Calculation Method for Predicting AM0 Isc from High Altitude Aircraft Flight Data

Matthew Myers and Dave Snyder (Ret.)

NASA Glenn Research Center, Cleveland, Ohio 44135

Abstract — **High altitude aircraft have been used by the space photovoltaic (PV) community to determine the air mass Zero (AM0) performance of solar cells for over fifty years. Relative to in-space measurement opportunities, these methods are generally cheaper and more readily available. The data obtained, however, must be corrected for residual atmospheric effects. This paper details the correction method currently being used for the calculation of the estimated AM0 short-circuit current (Isc) for photovoltaic devices flown on the NASA ER-2 calibration platform. This method would also be applicable to other high altitude methods where Isc data is collected over a sufficiently large range of altitudes. An initial comparison with a four junction (4J) cell flown on the CASOLBA high altitude balloon platform showed an agreement to 0.2%.**

I. Introduction

The AM0 characterization of PV devices using high altitude aircraft has become more challenging as technology has progressed. In particular, emerging four, five, and six junction devices have larger top cell band gaps which are more sensitive to the filtering effects of atmospheric ozone.

Details on the general method of high altitude aircraft testing have been previously published [1], [2]. As a summary, a device under test (DUT) is mounted at the bottom of a collimation tube onboard a high altitude aircraft. The tube is directed at the sun by the pilot using a sun-sight. The aircraft then descends approximately 10k-15k feet from its maximum altitude while monitoring the device Isc and air pressure. A method based on a modified Langley extrapolation is then used to estimate the AM0 Isc.

The influence of atmospheric ozone is an increasingly important factor when correcting the experimental data. An early ozone correction method based on silicon single junction devices involved simply multiplying the predicted AM0 Isc by a factor of 1.01. An improved correction method designed for use with multijunction cells was developed in 2002 [1]. This method involved the calculation of an ozone correction factor for a given cell chemistry, which was applied to every Isc data point from the flight prior to applying the Langley plot extrapolation. The recent development of photovoltaic devices with more than three junctions as well as a change of flight platform prompted a review of the correction method. Several changes were made. The correction method has been written into a single piece of software, referred to as Solar Cell High Altitude Correction Calculator (SCHACK). The calculation of an ozone correction factor is now performed for each individual data point based on cell external quantum efficiency (EQE) as well as estimated optical path ozone for the position at which that Isc measurement was made. The cell temperature is now used to correct for cell Isc thermal coefficient variations for each cell and data point. The software is also designed to accept as simple text files any AM0 spectra, cell EQE, ozone distribution model, and ozone absorption spectra to allow for ease of future improvements.

II. Method

A. Software Inputs

The software takes the following data as inputs: a standard model of the AM0 Spectrum, an ozone absorption spectrum, a model of the atmospheric ozone altitude distribution on the day and at the location of the flight, the cell EQE and Isc temperature coefficient, the measured DUT Isc vs pressure and temperature data, the solar elevation angle at the time and latitude of the flight, and the heliocentric distance on the day of the flight.

For the AM0 spectra, cell EQE, ozone absorption spectra, and ozone distribution, the software is designed to accept any model formatted as a simple text document containing tab-delimited ordered pairs. Units used are, respectively, (nm, W/m^2nm), (nm, decimal), (nm, mDU^{-1}), and (atm, DU).

Currently, the AM0 spectrum being used is the ASTMG173 model sourced from the NREL website [3]. The cell EQE is best measured directly for each cell being flown, although an EQE of a similar cell has been shown to result in minimal error. The ozone absorption spectrum is taken from NREL's Simple Solar Spectral Model [4].

The ozone atmospheric distribution model starts with the standard ozone distributions listed in the Earth Probe Total Ozone Mapping Spectrometer (TOMS) Data Products User's Guide [5], however this data is then modified for a given flight by using a linear interpolation for average flight latitude and satellite reported total ozone column, and by with a piecewise interpolation using natural log and quadratic functions for altitude/Umkehr level. The total ozone column itself is sourced from the OMI (Ozone monitoring Instrument) on the NASA Aura satellite. The total ozone column data for each degree of latitude and longitude is published daily on the TOMS website [6].

Solar elevation angle for the exact time and date of the flight is taken from the NOAA website located here [7]. The heliocentric distance is taken from the NASA Landsat 7 Handbook which lists this distance for each day of the year in AU to eight significant figures.

B. Calculations

After storing inputs in local program variables and checking the validity of the data, the software matches the abscissae of the data sets for the AM0 spectrum, cell EQE, and ozone absorbance spectrum so that numerical integration methods used in the ozone correction can be performed. The abscissae are matched by trimming the data sets to a domain common to all three and then linearly interpolating ordinate values for the data sets having the wider spaced abscissae to match the one with the most closely spaced abscissae. Next, the software does a point-by-point ozone correction of the Isc vs. pressure data by using the following process.

Each measured Isc value is corrected by multiplying it by the ratio of the theoretical current generated at AM0 conditions, I_{AM0}, to the theoretical current that would be generated given the amount of ozone predicted to be in the optical path, I_{O3}, as shown by the equation

$$I_{corr} = I_{sc}\frac{I_{AM0}}{I_{O3}} \tag{1}$$

where I_{corr} is the ozone corrected current and Isc is the measured current. I_{AM0} and I_{O3} are calculated by integrating the product of the relevant spectral irradiance in units of (photons/s*m^2nm) with the cell EQE. This calculation is performed numerically with a simple trapezoidal integration method. The correction factor for an individual data point, I_{corr}, then becomes

$$I_{corr} = I_{sc}\frac{\int P_{AM0}(\lambda)EQE(\lambda)d\lambda}{\int P(\lambda)EQE(\lambda)d\lambda} \tag{2}$$

where $P_{AM0}(\lambda)$ is the AM0 irradiance, and $P(\lambda)$ is the ozone attenuated solar irradiance. To calculate $P(\lambda)$, the pressure at which an Isc measurement was made is compared to the provided ozone distribution model. The ozone in the optical path to the sun is linearly interpolated for this data point, taking into account the present altitude and solar elevation. Next, the transmittance through the ozone in the optical path is computed using the equation

$$P(\lambda) = P_{AM0}(\lambda)e^{-\beta(\lambda)Oz} \tag{3}$$

where, β_λ is the ozone absorption coefficient, and O_Z is the predicted total ozone present in the optical path to the sun in Dobson units.

After using this method to correct each Isc value for ozone attenuation, each Isc value is then corrected for any temperature variation of the cell at the time of the measurement. The temperature values are measured using an AD590 temperature sensor mounted inside the cell holder. The temperature sensor is separated from the cell by 1mm of aluminum. The temperature correction is performed using the equation

$$I_{corr} = I_{sc} + (T_T - T_C)\alpha \tag{4}$$

where I_{corr} is now the temperature corrected I_{SC}, T_c is the cell temperature, T_T is the target temperature, and α is the I_{sc} temperature coefficient for the device.

The pressure values at which each Isc measurement were made are then converted to air mass based on altitude and solar elevation angle, and the Langley plot extrapolation method is then applied. This method calculates a least-squares fit to the log of I_{corr} vs air mass and then undoes the log of the y-intercept. The final step in the method is to correct for heliocentric distance on the day of the flight by multiplying the Langley plot result by the square of the distance in AU.

The software then outputs the predicted AM0 Isc as well as ancillary data such as the slope, intercept, and R^2 values of the Langley plot, the maximum recorded raw Isc value, and the ratio of the predicted AM0 Isc to the maximum raw value.

III. Temperature Correction

During the initial flights of the ER-2 platform, the temperature control system for the DUTs was shown to keep each of them within ~±1°C of their target 25°C temperature [2]. Because the temperature coefficients of typically flown cells are on the order of 0.01 $mAcm^{-2}°C^{-1}$, it was decided that temperature correction would not be necessary.

However, on the fifth flight of the 2017 season, the pilot held a steady altitude for approximately ten minutes after coming on-sun and prior to starting the descent. The initial exposure to the sun is where the sharpest change in cell temperature is seen as the temperature control system adjusts to the change in thermal environment. Usually, the on-sun condition and initial descent occur at nearly the same time. When looking at the Isc vs pressure plot from this flight, a sharp variance in Isc was observed during the on-sun temperature deviation (see figure 2 below). This influence was masked on previous flights where the on-sun condition and aircraft descent happened simultaneously, both of which change the Isc output of the cell.

Using the data from an InGaAs cell during the level part of this flight, an Isc vs. cell temperature plot was generated. The temperature coefficient derived from this plot was 8.9E-3 $mAcm^{-2}\,°C^{-1}$ which compares favorably to the published value of 0.009 $mAcm^{-2}$ $°C^{-1}$ [8]. The normalized Isc vs temperature plot is shown in figure 1 below.

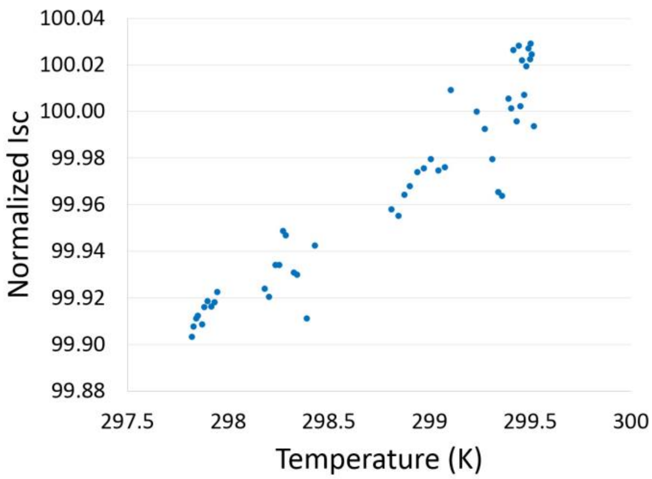

Fig. 1. Cell Isc vs. Temperature during Level Flight

The published temperature coefficient was then applied to the cell Isc vs. pressure data. Both the original uncorrected and temperature corrected plots of Isc vs pressure are shown in figure 2 below.

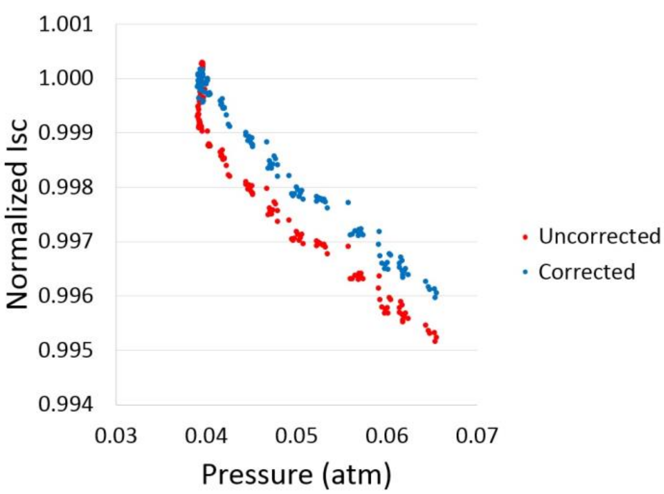

Fig. 2. Comparison of Temperature Corrected and Uncorrected Isc vs Pressure Plots

The AM0 Isc was recalculated with this temperature corrected data. The new AM0 Isc prediction varied by just under a tenth of a percent from the non-temperature corrected value and the R^2 value for the Langley extrapolation rose from 0.83 to 0.96. While the 0.1% difference is small in this case, the effect might be more pronounced with a different cell technology or if temperature control is not as precise for other flights either on the ER-2 or another calibration platform. The decision was then made to include the temperature correction of the Isc vs. pressure data in the software prior to the Langley plot extrapolation.

IV. Sample Flight Data

Figure one below shows a summary of the AM0 Isc predictions for six of NASA GRC's primary standards obtained over sixteen flights flown during a period of four years. The devices are isotype top cells (TC), middle cells (MC) and bottom cells (BC) of a traditional triple junction PV device. The flights varied greatly over the time of year (March through October), and therefore the solar elevation angles, overhead optical path ozone columns, and heliocentric distances also varied significantly. The data from flight four is from one of the last Learjet flights. The figure 3 below shows each flight's AM0 Isc estimate normalized to the average value of each cell. The results show the repeatability of a measurement is generally within ±0.5%. This suggests that the method is taking into account all relevant parameters that might vary from flight to flight reasonably well. The data is also tabulated in table I below.

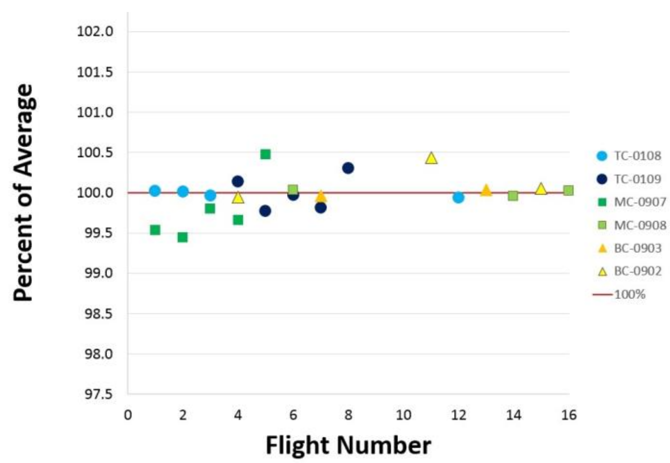

Fig. 3. Cell Measurement Variation with Flight

TABLE I
ESTIMATED AM0 ISC, GRC 3J SUB-CELLS (mA)

Flight	Date	TC0-108	TC-0109	MC-0907	MC-0908	BC-0902	BC-0903
1	10/8/2014	69.87		65.97			
2	10/10/2014	69.86		65.90			
3	10/14/2014	69.83		66.14			
4	3/26/2015		69.96	66.05			105.73
5	7/16/15		69.71	66.59			
6	7/21/15		69.84		66.25		
7	7/22/15		69.74			105.10	
8	5/18/16		70.08				
9	5/23/16						
10	5/24/16						
11	4/12/17						106.25
12	4/14/17	69.81					
13	5/9/17					105.18	
14	5/11/17				66.20		
15	5/12/17						105.84
16	5/15/17				66.24		
Average		69.84	69.87	66.13	66.23	105.14	105.94
Std Dev.		0.028	0.155	0.273	0.025	0.055	0.274

V. Comparison to Balloon

On April 8th of 2017, the The Centre national d'études spatiales (CNES) launched a high altitude balloon named CASOLBA to characterize a number of PV devices. Among these was an IMM four-junction cell, referred to here as IMM-1, which had been previously characterized on the ER-2 platform. A sister cell of IMM-1, referred to here as IMM-2, was also previously flown three times on the ER-2. The ER-2 estimated AM0 Isc for IMM-1 was around 0.17% higher than Casolba value, while the average IMM-2 estimate was nearly identical, being 0.01% lower than the CASOLBA value for IMM-1. Although this is only the result of one cell on one balloon flight, it does suggest that the ER-2 platform and the method used in the SCHACK software does compare favorably with higher altitude testing methods, even where newer, four-junction cell technology is concerned.

Summary

The measurements and calibrations labs at NASA GRC has written new software used to predict the AM0 Isc performance of primary flight standards from data obtained during high altitude aircraft flights. The method is based largely of the previous 2002 method [1]. Point by point factors for ozone correction, temperature correction, and the ability to quickly switch modeled parameters are some of the changes. Results from four years of flights as well as results from a recent balloon flight suggest the method is reliably providing consistent estimates despite varying flight conditions.

References

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