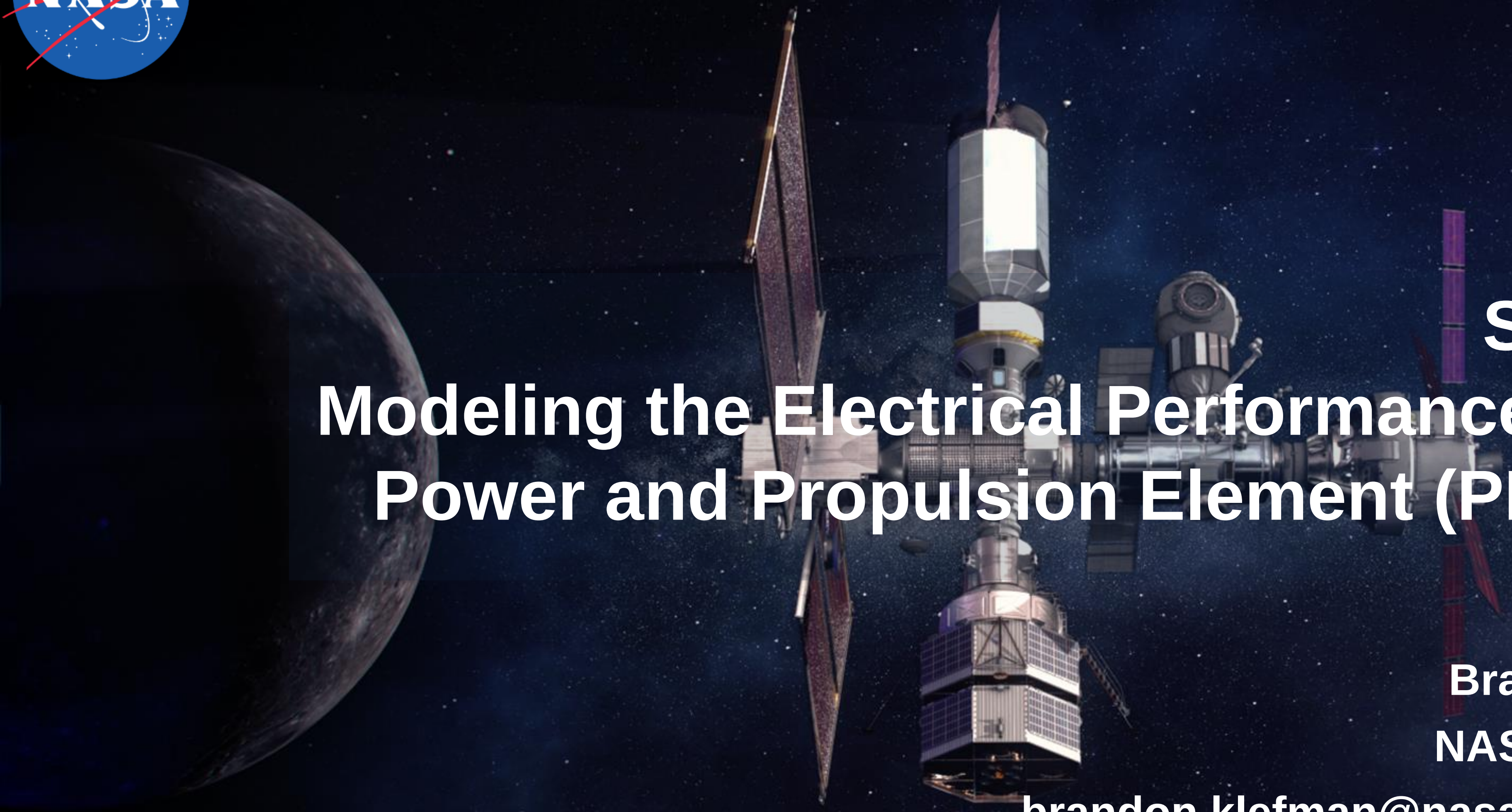

SPACE-Gateway: Modeling the Electrical Performance of the Gateway Power and Propulsion Element (PPE) Solar Arrays

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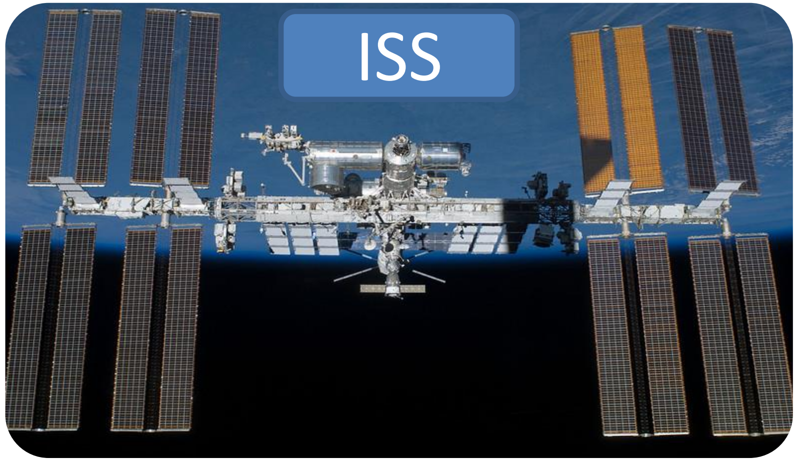
Overview

- **What is SPACE?**
- **SPACE Versions and History**
- **Gateway PPE**
- **The Integrated SPACE Solar Array Model**
  - Array Electrical Design
  - Solar Cell IV Curve
  - Solar Cell Thermal Modeling
  - Degradation
  - Shadowing
  - Glint Assessments
- **Conclusion**

What is SPACE?

- **SPACE (*System Power Analysis for Capability Evaluation*) is a computer model used to predict the electrical performance of space-based power systems**
- Developed entirely at NASA Glenn Research Center
- Critical for assessing electrical power systems (EPS) that cannot be assembled and tested end-to-end on the ground
- Given orbital conditions and EPS configuration, SPACE determines EPS capability
- Given a time-varying power consumption profile, SPACE’s load-driven mode (ECAPS) predicts the EPS state (power generation, battery SoC, etc.)

SPACE Versions



1988-present:
Originally designed to model the Space Station Freedom (and later ISS) EPS;
Still used for ISS today.

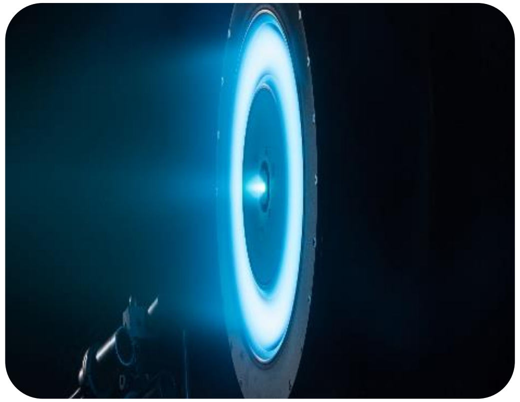
Validated many times with ISS on-orbit telemetry measurements.

2003:
Runner-Up for NASA Software of the Year

2010's-present:
"ECAPS" mode expanded to model various spacecraft (including MPCV & PPE) in support of NASA's new crewed programs

Derived Tools

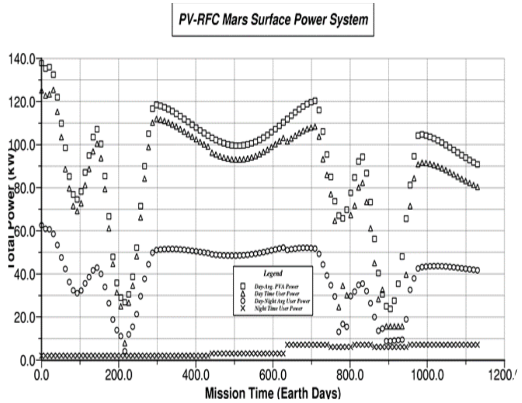
SEPSim
(Solar Electric Propulsion Simulator)



Integrates orbital mechanics for EP trajectories

MSEPS
(Mars Surface Electric Power System)

Predicts Mars solar EPS performance, incl. dust storm effects



Gateway Power and Propulsion Element (PPE)

- **Foundational Gateway element along with the Habitation and Logistics Outpost (HALO)**
  - PPE provides the power generation and propulsion capabilities for the Gateway over its 15-year life

- **Two Roll Out Solar Arrays (ROSAs) provide >55 kW power generation at EOL**
  - Leverages the SolAero Z4J solar cell technology

- **Includes solar electric propulsion (SEP) for Earth orbit raising (EOR) and orbit maintenance**

- **Being designed and built by Maxar Technologies**
  - Leverages the Maxar 1300 series bus

SPACE is a Complex Integrated Model

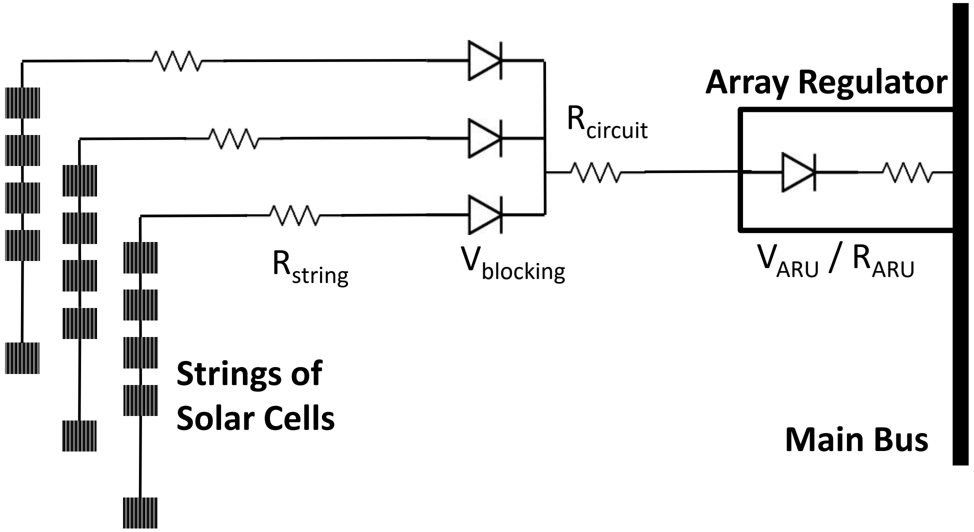
- **Accurately modeling solar cell performance requires knowledge of the integrated spacecraft**
  - Off-nominal attitudes and off-pointed conditions
  - Degradation (function of time on-orbit)
  - Temperature
  - Solar flux
  - Environment (LEO, GEO, lunar orbit, etc.)

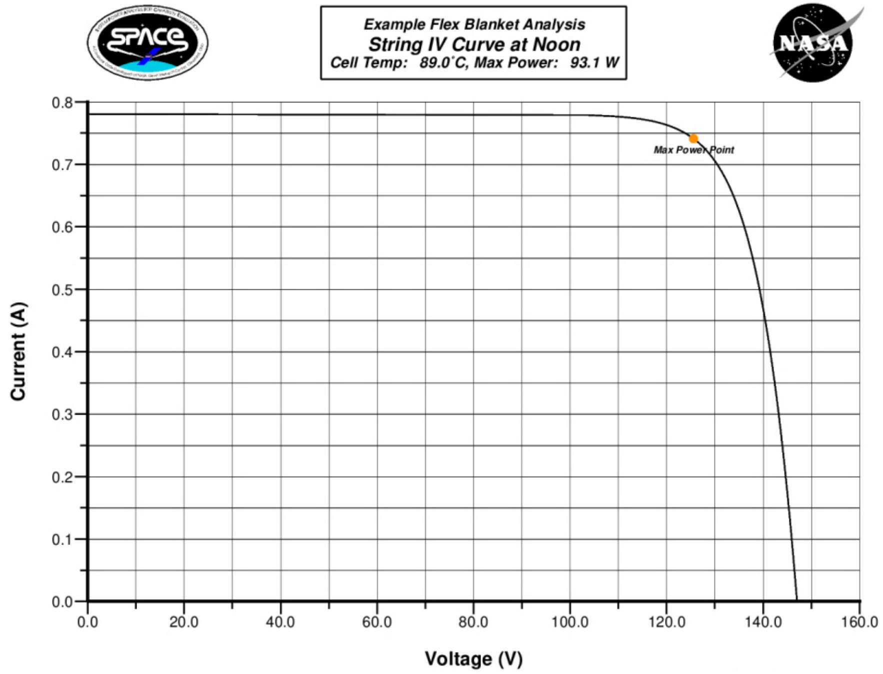
- **SPACE accounts for these many factors and provides a robust solution to assess a wide variety of mission operating conditions**
  - Solar array code *fully integrates* multiple components: solar cell IV modeling, array electrical design, PMAD, degradation, thermal, shadowing

Solar Array Model

- **SPACE models the entire solar array electrical design**
  - From solar cells to the upstream array regulator and any discrete components in between
  - User specifies the desired operating voltage of the solar array, or SPACE can utilize the maximum power point

- **Individual strings are modeled, accounting for appropriate connections to PMAD channels**
  - Blocking diode voltage drop, harness losses, and array regulator voltage drop are all modeled
  - IV curve is re-generated for any partially shadowed solar array strings to determine operating point
  - Accounts for PMAD channelization, which routes the solar array power to the appropriate spacecraft loads



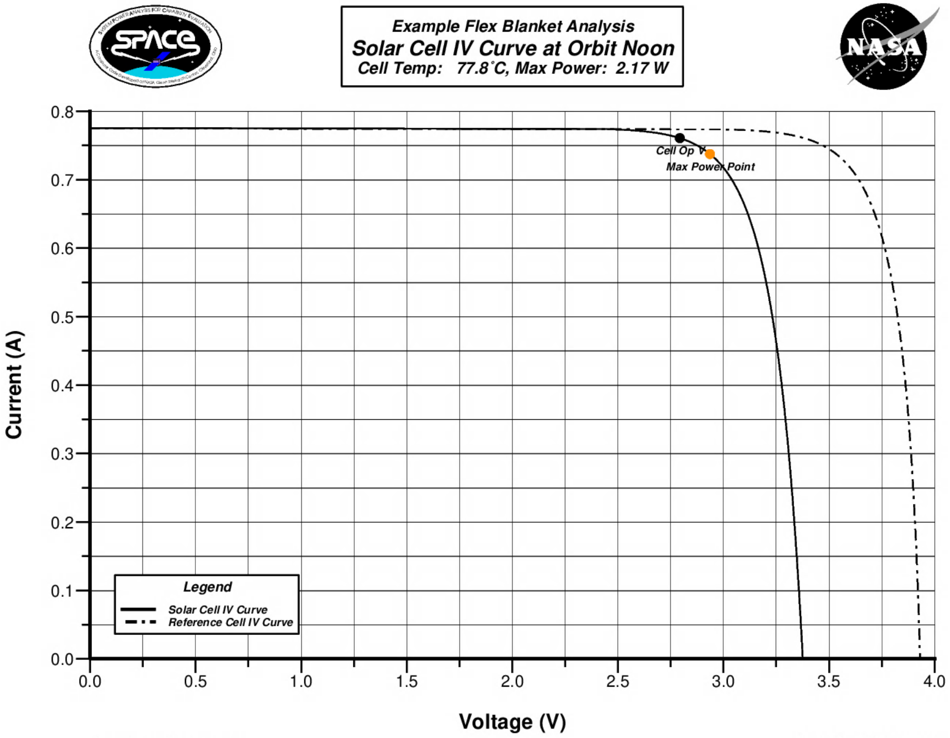


Solar Cell IV Model

- **Solar cell IV curve generated using the Hughes model[1]**
  - Solar cell operating voltage determined by user input minus voltage drop in upstream components (harness, diodes)
  - When Hughes model cannot find a solution, SPACE resorts to a simple linear model

$$I = I_{sc} - I_{sc}K_2\left[\exp\left(\frac{V + IR_s}{K_1V_{oc}}\right) - 1\right]$$

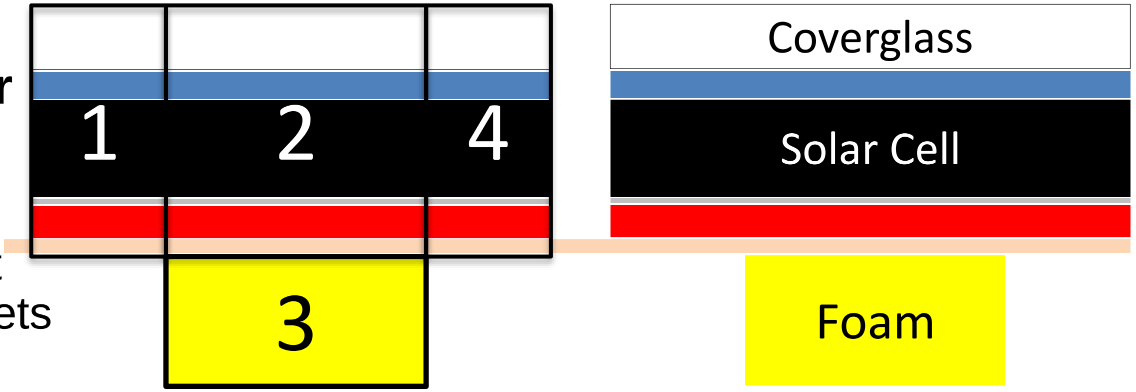
- **Highly robust – Hughes model solves even with non-optimal conditions**
  - Can model beyond EOL conditions (e.g., ISS) at extreme temperatures, in off-nominal scenarios, and more
  - Challenging to integrate newer/other solar cell IV models, as robustness is a unique advantage of SPACE



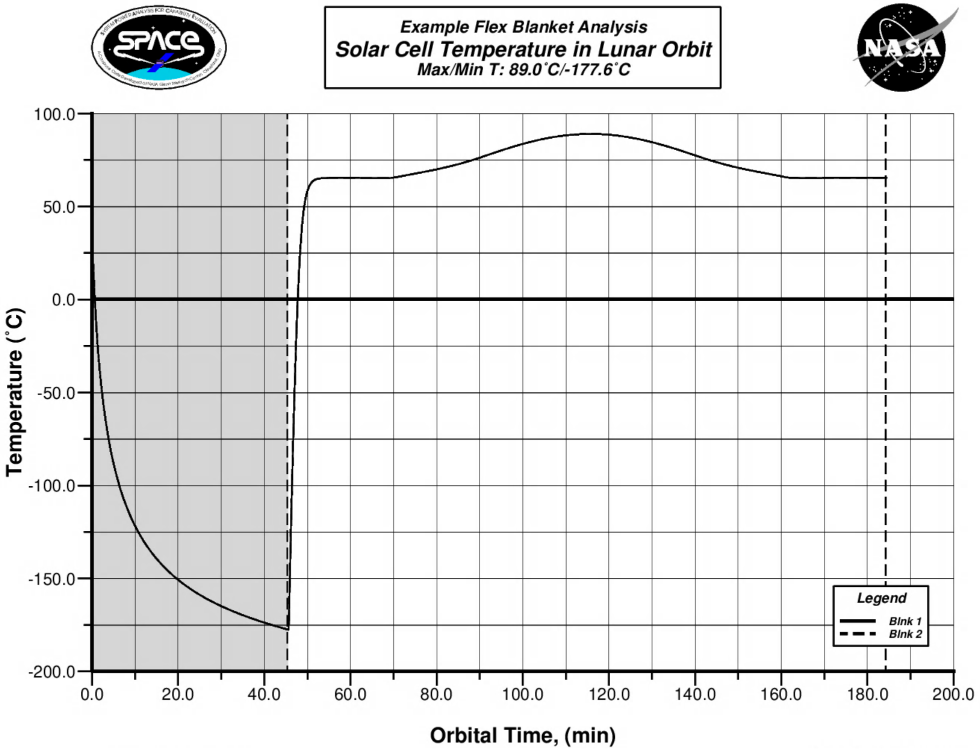
[1] Rauschenbach, H. S. (1976). *Solar Cell Array Design Handbook*. NASA Technical Reports Server. https://ntrs.nasa.gov/citations/19770007250

Generic N-Node Solar Cell Thermal Model

- **Simplified thermal model designed to predict solar cell operating temperatures in various operational conditions and environments**
  - Generalized nodes allow flexibility in modeling different types of solar cells and substrates (supports flex blankets and rigid panels)
  - Models degradation of material properties and variation due to temperature
  - Time-phased model predicts temperature in eclipse and sunlight
  - Limited to modeling solar cell alone in space (emulates tip of wing); neglects cross-wing conduction and spacecraft heating effects
- **Iterative calculation with cell IV model, as cell power generation varies with solar cell operating temperature**
  - This thermal model is integrated within the SPACE solar cell IV code (not a separate model)



Example 4-node model of a solar cell on a flexible blanket substrate

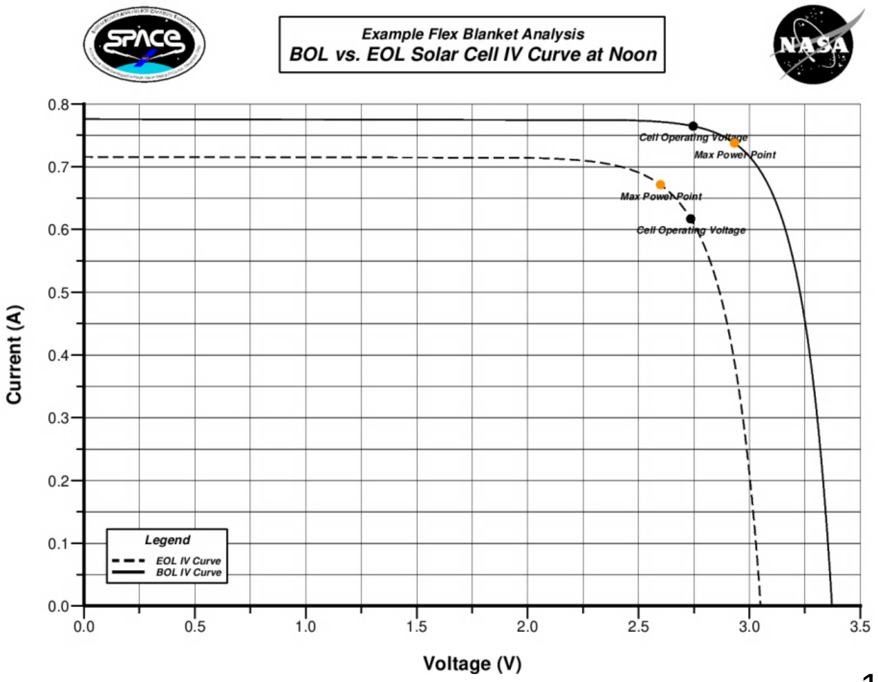


Degradation Model

- **Degradation modeling is data-driven and generic**
  - Variety of knockdown factors are available and specified as inputs to SPACE
  - Factors are all time-phased, allowing variation in damage throughout a multi-year mission
  - Radiation is specified as an annualized fluence; SPACE calculates knockdown factors accordingly
  - Knockdown factors are specified independently for each cell property: Isc, Imp, Vmp, and Voc
  - **Provides flexibility to tune the model with on-orbit telemetry**

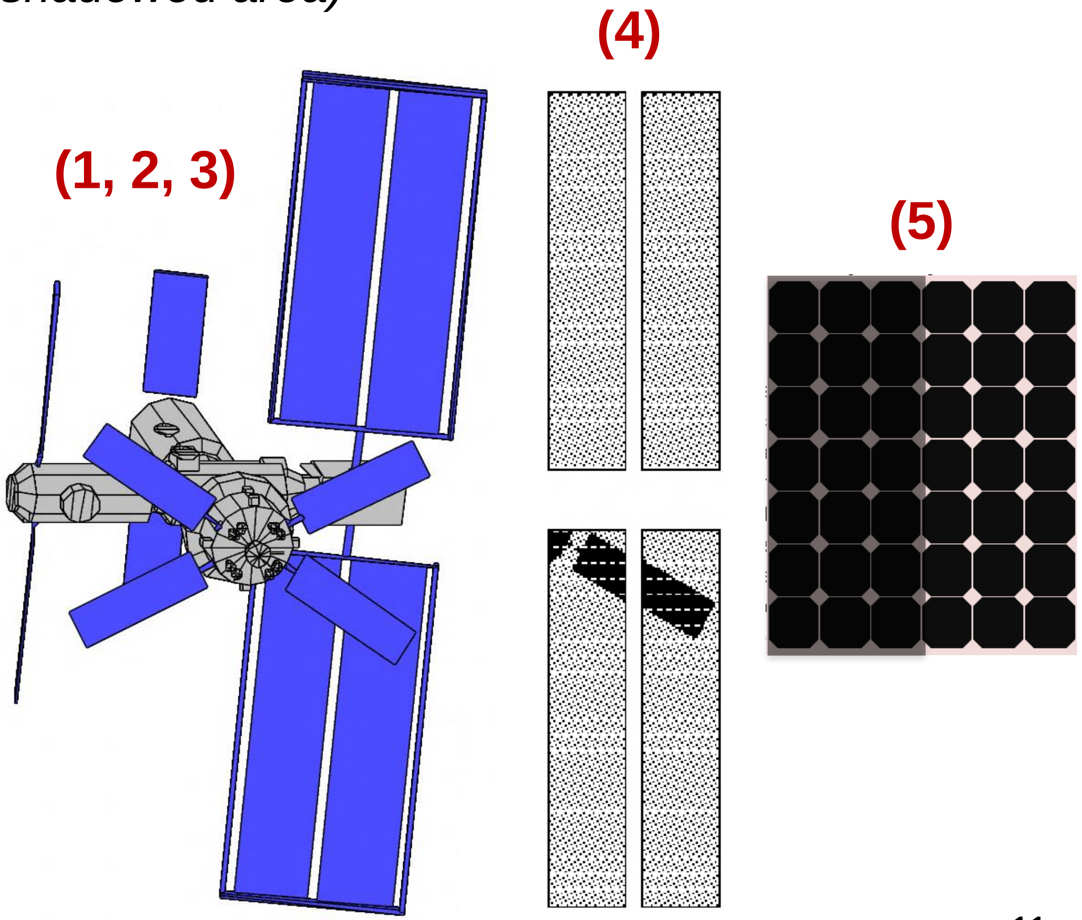
- **Modeling the radiation during the EOR phase of PPE is a new challenge for SPACE**
  - Significant radiation damage during first year of flight due to the spiral trajectory through the radiation belts
  - Results in non-linear degradation profile over the life of PPE

Degradation Mechanisms in SPACE	
Modeling/Measurement Uncertainty	Thermal Cycling
Cell Mismatch Loss	Atomic Oxygen
Blanket Flatness Angle	Plasma Sputtering
Glassing Loss	Contamination
MMOD	Rework Loss
UV Darkening	Random Failures
Radiation	Other Losses



Shadowing Model

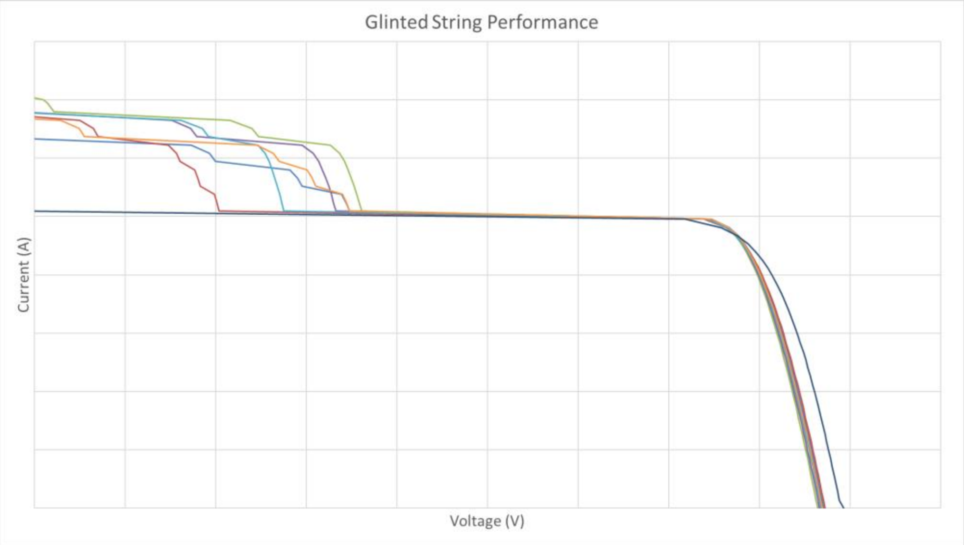
- **Calculates shadows cast by nearby hardware to compute realistic array power**
  - Uses actual solar cell and wiring layout
  - Properly computes string-by-string power loss *(not just shadowed area)*
- **SPACE shadowing process:**
  1. Model external spacecraft geometry on-orbit
  2. Incorporate electrical layout for array(s) of interest
  3. Orient vehicle (attitude) and gimbal components
     - Optimize array/radiator pointing within constraints
     - Account for gimbal locks, keep-out zones, etc.
  4. Calculate solar array shadow patterns
     - 3D ray intersection method
     - *Every* solar cell checked for shadowing
  5. Assess array performance from shadow patterns



Solar Array "Glint"

- **Localized high-flux intensities can occur when sunlight is reflected off specular (mirror-like) surfaces in the spacecraft design**
  - Often referred to as "glint" or "spacecraft albedo"

- **SPACE can be used to perform such assessments**
  - SPACE can model varying flux levels across a set of cells to determine the combined solar array string performance
  - SPACE's integrated thermal model can be used to determine the resulting increase in cell operating temperatures – **does this violate qualification limits?**
  - While extra flux leads to more power generation, upstream components may not be designed to handle these higher current levels (derating and thermal issues)



Conclusions

- **GRC's SPACE code is a complex integrated tool that enables NASA's mission success**
  - SPACE has been used in support of engineering development and operations of NASA's leading human spaceflight programs for over 30 years

- **SPACE will continue to be developed to meet the needs of NASA's future missions**

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Questions?

Thank you!

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Acronyms Used

ARU	Array Regulator Unit
BOL	Beginning of Life
EOL	End of Life
EOR	Earth Orbit Raise
EPS	Electrical Power System
GRC	Glenn Research Center
HALO	Habitation and Logistics Outpost
Imp	Max-Power Current
Isc	Short-Circuit Current
ISS	International Space Station
IV	Current-Voltage
MMOD	Micrometeoroids & Orbital Debris
MPCV	Multi-Purpose Crew Vehicle
PMAD	Power Management and Distribution
PPE	Power and Propulsion Element
ROSA	Roll-Out Solar Array
SEP	Solar Electric Propulsion
SoC	State of Charge
SPACE	System Power Analysis for Capability Evaluation
Vmp	Max-Power Voltage
Voc	Open-Circuit Voltage