An Integrated Approach to Modeling Solar Electric Propulsion Vehicles During Long Duration, Near-Earth Orbit Transfers

David A. Smith - NASA GRC (LSM)
Jeffrey S. Hojnicki - NASA-GRC (DSP)
Waldy K. Sjauw - NASA GRC (LSM)

50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference
Cleveland, OH

July 2014

Paper ID: AIAA-2014-3715

Motivation

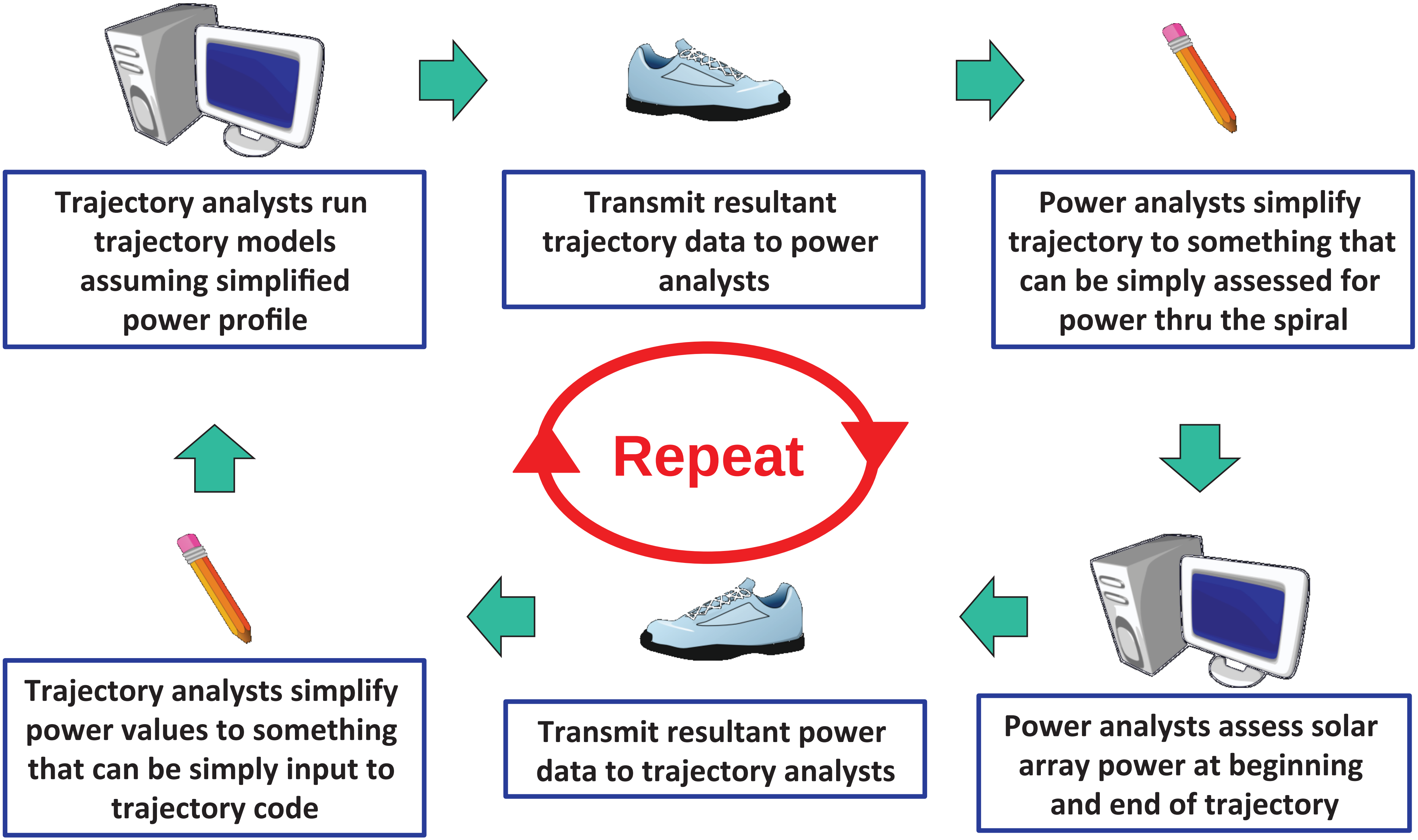
- **Traditionally, solar electric propulsion (SEP) vehicles operated in interplanetary space where predicting solar array performance is fairly straight forward**
  - Sun pointing easily achieved
  - No (or few) eclipse periods
  - Array degradation mechanisms operate on slow (month to year) time scales

- **Recent interest in using SEP in near-Earth environments is complicated by the issue of array degradation and therefore mission and vehicle design**
  - Transits through the Van Allen radiation belts significantly increases array degradation
    - Belts are not uniform
    - SEP LEO to higher energy orbit transfer trajectories are typically characterized by slow "spiral out" trajectories which can take months (or longer) to complete. Rate and amount of degradation highly dependent on transit time through the belts which has implications on vehicle and mission design
  - When operating in the near-Earth environment multiple eclipse induced on/off cycles which:
    - Shut off power generation with possible implications on mission duration and design
    - Have a thermal impact on the arrays and power system

☞ **To address the unique challenges of near-Earth SEP studies, develop a combined, integrated tool to replace current, manual non-integrated approaches**

Previous Method of Analyzing Earth Spiral Trajectory

Glenn Research Center
Cleveland, OH

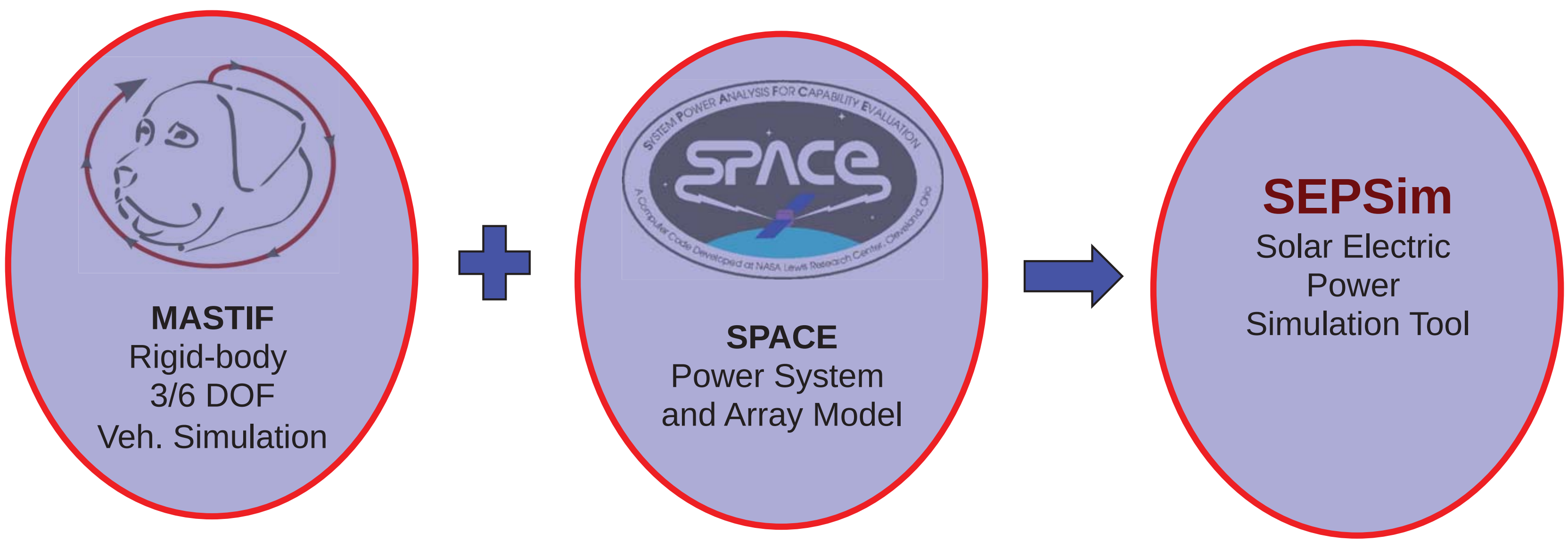


Solution to “Sneaker Net” Approach

- **“Sneaker Net” approach is time consuming and error prone**

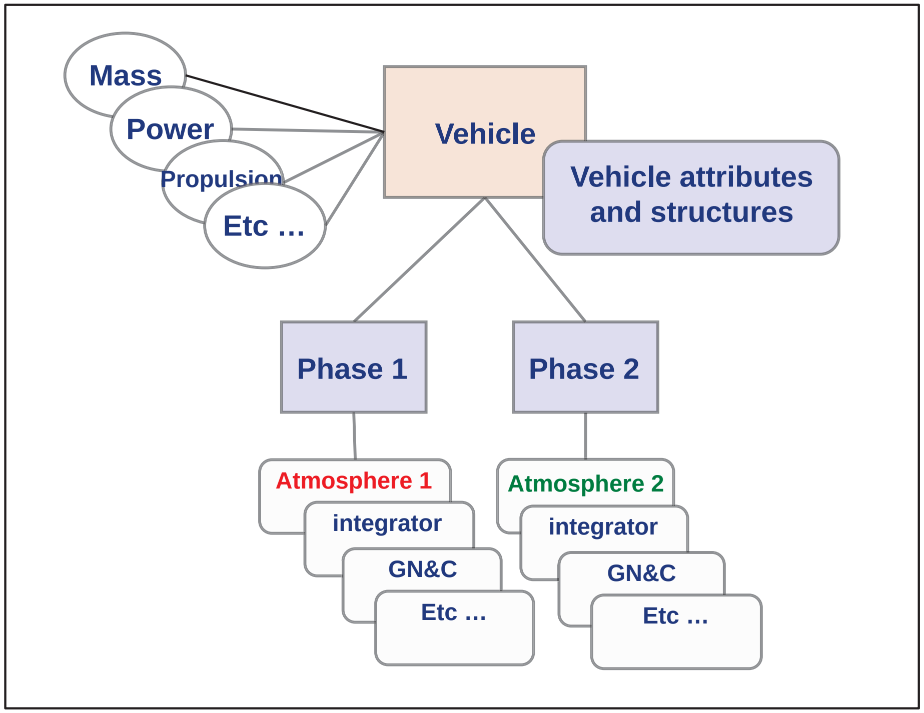
- **To address the integrated model approach, SEP Simulation (SEPSim) tool was developed by combining key components of two, previously independent tools developed and maintained at NASA GRC**

  - **Mission Analysis and Simulation Tool in Fortran (MASTIF)**: vehicle, mission and trajectory simulation tool
  - **System Power Analysis for Capability Evaluation (SPACE):** detailed solar array and power system model



MASTIF Overview

- **Mission Analysis and Simulation Tool in Fortran (MASTIF) is a F90/95, modular code developed and maintained at GRC under the Ares I project**
- **MASTIF is a framework on which to build a vehicle simulation and was designed to be modular and adaptable**
- **The central object (or structure) of MASTIF is a vehicle**
  - Models (power, mass, propulsion, etc …) are tied together through well defined interfaces define a vehicle (or vehicles)



- **Flight phases can be attached to vehicles to change atmosphere, numerical integrators, etc...**
  - In schematic example, vehicle passes through atmosphere 1 to atmosphere 2 - switch triggered by some user defined "event" (e.g. altitude)
- **MASTIF Includes:**
  - GN&C models
  - 3DOF (translational motion)
  - 6DOF (translational + rotation)
  - Multiple atmosphere models
  - Propulsion models
    - Liquid motors, solid motors, RCS
  - Multiple celestial body models
  - Mass property models
  - Oblate gravity
  - Rigid body
  - Ability to add flex body

SPACE

- **SPACE (System Power Analysis for Capability Evaluation) is a model that predicts the performance of spacecraft power systems**
  - SPACE was developed entirely at NASA Glenn, and has been under development since 1988

- **SPACE is a tool used for detailed spacecraft power modeling, with integrated capabilities unique in the industry:**
  - Detailed array degradation model
  - Ties to AE8/AP8 radiation models
    - AE9/AP9 in progress
  - PPU/DDU modes
  - Array pointing algorithms
  - Battery models
  - Array thermal model
    - Solar, Earth and power generated
  - Self shadowing
  - Housekeeping power model

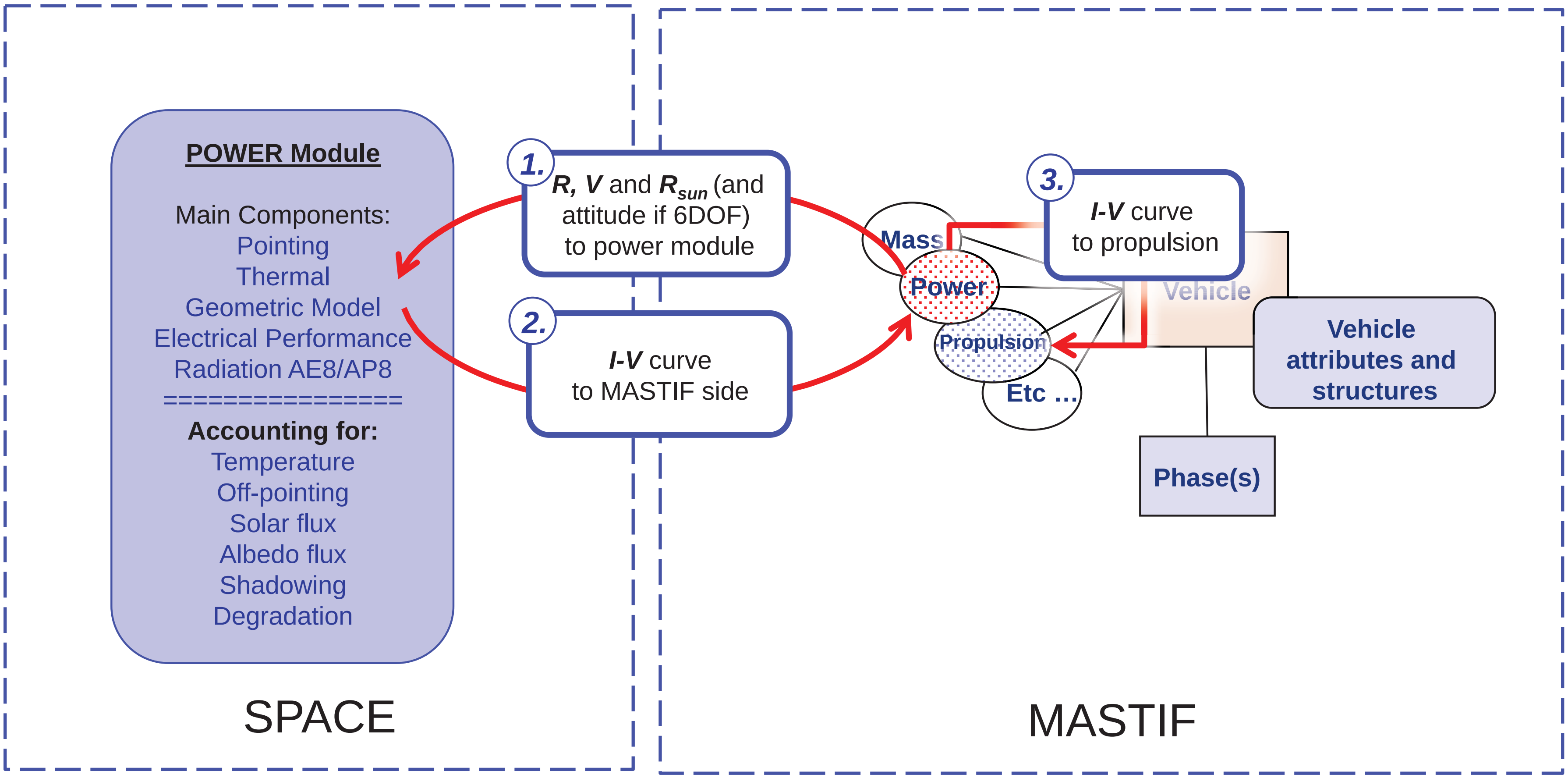
- **SPACE was the GRC Software of the Year Award winner in 2003, and runner-up for the agency award**

- **SPACE is recognized internationally for contributions to the ISS program**

- **Although originally developed ISS, a version of SPACE was developed the Orion Crew Exploration Vehicle project, and a version is being pursued that can assess performance of SEP systems**

Combined Tool (SEPSim)
MASTIF/SPACE Interface

Glenn Research Center
Cleveland, OH



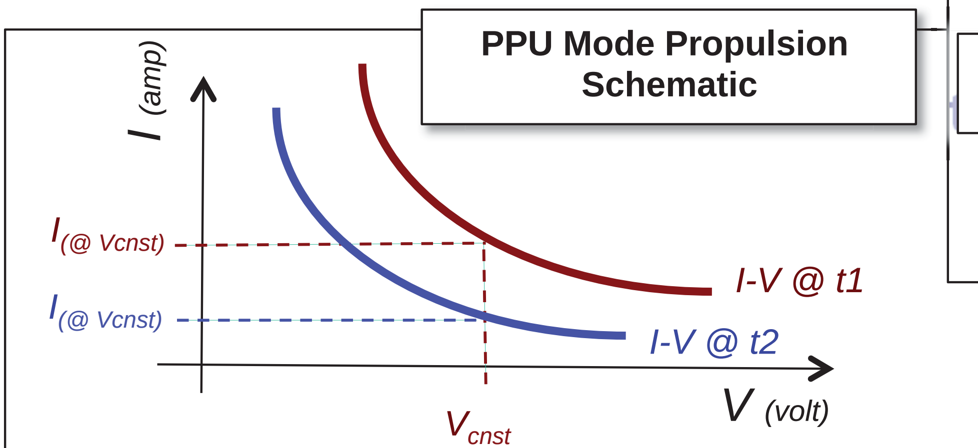
- **SPACE/Power module first major tie into MASTIF modular design to create SEPSim**
  1. ***R, V, R_{sun}*** and other geometric information passed from MASTIF side of interface to SPACE side
  2. ***I-V*** curves are passed back from SPACE to MASTIF
  3. MASTIF side of SEPSim then passes the I-V curve to the propulsion module where thrust is calculated

  ☞ Interface can be called at any frequency ≥ integration time step

Propulsion Module

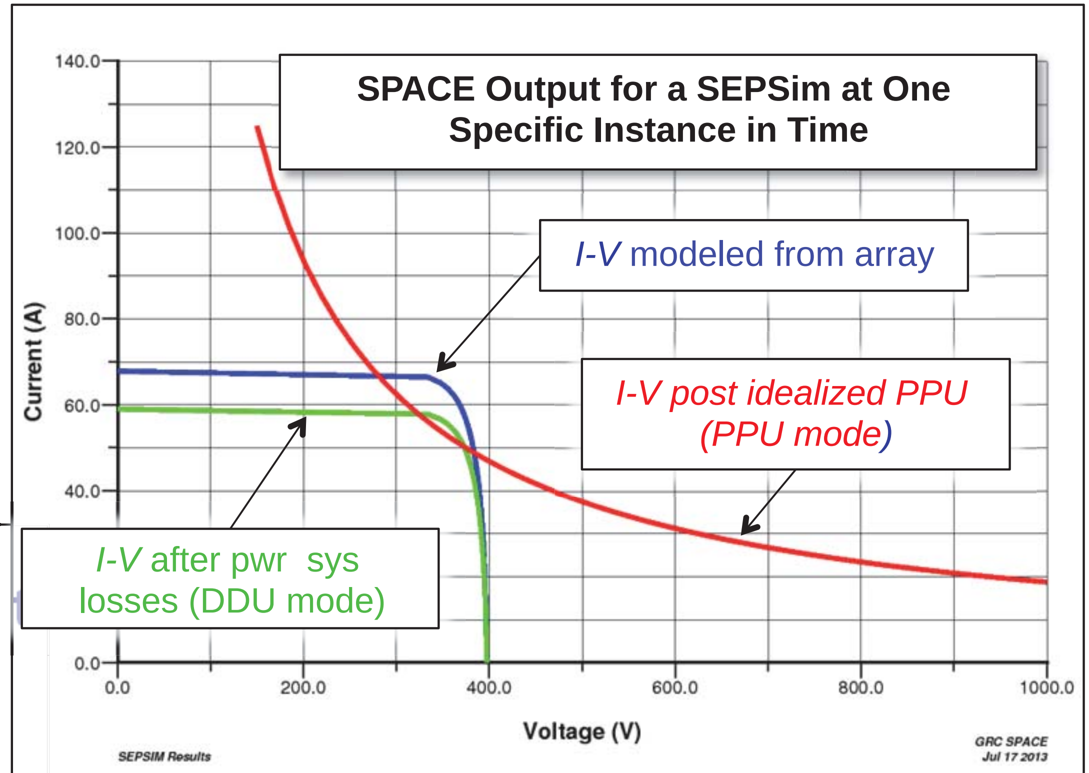
Glenn Research Center
Cleveland, OH

- **SEPSim is can be configured to simulate a wide variety of propulsion systems**
  - User specified models, tabular, etc …
- **SEPSim's <u>current</u> PPU mode is simplified model designed to return peak power at any voltage (red curve to right)**
- **Higher fidelity PPU models possible but not currently implemented**



$$P_{eng} = I_{(@V_{cnst})} \cdot V_{cnst} \qquad (watt)$$

$$Thrust = \frac{2 \cdot \eta_{eff} \cdot P_{eng}}{g \cdot I_{sp}} \qquad (N)$$



- ***I-V* curve from power module is passed to propulsion module where it is interrogated under:**
  - Constant voltage (this presentation)
  - Constant current
- **Resulting power is used in "standard EP" equation to calculate thrust which is then used to advance the vehicle states**

Example SEPSim Cases

Two notional cases are presented to illustrate the some of the capabilities of SEPSim

1. **Assumed 50 kW "EOL" Versus Time Variable Power Module (full SEPSim)**
2. **Perfect Pointing Versus Roll Hold (roll angle fixed to 0º)**

Simulation Parameters for Both Example Problems (50 kW Class SEPV - LEO to Earth-escape)

Initial and Targeting Conditions

	Initial Conditions	Target Conditions
sma (km)	6778 (alt = 400)	$200k$ (terminated near escape)
ecc	0	none
inc (deg)	28.5	none
raan (deg)	0	none
argp (deg)	180	none
truea (deg)	0	none
mass (kg)	6500	NA
epoch (UTC)	2015 Mar 15 00:00:0.00	NA

Simulation Details

array power class	50 kW class (details vary per simulation)
GN&C	Directional Adaptive Guidance (pitch and yaw)
roll steering	perfect pointing (unless otherwise noted)
integration time step	60 sec
subsytem freq (incl. power)	60 sec
Earth Shadow (On/Off)	On
Atmosphere Model	none
Fidelity Level	3DOF
Propulsion Model	Standard EP equation ($\eta_{eff} = 65\%$ and $I_{sp} = 3000sec$)
PPU Model (Yes/No)	Yes ($PPU_{eff} = 95\%$)
Simulation Termination	Earth Escape ($C3 = -2.0\ km^2\ sec^{-2}$)

simulations start in circular LEO at 28.5^o inclination

Simulation Parameters for Both Example Problems (50 kW Class SEPV - LEO to Earth-escape)

Initial and Targeting Conditions

	Initial Conditions	Target Conditions
sma (km)	6778 (alt = 400)	200*k* (terminated near escape)
ecc	0	none
inc (deg)	28.5	none
raan (deg)	0	none
argp (deg)	180	none
truea (deg)	0	none
mass (kg)	6500	NA
epoch (UTC)	2015 Mar 15 00:00:0.00	NA

Simulation Details

array power class	50 kW class (details vary per simulation)
GN&C	Directional Adaptive Guidance (pitch and yaw)
roll steering	perfect pointing (unless otherwise noted)
integration time step	60 sec
subsytem freq (incl. power)	60 sec
Earth Shadow (On/Off)	On
Atmosphere Model	none
Fidelity Level	3DOF
Propulsion Model	Standard EP equation ($\eta_{eff} = 65\%$ and $I_{sp} = 3000 sec$)
PPU Model (Yes/No)	Yes ($PPU_{eff} = 95\%$)
Simulation Termination	Earth Escape ($C3 = -2.0\ km^2\ sec^{-2}$)

pitch and yaw calculated from Directional Adaptive Guidance (DAG) GN&C module to target 200k km, simulation terminated at $C3 \geq -2\ km^2\ sec^{-2}$

----

no other orbital parameters targeted

Simulation Parameters for Both Example Problems (50 kW Class SEPV - LEO to Earth-escape)

Glenn Research Center
Cleveland, OH

Initial and Targeting Conditions

	Initial Conditions	Target Conditions
sma (km)	6778 (alt = 400)	200k (terminated near escape)
ecc	0	none
inc (deg)	28.5	none
raan (deg)	0	none
argp (deg)	180	none
truea (deg)	0	none
mass (kg)	6500	NA
epoch (UTC)	2015 Mar 15 00:00:0.00	NA

Simulation Details

array power class	50 kW class (details vary per simulation)
GN&C	Directional Adaptive Guidance (pitch and yaw)
roll steering	perfect pointing (unless otherwise noted)
integration time step	60 sec
subsytem freq (incl. power)	60 sec
Earth Shadow (On/Off)	On
Atmosphere Model	none
Fidelity Level	3DOF
Propulsion Model	Standard EP equation ($\eta_{eff} = 65\%$ and $I_{sp} = 3000sec$)
PPU Model (Yes/No)	Yes ($PPU_{eff} = 95\%$)
Simulation Termination	Earth Escape ($C3 = -2.0\ km^2\ sec^{-2}$)

roll assumed for perfect pointing (max sun) for problem 1 and roll hold (roll = 0) for problem 2

Simulation Parameters for Both Example Problems (50 kW Class SEPV - LEO to Earth-escape)

Initial and Targeting Conditions

	Initial Conditions	Target Conditions
sma (km)	6778 (alt = 400)	$200k$ (terminated near escape)
ecc	0	none
inc (deg)	28.5	none
raan (deg)	0	none
argp (deg)	180	none
truea (deg)	0	none
mass (kg)	6500	NA
epoch (UTC)	2015 Mar 15 00:00:0.00	NA

Simulation Details

array power class	50 kW class (details vary per simulation)
GN&C	Directional Adaptive Guidance (pitch and yaw)
roll steering	perfect pointing (unless otherwise noted)
integration time step	60 sec
subsytem freq (incl. power)	60 sec
Earth Shadow (On/Off)	On
Atmosphere Model	none
Fidelity Level	3DOF
Propulsion Model	Standard EP equation ($\eta_{eff} = 65\%$ and $I_{sp} = 3000sec$)
PPU Model (Yes/No)	Yes ($PPU_{eff} = 95\%$)
Simulation Termination	Earth Escape ($C3 = -2.0\ km^2\ sec^{-2}$)

- Power module called at integration time step
- Shadow effects are included
- All simulations are 3DOF
- No atmospheric drag

Simulation Parameters for Both Example Problems (50 kW Class SEPV - LEO to Earth-escape)

Initial and Targeting Conditions

	Initial Conditions	Target Conditions
sma (km)	6778 (alt = 400)	$200k$ (terminated near escape)
ecc	0	none
inc (deg)	28.5	none
raan (deg)	0	none
argp (deg)	180	none
truea (deg)	0	none
mass (kg)	6500	NA
epoch (UTC)	2015 Mar 15 00:00:0.00	NA

Simulation Details

array power class	50 kW class (details vary per simulation)
GN&C	Directional Adaptive Guidance (pitch and yaw)
roll steering	perfect pointing (unless otherwise noted)
integration time step	60 sec
subsytem freq (incl. power)	60 sec
Earth Shadow (On/Off)	On
Atmosphere Model	none
Fidelity Level	3DOF
Propulsion Model	Standard EP equation ($\eta_{eff} = 65\%$ and $I_{sp} = 3000sec$)
PPU Model (Yes/No)	Yes ($PPU_{eff} = 95\%$)
Simulation Termination	Earth Escape ($C3 = -2.0\ km^2\ sec^{-2}$)

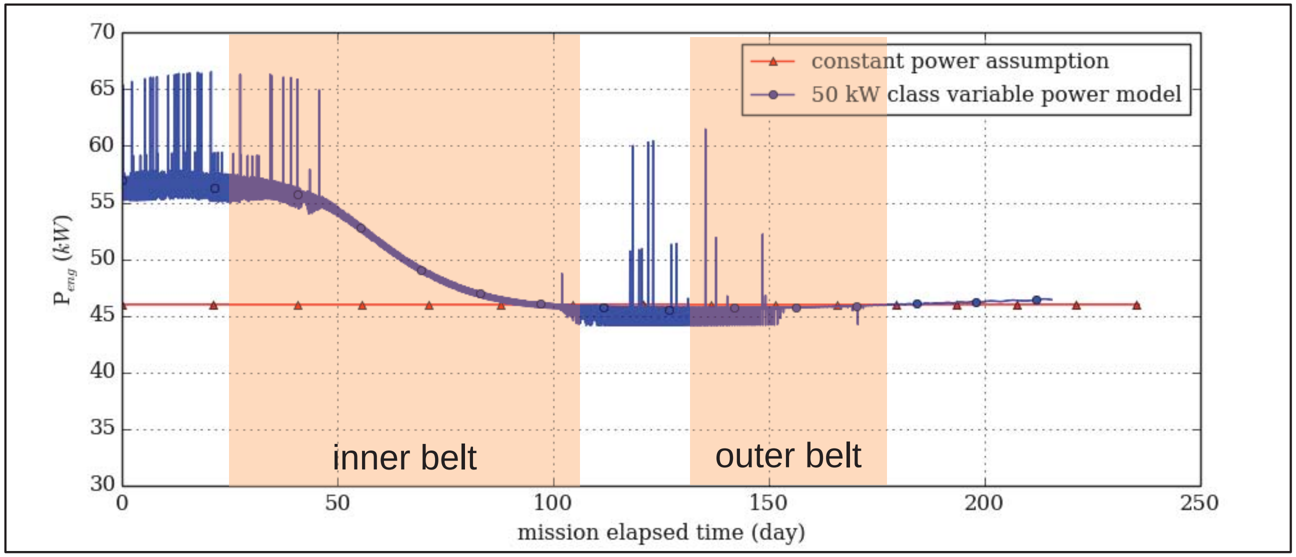
PPU mode w/ standard EP equations for propulsion model

Problem 1: Assumed 50 kW "EOL" Power Versus Time Variable Power Module (full SEPSim)

- **Problem 1: Assumed 50 kW "EOL" Versus Time Variable Power Module (full SEPSim)**
  - Examines results from "typical" EOL power assumption (i.e. excess power from oversized arrays is ignored) versus <u>using excess power in a notional vehicle for thrust</u>
    - Mission response to "extra power" at beginning of mission
    - Will illustrate array degradation
    - Will illustrate time variation in power generation to thermal conditions

Engine Power

Assumed 50 kW "EOL" Power Versus Time Variable Power Module (full SEPSim)



note that zero power conditions associated with eclipse are filtered and not plotted for clarity

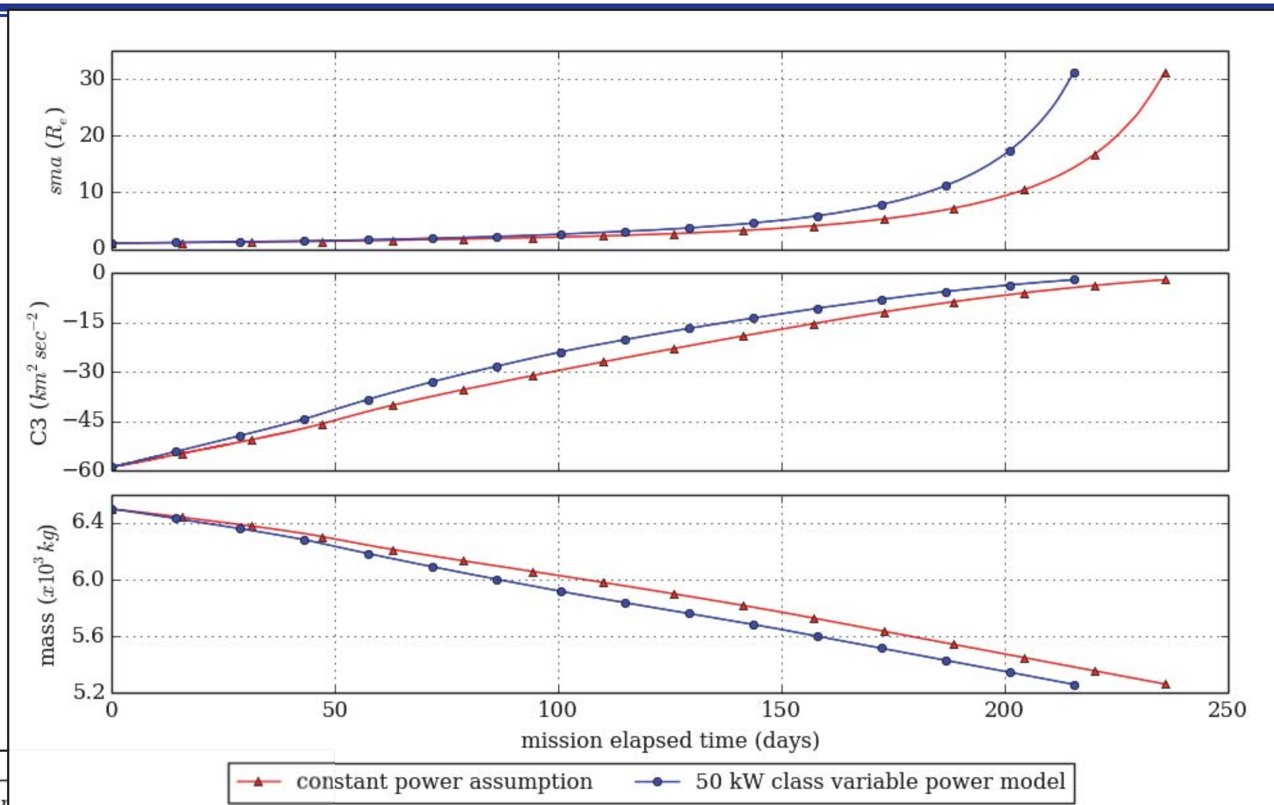
- **Engine power *<u>(post PPU)</u>* for 50 kW EOL case (red) and for the variable power case (blue)**
- **The "location" of the Van Allen radiation belts are indicated in orange using times associated with the following <u>approximate</u> altitude definitions:**
  - Inner belt: ~ 1600 to 13,000 km (from simulation data: ~ 30 to 115 day)
  - Outer belt: ~ 19,000 to 40,000 km (from simulation data: ~ 135 to 170 day)
- **Solar array degradation > 20% to day 100 (associated with inner belt)**
- **Array oversizing to compensate for degradation results "excess" power which could notionally be used for thrust (as in this example problem) or for compensation for array off-pointing, etc …**
- **Also see an indication of higher frequency "spikes" – thermal response to eclipse entry/exit (more later)**

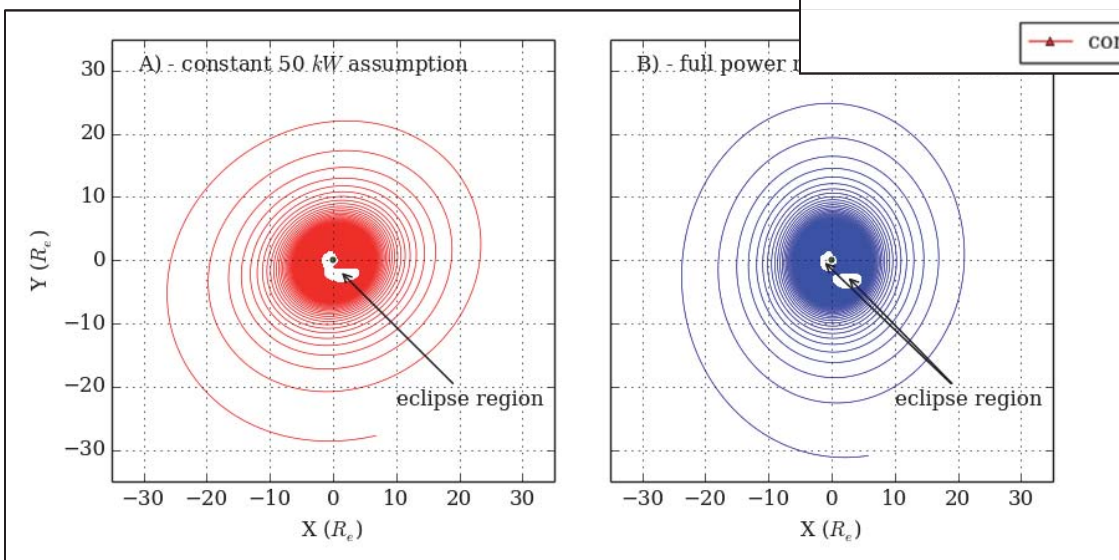
Orbital Parameters

Assumed 50 kW "EOL" Power Versus Time Variable Power Module (full SEPSim)

Glenn Research Center
Cleveland, OH

- 50 kW EOL (red) takes longer (~ 2 weeks) to reach orbital targets (*sma*) and C3 than does the case with the full power model (blue)
- Because these cased are run with a constant I_{sp} assumption, no appreciable mass savings (propellant) is realized; however, it is possible to assess those types of trades with SEPSim



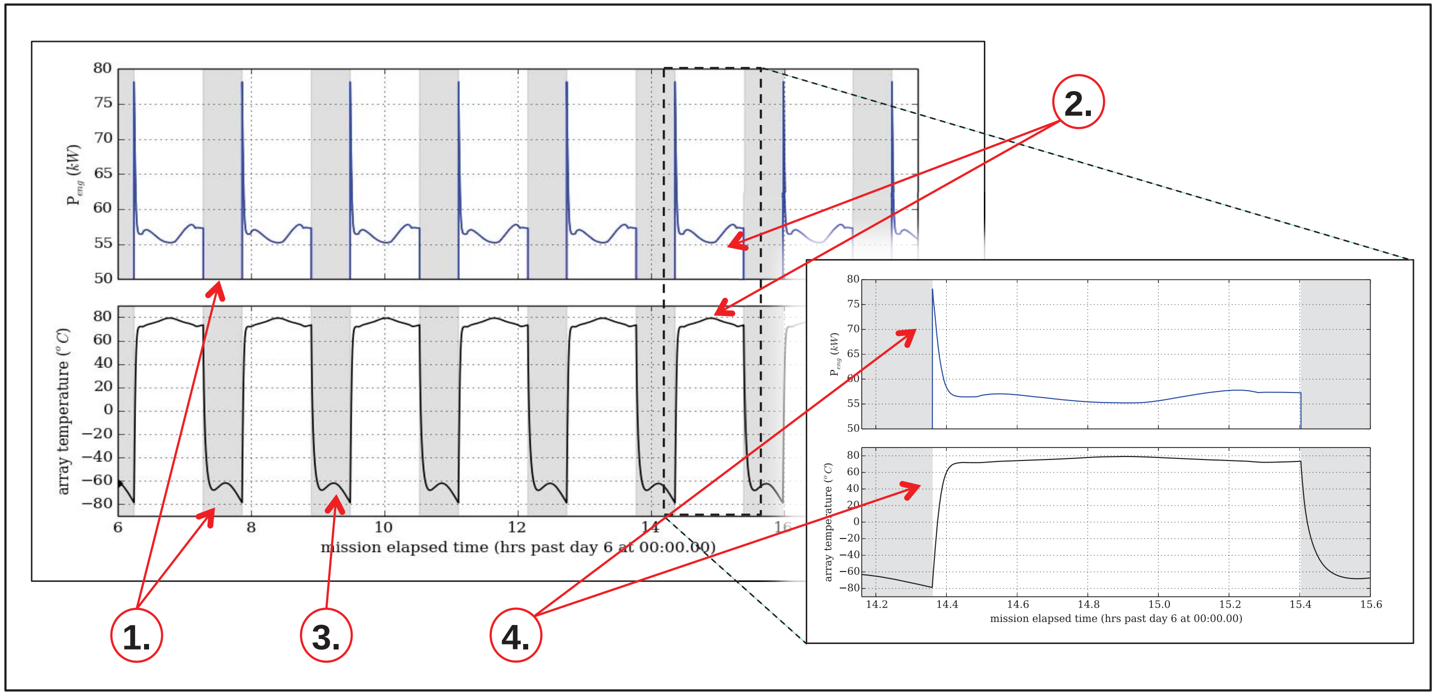


- Resulting spiral out trajectories illustrated (XY projections) (scaled to Re) as a reference
- Differences in orbit "shape" most likely due to eclipse history (indicated on plots)
- Final *ecc* and *inc* not targeted in this problem – could be with DAG GN&C

Power Generation (and Thrust) Response to Array Temperature

Glenn Research Center
Cleveland, OH

- Engine power (top panel) and solar array temperature (bottom panel) as a function of MET (day 6)
- Sub panel to focus on one eclipse cycle
- Eclipse periods are shaded
- Temperature: -80 to 80 °C
- Power: 0 to 57 kW (0 not shown) w/ "spikes" > 75 kW

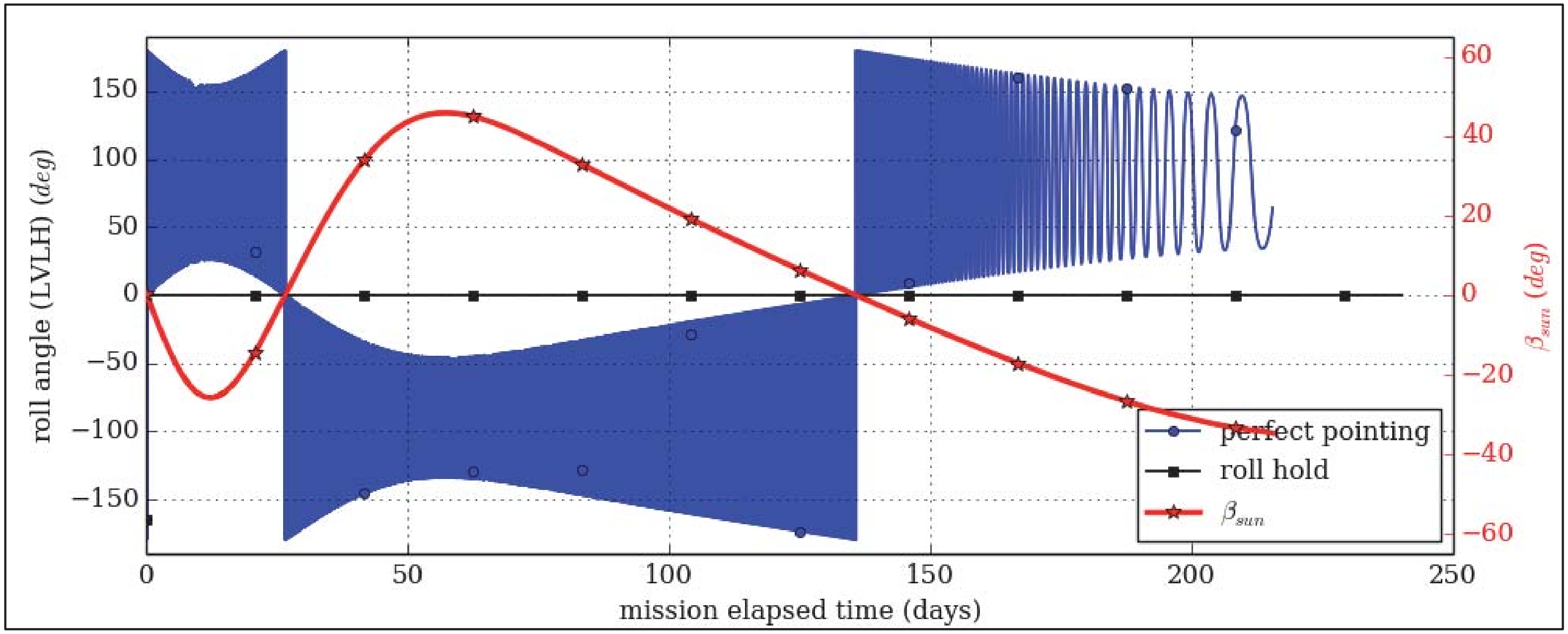


☞ Key features and relationships:

1. During eclipse, no solar heating or power generation, the arrays are at their coldest (~ -80 °C) and power generation is zero (no illumination)
2. Inverse relationship between power generation and array temperature
3. In addition to heating from the sun and power generation, heating from Earth can be seen during eclipse periods – eclipse temperature peak results from pointing algorithm tracking sun which persists for entire orbit even during eclipse
4. Power spikes result from power generation as the SEPV exits shadow and arrays are cold and is an example of a feature captured by SEPSim which could have impact on vehicle and mission design

Problem 2: Perfect Pointing Versus Roll Hold (roll = 0)

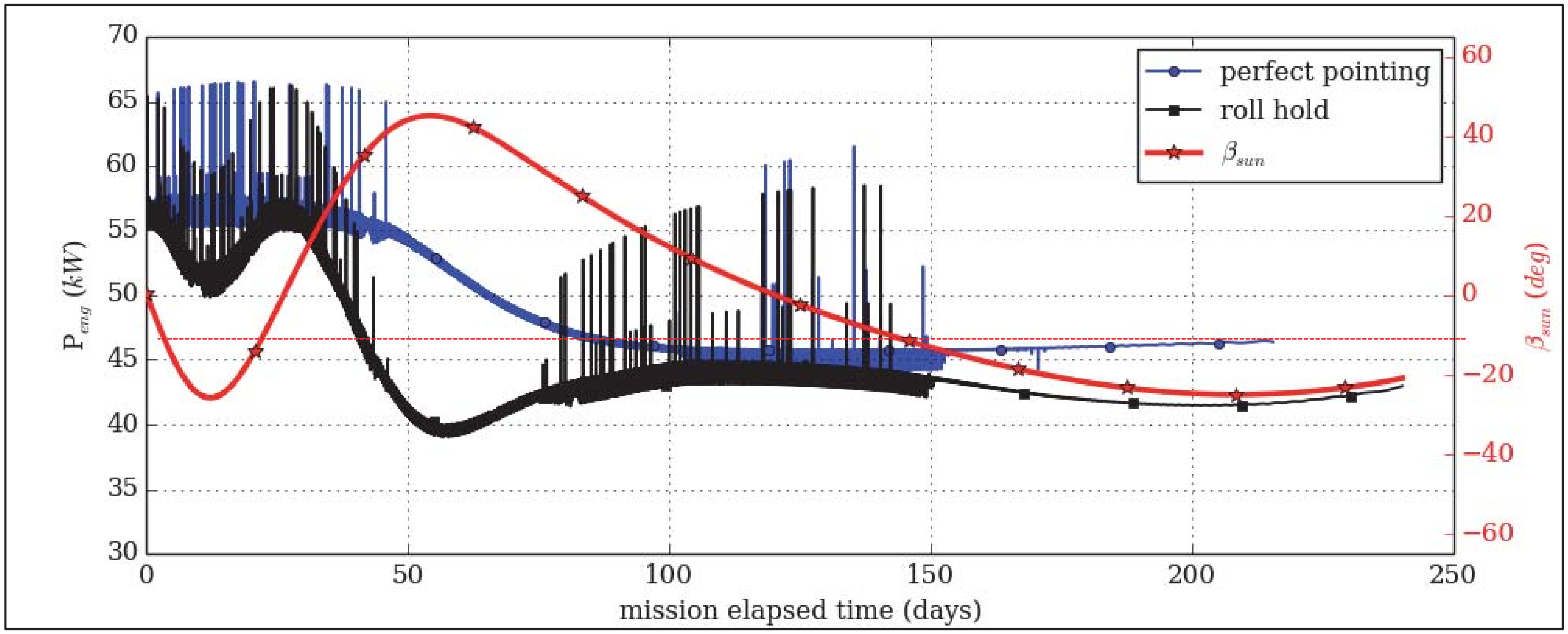
- **Problem 2: Perfect Pointing Versus Roll Hold**
  - Examines results of time varying power module under two different roll profiles – Illustrates the types of GN&C studies that can be achieved with integrated tool. In both cases, pitch and yaw are generated using Directional Adaptive Guidance (DAG)
    - **Perfect pointing** – vehicle rolled such that array axis is perpendicular to $\boldsymbol{R}_{sun}$ in order to maximize array exposure to sun
      - Note that this would have RCS implications – not modeled
    - **Roll hold** – vehicle not rolled (roll angle held at 0) to show impact of cosine power loss at high solar beta angles



Engine Power

Perfect Pointing vs. Roll Hold (roll = 0)

Glenn Research Center
Cleveland, OH



note that zero power conditions associated with eclipse are filtered and not plotted for clarity

- **Engine power for perfect pointing case (blue) (same profile as in previous problem), roll=0 case (black) and solar beta angle indicated in red (right axis)**
- **Roll hold case shows the power loss with being off pointed at high solar beta angles and resulting longer trip duration (~ 2 weeks)**
  - Note that early in mission (day < 50) power losses do not exceed EOL assumption of previous example

  ⇒ consideration for mission design, roll/no roll
- **These types of GN&C/power-coupling studies can be difficult to do in the non-integrated approach and should be easier, faster and more straight forward in an integrated tool like SEPSim**

Summary & Conclusions

Glenn Research Center
Cleveland, OH

- **SEPSim is an integrated tool which can be used in varying degrees of fidelity to study EP vehicles and specifically address issues associated with array degradation and eclipse crossings in near-Earth environments**

- **SEPSim was developed on a modular platform and can be expanded in fidelity and detail as programs and designs matures**
  - Being built on MASTIF architecture, SEPSim has access to all 3/6-DOF features of MASTIF, Monte Carlo wrappers, etc …

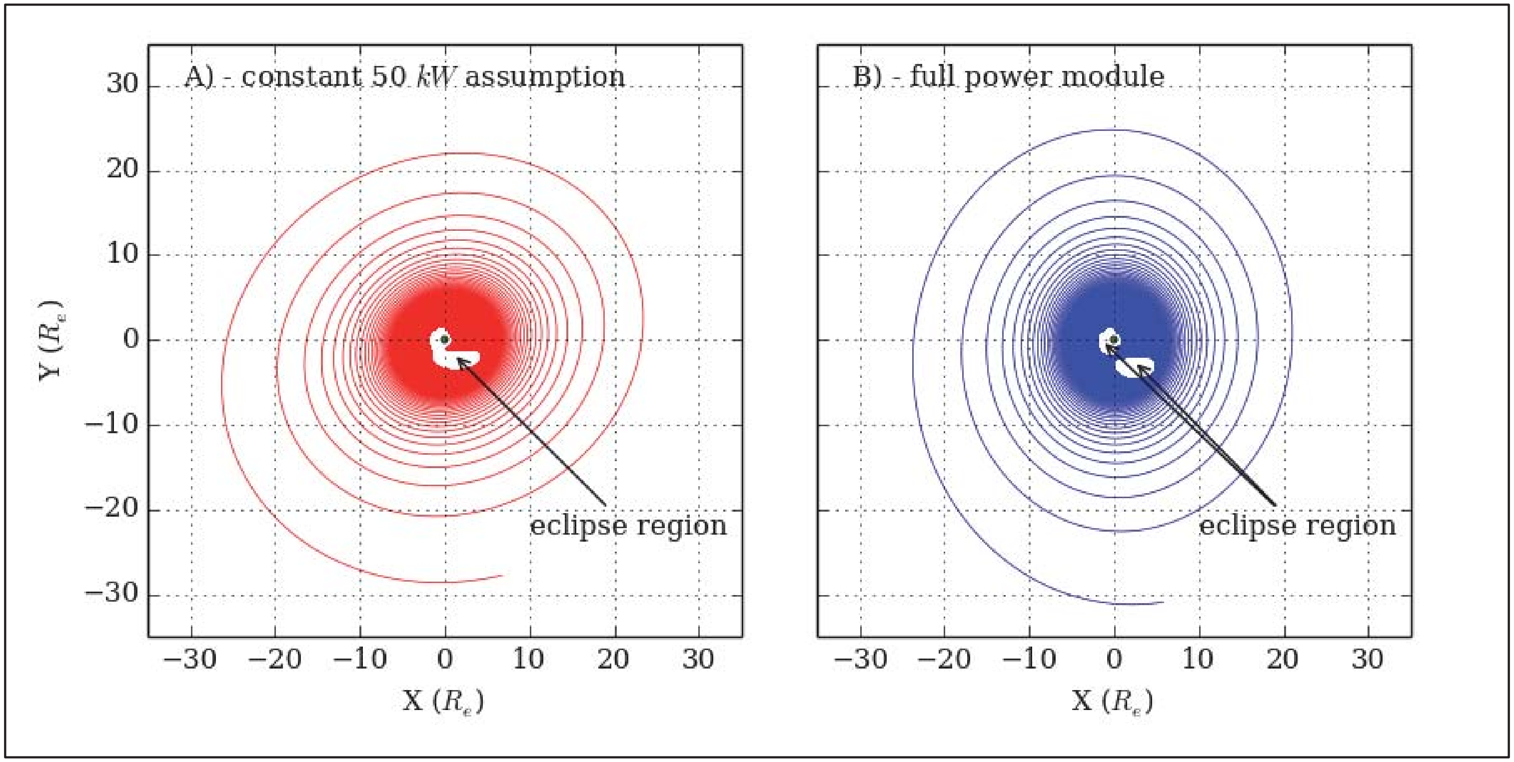
- **As NASA and industry continue to explore the use of EP systems to transfer payloads from LEO to higher energy orbits (eg. GEO, escape, etc …) the necessity for integrated studies will become more and more important**

- **Next logical step for SEPSim would be to extend the notional problems presented in this discussion to more realistic problems**
  - Improvement and enhancement to current 3DOF implementation (e.g. higher fidelity PPU and propulsion models)
  - 6DOF models and simulations (requires vehicle design, mass properties, RCS systems, etc …)

Backup Slides

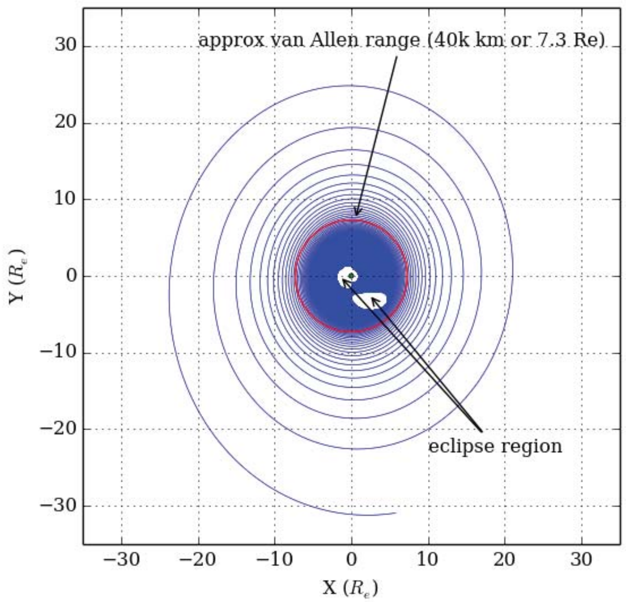
LEO to (near) Earth Escape Trajectories (X-Y projection)

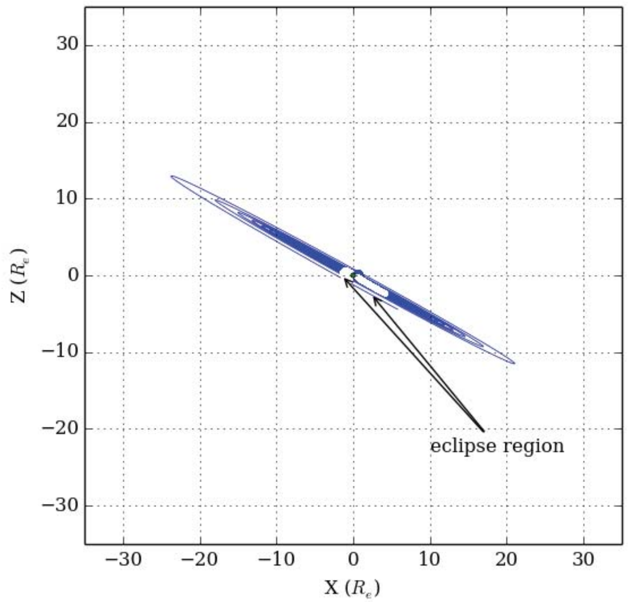
Glenn Research Center
Cleveland, OH

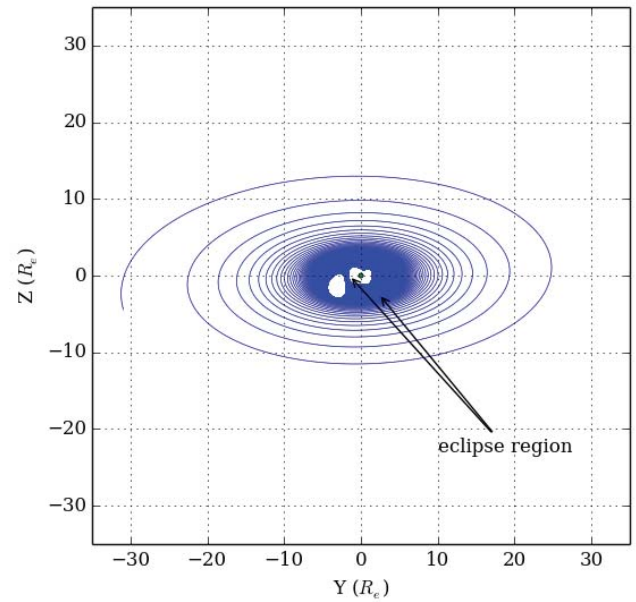


- XY (EME-2K) projections for LEO to near Earth escape (C3 = 2 $km^2\ s^{-2}$) (note: x and y axes scaled by earth Radius)
- Differences in spiral shape most likely result from slight differences in shadow history (eclipse regions indicated on plots)

Example of an EP Vehicle Spiral Out (LEO to near-Earth Escape)

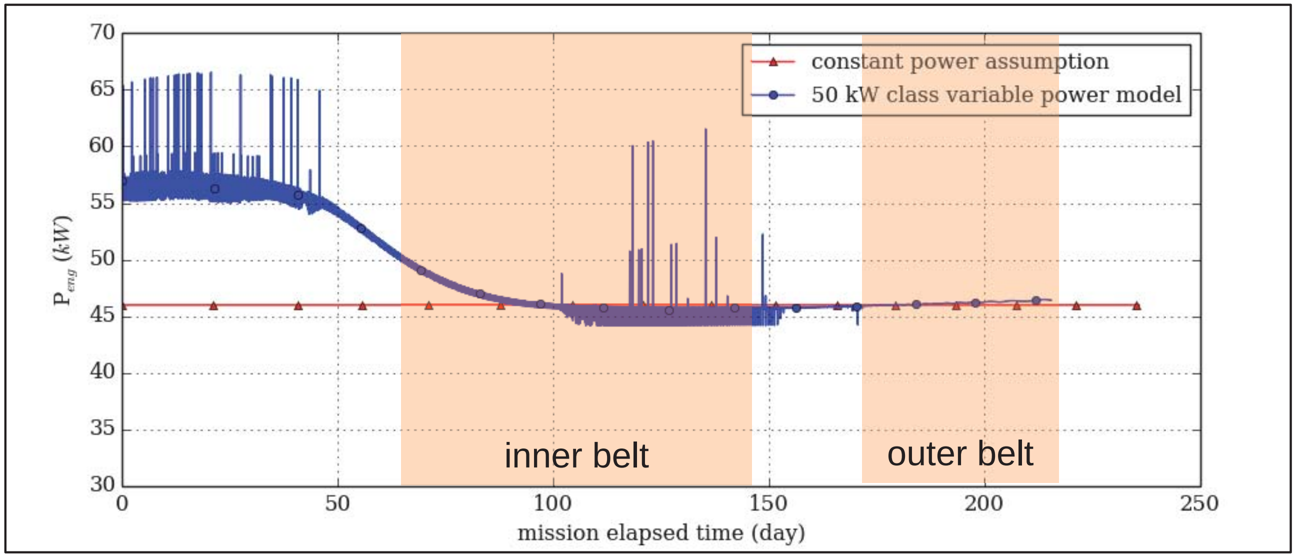


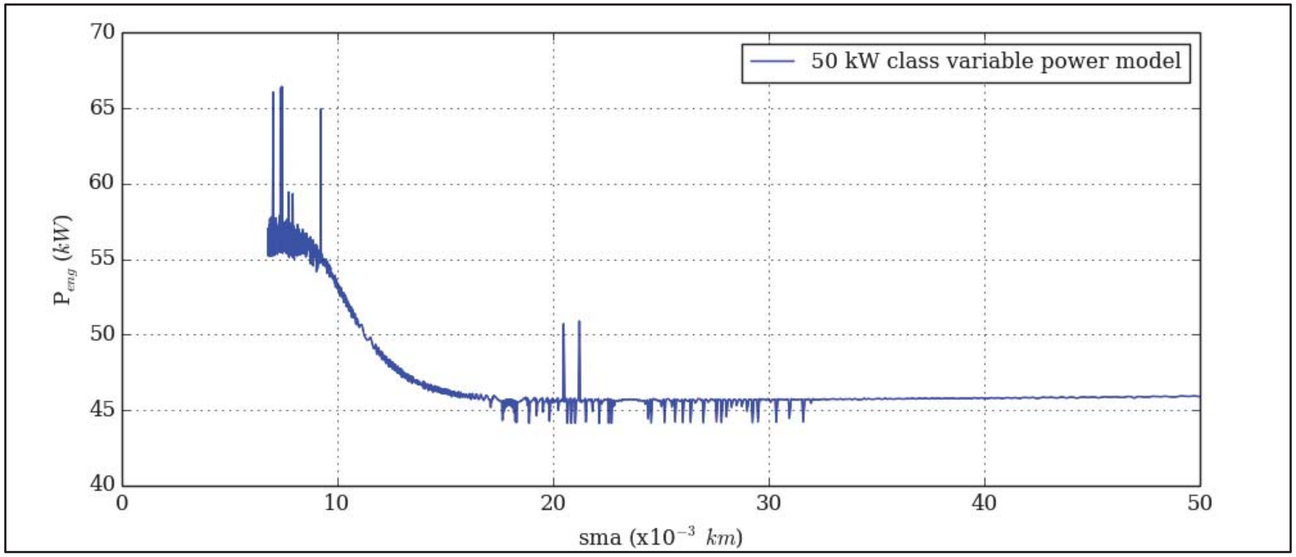




- **XY, XZ and YZ projections of low thrust LEO to escape trajectory**
- **For this example:**
  - T/W = $4x10^{-5}$ (2.8N, 6500 kg)
  - Spiral time = 7 months
- **Eclipse regions indicated as whited out regions**
- **van Allen altitudes (approximate location indicated on XY projection):**
  - Inner: 1600 to 13000 km (*1.25 to 3 Re*)
  - Outer: 19,000 to 40,000 km (*4 to 7.3 Re*) *approximate outer range indicated on XY projection

Engine Power as a Function of Time and Altitude (*sma*)



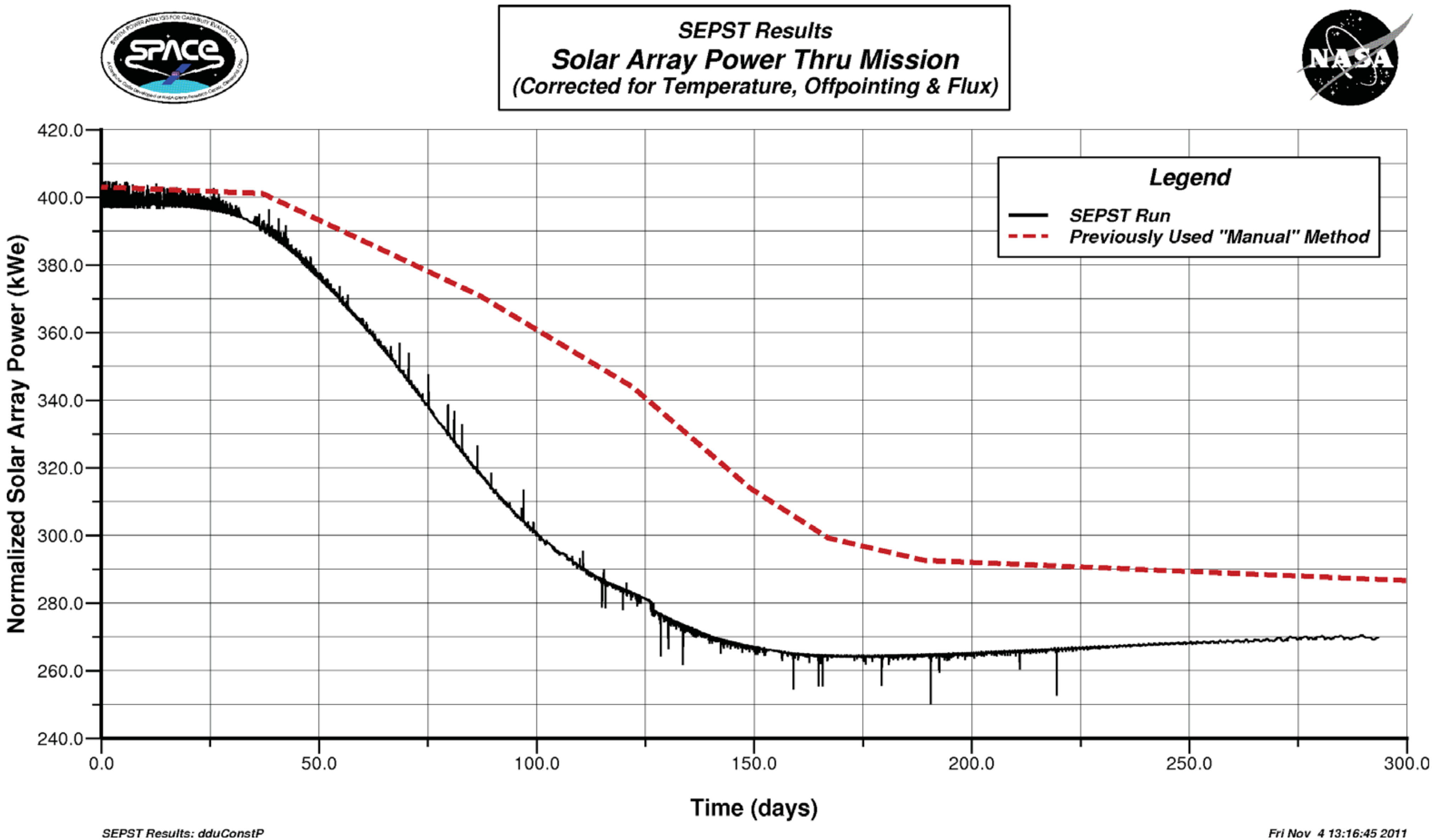


note that zero power conditions associated with eclipse are filtered and not plotted for clarity

- **Engine power *(post PPU)* for 50 kW EOL case (red) and for the variable power case (blue)**

Sample Results & Comparison

Glenn Research Center
Cleveland, OH

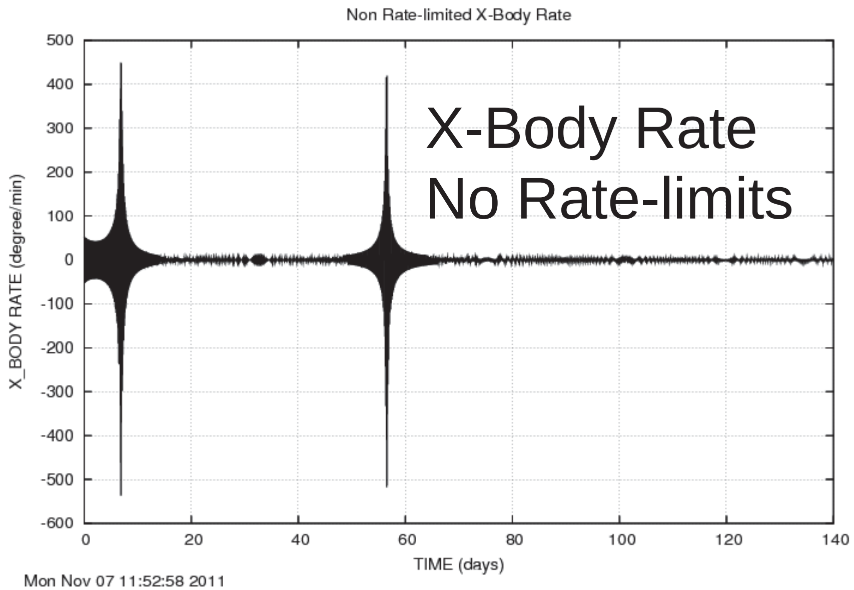


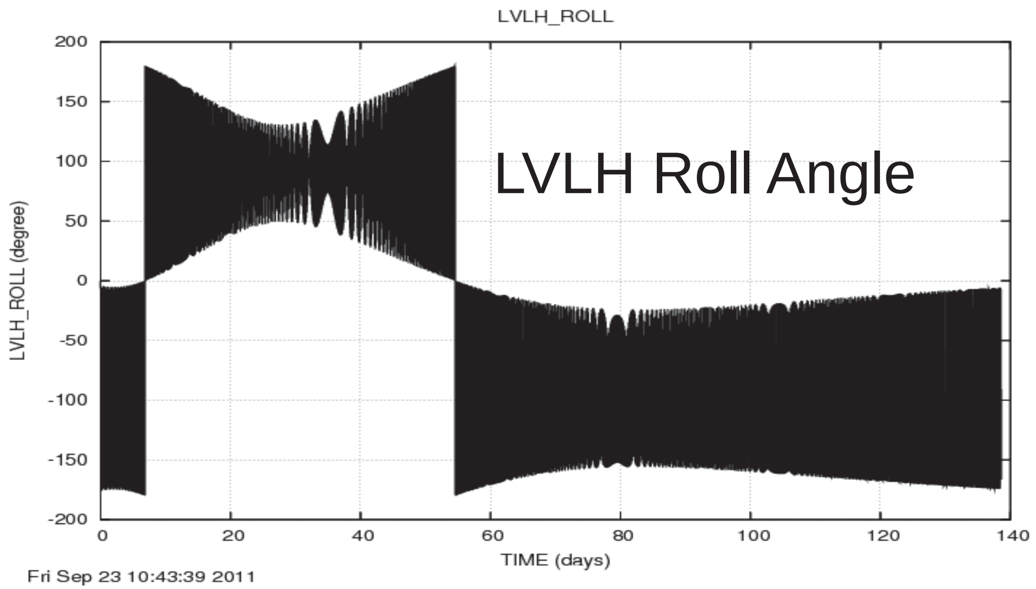
Availablity

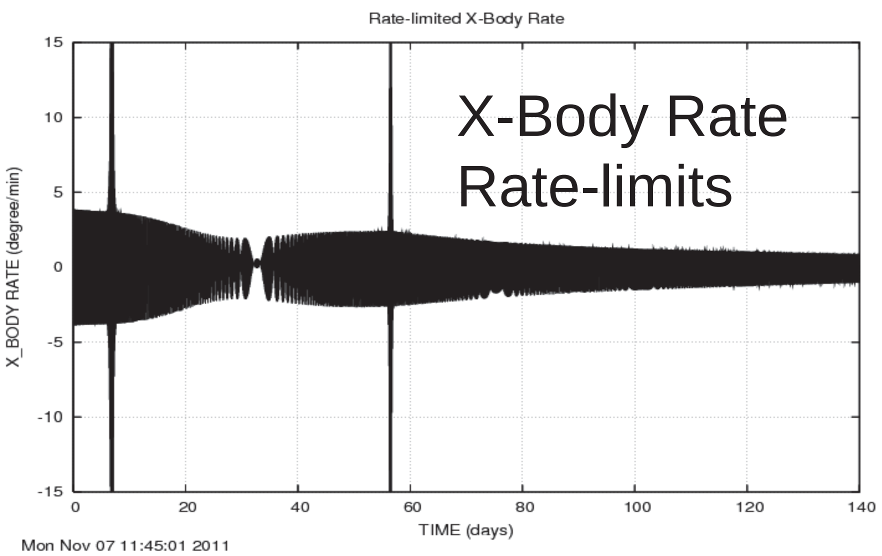
- **Status: SEPSim is a functioning code under ongoing development and enhancement – SEPSim is patent pending and available through licensing agreement with GRC**

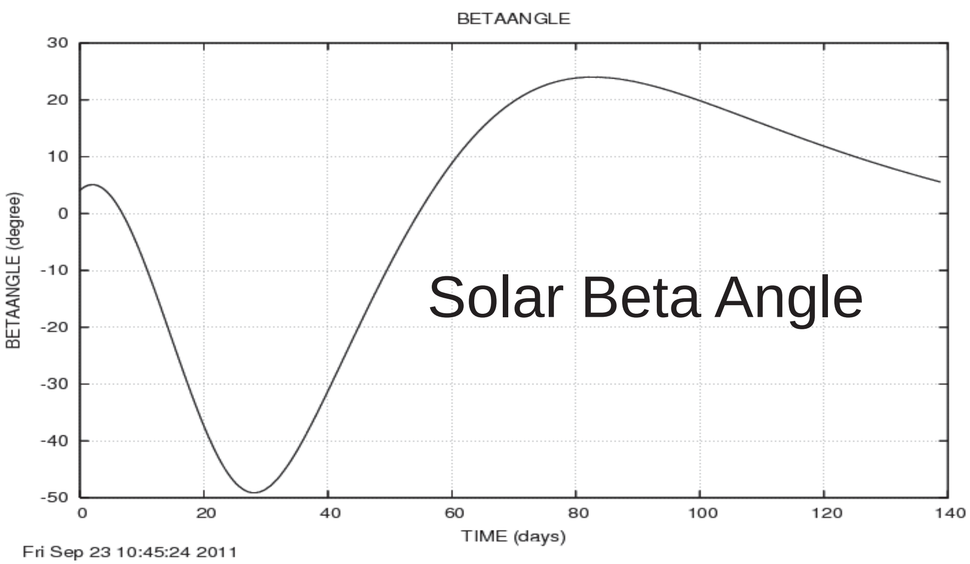
Sample Results & Comparison

Glenn Research Center
Cleveland, OH





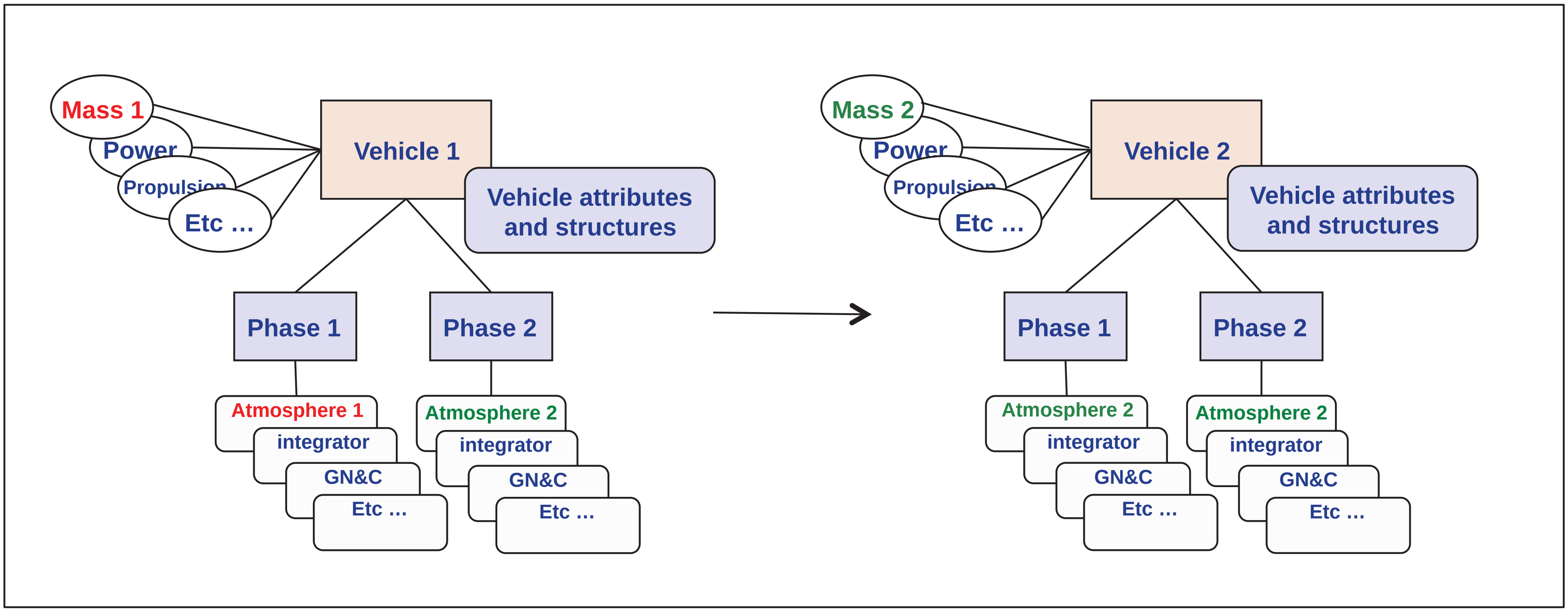




MASTIF Overview – Vehicle(s) Concept

- **Changing a key attribute on a vehicle (e.g. mass properties) necessitates the definition of a second vehicle**
- **Vehicles can be independent (multi vehicle simulation) or they can be "linked" in a sequence defined and controlled by user defined events**
  - When vehicles are linked, they can be thought of as segments of a larger vehicle

Example: Vehicle 1 jettisons mass at user defined condition (e.g. time, altitude, empty tank) necessitating mass 1 → mass 2 and change in vehicle definitions



SPACE

Glenn Research Center
Cleveland, OH

- **SPACE (System Power Analysis for Capability Evaluation) is a model that predicts the performance of spacecraft power systems**
  - SPACE was developed entirely at NASA Glenn, and has been under development since 1988
- **SPACE was the GRC Software of the Year Award winner in 2003, and runner-up for the agency award**
- **SPACE is recognized internationally for contributions to the ISS program**
- **Although originally developed ISS, a version of SPACE was developed the Orion Crew Exploration Vehicle project, and a version is being pursued that can assess performance of SEP systems**
- **SPACE is a tool used for detailed spacecraft power modeling, with integrated capabilities unique in the industry:**
  - Detailed array degradation model
  - Ties to AE8/AP8 radiation models
    - AE9/AP9 in progress
  - PPU/DDU modes
  - Array pointing algorithms
  - Battery models
  - Array thermal model
    - Solar, Earth and power generated
  - Self shadowing
  - Housekeeping power model