The altitude of the balloon was measured with a capacitance-type electronic transducer, manufactured by MKS Instruments, Inc., which read pressure within the range of 1,020 to 0.4 mbar (102,000 to 40 N/m²) with an accuracy of 0.05%. The transducer produced a dc level that was encoded as PCM data and decoded at the receiving station into pressure, and then the altitude was calculated from the pressure reading. A GPS receiver also computed and sent altitude information into the telemetry stream.

The GPS navigation system was used for flight tracking. The second GPS receiver was used as a backup. An onboard receiver was used to receive these signals for retransmission to the processor in the ground station. This

system can provide position data to an uncertainty of less than 0.5 mi (0.8 km). The GPS signal was multiplexed into the telemetry stream and updated every 8 seconds.

All the telemetry data was sent to the ground in the form of pulse code modulation. A UHF L-band transmitter in the CIP was used to generate the RF carrier. The L-band carrier was modulated by the pulse code and sent to the receiving station at Palestine.

An aircraft-type transponder was flown so that Air Traffic Control (ATC) could read the balloon's location on their radar systems during the descent portion of the flight. ATC was helpful in relaying to the recovery aircraft the exact position of the bottom payload during its descent on the parachute.

The purpose of the PCM command system is to send commands to the balloon, e.g., to turn the tracker on or off, terminate the flight, release ballast, etc. It was designed to reject false commands and was highly reliable in operation. The data was encoded on a frequency-shift-keyed audio carrier. This signal was then decoded into data and timing control. Each command consisted of a double transmission of the data word. Both words must be decoded and pass a bit-by-bit comparison before a command can be executed. Commands may be sent to the balloon from either the ground station at Palestine or from the recovery airplane.

The lower payload is suspended from the balloon by an 8.5-m diameter parachute. The top end of the parachute was fastened to the bottom of the balloon, and the lower payload (which contained the CIP, the battery power supply, and the ballast) was attached to the shroud lines. Appropriate electrical cables and breakaway connectors were rigged in parallel with the mechanical connections. The whole bottom assembly was designed to break away from the balloon and fall to earth while suspended from the parachute at termination of the flight.

4. FLIGHT SEQUENCE

4.1 PRELAUNCH PREPARATIONS

The balloon launch pad at the NSBF is a large circular area, 2,000 ft (600 m) in diameter. In the center of this large circle is another circular area, solidly paved, measuring 1,000 ft (300 m) in diameter. This circular launch pad allows layout of the balloon in precise alignment with the surface wind. Grass is planted in the area between the 2 circles, and a paved road surrounds the larger circle. Paved radials extend from the perimeter road toward the launch pad.

When all prelaunch preparations had been completed and the staff meteorologist had predicted favorable weather and winds at Palestine and for some 300 mi (480 km) downrange, the equipment was taken to the launch site. (Launches from Palestine are only authorized when the predicted termination point is at least 200 mi west of Palestine.)

At the launch pad, the main balloon, protected by a plastic sheath, was laid out full-length on the circular paved area. It was aligned with the direction of the wind and positioned so that the top of the balloon was on the upwind side. The top end of the balloon was passed under, then around a large, smooth, horizontal spool mounted on the front end of the launch vehicle. One end of this launching spool was hinged to the launch vehicle. The other end of the spool had a latch that could be released by a trigger mechanism. After the balloon was passed over the spool, the spool was pushed back to engage the latch so that the spool trapped the balloon. The top 10 m or so of the balloon was pulled forward from the spool, allowing the top payload to rest on the ground. It is this top 10 m of balloon that later received the helium gas during inflation. After the launching spool was latched, final preparations of the top payload began. The tow balloon was attached to the hoop with nylon lines, the clock was wound, the camera was energized, and a final checkout of the tracker and data encoder was performed.

The launch sequence began by inflating the tow balloon with helium. The main balloon was then inflated by passing a predetermined volume of helium through 2 long fill-tubes and into the balloon. The helium formed a bubble in the part of the balloon above the launching spool. Figure 4 shows the configuration of the flight train at this stage of preparation. The balloon was launched by triggering the latch on the launching spool. When the latch was released, a stout spring caused the free end of the spool to fly forward, rotating about the hinge, which released the balloon. As the balloon rose, the launch vehicle at the lower end of the balloon began to move forward (downwind). After the driver of the launch vehicle had positioned the vehicle directly below the balloon and had his vehicle going along at the same speed as the balloon, he released the latch on the pin and the lower payload was released. Figure 5 shows the balloon system and the launch vehicle a few seconds after release of the launching spool just as the downwind launch vehicle began to move. As soon as the main balloon quit oscillating, a signal was sent from the launch pad, which triggered the explosive charges on the ropes connected to the tow balloon. This released the tow balloon, and the launch sequence was complete.

4.2 FLIGHT

The balloon ascended at a rate of ≈ 900 ft/min (4.6 m/s) and reached float altitude after ≈ 2 hours. During the ascent, the flight controller at Palestine maintained a constant contact with ATC. Data from the onboard navigational system was continuously given to ATC so that air traffic in the area could be vectored around the balloon.

After the balloon had been launched, solar cell voltages interspersed with reference calibration voltages and thermistor voltages were fed into the telemetry system. These voltages were converted to PCM and were transmitted to the NSBF ground station along with the navigational, altitude, and other information from the CIP. At the ground station, the signals were decoded, recorded, and displayed in real time for monitoring of the flight. The balloon reached float altitude at 1433 UT (0933 local time), which was ≈ 4 hours before solar noon. The tracker was turned on by telemetry command about 1/2 hour after reaching float altitude, but it could not lock onto the sun at that time, presumably because the sun was not yet high enough. The tracker was therefore turned off and after another 1/2 hour (1030 local time) turned on again. This time the tracker achieved lock. Tracker operation was monitored by observing the output of the on-sun indicator and the outputs of the solar cell modules. Data was recorded from time of launch at 1228 UT through 1923 UT, when the flight was terminated. Solar noon occurred at ≈ 1830 UT for this flight.

4.3 FLIGHT TERMINATION

Shortly after launch, a ground recovery crew began driving toward the expected termination area in a special recovery truck. Approximately 2 hours after the balloon reached float altitude, the recovery airplane took off from Palestine with an experimenter and an observer aboard. This airplane was equipped with a radio system that allowed the crew to monitor the location of the balloon and to maintain constant communication with the balloon base and with the ground recovery crew. The airplane also had a full command system so that it could send commands to the balloon.

During the summer months, the winds at altitudes above 80,000 ft (24 km) blow from east to west at speeds of about 50 knots (25 m/s), so the airplane had to fly about 200 mi (330 km) west of Palestine to be in position for recovery. The pilot could fly directly toward the balloon at any time by flying toward the telemetered location of the balloon. This position information was generated by the GPS system on the balloon, telemetered to the Balloon Base at Palestine, and relayed from there to the airplane. The observer in the

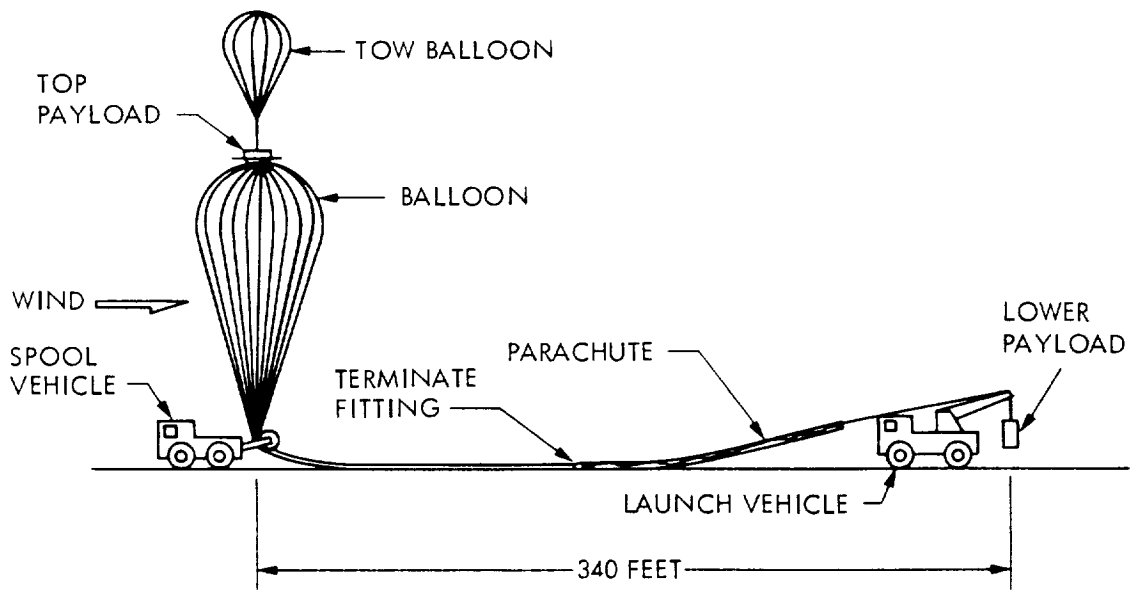


Figure 4. Flight Train Configuration

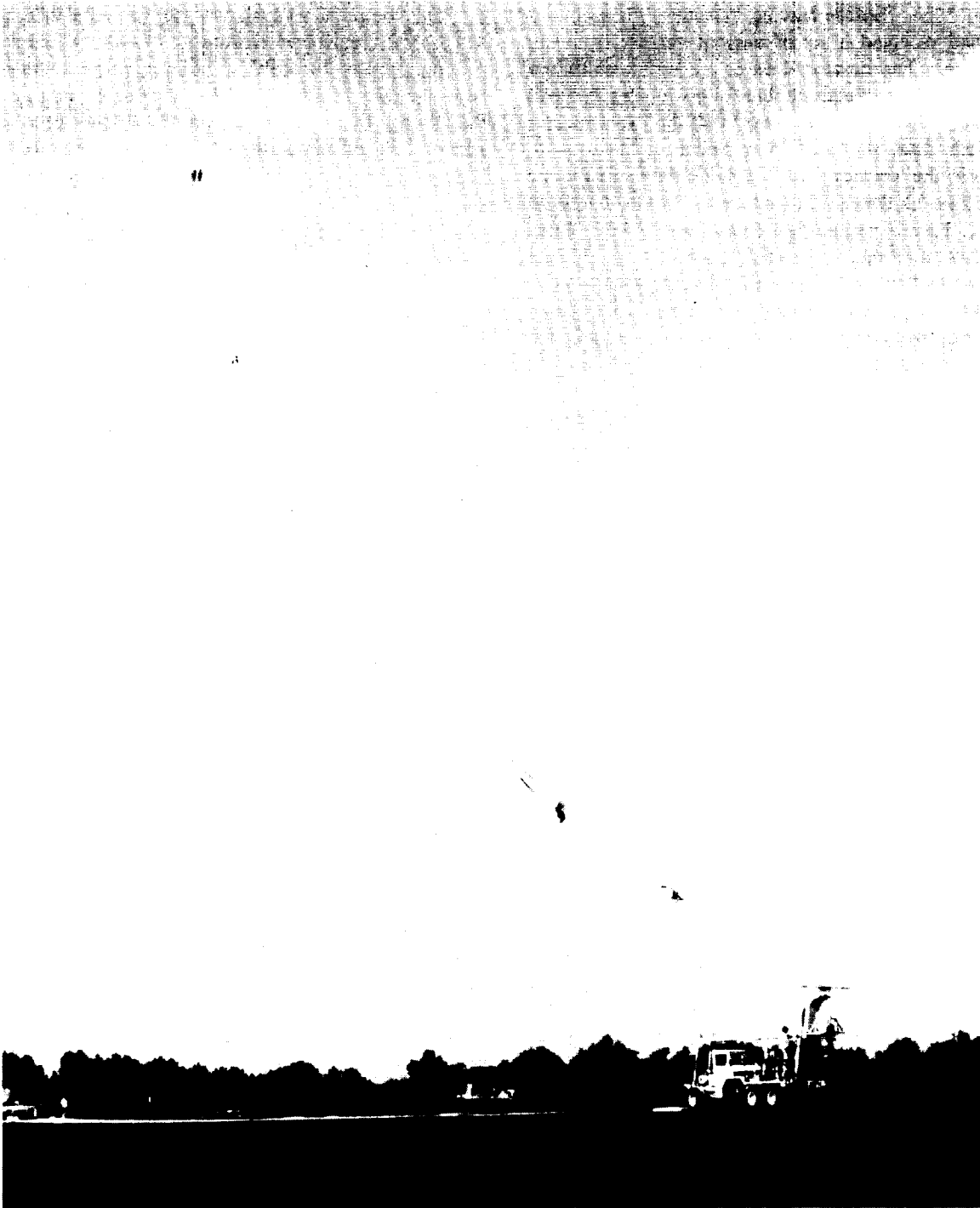


Figure 5. Balloon Launch

recovery airplane shared the responsibility for termination of the flight with the launch director in the NSBF control tower at Palestine. Before leaving Palestine, the recovery personnel had received a set of descent vectors from the meteorologists. The descent vectors are estimates of the trajectories that the payloads should follow as they descend by parachute. Upon receiving word that the experimenter had sufficient data, the pilot flew under the balloon to double check the accuracy of the GPS data. Using the descent vectors, he then plotted where the payloads should come down. He also established contact with ATC. When ATC advised that the descending payloads would not endanger air traffic, and when the descent vector plots showed that the payloads would not come down in an inhabited area, the observer aboard the airplane sent the commands to the balloon that terminated the flight.

The termination sequence consisted of first sending a command that disconnected power from the tracker and data encoder. Next a command was sent that cut the cables holding the top payload onto the top of the balloon and opened the poppet valves, which began to release helium. The next command cut the electrical cable running from the bottom payload to the top payload. The fourth command released the bottom parachute from the balloon, which allowed the bottom payload to fall away and caused the balloon to become top-heavy. As the bottom payload fell, a rip line attached to the top of the parachute opened a large section in the balloon. The balloon collapsed, the top payload fell off the balloon, its parachute opened, and all 3 objects began their descent.

The top payload descended for ≈ 38 minutes (average descent rate = 3,158 ft/min [963 m/sec]), and the bottom payload descended on its chute for 63 minutes (average descent rate = 1,904 ft/min [580 m/sec]). During this time, the pilot monitored the position of the bottom payload by visual reference. After reaching the ground, all 3 items had to be found. Since the bottom payload was observed at impact, locating it was not a problem, but a brief search pattern had to be flown in order to locate the balloon and the top payload. The locator beacon aided immensely in this search. This year the top payload did not separate from the balloon, and the 2 were found together. The precise locations of all 3 items were established by observation from the chase plane. The ground recovery crew was directed to each impact site by the pilot as he circled the area in the airplane.

This year the touchdown site was near the town of Carbon, Texas (south of Eastland) ≈ 200 mi (321 km) from Palestine. The total flight duration from launch until the terminate command was sent was ≈ 7 hours.

5. DATA ANALYSIS

The computer analysis was performed at JPL by using a TBASIC (registered trademark of the TransEra Corp.) program written for a PC. The program read the raw data from the files produced by the LabVIEW program during the flight, then corrected the fixed-load cell data for temperature and sun-earth distance according to the formula:

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

where

- $V_{T,R}$ = measured module output voltage at temperature T and distance R.
- R = sun-earth distance in astronomical units (AU).
- A = module output temperature coefficient.
- T = module temperature in degrees C.

A similar correction is made to the cells producing I-V curves. The correction shown above is made for all measured cell current values. A separate correction, utilizing a temperature coefficient appropriate for V_{oc} is applied to the cell voltages, but the factor for sun-earth distance is not used. This correction is made for all measured cell voltage values.

The remainder of this section describes the details of performing the above corrections and computing calibration values for the cells.

5.1 DATA STREAM DESCRIPTION

The data is sent from the computer on the balloon to the ground telemetry station in groups of data called frames. Each frame consists of 26 lines of data, and each line of data contains 43 words of data. The first line of data contains the frame synch word, a line count word, a frame count word, time of day, temperature data, calibration voltages, power supply voltages, the on-sun indicator reading, and a checksum word. The next 25 lines of data begin with a line synch word and a line count word. In line 2, this is followed by 30 data words, corresponding to the outputs of the fixed-load cells (channels 21 through 50). Words 33 through 42 contain fill data (7's) and word 43 is a checksum. The fixed-load cell readings are repeated 4 more times and sent in lines 3 through 6 using the same format as used in line 2. Line 7 begins with the line synch word and a line count word. Words 3 and 4 contain the voltage and current readings resulting from the first load resistor applied to cell 1. The next 38 words contain the voltage and current readings for the remaining 19 loads applied to cell 1. Word 43 is again a checksum. Lines 7 through 26 contain data for the 20 I-V cells in this same

format. The LabVIEW program receives the data in this format and, after producing a real-time display on the computer screen, stores the data on files as it was received.

5.2 FIXED-LOAD CELLS

The computer program performs its analysis in 2 steps. In the first step the cells with fixed loads are read from the files. The program begins by looking for the frame synch word marking the beginning of a frame. Once this word was found, the on-sun indicator reading was decoded. If this reading was greater than the minimum allowable value (OSIMIN), analysis proceeded by applying the temperature and earth-sun distance corrections to the data for each of the 30 fixed-load cells. Appropriate data for each cell (sums, sums of squares, and number of readings) was accumulated for computing averages and standard deviations after all the data was read.

The temperature for each cell was computed by weighing the values of the 6 RTDs (T1 - T6) on the panel. That is, if cell x was located physically on the panel midway between RTDs T1 and T2, and if T1 and T2 were both mounted under the same cell types as cell x, then the temperature for cell x would be taken to be an equally weighted average of T1 and T2. But if T1 was under a different cell type than that of cell x, then the temperature of cell x might more accurately be computed by applying a higher weighing factor to T2 than to T1. A certain amount of judgement is required of the analyst for choosing the weighing factors involved in the temperature readings. This is of some importance since the RTDs showed that there was a temperature gradient over the panel that became stronger as the flight progressed.

The analysis of the 1995 flight data for the fixed-load cells resulted in 1,104 readings for each cell. Averages and standard deviations were computed for each cell. These numbers are reported in Table 1.

5.3 I-V CHARACTERISTIC MEASUREMENTS

The second step in the computer analysis was to extract the data from the I-V cells. In this procedure, the frame synch word was found, then the on-sun indicator reading, and the cell temperatures just as in the procedure for the cells with fixed loads. If the on-sun indicator reading was at or above the OSIMIN threshold level, the current-voltage pairs for each cell were read. The currents were corrected for earth-sun distance and cell temperature just as described for the fixed-load cells, except that this correction was applied to every current reading and a temperature coefficient for I_{sc} was used. A correction was also made to the voltage readings using a V_{oc} temperature coefficient, but

no earth-sun correction was made. The application of the current and voltage corrections is equivalent to a translation in the current and voltage axes. The data for each cell was plotted as I-V curves and sent to the vendor of that cell. An I-V curve after the corrections have been applied is shown in Figure 6.

5.4 CALIBRATION RESULTS

Table 1 reports the calibration values of all the fixed-load cells calibrated on the 1995 balloon flight corrected to 28°C and to 1 AU (1.496×10^8 km). The table also reports the standard deviation of the 1,104 measurements, the preflight and postflight readings of each module in the X25 simulator, and a comparison of the preflight and postflight simulator readings. The simulator intensity was set with a silicon standard cell. No attempt was made to match the standard cell with each module as the purpose of the preflight vs postflight measurements is to make sure no damage occurred to the cells as a result of the flight. The table also reports the temperature coefficients that were measured for each module in our laboratory.

5.5 DATA REPEATABILITY

Several standard modules have been flown repeatedly over the 32-year period of calibration flights. Module BFS-17A, which had flown on 41 flights, was damaged in 1990 and is no longer available. In its history of 41 flights, the BFS-17A calibration values averaged 60.180, with a standard deviation of 0.278 (0.46%). In addition to giving a measure of the consistency of the year-to-year measurements, BFS-17A also provided insight into the quality of the solar irradiance falling on the solar panel, with regard to uniformity, shadowing, or reflections. This cell had been mounted in various locations on the panel over the years. Nevertheless, its readings were always consistent, which verified that there are no uniformity, shadowing, or reflection problems with the geometry of this system.

We have identified a group of solar cells that will be used as replacements for the function served by BFS-17A. Some cells from this group will be flown every year so that we can continue our year-to-year continuity checks. Two cells were flown from this group for the 1995 flight. One cell was a Si cell and the other was a GaAs cell from the Mantech program. Data from these cells is presented in Table 2. These measurements indicate that the 1995 calibration values, using our new data acquisition system, are consistent with those of previous years.

Table 1. 1995 Balloon Flight 8/31/95 120,000 ft, RV = 1.0094515, Flight No. 1545P

MODULE CALIBRATION DATA				COMPARISON SOLAR SIMULATOR & FLIGHT			GENERAL INFORMATION	
Module Number	Org.	Temp Intensity Adjusted Average	Std Dev	AM0, Solar Sim. 1 AU 28 Deg C. Pre-Flt	Post-Flt	Post-Flt. vs. Pre-Flt. (Percent)	Temp. Coeff. (mV/C)	Comments
94-101	Hughes	78.50	0.1293	77.99	78.54	0.71	0.08400	GaAs/Ge Refly
95-104	Hughes	70.47	0.0396	69.91	70.71	1.14	0.07480	Si 6 x 7 cm
95-101	Hughes	72.41	0.1954	71.99	72.94	1.32	0.08000	GaAs/Ge 4 x 6 cm
95-002	JPL	81.53	0.2035	80.84	80.92	0.10	0.07020	ASEC GaAs/Ge
73-182	JPL	67.95	0.1034	68.62	68.74	0.17	0.05170	Heliotek Si Refly
86-023	JPL	58.69	0.1274	58.34	58.14	-0.34	0.05610	GaAs Mantech Refly
95-127	MM	60.89	0.0635	60.76	60.47	-0.48	0.03120	Sharp Si
95-126	MM	88.88	0.3213	88.60	87.93	-0.76	0.10150	Bottom Cell
95-129	MM	78.09	0.2429	77.40	76.40	-1.29	0.08880	Dual Jcn
95-124	MM	84.47	0.2542	83.79	82.77	-1.22	0.04630	Top Cell
95-161	SPL	77.29	0.0676	76.43	76.47	0.05	0.02870	Top Cell
95-173	SPL	70.16	0.2338	68.03	68.13	0.15	0.13060	Bottom Cell Irr 1+15
94-117	SPL	80.46	0.1831	79.30	79.10	-0.25	0.06120	GaAs/Ge Refly
95-151	SPL	81.72	0.1557	81.24	80.78	-0.57	0.04710	K4 Si
95-154	SPL	85.09	0.1441	84.55	84.17	-0.45	0.03850	K6 Si
95-156	SPL	85.12	0.1483	84.20	84.13	-0.08	0.06920	GaAs/Ge Irr 1+15
94-118	SPL	83.10	0.1679	82.13	81.82	-0.38	0.06700	GaAs/Ge Refly
95-165	SPL	75.99	0.2460	74.78	75.01	0.31	0.07020	Bottom Cell
95-192	TRW	100.49	0.1881	---	---	---	0.06520	ASE Si 4 x 6 cm
95-184	TRW	84.39	0.1197	---	83.84	---	0.04040	Sharp Si 10 Ohm
95-190	TRW	94.17	0.1281	---	93.37	---	0.04840	Sharp Si 2 Ohm
95-182	TRW	68.37	0.1430	---	70.12	---	0.07090	Amorphous Si
95-186	TRW	83.72	0.1226	---	83.37	---	0.03230	Amonix Cell
95-183	TRW	68.37	0.2866	---	70.50	---	0.07580	Amorphous Si
95-187	TRW	84.24	0.1575	---	83.53	---	0.03290	Amonix Si
92-131	TRW	32.29	0.0883	32.66	32.63	-0.09	0.04480	Amorphous Si Refly
94-121	TRW	62.06	0.1077	61.46	61.05	-0.67	0.05960	Amorphous Si Refly

T2

Table 2. Repeatability of Two Standard Solar Cell Modules Over a 21-year Period

Flight Date	73-182	86-023
	HEK	Mantech GaAs
4/5/74	68.37	
6/6/75	67.88	
6/10/77	67.96	
7/20/78	68.20	
8/8/79	67.83	
7/24/80	68.00	
7/25/81	67.96	
7/21/82	68.03	
7/12/83	68.03	
7/19/84	67.62	
8/84 Shuttle		
7/12/85		
7/15/86		58.46
8/23/87		59.47
8/7/88		58.26
8/9/89		58.30
9/6/90		58.89
8/1/91		59.12
8/1/92		58.68
7/29/93	67.71	
8/6/94	67.77	58.91
8/31/95	67.95	58.69
No. of Meas.	13	9
Average	67.947	58.753
Std. Deviation	0.198	0.393
Max. Value	68.370	59.470
Min. Value	67.620	58.260
Max. Deviation	0.423	0.717

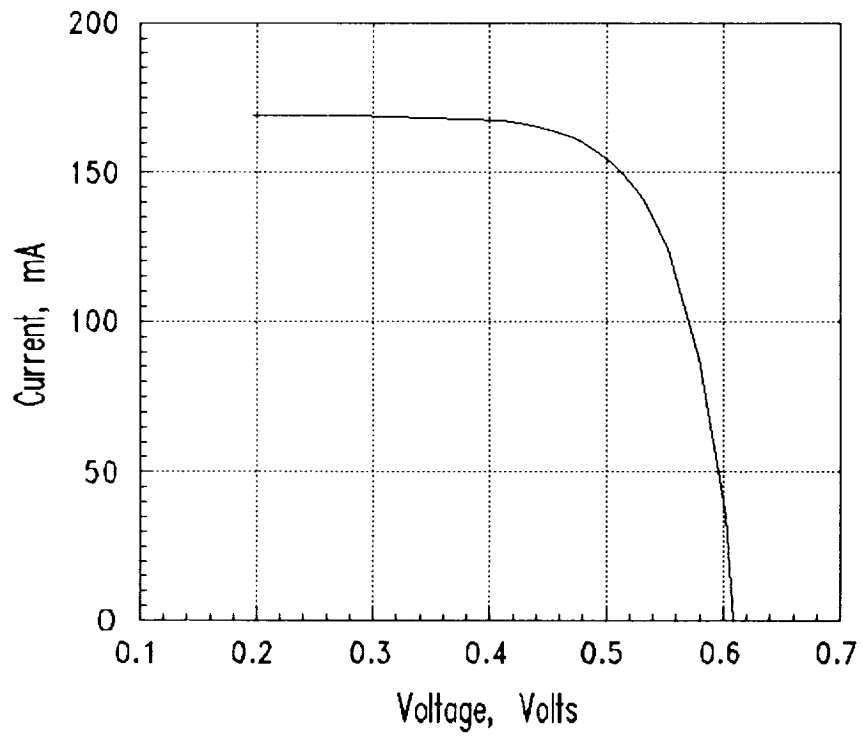


Figure 6. I-V Curve of an ASEC 10 Ohm-cm, 8 mil Si Cell

6. CONCLUSIONS

The 1995 balloon flight was a success. Two cells from previous flights were reflown this year. The calibration value of the Si cell, No. 73-182, was 67.95 which agreed very well with the average of 67.947 measured on 12 previous flights. The GaAs cell, No. 86-023, measured 58.69 on the 1995 flight and deviates only 0.12% from the average value of 58.761 measured on 8 previous flights. Although we only have 2 cells on this flight that can be compared with earlier flight measurements, we believe that the agreement is very satisfactory and the calibration values obtained from the 1995 flight can be used with a high degree of confidence.

7. REFERENCES

1. B. E. Anspaugh, R. G. Downing, and L. B. Sidwell, *Solar Cell Calibration Facility Validation of Balloon Flight Data: A Comparison of Shuttle and Balloon Flight Results*, JPL Publication 85-78, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, October 15, 1985.
2. *The Astronomical Almanac for the Year 1995*, U.S. Nautical Almanac Office, U.S. Naval Observatory, Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402, p. C14.

