

ER-2 High Altitude Solar Cell Calibration Flights

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Abstract — Evaluation of space photovoltaics using ground-based simulators requires primary standard cells which have been characterized in a space or near-space environment. Due to the high cost inherent in testing cells in space, most primary standards are tested on high altitude fixed wing aircraft or balloons. The ER-2 test platform is the latest system developed by the Glenn Research Center (GRC) for near-space photovoltaic characterization. This system offers several improvements over GRC's current Learjet platform including higher altitude, larger testing area, onboard spectrometers, and longer flight season. The ER-2 system was developed by GRC in cooperation with NASA's Armstrong Flight Research Center (AFRC) as well as partners at the Naval Research Laboratory and Air Force Research Laboratory. The system was designed and built between June and September of 2014, with the integration and first flights taking place at AFRC's Palmdale facility in October of 2014. Three flights were made testing cells from GRC as well as commercial industry partners. Cell performance data was successfully collected on all three flights as well as solar spectra. The data was processed using a Langley extrapolation method, and performance results showed a less than half a percent variation between flights, and less than a percent variation from GRC's current Learjet test platform.

I. INTRODUCTION

Characterizing the electrical performance of primary standards for use in calibrating air mass zero (AM0) solar simulators has been accomplished on a variety of platforms including both fixed wing aircraft and high altitude balloons. Past efforts include balloon campaigns by the Jet Propulsion Laboratory (JPL) and the Centre National d'Etudes Spatiales (CNES), as well as GRC's longstanding Learjet program. The ER-2 system augments GRC's testing capabilities. Similar in design to the Learjet flights, solar cells are mounted on a temperature controlled stage at the base of a 3:1 collimation tube which is directed at the sun by the aircraft using an optical sun sight. Measurements are taken as the aircraft descends. The data is then used to extrapolate AM0 performance. This new system offers several improvements over the current Learjet program:

- The ER-2 flies to 70,000 feet compared to the Learjet's ceiling of approximately 48,000 feet.
- The ER-2 accommodates twelve 2x2cm cells per flight (with the capability to double this capacity to 24) vs the Learjet's capacity of 6.
- The ER-2 test stage accommodates larger area cells than the Learjet, including super cells.
- The ER-2 flights include two spectrometers to collect solar spectra which may aide in processing the solar cell performance data.

- The ER-2 has a longer flight season, and this season complements the flight season of the Learjet program.
- The flight cost per cell is expected to be significantly less than that of the Learjet due to the larger cell capacity.

II. SYSTEM DESCRIPTION

The Lockheed ER-2 is a U2 airframe that has been converted to a research platform and is based at AFRC's Palmdale facilities. It can reach altitudes exceeding 70,000 feet in 45 minutes and is outfitted with two equipment pods located under the wings. Each of these pods can be outfitted with an open zenith view port. The view ports are located in the aft, unpressurized section of the pods. The pods also include a heated, semi-pressurized mid-section. The solar cell calibration equipment can be flown in either or both of these equipment pods. (See figure 1. Below)

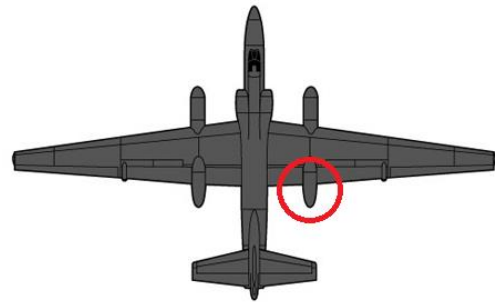


Fig. 1. Location of the experiment in the ER-2 aircraft. [1]

The calibration equipment is divided between the mid and aft sections of a wing pod. The aft section contains the collimation tube and the spectrometers. The mid section contains the data acquisition and control equipment

The pod aft section is exposed to the ambient temperature and pressure and has an unobstructed view of the sky above the aircraft through a windowless aperture measuring eight by eighteen inches. The collimation tube is positioned to look through this opening and has an eight inch square aperture and a length of 25 inches. At the bottom of the collimation tube is a 5.6" square temperature-controlled test stage to which devices under test are mounted. The spectrometers and pressure transducer are also located in the aft pod section and are contained in a temperature-controlled enclosure.

The pod mid section is held at a pressure of no less than 3.8 psi and is heated. The mid section contains the source-measure unit and multiplexer as well as the data acquisition computer

and temperature control system. The source-measure unit and multiplexer measure the electrical performance as well as the temperature of each cell. The data acquisition computer controls the Keithley source-measure unit and multiplexer and stores the measured data. This computer also controls and records data from the spectrometers located in the pod aft section. The temperature control unit is an independent system and maintains the temperature of the cell test stage and spectrometer enclosure as well as its own temperature enclosure. Figure 2. Below shows the layout of the system components in the wing pod.

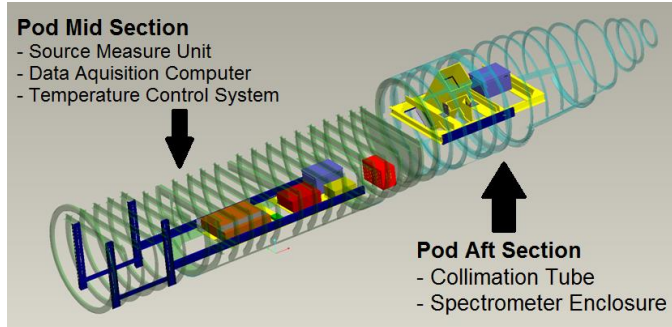


Fig. 2. Location of the components in the wing pod.

The test stage is temperature controlled by three cartridge heaters and contains mounting points for standard Near Space Characterization of Advanced Photovoltaics (NSCAP) cell holders. The stage also houses two sun sensors and the fiber

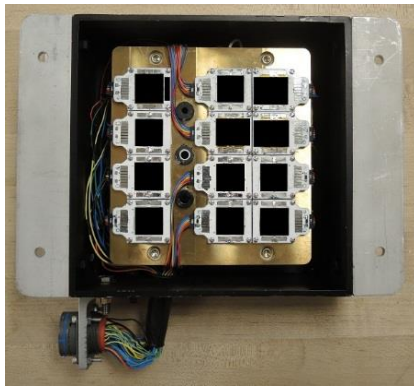


Fig. 3. Test stage containing 12, 2x2cm cells for testing

from the spectrometers. Electrical connectors for the devices under test are mounted to the edges of the stage. Figure 3 shows the test stage loaded with 12, 2x2cm cells.

To record solar spectra, two Ocean Optics spectrometers are connected by a bifurcated fiber-optic cable terminating in a cosine corrector mounted near the center of the test stage. Spectra were taken approximately once every ten seconds. The spectrometers were managed by the manufacturers software which used a factory calibration to report data in $W/m^2 nm$. The spectrometer enclosure was maintained at a temperature of $5^\circ C$

by the temperature control system. This temperature was chosen to be safely above the minimum operating specification of the spectrometers, but low enough to ensure adequate heat removal from the TEC of the sensor on the IR spectrometer.

III. FLIGHT PROCEDURE

A flight plan is chosen so that the aircraft will be flying along a chosen latitude from east to west within an approximately fifteen minute window centered around local solar noon. While flying this path, the aircraft descends at a rate of approximately 500-1000 ft/s from 70,000ft to 55,000ft. The pilot uses an optical sun-sight mounted in the cockpit to hold the collimation tube on sun (within 2.5°) for the duration of the run. During the descent, cell short-circuit current (I_{sc}), temperature, and ambient pressure are continuously recorded at a chosen sample rate, typically on the order of once every few seconds. Solar spectral data and IV curves are also recorded at a chosen interval. Cell temperatures are controlled throughout the flight. At the end of the run, the data acquisition system is powered down, while the temperature control system continues to run until the aircraft lands.

IV. FIRST CAMPAIGN

Three flights were conducted between October 8th and October 14th of 2014. On the first flight six 2x2cm cells were flown along with a camera. The camera was flown as a troubleshooting aide in case there was a problem with aiming the collimation tube. Figure 4 below shows the positioning of the camera and an image of the sun as seen from the stage during a flight.

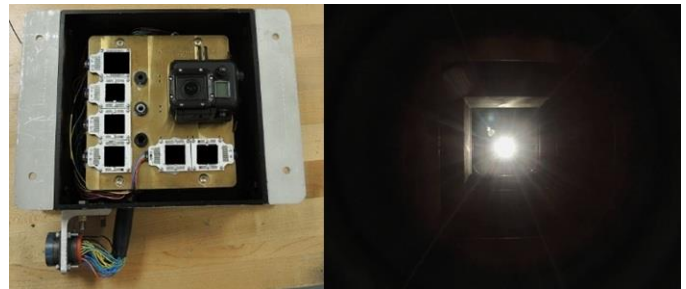


Fig. 4. Camera mounting and view of the sun from the stage

For the second and third flights, the stage was loaded with a full complement of twelve 2x2cm cells. Over the course of the three flights, seventeen unique cells were flown with several flown on multiple flights including GRC cells and cells from private industry. A GRC ZTJ top and middle cell previously flown on the Learjet were flown for all three ER-2 flights. For each flight, data collected included cell I_{sc} 's and IV curves, ambient pressure, cell temperature, and solar spectra. The first and second flights each covered an altitude range from roughly

70,000 to 55,000 feet, however due to a procedural error, the third flight only obtained data in the narrow range from 68,000 to 67,000ft. Even with this extremely limited set of data, the computed AM0 Isc values for this flight compared favorably to the values obtained for the same cells flown on other flights.

V. DATA ANALYSIS

A. AM0 Short Circuit Current

Determination of device AM0 Isc is obtained using the same modified Langley extrapolation method used for the Learjet program [2]. For a given cell, the short circuit current data is corrected point by point to account for ozone column above the cell. The overhead ozone column is approximated using a standard ozone profile [3] and interpolating for latitude, pressure, and the total daily ozone column as determined by satellite observation. Using this corrected data, the log of the Isc is then plotted vs. pressure yielding an approximately linear plot. This data is then extrapolated to zero pressure, corrected to a 1AU earth-sun distance, and reported as the AM0 Isc. An example of a Langley plot for one of the flown GRC cells is shown below in figure 5.

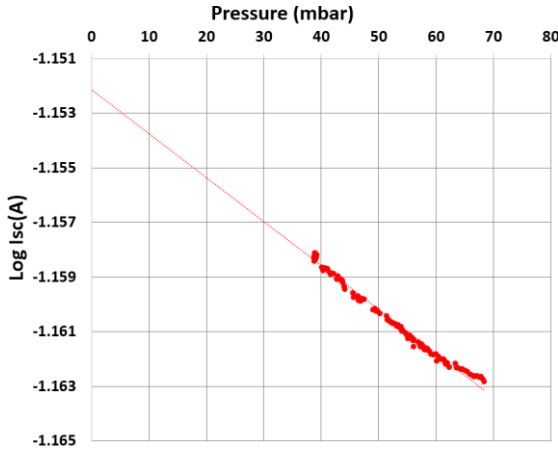


Fig. 5. Example of a Langley plot for a GRC Cell

No temperature correction was applied as the temperature control system maintained the temperatures of each of the cells at $25 \pm 0.5^\circ\text{C}$.

Several cells were flown for all three ER-2 flights which had also been previously tested using the Learjet system. It was found that for an InGaP top cell and GaAs middle cell that the average value for the three flights differed by less than 0.6 percent from the Learjet reported value, and by no more than half a percent between any two ER-2 flights. These variations improve when processing only the data taken at less than 60mb pressure ($> \sim 60,000\text{ft}$). The Learjet method itself has undergone studies comparing it to other AM0 evaluation methods and was found to agree favorably [4]. A study of errors and uncertainties with high altitude testing methods was

recently published as well [5]. A summary of the predicted AM0 Isc's for three GRC cells is shown below in table 1. Cells TC0108 and TC0109 are ZTJ top sub-cells, while MC0907 is a ZTJ middle sub-cell.

Table 1. Summary of predicted AM0 Isc values in milliamps

Full Data Set

Cell	TC0108	MC0907	TC0109
Flight One	69.93	66.00	70.10
Flight Two	70.23	66.06	
Flight Three	70.29	65.99	
Average	70.15	66.02	70.10
Standard Deviation	0.196	0.039	
Learjet Value	70.51	66.23	70.51
Lear Variation (%)	0.512	0.319	0.587

<60mb Data Only

Cell	TC0108	MC0907	TC0109
Flight One	70.34	66.00	70.58
Flight Two	70.33	66.07	
Flight Three	70.29	65.99	
Average	70.32	66.02	70.58
Standard Deviation	0.026	0.044	
Learjet Value	70.51	66.23	70.51
Lear Variation (%)	0.27	0.32	-0.09

B. Solar Spectra

The spectra measured at altitude showed an overall signature that closely resembled standard AM0 spectra, however the entire spectra was approximately 26% below expected intensities for the given altitude. The cause of this issue is still being evaluated. A correction was attempted by applying two scaling factors, one for each spectrometer. The factors were obtained by integrating over a relatively featureless range of the spectrum and comparing that value to the expected integral at the measurement altitude.

There was also a small shift (on the order of a few nanometers) in the major spectral lines. This shift varied linearly with wavelength. A correction was attempted by applying a linear shift in wavelength across the composite spectrum. The cause of this shift is most likely due to the temperature of the sensor. There is also a region of noise that occurs near the transition between the UV/Vis and IR spectrometers. Figure 6 shows a comparison between an AM0 standard spectrum[6], the recorded spectrum at $\sim 64,000$ feet, and the adjusted spectrum. The adjusted result appears to be

reasonable, however further evaluation regarding the validity of the data is ongoing.

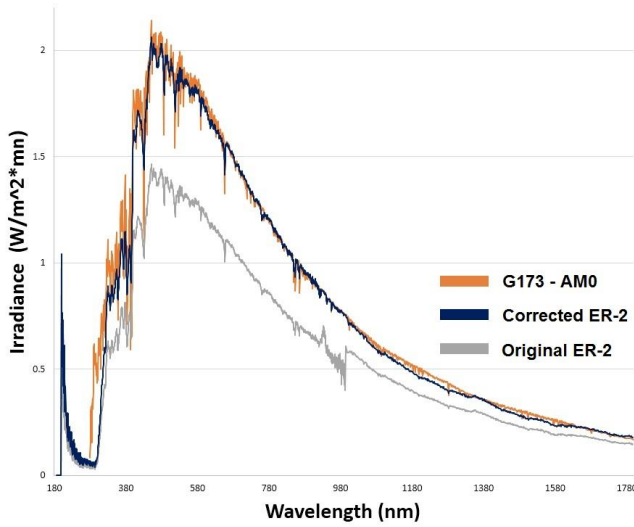


Fig. 6. Comparison of ER-2 spectra with standard AM0 spectrum

C. IV Curves

IV curves were obtained by using the source-measure unit to sweep a potential across the illuminated cells. IV curves were taken every 3-4 minutes as the aircraft descended. These curves were not corrected for ozone or residual atmosphere and are reported as low airmass IV curves as opposed to AM0. The curves show very good repeatability over the three flights. Figure 7 below shows seven different IV curves for the GRC ZTJ top cell TC0108. Three curves each are shown for the first two flights at different ambient pressures and one curve is shown for the third flight.

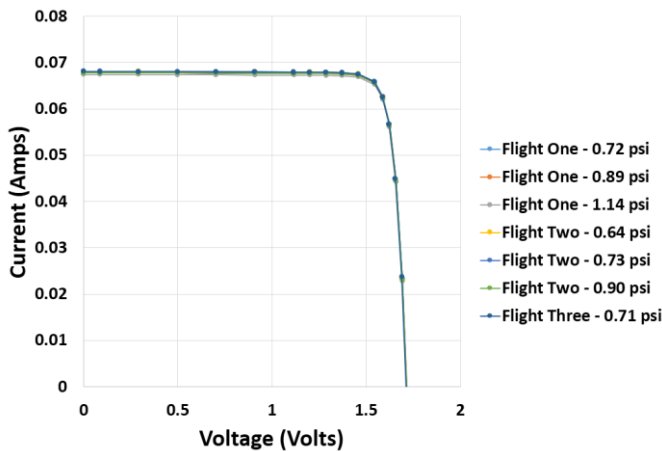


Fig. 7. Low airmass IV curves for GRC ZTJ top cell TC0108

The full curves nearly overlap when the full curve is shown, so figure 8 shows an extremely zoomed in view of the knee in figure 7, with a range of the y-axis of one milliamp. At this level, a predictable variation with ambient pressure

becomes apparent, as well as good repeatability between two flights at similar pressures.

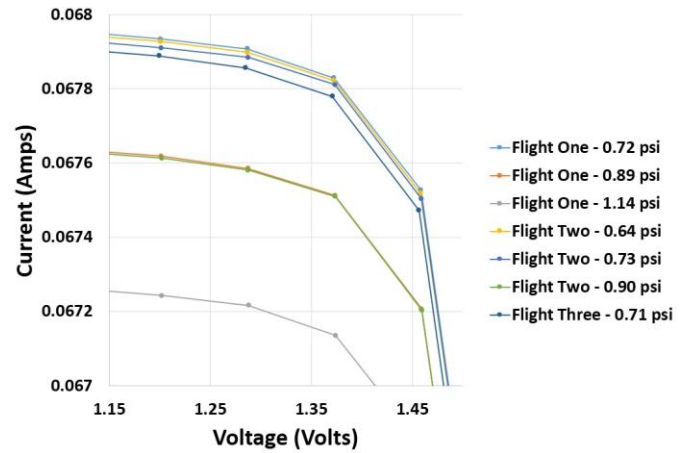


Fig. 8. Detail view of IV curves for GRC ZTJ top cell TC0108

D. Cell Temperatures

The temperature of the test stage is maintained by a PID controller. While the cell temperatures are not individually controlled, they are individually monitored using AD590 IC temperature transducers mounted in each NSCAP cell holder. Figure 9 below shows the temperatures for a GRC top and middle cell on two different flights.

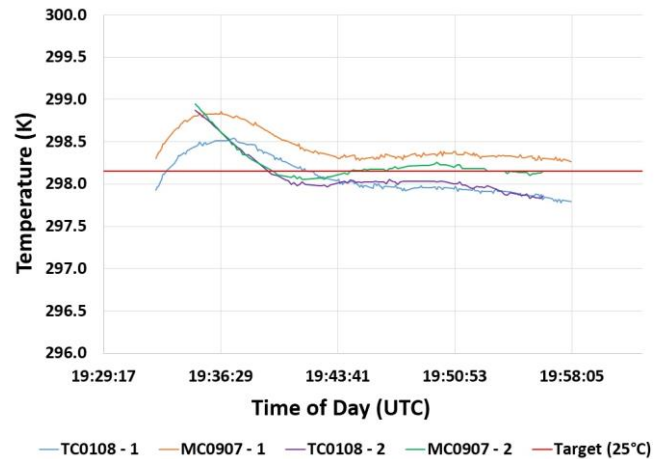


Fig. 9. Cell temperature variation during flight

The figure shows that after a slight bump in temperatures caused by initial cell illumination, the temperature of the cells were maintained within about a quarter of a degree Celsius of their target temperatures. Variation of temperature for an individual cell was within about a tenth of a degree after the initial on-sun disturbance.

VI. SUMMARY

Accurately predicting the in-space performance of solar cells is critical for the success of both NASA and commercial missions. Including a large margin for spacecraft power by increasing array size is prohibitively expensive due to the extreme cost per mass of a launch. Ground testing depends on accurately measured standard cells. This is increasingly challenging as cell technologies move to a greater number of junctions, as these types of cells are more sensitive to spectral discrepancies. The ER-2 has been demonstrated as a viable platform comparing favorably to existing methods and offering a number of improvements. System testing and development is ongoing, and further study of errors and uncertainties will continue as more flights are conducted. The second campaign of the ER-2 test program is scheduled for the beginning of July, 2015.

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