

JUNO Photovoltaic Power at Jupiter

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Abstract

This paper summarizes the Juno modeling team work on predicting the Juno solar array performance at critical mission points including Juno Orbit Insertion (JOI) and End of Mission (EOM). This report consists of background on Juno solar array design, a summary of power estimates, an explanation of the modeling approach used by Aerospace, a detailed discussion of loss factors and performance predictions, a thermal analysis, and a review of risks to solar array performance

Introduction

Juno – PV power at Jupiter

The Juno mission, the second mission under the New Frontiers initiative, will be the first solar powered mission to orbit Jupiter, meeting the challenge of extremely low light illumination and low temperature operation. Conceived as solar powered from the initial design, Juno combines scientific investigation with Spacecraft operation to effectively operate in the challenging Jupiter environment. Juno will observe Jupiter's gravity and magnetic fields, atmospheric dynamics and composition, and the coupling between the interior, atmosphere and magnetosphere that determine the planet's properties and drives its evolution. After launching on a Lockheed Martin Atlas V-551 rocket from Cape Canaveral in late 2011, the Juno spacecraft will get a gravity assist from an Earth flyby in October 2013. Arriving at Jupiter in August 2016, the spinning spacecraft will fly 32 polar orbits of the planet before a planned de-orbit to end the mission in October 2017. The orbits are configured to remain in continuous sunlight, thereby minimizing the battery sizing requirements. The mission duration and spacecraft orbit are also designed to minimize radiation exposure to levels that compare to more conventional solar array mission environments. As such, the Juno mission does not make the case that all missions to Jupiter can be managed with solar PV, but that with careful design, some types of scientifically valuable missions to Jupiter can be achievable. The Juno mission makes use of a spin-stabilized

spacecraft with three solar array wings spaced at 120° about the central bus. Figure 1 shows the spacecraft configuration.

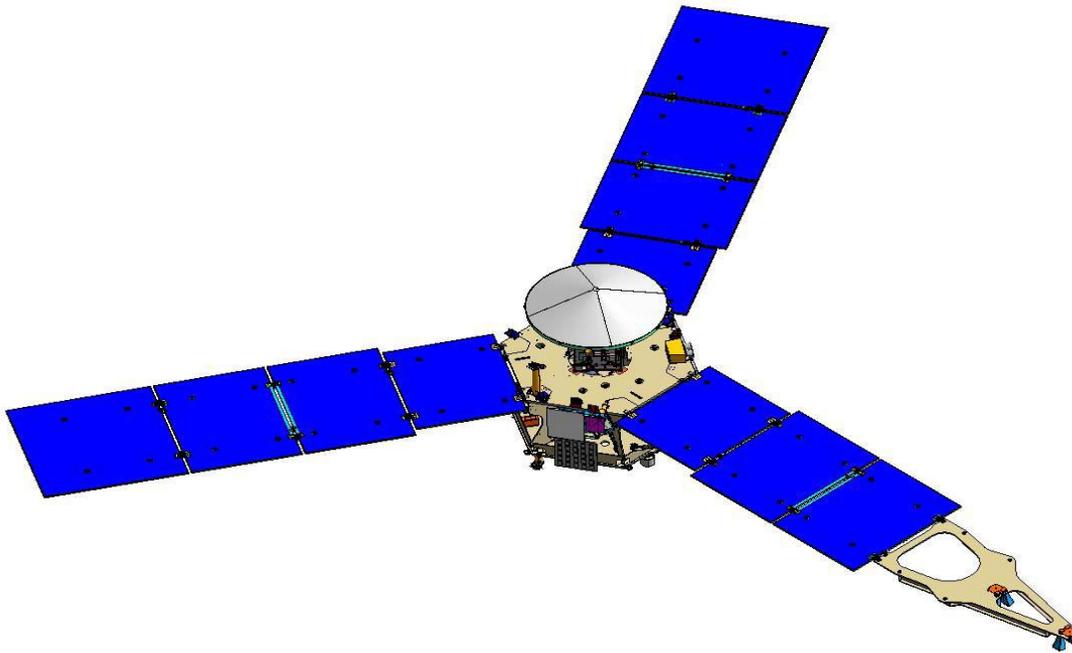


Figure 1. Juno Spacecraft and Solar Array

Wing 1 consists of three panels with a magnetometer boom at the terminal end. Wings 2 and 3 consist of four panels each. All outboard panels are the same size, while the innermost panel of each wing is smaller. Panels on each wing are numbered from the innermost panels as 1 to the outermost panels as 4. The three wings of the Juno Solar array consist in total of eleven panels.

The array is managed using string switching to provide power as needed by the loads. Unused power is left on the array as heat, eliminating the need for shunt regulation and shunt radiators while operating over the wide sun ranges (0.85—5.44AU) and temperatures (-140°C - $+85^\circ\text{C}$) encountered during the Juno mission. In the near-Earth solar ranges temperatures of the array are higher so that longer strings of cells in series are necessary to provide the required voltage. The number of switches available and the maximum current capacity handled by each switch was set initially through use of a Lockheed switch approach qualified on previous missions. Due to the funding and schedule constraints of Juno, it was not considered feasible to develop and qualify a modified or alternate power management system.

As temperatures decrease, cell voltage rises so that fewer cells are needed in series to produce the required voltage (voltage varies inversely with respect to temperature). The current decreases dramatically with increasing distance from the sun as the solar intensity decreases, so that more strings are needed in parallel to provide the total required power. These realities are exploited in the Juno design by having the three discrete string lengths matched for subsets of the mission and science phase. Note that as sun range increases and shorter strings are

switched, the longer strings can be left on. At the same time, the long strings operate further from the maximum power voltage point in effect leading to operating at reduced efficiency. Obviously, minimizing the number of strings and cells in the long and medium length strings would leave more room for the more efficiently operating short strings. The final selection was based on determination of the cell performance characteristics, power requirements throughout the cruise phase, and the selection of transition points where the reduced string length strings would begin contributing power. The critical input to this is the solar cell performance for which little statistically significant data existed; therefore extensive cell characterization and screening were implemented

The three string lengths selected are based on voltage and power set points for three phases of the mission: Inner cruise with sun ranges of 0.85 and 1.9AU (long strings), middle cruise with sun ranges of 1.8 to 3.75AU, and the outer cruise/Science phase from 3.75 to 5.5AU. There is overlap in the transition ranges in which different length strings are used together.

Panels are made of solar cell strings grouped into circuits. Strings of three lengths – short, medium, and long – populate each panel. The selection of the string lengths are designed to provide the needed voltages at various mission sun ranges. The strings are grouped into circuits of similar lengths. Circuits are switched as needed to support the bus loads as a function of spacecraft load and battery state of charge. Panels generally consist of a single string length with the single exception being Wing 3, panel 1, which is made up of short- and medium-length strings

Solar Cell Selection

The space environment at Jupiter is characterized by intense trapped particle radiation, low intensity sunlight (3.4% of the sunlight at Earth) and low operating temperature. The solar cells selected for the JUNO solar array must work efficiently in such LILT (low intensity, low temperature) conditions. LILT operation emphasizes defects in solar cell epitaxial layers that are not observed under 1 sun operation. As current is drastically reduced at low intensities, the effective impedance of the cell increases, allowing high resistance shunt paths to become active and significantly reduce solar cell performance.

In order to minimize the effects of LILT operation, JUNO had 2 choices. Develop and qualify a solar cell specifically designed to operate in LILT conditions, or perform comprehensive characterization testing of “off the shelf” qualified solar cells to understand the behavior and performance of such cells under Jovian LILT conditions. The program chose the latter option and embarked on an extensive test program of GaAs triple junction cells to fully understand how these cells would behave at Jupiter. A test matrix was devised in which performance measurements were taken of triple junction cells through a range of intensities – 0.85AU to 5.5AU – a range of temperatures of -140°C to 100°C and a range of radiation fluences – 0 to 1E15 1MeV electrons/cm².

From these performance measurements, it was possible to describe the behavior of the cells during the Cruise phase to Jupiter, Jupiter Orbit Insertion (JOI) and End of Mission at Jupiter

(EOM) by deriving a set of derating coefficients that operate on unradiated cell performance at 1AU, 28°C.

These coefficients are:

Intensity Coefficients – describe the loss of voltage and current as intensity is reduced from 1AU to 5.5AU

Radiation Coefficients – describe the loss of voltage and current as radiation is increased from zero to 8E13 (JOI) and 7E14 (EOM)

Temperature Coefficients – describe the gain in voltage and loss of current as temperature is reduced.

At first, it was assumed that the intensity coefficient for current was unity. In setting up the solar simulator, the intensity is defined by the short circuit current of the cell. Thus, at 5.5AU, the I_{sc} is expected to be reduced by a factor of 0.03306. The maximum power current, I_{mp} , was expected to be reduced by the same amount. However, first results showed that the I_{mp} reduction factor was greater. At first this was assumed to be calibration error in the simulator set up. Additional testing showed that the loss factor decreased as intensity reduced.

Intensity loss factor for current (at 5.5AU) was thus defined as:

$$I_{mp5.5AU,28C}/(I_{mp1AU,28C} \times \text{Intensity})$$

The factor for voltage (at 5.5AU) was defined as:

$$V_{mp5.5AU,28C}/V_{mp1AU,28C}$$

Coefficients for other intensities were defined similarly.

Radiation coefficients are well understood and are defined as:

$$I_{mprad, T}/I_{mpunrad, T}, V_{mprad, T}/V_{mpunrad, T}$$

Where T is the temperature at which the performance of unirradiated and irradiated cells is measured. This is normally, but not always, 28°C.

At 1AU, temperature coefficients are defined as

$$(V_{mpT1} - V_{mpT2})/(T1-T2), (I_{mpT1} - I_{mpT2})/(T1-T2)$$

Voltage coefficients are negative (voltage increases as temperature decreases), while current coefficients are positive (current decreases as temperature decreases). In order to compare the behavior of current vs. temperature at different intensities, the coefficient was normalized by dividing by the intensity.

Current temperature coefficient is thus:

$$(I_{mpI, T1} - I_{mpI, T2})/((T1-T2) \times I)$$

Where I is the intensity at which the measurements are made.

Early test results performed showed that intensity and radiation coefficients are independent of each other, but temperature coefficients are dependent on both intensity and radiation and radiation coefficients are temperature dependent.

In addition to providing preliminary values for intensity, radiation and temperature coefficients, early testing demonstrated two major findings.

- 1) The average performance of solar cells is limited by cells exhibiting degradation under LILT conditions. Performance can be improved by screening out cells that degrade the most. It was also shown that best average performance at EOL is achieved by testing cells at low intensity and screening for fill factor. Screening for I_{mp} or V_{mp} did not provide comparable improvement. Table 1 shows the improvement of power output and attrition resulting from discarding cells lower than the stated fill factor. It became clear that performance improvement came at the expense of high attrition.

Table 1. Screening Options

	Screening value	% Attrition	Power (mW/cm ²)
Spectrolab UTJ	0.60	0%	1.09
	0.73	37.5%	1.16
Spectrolab UTJ	0.79	62.5%	1.24

- 2) Current temperature coefficients have the most uncertainty in their measurement and are highly dependent on intensity and radiation. They are the main drivers for performance at 5.5AU and -140C. Voltage coefficients are less important. Table 2 shows the dependence on intensity and radiation.

Table 2. Temperature Coefficients

	Radiation 1MeV electrons/cm ²	Current Temperature Coefficient uA/cm ² /C (normalised)	
		1AU	5.5AU
	0	1.2	7.75
	1.00E+15	6.9	16.23

Early performance predictions show that, at Jupiter, increasing the current temperature coefficient from 6.9 uA/cm²/C to 16.23 uA/cm²/C decreases performance by 11%. Thus, obtaining good measurements for irradiated current temperature coefficients at low intensity became a priority.

After a competitive bid process, Spectrolab UTJ cells were selected for the JUNO mission. UTJ cells were then extensively tested at low intensities and high radiation fluences at Marshall Space Flight Centre (MSFC) to determine the optimum screening parameters and obtain more accurate values for temperature coefficients.

Radiation Analysis

The mission team performed a calculation to determine the 1MeV equivalent electron fluences for the JUNO mission. Fluences of electrons and protons within several energy bands plus estimates of solar flare protons experienced in the Cruise phase to Jupiter were provided. The calculation was performed according to the method specified in the JPL Blue Book (Reference 2). This method was devised to calculate 1MeV equivalent fluences in single junction GaAs cells. The method does produce a close approximation for the equivalent fluence in UTJ cells, dependent on the choice of conversion factor between the 10MeV equivalent proton fluence and the 1MeV equivalent electron fluence. For the model calculation, a value of 1000 was selected for this factor. The conversion factor for UTJ cells is likely lower. Shielding calculations were performed to calculate the front and back shielding thickness for the solar cells. For the front side, the cells were shielded by 12mil CMG coverglass (equivalent to 14.3mil fused silica). The rear side shielding of the solar panel substrate, adhesives, Kapton and germanium cell substrate amounted to 30mils fused silica equivalent. Electron and proton fluences were calculated for front and rear side, combined using the above stated conversion factor and doubled for margin (RDM2). The results are shown in Table 3.

Table 3. Radiation Analysis

			Shielding (mils)	
			30	14.3
Electron Front Fluence				6.6E+13
Proton Front Fluence				1.82E+11
Front Fluence				2.48E+14
Electron Back Fluence	5.45E+13			
Proton Back Fluence	5.14E+10			
Back Fluence	1.06E+14			
Total Fluence (RDM=1)				3.54E+14
Total Fluence (RDM=2)				7.08E+14

The calculated 1MeV equivalent electron fluence for RDM=2 is 7.08E14 1MeV equivalent electrons/cm². Spectrolab performed a similar analysis, but used RDCs (relative damage coefficients) appropriate for UTJ cells. They obtained a value of 6.7E14 1MeV equivalent electrons/cm². The close agreement of the two calculations plus the use of actual UTJ RDC's in the Spectrolab calculation suggests that the RDM2 equivalent fluence for the Juno mission is 6.7E14 1 MeV equivalent electrons/cm². This is a relatively low fluence for the Jovian environment, comparable to a typical GEO mission. The Jovian radiation environment is much more intense than GEO normally, but the low fluence is a product of the carefully designed orbits the spacecraft will fly around Jupiter, avoiding the worst of Jupiter's trapped radiation.

Extracting the Jovian trapped particle environment from the analysis produces a fluence post-Cruise at JOI of 8.11E13 1 MeV equivalent electrons/cm².

Performance Modeling

The approach to modeling performance at Jupiter is best summarized in Figure 2. The goal is to take performance data at 1AU, 28C and derate this performance to Jovian conditions – 5.5AU, -140C. The text between each box shows the coefficient needed to derate performance data from one box to another.

There are 3 ways to perform the calculations.

A – Derate for intensity (Box 1 – Box 2).

Derate for temperature change (Box 2 – Box 3)

Derate for radiation (Box 3 – Box 6)

Since radiation degradation is a strong function of temperature, it is important to measure the radiation coefficient at exactly the array temperature at Jupiter. As the thermal analysis was refined (see later paragraph) the temperature at Jupiter varied from -140°C to -130°C and closed at -133°C. It is also important to get a very good measurement of the unradiated temperature coefficients at low intensity

B - Derate for intensity (Box 1 – Box 2).

Derate for radiation (Box 2 – Box 5)

Derate for temperature (Box 5 – Box 6)

This path has the advantage that radiation coefficients can be measured at 28°C. The only uncertainty is in a good measurement of radiated, low intensity temperature coefficients.

C - Derate for radiation (Box 1 – Box 4).

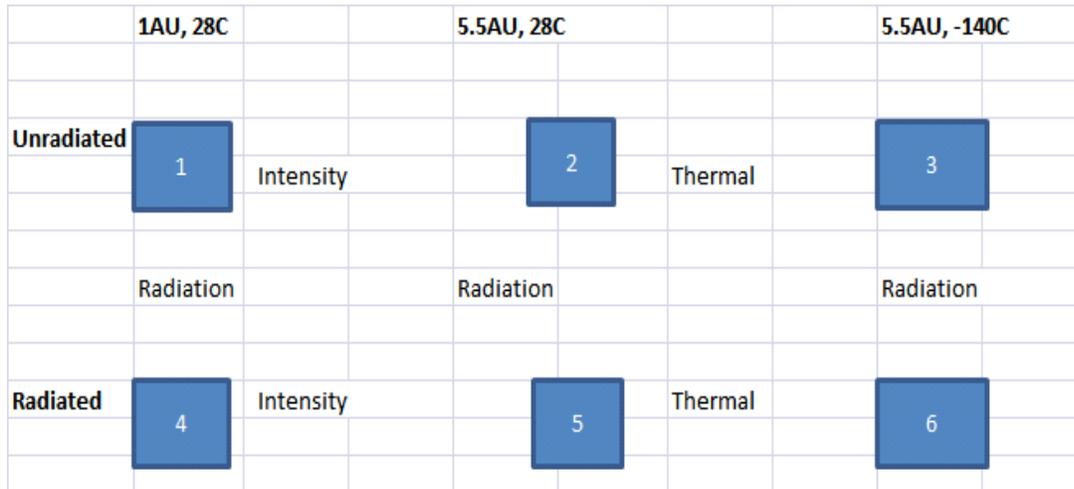
Derate for intensity (Box 4 – Box 5)

Derate for temperature (Box 5 – Box 6)

This path is most preferred, since the radiation coefficients at 1AU, 28°C can be checked against values in the UTJ Qualification Report. As stated earlier, intensity coefficients appear to be independent of radiation and so good values for this coefficient can be obtained from both radiated and unradiated samples. As in B, a good measurement of radiated, low intensity temperature coefficients is needed.

Path C is therefore the preferred path.

Figure 2. Modeling Approach



In addition to derating cell performance for intensity, temperature and radiation, other loss factors were included for panel assembly and other environmental factors such as UV, contamination and darkening of coverglass coatings due to low energy radiation.

These are discussed in a later section.

The second round of comprehensive radiation/low intensity testing was performed at MSFC (radiation) and JPL (low intensity measurements) to obtain temperature coefficients with more certainty and to obtain data at a more appropriate radiation fluence level of $7E14$ 1 MeV equivalent electrons/cm² for EOM and $8.1E13$ for JOI.

Screening

Extensive testing of UTJ cells was performed to obtain data on intensity coefficients and the effects of screening on performance and attrition. The effects of intensity on I_{mp} referred to earlier in Figure 3. The data is normalized such that unity is the expected I_{mp} value due to reduced intensity alone. With no screening, the additional losses are in excess of 6%. Screening at increasingly higher fill factor (FF) reduces the losses to a more manageable 2%. The effect is also shown for maximum power. Earlier data, ignoring intensity effects on current, had predicted considerable improvement of power due to screening. This graph shows the true effect. Here, unity is 1AU power reduced by intensity and the known voltage losses due to reduced intensity.

Figure 3. Effects of Screening on Pmp, Imp

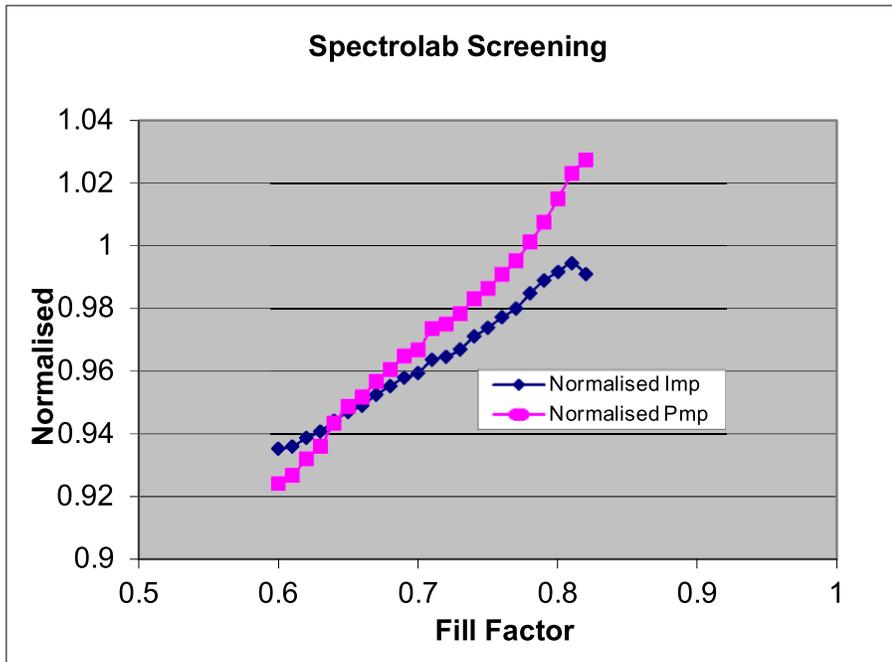
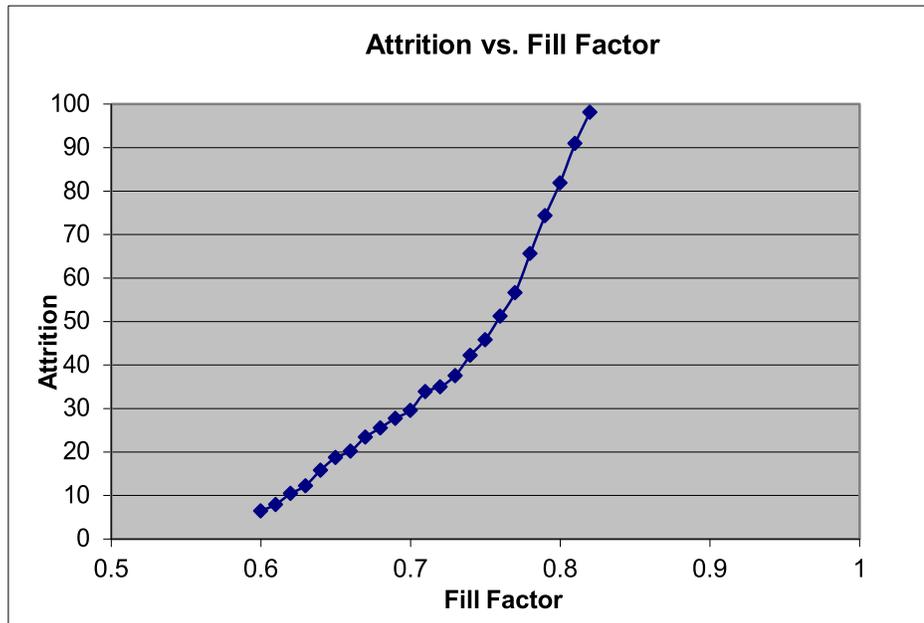


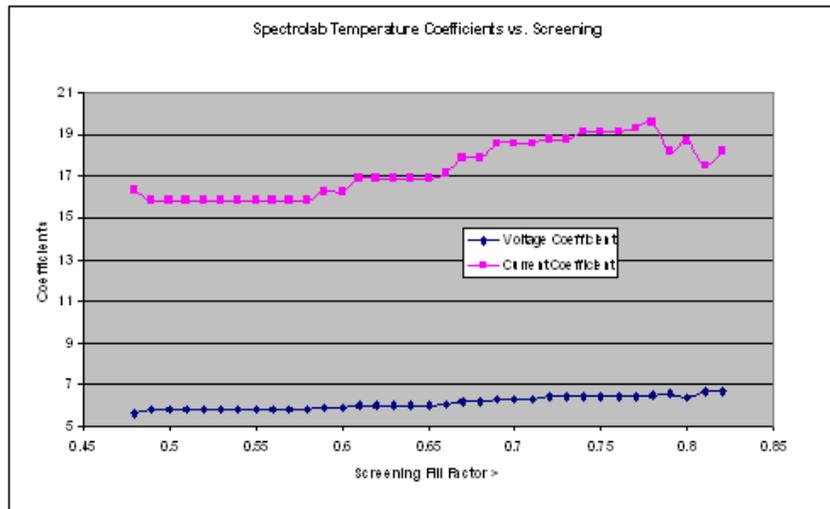
Figure 4 shows the effect on attrition as screening is performed at increasing fill factor. It is clear that maintaining performance at an acceptable attrition rate is difficult to achieve. The optimum balance appears to be at fill factors greater than 75% and attritions greater than 50%. After considerable discussion, it was determined that all CICs would be tested at 5.5AU on an X25 solar simulator and all cells below fill factor 0.78 would be removed. The 5.5AU data would also be used to box the remaining cells in current groups for matching into circuits.

Figure 4. Screening Effects on Attrition



Given the importance of temperature coefficients on predicting performance at Jupiter, work was also done on the effects of screening on these coefficients, as shown in Figure 5. Earlier data (on unscreened cells) had shown a reduction in voltage temperature coefficients (-6.5mV/C to -5.8mV/°C). The graph shows that screening produces an increase in voltage temperature coefficient as cells shunted by LILT effects are removed. Surprisingly, the current temperature coefficients continue to increase as screening is performed. Values are increased from 16 to 19 uA/cm2/°C as the screening FF is increased from 0.6 to 0.78. This detracts from performance at Jupiter, since the larger the coefficient, the lower the current at low temperature.

Figure 5. Effects of Screening on Radiated Temperature Coefficients



Coefficients from MSFC Testing

The 28 samples tested at MSFC were screened flight-like CICS with 12mil ITO coverglass. Calculations were performed to determine the 1MeV equivalent fluence required at the glass surface to produce a fluence in the cell of 6.7E14 1MeV equivalent electrons/cm2. A similar calculation was performed to determine the fluence required at the glass surface to produce the JOI fluence of 8.1E13 1MeV electrons/cm2 in the cell. The coefficients for intensity, radiation and temperature derived from the second set of comprehensive testing performed at MSFC and JPL are shown in the Figure 6. Additional boxes are added to the earlier described model so that the coefficients for both JOI and EOM can be displayed.

The main purpose of this testing was to provide additional data on temperature and intensity coefficients for current and voltage. The radiated temperature coefficients for current and voltage at EOM were calculated to be 17.35uA/cm2/C and -6.74mV/C respectively. These values compare favorably with the predicted values in Figure 4 and were the values selected for the performance model.

The intensity coefficient for current was found to vary from 0.947 to 0.955, which was somewhat lower than the earlier value of 0.98 predicted for screened parts (Figure 3). Nevertheless, the more conservative values were selected for the performance model.

There was some concern that testing 28 samples may be a relatively small sample size for predicting the behavior of thousands of flight cells and some uncertainty in the calculated values was anticipated. Although the current coefficient measurements were fairly consistent, voltage coefficient measurements showed a variability of about 3%. Preliminary performance predictions were based exclusively on the coefficients derived from this testing and using path B from Figure 2. Later predictions utilized the increased sample size of flight production data (for intensity) and UTJ Qualification data (for radiation) to reduce the uncertainty.

Figure 6. MSFC Test Results

CURRENT						
	1AU, 28C			5.5AU, 28C		5.5AU, -133C
0 Fluence	1	Intensity	0.9552	2	Thermal = 9.386	3
	Radiation = 1.0007			Radiation	0.9929	Radiation = 0.9687
8.11E+13 Cruise	4	Intensity =	0.9468	5	Thermal = 11.505	6
	Radiation = 0.9471			Radiation	0.9433	Radiation = 0.8488
7.24E+14 EOM	7	Intensity =	0.9514	8	Thermal = 17.359	9
VOLTAGE						
	1AU, 28C			5.5AU, 28C		5.5AU, -133C
0 Fluence	1	Intensity	0.8438	2	Thermal = -6.035	3
	Radiation = 0.9477			Radiation	0.9789	Radiation = 0.9902
8.11E+13 Cruise	4	Intensity =	0.8717	5	Thermal = -6.111	6
	Radiation = 0.889			Radiation	0.901	Radiation = 0.9728
7.24E+14 EOM	7	Intensity =	0.8552	8	Thermal = -6.74	9

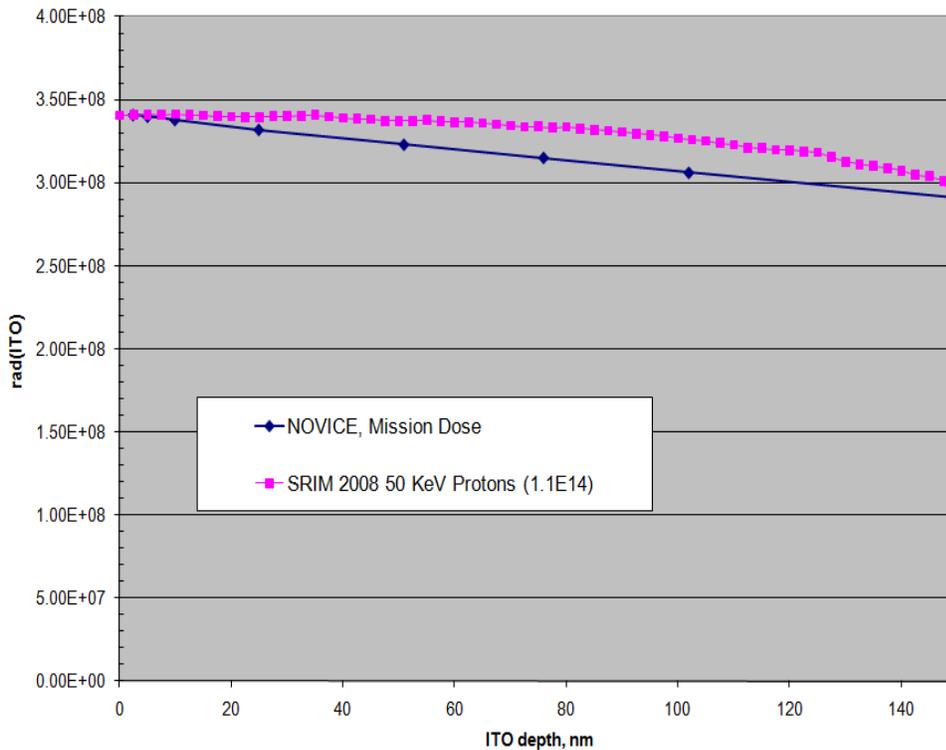
Coverglass Anti-Reflective and ITO coating UV and radiation tests

The Juno solar cell coverglass is coated with an anti-reflective (AR) coating and Indium Tin Oxide (ITO) to provide better performance (AR coating) and mitigate surface charge buildup (ITO coating). The coverglass will be exposed to ultraviolet (UV) radiation early in the mission and exposed to charged particle radiation at the end of the mission while orbiting Jupiter. Charged particle and UV irradiation tests were performed to determine the effects of UV and charged particle radiation on the transmission of light through the AR and ITO coatings in a wavelength range of 200 to 2000 nm.

Flight-like, Juno coverglass test samples were tested at the UV and proton irradiation test facility at the Marshall Space Flight Center (MSFC). The CMG samples coated with AR/ITO were 12 mil thick and 2cm x 2cm.

A total of 36 coverglass samples were irradiated with 1000 ESH vacuum UV. Twenty-four of these samples were irradiated at near normal incidence with 50keV proton radiation to fluence levels of 1X, 2X, 5X and 10X the mission dose. Figure 7 shows that the Juno mission absorbed dose in the AR/IRTO coating can be simulated by a fluence of $1.1E14$ of 50keV protons/cm². A 5th lot of samples was subjected to 2X proton fluence without the UV irradiation.

Figure 7. Total Ionizing Dose delivered to the ITO coating



Test Results

Figure 8 shows the combined effects of 1000 equivalent sun hours vacuum UV exposure and twice the end of mission ionizing radiation dose deposited into the ITO layer of the coverglass. The graph shows the average of transmission of 6 samples. Over the wavelength range 500 nm to 2000 nm, the transmission degradation is ~1.9%. This value was used in the model (see below).

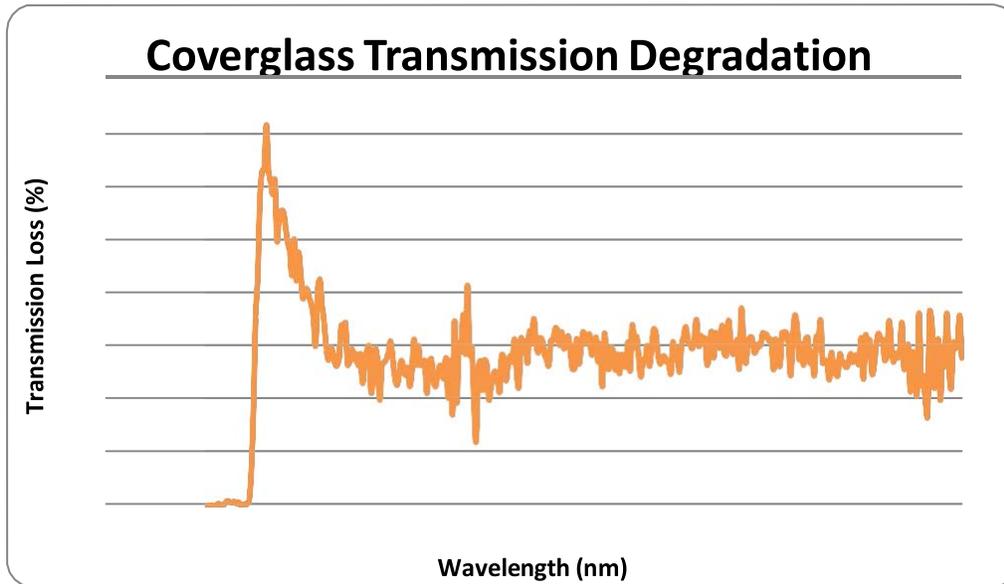


Figure 8. Coverglass transmission degradation for 1000 equivalent sun hours vacuum UV plus twice the end of mission ionizing dose deposited into the ITO layer of the coverglass.

The results of testing all samples at 1000 equivalent sun hours vacuum UV and from 1X through 10X mission dose of protons are shown in Figure 9. At 10X the end of mission ionizing radiation dose in the AR/ITO coating, the transmission degradation is 2.84%.

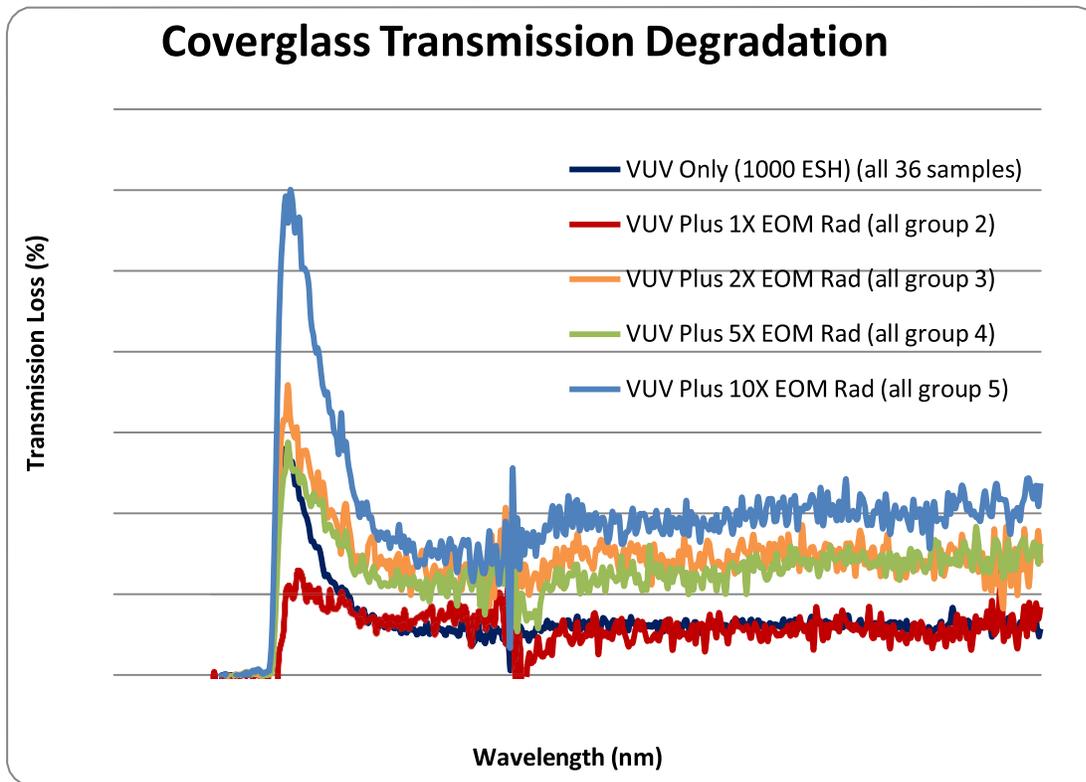


Figure 9. Coverglass transmission degradation for 1000 equivalent sun hours vacuum UV plus 1X, 2X, 5X, and 10X the end of mission ionizing dose deposited into the ITO layer of the coverglass.

Loss Factors

In addition to the measured coefficients for intensity, radiation and temperature, Table 4 lists the loss factors included in the performance predictions for EOM and JOI mission points. The intensity at JOI and EOM was confirmed by JPL to be 5.44AU, rather than the originally assumed value of 5.5AU. The intensity factor increased from 0.3306 to 0.3374. A combined UV/surface radiation dose darkening factor of 0.981 was used, based on the measurement shown in Figure 8. At EOM, there is a requirement that the array points off sun at an angle of 9.7 degrees. All solar panels were performance tested at 5.5AU. There was some considerable development work involved in setting up the Large Area Pulse Solar Simulator (LAPSS) station to provide a simulation of 5.5AU sunlight with acceptable uniformity. A report written on this work derived a calibration loss factor of 0.975 for this setup.

It should be noted that the assembly losses were best estimates based on the production experience of the contractors. When all flight panels had been built, the 1AU and 5.5AU LAPSS data was used to predict JOI and EOM performance. Using this actual data allowed all assembly losses to be set to unity with the exception of the LAPSS calibration loss factor.

Table 4. Assembly and Environmental Loss Factors

JUNO EOM Loss Factors			
	V		I
Assembly Losses			
Calibration (5.5AU LAPSS)			0.975
Production Variability			0.99
Assembly Loss	0.9957		
CIC Mismatch (BOL)			0.98
Coverglass Transmission Loss			0.99
Blocking Diodes	0.8 V		
Wing Harness	25 mV		
Environmental Factors			
Ultraviolet + ITO Darkening =			0.981
Contamination / Micrometeoroid =			0.99
Thermal Cycling			0.99
Intensity (5.444AU)			0.0337
Sun Angle (9.7 deg)			0.9857

Thermal Analysis

As part of the modeling effort, thermo-optical properties of the main components of the solar array were obtained. Since the array would experience hot conditions near Earth and cold conditions near Jupiter, the properties were tabulated as nominal, hot case and cold case. These are shown in the Table 5.

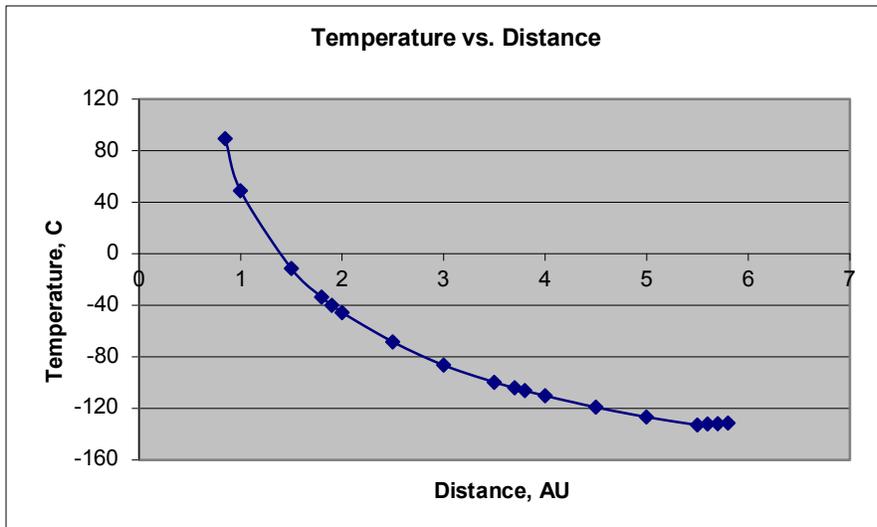
Table 5. Thermo-optical properties

	Nominal	Hot Case	Cold Case
UTJ Absorptivity	0.92	0.94	0.9
Graphite Emissivity	0.8	0.7	0.8
Glass Emissivity	0.82	0.73	0.82
Kapton Absorptivity	0.74	0.92	0.7
Kapton Emissivity	0.83	0.66	0.8
Black Kapton Emissivity	0.88	0.84	0.88

The thermo-optical properties were used in a model which calculates the array temperature at several points in the mission based on the calculated cell efficiency. The calculated temperature is then used to iterate the cell efficiency until the iterations close on a stable temperature. The thermo-optical properties were used in a model which calculates the array temperature at

several points in the mission based on the calculated cell efficiency. The calculated temperature is then used to iterate the cell efficiency until the iterations close on a stable temperature. The nominal case is plotted in Figure 10. The temperature at 0.85AU is 89 degrees (hot case calculations provide a temperature of 96 degrees. The temperature at 5.44AU at JOI is -133C. Further degradation of the array in orbit at Jupiter increases the temperature to -131.8C.

Figure 10. Array Temperature vs. Sun Range



String Switching

As stated in the Introduction, the array comprises three string lengths – long, middle and short. The switching scenario for each string type to provide power to the bus was determined in advance of the characterization of the solar cells in LILT conditions. The long strings have 22 cells series and provide sufficient voltage to charge the battery when the array is at its hottest temperature near Earth. The number of long strings (114) was the quantity required to meet power requirements at 1.9AU. The middle strings have 14 cells series and were designed to provide enough voltage to charge the battery at 1.8AU. The number of middle strings (369) was the quantity required to meet power requirements at 3.8AU (together with the long strings). The short strings have 13 cells series and were designed to provide enough voltage to charge the battery at 3.7AU. The number of short strings (848) was the quantity required to meet power requirements at 5.5AU (together with the long and middle strings). In reality, the total number of strings (1331) was also constrained by the available area on the 11 solar panels.

After the solar cells were characterized for operation in LILT conditions and the battery voltages were defined for 100% and 50% charge throughout the Cruise phase of the mission, it was possible to model the array at all points along the Cruise and determine the string voltages as the spacecraft approached Jupiter. Battery system data was obtained indicating that the voltage of a fully charged battery varied from 36.3 volts at 0.85AU to 33 volts at 5.5AU. For a 50% charged battery, the voltage varies from 32.3 volts to 29.4 volts. Figure 11 illustrates the

increase of string voltage with sun range and identifies the range at which each string type can provide enough voltage to charge the battery.

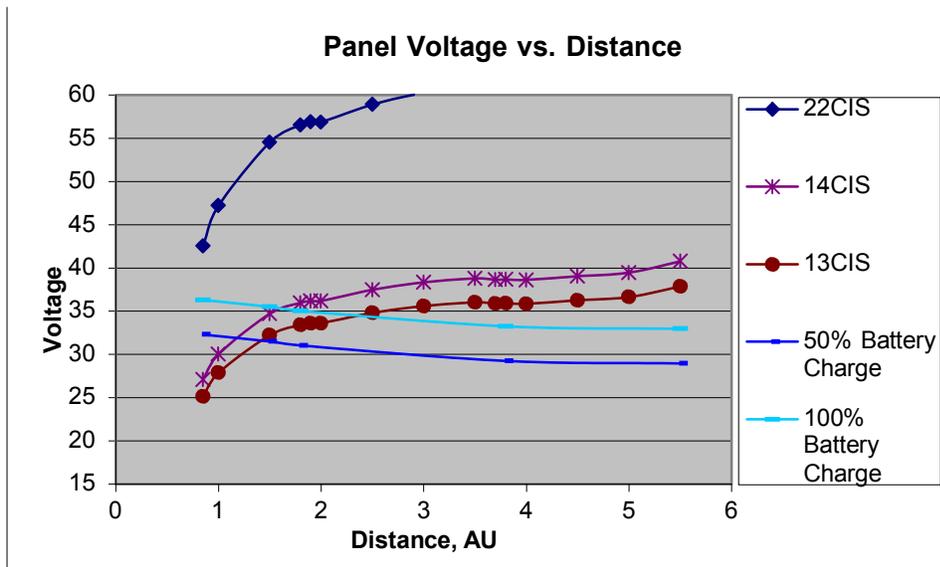
For middle strings, 50% charge voltage is achieved at 1.2AU; full charge voltage at 1.5AU

For short strings, 50% charge voltage is achieved at 1.5AU; full charge voltage at 2.5AU

Both string types therefore have the capability to provide power sooner than required.

The middle and short string circuits have many strings in parallel so that at large sun range, when the string current is very low, switching in a circuit provides a meaningful increment of power. If the middle and short circuits are allowed to switch on early in the mission, the switched circuit current may be enough to blow the 7amp fuse on each switch. Switching circuits on and off is executed by the Solar Array Switching Module (SASM). Controlling software for the SASM prevents inadvertent switching of the middle string and short string circuits until their current is less than 7 amps. The maximum number of strings parallel for middle strings is 40, while for short strings, it is 64. The array model was able to show that the 40P middle strings generate less than 7amp at 1.5AU and the 64P short strings generate less than 7 amp at 1.9AU. Thus, the critical points of the mission to prevent middle string turn on is 1.2AU – 1.5AU for middle strings and 1.5AU – 1.9AU for short strings.

Figure 11. String Voltages vs. Sun Range



Preliminary Performance Prediction

The performance prediction of the array is calculated at 29.4 volts, since this is the voltage required to charge the battery to 50% at Jupiter. Preliminary predictions were calculated using the Loss Factors of Table 4 and the Coefficients of Figure 6 derived from MSFC testing of 28 CICs. The model was run for several cases to see the effects of the measurement uncertainty of up to 3%. These cases all showed that the Vmp of the solar cell strings was maintained in fairly narrow ranges for each string type:

- short strings, 36 – 37 volts
- middle strings, 39 – 40 volts
- long strings, 62 – 63 volts

This provides ample margin for all three string types to fully charge the battery at Jupiter. As stated earlier, the array capability is driven by the solar cell string current and its derating due to intensity, radiation and temperature.

Preliminary estimates of array performance at Jupiter gave 438 – 440 watts at JOI and 385 - 400 watts at EOM. The wider range at EOM is due to the increasing uncertainty of measurements at high radiation, low intensity, low temperature.

Performance Prediction From Production Data

After all 11 Juno panels were assembled, they were LAPSS tested, subjected to Thermal Vacuum Testing and a Final Performance Test on the LAPSS. The final performance data was used to make a final flight power prediction. The array model was modified to calculate the performance of each solar cell circuit on the array at JOI and EOM based on the final LAPSS performance data for each circuit. LAPSS data at 1AU for all 1331 strings was obtained. The data was processed to provide average V_{mp} and I_{mp} for each of the 40 circuits on the array. These values were converted to J_{mp} (current density, A/cm²) and $V_{mp}/cell$, as these are the starting parameters for the array performance model. The model then set all assembly factors (production variability, mismatch, coverglass loss, assembly loss) to unity. Path C of Figure 1 was selected and radiation data for Box 1 – Box 4 and Box 1 – Box 7 were provided by the UTJ Qualification Report, since this provided 1AU, 28C radiation data from a sample larger than 28 cells. Comparing X25 steady state simulator data to the LAPSS data showed that the latter data was probably optimistic (i.e. the LAPSS was calibrated at the high end of its range). Consequently, the LAPSS uncertainty factor was increased to 5% from 2.5%. Predictions were then produced at Juno Orbit Insertion (JOI) and End of Mission (EOM), 5.44AU and normal incidence for each circuit of the array. These predictions included intensity, radiation and temperature corrections based on the extensive LILT testing performed at JPL and MSFC.

The following prediction of array power based on 1AU LAPSS data resulted:

- The JOI power is 450.5 watts at 29.4 volts.
- The EOM power is 411.9 watts at 29.4 volts.

These predictions are for normal incidence at 5.44AU.

Including the EOM angle of incidence of 9.7 degrees reduces the power prediction as follows:

- EOM power is 406.0 watts at 29.4 volts.

The revised predictions are 1.5% higher than the highest prediction of the preliminary performance estimates (438 watts at JOI and 400 watts at EOM). The improvement arises from a combination of the increased efficiency of flight cells compared to the LILT test cells and reduced assembly losses compared to the 4% anticipated.

LAPSS data at 5.5AU for all strings was also obtained. Again, average V_{mp} and I_{mp} for each of the 40 circuits was calculated. These values were converted to a pseudo - 1AU current density (by dividing by the intensity and cell area) and a $V_{mp}/cell$. The current normalization was required since the LAPSS data was taken at 5.5AU, but the power prediction is required at 5.44AU. The pseudo - 1AU J_{mp} still includes the actual current loss due to low intensity as a result of the fill factor loss. The voltage loss due to low intensity is inherent in the $V_{mp}/cell$. Setting intensity coefficient to unity for both current and voltage, predictions were then made at

JOI and EOL at 5.44AU and normal incidence for each circuit of the array. The 5% LAPSS uncertainty was maintained.

The following prediction of array power based on 5.5AU LAPSS data resulted:

- The JOI power is 464.2 watts at 29.4 volts.
- The EOM power is 425.4 watts at 29.4 volts.

These predictions are for normal incidence at 5.44AU.

Including the EOM angle of incidence of 9.7 degrees reduces the power prediction as follows:

- EOM power is 419.3 watts at 29.4 volts.

The 5.5AU LAPSS data produces predictions between 3% - 3.3% higher than the 1AU LAPSS data. The MSFC intensity coefficient for current was calculated to be 0.9552. However, the intensity coefficient derived from the 5.5AU LAPSS data is 0.98. Note that the coefficient calculated from earlier screening data (Figure 2) was also 0.98. This accounts for 2.5% of the improvement. The remainder may be LAPSS uncertainty at the lower intensity.

In conclusion, modeling from actual LAPSS measurements of the flight hardware suggest that the JOI estimate (for normal incidence) can be increased to the 450 - 465 watt range and the EOM estimate can be increased to the 412 - 425 watt range. If we increase the current intensity coefficient from 0.9552 to 0.98 (based on production LAPSS data and earlier Spectrolab testing), we can state the likely array power performance at normal incidence is as follows:

- The JOI power is 462.2 watts at 29.4 volts
- The EOM power is 422.6 watts at 29.4 volts.

Correcting for 9.7 degree incidence, the prediction becomes:

- EOM power is 416.6 watts at 29.4 volts.

Based on the available data, the mission team believes that this is the current best estimate of Juno solar array power at Jupiter.

Launch

The JUNO spacecraft lifted off from Cape Kennedy on August 5th 2011. The array is now operating at almost 2AU and following the performance prediction. The spacecraft will return to Earth for a gravity assist to Jupiter in October 2013.

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