Electrical Power System (EPS)

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What is EPS responsible for?

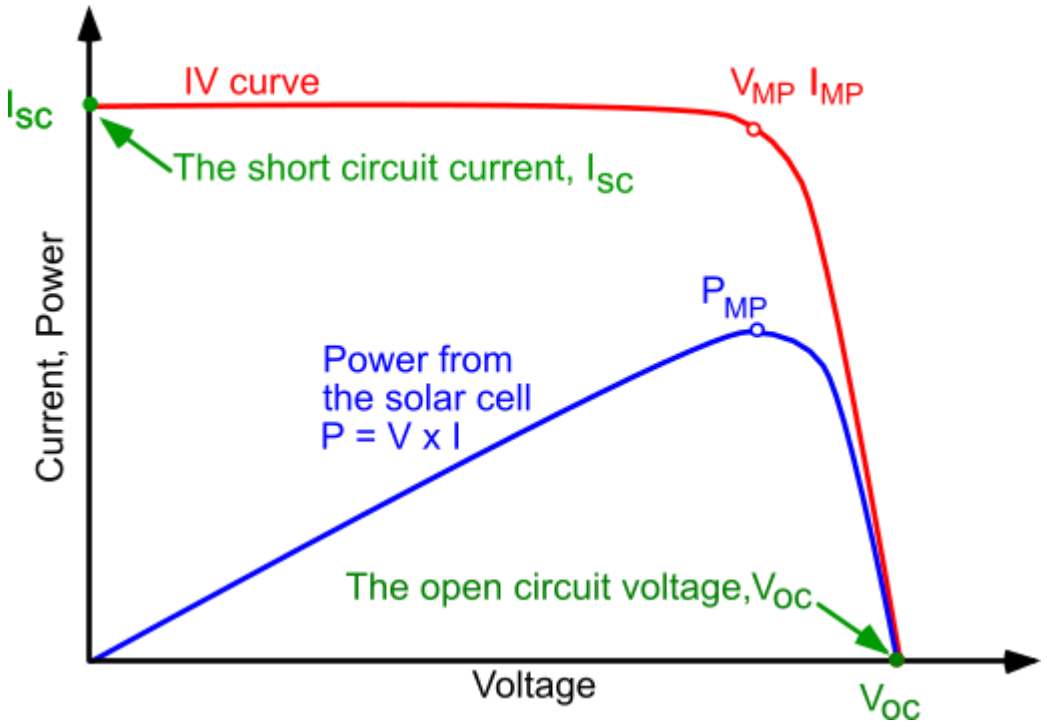
Generation	Storage	Regulation/Distribution	Power Inhibits

• How is power generated? Solar panels
• Array configuration (deployables/strings)
• MPPTs
• What is my energy per orbit
	• How is energy stored? Batteries
	• Battery sizing/config
	• Charge/discharge rates
	• Battery capacity
	• Battery voltage v. Solar array voltage
	• Protection circuits
	• Cell balancing
		• How is energy regulated or distributed? Through the EPS itself
		• Voltage regulation
		• Regulation tolerance
		• Buck, boost or buck/boost
		• Channels
		  • 3V, 5V, 12V, other
		  • How many?
		• Current output
			• Power path shall be two fault tolerant to ensure spacecraft is off and is safe to LV. Accomplished through inhibits.
			• Two-fault tolerant means that two of the inhibits could fail and the vehicle will remain off

Energy Harvesting Methods

- Direct Energy Transfer
  - Simplest method but least efficient
- Maximum Power Point Controller (MPPC)
  - Manually define IV curve set point
- Maximum Power Point Tracker (MPPT)
  - Measure IV curve and track max power point

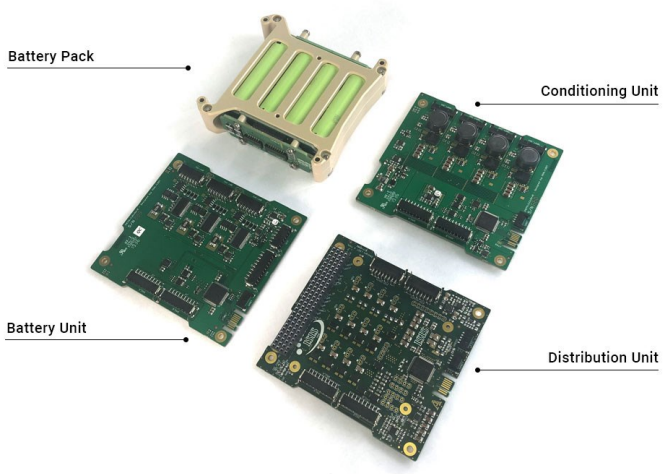
IV Curve for a Solar Cell



https://www.pveducation.org/pvcdrom/solar-cell-operation/iv-curve

Power Generation

- Solar Cells, Solar Arrays
  - Panel Configuration
  - System power positivity
- Maximum Power Point Tracking
  - Monitors panel output and adjusts to pull maximum power
  - Around 93%-97% efficient
- Batteries
  - Battery pack voltage vs solar array voltage
  - Must be able to last through an eclipse



Isispace EPS

https://www.isispace.nl/building-blocks/services/mission-design/

Regulation, Distribution, and Custom Boards

- Regulation/Distribution Requirements
  - Interface needs for each subsystem
  - Voltage rails required by subsystems
  - Average and inrush current requirements for each voltage rail
    - Calculate the current draw for each voltage rail by mode
  - Voltage, current, tolerance, and other details will be derived from the hardware specific interface control documents (ICD's)
- Technical requirements commercial off the shelf (COTS) hardware may not meet
  - Power inhibiting, proper safety inhibits for U.S. launch vehicles
  - Not enough serial ports, memory, or other peripheral features

Requirements

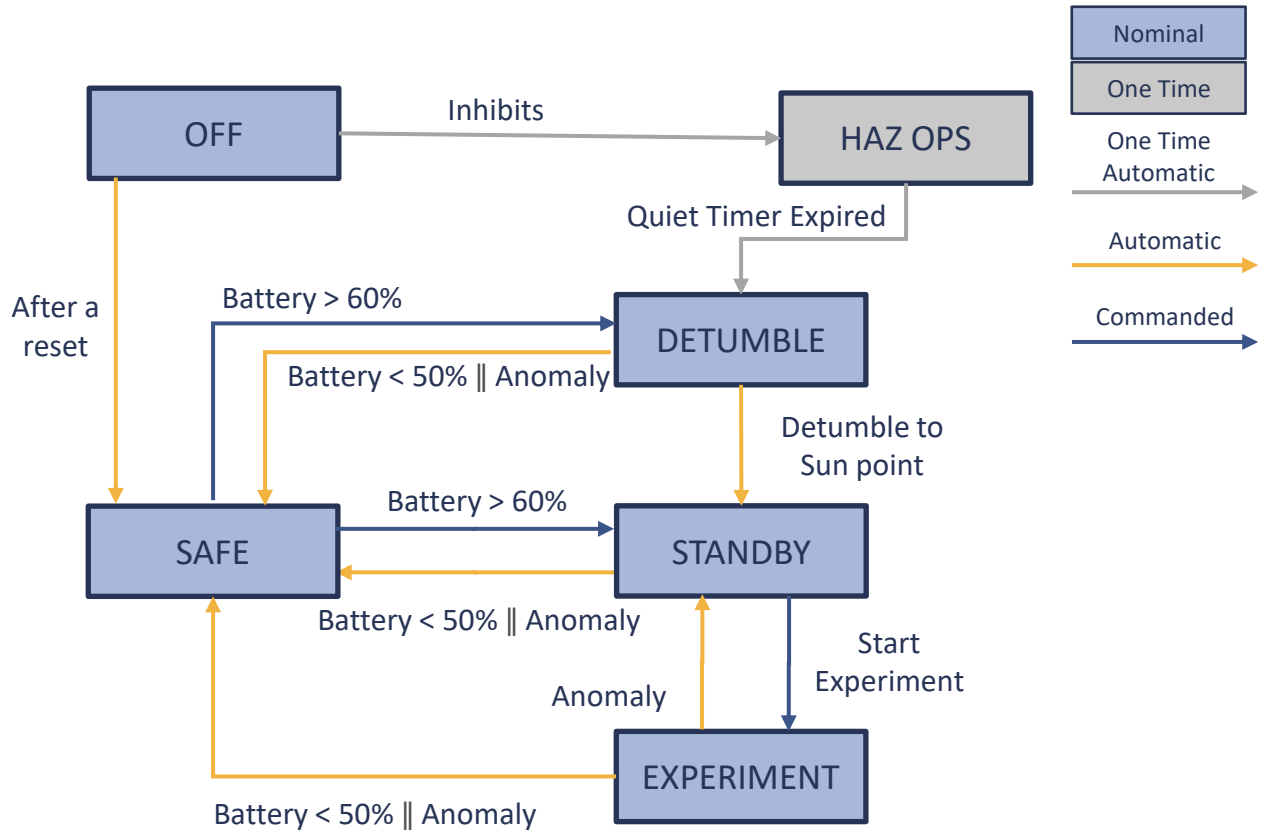
Requirements

- Drivers:
  - CONOPS
    - What does the spacecraft need to do? How long? How often?
    - Battery needs to survive in a tumble
    - Battery thresholds account for many automatic mode changes into safer modes
  - Systems
    - Powers the whole satellite
- Flow:
  - Determine top level drivers
    - “I need enough power for my satellite during its lifetime”
  - Determine derived requirements
    - e.g. Power draws in each mode, solar generation, battery storage capacity
  - Sanity check values
    - Do solutions that meet those requirements exist?
  - Important not to write requirements as expected performance

Some CONOPS Considerations

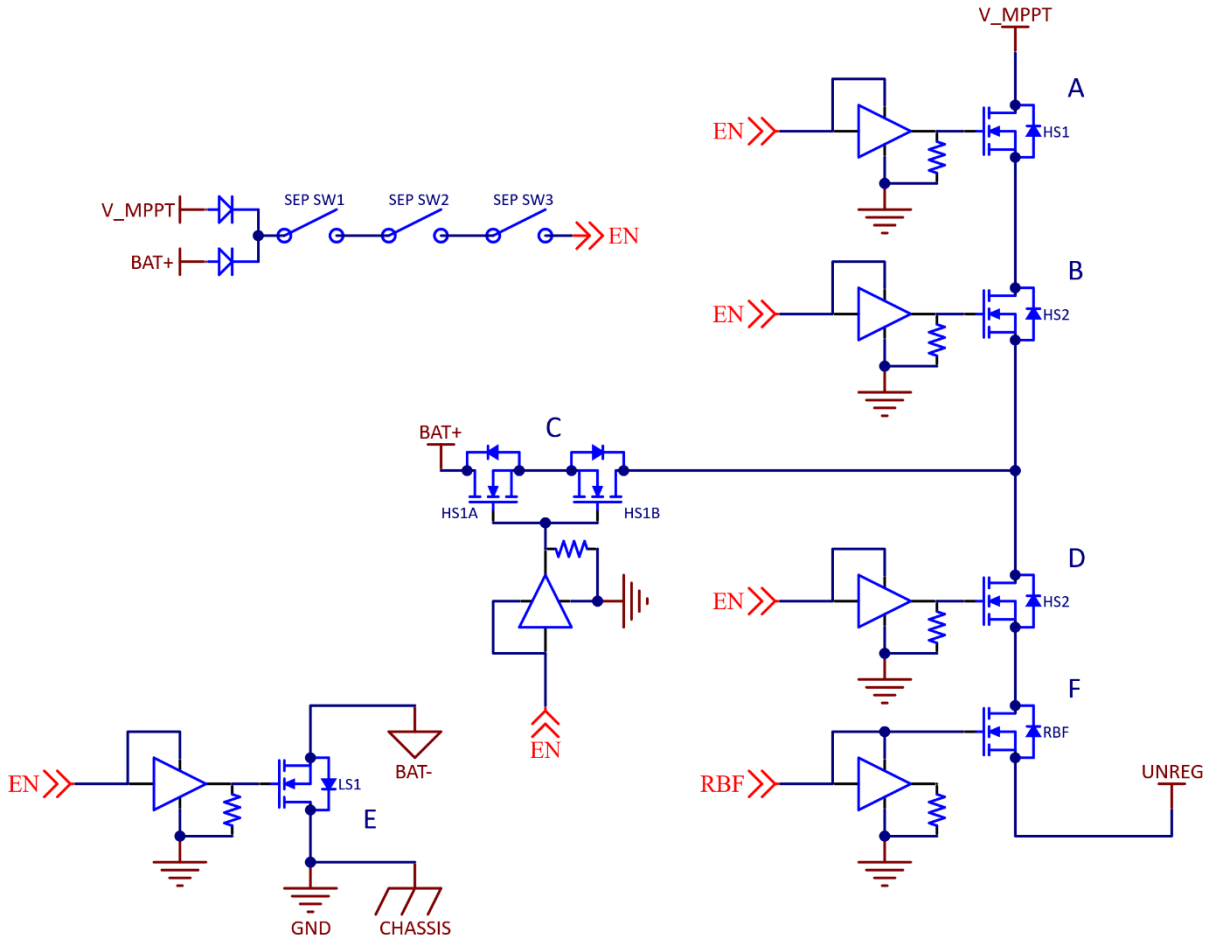
- Battery thresholds account for many automatic mode changes into safer modes
  - Satellite must be commanded to get out of Safe Mode
- For ShipSat (See Mission Design Course), mission dependent
  - When battery level gets below 50% SoC it will push the satellite into Safe Mode
  - When battery level gets above 60% the battery is safe to go into a higher power mode

ShipSat State Machine



Inhibits

- Purpose is to inhibit (stop) power from flowing through the system
  - Hard requirement per launch vehicle: If you do not meet them, you will not fly
  - Different launches have different requirements. UNP-levied requirement covers all
- Three types of electrical inhibits:
  - Activation – also known as separation switches, determine the state of the control signals for the power-rail inhibits
  - Power-rail – break the connection between a source and a load
  - Installation inhibits – also known as insert before flight (IBF) or remove before flight (RBF). Externally accessible control that ensures the satellite is off during ground operations, regardless of activation inhibit state
- Why is this important?
  - Ensure the satellite will not prematurely turn on and create hazards to the LV, LV crew, and other satellites



Analyses and Testing

Analyses: Power and Energy Budgets

These budgets answer…

How should the system be sized?

- How much solar power do I need/is it enough?
- How much battery capacity do I need/is it enough?

Am I power-positive in any given mode?

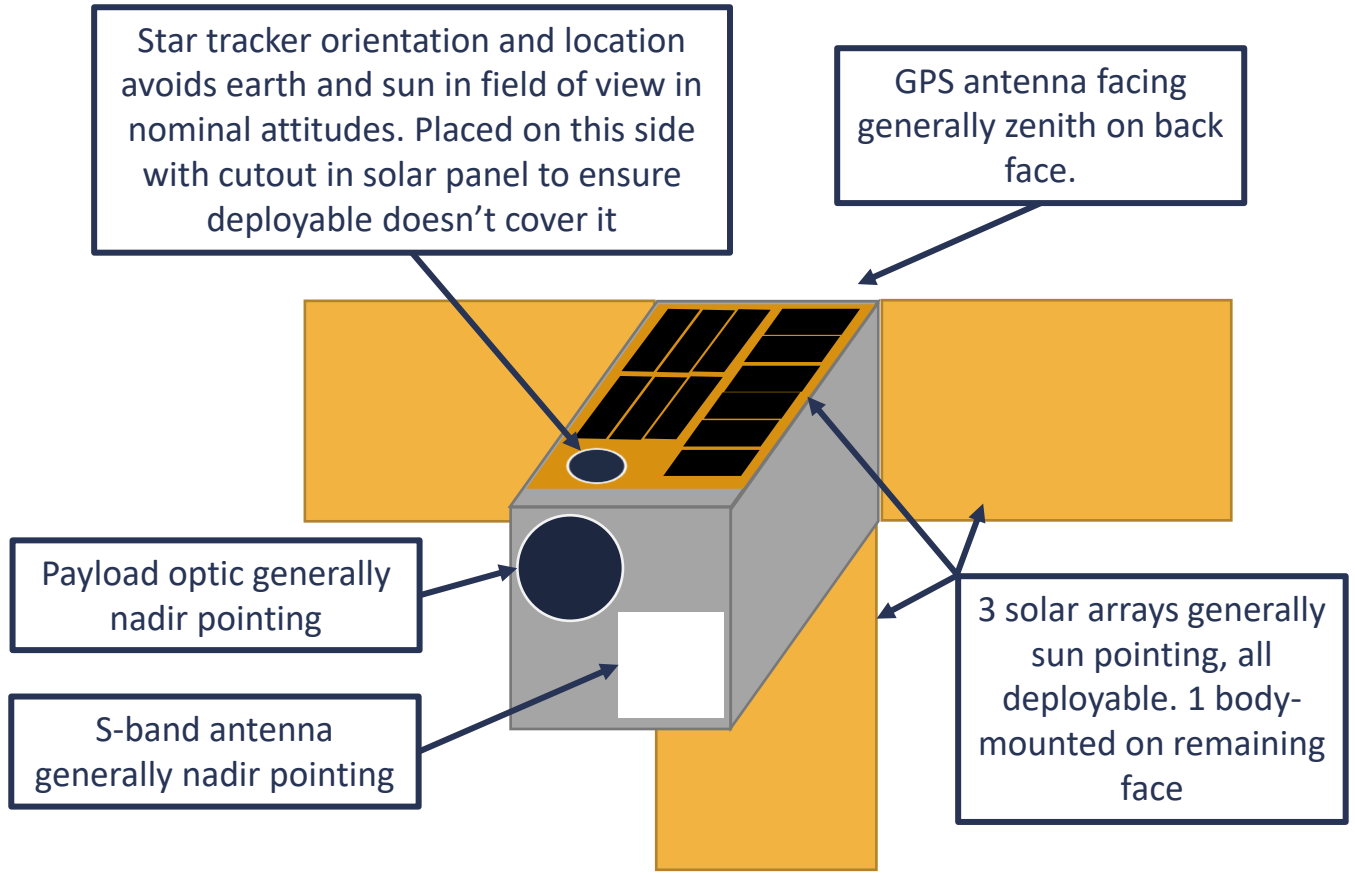
- What is the power draw of any given mode?

What are the impacts to CONOPS?

- How long can my payload be on?

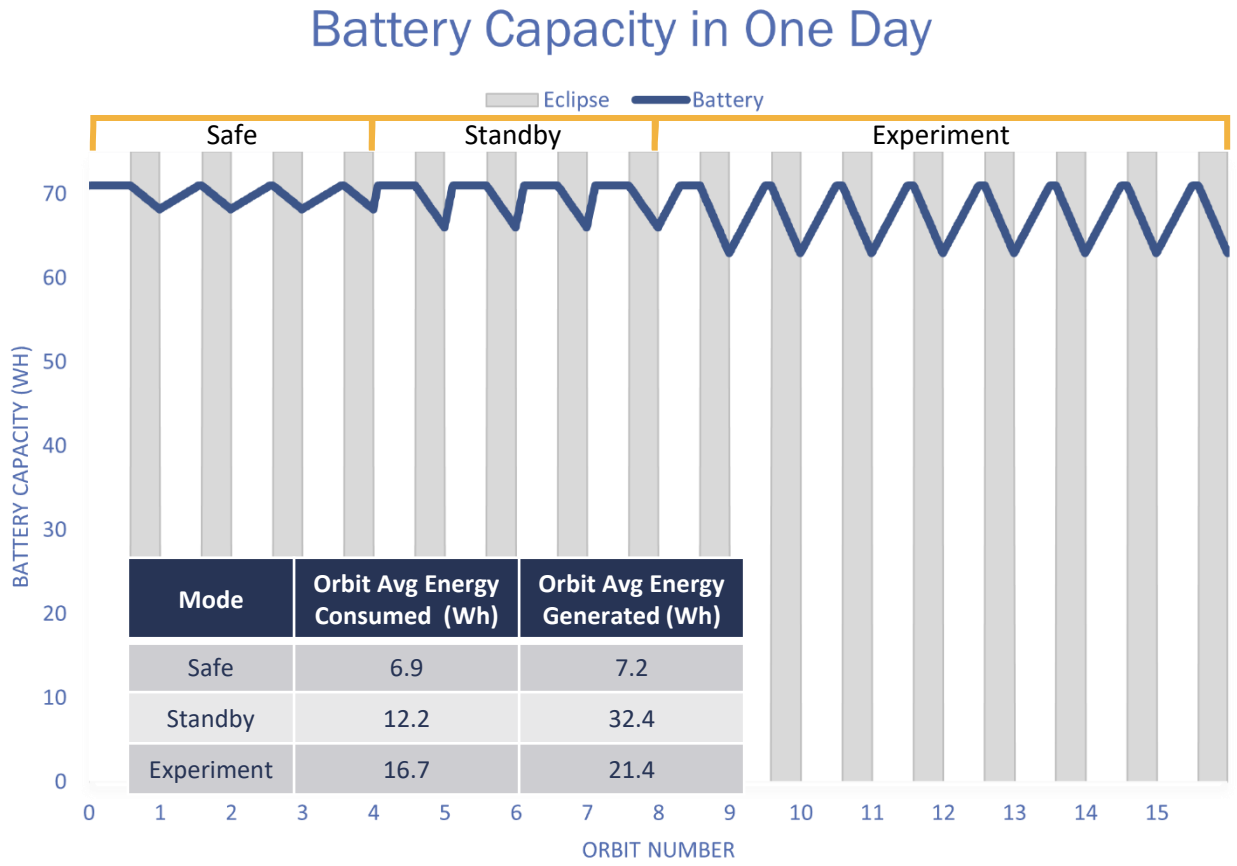
ShipSat Example

- 3 deployable panels, 1 body-mounted panel
  - Each panel can generate up to 12W
- Modes:
  - Safe, tumbling
    - 6.9 Wh draw, 7.2 Wh generation
  - Standby, sun-pointing
    - 12.2 Wh draw, 32.4 Wh generation
  - Experiment, imager nadir-pointing
    - 16.7 Wh draw, 21.4 Wh generation
  - Sequence: 4 safe, 4 standby, 8 experiment
- Assumptions
  - 40% in eclipse
  - Battery SOC must stay above 50%
    - If 50% is reached, switch to safe mode
    - Return to standby at 60%



Realistic CONOPS

- Assumed realistic mode sequence (mission dependent)
  - 4 orbits safe
  - 4 orbits standby
  - 8 orbits experiment
- Results
  - Power positive across all modes
  - Initial design closes, future work should critically evaluate assumptions



Mode	Orbit Avg Energy Consumed (Wh)	Orbit Avg Energy Generated (Wh)
Safe	6.9	7.2
Standby	12.2	32.4
Experiment	16.7	21.4

How can we refine and add more fidelity?

Refining Energy Balance

Improved CONOPS

- Mission sequence
  - Mode and component switching
- Environmental effects
  - Eclipse times
  - Solar panel temperatures
- Orbit and attitude

Consistency with other analyses

- ShipSat assumed 5 images per day, why is the imager on whenever it is in sun in the power/energy budgets?
- What are the requirements?

Margins

- Safe mode margin is small – somewhat concerning
- Other modes have plenty of margin and can accept more risk

Refining Energy Balance

Component duty cycles vs actual time-phasing of power draw

- Power duty cycle averages draw over an orbit rather than providing instantaneous draws
- Multi-orbit trends may be valid, but slopes within an orbit period are not
  - Imager on during day, off during night
  - Radio transmit on for a few minutes at high power draw, then off for a long time

Solar cell ageing

- End of life (EOL) vs beginning of life (BOL) efficiency
- Example: Spectrolab ITJ BOL 28.3% EOL 22.5%

Battery degradation

- Battery cycles on orbit and in testing
- Allowable depth of discharge will affect this

Power generation during imaging and tumble were very loose estimates

Shading of panels if applicable

Many more…

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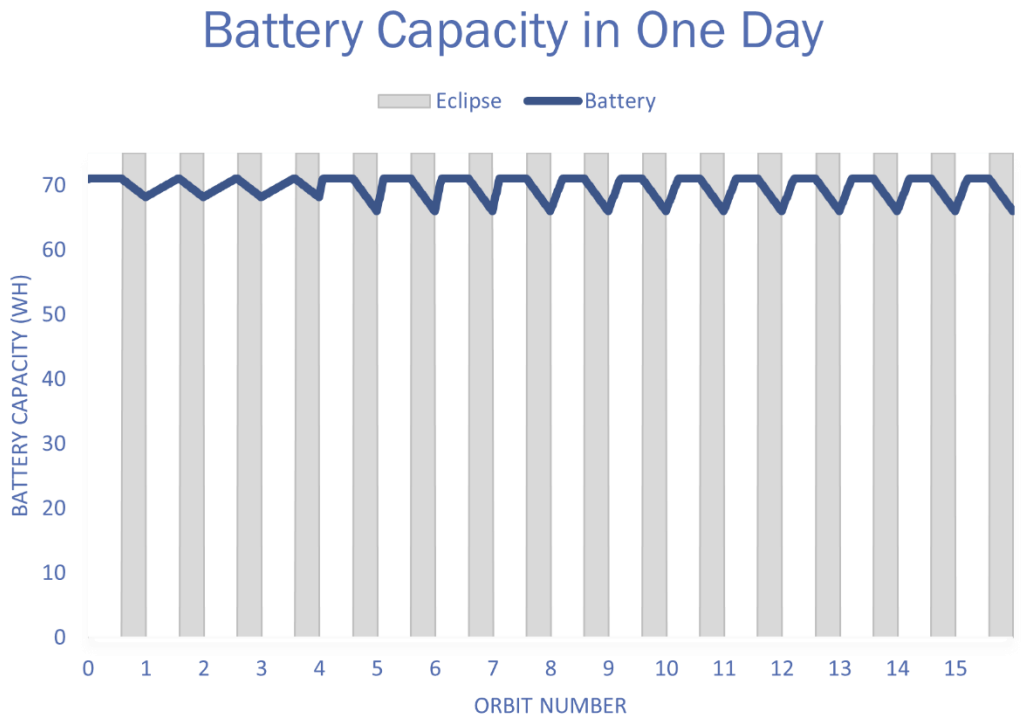
ShipSat Power Consumption

- Capture radio Tx and payload imager power consumption and duty cycles in energy budget
  - In pass, radio Tx will draw a full 6W
  - In experiment, imager will draw a full 5W
  - How does this impact the energy balance?

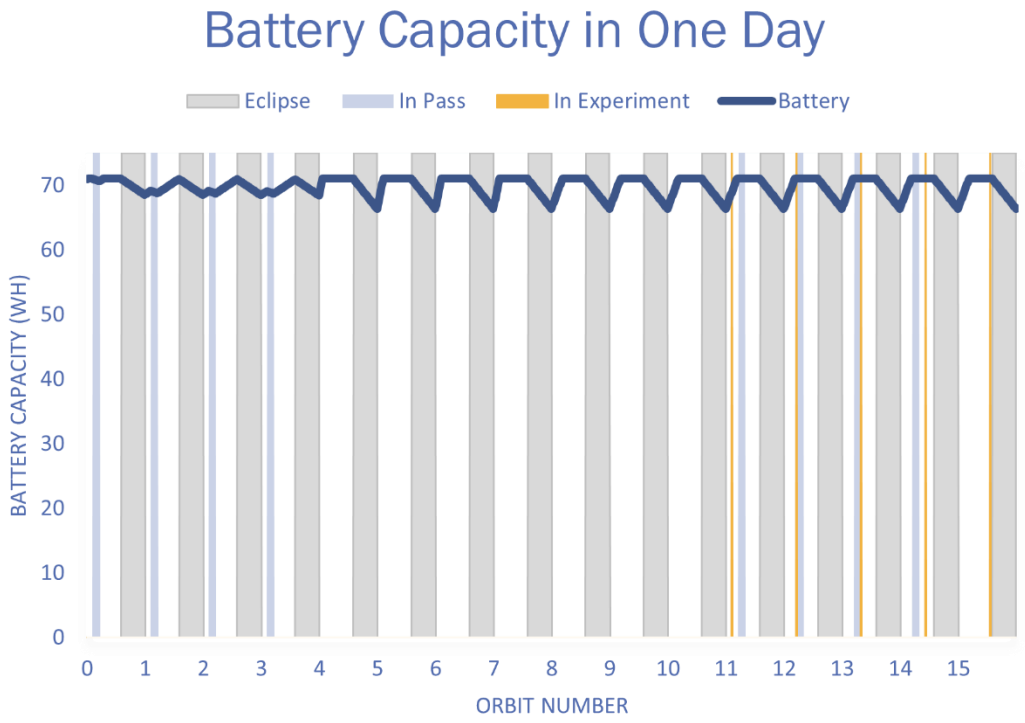
Component	Component Draw	Safe Mode		Standby Mode		Experiment Mode	
	(W)	Duty Cycle	Power Draw (W)	Duty Cycle	Power Draw (W)	Duty Cycle	Power Draw (W)
Power System	0.5	100%	0.5	100%	0.5	100%	0.5
Radio Tx	6	10%	0.6	10%	0.6	10%	0.6
Radio Rx	2	100%	2	100%	2	100%	2
ADCS	2	0%	0	100%	2	100%	2
CDH	1	50%	0.5	100%	1	100%	1
Heater(s)	2	50%	1	50%	1	50%	1
Payload Imager	5	0%	0	0%	0	60%	5
GPS	1	0%	0	100%	1	100%	1
Power Draw Per Mode			**4.6 W**		**8.1 W**		**11.1 W**

ShipSat Refined Energy Budget

Old



New



Radio TX slightly impacts safe mode. Experiment mode effects are negligible

UNP Testing

Solar Array Testing

- Verify array output with a known source for validation after environmental testing
- Verify maximum array output
- Verify array functionality with the MPPT/DET inputs to the power board

Battery Testing

- Capacity verification through charge/discharge testing
- Over-voltage cutoff verification
- Under-voltage cutoff verification

Regulation Load Testing

- Test regulators to maximum expected load plus 10%
- Verify line regulation to the most sensitive component on that rail
- Sub-system in-rush testing
- Power switch load testing

Inhibit Testing

- Verify power sources are disconnected from the system when inhibits switches are depressed
- Verify power sources are connected to the system when inhibit switches are released