Solar Cell Short Circuit Current Errors And Uncertainties During High Altitude Calibrations

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***Abstract* — High altitude balloon based facilities can make solar cell calibration measurements above 99.5% of the atmosphere to use for adjusting laboratory solar simulators. While close to on-orbit illumination, the small attenuation to the spectra may result in under measurements of solar cell parameters. Variations of stratospheric weather, may produce flight-to-flight measurement variations. To support the NSCAP effort, this work quantifies some of the effects on solar cell short circuit current (Isc) measurements on triple junction sub-cells. This work looks at several types of high altitude methods, direct high altitude measurements near 120 kft, and lower stratospheric Langley plots from aircraft. It also looks at Langley extrapolation from altitudes above most of the ozone, for potential small balloon payloads. A convolution of the sub-cell spectral response with the standard solar spectrum modified by several absorption processes is used to determine the relative change from AM0, Isc/Isc(AM0). Rayleigh scattering, molecular scattering from uniformly mixed gases, Ozone, and water vapor, are included in this analysis. A range of atmospheric pressures are examined, from 0.05 to 0.25 Atm to cover the range of atmospheric altitudes where solar cell calibrations are performed. Generally these errors and uncertainties are less than 0.2%.**

***Index Terms* — aerospace testing, error analysis, photovoltaic cells, solar power generation, solar simulator, solar cell calibration, space power, space technology.**

I. Introduction

Air Mass Zero, AM0, calibrated subcells are critical to the laboratory measurements of solar cells for on-orbit applications [1]. Present facilities capable of supporting calibration measurements of the short circuit current, I_{sc}, at or near AM0, include the CNES high Altitude facility, CASOLBA[2], and the NASA GRC Lear Jet[3]. A new facility, NSCAP, is under development for use with NASA High Altitude balloon program [4]. According to ISO 15387 [5], an error analysis for the NSCAP facility must be performed. Jenkins et al [6] performed an analysis for the Aircraft Method of calibration used at NASA Glenn. However, procedures have changed somewhat since then, and it is appropriate to include those considerations in this work. The purpose of this paper is to examine and quantify some of the atmospheric sources of error and uncertainty for the NSCAP program. It also includes modeling and calculations relevant to other altitudes. The evaluation of 0.2 to 0.1 Atm is interesting for the NASA Glenn Lear Jet Facility, since it provides a test of how well the Langley Plot works for aircraft flown solar cells. Round robin comparison of agreement between the various calibration methods is at the 1% level [7].

Small systematic errors approximately add. For instance four 0.1% errors generate a $1\text{-}0.999^4$, 0.3994%, result, while uncertainties add like the sum of squares, $\sigma^2 = \Sigma\sigma_i^2$. For instance four 0.5% uncertainties leads to a 1% uncertainty, or four 0.1% uncertainties leads to a 0.2% uncertainty. Either case suggests uncertainties < 0.1% are largely negligible while the causes of uncertainties >0.1% warrant some attention to maintain a better than 0.5% calibration system.

Three types of sub-cells, common to triple junction solar cells are examined: top InGaP cells, middle GaAs cells, and Bottom Ge cells. While the analysis is specific for the spectral response of specific solar cell types, small variations will produce insignificant differences.

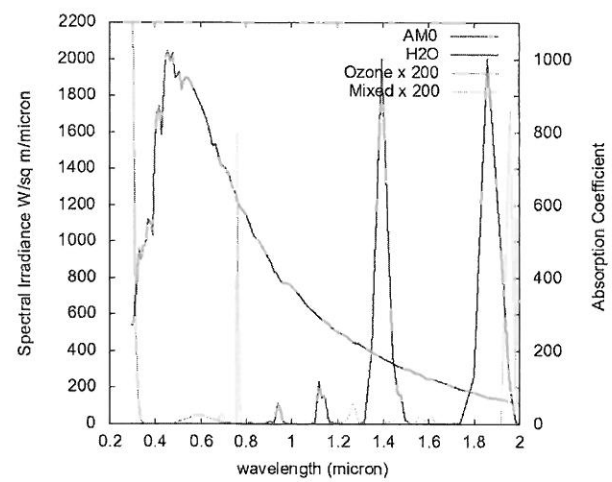

Fig 1. AM0 Spectrum with SPECTRL2 Absorption Coefficients.

This analysis investigates several atmospheric parameters: pressure, ozone, and water vapor. The treatment of the scattered "global" component of the spectrum is not considered here, since its treatment depends largely on the system design, i.e whether collimation or shading used. The measurements take place in a tenuous atmosphere and it is assumed to be negligible. Nor is scattering/absorption by aerosols or dust considered. The pressure portion of the analysys includes uniformly mixed gasses and Rayleigh scattering. In addition, a few other influences are examined: cell temperature, pointing angle, and incident solar radiation.

II. Analysis

A. SPECTRL2

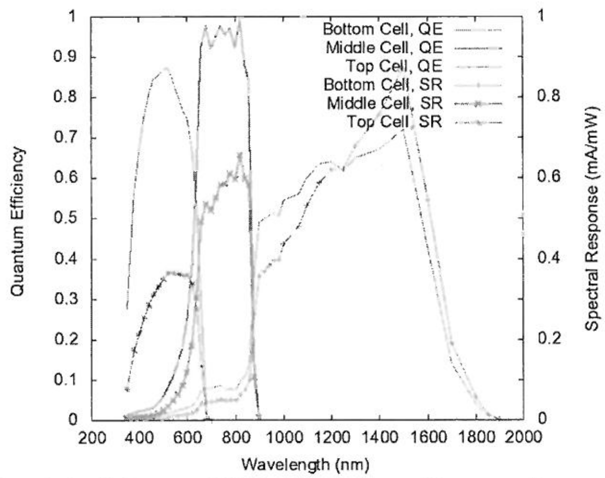

Fig 2. Subcell Quantum Efficiency and Spectral Response for a representative triple junction cell.

For this analysis the program SPECTRL2, available from NREL [8], is used to calculate absorption in the near UV, visible and near IR portions of the spectrum. This is a coarse resolution model, but includes the basic Beer's law scattering and absorption physics. It includes: Rayleigh scattering, H20, Ozone, Mixed Gasses absorption, and Aerosols (not used here). Absorption coefficients are illustrated in Fig. 1. It is designed for use near the ground, so only the "Direct" intensity is used, not the Total "Direct+Global" intensity, The parameters not being used in the course of a calculation are turned off, to give the AM0 spectrum modified by the component of interest. Since the interest is in fractional changes in cell performance, instead of absolute cell performance, this approach provides sufficient fidelity to assess the major absorption effects.

B. Solar Cell Types

Cell Type		I_{sc} (AM0)/cm^2
Top	InGaP	16.125
Middle	GaAs	18.416
Bottom	Ge	23.237

Table 1. Calculated AM0 Isc according to cell type.

Three types of Triple Junction solar cell sub-cells are analyzed: InGaP, GaAs, and Ge. The spectral response data for the subcells shown in Fig. 2, was obtained at NASA Glenn in the early 2000's, so these are not state-of-the-art cells. The resolution is coarse, mostly at 50 nm intervals, much coarser than the SPECTRL2 resolution. I_{sc} is calculated via a convolution of spectral response, S_λ, with the solar spectral irradiance (I_λ/A),

$$I_{sc} /A= \Sigma_\lambda\, S_\lambda * I_\lambda /A * d\lambda \qquad (1)$$

The results for the AM0 irradiance are given in Table 1. This is not for an earth-sun distance of R_{se} = 1.0 a.u., but for relative comparisons is acceptable.

C. Pressure

The dependence of I_{sc} on pressure is shown in Table 2. The calculation includes Rayleigh scattering, and mixed gasses absorption, including N_2, O_2 etc. It shows that the light attenuation has the most impact on the most blue sensitive top cell, as expected from Rayleigh Scattering. At High Altitude balloon pressures, >115 kft, the top cell current is reduced by less than 0.1%. At ¼ atmosphere, 250 mb, the top cell has lost 4% of its current. This does not include a non-zero sun zenith angle extension of the optical path.

Pressure (mb)	Altitude (kft)	Top	Middle	Bottom
0		1.0000	1.0000	1.0000
4	122.6	0.9993	0.9994	0.9999
5	117.4	0.9992	0.9992	0.9998
10	101.9	0.9983	0.9987	0.9997
20	86.9	0.9967	0.9977	0.9994
150	44.6	0.9758	0.9859	0.9953
250	34.0	0.9601	0.9831	0.9944

Table 2. Relative Isc dependence on pressure and altitude due to Rayleigh and molecular scattering.

D. Ozone

Pressure (mb)	Ozone (DU)	Top	Middle	Bottom
0	0	1.0000	1.0000	1.0000
3.96	16.2	0.9990	0.9995	1.0000
7.92	40.7	0.9975	0.9988	0.9999
15.8	82.85	0.9950	0.9976	0.9998
31.7	151.85	0.9909	0.9957	0.9997
127	286.55	0.9828	0.9919	0.9993
253	319	0.9810	0.9910	0.9993

Table 3. Relative Isc for a mid-latitude Ozone distribution based on a total column number of 350 Dobson Units.

Ozone, in general is not distributed uniformly with pressure. Since it is created by solar ultraviolet light interacting with atmospheric Oxygen, it can be described in a conceptual model as being uniform with pressure at high altitudes, until the UV begins to be attenuated and the ozone density relative to pressure declines. While the details of the chemistry are more complicated than this, this simple description gives some ideas of how to organize the non uniform atmospheric effects. Table 3 tabulates the ozone related I_{sc} reduction with both pressure and Ozone column number. The distribution with pressure is taken from "TOMS Version 7 Standard Ozone Profiles" [9] which includes a layered tabulated model of ozone number vs. pressure for low, mid-, and high latitudes for a range of total ozone numbers. The table also neglects the solar zenith angle optical path changes.

E. Water Vapor

Water has extremely strong absorption bands in the infrared. It has almost no effect on the top and middle junctions but can influence the bottom junction. Dessler [10] indicates the proportion in the Stratosphere is 4.5 to 7 ppmv. Table 4 assumes a uniform water distribution, proportional to pressure of 5 ppmv, or ppm number, not weight. An uncertainty is then expected of about 22%, in the water column for an altitude. Errors at high altitudes are 0.1% to 0.2%. In traditional Triple junction design the cell is current limited by the top cell. The bottom cell is current rich, and its operating voltage changes little with cell operating conditions. Even though water may have a significant impact on the sub-cell measurement, in practice the resulting laboratory measurement is affected little.

Pressure (mb)	H2O (cm)	Top	Middle	Bottom
0	0	1.0000	1.0000	1.0000
4	0.00009	1.0000	1.0000	0.9988
5	0.00012	1.0000	1.0000	0.9984
10	0.00024	1.0000	0.9999	0.9973
20	0.00047	1.0000	0.9999	0.9958
150	0.00353	1.0000	0.9997	0.9852
250	0.00588	1.0000	0.9995	0.9801

Table 4. Relative Isc dependence on water vapor, uniform distribution at 5 ppmv.

F. Temperature

Table 5 simply looks at the temperature coefficient of the material, using that to estimate the uncertainty. An uncertainty in temperature of ±1C generally gives an uncertainty of <0.1%. However, if the measurement is extrapolated to a new temperature, in addition to the temperature uncertainty, the temperature coefficient, C_T, uncertainty should be included.

	Cell Type	$dI_{sc}/dT/I_{sc}$ (25C)
Top	InGaP	0.054%
Middle	GaAs	-0.062%
Bottom	Ge	0.065%

Table 5. Subcell Temperature coefficients.

If $I_{sc}(T) = I_{sc}(T_0)(1+C_T\Delta T)$, then $\sigma_{Isc(T)} = \mathrm{sqrt}((C_T\ \sigma_T)^2 + (\sigma_{CT}\ \Delta T)^2)$. For large temperature extrapolations, ΔT, the temperature coefficient, σ_{CT}, uncertainty may dominate. For methods that control the temperature, the temperature uncertainty is an important concern.

G. Total Solar Irradiance

Throughout the solar cycle the intensity of the sun fluctuates somewhat as shown in Figure 3 [11]. Also during non-solar minimum periods the intensity also fluctuates on a daily to weekly basis as sunspots and faculae evolve on the solar surface. Data from ACRIM (Active Cavity Radiometer Irradiance Monitor) and similar instruments have been assembled into composites illustrating the historic solar irradiance as shown below. This shows an approximate 1.5 w/m^2, 0.1%, variation with solar cycle, and about a 5 w/m^2 range, suggesting a standard deviation of ±1.2 w/m^2, ±0.09%.

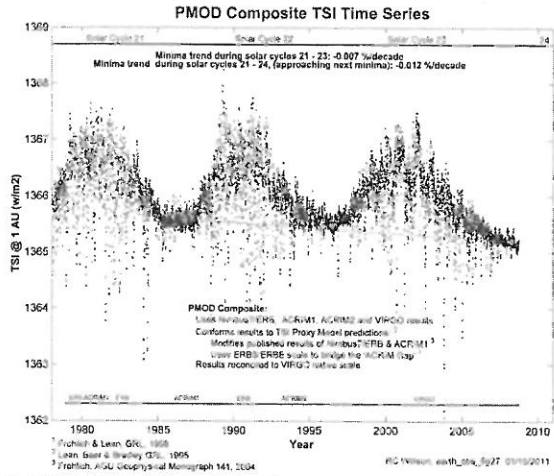

Fig 3. ACRIM Total Solar Intensity.

H. Pointing Angle

The solar intensity is proportional to cosine of the angle between sun and the normal to a surface. This suggests small errors in pointing are tolerable. Pointing accuracy of 1.8° gives 99.95% full intensity. 2.6° gives 99.9% of full intensity, and 5.7 gives 99.5% of full intensity. 2° pointing accuracy may be reasonable and gives sufficient accuracy of <0.1%.

III. Discussion

The errors due to atmospheric effects are mostly at the 0.1% level or better for data taken at altitudes higher than 5 mbars.

A. Langley Plots

Langley plots extrapolate a series of data based on Optical Air Mass, or absorptive path length, to zero air mass, pressure or path length. It is based on Beer's Law, $I(m_a) = I_0 \exp(-m_a * k)$ where I_0 is the Air Mass zero intensity, m_a is the Air mass, and k is an extinction coefficient. It is not strictly true due to non-uniformity of the atmosphere, and the spectral dependence of k. However, for the Aircraft calibration method, the extrapolation appears to work well. The calculations above give an opportunity to test how well the extrapolation can be expected to work. This examination looks at two portions of the Stratosphere, the lower stratosphere, from about 250 mbars to 100 mbars, appropriate to the aircraft method, and a mid stratosphere region, 30 to 10 mbars. This mid-level region may be of interest for small high altitude balloon payloads.

B. Pressure

Stratosphere	Top cell	Middle	Bottom
Mid	0.99997	0.99986	0.99998
Lower	0.99986	0.99886	0.99963

Table 6. Langley Plot logarithmic extrapolation to zero pressure.

The Langley Plot extrapolation due to pressure dependent Rayleigh and uniformly mixed gases, shown in Table 6, appears to work well, based on calculations of relative I_{sc}. The mid-level extrapolations return to unity to within 0.015%. For the Top and bottom cell in the lower stratosphere the agreement is also within 0.015%. For the middle cell the O2 absorption line near 760 nm is strong and has some detrimental effect. However the extrapolation is still within 0.15%.

C. Ozone

The ozone extrapolation is complicated because of its non-uniform distribution in the atmosphere. As the ozone producing UV wavelengths are absorbed the fractional ozone density is reduced. This causes the Langley Plot with pressure, or Air Mass, to begin to level off at higher pressures as shown in Table 3. It is clear that the top sub-cell is most influenced by Ozone absorption.

By rescaling the Langley Plot by Ozone number instead of pressure, Table 7 shows that if the Ozone distribution is known, an extrapolation can be quite successful.

In the mid stratosphere, where the ozone distribution is more uniform, above the big drop in ozone creation in the lower stratosphere, extrapolation by pressure works well again as shown in Table 8.

Stratosphere	Top Cell	Middle Cell	Bottom Cell
Middle	0.99996	0.99997	1.00002
Lower	0.99999	0.99999	0.99996

Table 7. Logarithmic Extrapolation via Ozone to Zero Ozone.

Middle	0.99959	0.99978	1.0000

Table 8. Extrapolation of Ozone absorption via pressure to zero pressure.

This suggests a separate accounting for ozone is not needed for Langley plots in the 30 to 16 mb region. Applying a pressure based extrapolation, where the ozone distribution is expected to be more uniform is accurate to better than 0.05%, which is quite practical.

D. Water Vapor

The water vapor absorption is strong in the infrared. While the middle and top cells are unaffected, the bottom cell is affected significantly, with 2% reductions in I_{sc}. From the curvature in the Langley plot it is apparent that the Beers law assumption is breaking down. Table 9 shows the error introduced is about 0.05% for the mid-stratospheric extrapolation to AM0, and is negligible. However, lower stratospheric error is over 0.3%, enough to be concerned.

Stratosphere	Top Cell	Middle Cell	Bottom Cell
Middle	1.00000	0.99998	0.99952
Lower	1.00000	0.99997	0.99685

Table 9. Logarithmic Langley Plot extrapolation of relative Isc to zero pressure.

D. Error Analysis

In this section the errors and uncertainties will be summarized. Those less than 0.05% will be ignored.

Mechanism	High Altitude			Langley Plot Mid-Strato-sphere			Langley Plot lower Stratosphere		
Sub-cells	Top	Middle	Bottom	Top	Middle	Bottom	Top	Middle	Bottom
Pressure	0.07%	0.06%	0	0	0	0	0	0.12%	0
Ozone	0.10%	0.05%	0	0	0	0	0	0	0
Water	0	0	0.1%	0	0	0.05%	0	0	0.32%
Total	0.17%	0.11%	0.1%	0	0	0.05%	0	0.12%	0.32%

Table 10: Summary of errors in high altitude measurements greater than 0.05%

The primary point of Table 10 is that these errors are small compared to the accuracy of the measurements. The spectral sources of error at high altitude are small. The ozone column based Langley extrapolation does not introduce error. The bottom cell measured at low altitude includes some offset due to water vapor.

E. Uncertainties

Table 11 includes estimates of uncertainties for various mechanisms. With a few exceptions these are described previously in the text. The Ozone uncertainties are due to structure in the distribution that is not included in the coarse model used. Also the in the calculations above a specific total ozone number of 350 Dobson units is used. In practice it can vary from 250 to 450. The modeling that is performed in Lear flight data analysis includes the variation as measured daily by satellite. The structure of the ozone distribution is assumed to be a major cause of the flight-to-flight variation observed.

The temperature uncertainties are assumed to be entirely due to a temperature measurement of ±1C. It does not include uncertainties due to extrapolating the temperature dependence to Laboratory temperatures.

F. Flight-to Flight Variations.

NASA Glenn has a series of data indicating variations of multiple calibration measurements of some cells [12]. This is shown in figure 4.

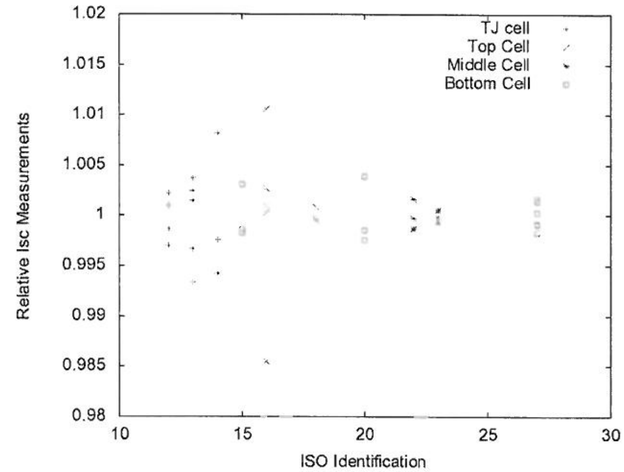

Fig 4. Flight-to-Flight variations of Lear Isc calibration measurements.

In figure 4, the "ISO number" simply indicates individual cells. The Triple Junction cells and Top cells are expected to behave similarly since the Triple Junction cell is current limited by the top cell. Of 22 top and Triple Junction flights the standard deviation was 0.51% with a maximum deviation of 1.5%, of 7 middle cell flights the standard deviation was 0.1% with a maximum deviation of 0.13%. And of 12 bottom cell flights, the standard deviation was 0.2% with a maximum deviation of 0.4%. For top cells, because the standard deviation is less than half the maximum deviation, we claim an estimated standard deviation of 0.75%.

IV. CONCLUSIONS

The atmospheric and environment related error are generally estimated to be less than 0.2%. High altitude

Mechanism	High Altitude			Langley Mid-Strato-sphere			Langley Lower Stratosphere		
Sub-cells	Top	Middle	Bottom	Top	Middle	Bottom	Top	Middle	Bottom
Ozone	0.05%	0	0	0.25%	0.15%	0	0.50%	0.25%	0
Water	0	0	0.12%	0	0	0.06%	0	0	0.44%
Pointing	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Solar Irradiance	0.09%	0.09%	0.09%	0.09%	0.09%	0.09%	0.09%	0.09%	0.09%
Temperature	0.05%	0.06%	0.07%	0.05%	0.06%	0.07%	0.05%	0.06%	0.07%
Sum	0.15%	0.15%	0.19%	0.29%	0.18%	0.16%	0.52%	0.29%	0.47%

Table 11. Estimated Uncertainties for various mechanisms >0.05%.

uncertainties are also less than 0.2%. This does not include uncertainties in temperature extrapolation from flight temperatures to 25C or 28C, which should be evaluated based on temperature coefficient uncertainties. Accuracies of a few tenths of a percent are a reasonable goal for high altitude solar cell calibrations.

Water vapor affects measurements of the bottom cell in the aircraft method. However, since the bottom cell is usually designed to be current rich, it should not have much impact on ground measurements. This may be of concern to multijunction cells beyond three junctions. It may be possible to use weather service dew point measurements to improve this analysis.

The Langley Plot method is demonstrated to compensate for the atmospheric absorption losses in the lower altitude methods in most cases. Compensating for the ozone distribution in principle can be effective, but variations in the actual distribution from the model produce some uncertainty.

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