JUNO – Photovoltaic Power at Jupiter

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Introduction

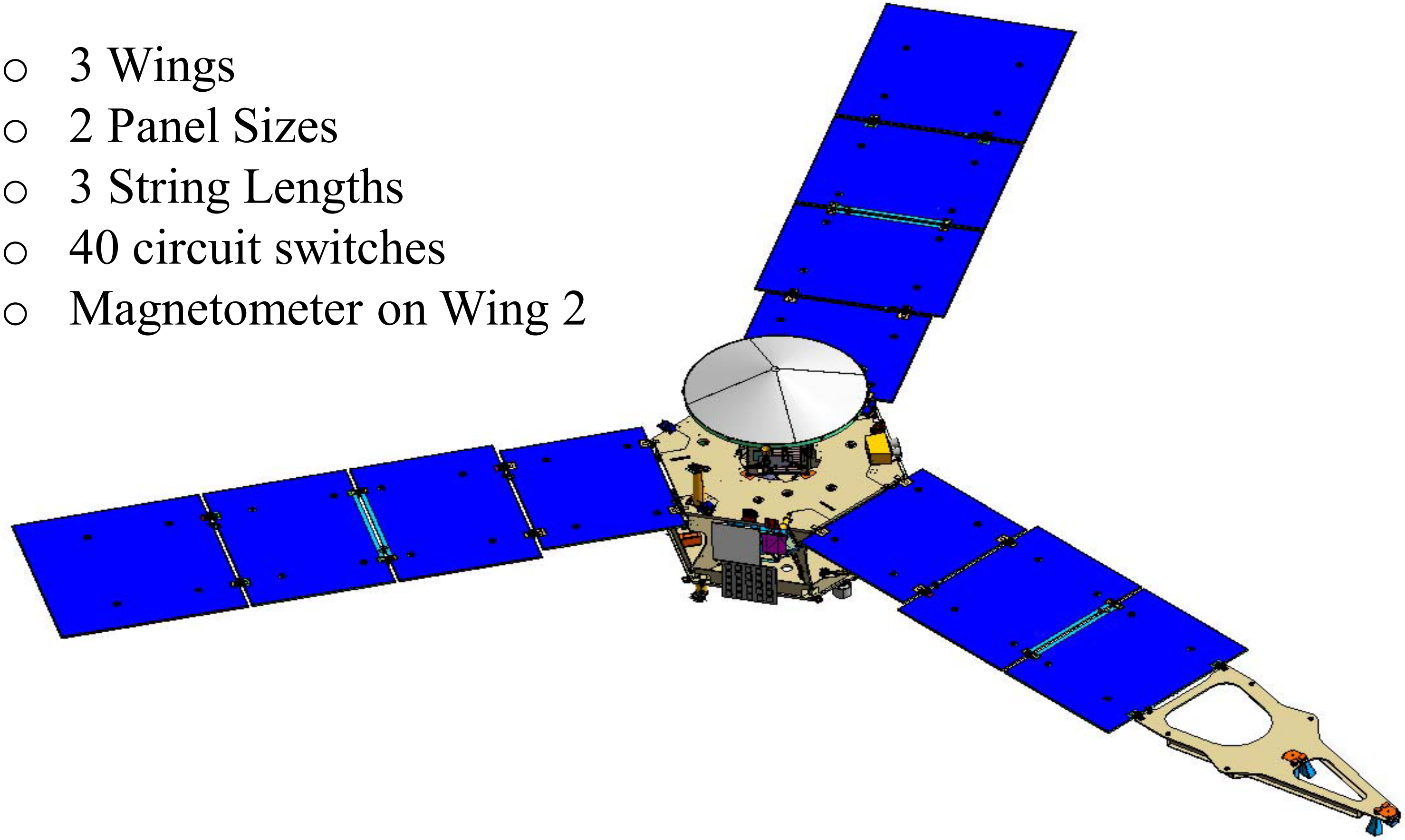
- First mission to an outer planet powered by PV
- Jupiter is at 5.44 AU
- Intensity is 3.4% of that at Earth
- LILT (Low Intensity, Low Temperature) conditions prevail
  - → potentially 5.5 AU, -140 C
- Spacecraft takes 5 year cruise to Jupiter
- Mission consists of 32 orbits at Jupiter - 1Year Duration
- Orbits around Jupiter have been devised to minimize total radiation fluence on the array
  - → about equivalent to a 10 year GEO mission

Goals:

- ❑ Measure trapped particle radiation energies and flux
- ❑ Measure magnetic field
- ❑ Measure Jovian weather systems

Solar Array Description

- 3 Wings
- 2 Panel Sizes
- 3 String Lengths
- 40 circuit switches
- Magnetometer on Wing 2



Solar Array Description

- Three string lengths to provide power throughout cruise range from 0.85 AU to 5.44 AU
- As sun range increases, temperature decreases and shorter strings achieve enough voltage to charge battery
- By requirement, strings power spacecraft in the following ranges:

Long	22CIS	0.85AU – 1.90AU
Middle	14CIS	1.80AU – 3.75AU
Short	13CIS	3.75AU – 5.44AU

- Solar Array Switching Module (SASM) ensures that middle and short strings are not enabled until their circuits generate < 7 amps
- 40 Circuits are switched by the SASM
  - Long – 16 switches (1 – 10 strings parallel)
  - Middle – 10 switches (32 – 40 strings parallel)
  - Short – 14 switches (44 – 65 strings parallel)

Solar Cells for Jupiter

- Decision made to use off-the-shelf qualified cells rather than develop a cell for LILT application based on availability and cost
  - → UTJ Triple Junction Cells selected

- Cells needed to be characterized in Jupiter environment
  - → LILT operation can result in shunts not observed at 1 AU
  - → Variation of cell parameters and loss factors with temperature becomes non-linear at low temperatures

- Extensive test plan developed for applicable ranges of intensity, temperature, and radiation

Solar Cell Coefficient and Loss Factor Calculations

- LILT behavior can be summarized in terms of coefficients for each environment

Intensity

- $Imp_{5.5\ AU,\ 28C}$ / ($Imp_{1\ AU,\ 28C}$ x Intensity)
- $Vmp_{5.5\ AU,\ 28C}$ / $Vmp_{1\ AU,\ 28C}$

Temperature

- $(Imp_{I,\ T1} - Imp_{I,\ T2}) / ((T_1 - T_2) \times I)$
- $(Vmp_{T1} - Vmp_{T2}) / (T_1 - T_2)$

Radiation

- $Imp_{rad,\ T} / Imp_{unrad,\ T}$
- $Vmp_{rad,\ T} / Vmp_{unrad,\ T}$

- Current Coefficients for intensity and temperature are normalized for intensity (I) in order to compare behavior over the intensity range
- Extensive testing identifies any interdependencies between coefficients

Preliminary Findings

- LILT effects may drastically reduce performance of some cells
- Solar array panel performance is enhanced by cell screening resulting in panels that are consistent and predictable.
- Screening should be done based on 5.5 AU, 28 C beginning of life (BOL) cell data
- A study of screening by cell parameter revealed that fill factor provides greater improvement than Vmp, Imp, or Pmp
- Attrition rate is high to achieve significant improvement

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

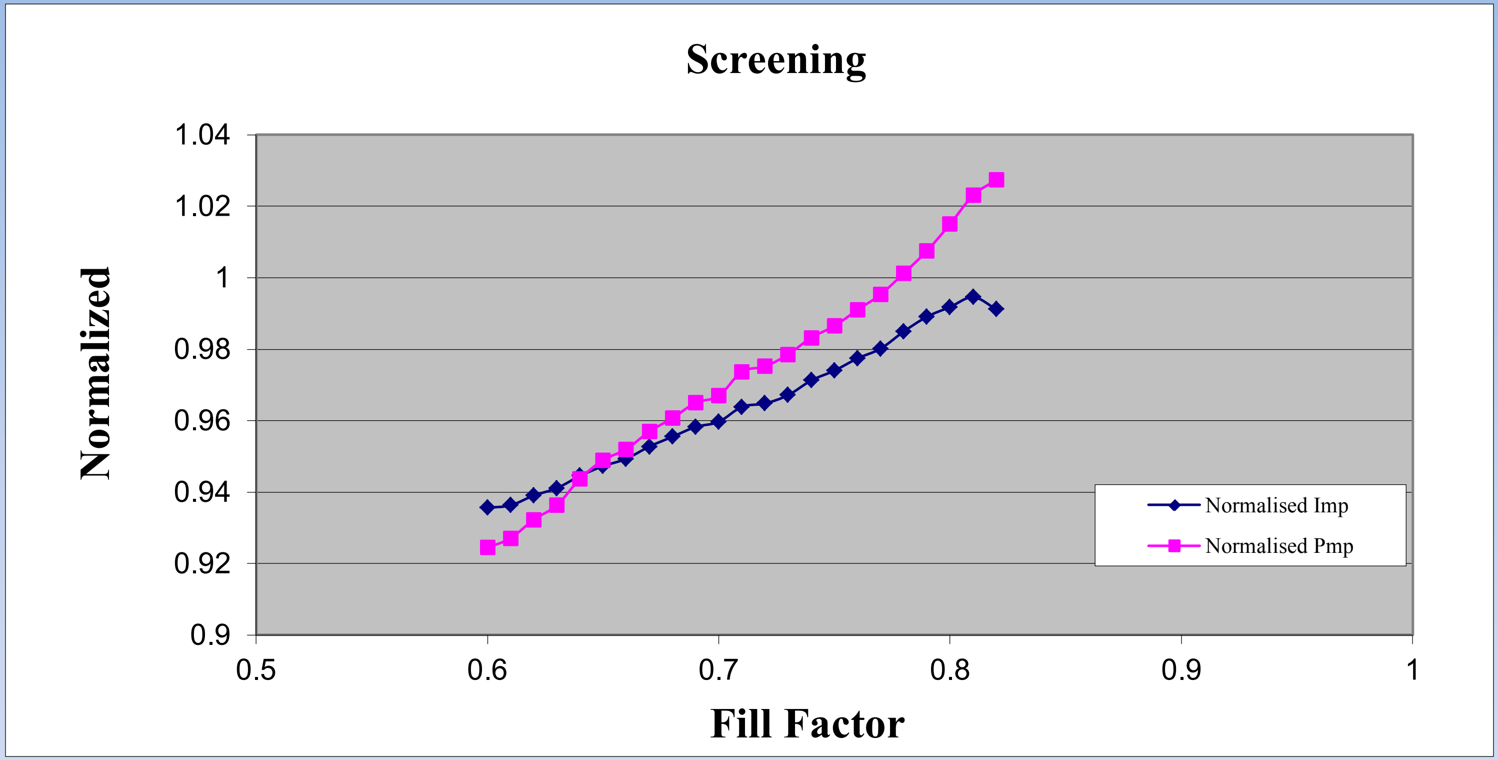
Investigation Goals

- Current temperature coefficients drive performance at Jupiter
- Increasing from 6.9 $uA/cm^2/C$ to 16.23 $uA/cm^2/C$ reduces output at Jupiter by 11% at -140 C, 5.5 AU
- Important to obtain measurements of radiated temperature coefficients with low uncertainty

  → Primary Goal
- A second solar cell test suite was initiated to provide low uncertainty measurements

  → MSFC Testing

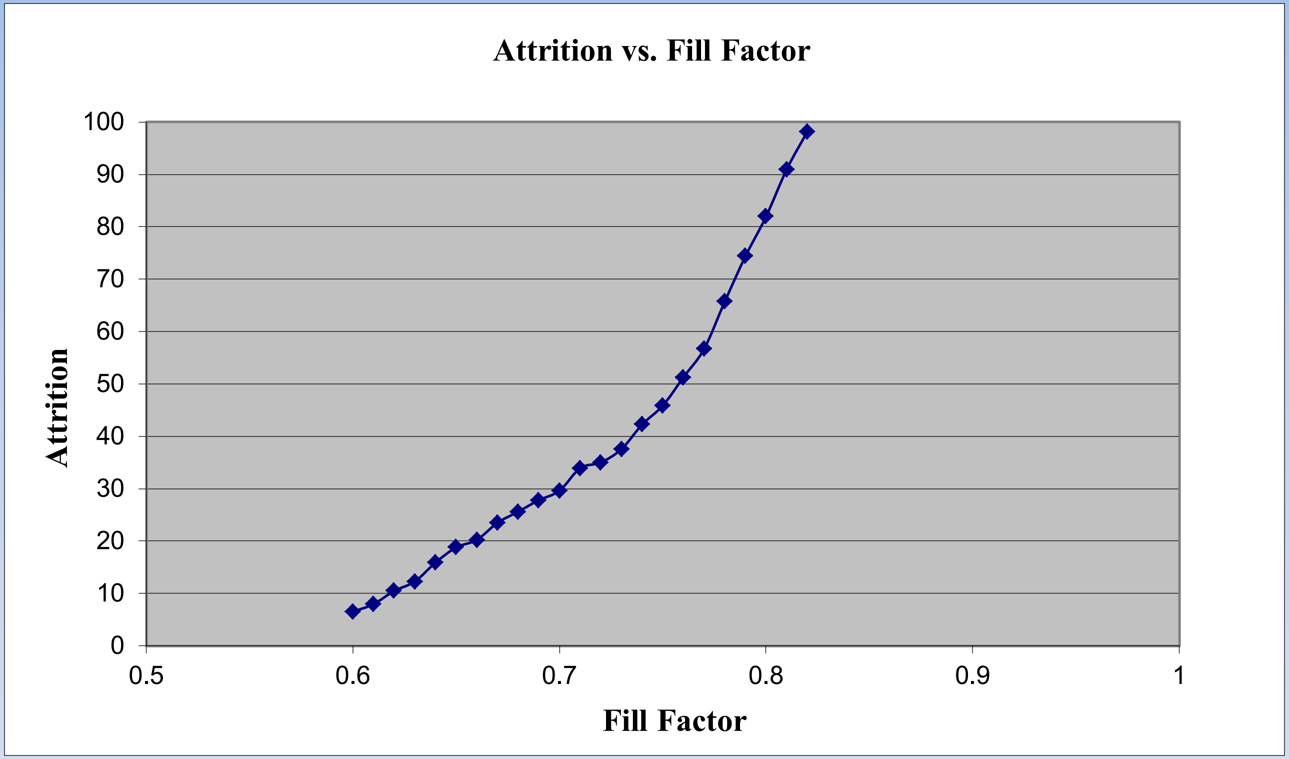
Screening



- Unity represents power and current at 1 AU multiplied by intensity factor
  → Values < 1 indicate intensity coefficients for current and voltage

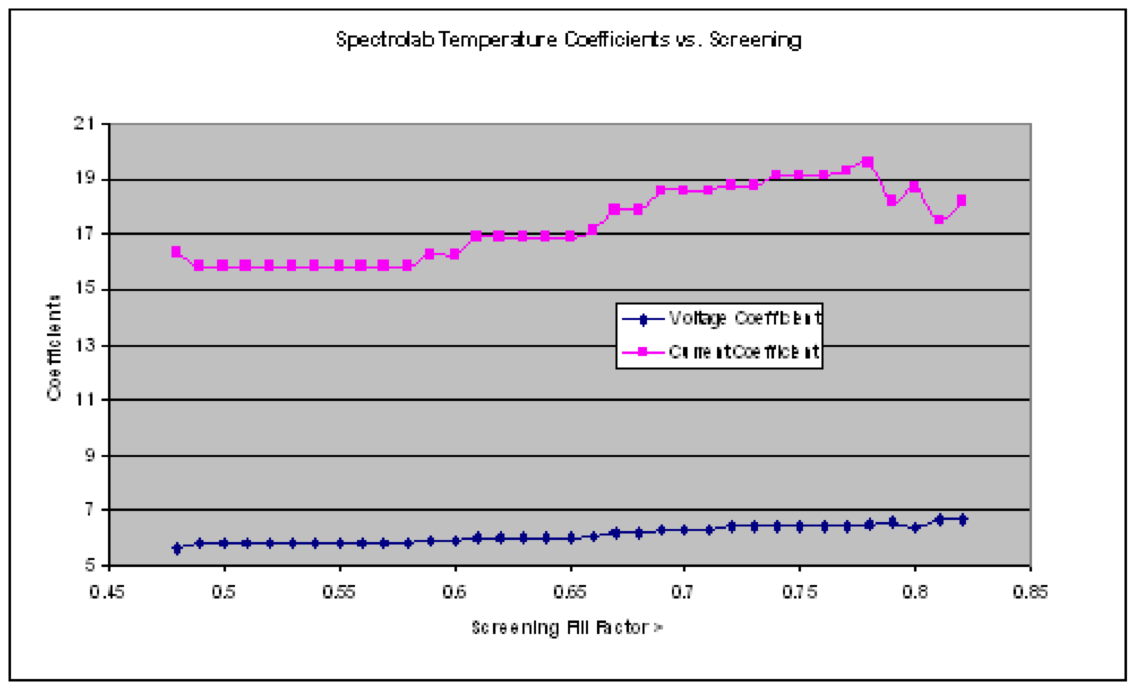
Note that screening improves power output, but current stays < 1

Observed Attrition



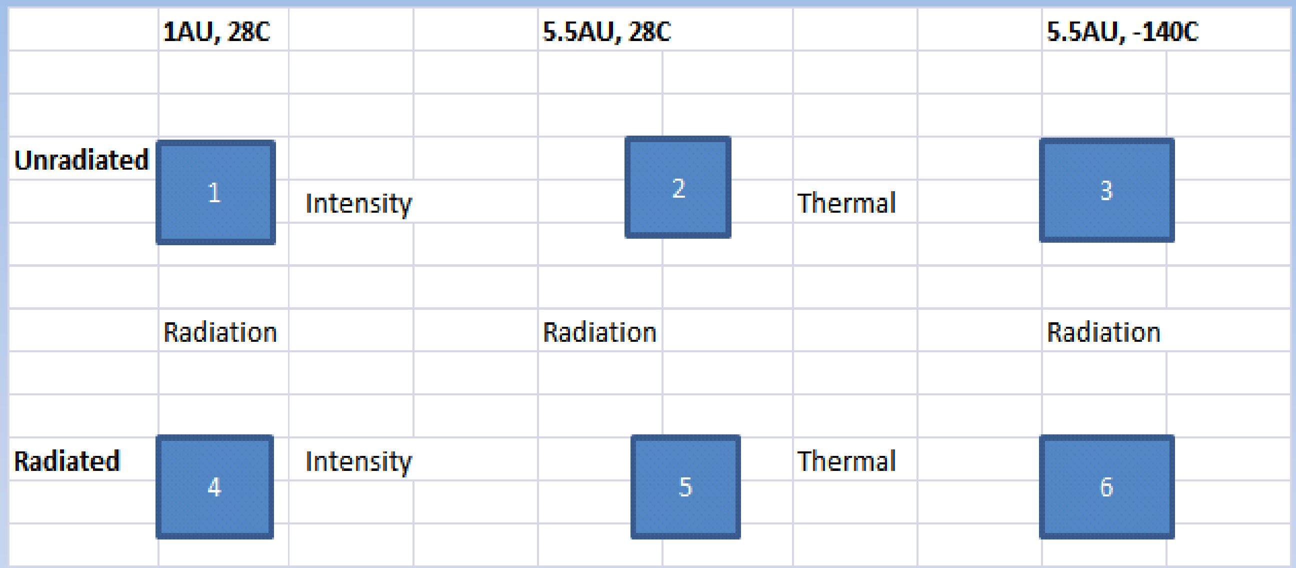
- A fill factor of 0.79 was selected as screening parameter

Effects of Screening on Temperature Coefficients



- Screening increases both current and voltage temperature coefficients
  - → Increased current temperature coefficient reduces performance at Jupiter

Modeling Approach



Path A – 1-2-3-6

- Radiation loss measured at correct intensity and correct temperature and accurate measurement of unradiated temperature coefficients

Path B – 1-2-5-6

- Radiation loss measured at correct intensity and accurate measurement of irradiated temperature coefficients

Path C – 1-4-5-6

- Use qualification radiation loss factors and accurate measurement of irradiated temperature coefficients → preferred path

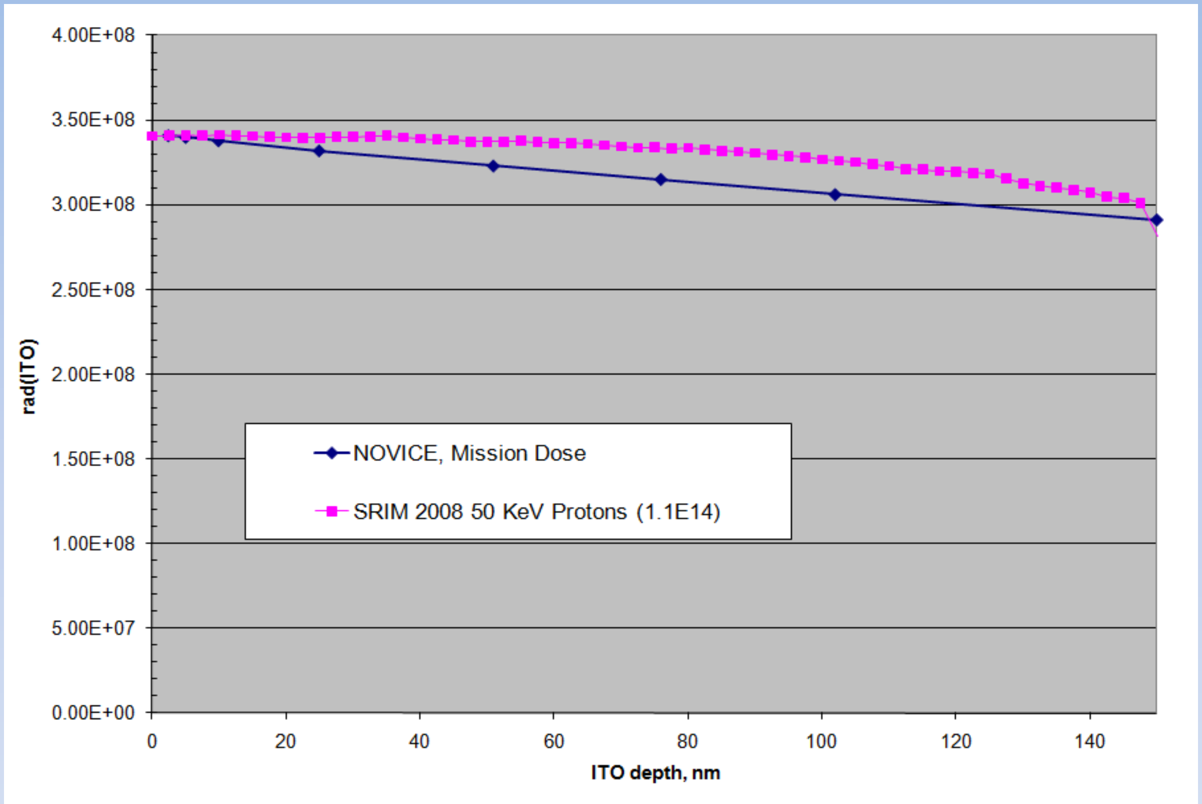
Measurements from MSFC Data

CURRENT									
	1AU, 28C			**5.5AU, 28C**				**5.5AU, -133C**	
0 Fluence	1			2		Thermal =		3	
		Intensity	0.9552			9.386			
	Radiation =			Radiation	0.9929			Radiation =	
	1.0007							0.9687	
8.11E+13	4	Intensity	0.9468	5		Thermal =		6	
Cruise						11.505			
	Radiation =			Radiation	0.9433			Radiation =	
	0.9471							0.8488	
7.24E+14	7	Intensity	0.9514	8		Thermal =		9	
EOM						17.359			

Measurements from MSFC Data

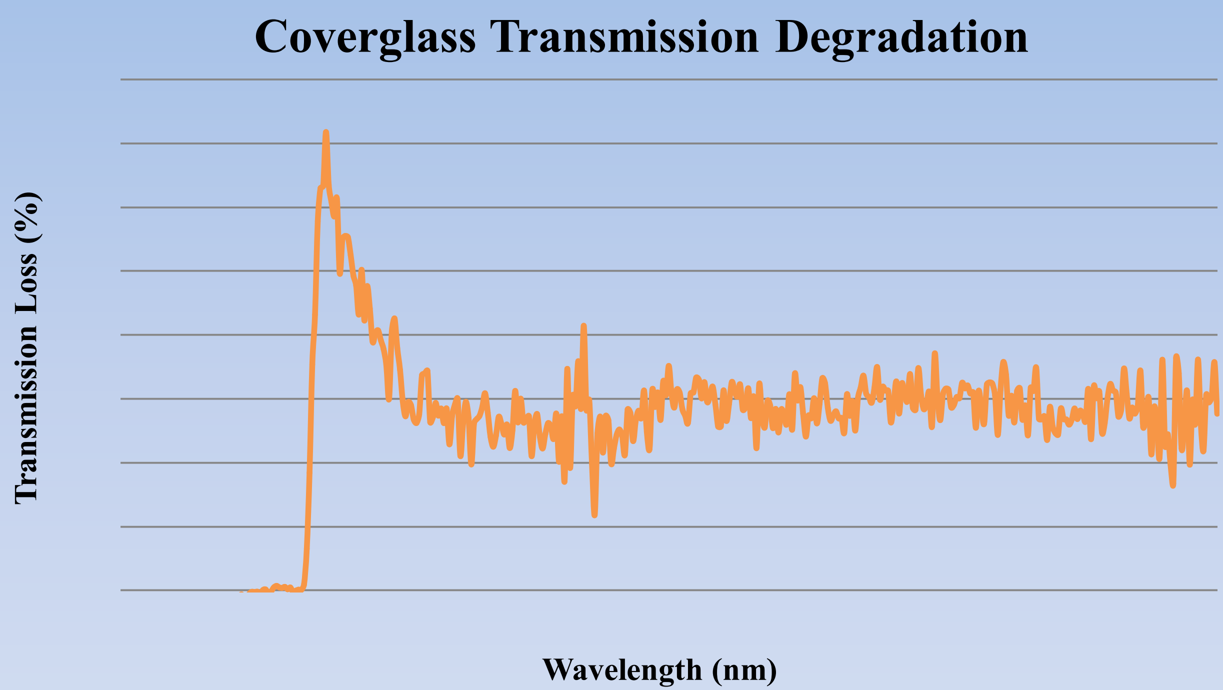
VOLTAGE									
	1AU, 28C			**5.5AU, 28C**				**5.5AU, -133C**	
Fluence									
0						Thermal =			
	1	Intensity	0.8438	2		-6.035		3	
	Radiation =			Radiation	0.9789			Radiation =	
	0.9477							0.9902	
8.11E+13	4	Intensity =	0.8717	5		Thermal =		6	
Cruise						-6.111			
	Radiation =			Radiation	0.901			Radiation =	
	0.889							0.9728	
7.24E+14	7	Intensity =	0.8552	8		Thermal =		9	
EOM						-6.74			

Mission Depth-Dose Profile for ITO Coating



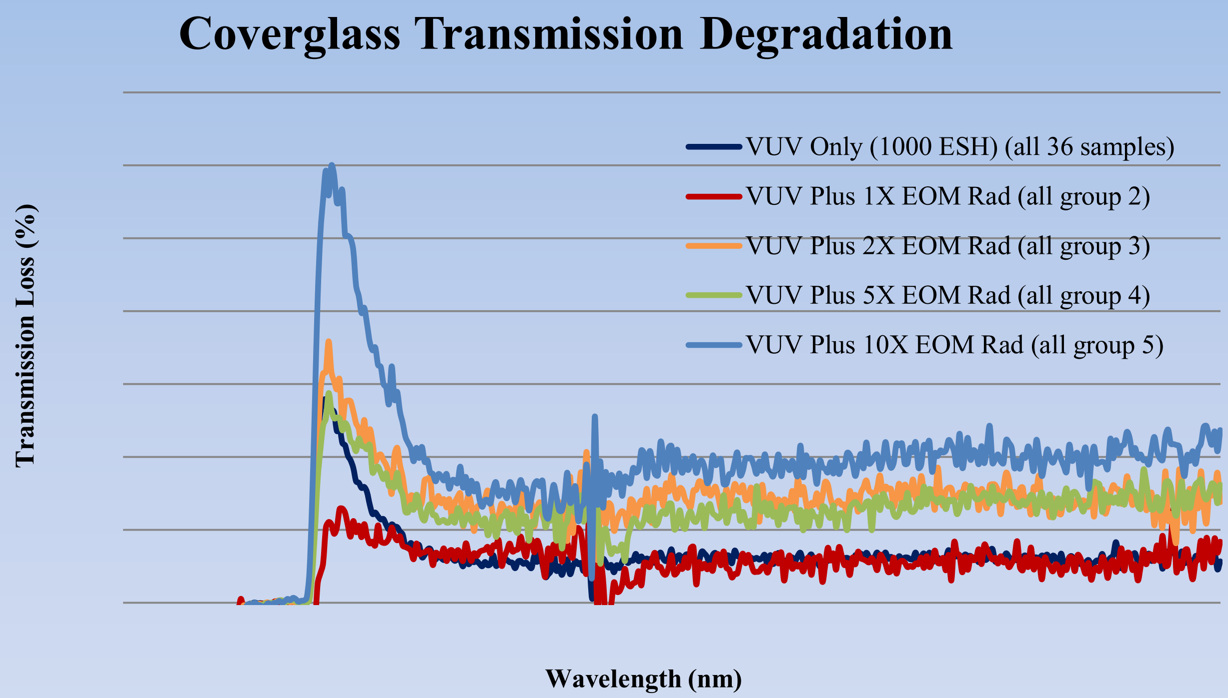
- Mission dose in ITO coating can be approximated by exposure to 50keV proton beam

Transmission Loss in ITO Coating



- 1000 hours UV + 2X mission dose of protons
- Convolution of transmission data with solar spectrum and spectral response of TJ cell produces loss factor of 1.9%

Transmission Loss in ITO Coating



- 1000 hours UV + 10X mission dose of protons
- Convolution of transmission data with solar spectrum and spectral response of TJ cell produces loss factor of 2.84%

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	

- Jovian proton and electron energy spectrum and flux data provided by JPL Jupiter Orbit Insertion (JOI)
  → 8.11 E13 1MeV equivalent electrons/cm^2
- End of Mission (EOM)
  → 7.08 E14 1MeV equivalent electrons/cm^2

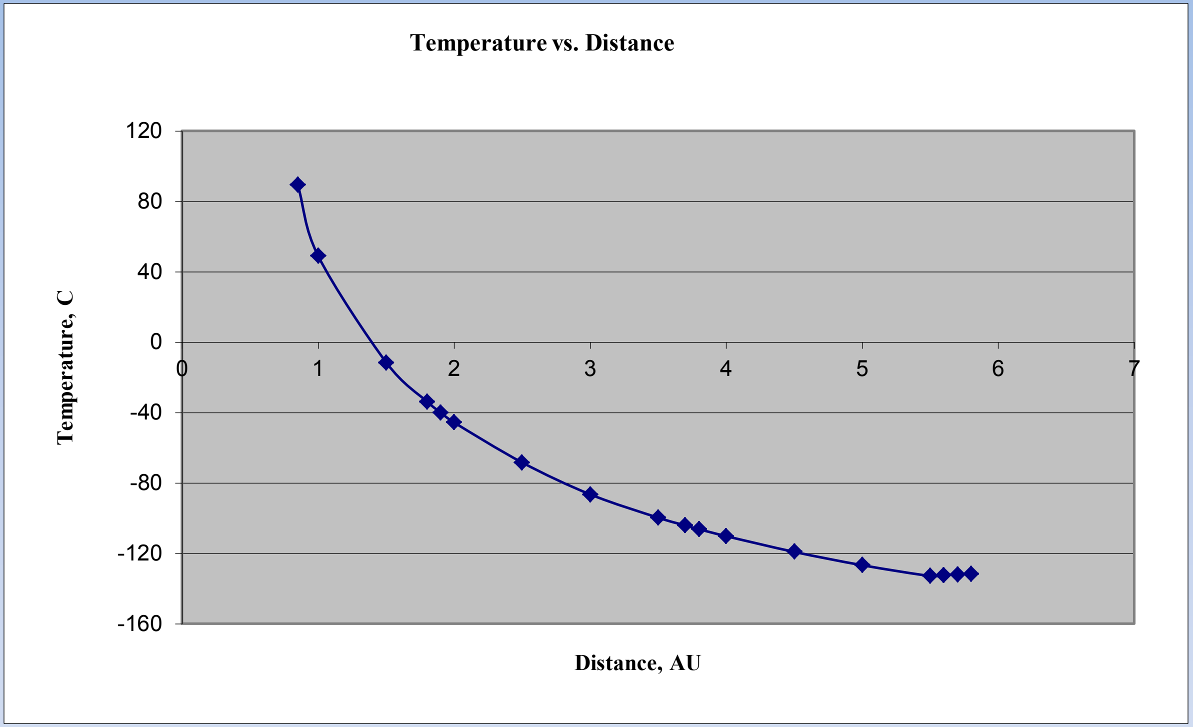
Loss Factors

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

Thermo-Optical Properties

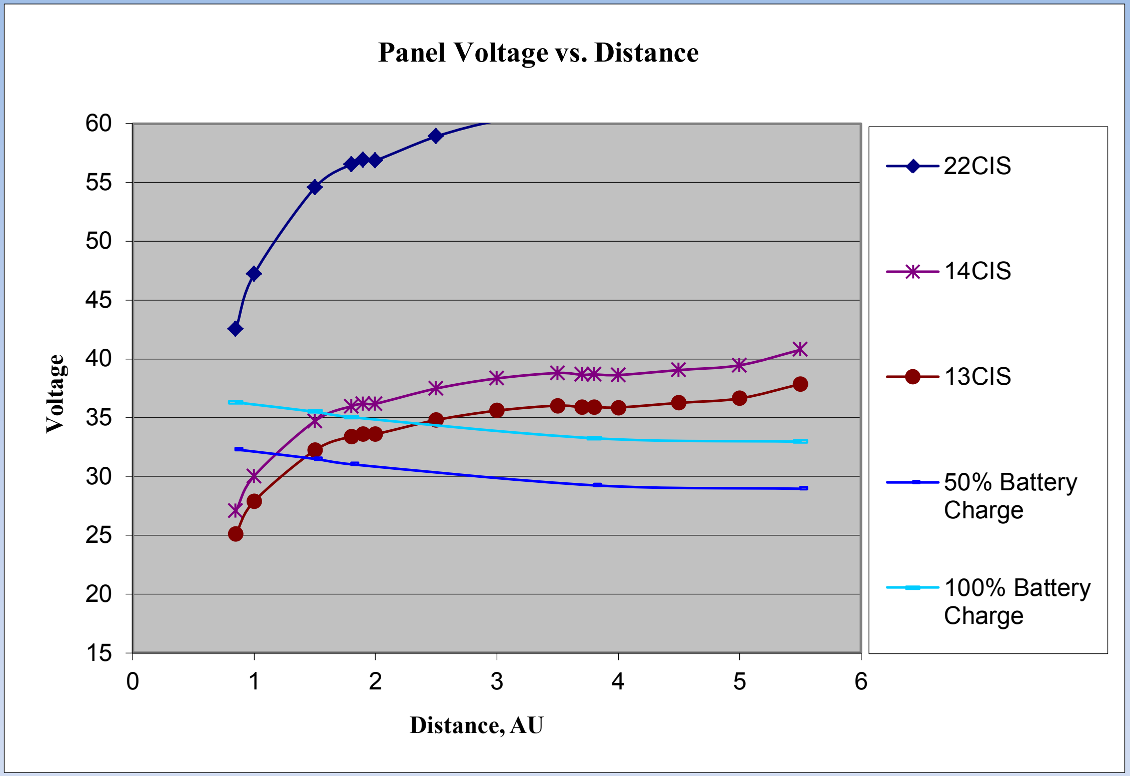
	Norminal	Hot Case	Cold Case
UTJ Absorptivity	0.92	0.94	0.9
Graphite Emistivity	0.8	0.7	0.8
Glass Emistivity	0.82	0.73	0.82
Kapton Aborptivity	0.74	0.92	0.7
Kapton Emistivity	0.83	0.66	0.8
Black Kapton Emistivity	0.88	0.84	0.88

Temperature Variation - Cruise



- Thermal analysis shows that temperature at Jupiter is -132C

String Switching



- Actual analysis shows that middle and short strings can charge battery as follows:

Battery Charge	50%	100%
Middle	1.2 AU	1.5 AU
Short	1.5 AU	2.5 AU

Performance Prediction

- As-built 1AU, 28C LAPSS data for all strings on the 11 panels was used to derive a Jmp and Vmp/cell (the starting parameters for the array performance model) for each of the 40 switched circuits. All manufacturing and assembly losses set to 1.
- Based on 1AU, 28C LAPSS data, at normal incidence, array power at Jupiter is 1.5% higher than original prediction:
  - The JOI power is 450.5 watts at 29.4 volts
  - The EOM power is 411.9 watts at 29.4 volts.
- As-built 5.5AU, 28C LAPSS data was also obtained for all panels. This data showed that the current intensity coefficient over all production was 0.98 (compared to the measured value of 0.9552 on 28 cells)
- Based on 5.5AU, 28C LAPSS data, at normal incidence, array power at Jupiter is 1.5% higher than original prediction:
  - The JOI power is 462.2 watts at 29.4 volts
  - The EOM power is 422.6 watts at 29.4 volts.

→ Mission Requirements is 405 watts at End of Mission.