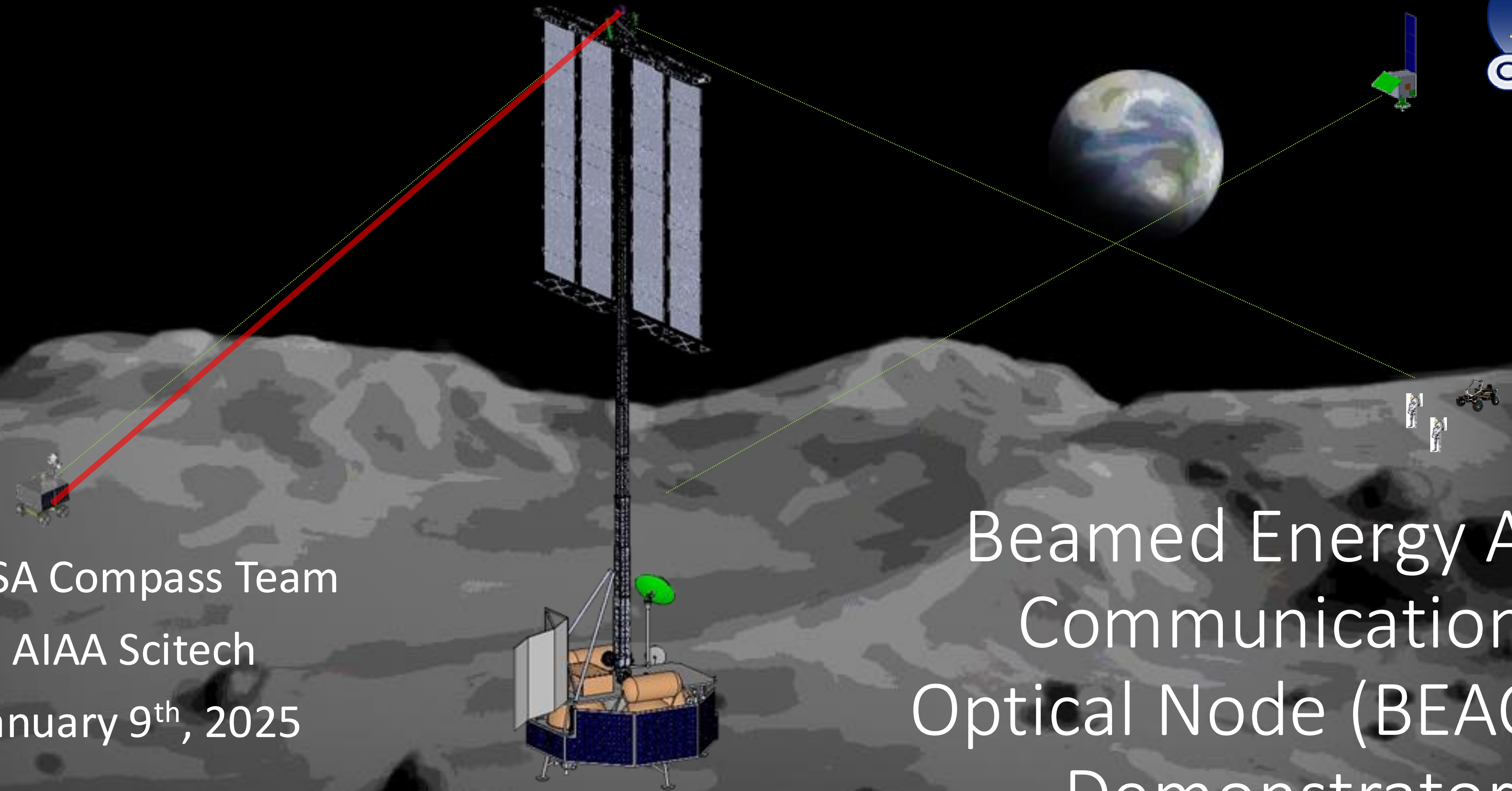


Beamed Energy And Communications Optical Node (BEACON) Demonstrator

NASA Compass Team

AIAA Scitech

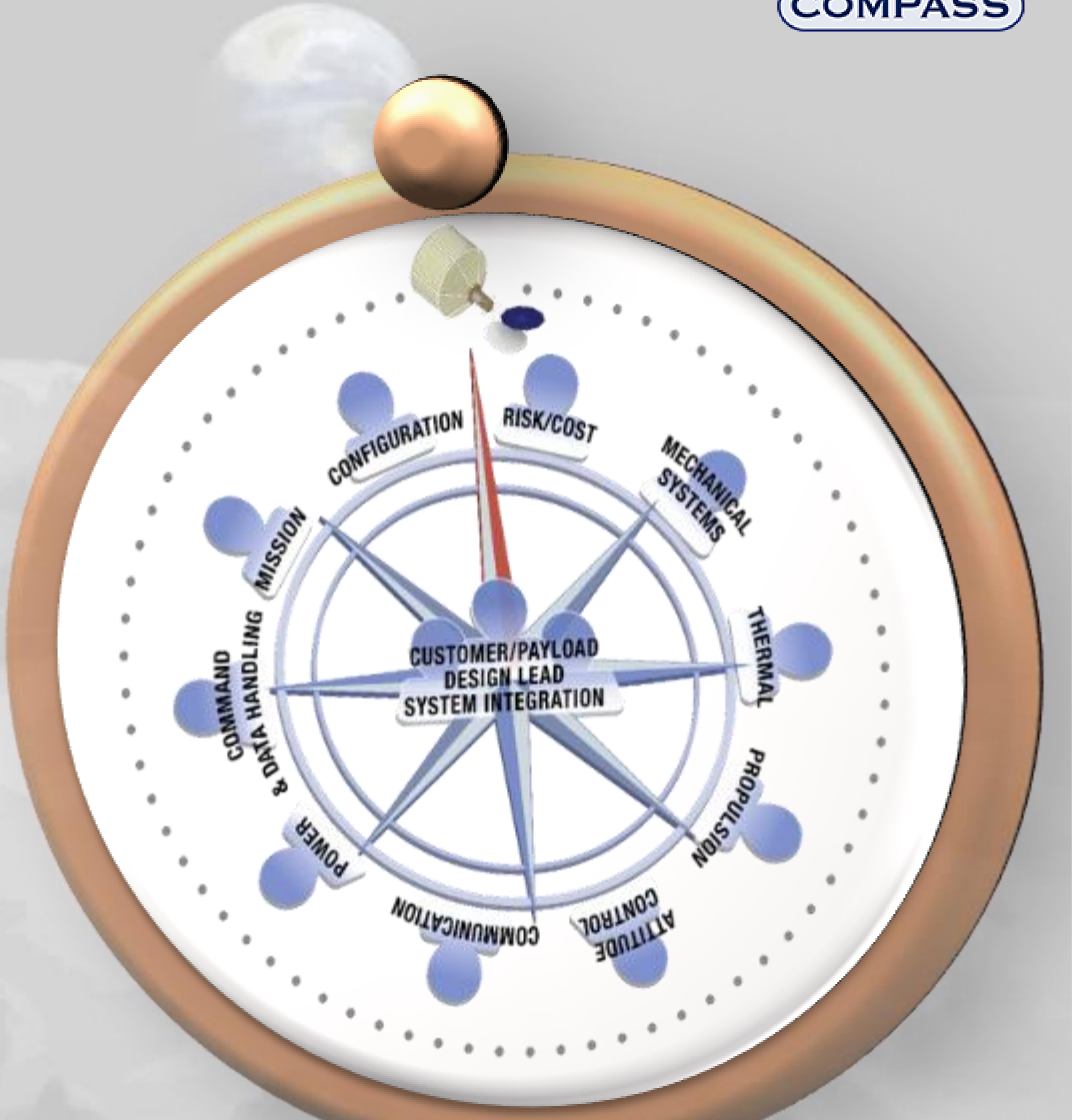
January 9th, 2025

Steve Oleson, Timothy Gray, Elizabeth Turnbull, Geoffrey Landis, Michael Gasper, Lucas Shalkhauser, Obed Sands, Brent Faller, Natalie Weckesser (NASA)
James Fittje (SAIC), and Anthony Colozza, John Gyekenyesi, Thomas Packard, David Squires (HX5)

Compass Team

- The Compass concurrent engineering team was formed in 2006, and over 200 designs have been produced to-date
- The team includes experts from each discipline of space vehicle and mission design, collected from their respective discipline-area branches (matrix)
  - Branch knowledge and experience is leveraged through review of their representative's product(s)
- The experts are gathered in one room and collaborate in real time to perform analyses
- This approach results in quickly achieving high quality engineering designs without inefficiencies experienced by isolated teams

Compass Team Members 2006-2016



Team Roster

- Customer- Mike Barrett, Jeremiah McNatt (STMD), Lee Mason (LAT)
- Team Lead- Steve Oleson
- Systems Integration- Tim Gray, Jim Fittje, Betsy Turnbull
- Laser, Optics, Beacons: Geoffrey Landis, David Squires, Obed Sands
- Power and Thermal- Tony Colozza
- Communications- Obed Sands, Mike Gasper
- Structures- John Gyekenyesi
- Command and Data Handling – Lucas Shalkhauser
- Position, Navigation, and Timing – Brent Faller
- Coverage Analysis – Mike Gasper
- Configuration – Tom Packard
- Cost – Natalie Weckesser

Approach

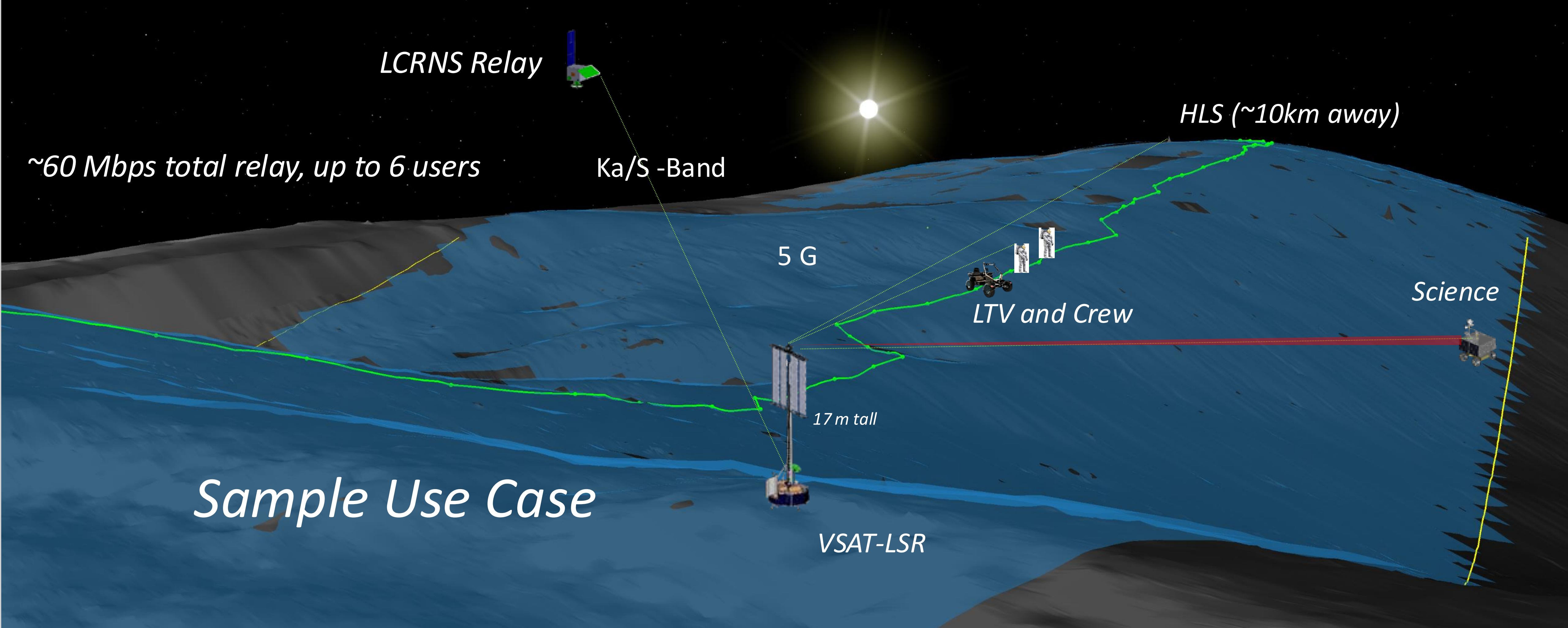
- Start with the Vertical Solar Array Technologies (VSAT)/ Lunar Surface Relay (LSR) Demonstrator (fall 2023)
- Same landing location and mission: BUT now evaluate a demonstration of beaming power to users up to 10 km away
- Same large Commercial Lunar Payload Services (CLPS) lander – assume successful delivery to lunar surface (azimuth within +/- 5°, Slope<10°) (100m x 100m)
  - Limited to 625 kg payload based on Griffin CLPS
- Assume demonstrator at south pole (Shackleton rim)
- Assume 100 hrs max darkness on solar array wings (SAWs): operate relay and charging within mass/cost limits
- Assume lander deactivated – no reused systems
- Use Gov't Baseline boom and (partially populated) SAWs
  - Integrate 5G and other comm equipment to top of boom
- Utilize top of lander deck to allow deployment of antennas and charge stations
- Baseline laser, run one off for microwave

Objectives and Requirements

- **Objective:** Maximize line-of-sight for relay and laser power by considering lunar surface topology and horizon distance (~5 km due to curvature).**Elevation Importance:**Solar array, 3GPP antennas, and laser beam director must be positioned at higher elevations for optimal sunlight and access to a broader landscape.
- Frequent illumination and user accessibility are key factors in positioning.
- **VSAT Project Highlights:**Developed by NASA for a vertical solar array mounted on a 10+ m mast.
- Targeted deployment on a Commercial Lunar Payload Services (CLPS) lander.
- Designed to deliver 10 kW of initial power near the lunar south pole by 2028.
- **Design Features:** Uses the government VSAT reference for structural design and power source.
- Antennas and laser director mounted at the top allow 10 km viewing distance.
    1. **System Requirements:**Deploy/redeploy a ~10 kWe class array (7 kWe operational) on a >10 m tower with shadow periods <100 hours during lunar winter.
    2. Survive lunar nights with minimal relay during solar darkness.
    3. Deliver up to 500 W to remote users (CLPS landers, VIPER rovers, Lunar Terrain Vehicle) within a 10 km range.
    4. Provide 3GPP relay at 60 Mbps for up to six users within 10 km using dual 180° antennas.
    5. Backhaul communication via LCRNS satellites using Ka/S-band links and a 1 m antenna.
- **Mission Parameters:** Designed for a 5-year lifetime with an 18-month demonstration period.
- Limited to a total landed system mass of 625 kg for medium-sized CLPS landers.

Demonstration Requirements

- Power
  - Floor
    - VSAT: Boom and solar array deployment and retraction and leveling
      - 5 kW, at least two redeployments (before and after a shadow period)
      - Mechanical: Demonstrate deployment/retraction/deployment for a minimum 15 m boom
      - Power: Demonstrate low mass solar array deployment/folding/redeployment, evaluate dust/thermal impacts on the array
    - Beam power to CLPS or Volatiles Investigating Polar Exploration Rover (VIPER) rover class (needs 50W or 140W continuous, respectively) up to 10 km away
  - Desired
    - Beam power to LTV 10 km and provide 300W continuous
- Relay/Comm
  - Floor
    - 5G network for 60 Mbps (up to 6 users) during daylight (VSAT powered), relay to either LCRNS or Earth
    - No power heavy position, navigation, and timing (PNT) (retroreflectors from CLPS lander and simple clock)



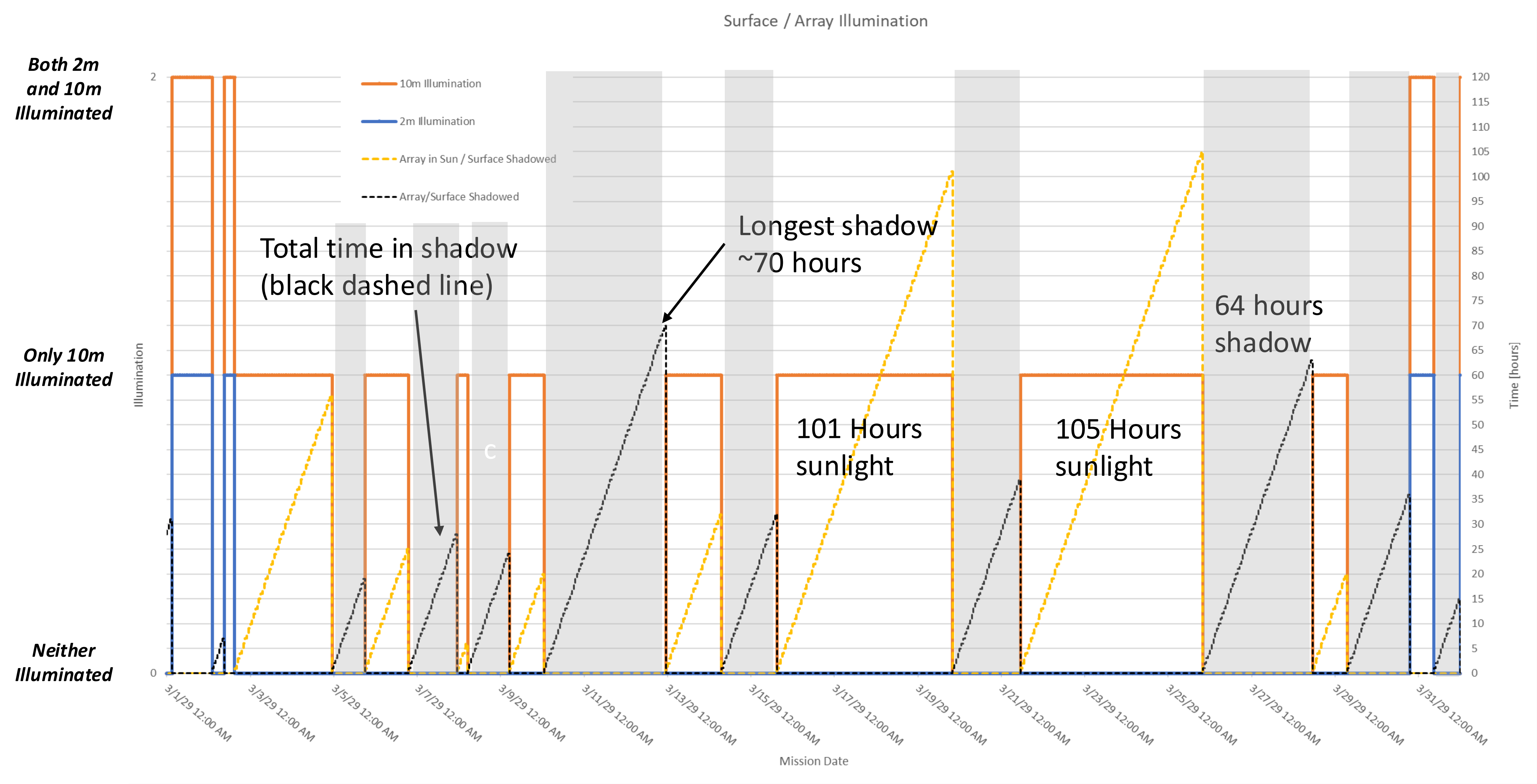
Pre-placed Lunar Surface Relay Tower on Shackleton Ridge provides

- *HLS full coverage – even during a walkback*
- *Provides relay for science users (60 Mbps) up to 10 km away*
- *Powers users in view up to 10 km away: Reduces energy storage needs to <100 hrs from 700 hrs in winter!*

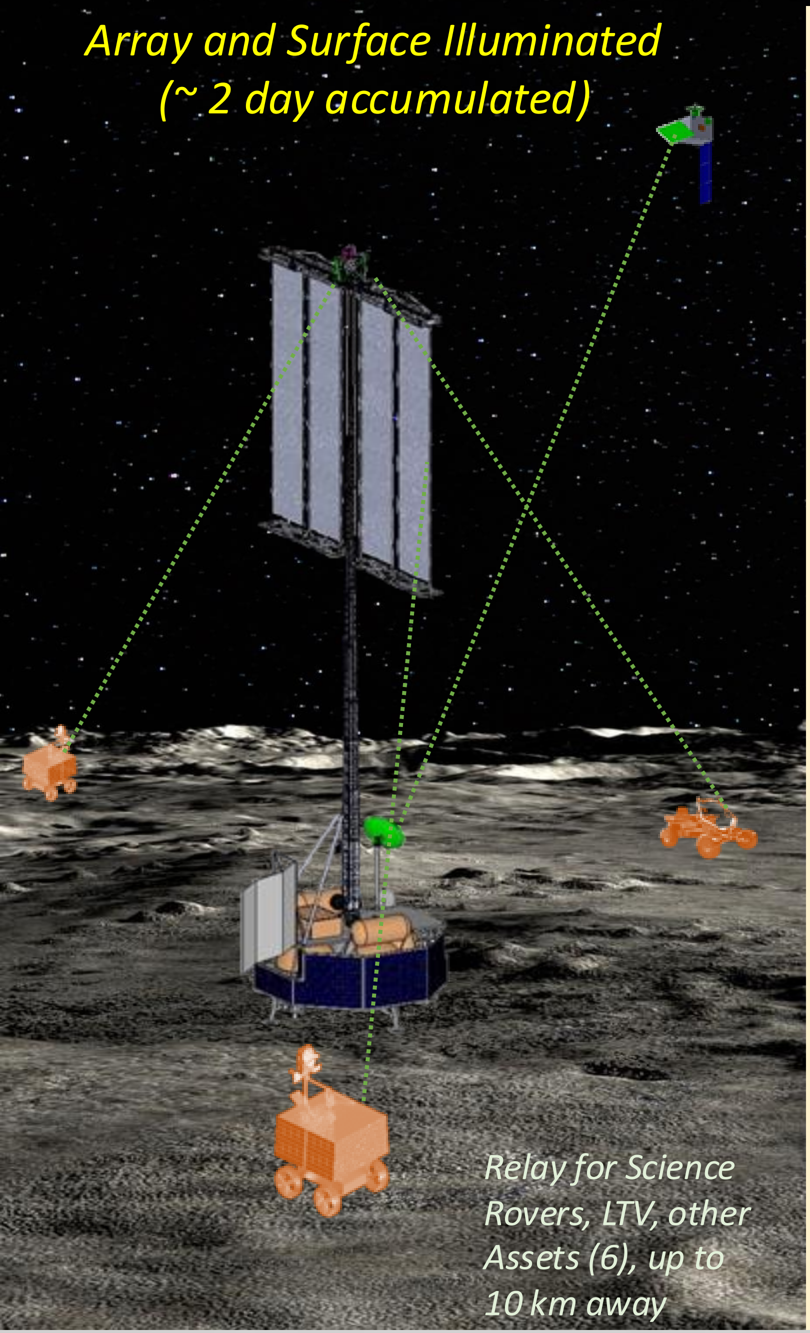
Shackleton Crater

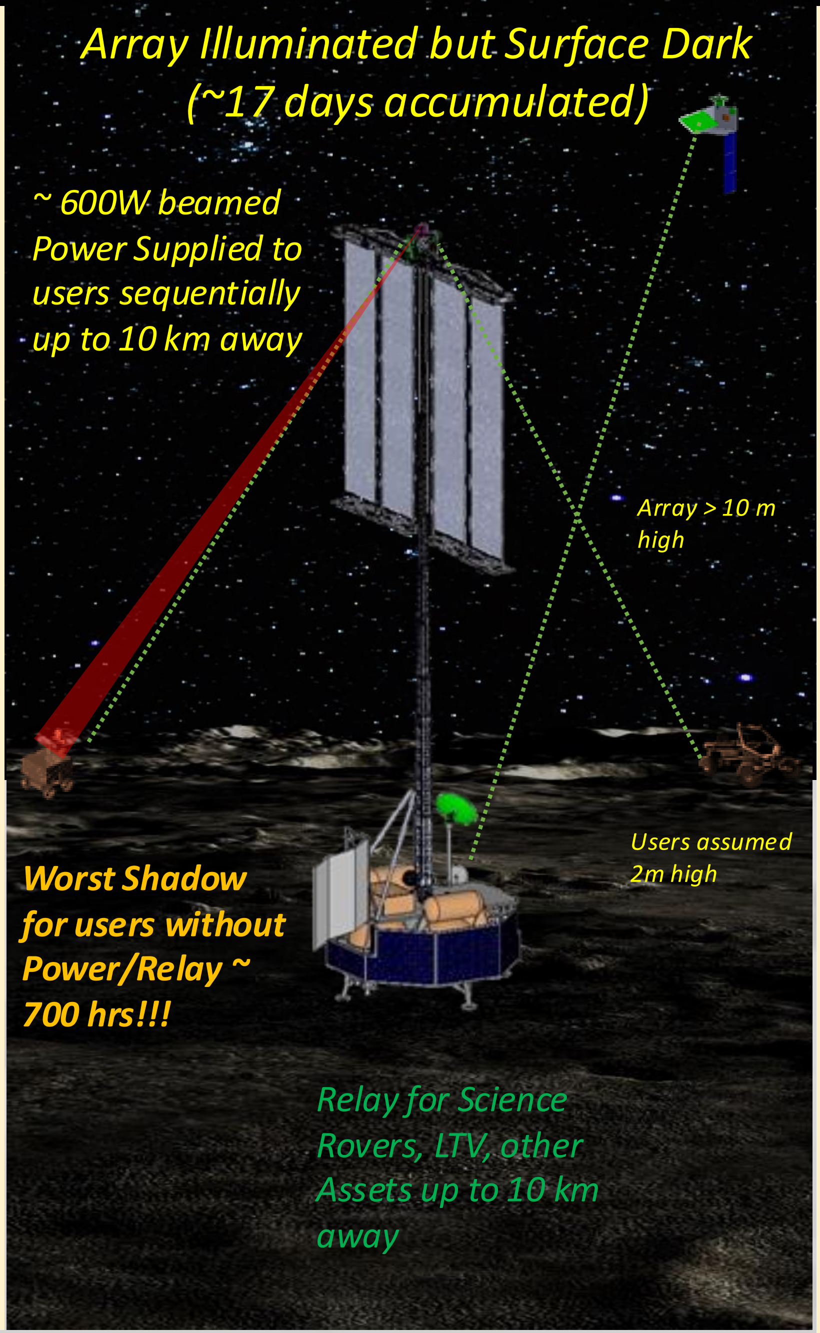
‘Worst’ Case Shadow: March 2029

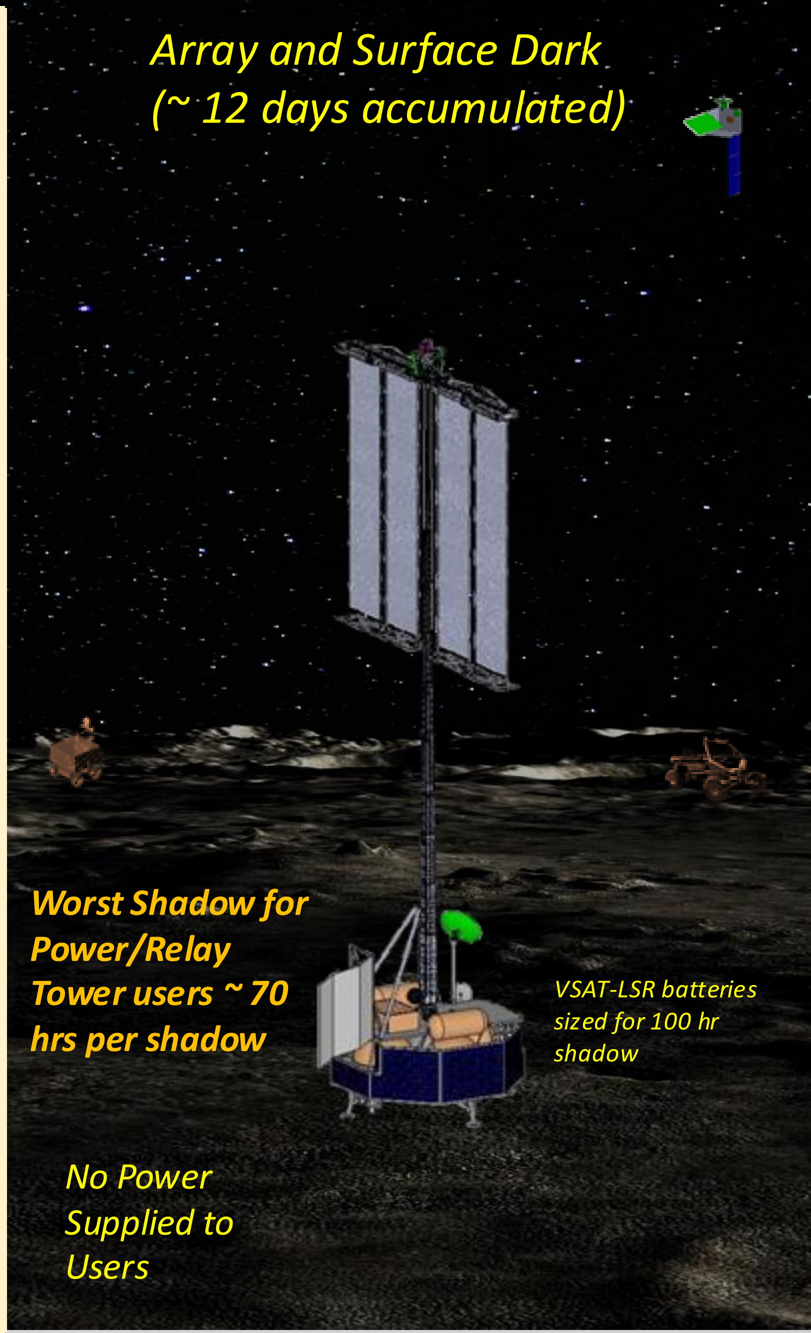
* Assumes sun visibility > 50% as full illumination



Operating CONOPs during a Winter Month, Shackleton Ridge (March 2029)







Lunar Surface Beamed Power/VSAT/5G/Relay Demonstrator

Power Laser Optic 10cm (21 arc sec beam), track to 2 arcsec

Irradiance from beacon: ~1 μW/m²

5cm Laser beam at output

1600 W CW Fiber Laser 1070 nm (40% eff.) (beam)

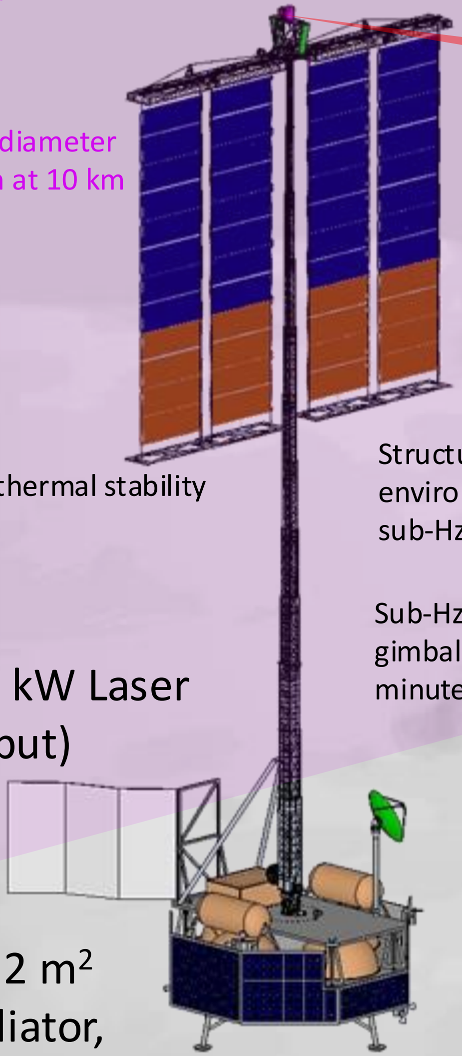
80% of beam on PV array (assumed jitter/pointing error)

1.5 m Dia PV array 50% eff (22% eff in sun)

1 m D, 1/e² beam (~ 2000 W/m² avg)

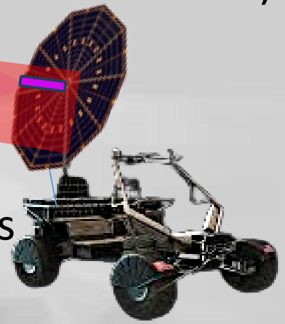
1.6km diameter beacon at 10 km

7 kW SA (includes bus and 30% growth)



1-10 km separation

Beacon, 1600mW @ 808 nm, 8° beamwidth



300W continuous power

Laser & thermal stability

Structure disturbance environment should be sub-Hz

95% batt charge eff.

Sub-Hz disturbances from gimbals, Damps in minutes

300W continuous power

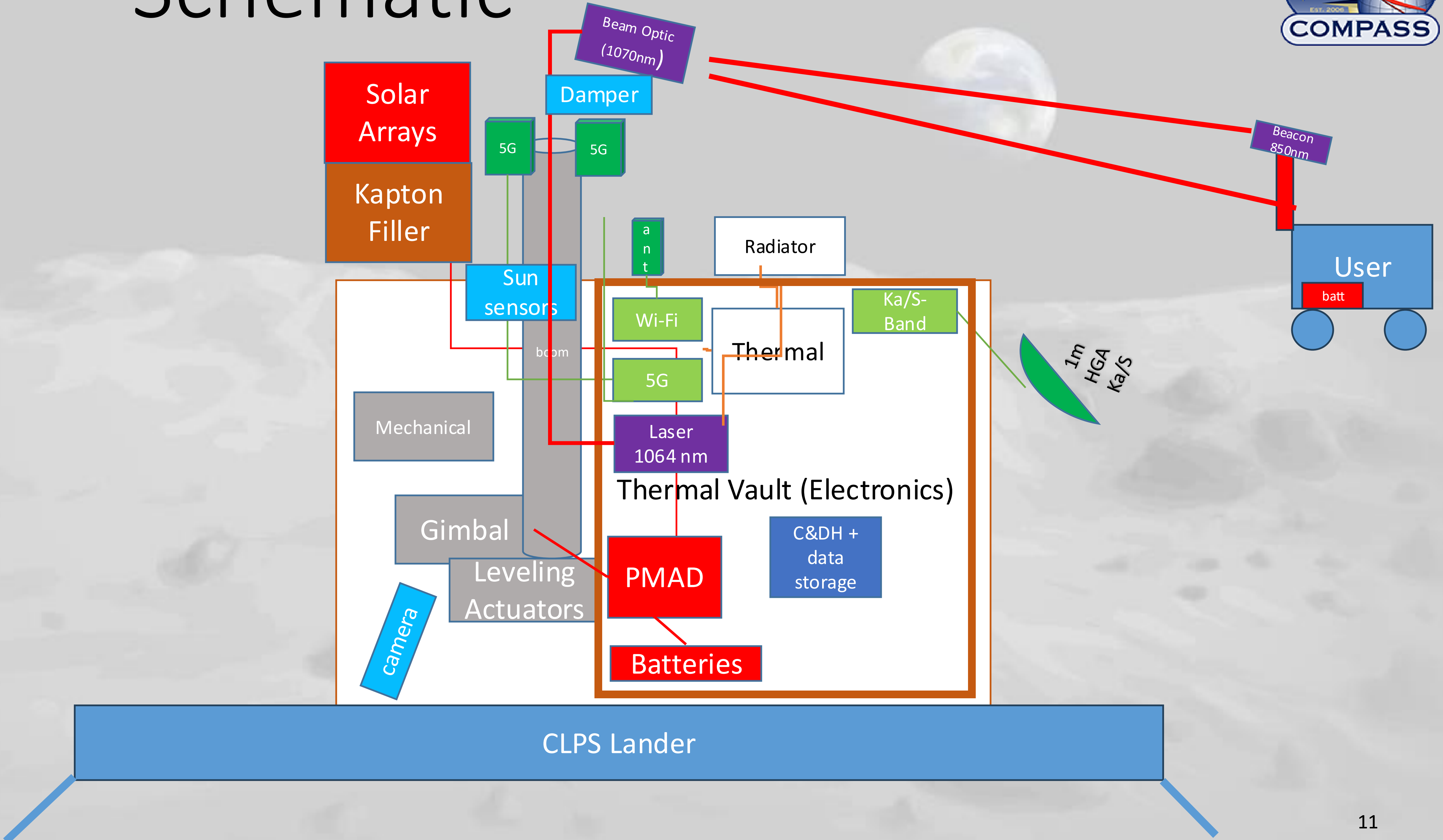
3.8 kW Laser (input)

11.2 m² radiator, two sided

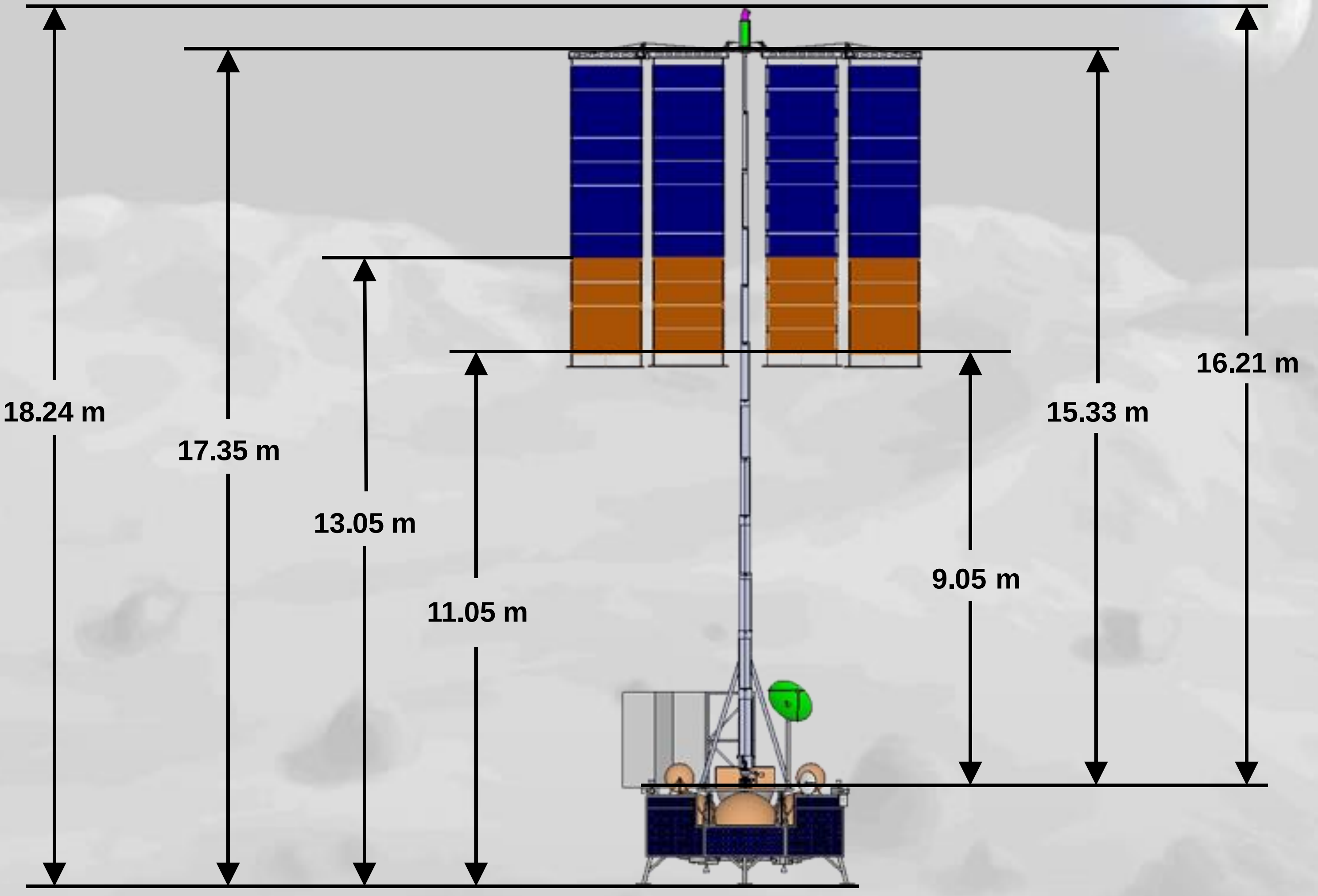
End to End Power Efficiency to User ~ 12%

Laser (~ 1m Dia) (40%) → Spot Beam % Energy on Target Array (84%) → 85% Beam Capture Percentage on Array → Laser Cell (TRL 4/5) Efficiency (50%) → PMAD/ Charge Battery 95%

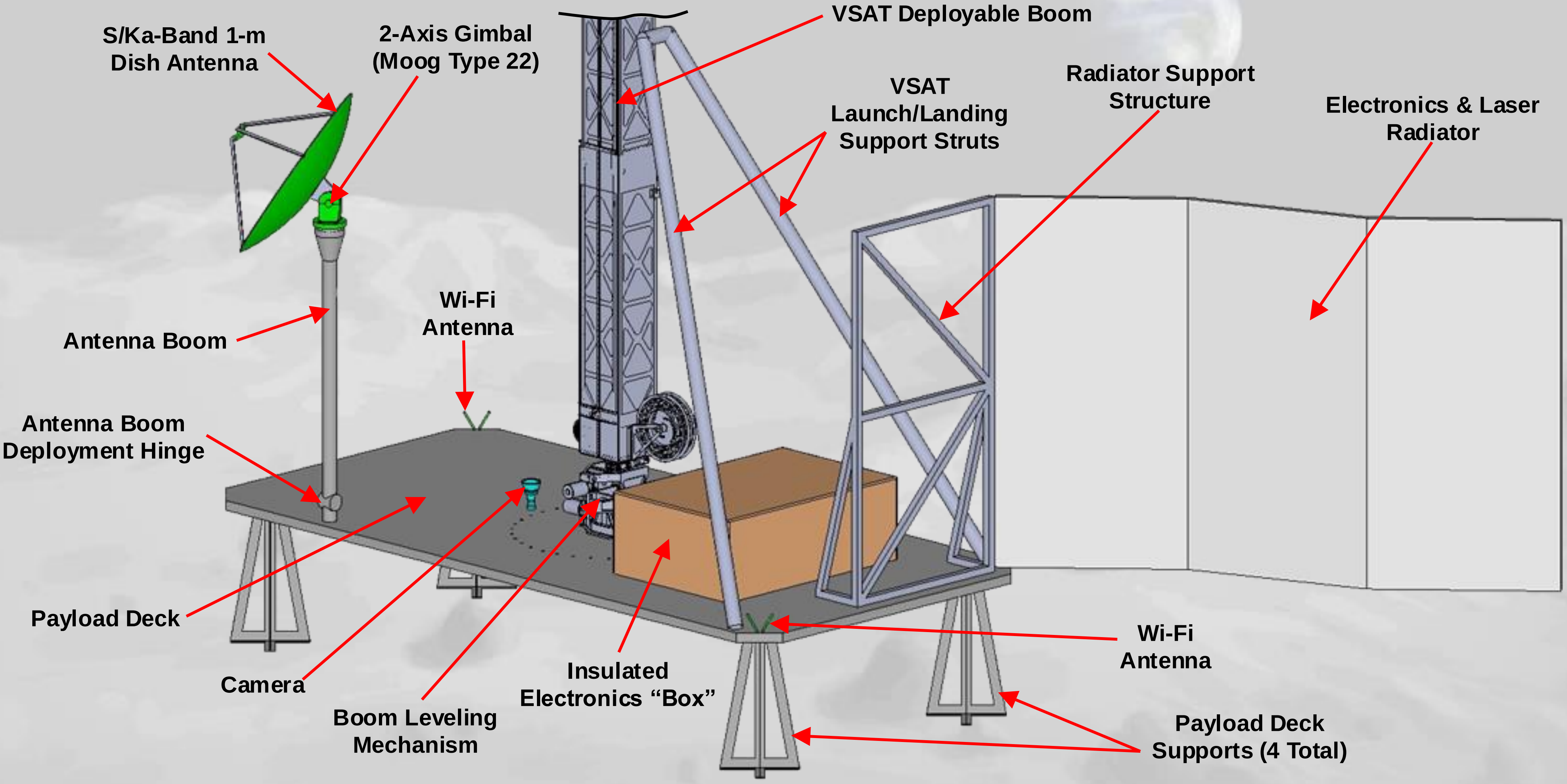
Schematic


Beam Optic
(1070nm)
Damper
Solar Arrays
Kapton Filler
5G
5G
Sun sensors
boom
a
n
t
Radiator
Wi-Fi
Thermal
Ka/S-Band
5G
Laser 1064 nm
Thermal Vault (Electronics)
Mechanical
Gimbal
Leveling Actuators
camera
PMAD
C&DH + data storage
Batteries
1m HGA Ka/S
Beacon 850nm
User
batt
CLPS Lander

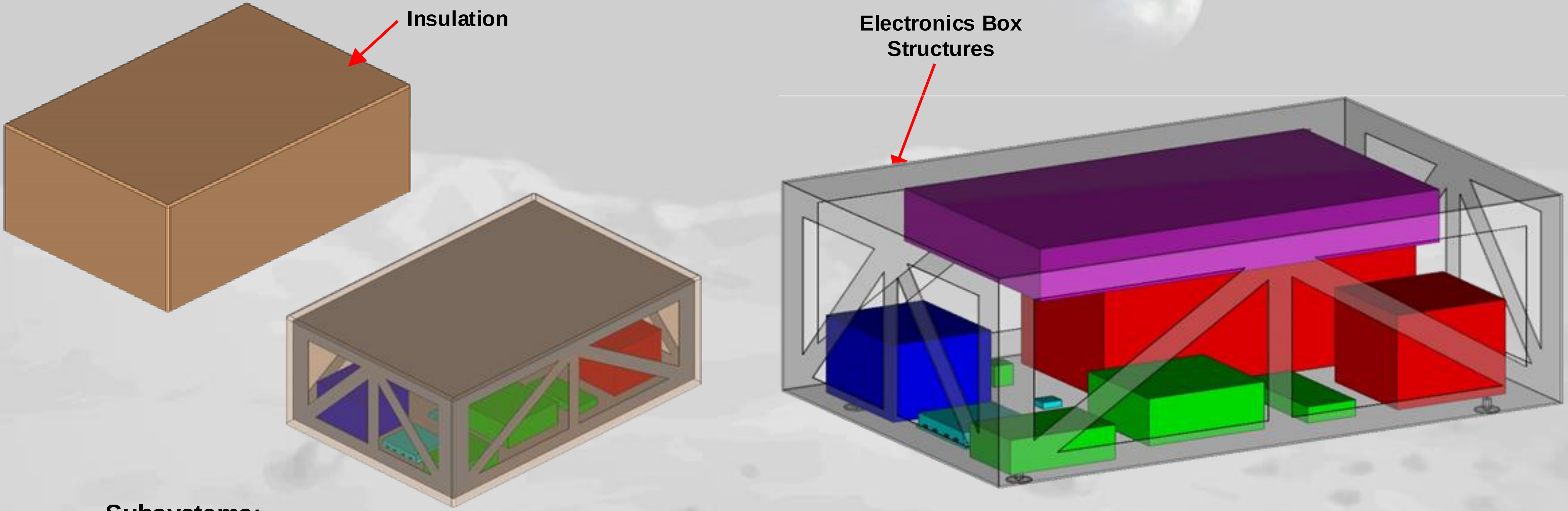
VSAT Lunar Surface Power Deployed Dimensions



VSAT-SR Payload Deck Components



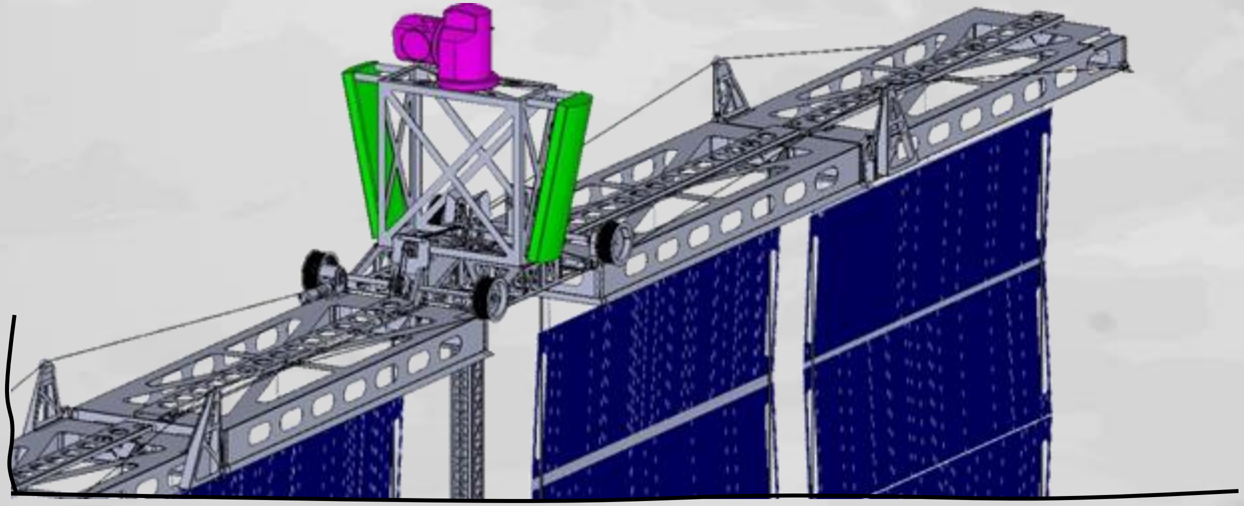
VSAT Lunar Surface Beam Power Electronics Box Components

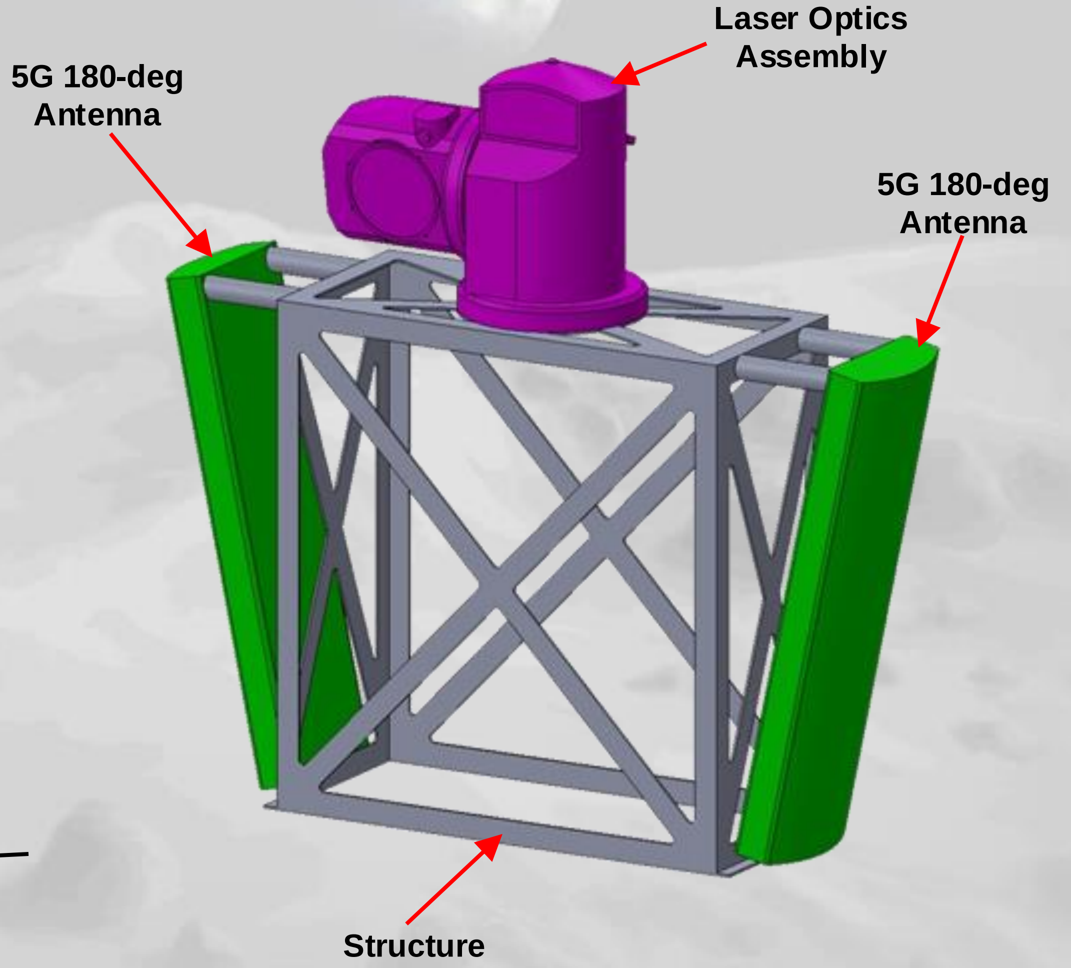


Subsystems:

Communications: S/Ka-Band, Wi-Fi, 5G Electronics
Attitude Determination & Control: Atomic Clock, Camera Electronics
Electrical Power: PMAD, Battery
Command & Data Handling: Avionics Enclosure
Laser

VSAT Lunar Surface Beam Power Components On Top Of VSAT Structure (1/2)





Major Risks

- Redeployment of Boom
- Dust
  - Mechanisms
  - Arrays
  - Radiators
  - Laser optics and beam actuators (including beacon on users)
- Landing
  - Small landing 100m ellipse (CLPS)
  - <30 cm debris
  - $\leq 10°$ slope
- Longer shadow than predicted
  - 100 hrs design vs ~70 hrs predicted
- Lower temps than predicted
- Use of heat pipe radiator with lasers that require tight temp controls (a few °)
- Low storage temp motors/mechanisms/camera heads/lights/gimbals

Lessons Learned

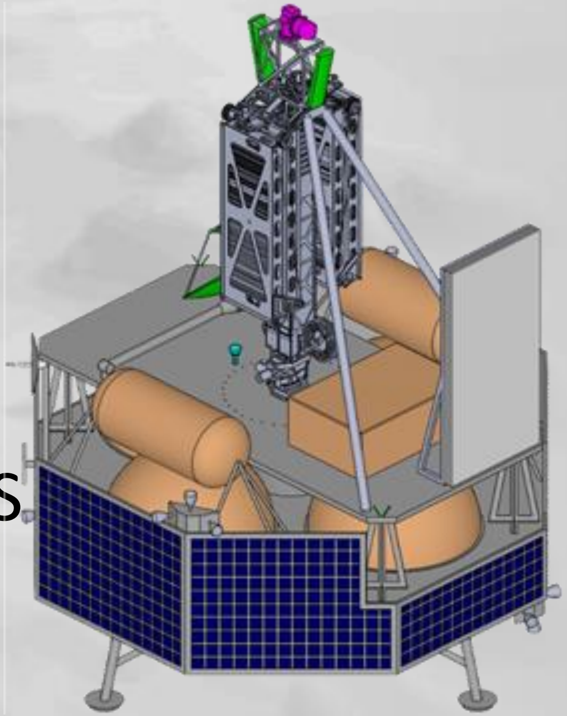
- Combining a VSAT and LSR demonstration together is a win-win for both technology demonstrations
  - The LSR gets the tower height it needs as well as power
  - The VSAT gets a communications link as well as a primary power customer on the deck
- Beyond demonstration objectives, this platform could provide useful relay (~60 Mbps) and power (up to 4.3 kW for mobile users) to science and HLS users
- Integrating to a Griffin-type CLPS
  - Reduces launch and lander costs, Eliminates the need for off-loading and mobility, and provides a stable platform
- Choosing a site that benefits both power and relay
  - Eliminates power supporting nearby (100s m) HLS users BUT avoids HLS landing ejecta concerns
  - Still provides mobile HLS and Science users with power and ~ 10 km relay from HLS and science users back to Earth thru LCRNS relay or direct to Earth (DTE)
- Providing an overnight battery for anything but survival is too heavy for the CLPS lander (at current mass capabilities)
- The VSAT power system is limited to ~5 kWe due to CLPS payload mass constraints (~10 kW class solar array half populated with cells)
- The VSAT tower will reduce user night-time lengths from ~700 hrs to ~100 hrs for polar winter
- In addition to powering LSR, VSAT power could be used to charge HLS & science users during long periods (~700 hrs) when the surface is shadowed but the VSAT array is not.
  - This provides winter users with an additional ~ 16 days of operations (charging) during dark surface period: important to science users?
- Landing accuracies of 100m x 100m (claimed by some vendors of CLPS) are imperative to place the VSAT in a highly illuminated landing site
  - Shackleton Ridge selected as representative
  - A mobile VSAT-LSR, while too heavy for the selected CLPS lander, could eliminate this constraint

Lessons Learned (Beamed Power Demonstrator)

- Demonstrating beamed power from a VSAT tower to users 1-10 km away is feasible
- Powers of up to 300W can be provided to users when they are in darkness
  - End to end efficiency <10% offset by flexibility and ease of remote powering mobile assets to operate or survive the night
- Users such as CLPS, small rovers and perhaps lunar terrain vehicle (LTV) (survival only) can use beamed power to reduce battery sizes to only 70 hrs operations instead of ~700 hrs during winter for most polar locations
- A beacon from the user to the Power Tower is an effective way to link power to the users with relatively little overhead
- The laser, optics, beacon, and PV technologies may not be available by the 2028 launch date

Next Steps

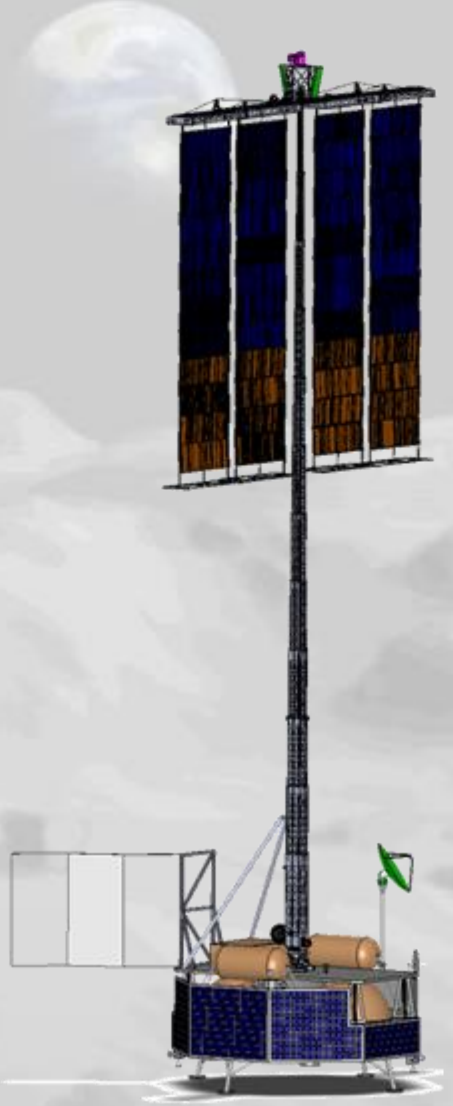
- Better evaluate the charging use case and systems for mobile users
  - How to integrate to the CLPS lander
  - What mobile users could we expect in 2030? LTV? What other science users?
- Evaluate other potential good sites for power and relay – especially to support other potential HLS sites
- Can waste heat keep a rover warm while solar array is deployed?
- Investigate potential cost savings by reusing some of the CLPS lander systems
  - May cost more than its worth



Backups

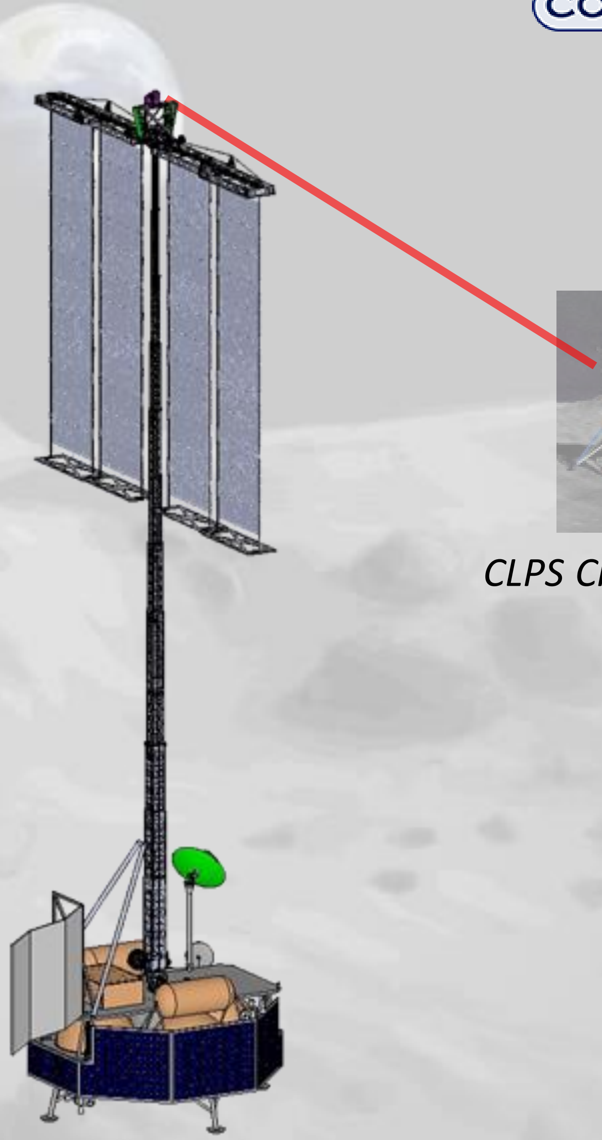
TRL<6

- VSAT System: 5
- Power:
  - Laser: 4-5
  - Optics: 5-6
  - User Beacon:5-6
  - Laser Tuned PV cells: 5
  - Dual use PV array to handle off-pointed laser beam: 3-4
- Thermal: none less than 6
- Mechanical:
  - Boom: 5
  - Store motors at 50K: 5
- Comms:
  - 5G: 5
  - Wi-Fi: 4/5
- C&DH: none less than 6
- PN&T:
  - Lights: TRL 5



VSAT with Beamed Power Delivery Conceptual Design

- Purpose: Evaluate both laser and microwave power delivery demonstration from the previous VSAT/LSR Compass concept. Deliver up to 300W up to 10 km sequentially to CLPS class landers, VIPER class rovers, unmanned LTV near the south pole
- Customers: STMD, ESDMD, SMD
- Mission Date/Class/duration:
  - 2028 / Demonstrator (single string)/18 Month(night survival ~ 100 hrs max)
  - Class D (18 months)
  - Zero-fault tolerant
- Demonstrate
  - Floor: Beaming Power to small science landers and rovers, primarily to allow shadowed survival/operations (50–300 W continuous)
  - Desired: Add beaming power to LTV to survive the night (~ 300W continuous)
- FOMS: Systems demonstrated, Power beamed/distance, end to end efficiency, Keep flight system costs low
- Launch and lander Falcon H recovery / Griffin lander (625 kg payload-Polar)
  - Try to keep withing landing mass
    - Reduce some of VSAT/LSR mass to allow for the <80 kg beam delivery system
- Trade Laser (baseline) and microwave (option)
- Product: Purpose, conops, trades, viewability, CAD layout, System mass/power rollup, subsystem designs, cost, risk, Lessons learned, next steps

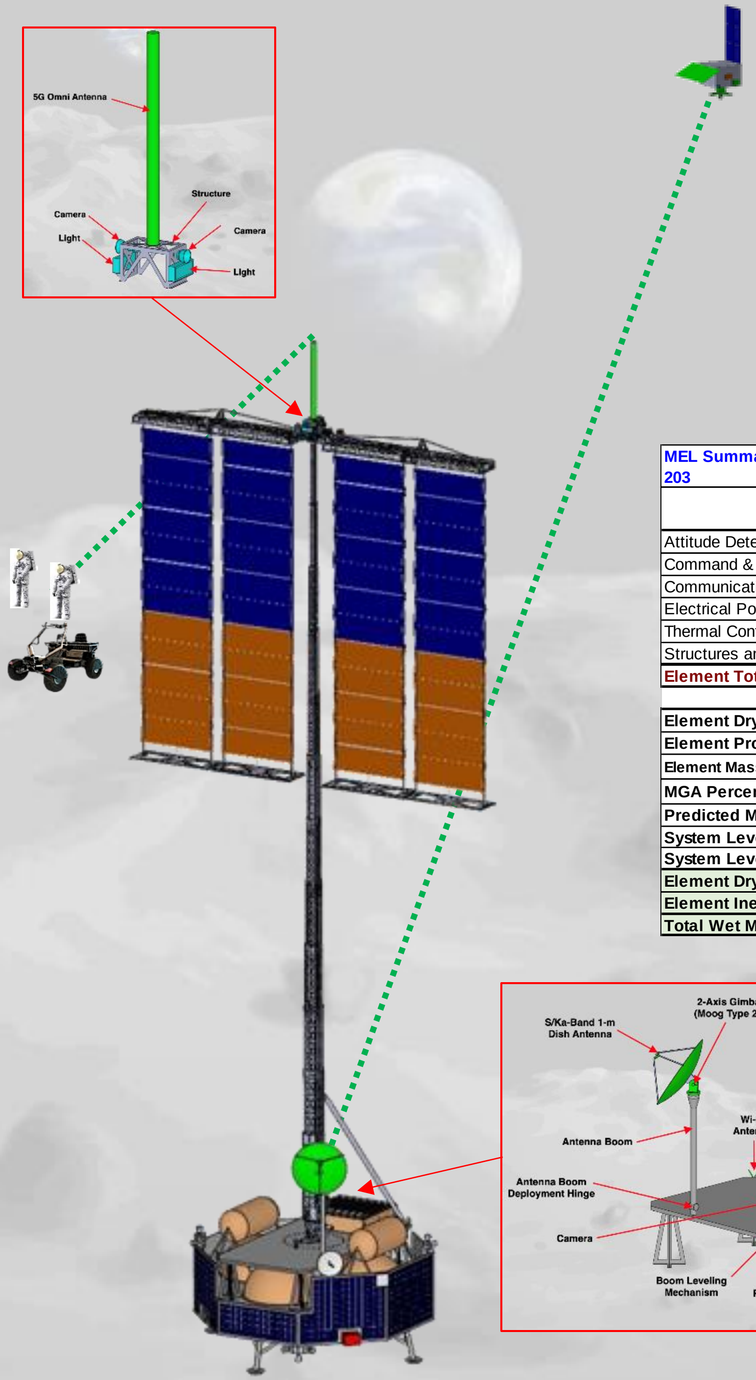


Demonstrator

CLPS Class Lander

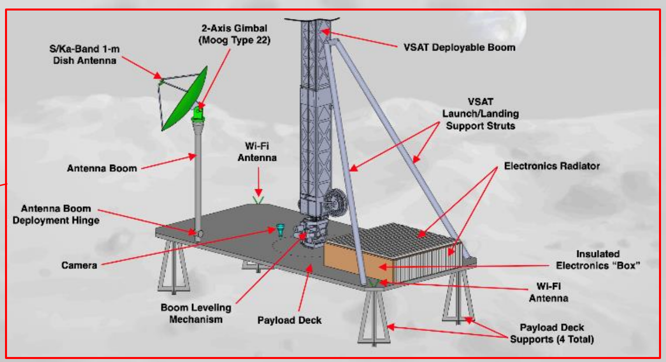
Past Design (Starting Point): VSAT-LSR Demonstrator

- ***Demonstrate*** Vertical Solar Array Technologies (VSAT) AND Lunar Surface Relay (LSR) technologies with science and HLS users.
- Mission:
  - VSAT: Demonstrate redeployment of an ~10 kW class array (5 kWe actual), >10 m Tower to get <100hr shadow periods on lunar south pole, winter, survive lunar night *(mass constraints kept power collected/provided to 5 kW).* Provide up to 4.3 kWe total to up to 4 power users
  - LSR: 5G relay at 60 Mbps total for up to 6 lunar surface users, up to 10 km distant using Omni antenna. Relay with Earth thru LCRNs frozen orbit relaysats, using a Ka/S-band link with 1 m antenna
- Launch: Falcon H Recovery, 2028
- Griffin class lander: ~ 625 kg payload to South lunar pole, spring
- Power: 5 kWe Power system, 120VDC, ~7 kWhr ion batteries for ~100 hr night-time storage
- Thermal: Radiator for heat rejection and insulated, thermally isolated vault for electronics to maintain temperature during shadow. Heaters for maintaining external components (charge ports)
- C&DH: ~ 4 Tb non-volatile storage (18.5 hours of data buffering at 60 Mbps)
- PN&T: One atomic chip clock for Timing to users, Laser Retroreflectors for navigation assumed to be included on CLPS landers
- Mechanical: ~15m telescoping, stowable/re-deployable, leveled boom (<<1°), single gimbaled 1m dish



LV Summary: Case 1_VSAT_LSR CD-2023-203	Single Launch
Architecture Details	All
Launch Vehicle	Griffin Lander (representative)
Performance (pre-margin)	625
Margin (%)	0%
Performance (post-margin)	625
Total Wet Mass w/% Growth	607
Available LV Margin	18
Available LV Margin (%)	3%

MEL Summary: Case 1_VSAT_LSR CD-2023-203	VSAT_LSR
Main Subsystems	Basic Mass (kg)
Attitude Determination and Control	3.3
Command & Data Handling	20.3
Communications and Tracking	21.8
Electrical Power Subsystem	148.4
Thermal Control (Non-Propellant)	30.2
Structures and Mechanisms	209.3
Element Total	*433.4*
Element Dry Mass (no prop,consum)	433.4
Element Propellant	0.0
Element Mass Growth Allowance (Aggregate)	108.5
MGA Percentage	25%
Predicted Mass (Basic + MGA)	541.8
System Level Mass Margin	65.0
System Level Growth Percentage	15%
Element Dry Mass (Basic+MGA+Margin)	606.8
Element Inert Mass (Basic+MGA+Margin)	606.8
Total Wet Mass (Allowable Mass)	*606.8*



References

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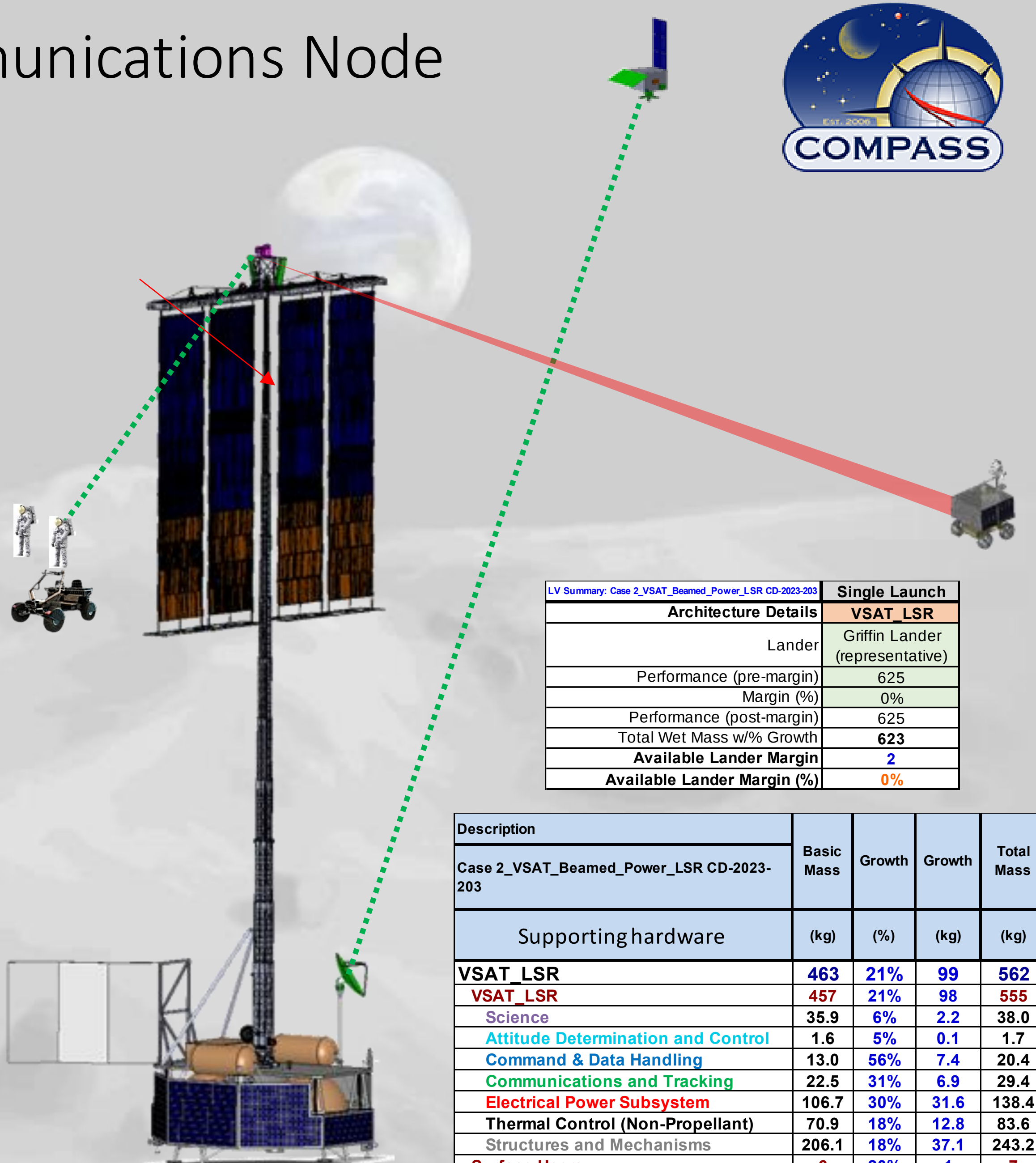
- Geoffrey A. Landis, *Laser Power Beaming for Lunar Polar Exploration*, AIAA 2020-3538
- A. Marcinkowski et al., *Lunar Surface Power Architecture Concepts*, 2023 IEEE Aerospace Conference, Big Sky, MT, USA, 2023.
- Robertson, B., et al., *The Effectiveness of Power Distribution Systems for Deployment on the Lunar Surface*, presented at the AIAA ASCEND 2021, Las Vegas, NV.
- Raible, Daniel Edward. *Free space optical communications with high intensity laser power beaming.* Ph.D. diss., Cleveland State University, 2011.

Further Work Areas (Beamed Demonstration)

- Evaluate what beaming technologies could be available for the 2028 launch date
- Refine the laser to optic and beacon design
- Refine the operations and equipment needed for a user
- Refine PV cell many string approach to allow off-pointing, jitter
- Assess the jitter, pointing errors from the tall, light tower
- Assess how the fiber optic feed could be restowed during VSAT retraction test
- Laser fiber cable deployment
- User actual power/energy usage
- Heat pipe radiator (deployable and needs to freeze at night) – or do pump loop and not allow to freeze
- Optical comm link option

BEACON: Beamed Power and Communications Node Demonstrator Summary

- ***Demonstrate*** Vertical Solar Array Technologies (VSAT) AND Lunar Surface Relay (LSR) technologies AND Power beaming with science and human landing system (HLS) users.
- Mission:
  - **VSAT**: Demonstrate redeployment of an ~10 kW class array (5 kWe actual), >10 m Tower to get <100hr shadow periods on lunar south pole, winter, survive lunar night *(mass constraints kept power collected/provided to 5 kW).*
  - **Lunar Surface Relay**: 5G relay at 60 Mbps total for up to 6 lunar surface users, up to 10 km distant using Omni antenna. Relay with Earth thru Lunar Communications Relay and Navisgations System (LCRNS) frozen orbit relaysats, using a Ka/S-band link with 1 m antenna
  - **Laser Beamed Power**: Provide up to 500W beamed power to users up to 10 km away
- Launch: Falcon H Recovery, 2028 or later
- Griffin class lander: ~ 625 kg payload to South lunar pole, spring
- Power: 5 kWe Power system, 120VDC, ~7 kWhr ion batteries for ~100 hr night-time storage
- Laser Beam: 4 kW laser, 10 cm beacon director on top of boom, provide up to 500We power to users 1-10km away
- Thermal: Radiator for heat rejection and insulated, thermally isolated vault for electronics to maintain temperature during shadow. Heaters for maintaining external components (charge ports)
- C&DH: ~ 4 Tb non-volatile storage (18.5 hours of data buffering at 60 Mbps)
- PN&T: One atomic chip clock for Timing to users, Laser Retroreflectors for navigation assumed to be included on CLPS landers
- Mechanical: ~15m telescoping, stowable/re-deployable, leveled boom (<<1°), single gimbaled 1m dish, dual gimbaled laser beam director



LV Summary: Case 2_VSAT_Beamed_Power_LSR CD-2023-203	Single Launch
Architecture Details	**VSAT_LSR**
Lander	Griffin Lander (representative)
Performance (pre-margin)	625
Margin (%)	0%
Performance (post-margin)	625
Total Wet Mass w/% Growth	**623**
Available Lander Margin	**2**
Available Lander Margin (%)	**0%**

Description Case 2_VSAT_Beamed_Power_LSR CD-2023-203	Basic Mass	Growth	Growth	Total Mass
Supporting hardware	(kg)	(%)	(kg)	(kg)
VSAT_LSR	**463**	**21%**	**99**	**562**
VSAT_LSR	**457**	**21%**	**98**	**555**
Science	35.9	6%	2.2	38.0
Attitude Determination and Control	1.6	5%	0.1	1.7
Command & Data Handling	13.0	56%	7.4	20.4
Communications and Tracking	22.5	31%	6.9	29.4
Electrical Power Subsystem	106.7	30%	31.6	138.4
Thermal Control (Non-Propellant)	70.9	18%	12.8	83.6
Structures and Mechanisms	206.1	18%	37.1	243.2
Surface Users	**6**	**20%**	**1**	**7**
Electrical Power Subsystem	5.9	20%	1.2	7.0