

SPECTTRA: A Space Power System Modeling and Simulation Tool

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A Satellite Power Electronic Component Technology Trades and Rapid Analysis (SPECTTRA) tool for technology trade analysis is introduced. SPECTTRA is a Matlab Simulink tool in the beta development stage for conceptual analysis, component sizing, technology and system trades and payoff studies and design of experiment analysis for spacecraft power systems. Satellite orbits are propagated for any given two line element, permitting the analysis of load demands and electrical power subsystem behaviors for various mission scenarios and components. Anticipated performance of theoretical or materials, such as solar array, battery and wire materials are able to be simulated through applying their fundamental properties to documented. Power conversion losses and distribution losses are considered in addition to design life considerations, such as end of life performance and degradation. SPECTTRA permits as much or as little user interaction as desired by being operated using a graphical user interface (GUI); a user can therefore select only which fields are of interest for a simulation. An additional GUI is used for data analysis and plotting functions.

Nomenclature

<i>BOL</i>	=	beginning-of-life
<i>DET</i>	=	direct energy transfer
<i>EOL</i>	=	end-of-life
<i>GUI</i>	=	graphical user interface
<i>f, g</i>	=	generic functions
<i>I-V</i>	=	current-voltage relationship
<i>I/O</i>	=	input-output
<i>LEO</i>	=	low earth orbit
<i>LOS</i>	=	line of sight
<i>PPT</i>	=	peak power tracker
<i>TLE</i>	=	two line element

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I. Introduction

SPACE power system design is a highly coupled process requiring knowledge of all aspects of an intended mission. Spacecraft power system requirements are dependent on orbit parameters, power system load demands, subsystem active/idle states, and mission requirements.¹ The amount of time a satellite will be sunlit and the mission power demands will directly influence the power architecture used, including solar array and battery selection. Analytical preliminary design tools facilitate system development through trade analysis, sizing and cost studies of components and technologies prior to costly outlays. SPECTTRA presents a GUI-based analytical preliminary design tool for estimation of space power system performance through component and architecture trades and mission simulation.

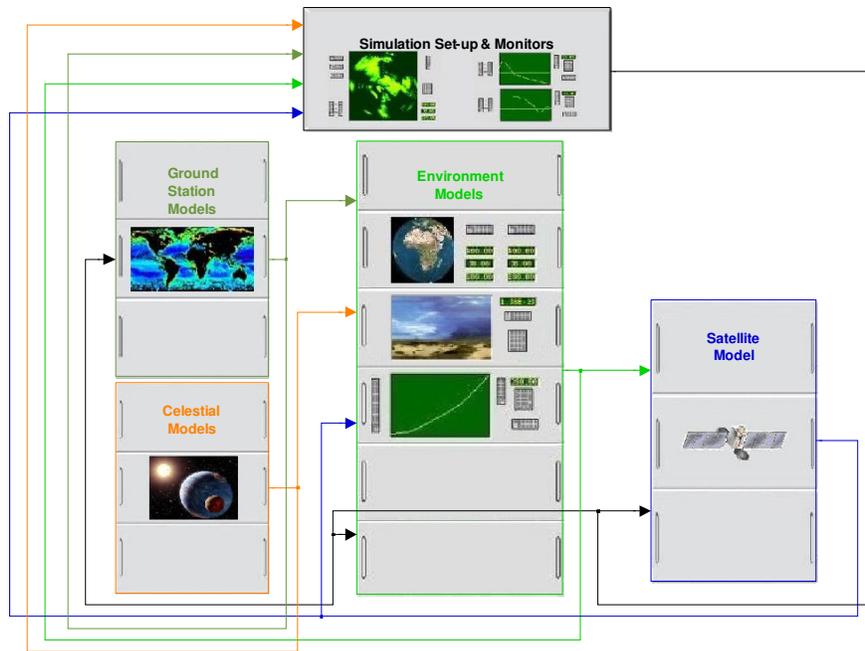


Figure 1 Top Level SPECTTRA Simulation

Many design concepts that may be ignored in traditional preliminary design methods can be pursued in SPECTTRA, such as improved system sizing through simulating active/idle load demands of a particular mission. Analyzing system degradation and EOL performance is also supported through a satellite design life input, satellite exponential degradation function and electrical component efficiency functions, allowing for performance estimation throughout the design life.

Research direction can also be driven by the results of a preliminary design study, e.g. knowing expected values for physical properties of conductors and solar panels or efficiencies of power converters allows expected benefits of new technology to be simulated over the design life of a satellite. Results of such a study can justify further research on a given component or material.

SPECTTRA, Fig. 1, was developed to model typical space power architecture and components. It was also developed to be configurable, permitting satellite power preliminary design analysis such as

- design of experiment studies
- power system conceptual design
- power margin analysis
- component sizing analysis
- technology and system trade studies
- EOL performance analysis.

SPECTTRA created a space power system analysis platform by drawing extensively from the framework developed for the Simulink-based INSIGHT parametric satellite model created at the Air Force Institute of Technology for threat modeling and analysis.²

Transients and higher order effects are not considered in SPECTTRA; component models are traceable to component physics, but use averaged solutions with a one-hertz resolution. This permits long-term full design-life studies to be performed by a fast running model; it was never desired to develop a high fidelity simulation due to the levels of complexity this would entail, slower simulation times and the many, possibly fallacious, assumptions that would necessarily be made at every level of the model. This would also render it impossible for a user to quickly setup a simulation, estimate the power demands for the life of a satellite, change components or parameters and create another estimate.

II. Architecture and Operation of SPECTTRA

SPECTTRA inherited and further developed the INSIGHT satellite model framework that incorporated a coupled system of generic subsystem models found on many satellites as described in Ref. 3. Subsystem models were developed for the Attitude Determination and Control Systems (ADCS), Telemetry Tracking and Command (TTC), Command and Data Handling (CDH), Thermal Management, Payload and Power Regulation Systems.² The interconnection between satellite subsystems, ground stations for telemetry tracking, two-body orbit propagation and mission demands is simulated; however the model did not allow for detailed power system component analysis nor was it flexible enough to simulate different main mission payloads types and their effect on load demand.

SPECTTRA further developed this structure to model load demands of the various subsystems; active/idle voltage states are configurable for each subsystem. The SPECTTRA payload model was developed such that many generic mission scenarios can be simulated including its effect on power demands. The power regulation system in SPECTTRA was developed to contain advanced and user configurable models of components, such as the solar array, bus regulation method and load switches.

Incorporating future functionality is also being facilitated through an architecture that allows for the removal and replacement of model components with new Simulink components that retain the required SPECTTRA data signal format. Data important to power analysis will thereby be logged and displayable in the analysis tools. This capability permits proprietary Simulink models to be developed and interfaced with SPECTTRA.

A. SPECTTRA GUI

SPECTTRA is interfaced through a GUI interface, Fig. 2; this was developed for system initialization, parameter selection, and simulation running. In operation, a user would first open the GUI and then open SPECTTRA Simulink model. A user can then either accept all present parameter values and simulation conditions (defaults or previously saved) or make changes to any desired subsystem. A user is guided along the setup process as fields only become accessible after a required action, e.g. parameters are not selectable prior to a model being loaded. A conscious action is also required to permit access to parameters, forcing a user to select “Edit Subsys” to gain access to subsystem parameters; thereby undesired changes are potentially avoided.

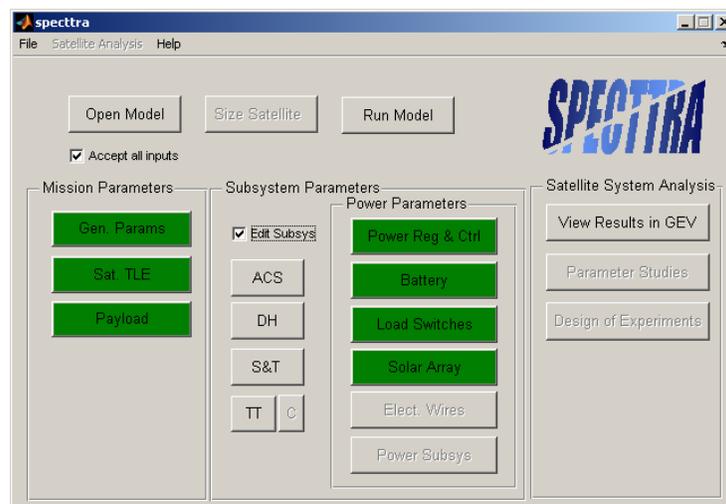


Figure 2 SPECTTRA Main GUI

The GUI allows a user as much or as little interaction with subsystem parameters as desired. Default parameters are standard in SPECTTRA and a user could potentially have little interaction with the parameters or could only

interact with the parameters of one subsystem. The SPECTTRA GUI also has a button connecting the user to the analysis viewer, where data from a previous simulation or the most recent run can be analyzed.

B. Power Subsystem Architecture

The SPECTTRA space power subsystem was developed to simulate various space power architectures in a similar format as the chart in Fig. 3 describes. Currently the SPECTTRA power subsystem considers only DC power system components. The system is designed to accommodate a user simulating a desired architecture by selecting library blocks and GUI mask parameters.

Users can select or enter proprietary data for solar array material, solar array dimensions, DC converter efficiencies, connecting wire materials and lengths, connector resistances, and load switch regulation parameters among other quantities. To simulate only the desired architecture, individual library blocks are used for different regulation techniques (presently series regulator and PPT models are available).

Subsystems are considered as loads in electrical power architectures. Active/idle voltage and current states, user selectable for each respective subsystem, are used to compute power demand from each system. Switching from active to idle is calculated based on mission parameters, such as lighting and targeting conditions. The total loads demands are then used to calculate the total required power from the power system.

Power available is calculated using satellite spatial conditions from the two body orbit propagator determining irradiance conditions of the solar array. The solar array model then estimates the power available based on the selected solar array parameters and component physics. Load demands greater than available solar power are augmented with the battery simulating discharging; if load demands are less than the available solar power, the battery simulates recharging if it is needed. Excess power is simulated as being shunted.

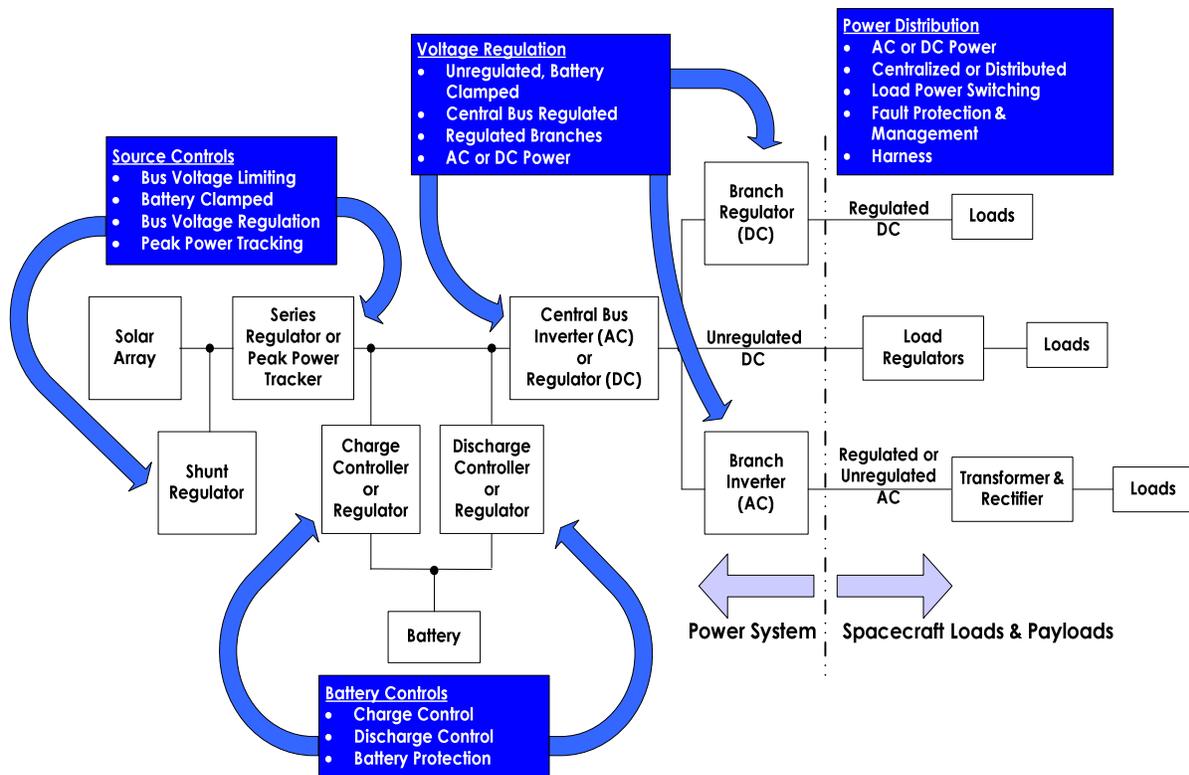


Figure 3 Space Power Architecture

The user selected power regulation method simulates power conversion of solar array outputs to the desired bus voltage level. The solar array calculates both the PPT point as determined through an I-V curve and the regulated I-V values simultaneously. Selected regulation method determines which relationship is used in calculations. The PPT model uses boost and buck DC converters to keep the main bus voltage to the desired level. Converter inefficiencies are estimated and voltage drop to the load branches is considered. The series regulator model operates

with a constant solar array voltage and does not incorporate DC converters. Load switch models then regulate power converted for each load voltage and current requirement and the voltage drop and losses associated with each converter and conductor.

Sizing functions run prior to simulation aid in the initialization and reduce the likelihood that a component will be over/under sized for the simulation. Sizing of power components takes into account expected sunlight conditions of the satellite orbit, degradation of components and the average and maximum power demand.¹ The SPECTTRA sizing functions have been developed to simulate satellite operations for long periods of time to detect absolute maximum power demand that will occur. A situation where the battery and solar array cannot meet load demands would therefore not occur during normal operations. System failure modeling is not considered at this time; however it may be incorporated in the future.

C. Data Logging

Parameters important to simulation analysis are logged in text files by a simulation monitor system, Fig. 4. Logged parameters include:

- Sun position and conditions
- Lunar position
- Satellite ECI spatial positions and simulation time
- Battery charging logic, current, voltage, temperature, state of charge
- Payload parameters including power demand, target spatial relationship with payload, and scenario logic parameter
- Power regulation data including power demand for all subsystems, power available, and losses
- Solar array maximum power points, open circuit voltage, closed circuit current and operating points
- Subsystem power parameters
- Masses for each subsystem.

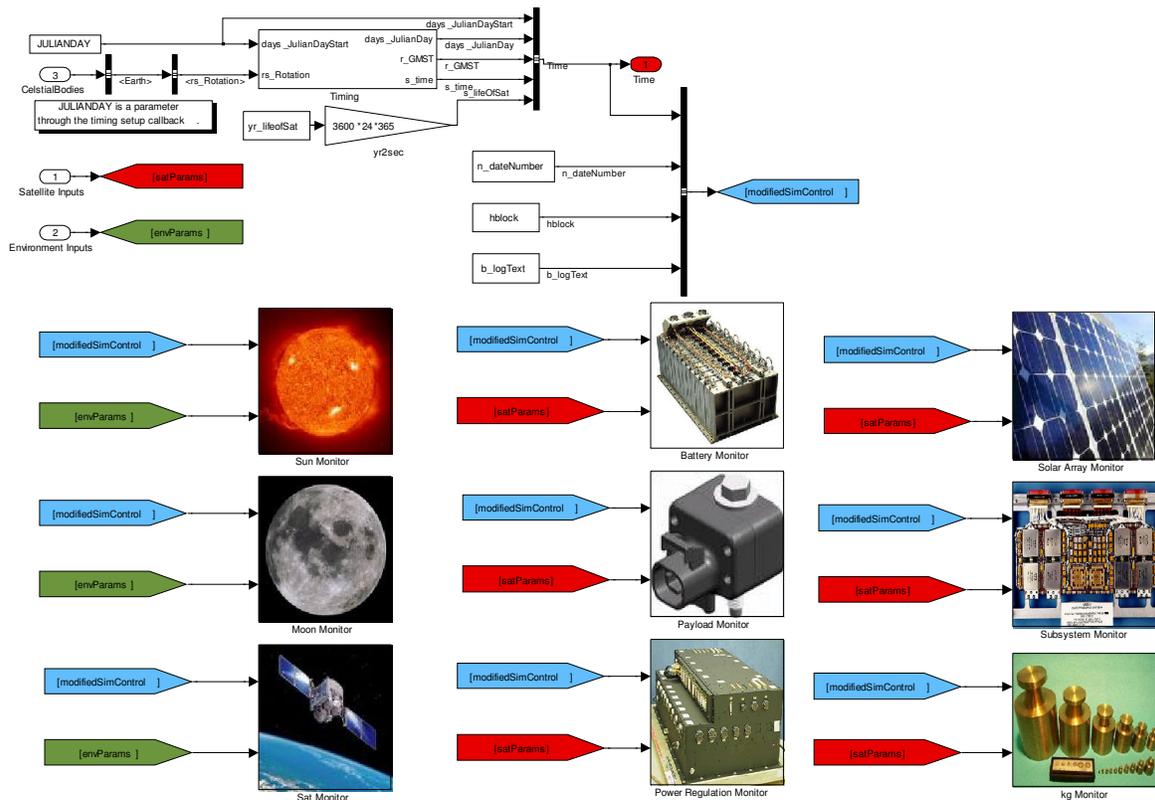


Figure 4 SPECTTRA Data Logging Subsystems

D. SPECTTRA Analysis Viewer

Data logged during the simulation is available for analysis by directly accessing the output text files or through the dedicated SPECTTRA Viewer analysis tool, Fig. 5. This tool was also developed to analyze simulation results through data plotting for the entire simulation or a specified time period.

The ability of the viewer extends to displaying a 3-D globe with the satellite's orbit and ground track for either the entire simulation or a desired time period. The time point for which data is displayed is controlled by a slider bar at the bottom of the viewer. Instantaneous values for power system analysis are displayed bar graphs. Full simulation time results for various power system quantities are also immediately displayed below the bar graphs; a pull-down menu allows for the desired data to be displayed. Detailed analysis is available in the "Analysis" menu; figures are plotted for logged data from each modeled subsystem, the payload, the power system and the solar array.

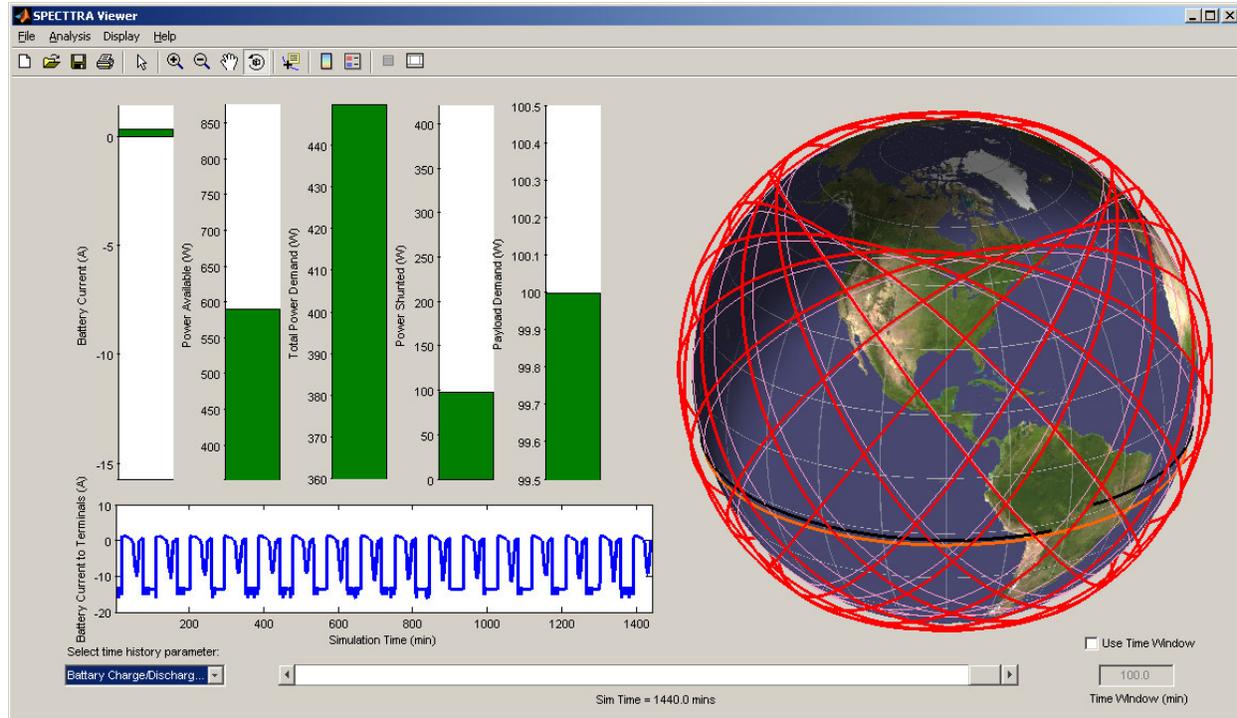


Figure 5 SPECTTRA Viewer

III. SPECTTRA Power System Component Models

The following section overviews power system component models developed in SPECTTRA. Systems such as the ADCS, TTC and CDH are not discussed; the overall functionality of these systems is retained from IMPULSE, however power system parameters were added or refined for the purposes of SPECTTRA. Discussions of the payload model, power regulation and control model, solar array model, battery, and components is presented.

To facilitate material trade studies individual electrical components are modeled; this includes electrical wires, electrical connectors and DC-DC converters. Each component is modeled using averaged solutions, i.e. transients are not considered at this level, mass of each component is also calculated in addition to the electrical losses incurred.

E. Main Mission Payload Model

SPECTTRA developed a main mission payload model, Fig. 6; this model considers the payload mission scenario to calculate power demand. Power fluctuations such as those occurring when an imaging payload is activated when in line of sight to its target are thereby simulated. The SPECTTRA payload model offers user configurable active/idle voltage and current states and scenario conditions.

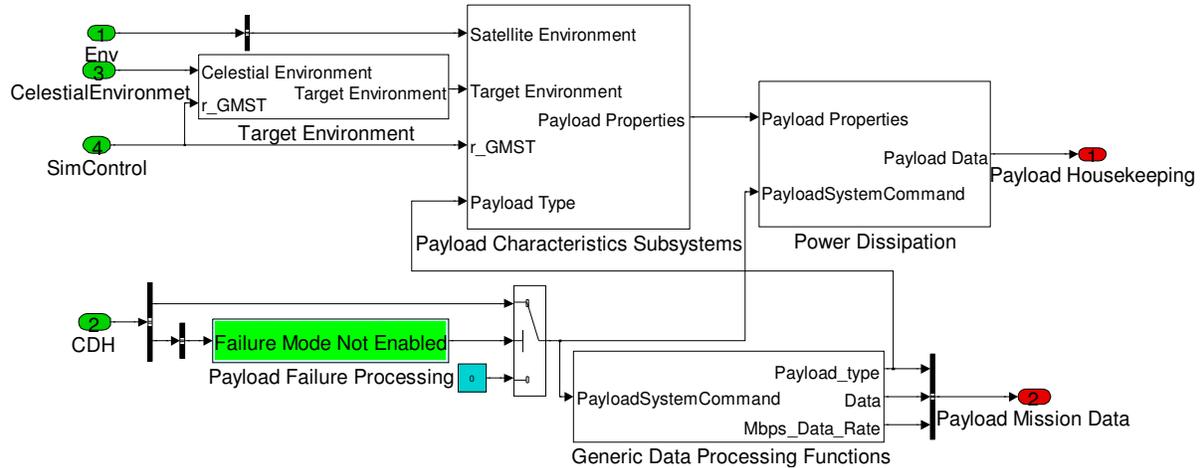


Figure 6 Payload Model

To permit the simulation of many types of missions it is assumed that targeting and lighting considerations are the primary limiting factors of most missions. This methodology provides for the realization of many mission types, for example a laser comm. mission that is active both in day and night would be represented as a targeting mission with no lighting consideration (active whenever the satellite is in LOS with its ground station). Similarly, a target driven imaging mission would be considered as a targeting mission active only when the target is in daylight (or different user selected lighting conditions).

For determining LOS conditions of the satellite to the target and the target to the sun, relative position vectors of the satellite and sun to the target were used.⁵ A mask angle can also be input to simulate excluding payload activity below a certain elevation angle over a target; for instance this could be used to simulate avoiding imaging the side of a mountain instead of a city. Constantly active payloads are also selectable, in which case idle states, lighting and targeting parameters are removed from the user's selection.

F. Solar Array Model

In order for the power system architecture to accurately model the variability in the power availability, the SPECTTRA solar array model was developed. The SPECTTRA solar array subsystem, illustrated in Fig. 7, is modeled at the solar cell level based on the AIAA Space Power System Design Course. The IV curved for the solar array is generated using the short circuit current density, maxim power current density, the maximum power voltage, and open circuit voltage for a particular array material. Five materials are defined in the solar array model including, crystalline Silicon, high efficiency crystalline Silicon, single junction GaAs, dual junction GaAs, and triple junction GaAs. Cell current and voltage degradation due to temperature default values are also set based on the material selection. Default parameters may be overwritten to provide the modeling of different data sets. The model also includes several options for coverglass materials and thickness to determine the coverglass transmissivity losses approximation. Remaining degradation terms for BOL and EOL for both current and voltage are defined by the user. The voltage losses include block diodes, cell interconnect resistance, radiation and thermal cycling. While the current losses include the calibration error, cell mismatching, ground handling contamination, micrometeoroid/orbital debris, on-orbit contamination, radiation, and ultraviolet light darkening. The cell size, active area, number of solar cell strings in parallel, and number of cells in string are defined in the configuration of the solar array. The number of solar cell strings in parallel and number of cells in strings are defined by the sizing of the power system. The user may also specify idealized one axis tracking or body fixed tracking to determine the cosine losses for the sun incidence on the solar array.

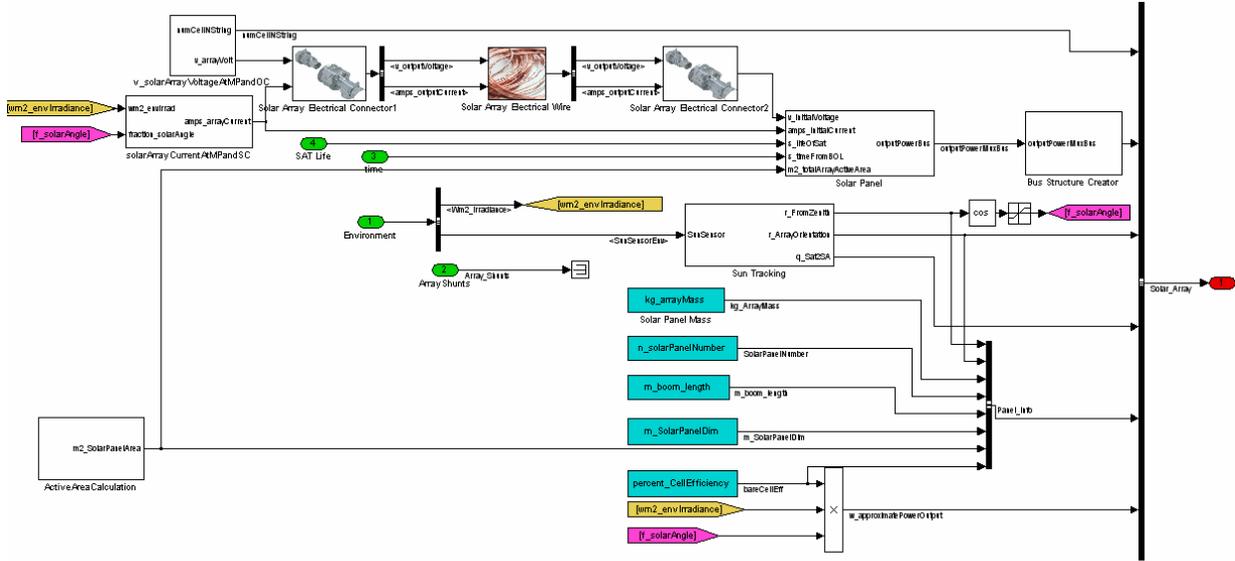


Figure 7 Solar Array Model

G. Battery Model

The energy storage method for the SPECTTRA spacecraft model is the battery model. The battery model was leveraged directly from the INSIGHT development. The model uses table lookups to determine the discharge and charge rates of the NiCad, Ni H, and Lithium Ion batteries at the state of charge.

H. Power Regulation and Control Model

The SPECTTRA power regulation and control subsystem, Figure 8, contains the main bus power regulation method (Regulated or PPT), the charging current calculator, and the battery charge/discharge regulation system. Ancillary systems used for consistency and logic control of systems include power regulation mass calculation, charging logic, bus voltage simulation control and max power available calculations.

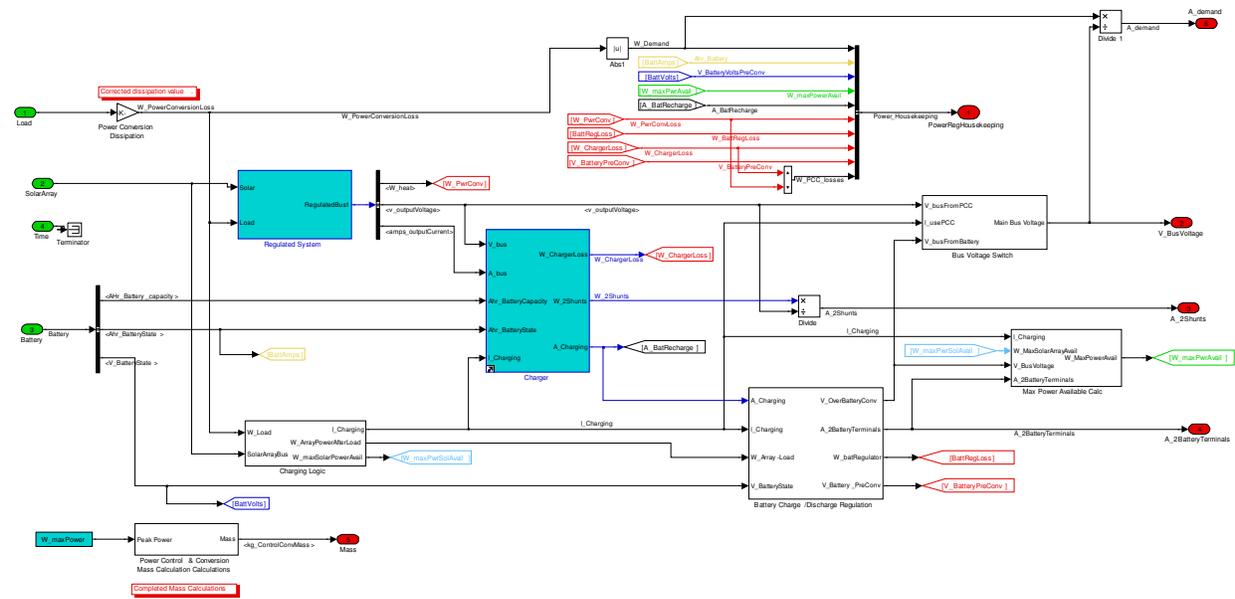


Figure 8 Power Regulation and Control Model

In operation the PPT model uses DC-DC converters to control the solar array determined maximum power point to the desired main bus voltage level. A user specified voltage margin or error is also selectable. Voltage drop from the PPT to the bus is calculated through an electrical wire model. The output of the PPT system feeds the charger subsystem.

If a regulated system was used instead of the PPT, the regulated outputs of the solar array would connect directly to the main bus with no DC-DC converters. The output of the regulated system would then similarly feed the charging system.

The charging system is controlled by the charging logic system. This system determines if it is possible to charge the battery based on load demand and solar array outputs. It also assumes that battery charging is secondary to subsystem operation; only in the situation where there is excess power available and the battery does not have a full charge will the battery be recharged. The present charging system model considers two modes, trickle and regular charging.

A battery charge/discharge regulator is fed by the charging subsystem. This system switches the battery current between charge and discharge mode. For charging is regulated by the system described above, discharging is regulated by a DC converter that keeps the battery discharge voltage at the main bus level.

Ancillary systems, such as the bus voltage switch system and the maximum power calculation are used to monitor voltage and power parameters for data logging and consistency checking. A power regulation component mass calculator system is also included for data signal logging.

I. Load Switches/Branch Regulators Model

The load switch model, Fig. 9, architecture currently assumes to have one branch and load regulator for each subsystem. DC-DC converters are employed to regulate the branch voltage to each subsystem's desired voltage level and simulated the associated losses. Wire models are also included in each regulator to simulate the voltage drop from the regulator to the load. Degradation of converter efficiencies or calculation of converter efficiencies based on power output is supported. Planned revisions to this subsystem include additional architecture types that can better represent the physical locations of the load

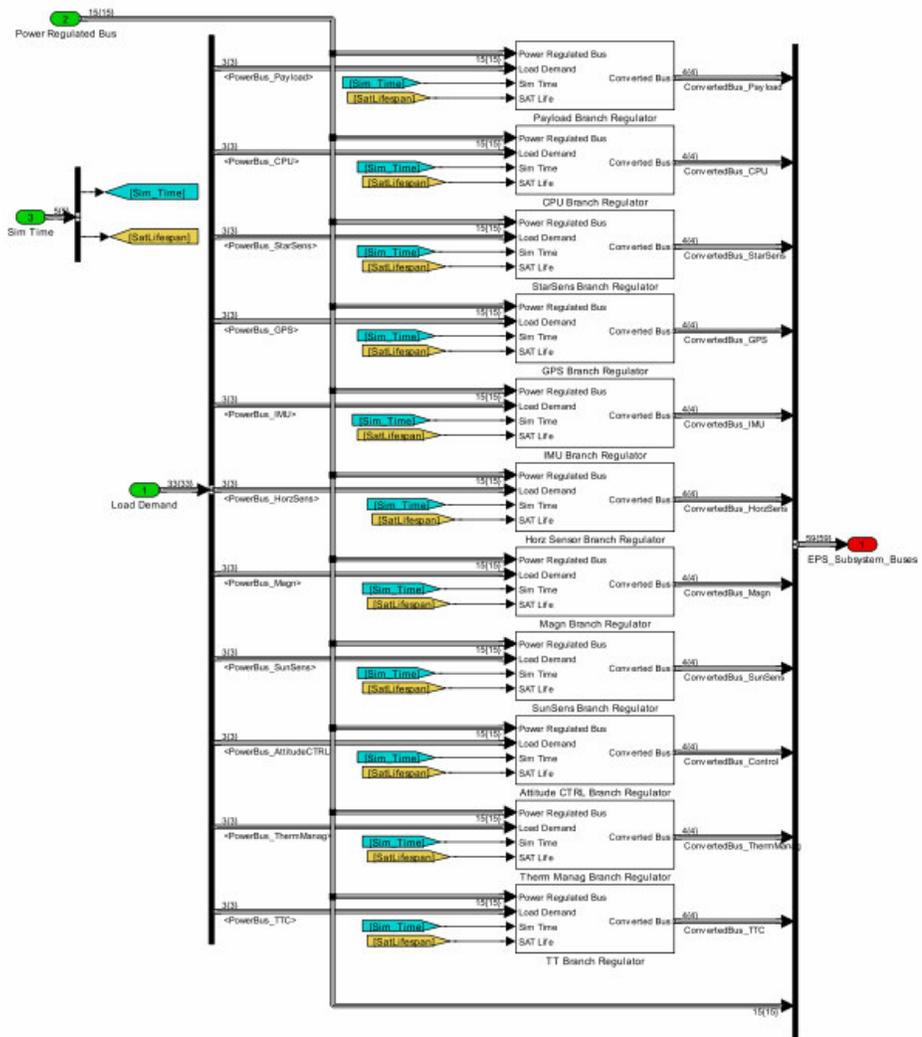


Figure 9 Load Switch Model

regulators with respect to the loads and the main bus.

J. Electrical Wire Model

The electrical wire model, interface shown in Fig. 10, calculates voltage drop across a wire connecting electrical components. The inputs are voltage and current; outputs is a bussed signal containing the voltage at the end of the wire, current through the wire, wire length in meters, wire mass in kilograms and resistance in ohms.

Wire resistance and mass are calculated using fundamental properties of resistivity and density and applied to the input voltage to calculate voltage drop,

$$V_{out} = V_{in} - R \cdot I, \quad (1)$$

where V_{out} is the output voltage of the wire in volts, V_{in} is the input voltage in volts, R is the resistance of the wire in ohms and I is the current flowing through the wire.⁶ This method of calculation also permits a user to input new materials such as ones under development to analyze a potential technology payoff, by editing the data set of wire materials.

The resistance of a wire is calculated as

$$R = \left(\rho \frac{l}{A} \right) / n, \quad (2)$$

where ρ is the resistivity of the material in ohm-meters, A is the AWG-gauge cross sectional area of the wire, l is the length of the wire in meters, and n is the number of wires.⁵ The default value for n is one, if a twisted set of wires is used, n will be equal to the number of wire, with the resulting resistance considered as a parallel set of identical wires. Wire mass is calculated as a function of density and volume (cross sectional area and wire length in this case),

$$M = \kappa(A \cdot l) \cdot n \quad (3)$$

where, M is the mass of the wire in kilograms, κ is the density of the material in kilograms per cubic meter, A is the AWG-gauge cross sectional area of the wire, and l is the length of the wire.⁷

Wire diameter is a user selected field from a drop down list of AWG-gauges. AWG wire gauges are used to accommodate using industry standard wire diameters; it is up to the user to know if the wire is sufficient for the modeled application.

K. Electrical Connectors

Electrical connectors, interface in Fig. 11, such as those used to connect a wire to a given subsystem, are represented as a fixed user input resistance. The voltage drop over an electrical connector is calculated in the same manner as in Eqn. 1.

The wide variety of connectors available and the level of detail required to include a representation of them makes it impossible for SPECTTRA to include a database of connectors. The default value of resistance for an electrical connector is 0.0017259 ohms and the default mass is 0.025 kilograms.

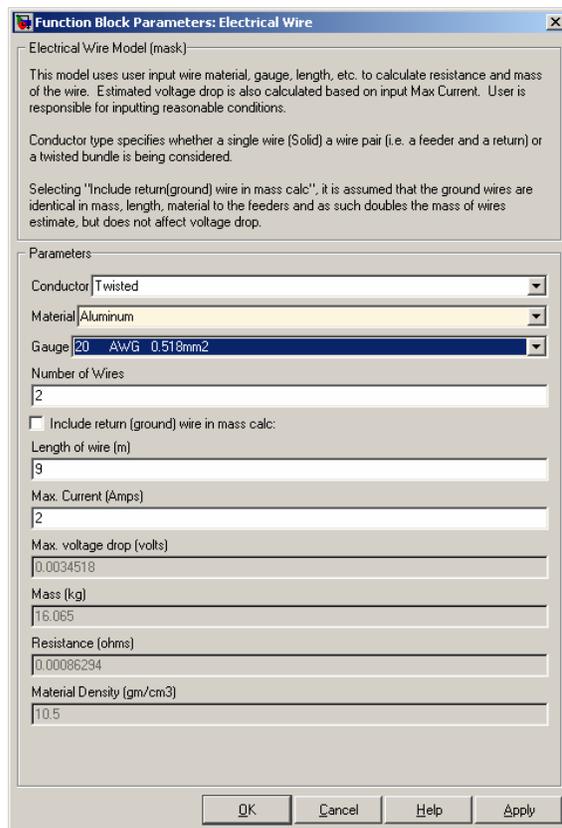


Figure 10 Electrical Wire Mask

L. DC-DC Converters

DC-DC boost (step-up) and buck (step-down) converters are used in load switches and the PPT model to control output voltage. DC converters typically operate with switching frequencies from 100 Hz to 20 kHz.⁸ For the purposes of SPECTTRA, which has a 1 Hz resolution, averaged solutions were used which do not consider voltage and current ripples and other high frequency components.

Duty cycle for each converter is based on the desired output voltage to the input voltage. The ratio of total input power to total output power plus converter losses,

$$P_{out} + P_{loss} = P_{in} , \quad (4)$$

must be accommodated. For a DC-DC buck converter the duty cycle relationship between I/O voltages and current is

$$\frac{V_{out}}{V_{in}} = \frac{I_{in}}{I_{out}} = k , \quad (5)$$

where k is the duty cycle.⁸ For a DC-DC boost converter, the duty cycle relationship is

$$\frac{V_{out}}{V_{in}} = \frac{I_{in}}{I_{out}} = \frac{1}{1 - k} , \quad (6)$$

where k is less than 1 and $V_{out}/V_{in} > 1$.⁸ Power conversion losses,

$$P_{loss} = \left(1 - \frac{eff}{100}\right) \cdot P_{in} , \quad (7)$$

where eff represents the converter efficiency.

Converter efficiency values are determined either by a fixed user input efficiency, through an initial fixed efficiency that degrades with the satellite similar to solar array degradation, or with a user defined 1-D lookup table of total output power.

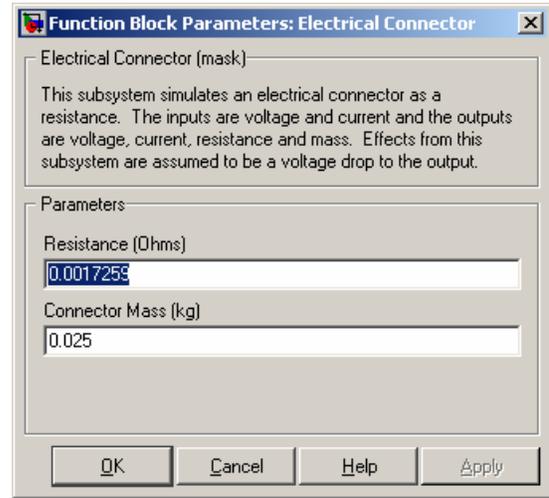


Figure 11: Electrical Connector Mask Interface

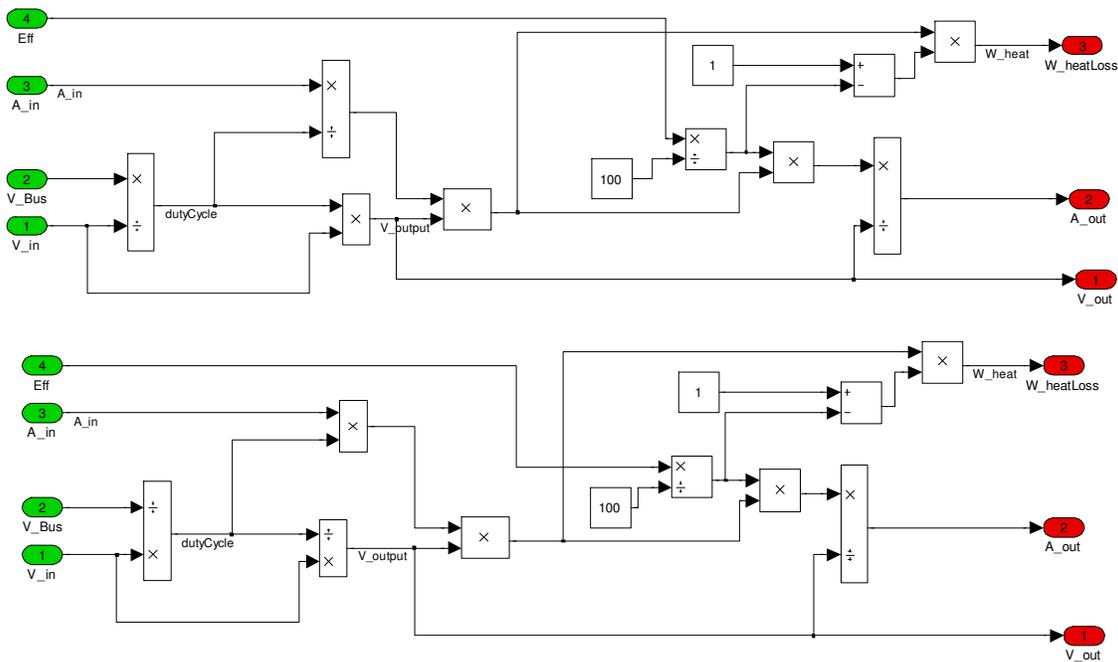


Figure 12 Boost (top) and Buck (bottom) Converter Models

IV. Simulation Data Analysis

For consideration herein, results are presented from a simulation of an example main mission imaging payload for a LEO satellite. A target at the location of latitude 39° 10' 45" N and longitude 82° 5' 46" W was selected; a targeting payload scenario was defined such that the payload would only be active when the target is sunlit and the satellite is within LOS of the target. Data for one day of satellite operation was simulated. For the power regulation system a PPT was selected and default parameter values were used.

Simulation data was analyzing using the SPECTTRA Viewer and figures were generated through user selection. Payload parameters are displayed in Figure 13. This figure illustrates the functionality of the payload in the first two graphs: the first graph displays the lighting conditions of the target (1 is sunlit, 0 is umbra), the second graph displays satellite LOS to target (1 is within LOS, 0 is LOS not met). This targeting mission required both conditions to be met; the results display this functionality in the bottom graph which shows spikes of payload activation only when both conditions are met.

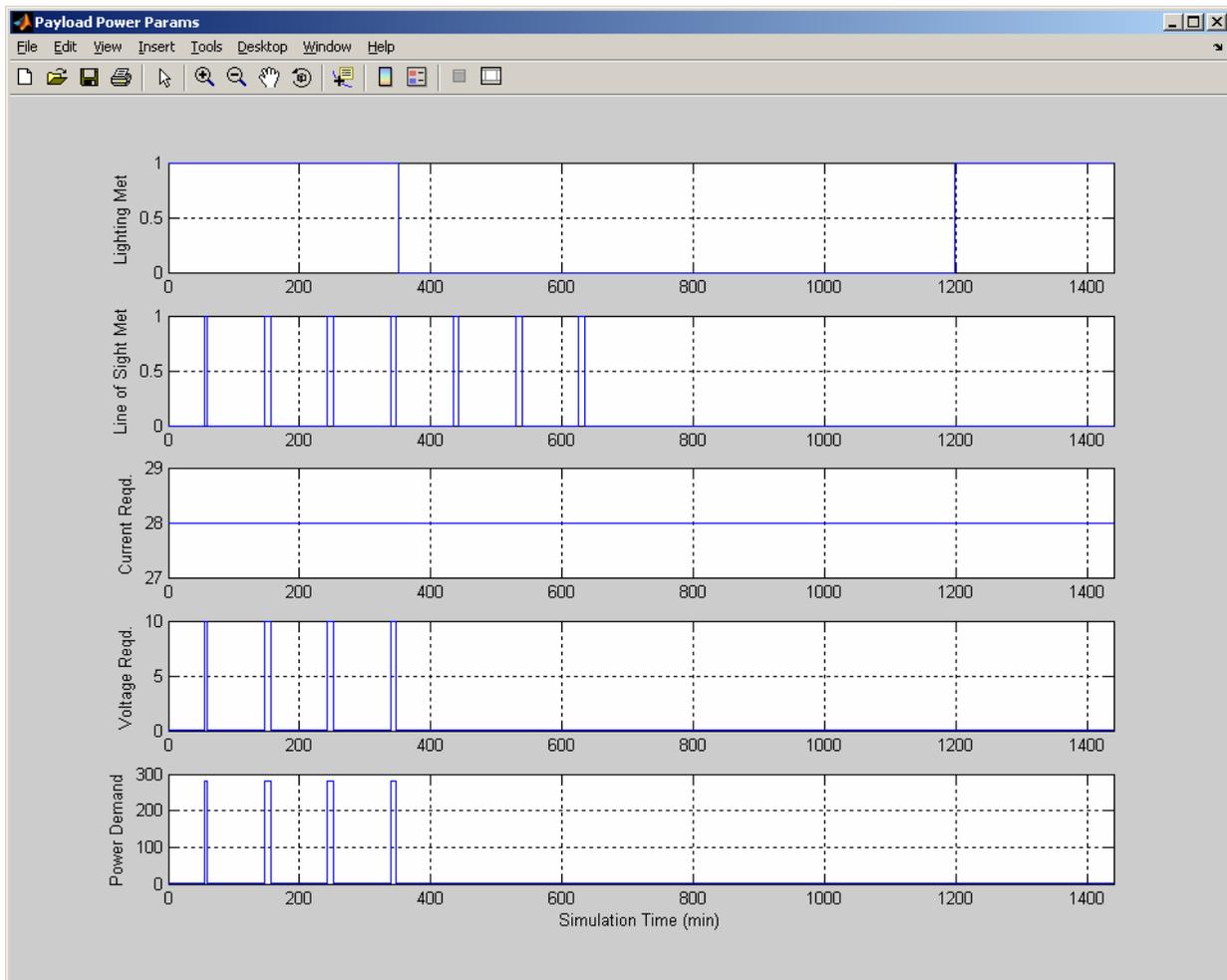


Figure 13 Payload Parameter Analysis

Solar array parameters for the simulation are shown in Figure 14. These graphs illustrate the solar array parameters of maximum power points, short and open circuit points and the operating power.

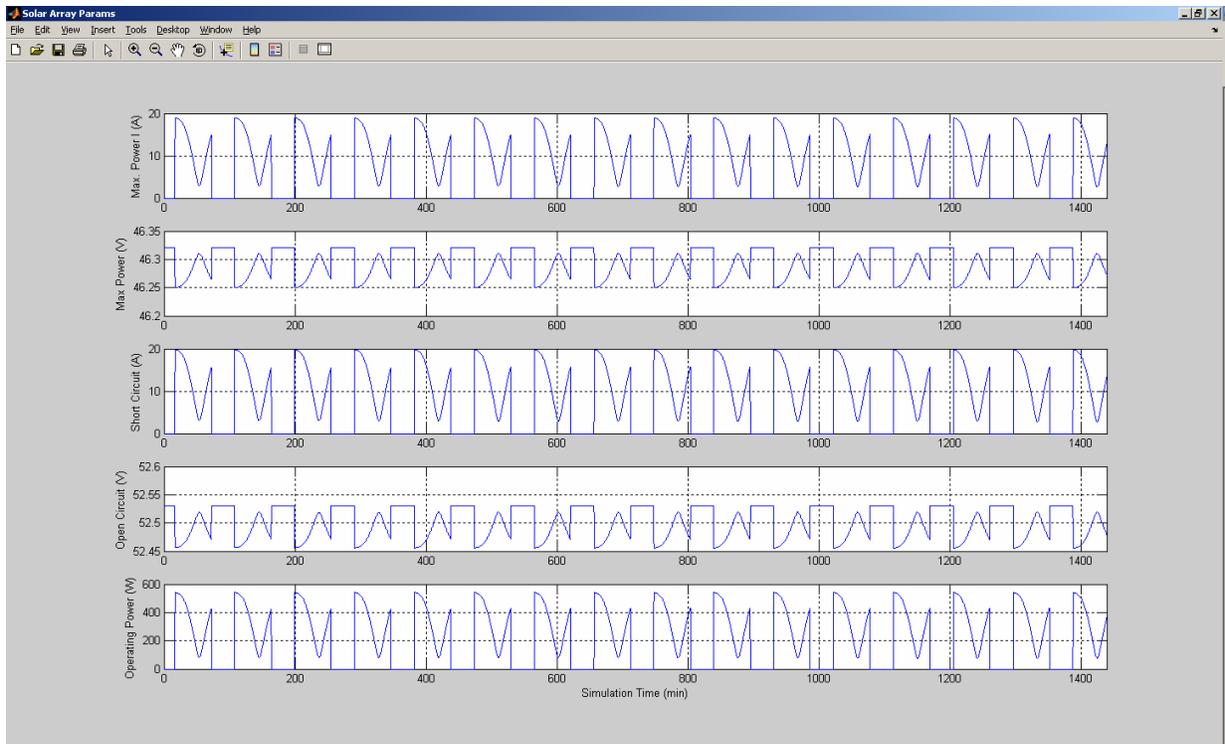


Figure 14 Solar Array Analysis

Analysis of the power system architecture is displayed in Figure 15. This graph plots the total power available, the total satellite power demand, the battery charging power and the power dissipated by shunts. The subset figure displays data for a user selected 100 minute window of the simulated data. This figure was generated using the time slider bar described above.

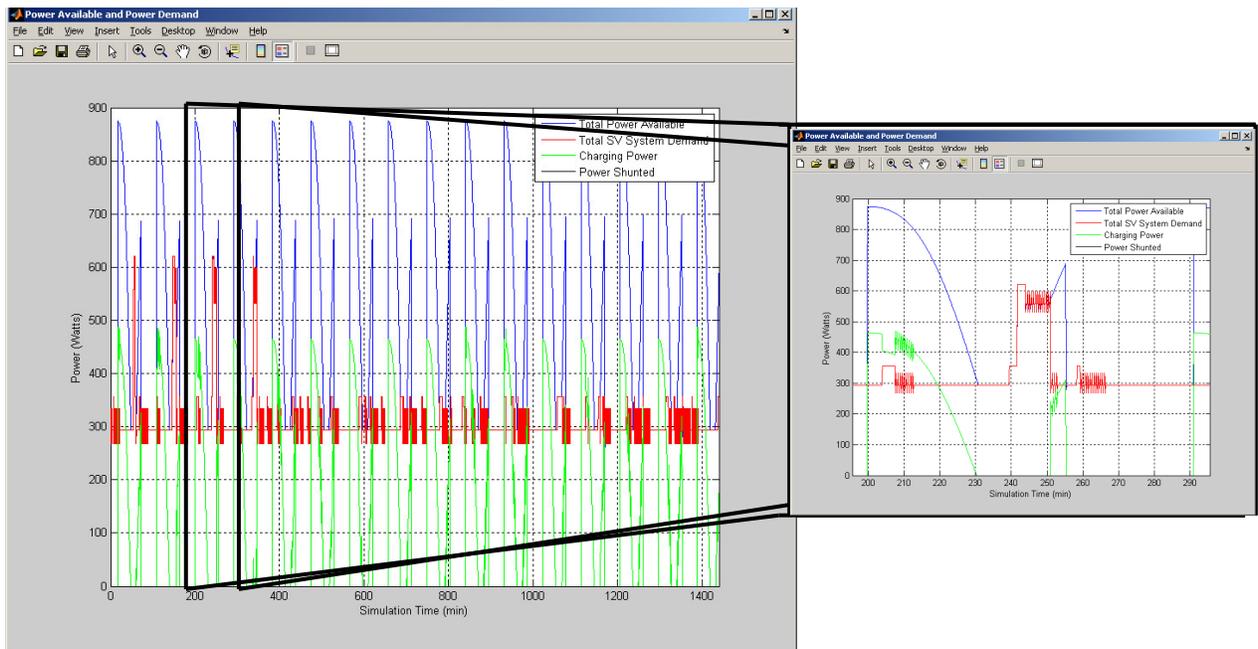


Figure 15 Analysis of Power System Architecture

V. Conclusion

An analytic tool for space power architecture analysis and design has been presented. SPECTTRA represents a coupled space vehicle system model that considers all major subsystems and orbit parameters. Power system models, components and sizing tools facilitate sensitivity analysis to changes in architecture and subsystem configuration. With payload missions simulated and load demands available for analysis for the life of a satellite, SPECTTRA permits analyses, trade studies and parameter studies for many power system studies.

Acknowledgments

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