A Summary of The 2000-2001 NASA Glenn Lear Jet AM0 Solar Cell Calibration Program

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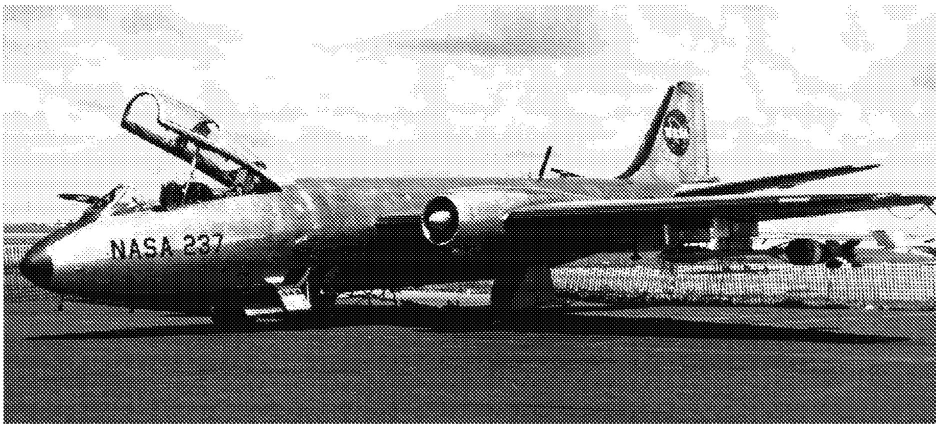
Calibration of solar cells for space is extremely important for satellite power system design. Accurate prediction of solar cell performance is critical to solar array sizing, often required to be within 1%. The NASA Glenn Research Center solar cell calibration airplane facility has been in operation since 1963 with 531 flights to date. The calibration includes real data to Air Mass (AM) 0.2 and uses the Langley plot method plus an ozone correction factor to extrapolate to AM0. Comparison of the AM0 calibration data indicates that there is good correlation with Balloon and Shuttle flown solar cells. This paper will present a history of the airplane calibration procedure, flying considerations, and a brief summary of the previous flying season with some measurement results. This past flying season had a record 35 flights. It will also discuss efforts to more clearly define the ozone correction factor.

HISTORY

The design and sizing of space solar arrays requires precise calculations. Too large an array and the satellite will run hot having to reject the excess energy and have increased launch costs, too small and the satellite will not fulfill its mission draining the batteries and shortening life expectancy. The need for AM0 calibrated solar cells is obvious. One method of calibration is the Langley plot method. This method was developed in the early 1900's when a relationship was found between the solar intensity and the thickness of the atmosphere the sunlight must pass through (Air Mass). Plotting the logarithm of solar cell short circuit current, proportional to solar intensity, as a function of air mass permits extrapolation to an unmeasured air mass and AM0 (ref. 1). Early ground based measurements were done throughout the day as the sun moved across the sky, passing through more atmosphere in the early and late hours and minimizing at solar noon. This method was later used with an airplane, changing altitude to vary the air mass.

The first solar cell calibration airplane flight took place on June 13th, 1963. The airplane was a modified B57B airforce jet, flying120 flights between 1963 and 1967 (Figure 1). The test cells were placed at the end of an exposed 4:1 collimating tube mounted in the fuselage, this tube was designed to allow 2° change in pointing. Next to the collimating tube was a cavity radiometer to measure the solar intensity. The pilot keeps the tube pointed at the sun during measurements using a sun sight in the cockpit aligned to the tube. Because of the technology limitations, the plane would fly level at several altitudes while measuring the amplified voltage from a 1 ohm shunt resistor using a strip chart recorder. On the ground, the data was plotted manually to determine the intercept points. Data was taken at different altitudes reaching an air mass of 0.25 or 50000 feet along 40°N latitude.

Early data analysis pointed out two important anomalies. First, the AM0 extrapolation was slightly low compared to radiometer data, this was found to be due to ozone absorption of sunlight in the upper atmosphere. Second, a change in the data linearity was seen when the plane flew below the tropopause, this was because of Mie scattering from particles and absorption by moisture; primarily in the blue end of the spectrum (ref. 2). As a result, a 1% correction was applied to the data to account for ozone absorption and all flight data below the tropopause was not used.



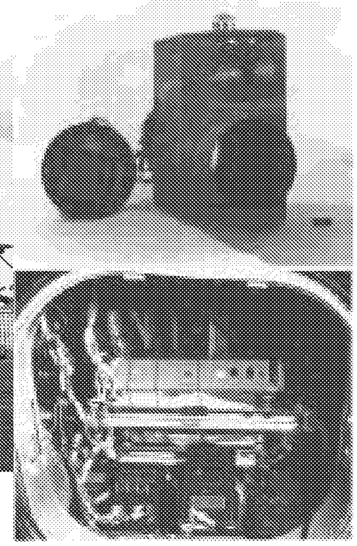


Figure 1: B57B and Collimating Tube, Radiometer and Electronics

The second plane used for calibration was an F106 (Figure 2). This plane was also modified as above and flew 85 flights between 1975 and 1981. This plane flew in the south at ~30°N with a higher sun angle and was able to reach AM 0.17 at the same altitude of 50,000 feet. The calibration technique was similar to that used above.

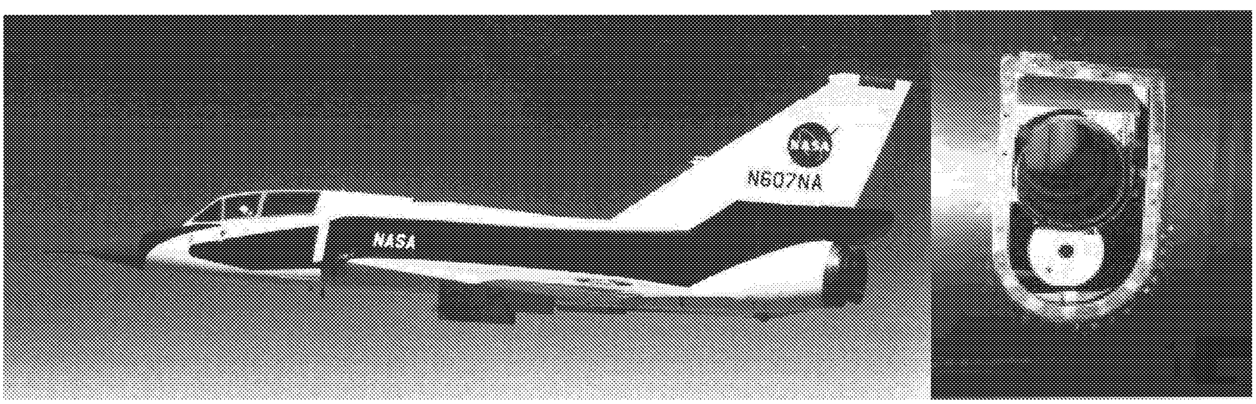


Figure 2: F106 and Collimating Tube with Radiometer

The third and current plane used is a Lear 25A jet. It is still used today and has flown 324 flights since 1984. The plane can fly to ~50,000 feet and gets above AM0.2 at 45N latitude. The flying technique and electronics have progressed to a point where the plane now flies a continuous descent while taking data rather than remaining level over a range of altitudes. A window of the plane was removed to provide sun access for the collimating tube. An operator is no longer required to fly, everything can be controlled from the cockpit.

The Lear test setup has a 5:1 collimating tube illuminating a 4.1 inch diameter temperature controlled plate. The tube angle can be adjusted between 19° and 51° for the sun angle. The electronics are computer controlled and provide an active bias on the test cell to measure short circuit current. In addition to short circuit current, open circuit voltage and full IV curves (>25 points) can also be measured. During descent up to 6 cells, a pressure transducer, thermopile, temperature sensor, and "take data" signal are all measured. The solar cells are measured using kelvin probes (power leads + sense leads) assuring accurate measurements at the cell. The cells are held at a constant temperature ±1° C, this can be set by the computer allowing for temperature dependence. Occasionally, an absolute cavity radiometer with a 5° FOV is flown to measure solar intensity. The new test plate also contains access for a fiber optic connection. This fiber provides input for spectroradiometer which can measure the solar spectrum from 250-2500 nm with 6 nm resolution, a second spectrometer is now available which measures the spectrum from 200-800 nm with 1 nm resolution. Both of these spectrometers will be used to check for any spectral anomalies and provide information on the ozone absorption.

Figure 3: Lear 25A (2nd window on right removed)

The test electronics consist of a Keithley 2420 Sourcemeter connected to the plate by a Keithley 7001 Scanner, both controlled by a Grid 386X computer through an IEEE488 interface. The test plate holds up to 6 solar cells with 2 front contacts for each cell and 2 back contacts common to all 6 cells (the plate) . A temperature sensor in the plate is used to regulate two 40W heaters.

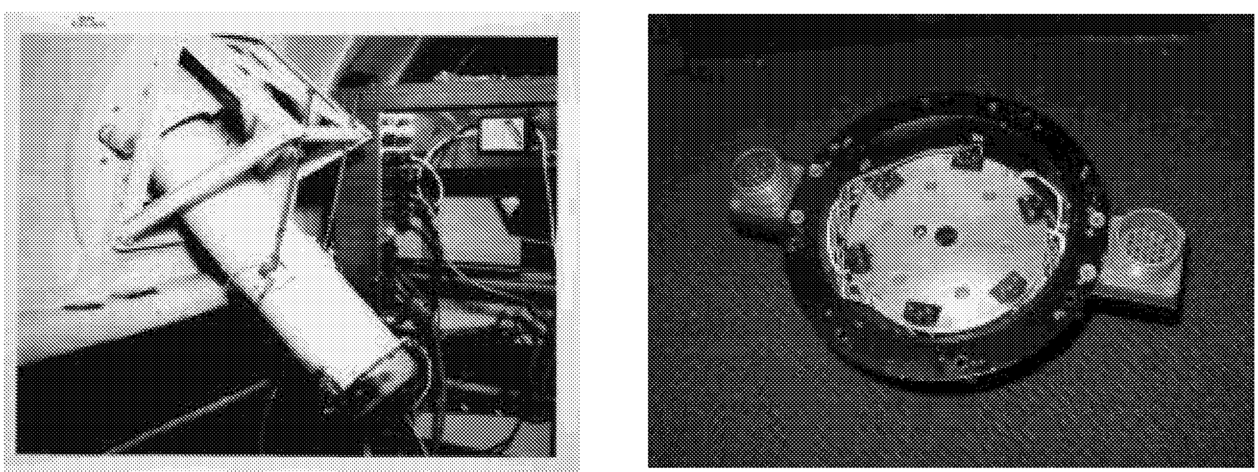


Figure 4: Collimating Tube and Cell Test Plate

Error analysis on this calibration method shows that the accuracy is with ± 1% (ref. 3). This accuracy has been shown to be comparable with other calibration techniques from around the world (ref. 4).

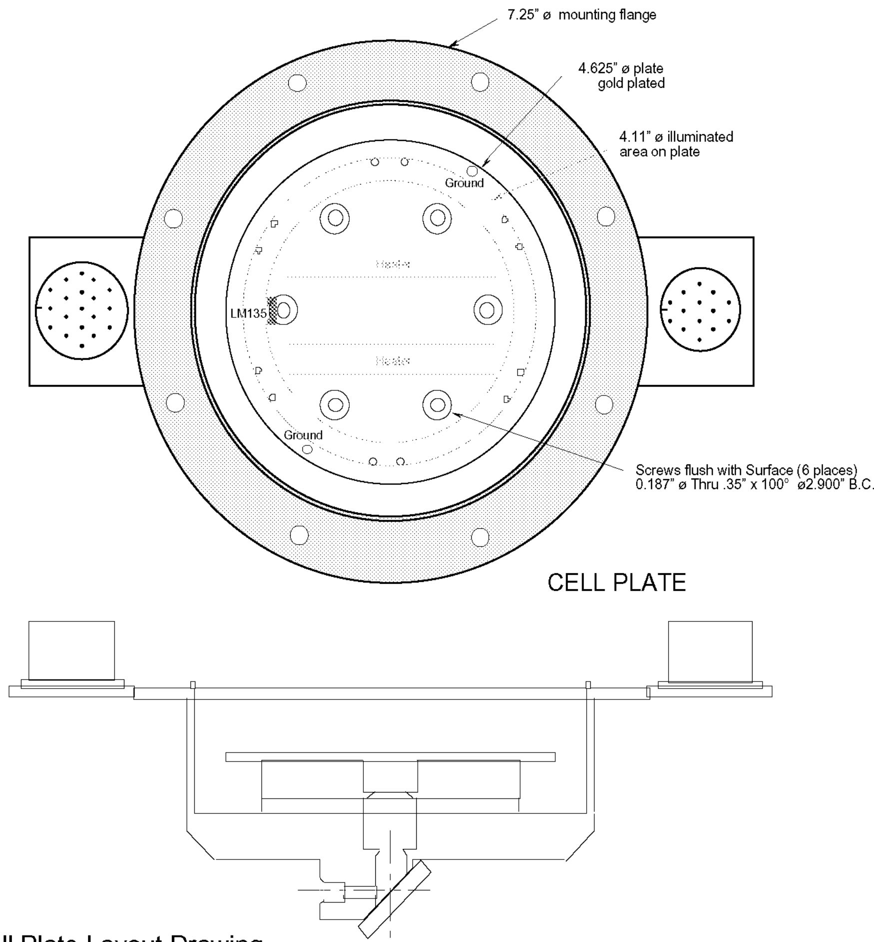


Figure 5: Cell Plate Layout Drawing

LANGLEY PLOT METHOD

Solar cells can be calibrated using the Langley Plot Method. This method was developed by Samuel P. Langley in the early 1900's. It involves plotting the Log of short circuit current (I_{SC}) vs. Air Mass, where air mass is the amount of atmosphere sunlight must pass through to reach a test cell. A linear fit through the data points predicts an AM0 intercept by extrapolation . Traditional Langley plots were done on the ground at high elevations and the air mass varied as the sun moved across the sky throughout the day, air mass being the lowest at solar noon. Clouds and moisture in the atmosphere often skew the results of this method and it required constant spectral correction. The airplane method uses altitude to vary air mass with all the measurements at or near solar noon. Therefore the airplane method can achieve much lower air mass and cleaner air then the ground-based methods applying a small ozone correction to the data with approximately a 3% difference between the measured data and the extrapolated AM0 value.

Air Mass is calculated as shown using the measured pressure p, where p_o = 14.6944 psi, and the Sun Declination angle θ. The measurements are also adjusted for earth sun distance r by multiplying by $1/r^2$. Both θ and r can be found in an astronomical almanac. All calibrations are made at 25°C.

$$\text{Air Mass} = \frac{p}{p_0}\sec(\theta) \qquad \text{Earth to Sun } I_{SC} \text{ Correction} : I_{SC} = \frac{I_{SC\,measured}}{r^2}$$

An example of the Langley Plot method is shown in Figure 6, notice that the intercept calculation does not vary by much even with noise. The two lines above and below the center one indicate different linear extrapolations with

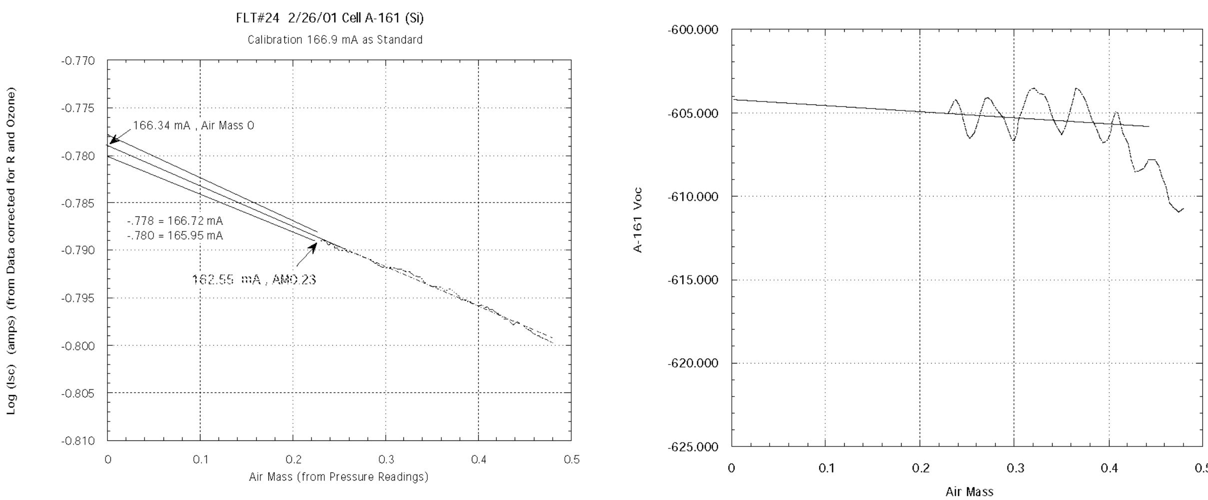


Figure 6: Langley Plot of Cell Data I_{SC} and V_{OC}.

intercepts as shown varying by less than .2%. The second plot also shows that this method can be applied to open circuit voltage (V_{OC}), there is more scatter in the voltage measurement due to its temperature sensitivity, the drop at the end of the curve is due to a drop in temperature.

FLIGHT DATA

The 2000-2001 flying season was a record 35 flights. The data in Table I is a partial summary of the season results, some of the solar cells have been calibrated previous years. There were a total of 51 different cells flown, the data is only a partial list for proprietary reasons, future season summaries will publish more results as permission is granted. Only short circuit currents (I_{SC}) is presented and includes a 1% correction for ozone, open circuit voltage (V_{OC}) was measured but the data is only preliminary. The cells with "A" in the name represent NASA GRC standards. The design of the plate allows for testing of "bare" cells which have front and back contacts, the front contact is made using a spring loaded clip. Some of the cells with higher standard deviations may have had poor connections and/or equipment problems during the flight. The data represents a variety of cell types ranging from Si to the triple junction InGaP/GaAs/Ge.

The flying seasons extend between late October and March which are the limitations of the adjustments to the collimating tube. The collimating tube is set based on the sun angle which changes approximately .3° per day. This season is also the time of year when the tropopause drops low enough for the plane to fly above it and get data during a10000 foot descent. Data on the tropopause can be obtained from weather balloons on the morning before a flight which is used to determine if a flight will be made that day.

OZONE CORRECTION

The airplane is capable of flying to altitudes close to 50,000 feet. In the airplane calibration technique, the data was found to be inaccurate for two reasons, one being moisture and scatter in the atmosphere and the second being ozone absorption. Moisture in the atmosphere could be virtually eliminated by staying above the tropopause, the tropopause is lower (<40,000 feet) during colder months of the year. Ozone exists at much higher altitudes and therefore a correction was applied to the AM0 extrapolation,.Ozone typically absorbs light from 200-800 nm (ref. 5,ref.6), and varies across this band (see figure 7). The ozone correction was found to be 1% based on early calculations using ozone absorption coefficients plus the amount of ozone, both applied to the spectral response of Si and GaAs solar cells.

Table I : 2000-2001 Flying Season Calibration Data (all include a 1% ozone correction)

Cal Value	Flight Count	Average	Std Dev	Cell	Area (cm)	Cell Type
	5	176.43	3.88	"Wb13R"	4	Si
166.9	18	165.62	0.83	"A-161"	4	Si
151.2	7	149.61	0.81	"SSF-2"	4	Si
109.8	6	106.28	1.19	"A-133"	4	GaAs
22.5	5	25.71	0.26	"160-2"	0.5	InGaAs
134.8	6	129.21	1.41	"A-181"	4	InP
	7	61.48	0.95	"134-5-6"	4	InGaP
	7	63.61	0.26	"133-5-4"	4	Dual Junction
122.9	1	119.22		"A-188"	4	GaAs
	5	71.81	0.31	"132-5-2"	4	GaSa w/InGaP window
115.3	2	110.91	0.75	"A-168"	4	GaAs
77.8	5	74.91	0.44	"A-186"	1.77	Si
257.6	1	251.98		"A-190"	8	GaAs
162.9	1	164.18		"A-177"	4	Si
113.4	1	107.49		"A-166"	4	GaAs
150.7	3	148.53	0.37	"A-104"	4	Si
	2	61.15	0.15	"TS 2-29	4	Triple Junction
	2	62.44	0.90	"SL 5-5-6	4	Triple Junction
	5	128.05	0.96	"ISO-1"	4	GaAs
	2	112.80	0.20	"ISO-2"	4	GaAs
	4	167.99	0.66	"ISO-6"	4	Si
	2	178.32	0.22	"ISO-5"	4	Si
	3	153.24	0.34	"ISO-3"	4	Si
	2	119.38	0.01	"ISO-4"	4	GaAs

This ozone correction worked well for many years but as different cell types enter the market, This correction factor will be changed to reflect cell types. Solar cells with higher bandgaps are more sensitive in the ozone absorption bands and will require a greater correction. Today, the amount of ozone in the atmosphere is measured continually and therefore a more precise ozone quantity can be applied. This ozone correction factor will be discussed in greater detail in the future. Preliminary results of this correction factor applied to previously flown cells show that the range of error for the airplane calibration method will decrease.

Ozone Absorption Coefficients (OAC), Figure 7 illustrates the OAC in the UV, VIS, and NIR portions of the spectrum. These coefficients must be applied to the amount of ozone to determine the loss in cell performance. The amount of ozone in the atmosphere is measured both by the TOMS satellite and surface measurements in Dobson units. 1 Dobson Unit (DU) is defined to be 0.01 mm thickness at stp (0°C 1 atm).

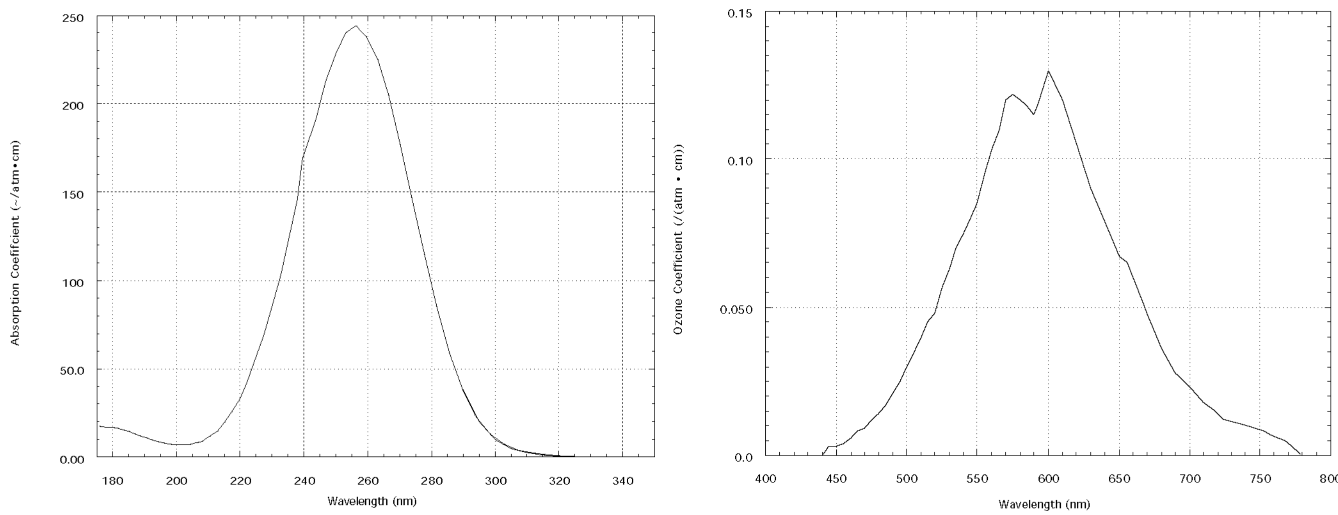


Figure 7: Ozone Absorption Coefficients

CONCLUSION

The NASA Glenn Lear Jet AM0 Solar Cell Calibration Program has been running for 16 years with hundreds of flights and over a35 year history. Error analysis of the calibration resulted an accuracy of ±1% and an international intercomparison of calibration techniques shows good agreement. With the improvements to the electronics and the application of a new improved ozone correction factor the accuracy of the calibration will improve. The facility is available for calibrations at a very reasonable cost.

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