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## OZONE CORRECTION FOR AM0 CALIBRATED SOLAR CELLS FOR THE AIRCRAFT METHOD

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### ABSTRACT

The aircraft solar cell calibration method has provided cells calibrated to space conditions for 37 years. However, it is susceptible to systematic errors due to ozone concentrations in the stratosphere. The present correction procedure applies a 1% increase to the measured  $I_{sc}$  values. High band-gap cells are more sensitive to ozone absorbed wavelengths (0.4 to 0.8  $\mu\text{m}$ ) so it becomes important to reassess the correction technique. This paper evaluates the ozone correction to be  $1+O3 \times Fo$ , where  $O3$  is the total ozone along the optical path, and  $Fo$  is  $29.8 \times 10^{-6}/\text{du}$  for a Silicon solar cell,  $42.6 \times 10^{-6}/\text{du}$  for a GaAs cell and  $57.2 \times 10^{-6}/\text{d.u.}$  for a InGaP cell. These correction factors work best to correct data points obtained during the flight rather than as a correction to the final result.

### INTRODUCTION

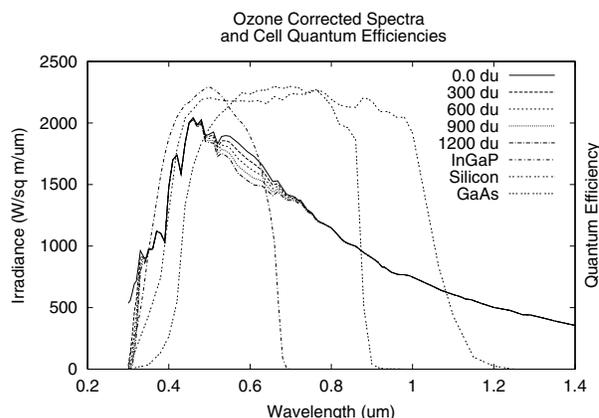
The NASA GRC aircraft calibration method has been used to provide the aerospace industry with cells calibrated to orbital conditions for 37 years. The method measures  $I_{sc}$ , the short circuit current, at AM0, air mass zero, for setting solar simulators to space conditions during ground-based measurements. This method has an accuracy of 1% for Silicon cells based on the standard deviation of the measurements and a comparison with balloon and shuttle measurements [1].

The method is susceptible to a systematic error due to the nonuniform distribution of ozone in the atmosphere. This error is presently accommodated by multiplying the measured  $I_{sc}(\text{AM0})$  by an ozone correction factor of 1.01 based on calculations for Silicon cells [1].

However, cell technologies have changed and higher band-gap materials are becoming more important, particularly in multi-junction cells. These cells are more sensitive to changes in the ozone absorbed portions of the spectrum. In addition, daily ozone measurements have become available from the Earth Probe TOMS (Total Ozone Mapping Spectrometer) [2]. This makes it possible to modify the ozone correction according to flight conditions. Both reasons make it important to reassess and improve the procedure for ozone correction in the aircraft calibration method.

The revised procedure consists of two steps. First, the cell spectral response function is integrated with the solar irradiance spectrum and an ozone corrected irradiance

spectrum. The results are compared to provide  $Fo$ , the correction per matm-cm of ozone, for the appropriate cell technology. Second, an ozone correction factor is calculated from the measured ozone in the optical path,  $O3$ , using  $Fo$ . Initially this was applied to the extrapolated value from a Langley plot. However, especially for higher band gap materials, it proves more useful to apply the correction to the flight data before performing the Langley plot extrapolation.



**Figure 1.** Ozone corrected irradiance and solar cell quantum efficiencies.

### MODEL

As a basis for obtaining ozone adsorption corrected spectra, the Simple Solar Spectral Model (SSSM) from NREL was used [3]. The Langley Plot technique used by the Aircraft Calibration Method [1] to extrapolate to orbital conditions (AM0) corrects for adsorption processes that are proportional to air pressure. Since data is taken above the tropopause, the water and dust of the troposphere is not of concern. But since most of the ozone is concentrated in a layer above the data acquisition region, this correction to the spectrum must be included. The irradiance as a function of wavelength is given by:

$$I(\lambda) = H_o(\lambda) \exp(-\alpha_o(\lambda) \times O3) \quad (1)$$

where  $H_o$  is the extraterrestrial irradiance at 1.0 au from the sun,  $\alpha_o$  is the ozone adsorption coefficient as a function of wavelength, and,  $O3$ , is the ozone along the optical path.

The ozone absorption coefficients used are those in SSSM. Figure 1 shows the irradiance for five ozone levels given in Dobson Units (du, matm-cm). Ozone absorption effects the spectrum principally in the range of 0.4 to 0.8  $\mu\text{m}$  as well as below 0.35  $\mu\text{m}$

Two standard cells that have frequently been flown are A-161, a Silicon cell, and A-133, a GaAs cell. They provide a set of data that can be used to investigate the accuracy of the ozone correction technique. In addition, correction factors for an InGaP cell, typically used as the top cell on multijunction cells, are also calculated. Quantum efficiencies for these cells are available at 20 nm intervals, and are also shown in fig. 1. A-161 and A-133 data were measured in our lab. A InGaP quantum efficiency was obtained from Aiken et al [4]. It is apparent that the higher band gap materials are more affected by the ozone adsorption.

The quantum efficiencies were converted to spectral response functions and convoluted with the WM0 based irradiance spectrum [3] shown fig.1 to calculate  $I_{sc}$  as a function of Ozone. The results are shown in table 1. The ozone correction factor,  $F_o$ , is defined as:

$$F_o = (I_{sc}(0)/I_{sc}(\{O_3\}) - 1) / \{O_3\}. \quad (2)$$

Total Ozone	$I_{sc}(\text{Si})$ mA/cm <sup>2</sup>	$I_{sc}(\text{GaAs})$ mA/cm <sup>2</sup>	$I_{sc}(\text{InGaP})$ mA/cm <sup>2</sup>
0 du	41.24	29.30	17.57
600 du	40.50	28.57	16.99
1200 du	39.81	27.88	16.45
$F_o(/du)$	$29.85 \times 10^{-6}$	$42.56 \times 10^{-6}$	$57.16 \times 10^{-6}$

**Table 1.** Calculated  $I_{sc}$  as modified by ozone adsorption.

In order to estimate the precision of the integration for calculating  $F_o$ , two methods were used. First, a second set of spectral response (SR) measurements from A-161 was used to compare with the initial result. Secondly, half the measurements were discarded to create two data sets where the resolution was reduced from about 20 nm to about 40 nm. These results are summarized in Table 2.

A-161 $F_o$ Calculation	$F_o$ from full SR data set (/du)	$F_o$ from half resolution SR data set (/du)
SR Data Set A	$29.85 \times 10^{-6}$	$29.60 \times 10^{-6}$
SR Data Set B	$29.64 \times 10^{-6}$	$29.50 \times 10^{-6}$

**Table 2.** Precision of  $F_o$  Calculation for a Silicon solar cell.

From this data, the precision of the integration appears to be about as good as the SR data, and better than 1%. If the ozone correction for a cell is even as high as 5%, the

influence of this uncertainty on the final  $I_{sc}$  is less than 0.05%.

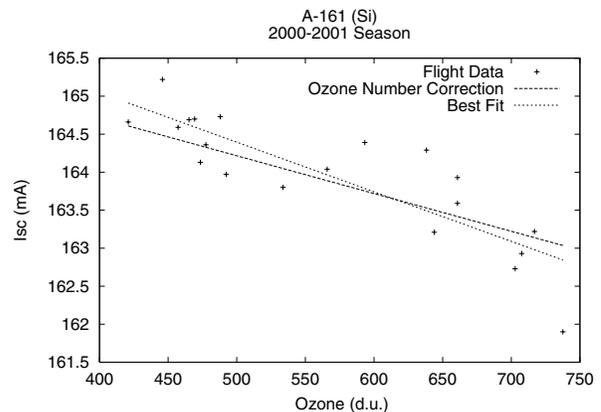
## APPLICATION TO FLIGHT DATA

The flight procedure is described in more detail elsewhere [1]. Briefly, the plane flies along 45N latitude, from about 82W to 85W longitude. The flight typically reaches a peak altitude near 50,000 ft (120 mb) and descends to the tropopause, usually lower than 35,000 ft (250 mb) during the flying season. Flights take place in the late October through the end of March, when the tropopause is lower than at other times of the year.  $I_{sc}$  and  $V_{oc}$  of up to six cells are measured as a function of atmospheric pressure during the decent. The temperature of the cells is controlled to near 25°C during the flight. To find  $I_{sc}(\text{AM0})$  the Langley Plot method is used, extrapolating the logarithmic  $I_{sc}$  data as a function of pressure or air mass to zero. This value is then corrected for the Earth-Sun distance to bring the reported value to 1.0 au.

From Appendix A of reference 2, about 80% to 85% of the ozone is above the top of flight profile, 120 mb. The ozone is estimated as  $0.83 \times O_n / \cos(Z)$  where  $O_n$  is the reported ozone number for 45N 83W and  $Z$  is the zenith angle.

## Short Term, Si

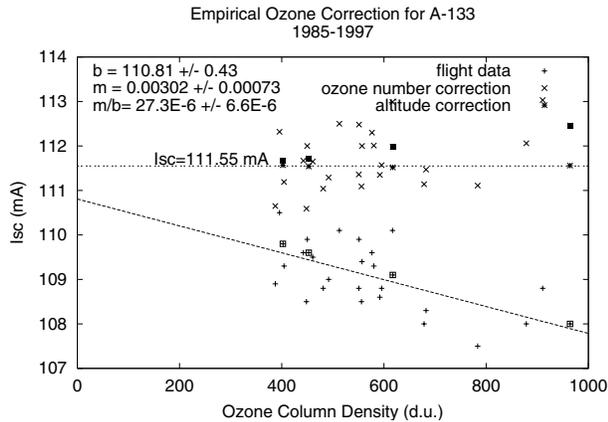
A-161 was flown 20 times during the 2000/2001 flying season. It had an average  $I_{sc}$  of  $165.59 \pm 0.81$  ma. Daily ozone numbers were obtained from the Earth Probe TOMS web site [5] for 45N83W, a position along the flight path. The zenith angle ranges from 48° to 68° during the flying season. The ozone number varied from 278 to 445 for flight days during the season with an average of 357.



**Figure 2.** Comparison of A-161 flight data with the silicon cell ozone correction model.

Figure 2 shows a plot  $I_{sc}$  corrected for  $R_e$ , Earth-Sun radius, for A-161 for the 2000-2001 season plotted against the total ozone measurement adjusted as described above

for zenith angle. Applying the model to each of the  $I_{sc}$  measurements gives  $I_{sc}(A-161)=166.70\pm 0.47$ . The model curve shown in fig. 2, ozone number correction, is  $166.70/(1+F_s \times O_3)$ . The reduction of the standard deviation of the measurements by 40% suggests that this is an important contribution to the analysis.



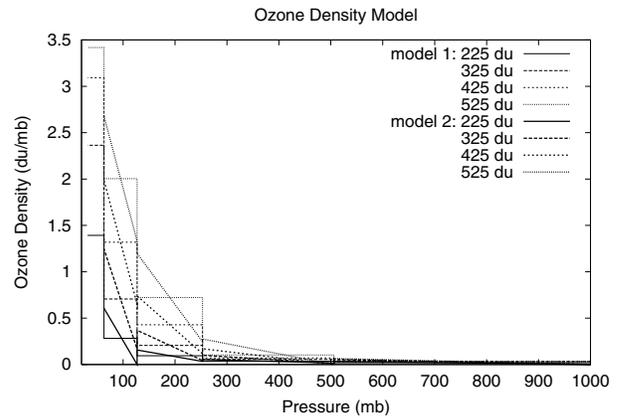
**Figure 3.** Dependence of A-133  $I_{sc}$  measurements on total ozone number.

### Long Term Measurements, GaAs

A-133 was flown over 28 times between 1985 and 1997. Total ozone measurements are available for most of the period, but not from December 1994 to July 1997 [5].  $I_{sc}$  over this time period was  $109.08\pm 0.72$ . Using the simple total ozone based correction described above gives an  $I_{sc}$  of  $111.74\pm 0.63$ . The slope of the uncorrected data is  $I_{sc} \times 27.3 \times 10^{-6}$ , significantly less than the  $42.6 \times 10^{-6}$  expected from model. The corrected data, also shown in fig. 3, demonstrates the ozone number based correction gives an over-correction since data from high ozone flights are typically corrected to higher values than the lower ozone data.

To improve the method, the correction should be applied to each data point in order accommodate the changes in ozone density as the plane descends. The altitude dependent ozone profiles in Reference 2 can be used to calculate ozone absorption variations with pressure. Dividing the ozone contribution in each layer by the thickness in pressure, the profiles in Table A.1. of Reference 2 can be used to generate an ozone density model as a function of total ozone and pressure or altitude.

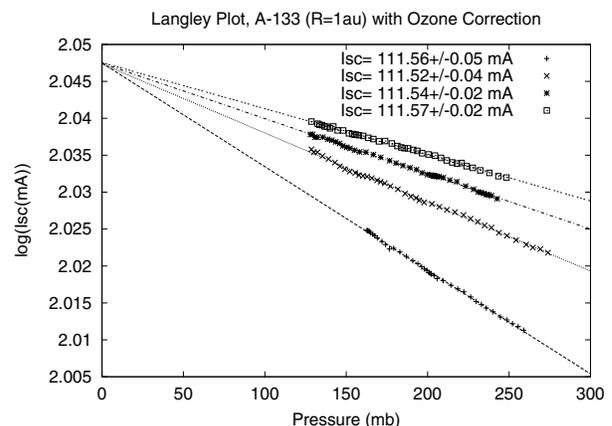
Two ozone density models are shown in figure 4. The first used a uniform density in each layer. The second model uses a linear interpolation between the average density at each boundary, which is then adjusted to give the correct ozone amount in each layer. The second model is the one used to correct the flight data in figure 5.



**Figure 4.** Ozone density models. Model 1: Uniform density in each layer, Model 2: Linearly varying density in each layer.

To develop an altitude dependent ozone correction, the ozone density as a function of pressure is integrated from the measured altitude to zero pressure. The model [2] gives ozone profiles for ozone numbers at intervals of 50 du. For each interval the fraction of ozone above the pressure point is used to scale the reported ozone number.

Each  $I_{sc}$  measurement is then multiplied by  $1+F_o \times O_3 / \cos(Z)$ . This gives an ozone corrected  $I_{sc}$  measurement. Figure 5 shows this flight data corrected for ozone using the pressure measurement. This data converges to a very narrow range indicating this is a better method for the ozone correction since the ozone density variation with altitude, significantly affects the extrapolation to air mass zero.



**Figure 5.** Selected A-133 flight data including altitude dependent ozone correction.

## SUMMARY

This paper describes a method for correcting high altitude  $I_{sc}$  data for ozone absorption in the atmosphere. The two parts of the method are first to calculate a correction factor which is based on the spectral response of the cell technology. Then use satellite ozone data to correct flight data measurements on a point-by-point basis before extrapolation using the Langley Plot method to air mass zero.

The correction coefficients for several cell technologies are as follows: Si,  $29.8 \times 10^{-6}/du$ ; GaAs,  $42.6 \times 10^{-6}/du$ ; and InGaP,  $57.2 \times 10^{-6}/du$ . These values are expected to be accurate to better than 1% based on integration analysis. These coefficients generally result in corrections between 1% and 3%, slightly higher than has been used in the past.

The initial attempt to apply a correction based only on the optical path angle and the ozone number proved to not work well for higher bandgap materials. But applying an ozone correction to each measured point before performing the Langley Plot extrapolation appears to work well.

For the next flying season (2002-03) the equipment to actively acquire solar spectra during the flight will be available. This will permit the measurement of the ozone absorption during the progress of the flight. This will permit the correction of  $I_{sc}$  data based on known conditions to further improve the compensation for ozone absorption.

## REFERENCES

- [1] P.Jenkins, D. Brinker and D. Scheiman, "Uncertainty Analysis of High Altitude Air Mass Zero Solar Cell Calibration", *26<sup>th</sup> IEEE PVSC*, V26-206, 1997, pp.857-860..
- [2] McPeters, R.D. et al, "Earth Probe Total Ozone Mapping Spectrometer (TOMS) Data Products Users Guide", NASA TP 1998-206895, 1998.
- [3] Bird, R., and Riordan, C., "Simple Solar Spectral Model for Direct and Diffuse Irradiance on Horizontal and Tilted Planes at the Earth's Surface for Cloudless Atmospheres", SER/TR-215-2436, December 1984.
- [4] D. Aiken et al, "High Efficiency Triple Junction Manufacturing and Development at Emcore Photovoltaics", *Space Photovoltaic Research and Technology 2001 (SPRAT XVII)*, NASA Glenn Research Center, 2001.
- [5] <<http://toms.gsfc.nasa.gov/ep/ep.html>>.



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