

Laser Power Beaming for Applications on the Moon

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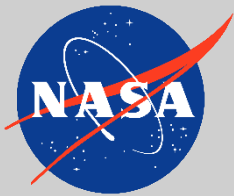
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Space Power Workshop

Torrance, CA

April 29-May 1, 2025



Lunar Beamcraft Study Purpose

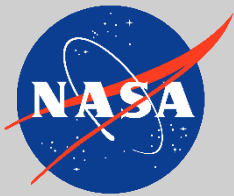


- Science missions envision a a network of surface stations (or rovers) deployed at multiple locations across the lunar surface
 - All latitudes from equatorial to polar
 - All longitudes from Earth-facing to farside
- Desire to operate at all times during the lunar cycle: both day and night operation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

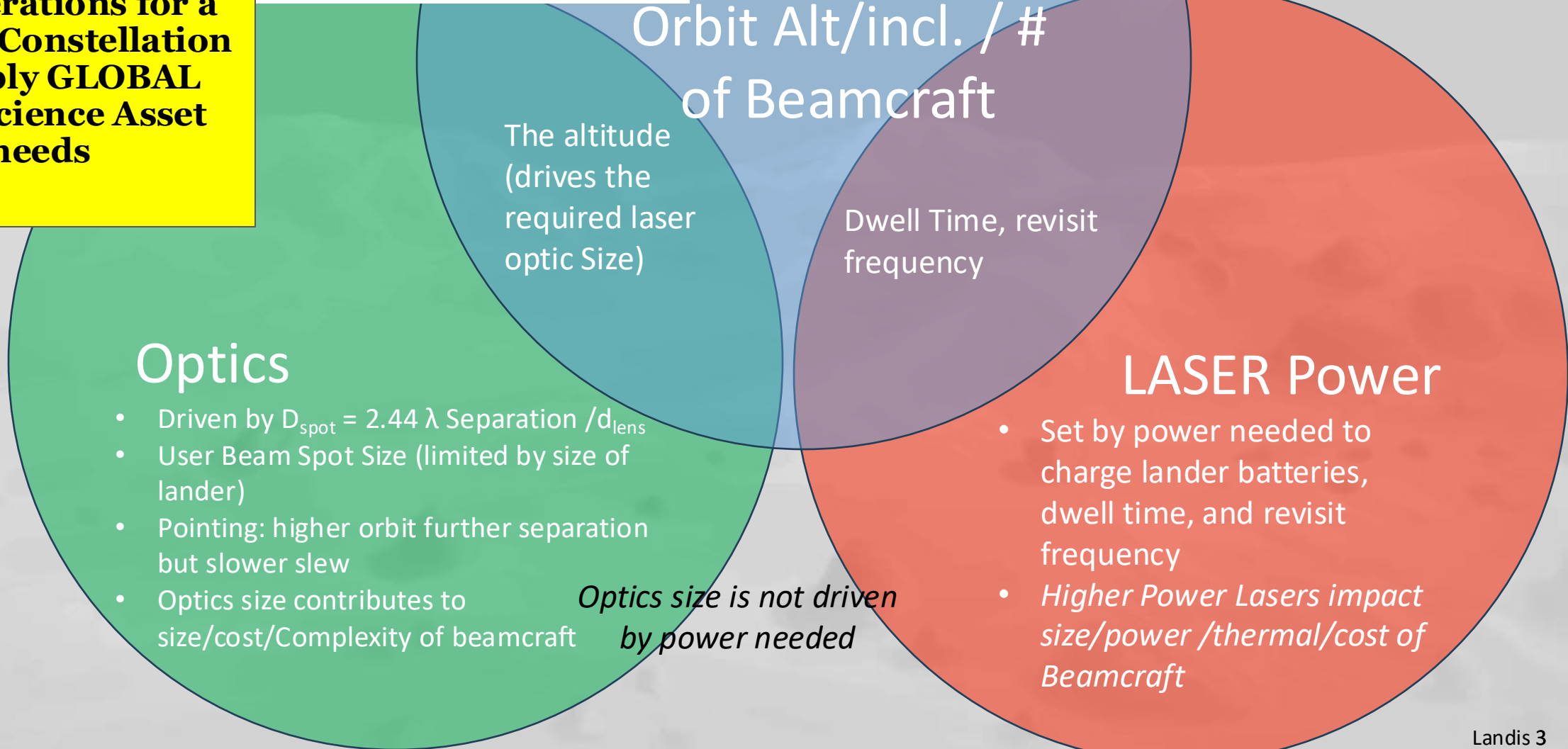


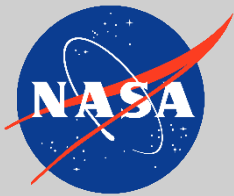
Main Design Trade Considerations for a Beamed Constellation to supply GLOBAL small science Asset needs

*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*

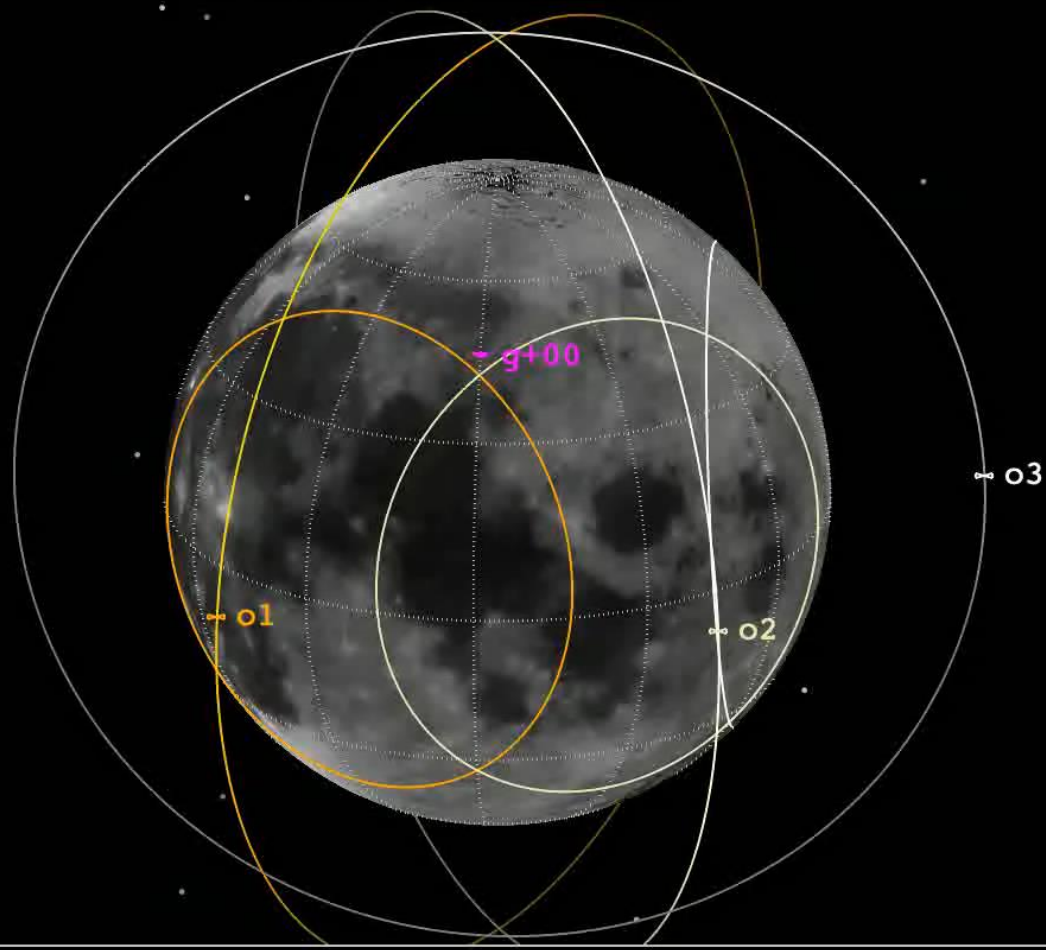




Mission: SOAP Contact Window Analysis

(3 Polar Orbiters, 90° Inc to Mid-Lat Station)

.Moon CI Observer View



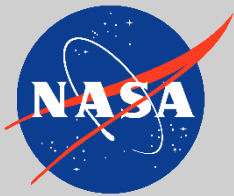
elevation: gnd+00 to orbiters
2024/01/03 20:02:00.0001 UTC

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. $T_p = 3.17$ 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)



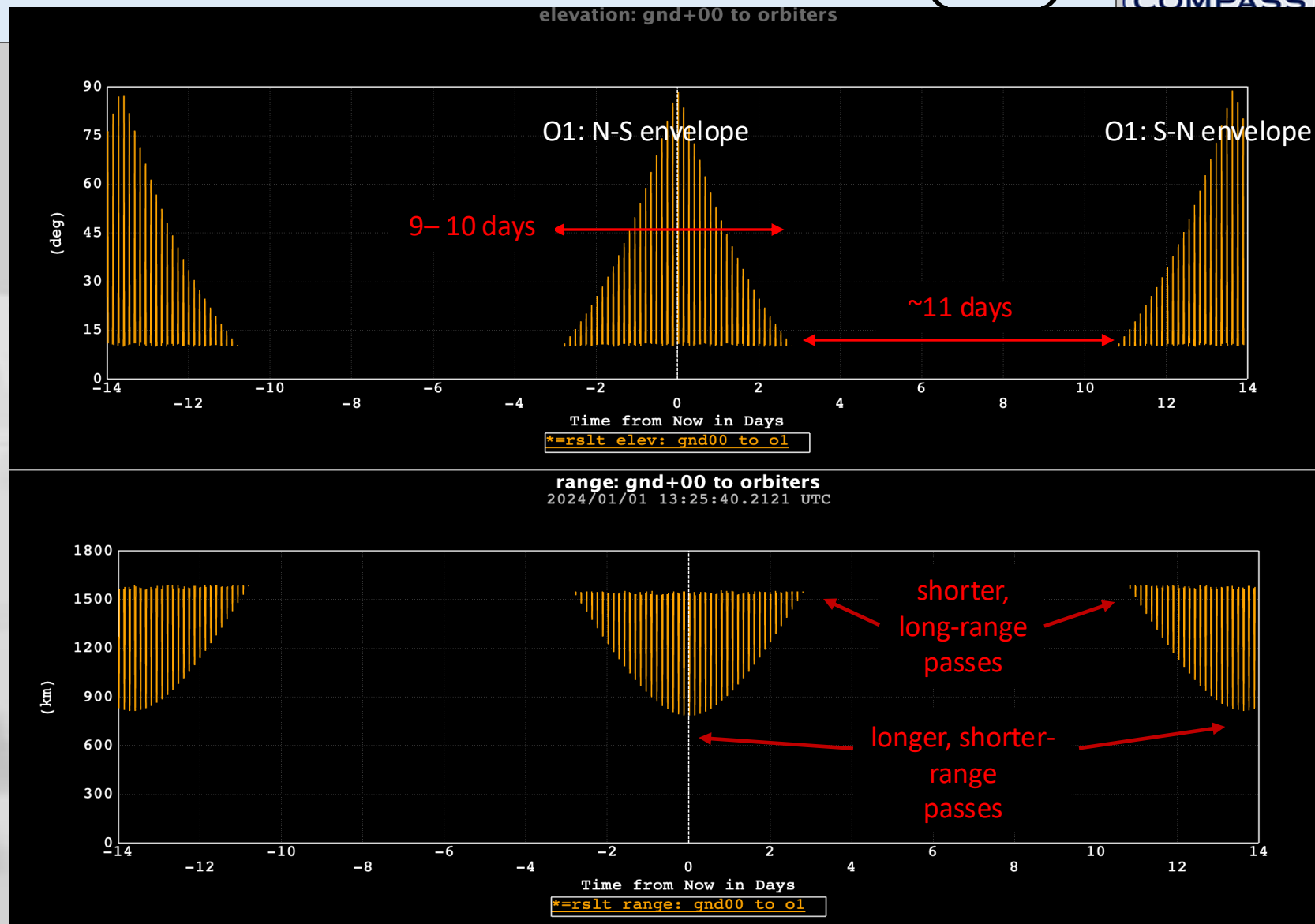
Mission: Closer Look at Orbiter Passes (O1)

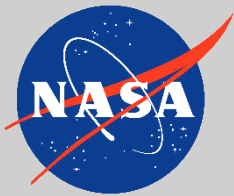


Each orbiter can be seen by the ground station 1x per 3.17 hr orbit until the moon's rotation under the orbital plane drifts the pass downrange and the orbiter can no longer be seen over the 10° horizon mask

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.

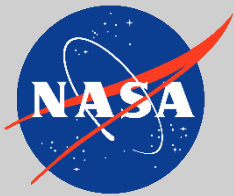




Choice of laser and photovoltaic receiver



- 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 \pm 10

Mode of Operation CW/Modulated

Power Tunability, 10-100%

Power Stability, \pm 0.5%

Output Fiber Core Diameter, 50, 100 and 200 μ m

Beam Quality, BPP 2, 5, 10 mm \times mrad

Operating Temperature Range, 10-40 $^{\circ}$ 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 \times 760 \times 177 mm

Weight, <80 kg

Power Consumption, 16 kW

Efficiency = \sim 38 %

Average Power Mode, 3 kW

Dimensions, 448 \times 760 \times 88 mm

Weight, <45 kg

Power Consumption, 7.8 kW

Efficiency = \sim 38%

- Spacecraft carries two lasers to give redundancy

Power System Component Illustration

Laser Beam

Dual Axis Tracking
Solar Array & Laser
Receiver

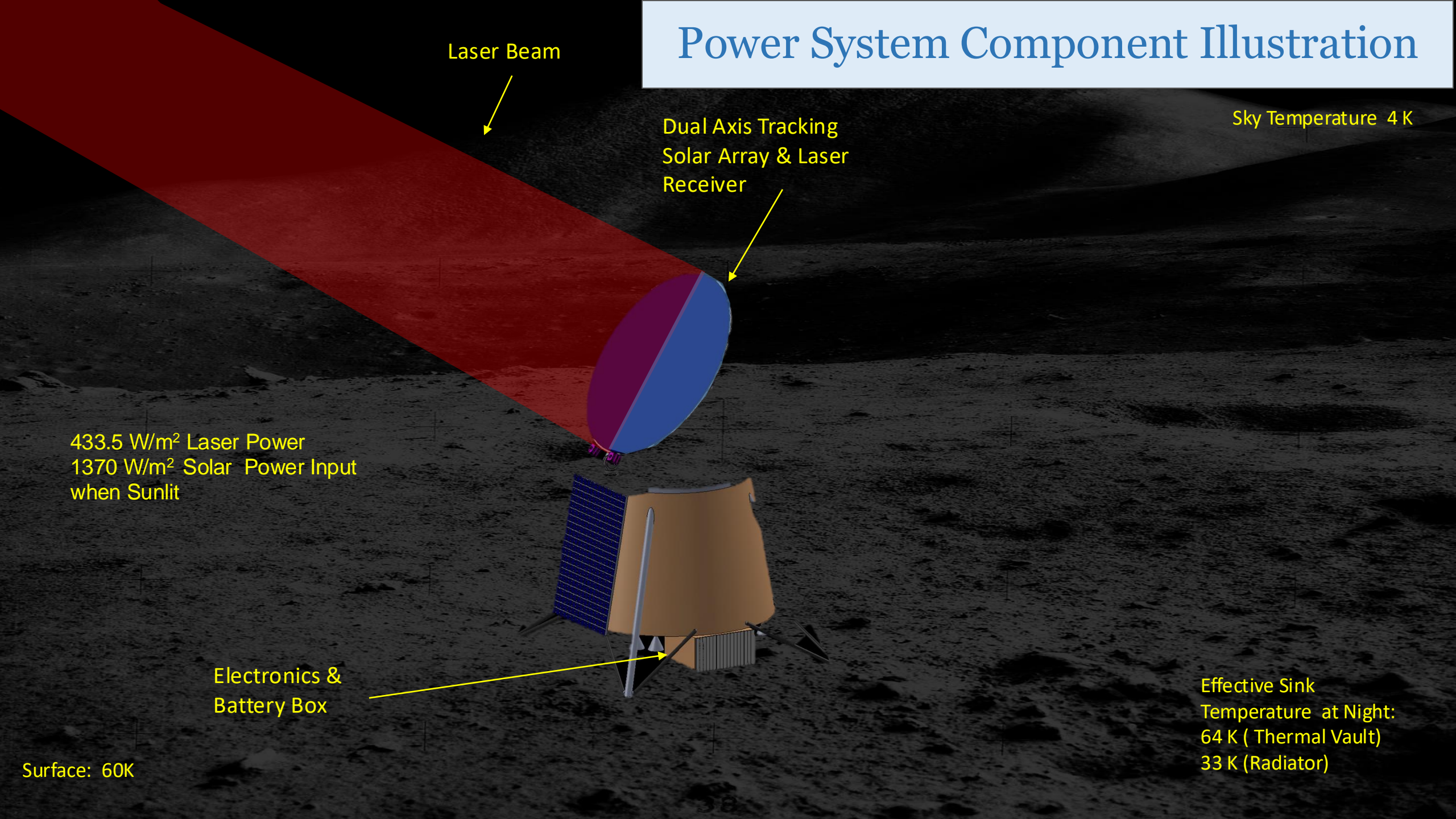
Sky Temperature 4 K

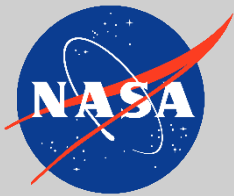
433.5 W/m² Laser Power
1370 W/m² Solar Power Input
when Sunlit

Electronics &
Battery Box

Effective Sink
Temperature at Night:
64 K (Thermal Vault)
33 K (Radiator)

Surface: 60K





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.

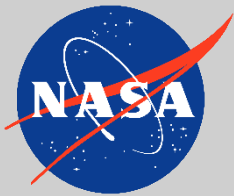
$$E_t = P_c t_b \eta_{bc} + P_c t_t$$

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

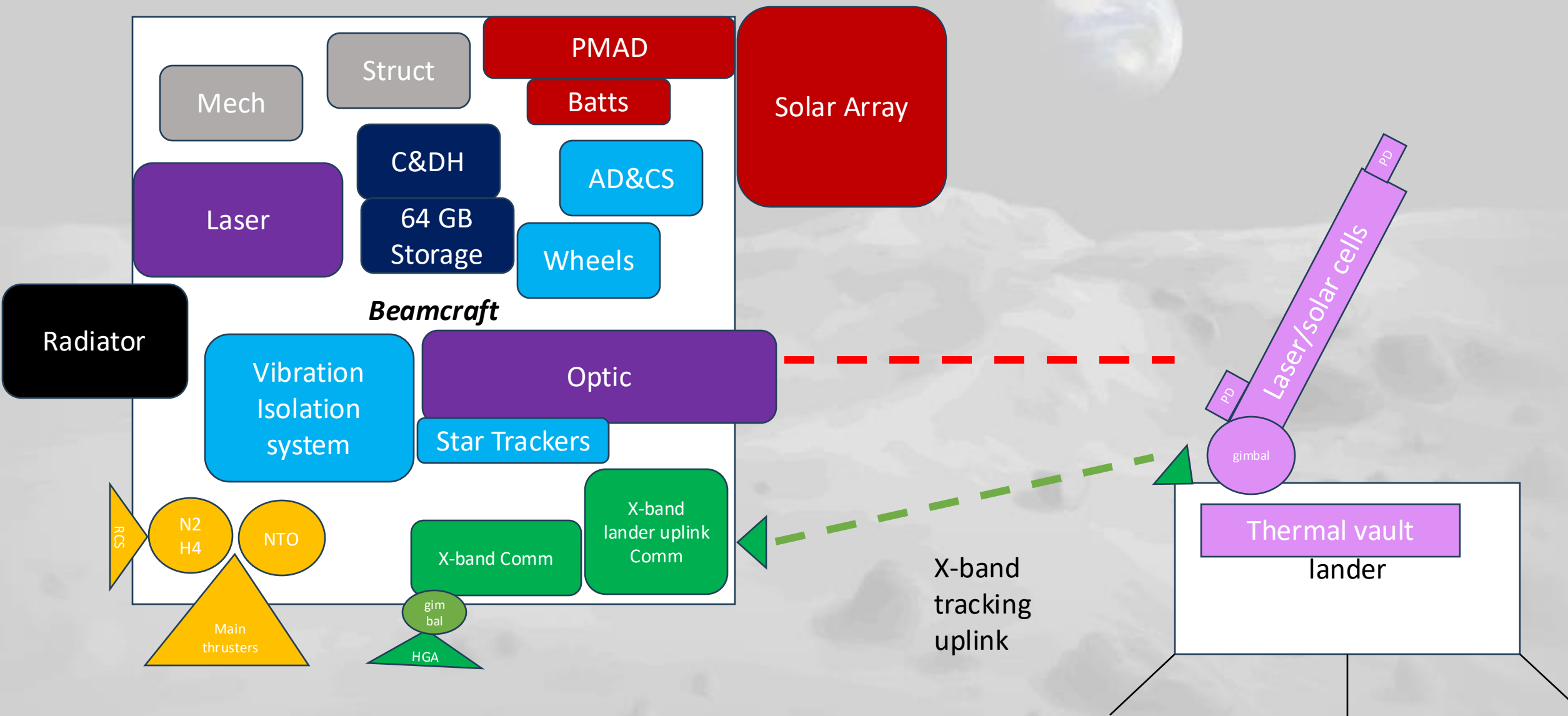
$$P_{\text{Lin}} = P_{\text{Lout}} \eta_L$$

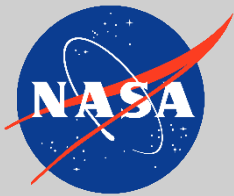
Item	Value
Power Transmission Time (t_t)	0.25 Hr
Shadow (No Power Transmission) (t_b)	2.75 Hr
Battery Charging Efficiency (η_{bc})	0.95
Array Fill Factor (η_{ff})	0.85
Laser Beam Spill (η_{bs})	0.5
PV Cell Efficiency (based on laser) (η_{sc})	0.5
Laser Efficiency (η_L)	0.4

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/m². 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



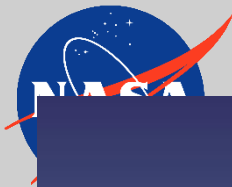
1.5 Meter Primary Mirror for Kepler Spacecraft
Image courtesy NASA/JPL

References:

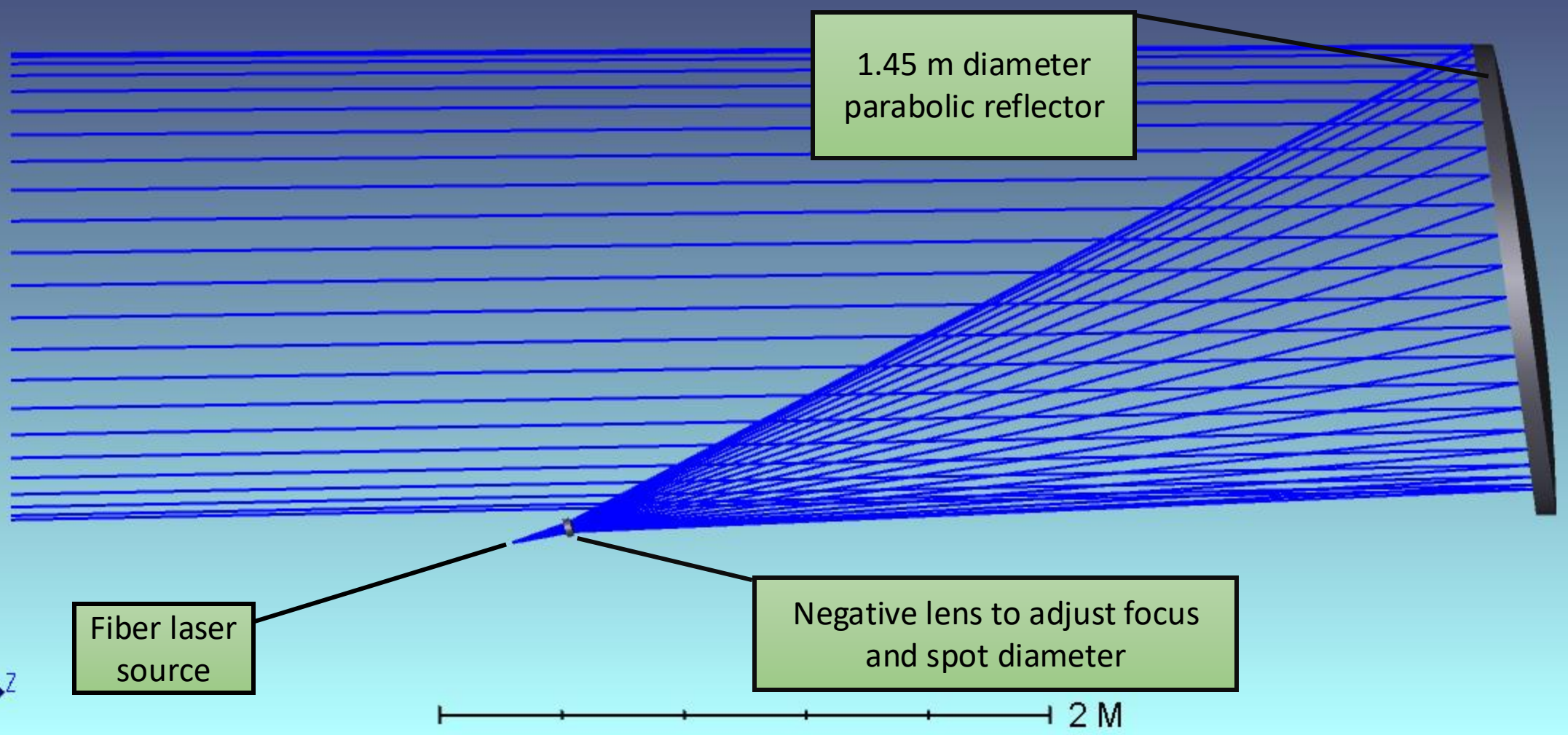
K. Kosi (2008), "Focus Mechanism for Kepler Mission," 39th Aerospace Mechanisms Symposium, NASA/CP—2008–215252, p. 373;

<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

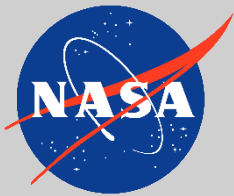


Fiber laser source

1.45 m diameter parabolic reflector

Negative lens to adjust focus and spot diameter

2 M



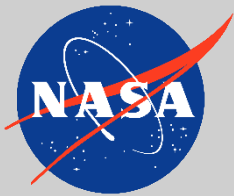
Estimated Power Delivery and Laser/Optic Sizes

Beam spot size

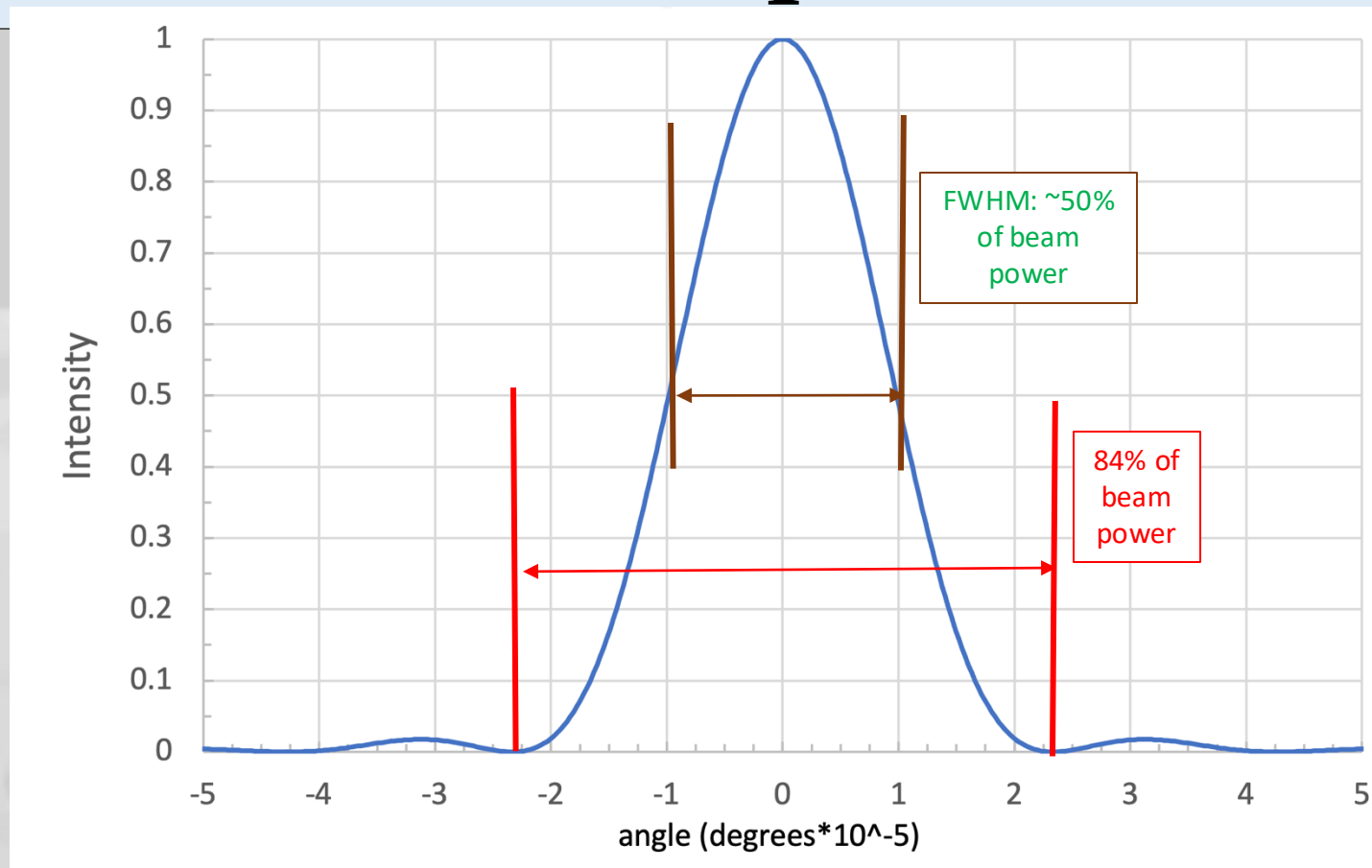
laser wavelength	1.07 microns
beam director diam.	1.4 meter
beam div angle (full)	1.86486E-06 radians
beam div angle (°)	0.384654397 arcseconds
spot diam. (84% of power)*	2.98 meters
spot diam (FWHM, ~50% of power)	1.49 meters

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

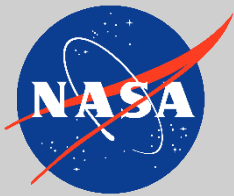
number of nighttime users per orbit plane	3
nighttime power needed (W)	50
Night length (days)	14
Whr required (for battery if unbeamed)	16800
Surface assets battery mass (if unbeamed)	114
# of Beamcraft per orbit plane	1
Time between Beamcraft visits (hrs)	3.2
W-hr required (for battery if beam serviced)	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 spread



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



Power Generation - Lander

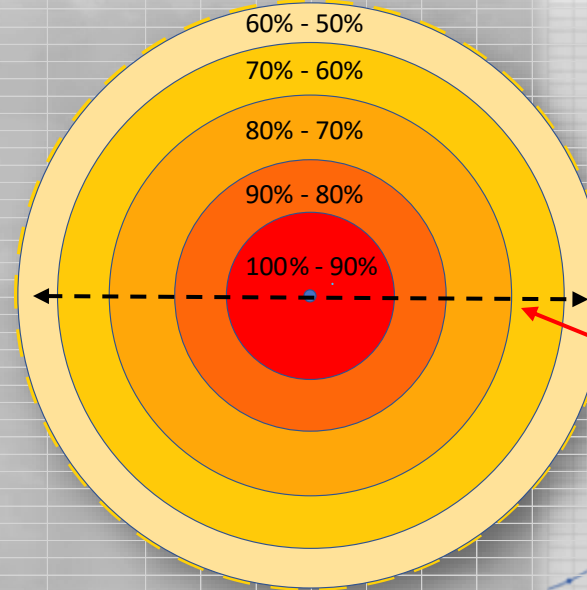


- Gaussian beam distribution introduces complexities into power generation design
 - Non-uniform irradiation across beam-spot means cells produce different amounts of current based on location within beam

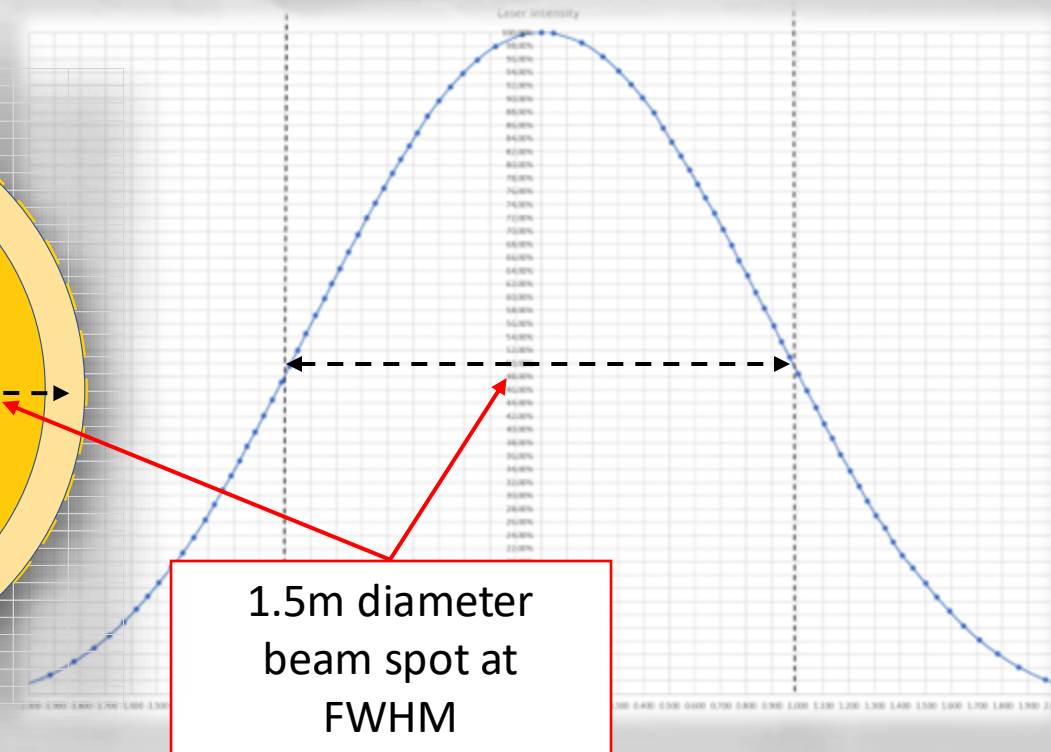
Bins:	Diam [m]	Total Area [m2]	Avg. Flux [W/m2]
Bin 1 Radius:	0.429	0.145	1636.93
Bin 2 Radius:	0.696	0.380	1435.88
Bin 3 Radius:	1.029	0.832	1271.33
Bin 4 Radius:	1.296	1.319	1092.68
Bin 5 Radius:	1.500	1.767	926.10

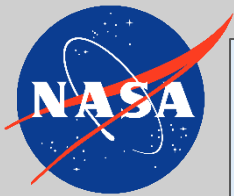
Power			
Bin	# of Strings	Total Power [W]	Total # of cells
1	7	68.9	119
2	13	112.3	221
3	25	191.3	425
4	26	171.1	442
5	24	133.9	408
Total	95	677.5	1615

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



Distribution of laser intensity for Gaussian beam

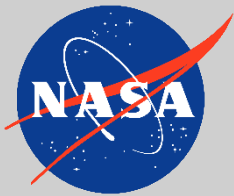




Laser spot non-uniformity challenges



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

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

• Closed Loop

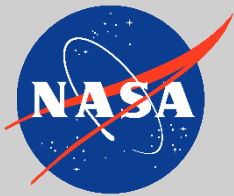
- Start with have position knowledge of ~200m RSS (based on LRO experience) and 1.5 arcsec knowledge (StarCamera)
- search in a 300 m diameter (Defocus (to 200m D) large high-power laser to raster scan area of interest
 - ✓ First use a photo detector on lander and relay up resulting sense of laser to 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 jitter to be tightly controlled

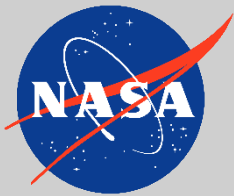


Beacon Option



- 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

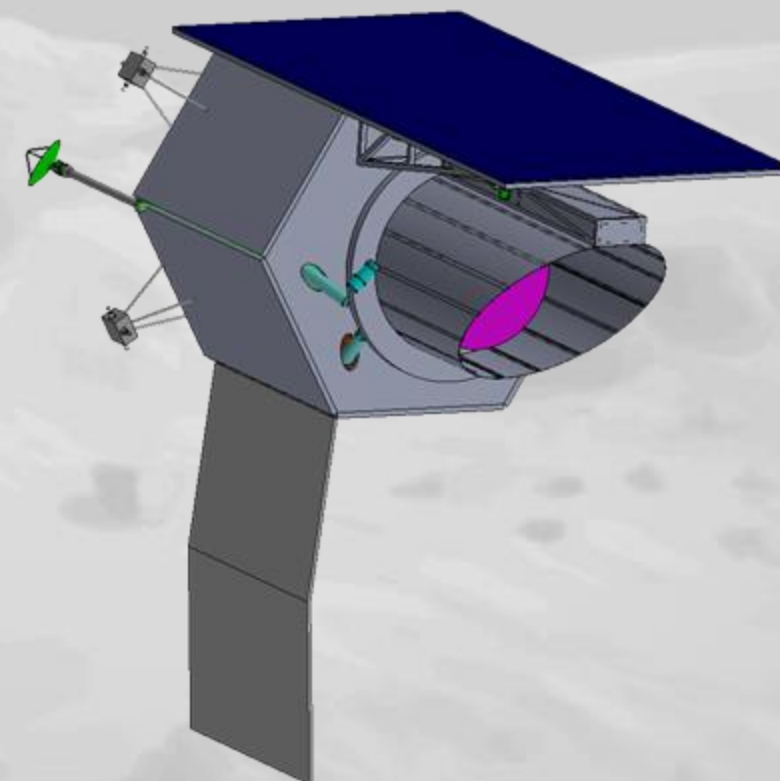
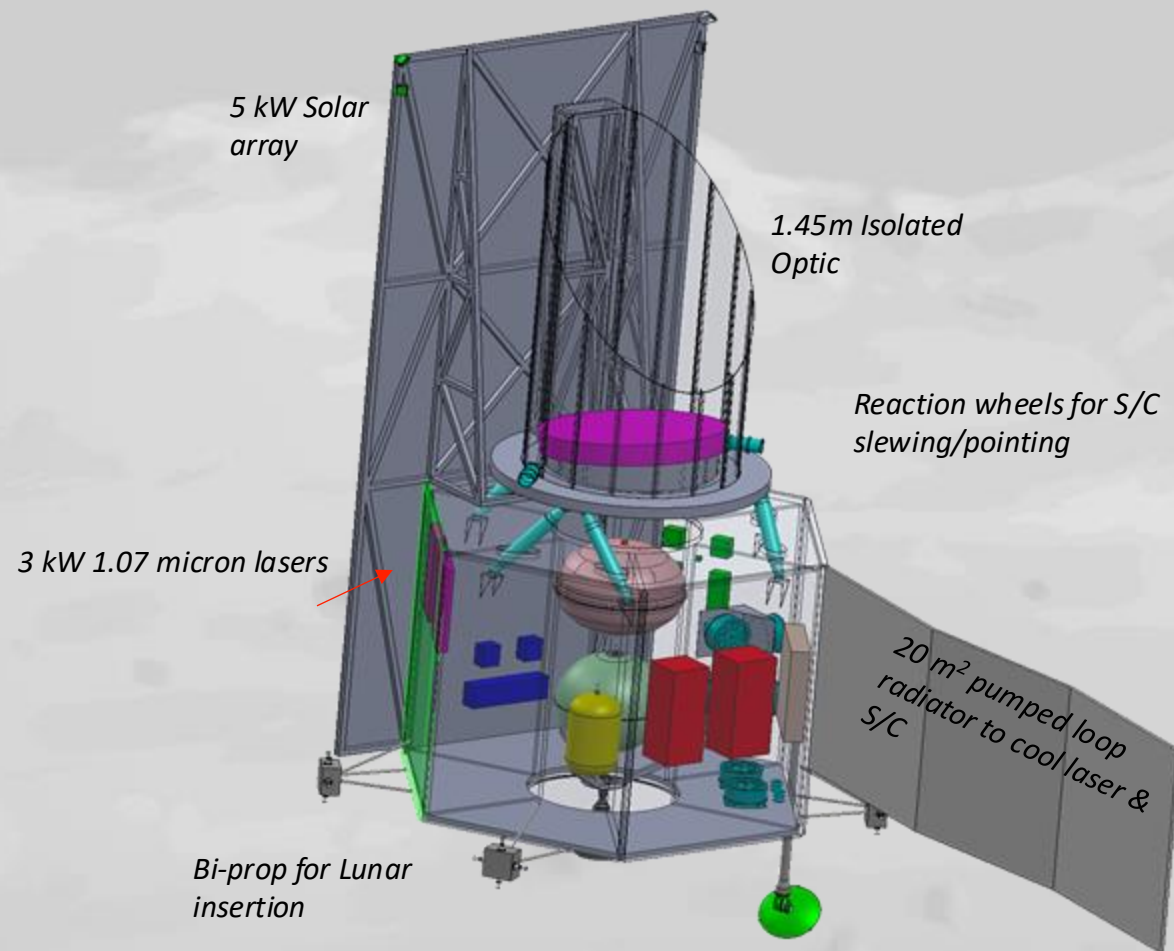


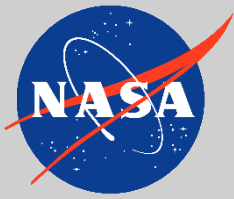


Laser Beamcraft for Global Science Landers



~ 3500 kg Beamcraft



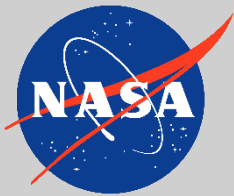


Lunar Beamcraft and Lander Payload Mass Equipment List



Description	Basic Mass	Growth	Growth	Total Mass
Case 1_Lunar_Beam_Craft CD-2023-207	(kg)	(%)	(kg)	(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

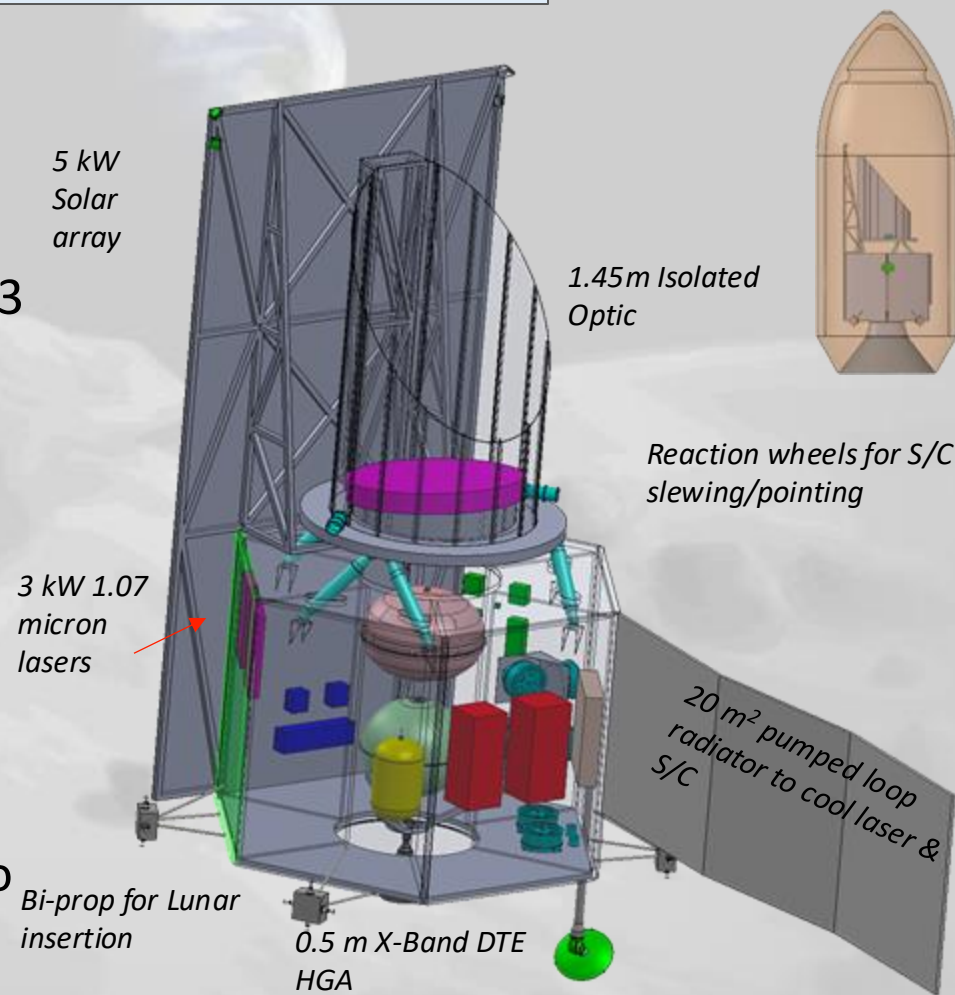
mass growth allowance
per AIAA mass
estimation standards



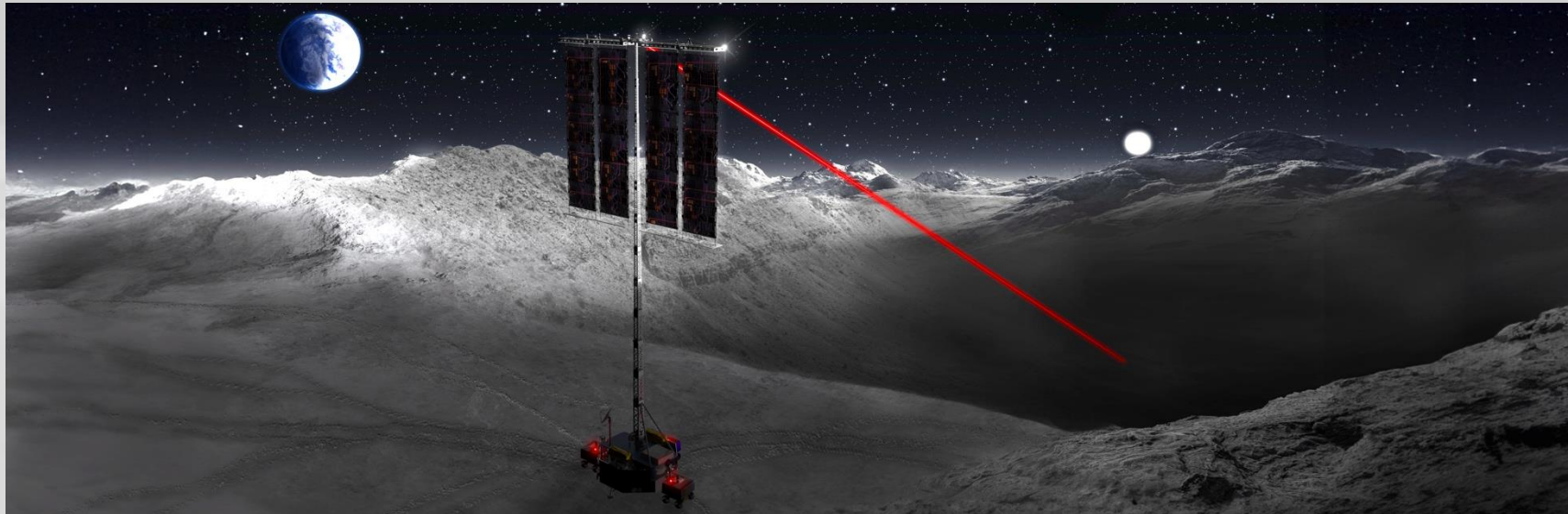
Summary: power from lunar orbit



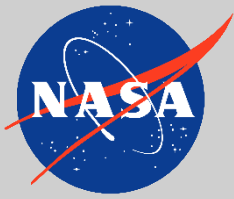
- Feasible to make a 3-kW Laser Beamcraft to power science landers in the dark and relay on the far-side
- Mission: Three Beamcraft launched individually to 800 km polar lunar orbits, offset by 60°, each supports 6 science landed assets at a time (3 shadowed/ 3 sunlit)
 - If surface stations are located 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, $\sim 2.5\text{m}$ laser spot at maximum 1500 km distance
- Cost analysis: $\sim \$2.2\text{B}$ 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 $\sim \$2.8\text{B}$ compared to landing large, overnight power systems



Surface to Surface Power Beaming



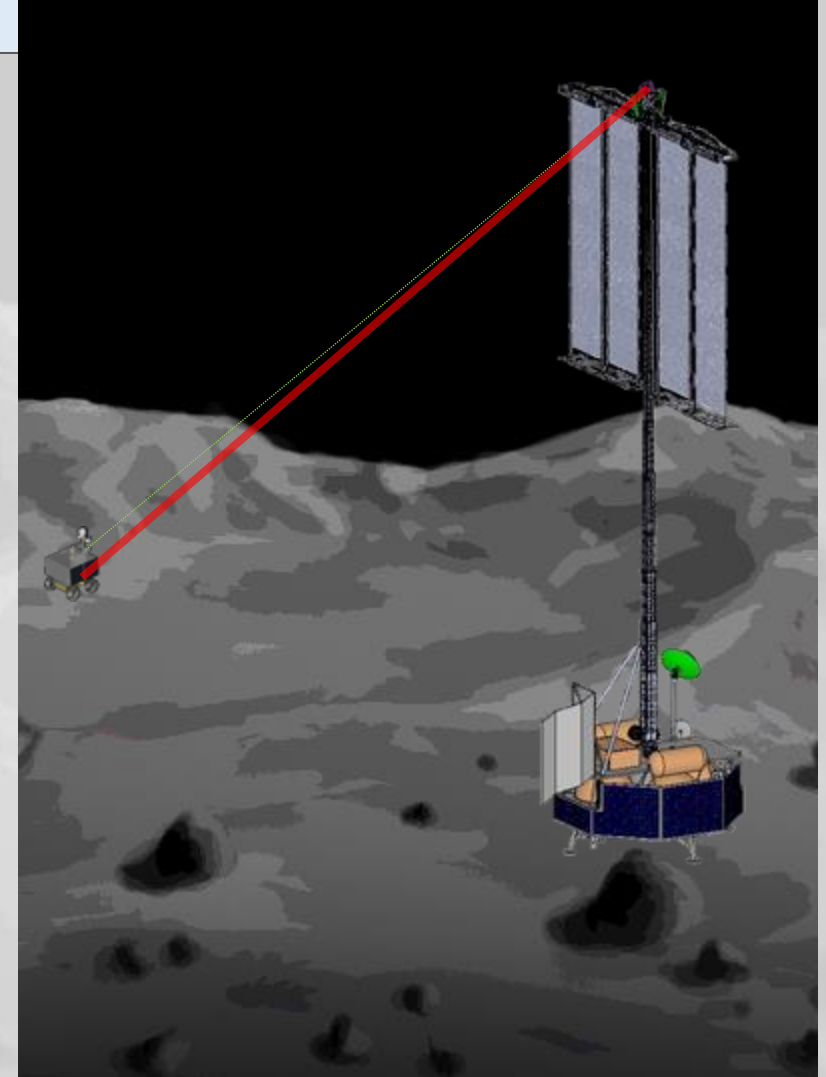
- **Objective:** design study of a near-term application of power beaming for transmission of electrical power to landers or rovers
- **Baseline requirements:** deliver 300 W user power at up to 10 km distance. Beam station mass <625 kg (to fit on CLPS lander)
- **Constraints:** near-term assumptions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

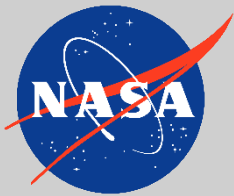


Surface to Surface Power Beaming

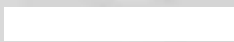


Due to surface irregularities and the close horizon of the moon, to achieve 10-km transmission the laser must be elevated above the surface. The Vertical Solar Array Technology (VSAT) program is developing a solar array mounted on a 10-m tall mast, intended to fit on a Commercial Lunar Payload Services (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.





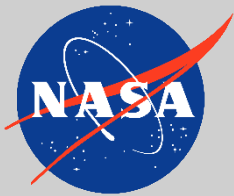
Overview of structure



Beaming station stowed



Beaming station deployed



Laser station



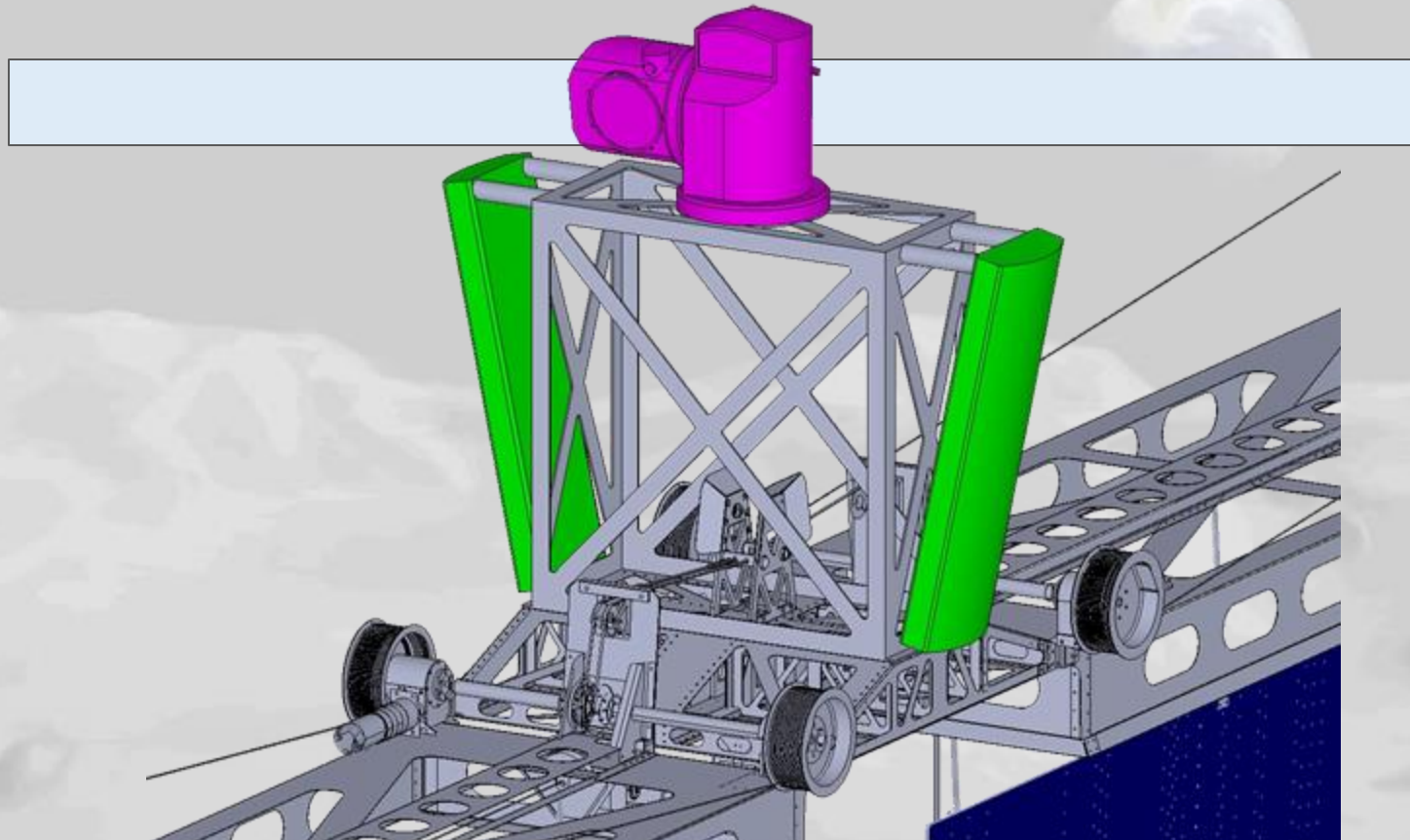
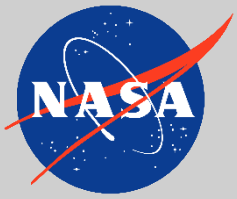
Design

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.

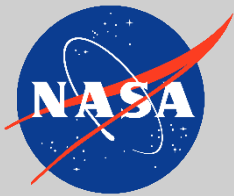
A 7 m² deployable radiator keeps the laser within operating temperature limits. 1595 W of laser optical power is directed by a steerable beam director with a 10-cm primary optic, resulting in a 1.5-m spot diameter (FWHM) at the maximum 10-km range.

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



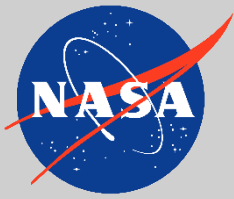
*detail showing beam director (magenta)
and data-relay antenna (green) at apex of
mast*



Concept of Operations



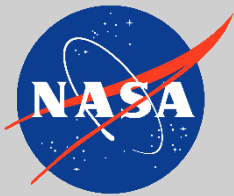
- The system beams power for 57% of the time, with 44% of the time idle (accounting for the time when the VSAT array is itself in shadow). 1595 Watts of optical power are output in the beam.
- Accounting for receiver efficiency and beam losses, this results in an output onto the 1.5-meter receiving photovoltaic 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

