Laser Power Beaming for Applications on the Moon

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Lunar Beamcraft Study Purpose

- Science missions envision a a network of surface stations (or rovers) deployed at multiple locations across the lunar surface
  - All latitudes from equatorial to polar
  - All longitudes from Earth-facing to farside
- Desire to operate at all times during the lunar cycle: both day and night operation
  - May reduce operational pace during night operations, but still operates

Problem statement

- Night time operation is a **severe** problem for small landers
- Explore a power/relay beamcraft solution for providing ~50W of nighttime power to multiple science landers in the 2030's *anywhere* on the moon
  - *Reduces the 250+kg batteries/equipment needed for lunar night*
  - *Provides far side (and nearside reduced mass) comm relay*
- Figures of Merit
  - Many year lander operation
  - Reduction of science lander landed mass (~ $1.2M/kg delivery) in lieu of orbiter beamcraft mass (~$300K/kg)
  - Relay comm support for far side/nearside

Main Design Trade Considerations for a Beamed Constellation to supply GLOBAL small science Asset needs

Lower orbits: Allow smaller optics BUT require more beamcraft/more ΔV. Longer outages require larger lander batteries

More Beamcraft more cost

Higher orbits: Require larger optics BUT fewer beamcraft. Shorter outages/longer dwell times allow smaller lander batteries and lower power lasers

Orbit Alt/incl. / # of Beamcraft

The altitude (drives the required laser optic Size)

Dwell Time, revisit frequency

Optics

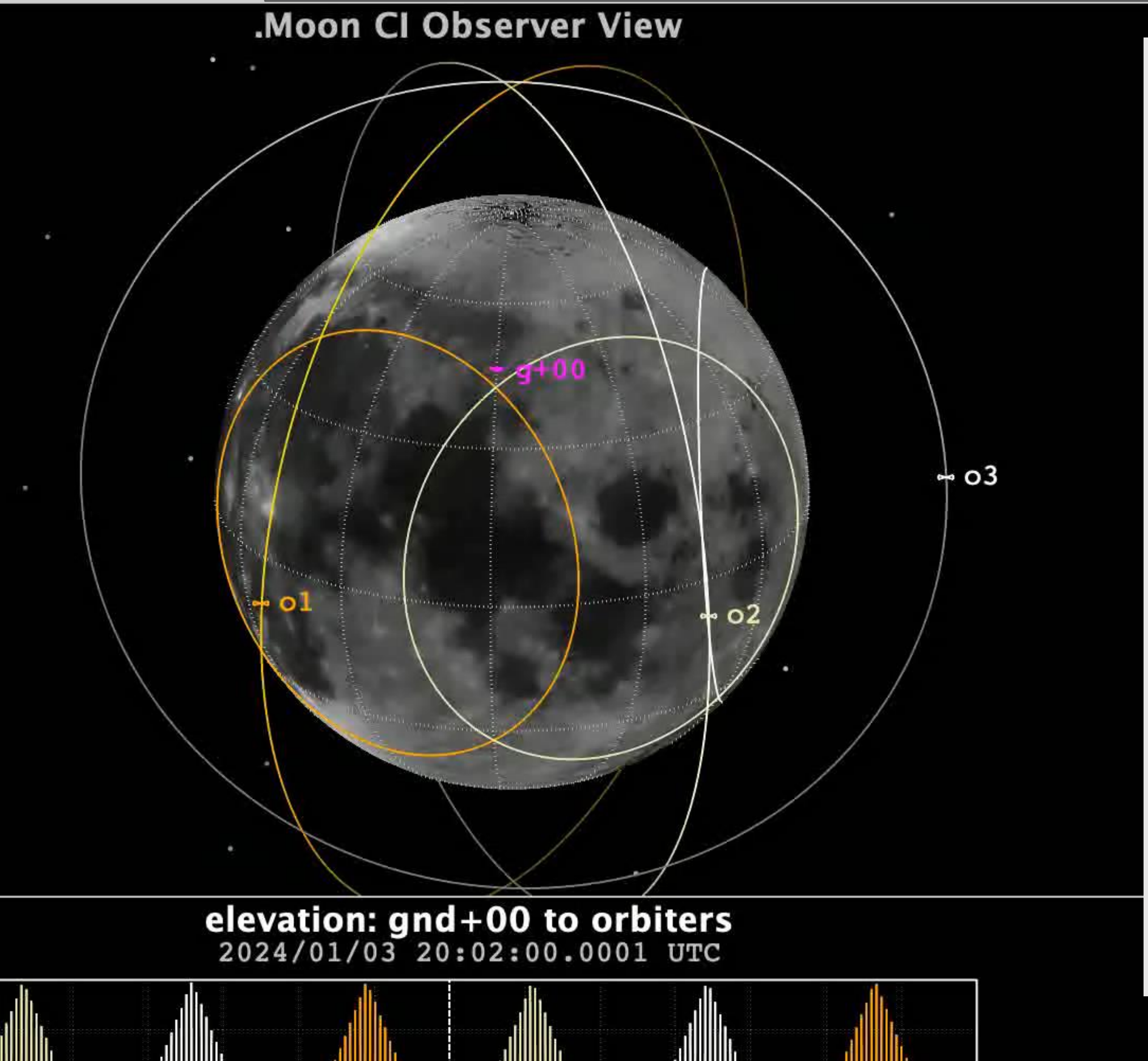
- Driven by D_{spot} = 2.44 λ Separation /d_{lens}
- User Beam Spot Size (limited by size of lander)
- Pointing: higher orbit further separation but slower slew
- Optics size contributes to size/cost/Complexity of beamcraft

Optics size is not driven by power needed

LASER Power

- Set by power needed to charge lander batteries, dwell time, and revisit frequency
- *Higher Power Lasers impact size/power /thermal/cost of Beamcraft*

Mission: SOAP Contact Window Analysis
(3 Polar Orbiters, 90° Inc to Mid-Lat Station)



Satellite Orbit Analysis Program (SOAP) software used to evaluate contact windows between various orbit configurations and surface science stations

- Three satellites in 800-km circular polar orbits
  - The requirement for three orbital planes is driven by the need to service all latitudes. If the science stations are only at near-polar latitudes (or only at near equatorial latitudes, only one beamcraft is needed)

Assumptions

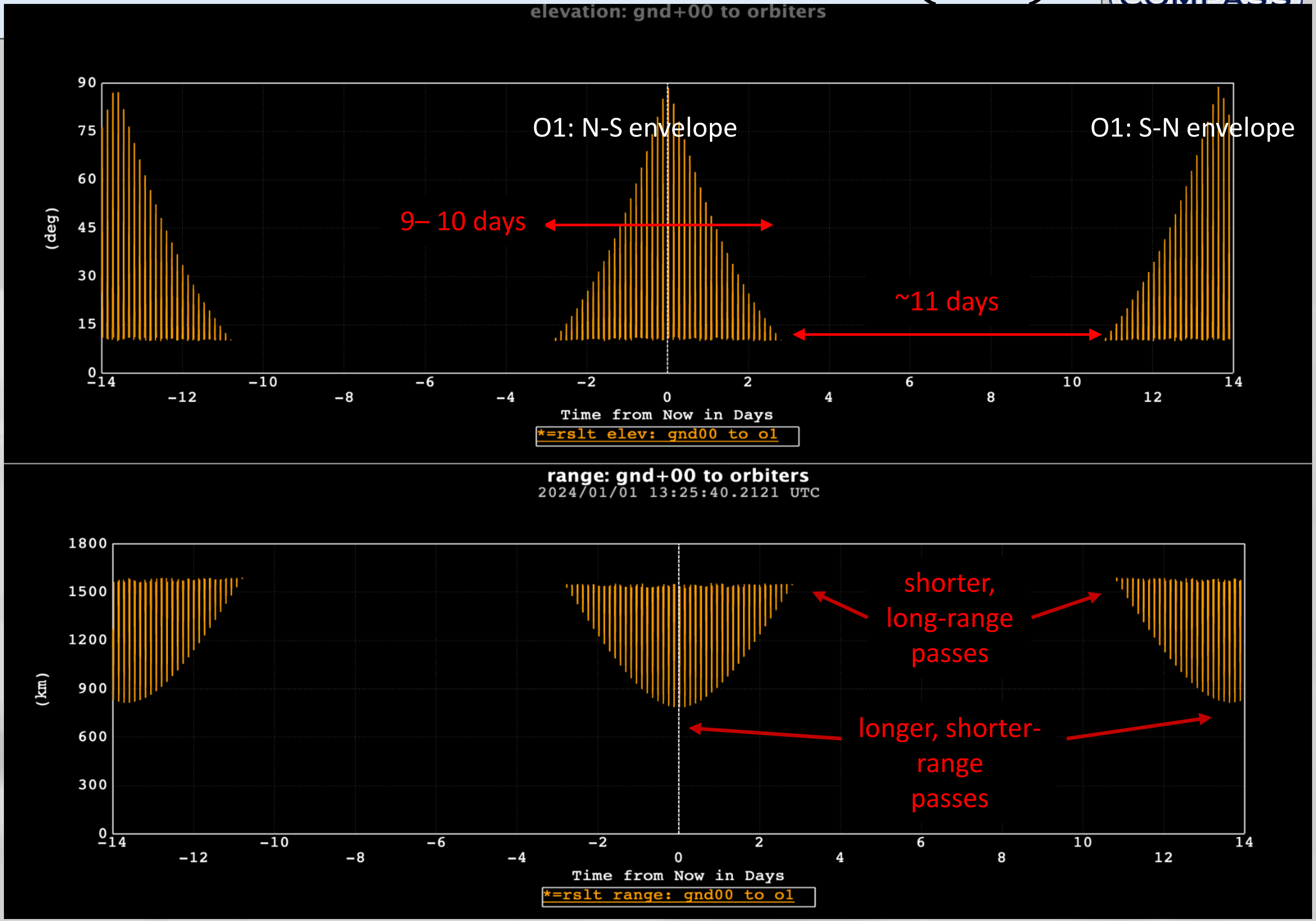
- Operational orbits were determined to be 800 km, circular, polar. Tp = 3.17 hr
- Orbiter station keeping assumed
- RAAN separation:
  - Full coverage for 3 orbiters by spacing orbits 60° apart (3x N-S + 3x S-N passes)
  - Full coverage for 2 orbiters by spacing orbits 90° apart (2x N-S + 2x S-N passes)
- TA spacing: staggering passes for times of overlapping coverage (i.e., station in view of more than 1 satellite) would be beneficial and should be included in future work
- Orbiters simulated with 47.5° half-angle, Nadir-pointer, simple conic sensor (SOAP sensor package)

Mission: Closer Look at Orbiter Passes (O1)

Each orbiter can be seen by the ground station 1x per 3.17 hr orbit until the moon's rotation under the orbital plane drifts the pass downrange and the orbiter can no longer be seen over the 10° horizon mask

This "series of passes" forms an envelope lasting ~9-10 days with quality of passes ranging from short-long-range, to long- short-range and then back to short-long-range

Each orbiter's contact envelope repeats approximately every 14 days with the first contact during the N-S passage, and the second on the S-N passage.



Choice of laser and photovoltaic receiver

- For a laser with wavelength matched to the peak efficiency of the photovoltaic receiver, power conversion efficiency of the receiver is ~50%
  - Optimum wavelength of the photovoltaic receiver depends on choice of semiconductor
  - Can either match the laser wavelength to the photovoltaic cell, or can choose the photovoltaic cell technology to match the laser wavelength
- Laser requirements
  - High efficiency (optical power out/electrical power in)
  - Good beam quality
  - Available at high CW power
  - High TRL
- Semiconductor diode lasers have good efficiency but too poor beam quality
- **Choice of laser based on these requirements is a diode-pumped fiber laser**
  - Cells are available that match the 1.07μ laser wavelength

Laser (tuned to our power range)
baseline: commercially available fiber laser

- This is an example showing specifications for a commercially available laser at the wavelength and power level baselined.
- Note that while this example laser is not space qualified, other lasers using this technology have been flown.
- Higher laser efficiencies (>50%) has been demonstrated, but for this project we baselined a commercially available model

Optical Characteristics

Central Wavelength Range, 1070 nm ±10

Mode of Operation CW/Modulated

Power Tunability, 10-100%

Power Stability, ±0.5%

Output Fiber Core Diameter, 50, 100 and 200 µm

Beam Quality, BPP 2, 5, 10 mm × mrad

Operating Temperature Range, 10-40 °C

Cooling: Water

Supply Voltage, 50/60 Hz, 3-phase, 400-480 VAC

*** Output Power 4 and 6 kW available soon**

General Characteristics

Average Power Mode, 6kW

Dimensions, 448×760×177 mm

Weight, <80 kg

Power Consumption, 16 kW

Efficiency = ~38 %

Average Power Mode, 3 kW

Dimensions, 448×760×88 mm

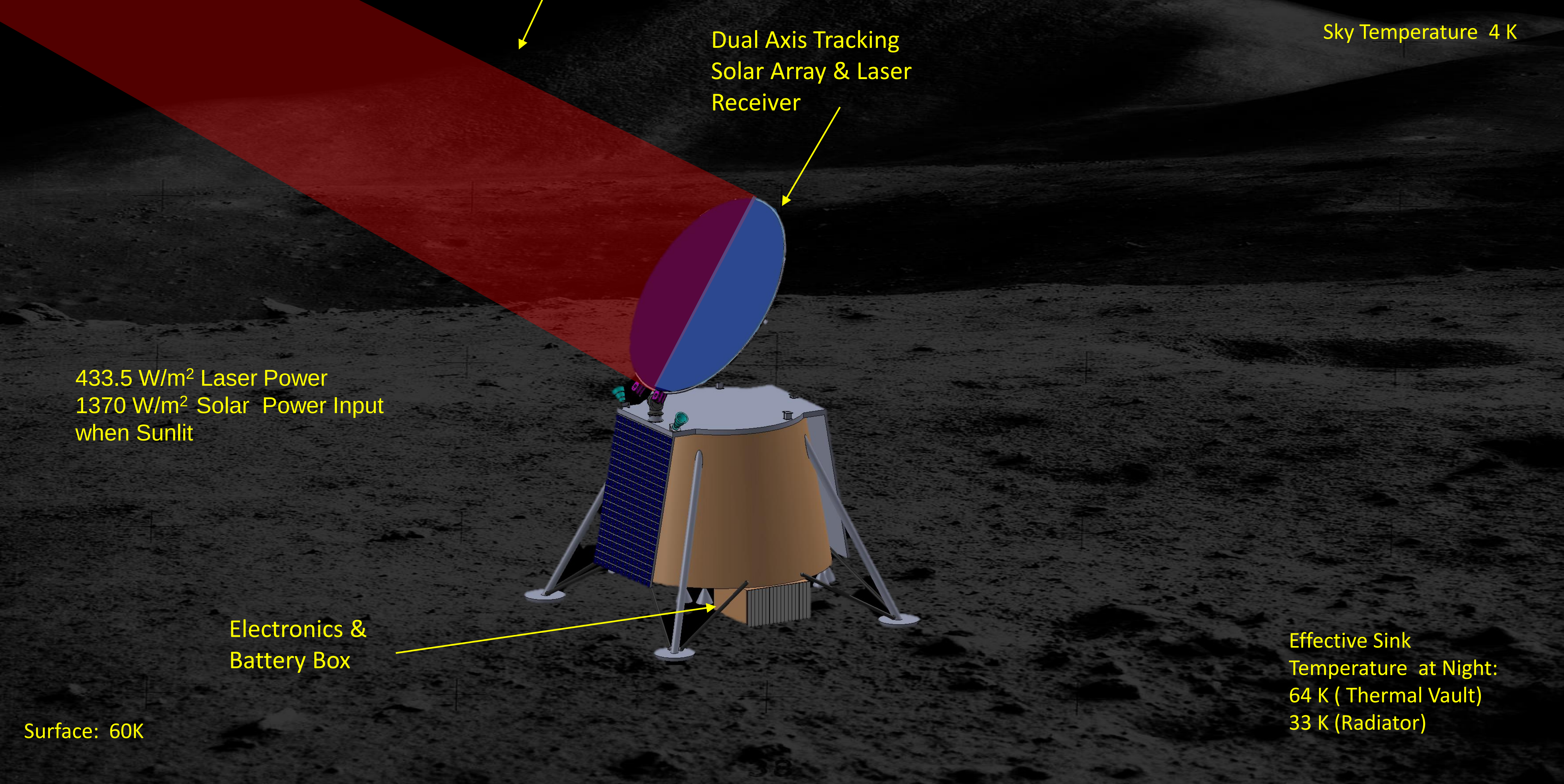
Weight, <45 kg

Power Consumption, 7.8 kW

Efficiency = ~ 38%

- Spacecraft carries two lasers to give redundancy

Power System Component Illustration



Laser Beam Power Requirements

The laser beamed power output (P_{lout}) requirement is based on the continuous power level the load utilizes (P_c) and the total energy that needs to be transmitted (E_t) and the various inefficiencies of the system.

$$E_t = P_c t_b \eta_{bc} + P_c t_t$$

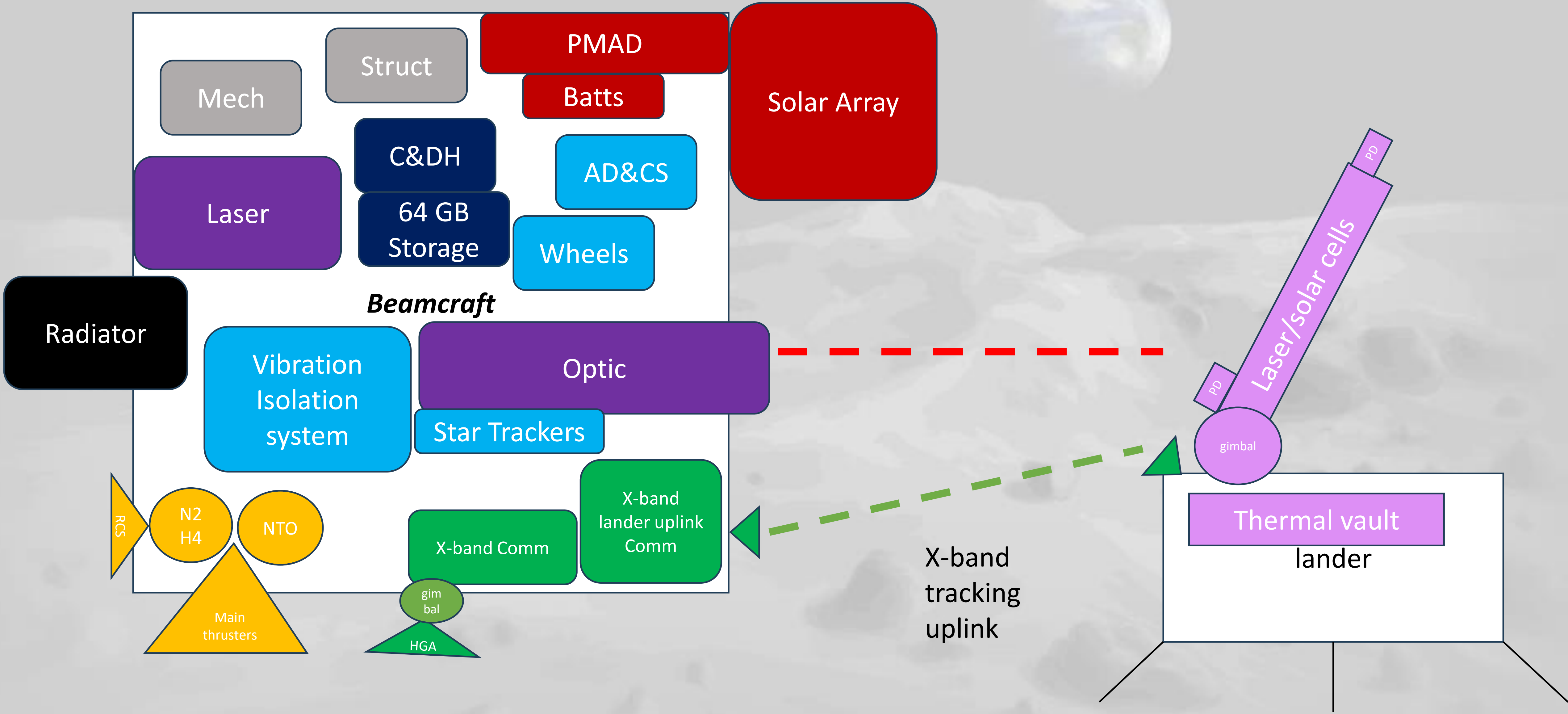
$$P_{Lout} = (E_t/t_t)/(\eta_{ff}\ \eta_{bs}\ \eta_{sc})$$

$$P_{Lin} = P_{Lout}\ \eta_L$$

Item	Value
Power Transmission Time (t_t)	0.25 Hr
Shadow (No Power Transmission) (t_b)	2.75 Hr
Battery Charging Efficiency (η_{bc})	0.95
Array Fill Factor (η_{ff})	0.85
Laser Beam Spill (η_{bs})	0.5
PV Cell Efficiency (based on laser) (η_{sc})	0.5
Laser Efficiency (η_L)	0.4

Continuous Load Power (P_c, W)	Laser Beam Power (P_{lout}, W)	Power to Laser (P_{in}, W)	Receiving Array Output (W)	Power to Battery (W)
39.75	3000	7800	637	510

Beamcraft Schematic



Primary Mirror

We are basing the primary mirror on the Kepler telescope mirror:

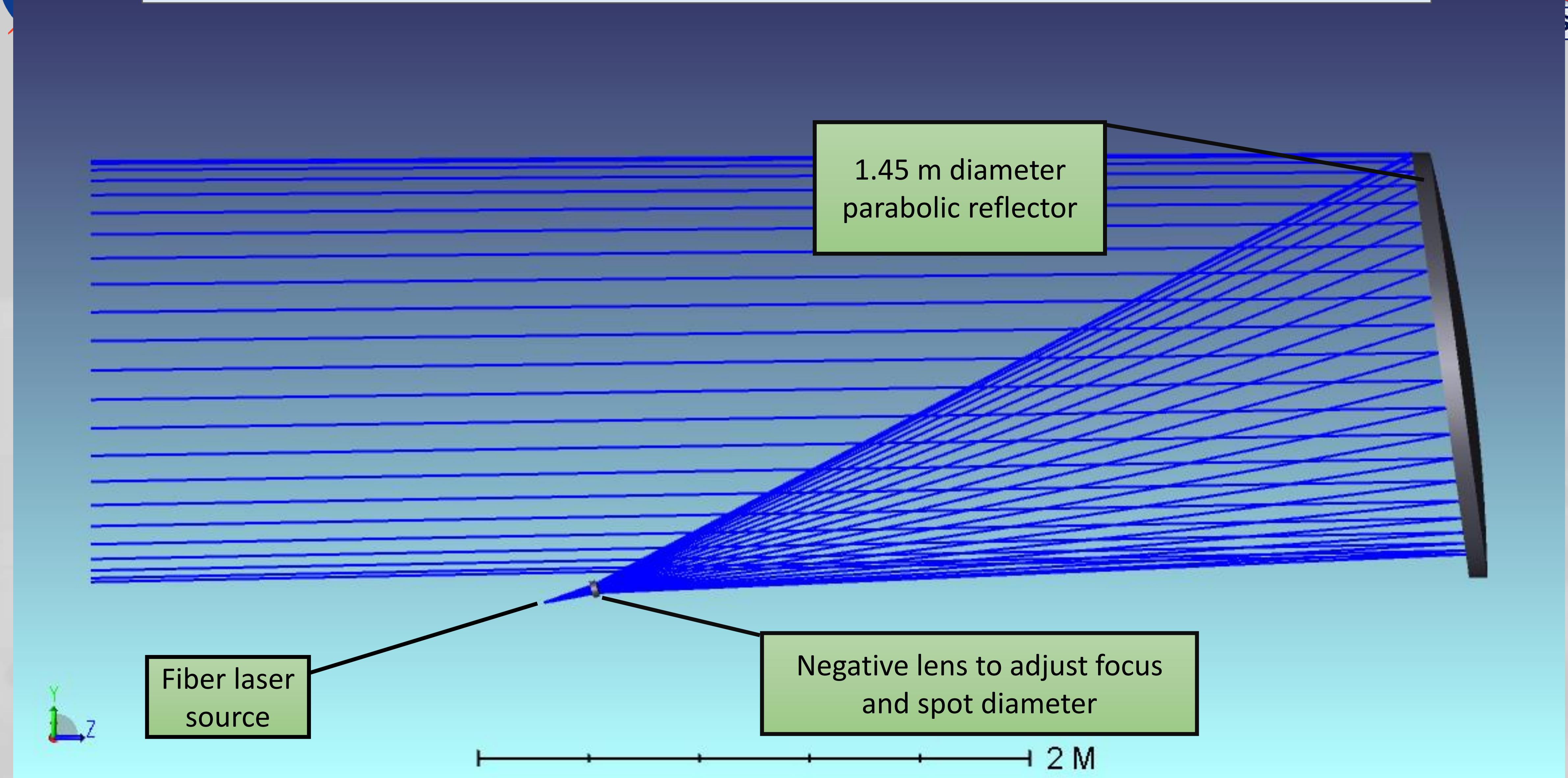
Diameter of mirror: 1.45 m
Mass: 86 kg
Material: Corning Ultra-low expansion (ULE) glass
Reference: Kosi 2008

The current state of the art in spacecraft primary mirrors is the 2.4-meter WFIRST mirror, with a mass of 50 kg/m^2. For a 1.4-meter mirror, this would come to 77 kg, slightly (but not significantly) lower.
(This is a conservative estimate, since our mirror is smaller diameter and thus could be thinner).
Reference: Stahl 2020

1.5 Meter Primary Mirror for Kepler Spacecraft
Image courtesy NASA/JPL

References:
K. Kosi (2008), "Focus Mechanism for Kepler Mission," 39th Aerospace Mechanisms Symposium, NASA/CP—2008–215252, p. 373; https://ntrs.nasa.gov/api/citations/20080023060/downloads/20080023060.pdf#page=373
H.P. Stahl (2020), "Advanced ultraviolet, optical, and infrared mirror technology development for very large space telescopes," *Journal of Astronomical Telescopes, Instruments, and Systems*, 6, No. 2, 025001, https://www.spiedigitallibrary.org/journals/Journal-of-Astronomical-Telescopes-Instruments-and-Systems/volume-6/issue-2/025001/Advanced-ultraviolet-optical-and-infrared-mirror-technology-development-for-very/10.1117/1.JATIS.6.2.025001.full

Layout/Principle of Operation



Estimated Power Delivery and Laser/Optic Sizes

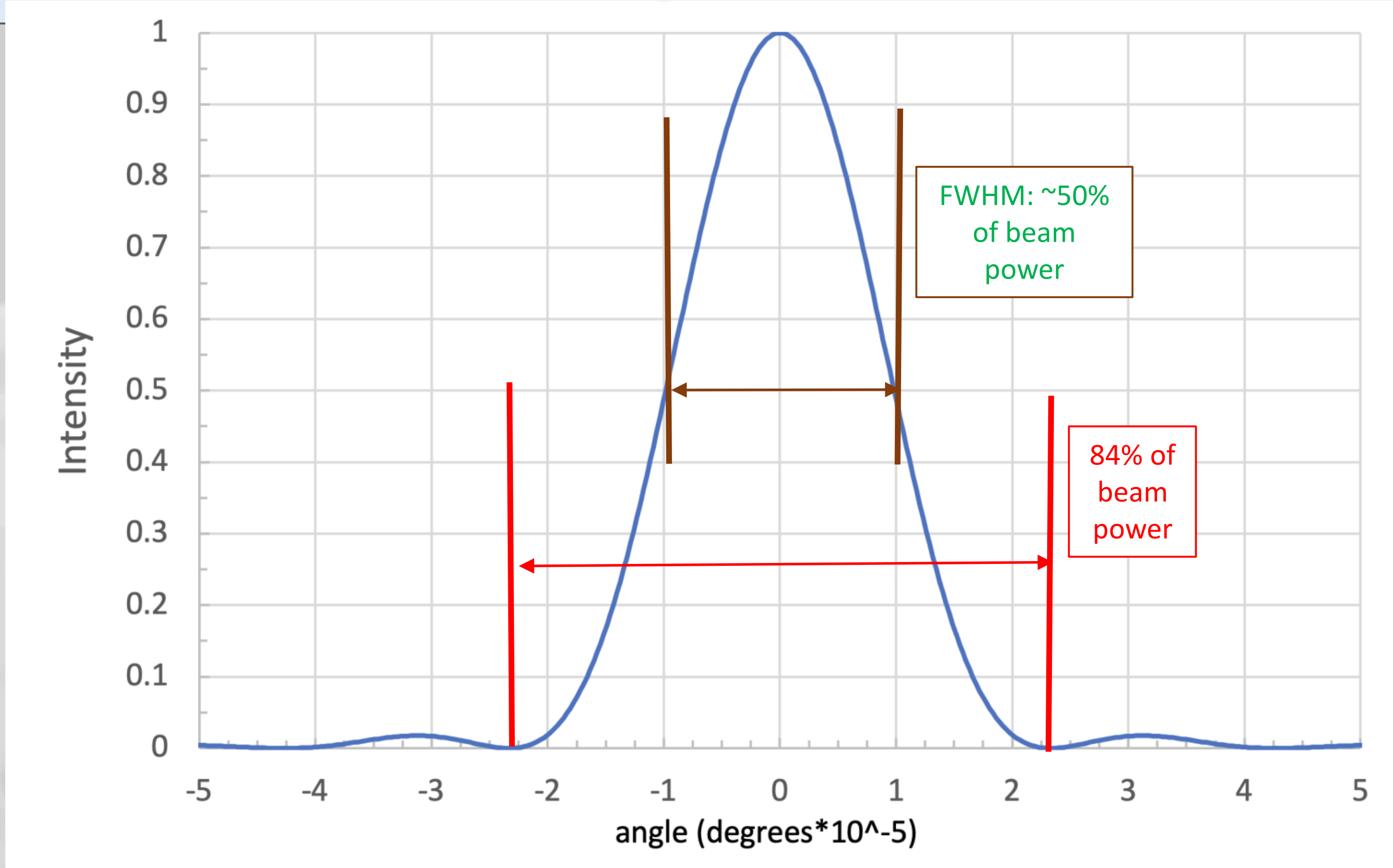
number of nighttime users per orbit plane	3
nighttime power needed (W)	50
Night length (days)	14
Whr required (for battery if unbeamed)	16800
Surface assets battery mass (if unbeamed)	114
# of Beamcraft per orbit plane	1
Time between Beamcraft visits (hrs)	3.2
W-hr required (for battery if beam serviced)	160.0
Surface asset Battery mass (kg) (if beamed)	0.8
Duration of Beamcraft pass (min)	15
Watts needed at surface asset per pass	640
W/m^2 of surface asset Beam Receiver	1500
surface asset receiver size	1.5 - 1.7 m
fraction of array covered with photovoltaic cells	0.9
Laser receiver eff	0.5
Power beam energy needed at receiver (W)	1422.2
Fraction of beam collected	0.5
Power beam at surface (W)	2844.4

Cosine loss cross track	0.98
Beamcraft beam laser eff	0.38
Beamcraft input laser power (kW)	7.6
Beamcraft energy storage kW h	6
Beamcraft battery tech (Whr/kg)	192
Beamcraft battery mass kg	30
Beamcraft illumination time (hrs)	2.5
Beamcraft solar array size estimate (kW)	2.3

Beam spot size		
laser wavelength	1.07	microns
beam director diam.	1.4	meter
beam div angle (full)	1.86486E-06	radians
beam div angle (°)	0.384654397	arcseconds
spot diam. (84% of power)*	2.98	meters
spot diam (FWHM, ~50% of power)	1.49	meters

*Assumes tracking collector. Divide by Cos(45°) if flat.

Beam spread



- 1070 nm laser, 1.4 m mirror. Intensity relative to intensity at beam center

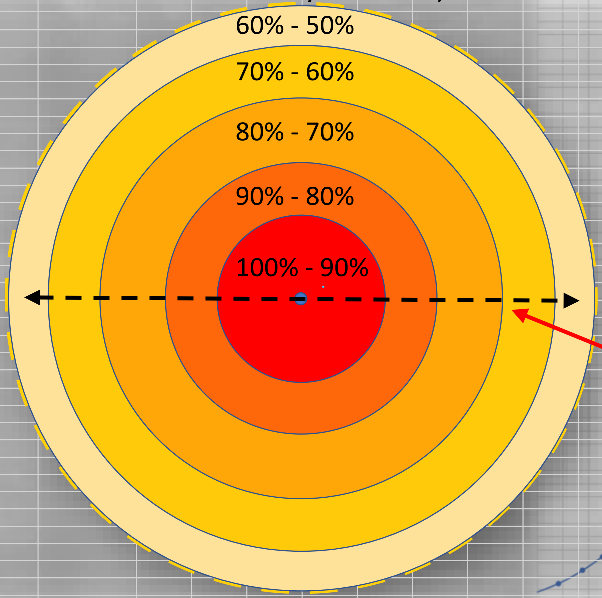
Power Generation - Lander

- Gaussian beam distribution introduces complexities into power generation design
  - Non-uniform irradiation across beam-spot means cells produce different amounts of current based on location within beam

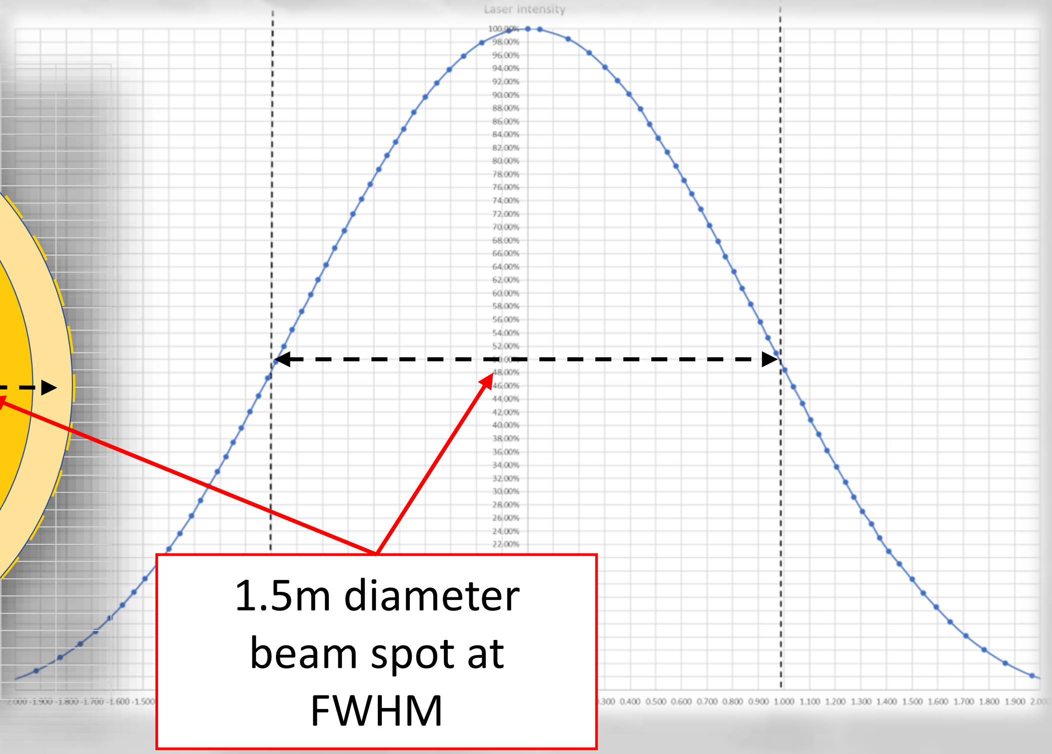
Bins:	Diam [m]	Total Area [m2]	Avg. Flux [W/m2]
Bin 1 Radius:	0.429	0.145	1636.93
Bin 2 Radius:	0.696	0.380	1435.88
Bin 3 Radius:	1.029	0.832	1271.33
Bin 4 Radius:	1.296	1.319	1092.68
Bin 5 Radius:	1.500	1.767	926.10

Power			
Bin	# of Strings	Total Power [W]	Total # of cells
1	7	68.9	119
2	13	112.3	221
3	25	191.3	425
4	26	171.1	442
5	24	133.9	408
Total	95	677.5	1615

Representative beam-spot
(Areas broken down by
10% intensity intervals)



Distribution of laser intensity for Gaussian beam



Laser spot non-uniformity **challenges**

- Laser spot is non-uniform (higher power in center)
  - Could design an array to be tolerant of non-uniform illumination
  - could use a diffuser to remove non-uniformity (adds losses x%)
  - Fresnel lens (makes tracking harder
  - ✓ Active maximum power-point tracking on *sets* of cells for variable illumination intensity using DC/DC convertor
- Distance varies 800-1500 km; changes spot diameter ~ 50%
  - We added focus adjustment to allow spot size to be dynamically controlled
- Pointing accuracy means central spot NOT necessarily in center of array
  - Need to control spacecraft jitter

Pointing the laser

- Several options considered:
- ~~Open loop~~
  - ~~'know' where surface user is ~1m~~

Not clear that we have sufficient orbital knowledge to point to < meter accuracy without feedback

- Open loop + fine tuning
  - Once in contact, scan to center beam

- Closed Loop
  - Start with have position knowledge of ~200m RSS (based on LRO experience) and 1.5 arcsec knowledge (StarCamera)
  - search in a 300 m diameter (Defocus (to 200m D) large high-power laser to raster scan area of interest
    - ✓ First use a photo detector on lander and relay up resulting sense of laser to Beamcraft using X-Band link
    - ✓ Progressively re-focus to tighter beams to walk beam onto the lander
- How to 'stay on target':
  - ✓ Detectors at edge of solar array
  - ✓ Information returned to Beamcraft with RF link

This solution allows tracking without a beacon on the receiver, but does not allow for realtime correction of pointing to correct for jitter

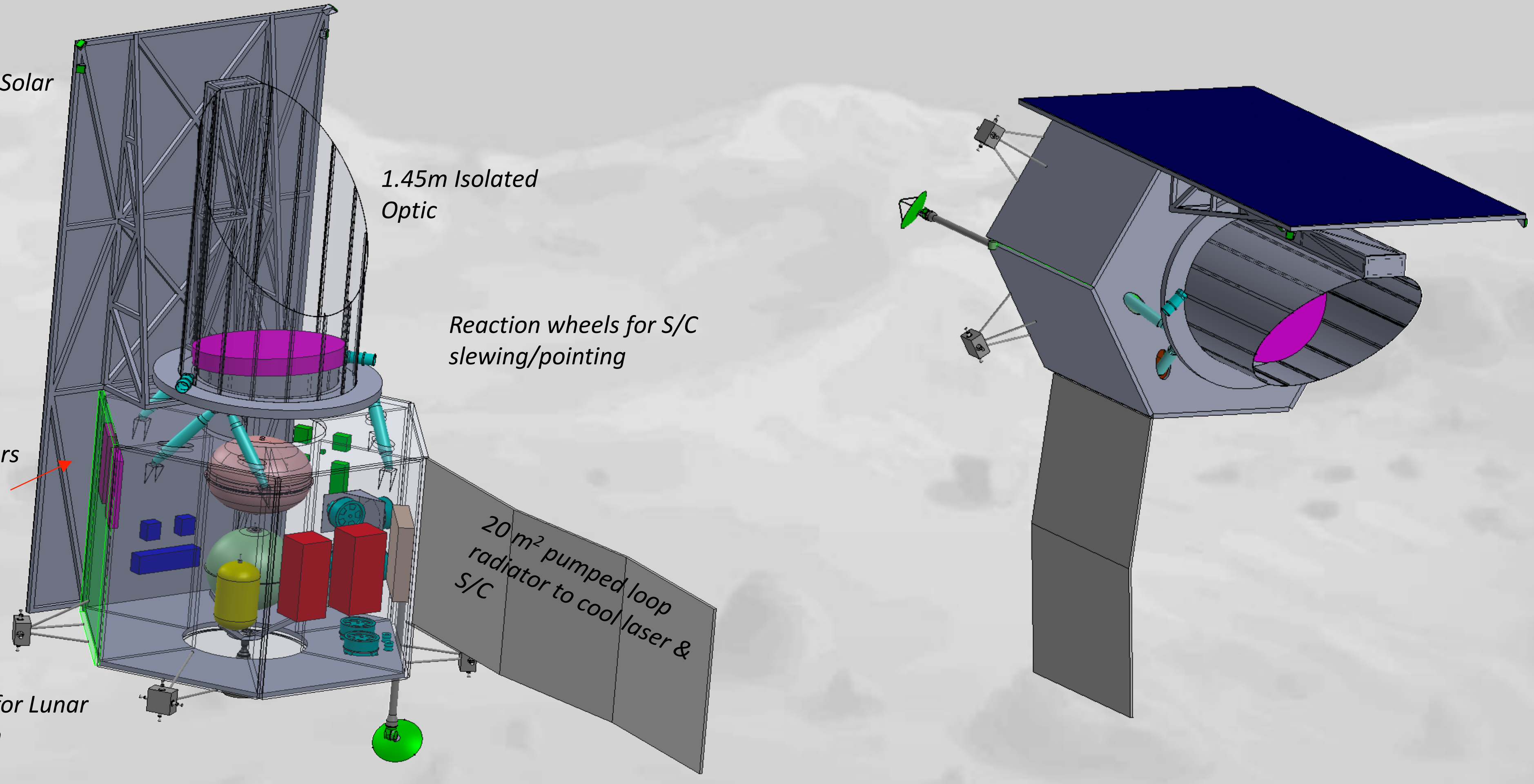
- Requires spacecraft jiitter to be tightly controlled

Beacon Option

- Laser beacon on the lander:
  - Diode laser at different wavelength from power beam
  - Coarse pointing to beamcraft (divergence angle ~ 10 mrad)
  - Lander knows roughly where and when to point to the Beamcraft
- Required laser power 7 W
  - Semiconductor diode laser can be used
- Photon counter on Beamcraft
  - (dichroic beam-splitter uses same main optic)
- This solution allows the beamcraft to correct jitter in realtime

Laser Beamcraft for Global Science Landers

~ 3500 kg Beamcraft



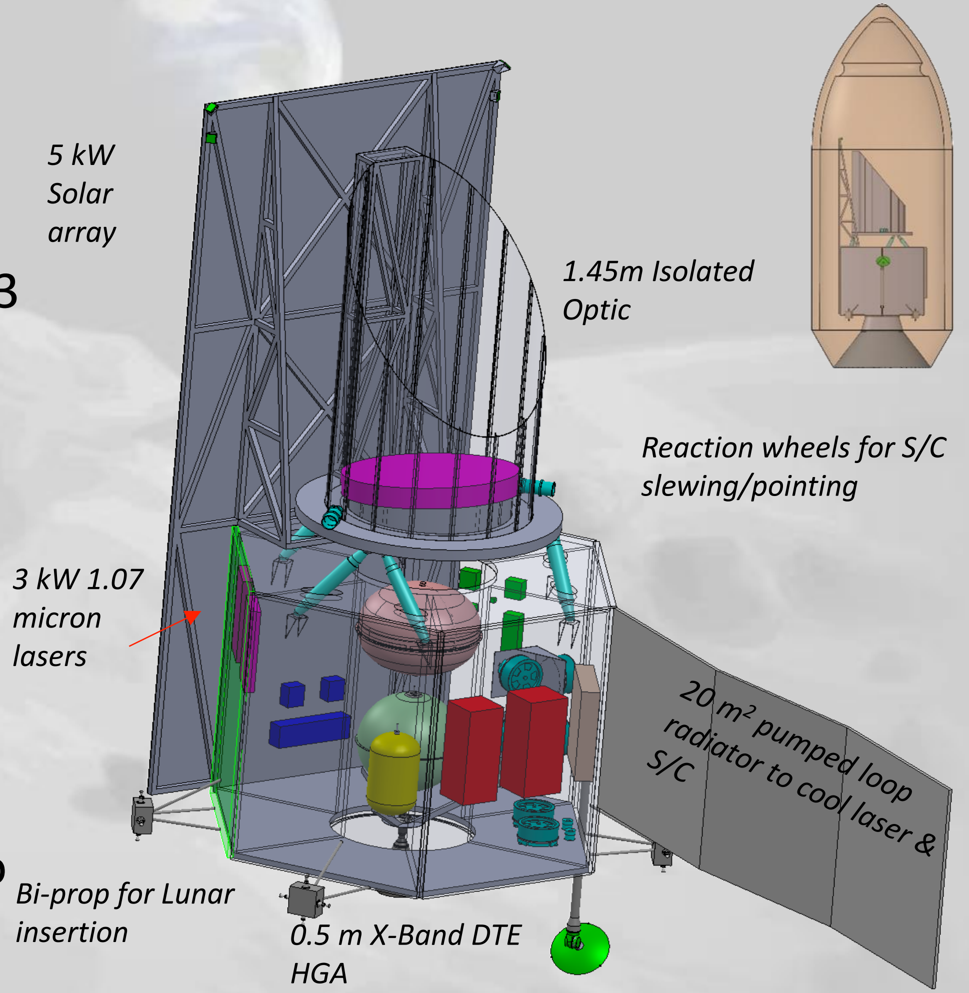
Lunar Beamcraft and Lander Payload Mass Equipment List

Description Case 1_Lunar_Beam_Craft CD-2023-207	Basic Mass (kg)	Growth (%)	Growth (kg)	Total Mass (kg)
Lunar Beam Craft	2905	14%	418	3324
Spacecraft	2818	14%	401	3220
Laser system	186.3	24%	44.6	230.9
Attitude Determination and Control	108.0	7%	7.7	115.7
Command & Data Handling	39.2	36%	14.1	53.3
Communications and Tracking	12.8	11%	1.4	14.2
Electrical Power Subsystem	450.5	35%	157.7	608.2
Thermal Control (Non-Propellant)	197.1	18%	35.5	232.6
Propulsion (Chemical Hardware)	114.1	5%	6.0	120.1
Propellant (Chemical)	964.0	0%	0.0	964.0
Structures and Mechanisms	746.4	18%	134.3	880.7
Lander Modifications	87	19%	17	104
Science	14.6	0%	0.0	14.6
Command & Data Handling	11.6	36%	4.2	15.8
Communications and Tracking	5.3	12%	0.6	5.9
Electrical Power Subsystem	27.5	30%	8.3	35.8
Thermal Control (Non-Propellant)	10.8	18%	1.9	12.7
Structures and Mechanisms	17.3	11%	1.9	19.2

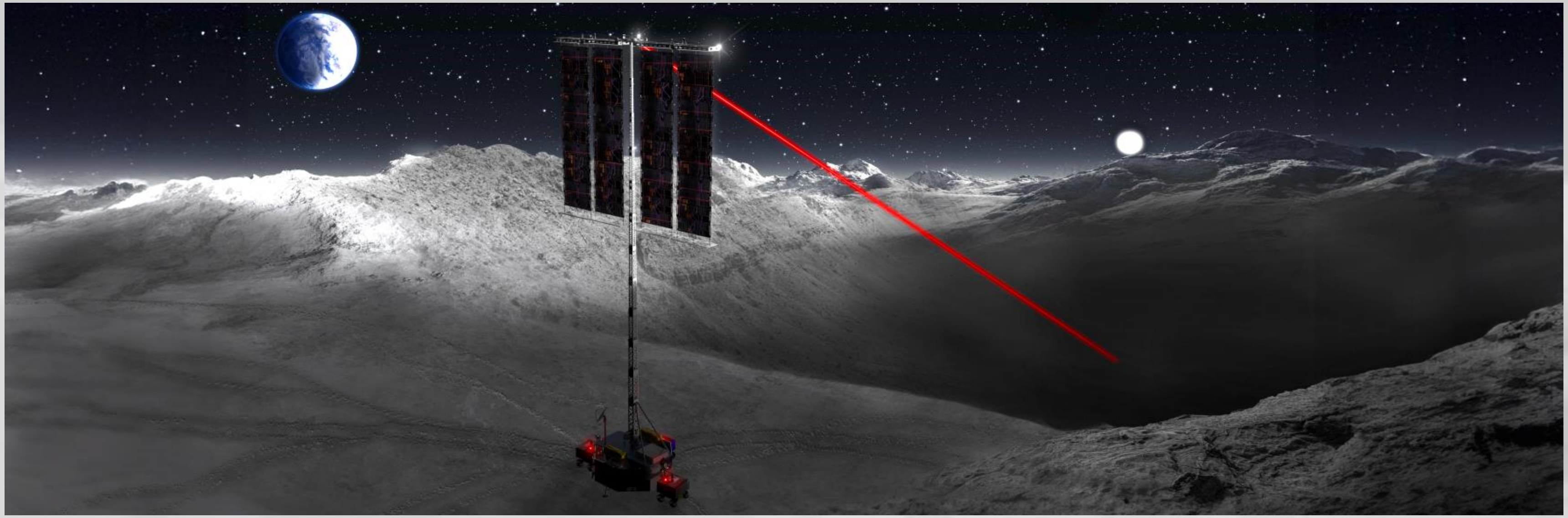
mass growth allowance per AIAA mass estimation standards

Summary: power from lunar orbit

- Feasible to make a 3-kW Laser Beamcraft to power science landers in the dark and relay on the far-side
- Mission: Three Beamcraft launched individually to 800 km polar lunar orbits, offset by 60°, each supports 6 science landed assets at a time (3 shadowed/ 3 sunlit)
  - If surface stations are located only in near-polar or in near-equatorial locations, one beamcraft is needed
  - Three orbital planes are required for mid-latitudes
- Laser: 3 kW (8 kWe input), 1.07 µm terrestrial technology, 38% efficient
- Optics: Based on 1.45 m Kepler telescope, ~2.5m laser spot at maximum 1500 km distance
- Cost analysis: ~ $2.2B for three Laser Beamcraft with 25% reserves, no launch or Phase E
  - Breakpoint showed at least 10 science landers make the beamcraft option attractive
  - Saves ~$2.8B compared to landing large, overnight power systems



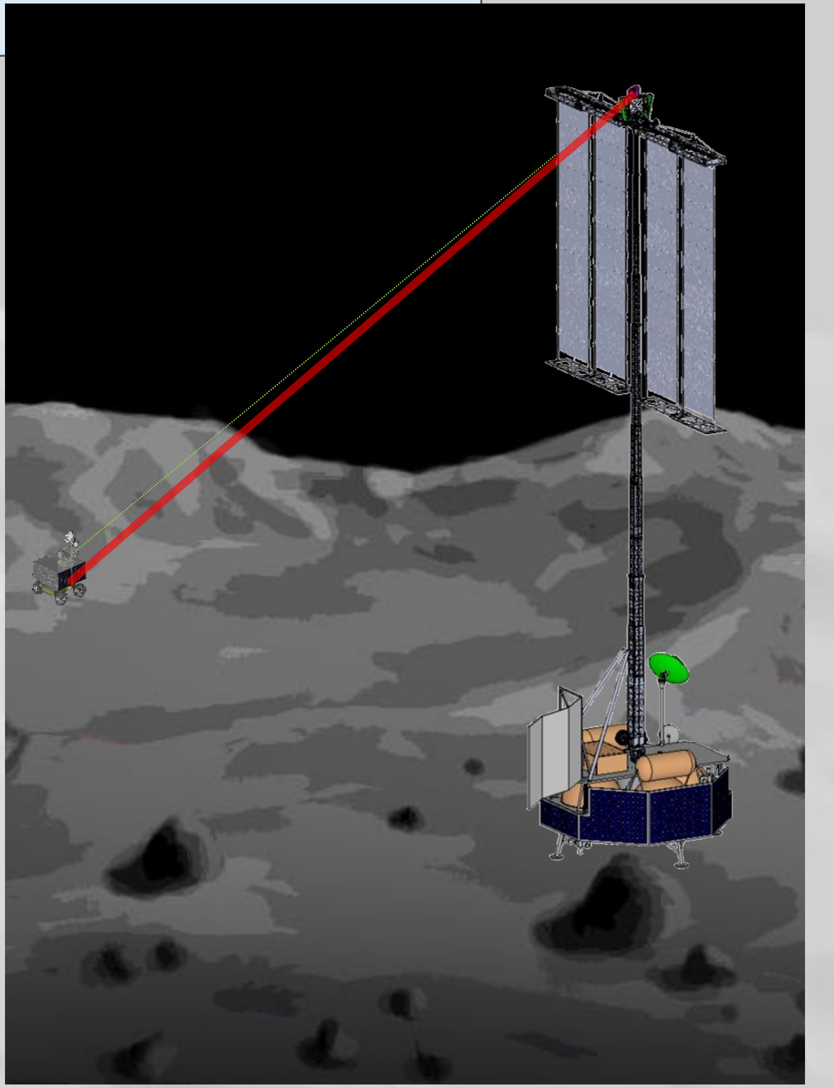
Surface to Surface Power Beaming



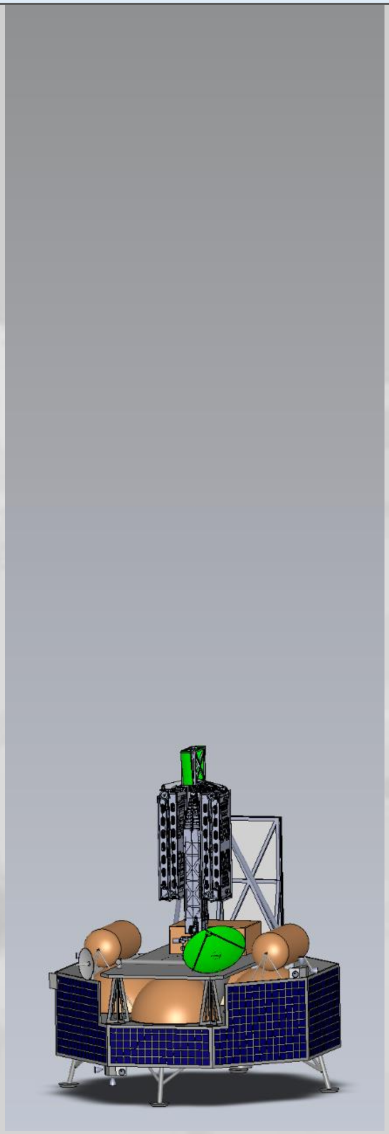
- **Objective**: design study of a near-term application of power beaming for transmission of electrical power to landers or rovers
- **Baseline requirements:** deliver 300 W user power at up to 10 km distance. Beam station mass <625 kg (to fit on CLPS lander)
- **Constraints:** near-term assumptions (no new technology), incorporating realistic mass growth and margins; target deployment 2028.

Surface to Surface Power Beaming

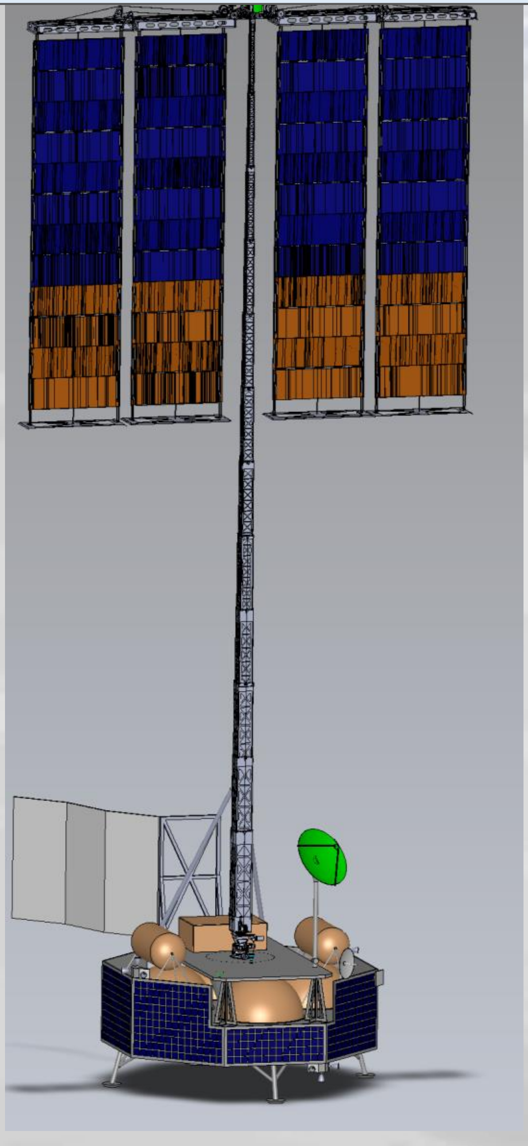
Due to surface irregularities and the close horizon of the moon, to achieve 10-km transmission the laser must be elevated above the surface. The Vertical Solar Array Technology (VSAT) program is developing a solar array mounted on a 10-m tall mast, intended to fit on a Commercial Lunar Payload Services (CLPS) lander, with target readiness date of 2028. At an optimum location near the south pole, the elevated array produces power for a majority of the lunar day.



Overview of structure



Beaming station stowed



Beaming station deployed

Laser station

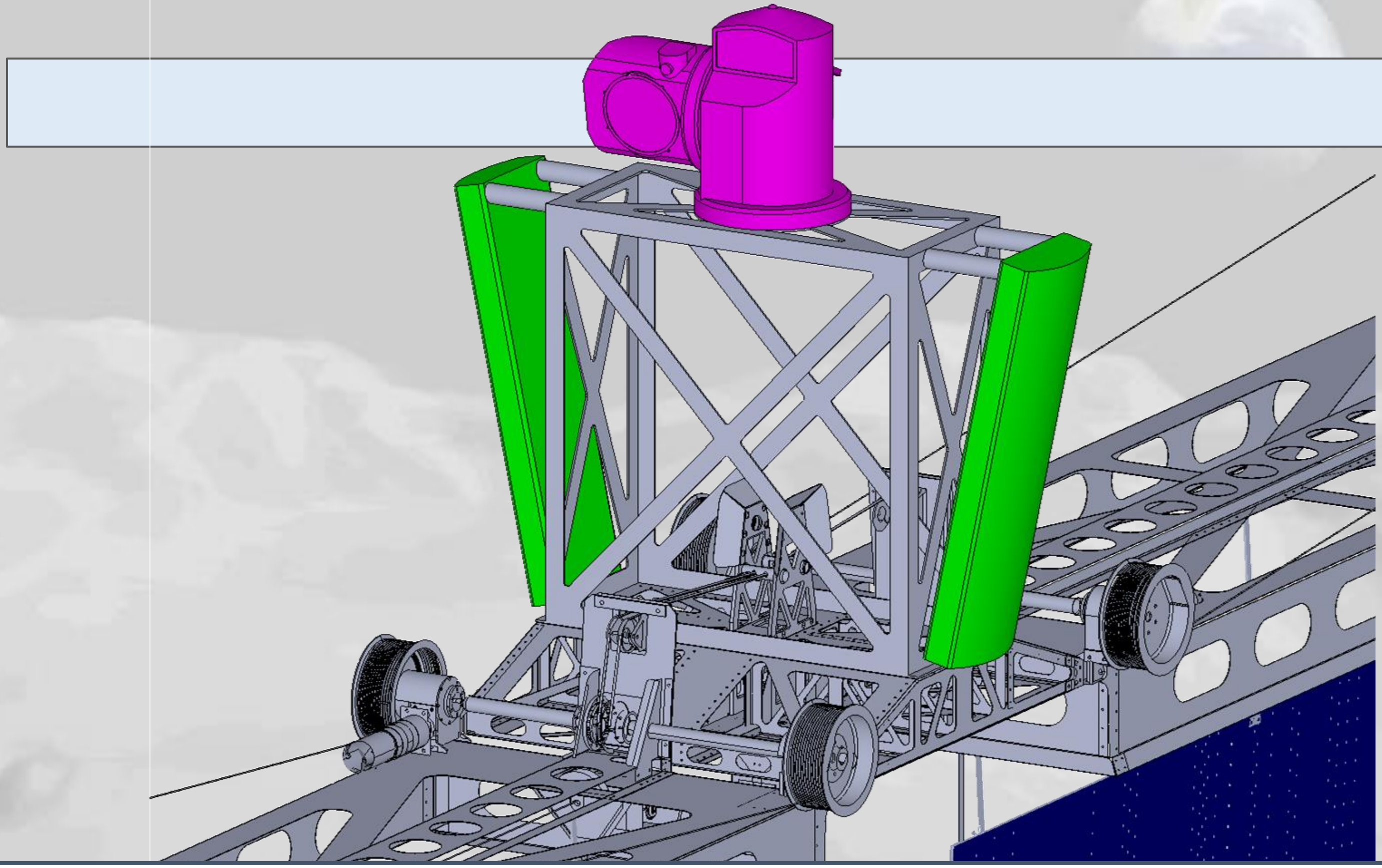
Design

A 1.07-μ diode-pumped fiber laser based on a commercially-available model with 40% electrical to optical power conversion efficiency is mounted on the deck of the lander. Laser output is sent to the apex-mounted beam director by a fiber-optic cable.

A 7 m^2 deployable radiator keeps the laser within operating temperature limits. 1595 W of laser optical power is directed by a steerable beam director with a 10-cm primary optic, resulting in a 1.5-m spot diameter (FWHM) at the maximum 10-km range.

A 3.4-W diode-laser beacon on the receiver enables precise pointing of the beam. An array of InGaAs photovoltaic cells with conversion efficiency of 50% at the laser wavelength was baselined.

This results in an output of 540-W DC on a 1.5-meter receiving photovoltaic array (slightly more if a larger receiving array is used). Of this received power, 300 watts is directly available to the user, while 242 watts is used to charge batteries for use while the beam is not available. The system also incorporates a 5G 60-Mbps data relay



detail showing beam director (magenta) and data-relay antenna (green) at apex of mast

Concept of Operations

- The system beams power for 57% of the time, with 44% of the time idle (accounting for the time when the VSAT array is itself in shadow). 1595 Watts of optical power are output in the beam.
- Accounting for receiver efficiency and beam losses, this results in an output onto the 1.5-meter receiving photovoltaic array of 542 watts. Of this, 300 watts is directly available to the user, while 242 watts is directed to the batteries for use while the beam is not available.

Mass equipment list

MEL Summary: Case 2_VSAT_Beamed_Power_LSR CD-2023-203	VSAT_LSR
Main Subsystems	**Basic Mass (kg)**
Laser and beam director	35.9
Attitude Determination and Control	1.6
Command & Data Handling	13.0
Communications and Tracking	22.5
Electrical Power Subsystem	106.7
Thermal Control (Non-Propellant)	70.9
Structures and Mechanisms	206.1
Element Total	***456.7***
Element Mass Growth Allowance (Aggregate)	98.0
MGA Percentage	21%
Predicted Mass (Basic + MGA)	554.7
System Level Mass Margin	68.5
System Level Growth Percentage	15%
Element Dry Mass (Basic+MGA+Margin)	623.2
Element Inert Mass (Basic+MGA+Margin)	623.2
Total Wet Mass (Allowable Mass)	***623.2***

Summary: surface to surface power beaming

- A conceptual engineering design was done for a fiber-laser based beaming station on a VSAT solar array
- Beams power to a photovoltaic array on a rover or lander inside a permanently shadowed lunar crater at a distance of at least 10 km
- System can fit in the constraints of a Commercial Lunar Payload System (CLPS) lander