



A Concept of Operations for Tunable Optical Orbital Power Beaming to the Lunar Surface

E. Ballantyne



SACD
SYSTEMS ANALYSIS AND CONCEPTS DIRECTORATE



Agenda

- Space-Based Solar Power (SBSP) Background
- Frequency Down-selection
- General ConOps
- SBSP System Power Classes
- Client Charge/Discharge Analysis Results



Space-Based Solar Power Background

- Beaming power in the form of microwave or optical frequencies to some receiver
- **Why?**
 - Exploration of permanently shadowed regions
 - Surviving lunar night
 - Reducing landed mass on the lunar surface
 - Search and Rescue activities on the lunar surface
 - Power flexibility for roving assets
- **Current & Ongoing studies:**

Who?	What?	When?
Naval Research Laboratory	SBSP component payload aboard the X-37B Space Plane	2020
California Institute of Technology (Caltech)	SBSP Demonstration	2023
Japan & Air Force Lab (DARPA)/Northrop Grumman	SBSP Demonstrations	2025
China	SBSP Demonstration and fully operational station	2030
ARFC, ARC, GRC, LaRC, DoD, and DARPA	Ongoing Research on power beaming and enabling technologies to power aerial vehicles on Earth and Lunar surface assets	---
JPL and MSFC	Working on Lunar SBSP	Now
LaRC	Orbital Power beaming to Assets on the Lunar Surface (OPAL)	Now



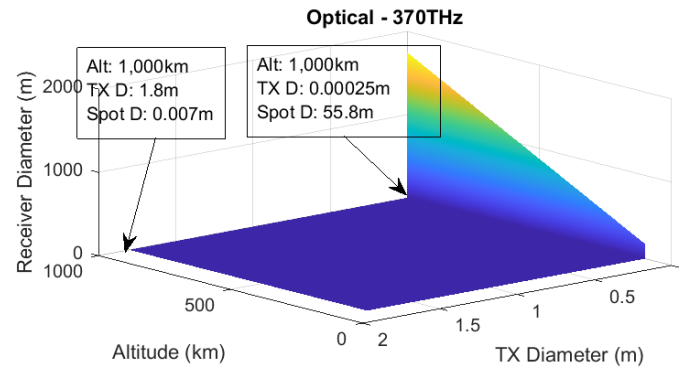
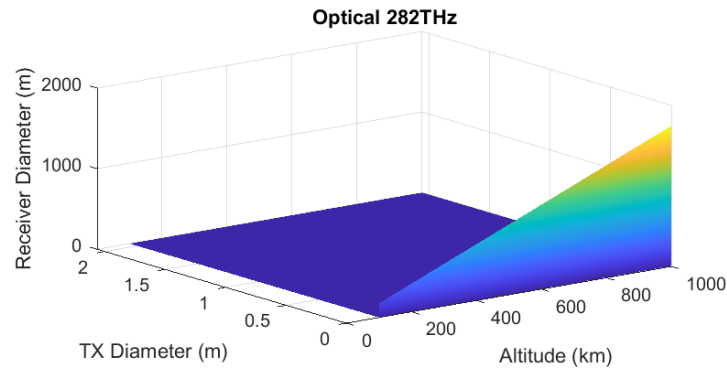
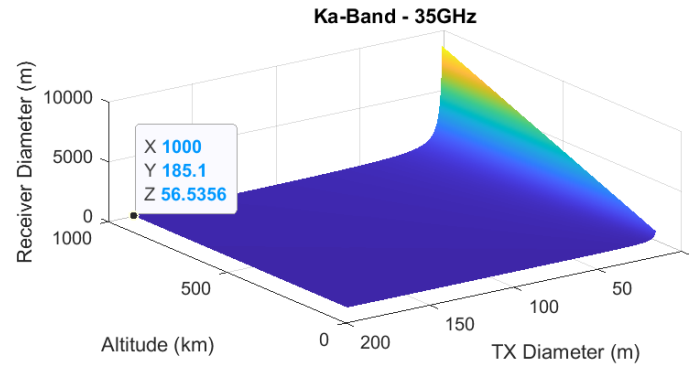
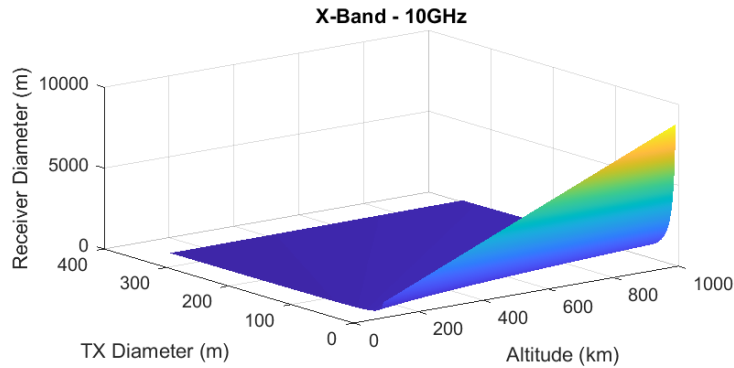
Agenda

- Space-Based Solar Power (SBSP) Background
- Frequency Down-selection
- General ConOps
- SBSP System Power Classes
- Client Charge/Discharge Analysis Results

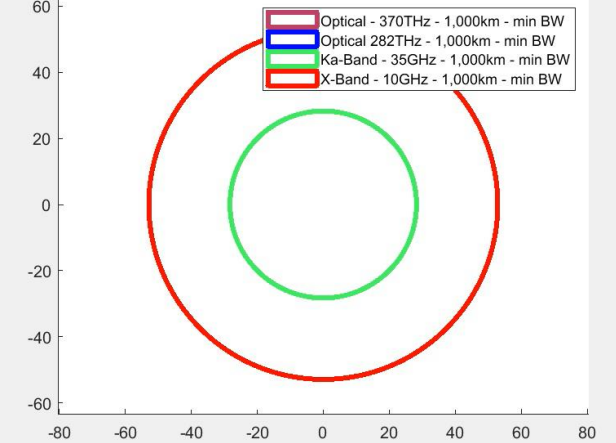
Frequency Options – Spot Size on Lunar Surface



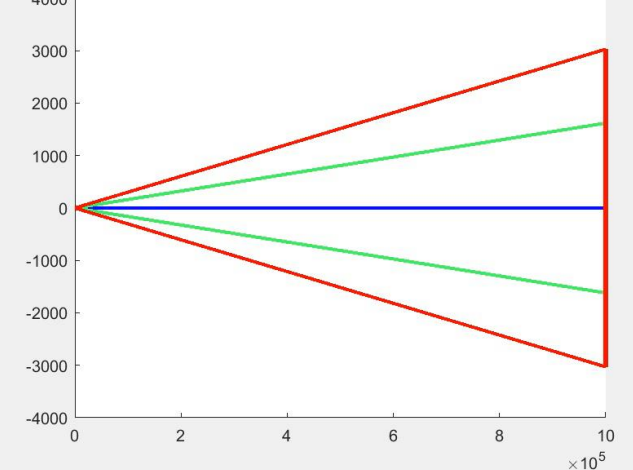
Receiver Size at varying alts and TX sizes



Beamsize on surface - Min POSSIBLE beamsize

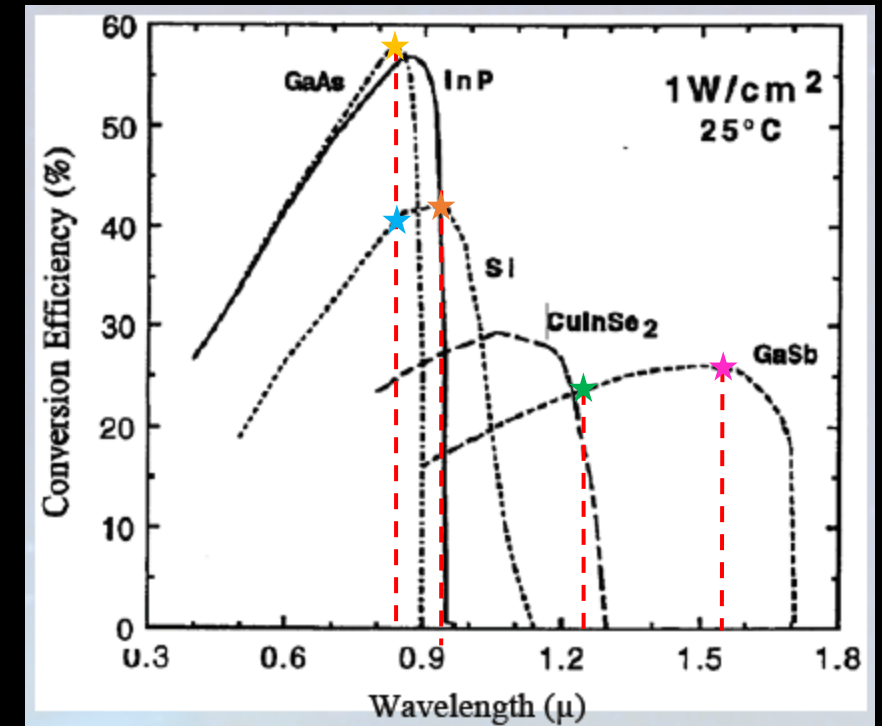


Beam Visualization - Minimum POSSIBLE Beamwidth



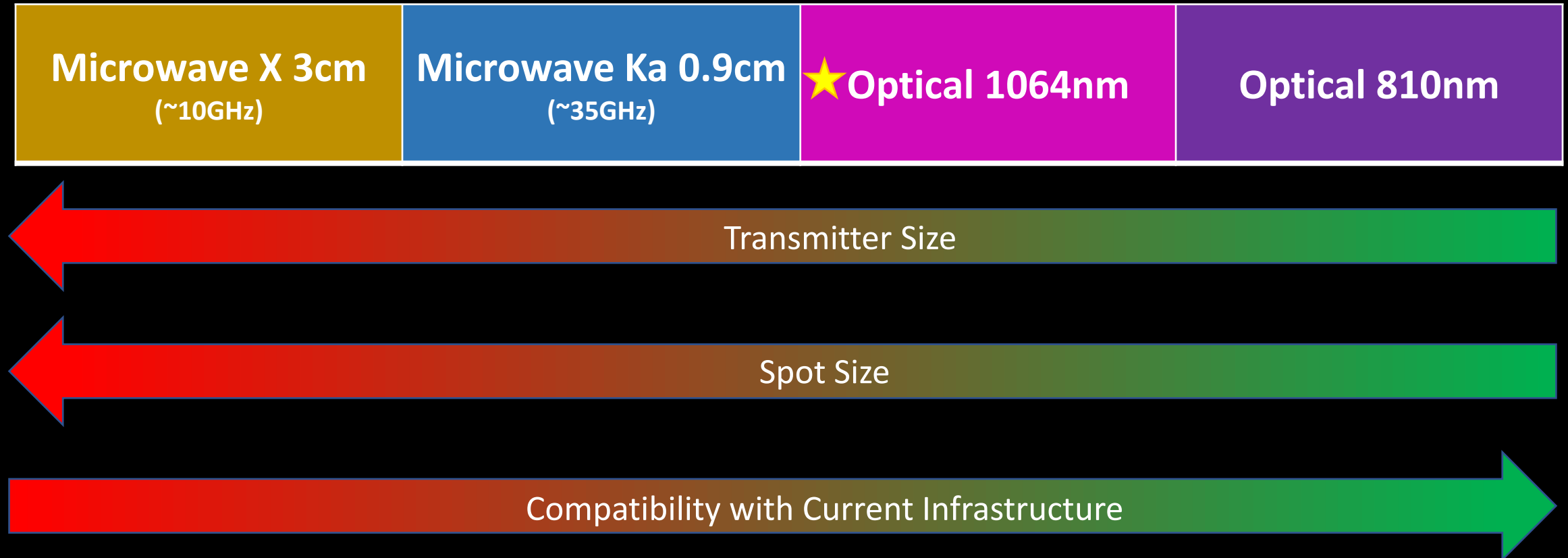
Optical Frequency – Solar Array Compatibility

- **In General:**
 - THz range = A few key frequencies between 780 – 1600nm
- **810nm:**
 - Characterized by low attenuation
 - Inexpensive transmitter & detector components (*for comms)
- **1064nm:**
 - Extremely low attenuation values.
 - Transmission components are limited and typically bulky (e.g. YdYAG Solid state lasers)
 - 980nm pump lasers are available but 980nm experience more atmospheric attenuation
- **1250nm:**
 - Low attenuation
 - Transmitters are rare
 - Only lower power telecom lasers are commercially available
- **1550nm:**
 - Well suited due to low attenuation
 - High quality transmitter and detector components available



Landis, G. A. (2020, Oct 27-29). Retrieved from NASA NTRS: <https://ntrs.nasa.gov/api/citations/20205008400/downloads/Landis-Lunar%20power%20Deep%20Space%20Conf%20presentation%20V2.pdf>

Frequency Down-selection



Challenges Associated with Optical

- The factors that benefit the system are the same factors that create challenges

Smaller spot size: Less power required	Smaller spot size: Finer pointing required
Compatible with Si solar arrays	Gaussian behavior of beam complicates beaming to solar arrays
Higher power concentration capabilities	Low TRL and technology uncertainties
	Irradiance and spot size vary across orbit



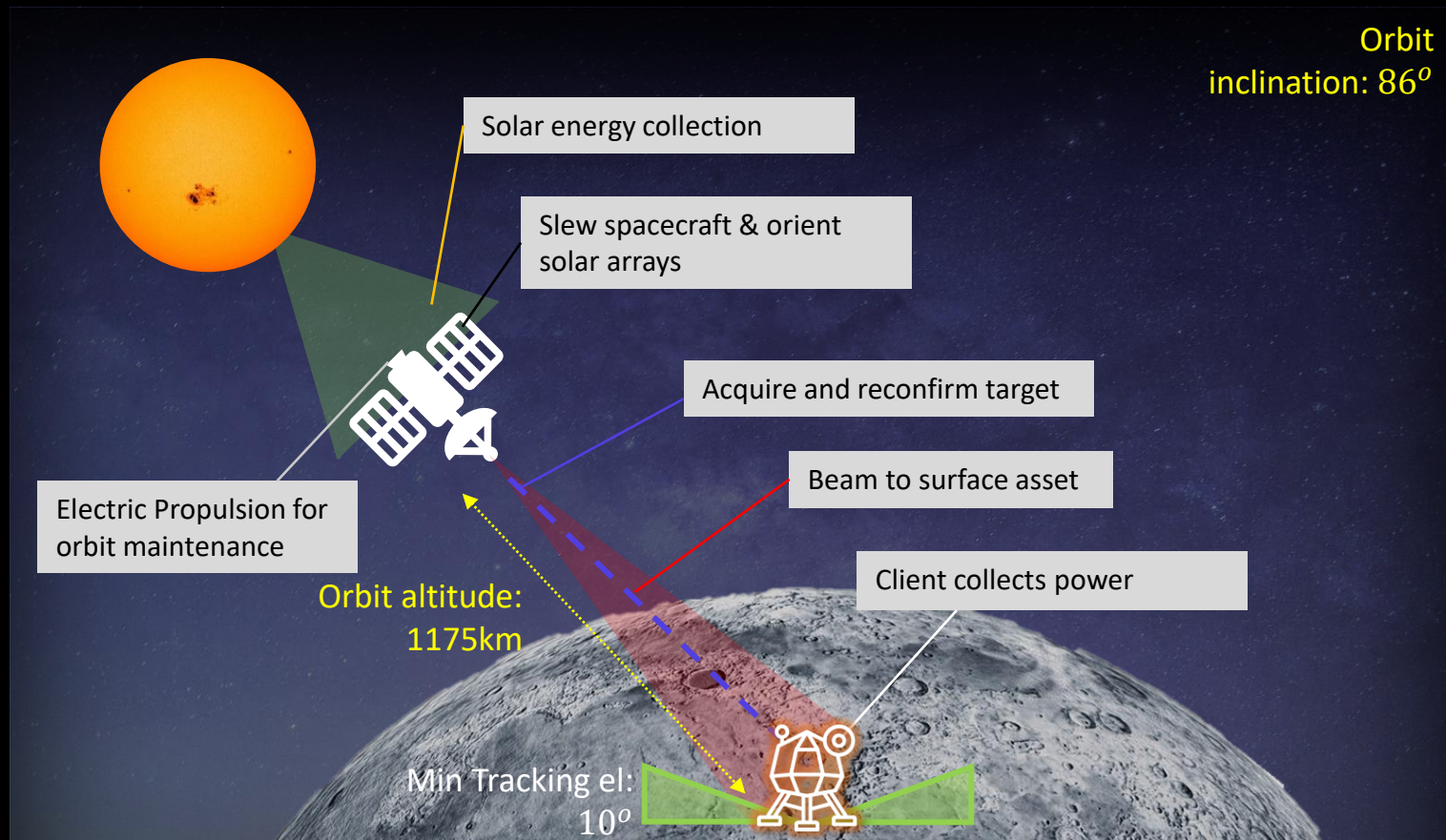


Agenda

- Space-Based Solar Power (SBSP) Background
- Frequency Down-selection
- General ConOps
- SBSP System Power Classes
- Client Charge/Discharge Analysis Results

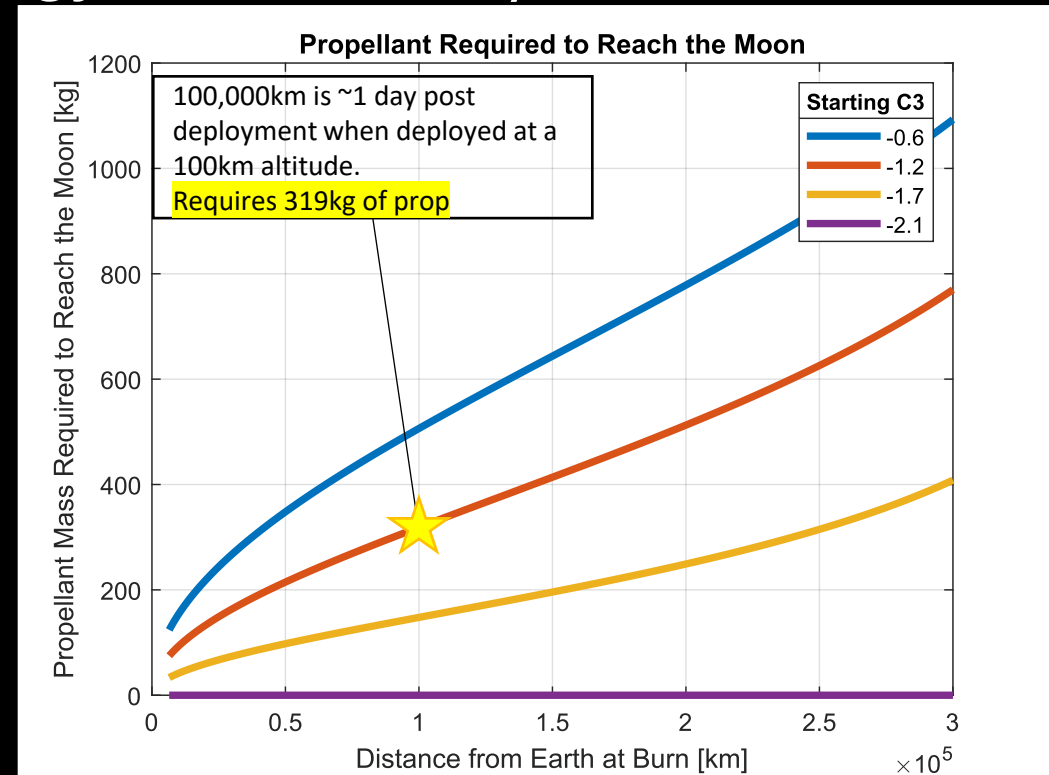
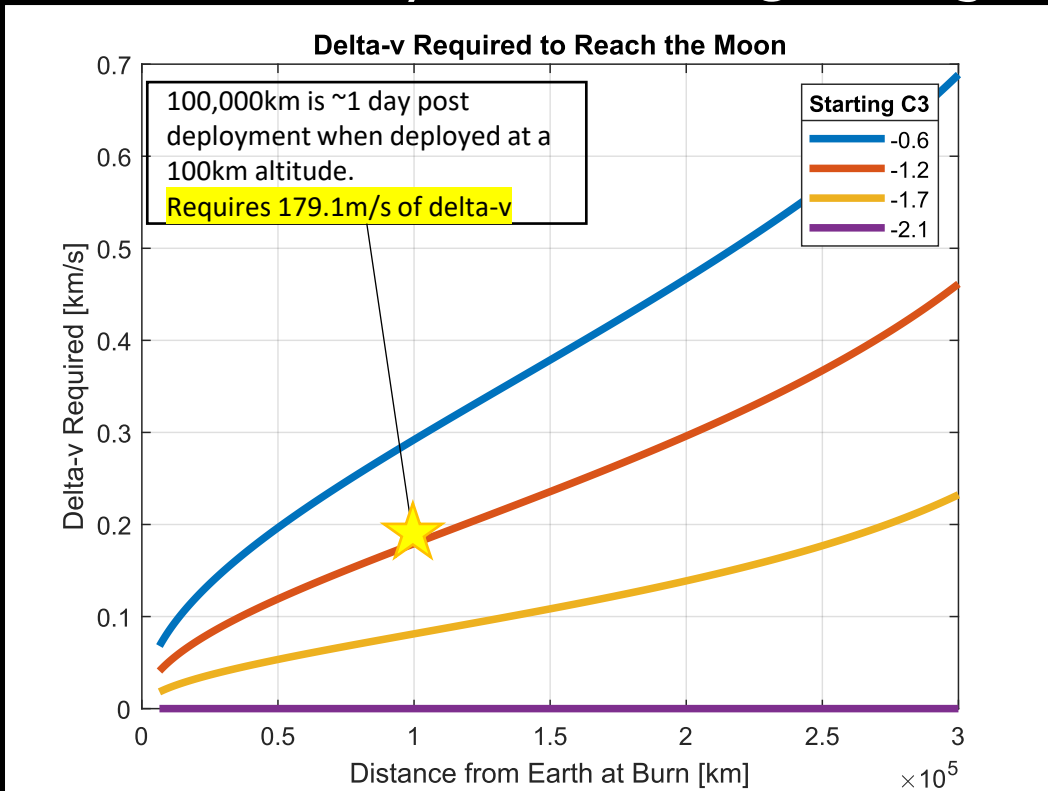
Lunar SBSP Spacecraft Concept of Operations

- The focus of this study is to provide power to the lunar south pole
- A near-frozen, near-polar orbit was selected



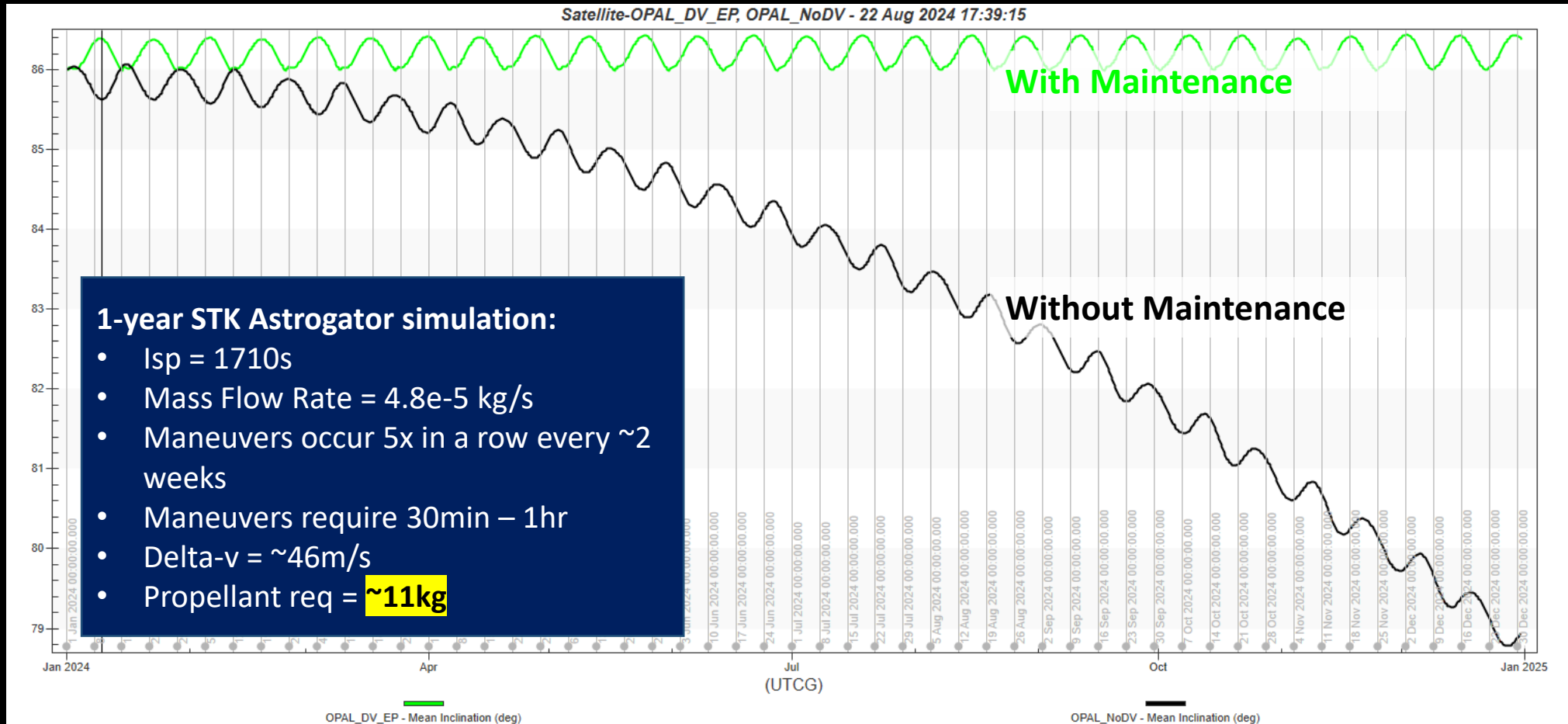
Getting to the Moon

- Chemical stage, Hydrazine propulsion system ($I_{sp} = 220s$)
- Assumes a Trans-Lunar Injection C_3 Energy of -0.6 to $-2.1 km^2/s^2$ with a goal C_3 energy of $-2.1 km^2/s^2$:



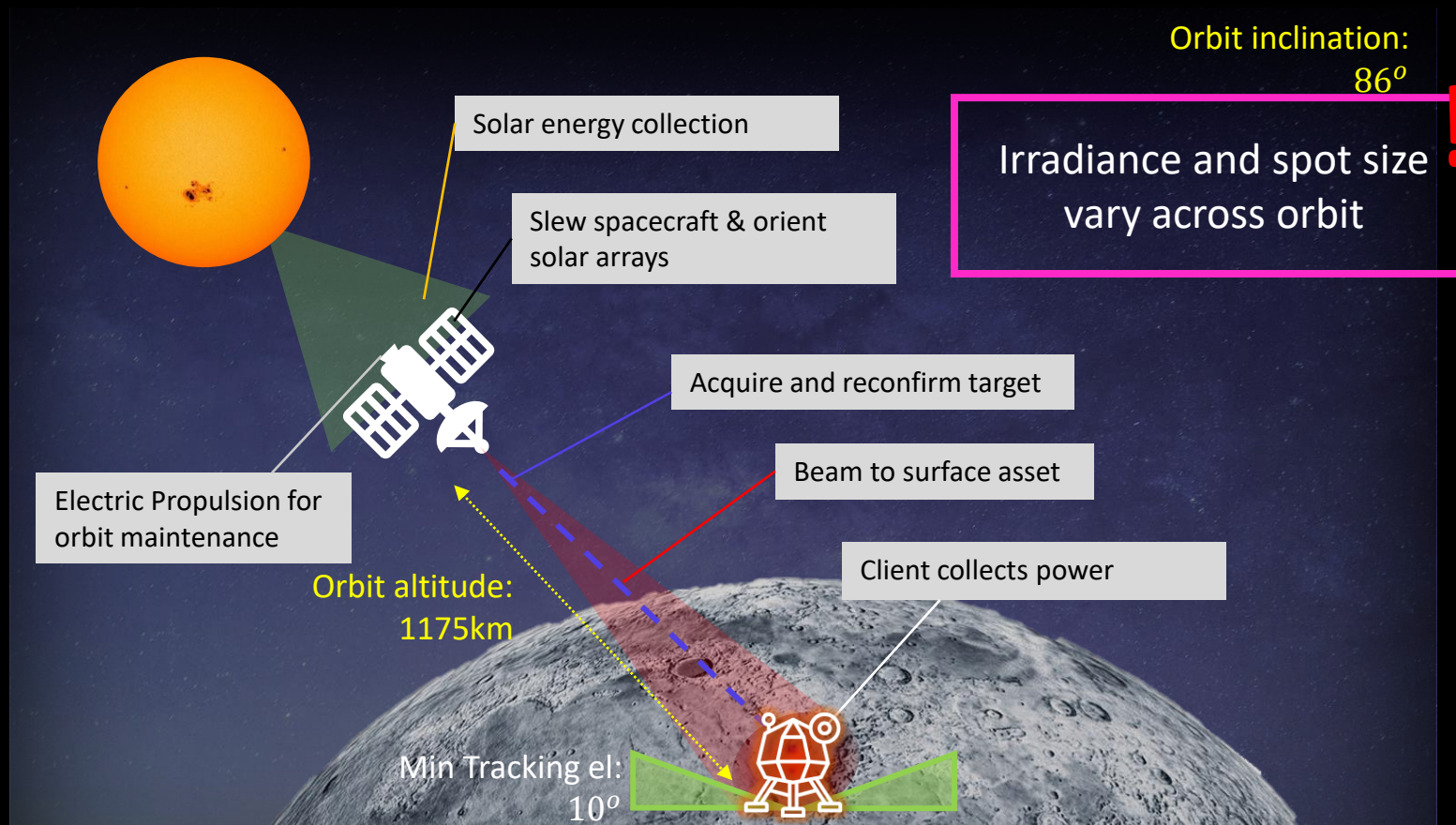
Maintaining the Orbit

- In order to reduce mass on the spacecraft, electric propulsion is assumed for orbit maintenance



Lunar SBSP Spacecraft Concept of Operations

- The focus of this study is to provide power to the lunar south pole
- A near-frozen, near-polar orbit was selected



Class 1

Client Operating Power: 0.1 kW
 S/C Beam Power: 4 kW
 Example clients: CLPS Landers (e.g., Nova-C, Peregrine, etc.)

Class 2

Client Operating Power: 0.5 kW
 S/C Beam Power: 16 kW
 Example clients: VIPER, Lunar Terrain Vehicle (survival mode)

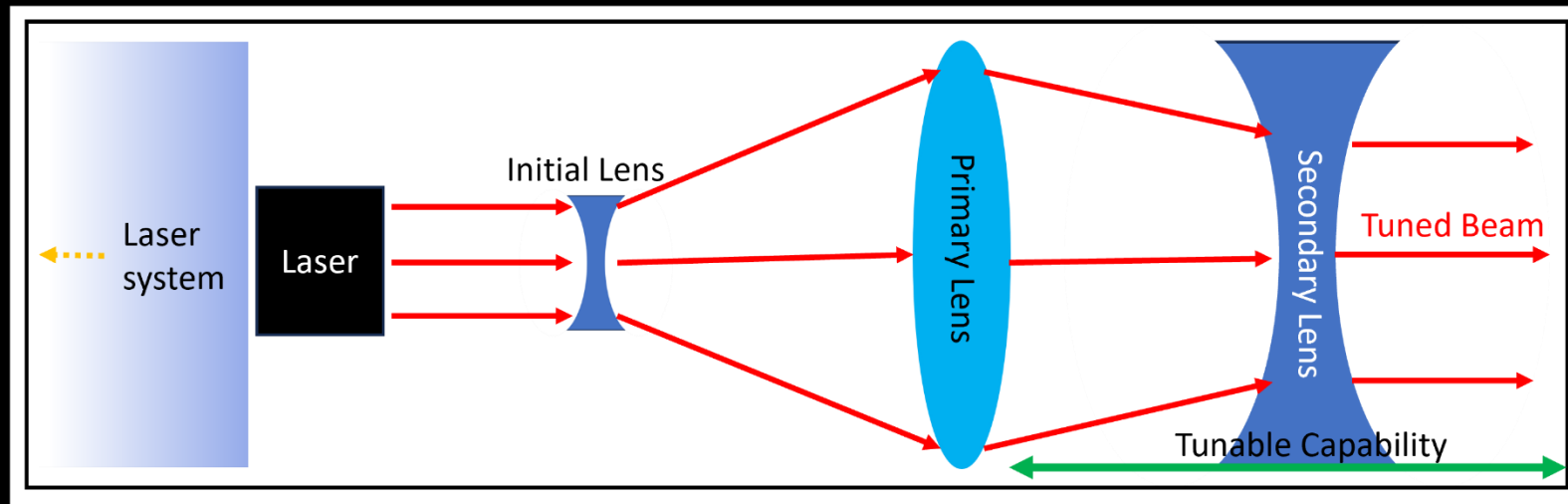
Class 3

Client Operating Power: 2 kW
 S/C Beam Power : 30 kW
 Example clients: Lunar Terrain Vehicle (crewed mode), Pressurized Rover (survival mode)

Current OPAL systems analysis capabilities span multiple client power levels and several spacecraft.

Laser System Tunability

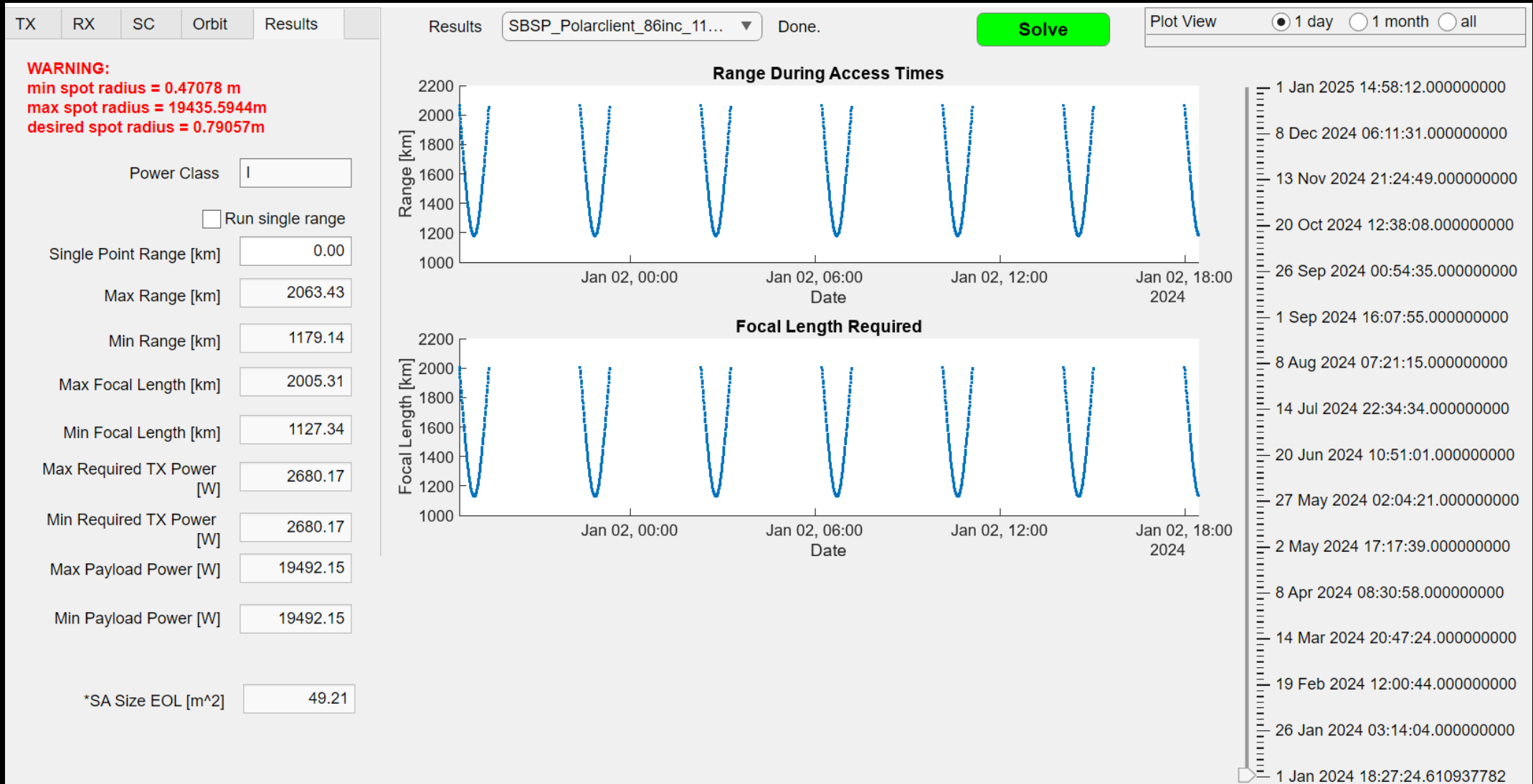
- Focal Length Tunability: To address concerns about spot size variation across orbit
 - With either lenses or mirrors



- Power Tunability:
 - $I \cong PA_{eff}$
 - Tuning transmitted power will allow for focusing the power concentration on the surface



Laser System Tunability – Focal Length Variation





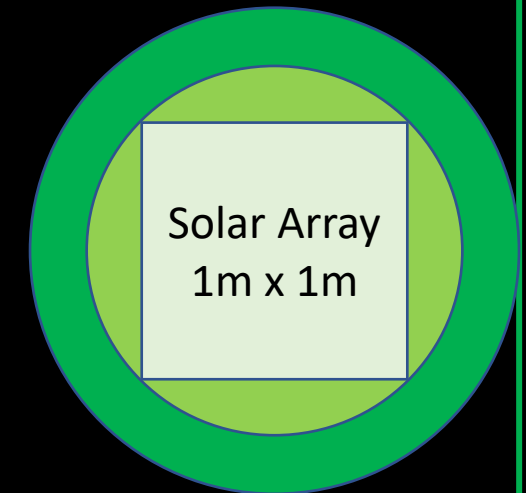
Agenda

- Space-Based Solar Power (SBSP) Background
- Frequency Down-selection
- General ConOps
- SBSP System Power Classes
- Client Charge/Discharge Analysis Results

SBSP System Power Class I

- Defined based on current CLPS lander designs:
 - Top-mounted solar arrays assumed as the receiver
 - Provide power to survive lunar night/shadowed periods

Parameter	Value	Notes
Assumed Irradiance	$I = 1365W/m^2$	Based on the solar flux density that would otherwise be received from direct sunlight.
Assumed receiver area	$A_{SA} = 1m^2$	Based on current estimates of solar array sizing for CLPS and LTVs
Spot Size Area	$A_{SS} = \pi \frac{(l^2 + w^2)}{4} (1.25) = 1.96m^2$	Set based on receiver areas. Assumes square/rectangular solar arrays inscribed within a circular spot size with 25% margin applied.
Power Beamed to the Surface	$P_{req} = (1.5)IA_{SS}$ $= 4.05kW$	Required power at the surface based on irradiance and solar array area assumptions. Power is based on the solar array case. Irradiance can vary for smaller spot sizes but still max out based on this power. 50% margin applied.

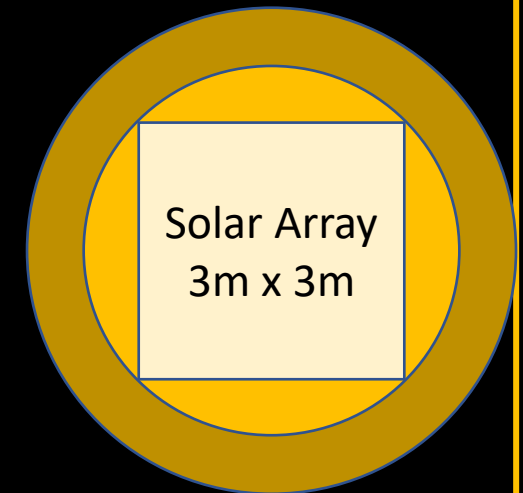


*Minimum spot size is limited by waist at the focal length of the beam

SBSP System Power Class II

- Defined based on near future lunar terrain vehicles:
 - Top-mounted solar arrays assumed as the receiver
 - Provide power for survival at extreme locations

Parameter	Value	Notes
Assumed Irradiance	$I = 1365W/m^2$	Based on the solar flux density that would otherwise be received from direct sunlight.
Assumed receiver area	$A_{SA} = 3m^2$	*TBD – Based on current estimates of solar array sizing for CLPS and LTVs
Spot Size Area	$A_{ss} = \pi \frac{(l^2 + w^2)}{4} (1.25) = 7.85m^2$	Set based on receiver areas. Assumes square/rectangular solar arrays inscribed within a circular spot size with 25% margin applied.
Power Beamed to the Surface	$P_{req} = (1.5)IA_{ss} = \mathbf{16kW}$	Required power at the surface based on irradiance and solar array area assumptions. Power is based on the solar array case. Irradiance can vary for smaller spot sizes but still max out based on this power. 50% margin applied.



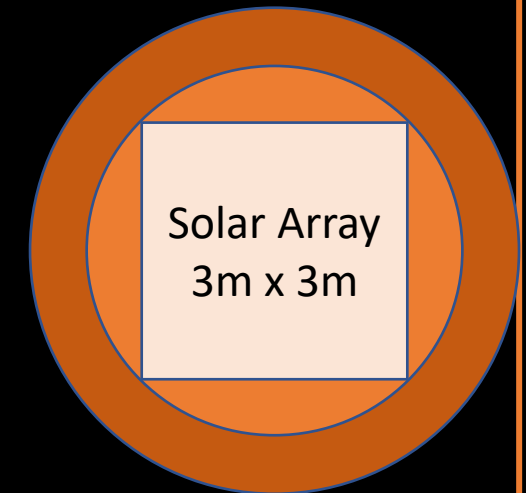
[Riesing-SPIE-2022-v5.pdf \(nasa.gov\)](#)

*Minimum spot size is limited by waist at the focal length of the beam

SBSP System Power Class III

- Defined based on future crewed rovers:
 - Top-mounted solar arrays assumed as the receiver
 - Provide contingency and/or supplementary power for survival and extended exploration

Parameter	Value	Notes
Assumed Irradiance	$I_{RX} = \frac{P_{req}}{A_{ss}} = \sim 2.55 kW/m^2$	Slightly more reasonable conops based on increased receiver sizing, however, requires higher power, and significant augmentation on the ground side.
Assumed receiver area	$A_{SA} = 3m^2$	*TBD – Based on PR and surface hab solar array area
Spot Size Area	$A_{ss} = \pi \frac{(l^2 + w^2)}{4} (1.25) = 7.85m^2$	Set based on receiver areas. Assumes square/rectangular solar arrays inscribed within a circular spot size with 25% margin applied.
Power Beamed to the Surface	$P_{req} = (1.5)IA_{ss} \cong 30 kW$	TBD* - Required power at the surface based on possible pressurized rover and surface habitat power requirements. 50% margin applied.



[Riesing-SPIE-2022-v5.pdf \(nasa.gov\)](#)

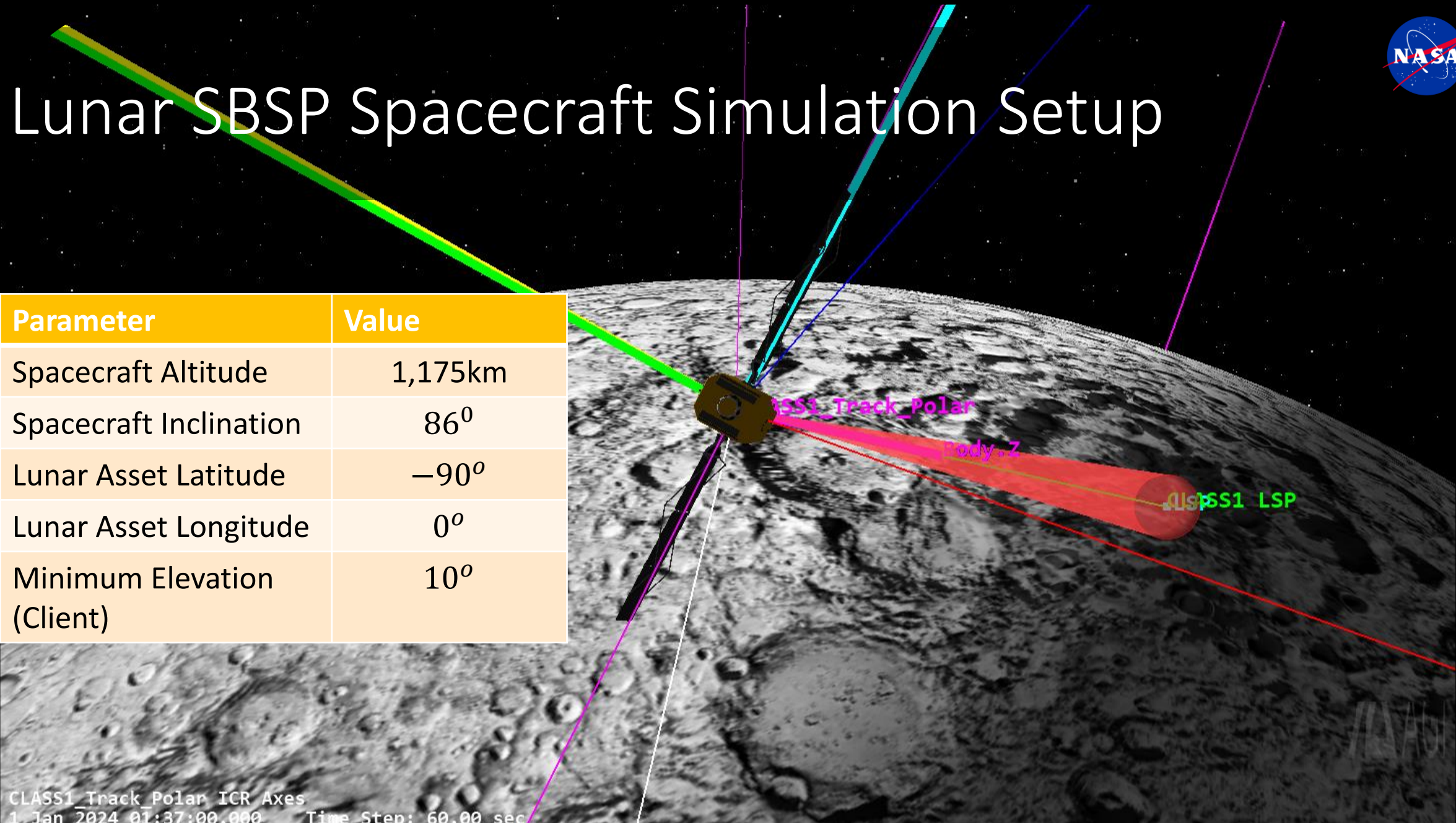


Agenda

- Space-Based Solar Power (SBSP) Background
- Frequency Down-selection
- General ConOps
- SBSP System Power Classes
- Client Charge/Discharge Analysis Results

Lunar SBSP Spacecraft Simulation Setup

Parameter	Value
Spacecraft Altitude	1,175km
Spacecraft Inclination	86°
Lunar Asset Latitude	-90°
Lunar Asset Longitude	0°
Minimum Elevation (Client)	10°



Charge/Discharge Results – Class I

Class 1:

Operating Power: 100W

Battery Size: 700Whr

Receiver Type: Si Solar Arrays

Receiver Efficiency: 40%

Tracking solar arrays

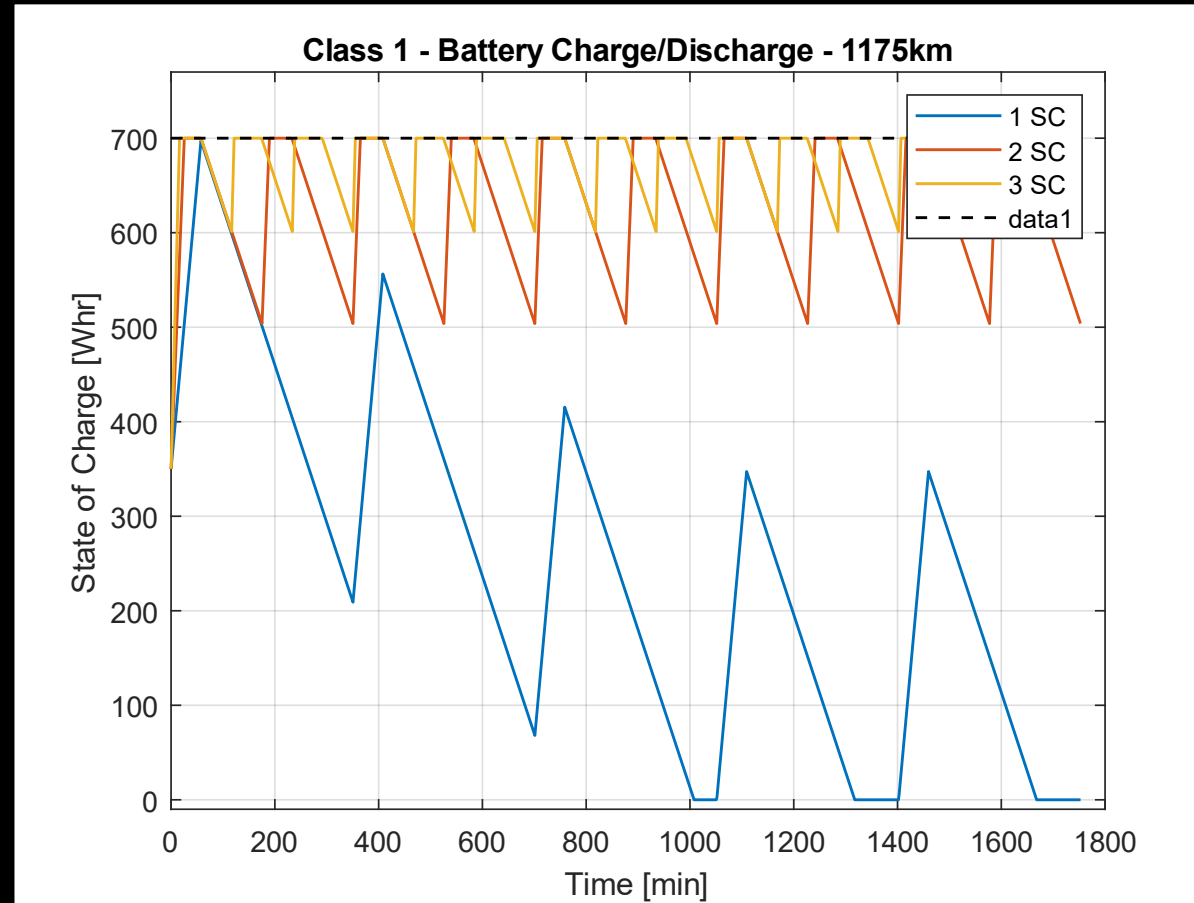
Class 1:

1 Spacecraft: Partial support

2 Spacecraft: Full support

3 Spacecraft: Full support

Max Charge Capability: ~443Wh



Key:

Minimal Support: Client will require sunlight as primary source of power

Partial Support: With only SBSP, client either reaches DoD below 50% and/or client can be temporarily fully supported by SBSP.

Full Support: Client can be fully supported with no additional sunlight. Max DoD does not reach 50%.

Charge/Discharge Results – Class II

Class 2:

Operating Power: 500W

Battery Size: 2500Whr

Receiver Type: Si Solar Arrays

Receiver Efficiency: 40%

Tracking solar arrays

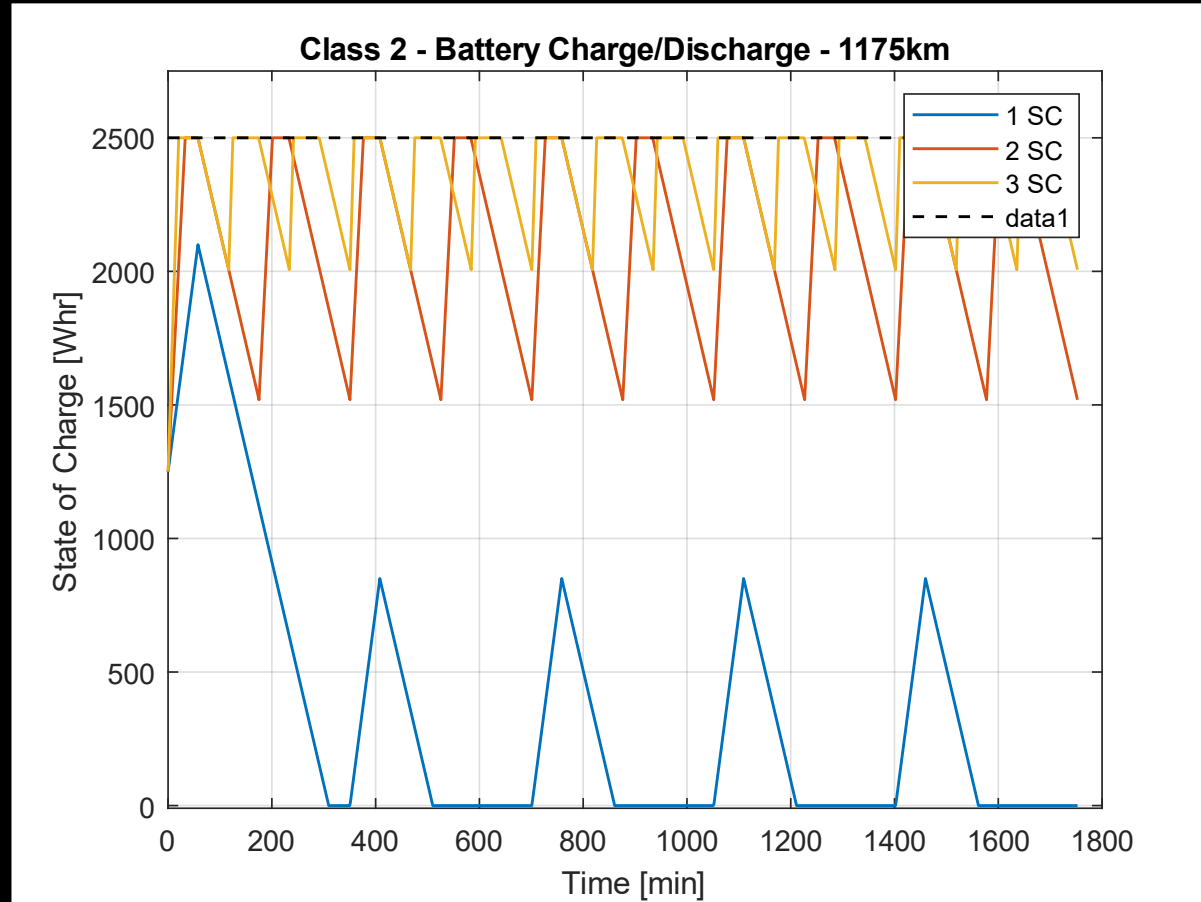
Class 2:

1 Spacecraft: Partial support

2 Spacecraft: Full support

3 Spacecraft: Full support

Max Charge Capability: ~1.33kWh



Key:

Minimal Support: Client will require sunlight as primary source of power

Partial Support: With only SBSP, client either reaches DoD below 50% and/or client can be temporarily fully supported by SBSP.

Full Support: Client can be fully supported with no additional sunlight. Max DoD does not reach 50%.

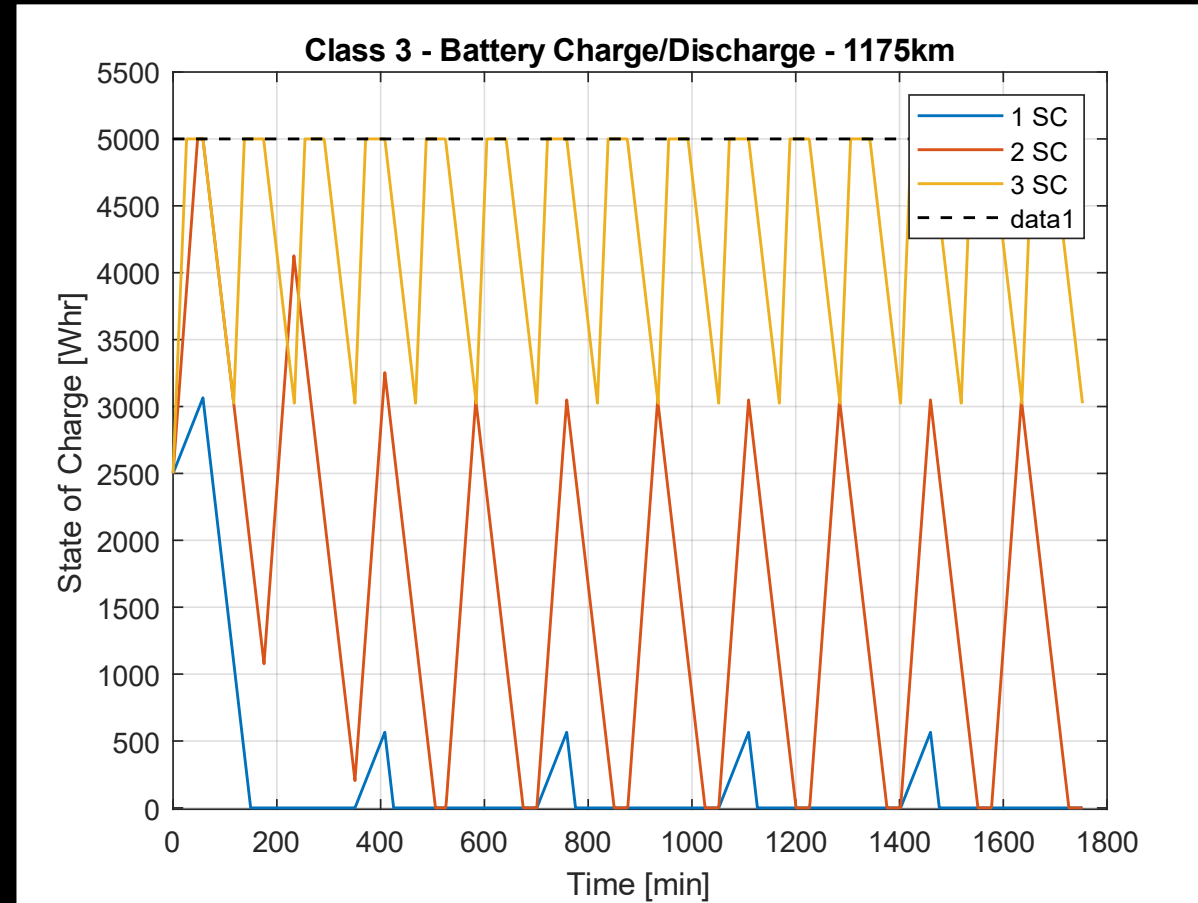
Charge/Discharge Results – Class III

Class 3:

Operating Power: 2,000W
 Battery Size: 5000Whr
 Receiver Type: Si Solar Arrays
 Receiver Efficiency: 40%
 Tracking solar arrays

Class 3:

1 Spacecraft: Minimal support
 2 Spacecraft: Partial support
 3 Spacecraft: Full support
 Max Charge Capability: ~2.5kWh



Key:

Minimal Support: Client will require sunlight as primary source of power

Partial Support: With only SBSP, client either reaches DoD below 50% and/or client can be temporarily fully supported by SBSP.

Full Support: Client can be fully supported with no additional sunlight. Max DoD does not reach 50%.



Summary of Results

- Space-Based Solar Power (SBSP) Background
 - These studies are being done!
 - Commercial space industry is working towards developing these beaming technologies.
- Frequency Down-selection
 - Optical frequencies are optimal for the moon due to the small beam in conjunction with the lack of atmosphere.
 - Some sort of tunability will be necessary – whether spot size or power or both.
- General ConOps
 - A client-focused system will allow for more flexible power distribution.
 - These are large systems and will require reductions in mass when possible.
 - Staging and/or delivery is likely necessary to arrive at the moon. EP is useful for orbit maintenance.
- SBSP System Power Classes
 - Designs have been generated for near term, future term, and far future.
- Client Charge/Discharge Analysis Results
 - SBSP can provide power support to the lunar surface!

What's Next?

- Many NASA centers and commercial space industry are studying SBSP.
- Biggest Challenges:
 - Uncertainties in the laser system design
 - Thermal – High power results in high temperatures
 - Mass – These are large systems
 - Improving technologies in other areas can improve this design (solar array efficiencies, radiator technologies, etc.)
 - Concept of Operations
- The OPAL team is continuing their study into the next fiscal year focusing on:
 - Generating a more well-defined set of ConOps
 - Generating high-level requirements for a tunable laser system
 - Focus on creating a design to allow flexible power beaming service



Questions?