Beamed Energy and Communications Optical Node (BEACON) Demonstrator

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Due to long shadow periods (2 weeks or greater) on the south pole, concepts to raise solar arrays to a sufficient height at specific locations have shown the capability to provide power to surface users for much longer periods. Such a tower can also provide a 3rd Generation Partnership Project (3GPP) service for users up to 10 km away, dependent on terrain. An option to deliver power, albeit with low efficiency, using a laser beam coupled with the tower height could provide mobile and fixed users power during darkness, reducing their battery requirements. A demonstration of these technologies in the lunar environment is crucial to support future Artemis campaigns as well as potential emerging lunar infrastructures. A demonstrator design of a 15 m deployed boom on the south pole has been shown to enable both the gathering of kilowatts of power and the provision of 3GPP relay and backhaul given an appropriate lunar location. Using a laser to send power to a photovoltaic receiver has been proposed to transmit electrical power on the moon, particularly for applications such as powering a rover in near-polar permanently shadowed regions (PSR) where solar power is not available. In this work, the Compass team performed a conceptual engineering design study of a near-term laser surface-to-surface power beaming and relay station using a tower to simultaneously carry the power source (Vertical Solar Array Technologies (VSAT) [1]**), the 3GPP relay antenna, and the laser telescope.**

I. Introduction

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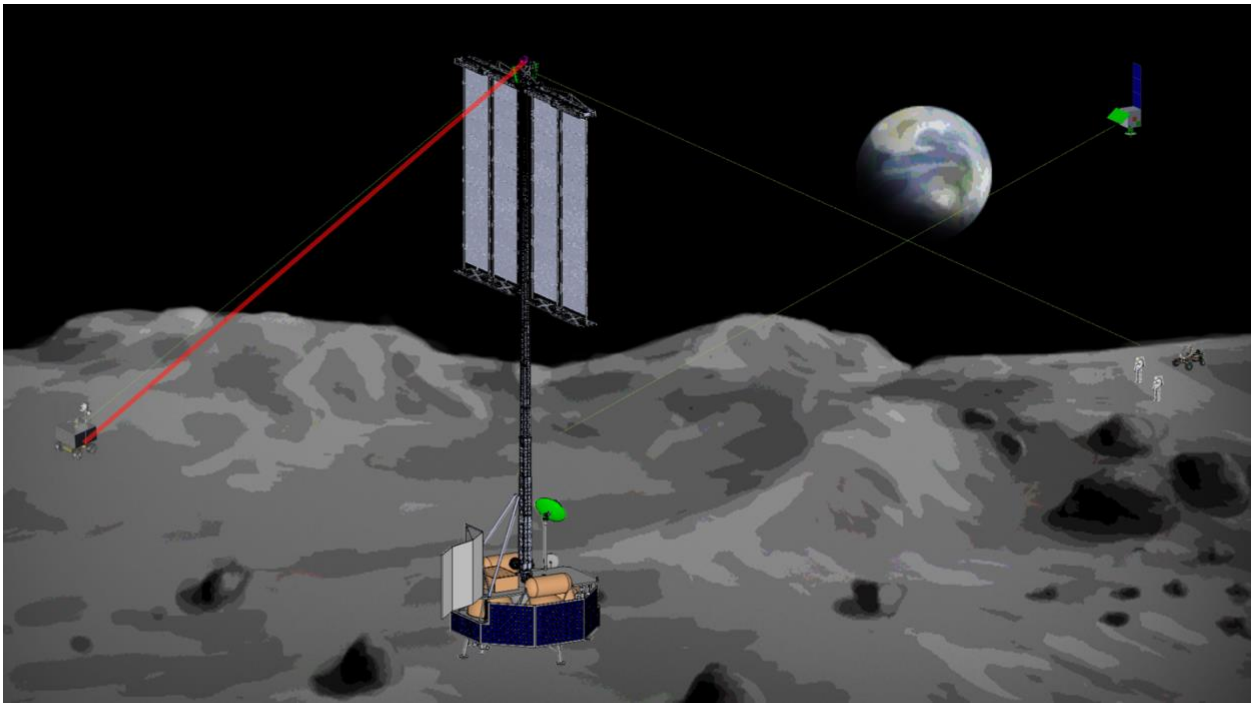

Fig. 1 Depiction of the BEACON beaming power to a distant rover while providing communications links to astronauts on the surface.

At the lunar south pole, extended shadow periods of two weeks or more create significant challenges for providing a continuous power supply. To address this, concepts have been proposed to elevate solar arrays to specific heights, ensuring prolonged power availability to surface operations in select areas. Such elevated structures could also support a 3rd Generation Partnership Project (3GPP) service reaching users as far as 10 km away depending upon the tower placement and the nearby terrain. Additionally, combining this height with laser-beam power delivery, though low in efficiency, could offer power solutions to both mobile and stationary users during darkness, potentially reducing their battery needs. Testing these technologies on the moon—specifically, towers with solar arrays, 3GPP capabilities, and laser beaming—will be essential to support future Artemis missions and upcoming lunar infrastructure.

A prototype tower boom design, approximately 15 m in height and deployed at the lunar south pole, demonstrates the capability to collect kilowatts of power while also providing 3GPP relay and backhaul services in optimal lunar locations. Leveraging laser technology to transmit power to photovoltaic receivers is particularly promising for powering rovers in permanently shadowed regions (PSR) where solar energy is inaccessible [2], [3]. In this study, the Compass team has conducted a conceptual engineering design assessment of a near-term laser-based surface power beaming and relay station. This tower concept integrates Vertical Solar Array Technologies (VSAT) [3], a 3GPP relay antenna, and a laser beam director, presenting a multifunctional solution for the lunar environment.

A. Study Approach:

To maximize the line-of-sight service area for relay *and* laser power, surface topology and the distance to the horizon of the moon (~ 5km only considering curvature) must be considered. It is desirable to position the solar array, 3GPP antennas, and laser telescope at an elevation above the surface where sunlight is available more often than not and there is access to a large swath of lunar landscape where users may be located. The VSAT project is a NASA effort developing a solar array mounted vertically on a 10+ m tall mast, designed for emplacement on a Commercial Lunar Payload Services (CLPS) lander to provide 10 kW beginning of life power near the south polar region of the moon, with a target readiness date of 2028. The Compass team used the government VSAT reference design for the structural tower and the power source for this study. By mounting the 3GPP antennas and laser beam director at the top of the solar array mast, a viewing distance to power/relay users up to 10 km away is possible, given that the more frequently illuminated areas are at higher relative altitudes. This concept is shown in Fig. 1.

Requirements for the system were that it be able to demonstrate:

1. Deployment and redeployment of an ~10 kWe class array (7 kWe actual) on a greater than 10 m tower to get maximum shadow periods of less than 100 hours on lunar south pole during winter.
2. Surviving the lunar night. (Note that no energy would be made when the solar array is in darkness and only minimal relay would be provided.)
3. Delivering up to 500 We to remote power users (up to 10 km) including CLPS landers, VIPER [4] class rovers, or the proposed Lunar Terrain Vehicle (LTV). [A previous design, without the power beaming demonstrator but with all other systems, provided up to 4.3 kWe total to as many as four power users plugged in to the demonstrator.
4. Providing lunar surface relay with backhaul: 3GPP relay at 60 Mbps total for up to 6 lunar surface users at up to 10 km distance using an omni antenna. Relay with Earth through Lunar Communications Relay and Navigation Systems (LCRNS) frozen orbit relay satellites, using a Ka/S-band link with a 1 m antenna.

The system lifetime was set for 5 years with an initial 18-month demonstration period. A total system landed mass was limited to 625 kg to enable delivery by medium sized CLPS landers.

B. Potential Users:

Potential users include servicing multiple science rovers/landers or providing the LTV with keep alive power during lunar night or when in shadow. The VIPER-class science rovers are assumed to rely on their own solar power during the lunar day. Under conditions where the VSAT array is illuminated but the rovers are shadowed, they can be provided with up to 500W to allow for shadowed operations (up to 600 hrs during solar winter months). When both the rovers and the VSAT are in complete darkness, no power is supplied, and the rovers must survive on their own batteries (for up to 100 hrs). For the LTV, targeted for deployment in 2029, the vehicle will require approximately 300W for *survival* during its periods of darkness.

II. Design and Concept of Operations

A. Design Layout Summary:

Figure 2 shows the 3GPP and beaming telescope mounted on the top of a VSAT array which is in turn fixed to a representative CLPS lander. The 3GPP relay antennas are derived from terrestrial designs. The backhaul Ka-band system is placed on the deck with a 1 m diameter antenna which links to the planned LCRNS relay satellite spacecraft constellation. The beam director for the laser is shown in green at the top of the mast, based on a prototype unit developed by the University of California Santa Barbara [3]. The 1.07-μ diode-pumped fiber laser source is mounted on the deck of the lander, with laser output sent to the beam director by a fiber-optic cable. A 7 m^2 deployable radiator keeps the laser within operating temperature limits. The system is powered by the 7 kWe VSAT array. Note that the bottom third of the array consists of only a Kevlar blanket rather than solar cells. This allows the technology demonstration [3] to show capability of deploying a larger array while remaining within mass limitations.

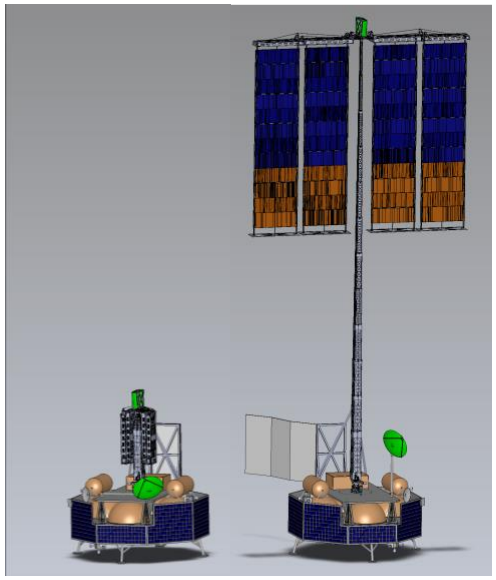

Fig. 2 Beaming station stowed (left) and after deployment of the thermal radiator, VSAT array, and 15 m mast (right).

B. Concept of Operations:

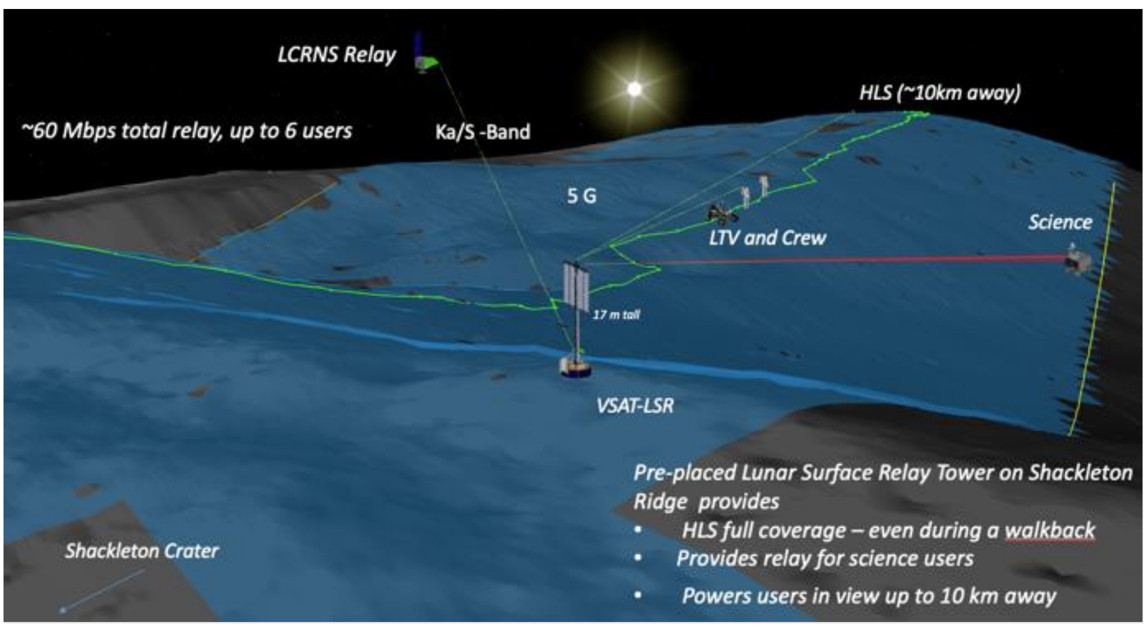

Fig. 3 1 BEACON Lander and Potential Users.

The system is able to relay 3GPP and beam power when the VSAT arrays are illuminated. During the winter on the south pole (the limiting design case) this occurs nearly 60 percent of the time. About 1600 W of optical power can be output in the beam. Accounting for receiver efficiency and beam losses, this results in up to 500 W available to the user.

An assumed mission would involve the deployment of the BEACON payload on a CLPS lander, using a representative medium-class CLPS lander launched by a Falcon Heavy rocket. The landing site selected for this study was Shackleton Ridge, which offers a high-altitude location that is over 1 km away from a potential Human Landing System (HLS) landing zone. This site also has a relatively gentle slope (less than 10 degrees) and minimal debris presence. A graphical representation of the BEACON lander with potential users is shown in Fig. 3. A coverage analyses traded tower height and showed that towers over 14 m provided sufficient coverage of the areas around the potential HLS landing site to provide communications and power for potential science excursions (Fig. 4). It should be noted that this site was assumed to demonstrate the BEACON functions and coverage, but they may be different for other potential sites. The landing is assumed to occur during the lunar summer, at least one month before the anticipated HLS landing, to optimize the timeline for subsequent operations.

Following the landing, commissioning and checkout will occur over several days. Initial deployment and operations assume CLPS-provided power for approximately fourteen continuously illuminated days at 625W, with the potential to extend this period up to the first lunar eclipse. Key deployment activities include unlocking and deploying the VSAT boom equipped with a dust sock, as well as the deployment of the Solar Array Wings (SAWs). A camera mounted at the base of the lander will capture the deployment process in 4K resolution. Relay antennas will also be deployed during this phase, and the main SAW gimbal will begin to track the sun, with a need to periodically unwind the gimbal cable every month. After two weeks, the CLPS lander will be deactivated and safed, with no further reuse of CLPS systems anticipated.

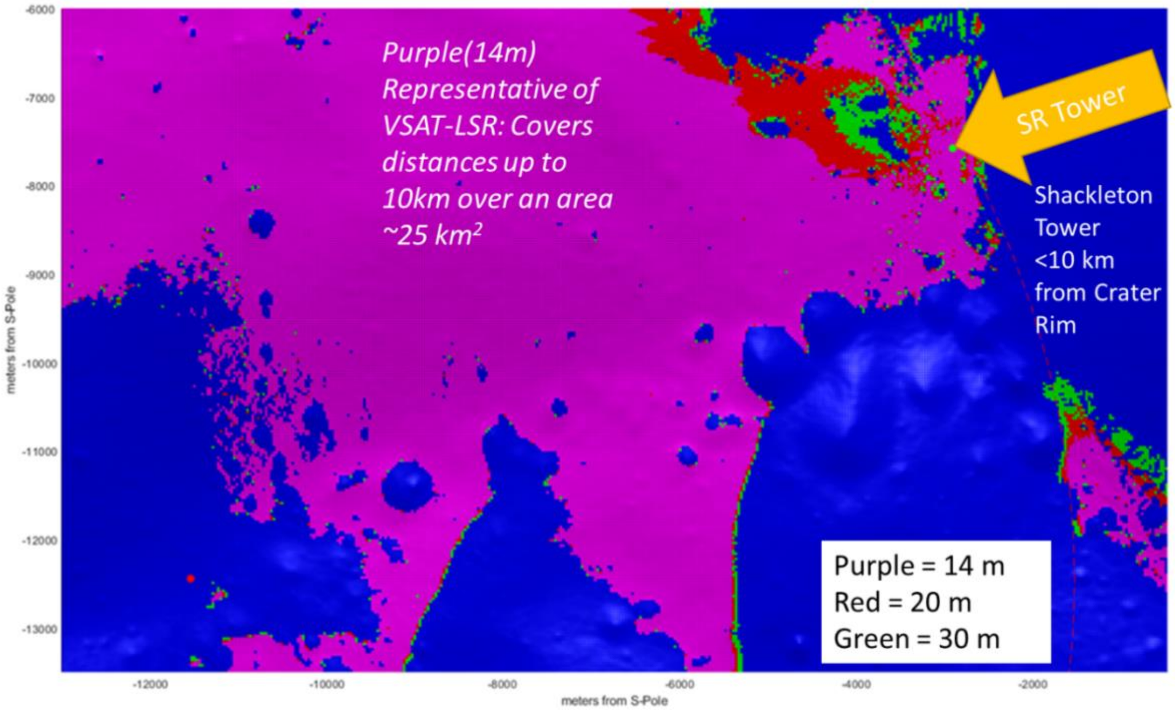

Fig. 4 Trade of BEACON Tower Height to provide 'off landing site' relay and power coverage from Shackleton Ridge.

The BEACON 3GPP/Relay capabilities could support HLS as envisioned during the summer for up to two weeks. This system could provide around 60 Mbps total bandwidth, supporting up to six users via LCRNs. A restow and redeployment demonstration test of the VSAT boom and arrays will be conducted after HLS support, with the goal of completing this test in under 40 hours.

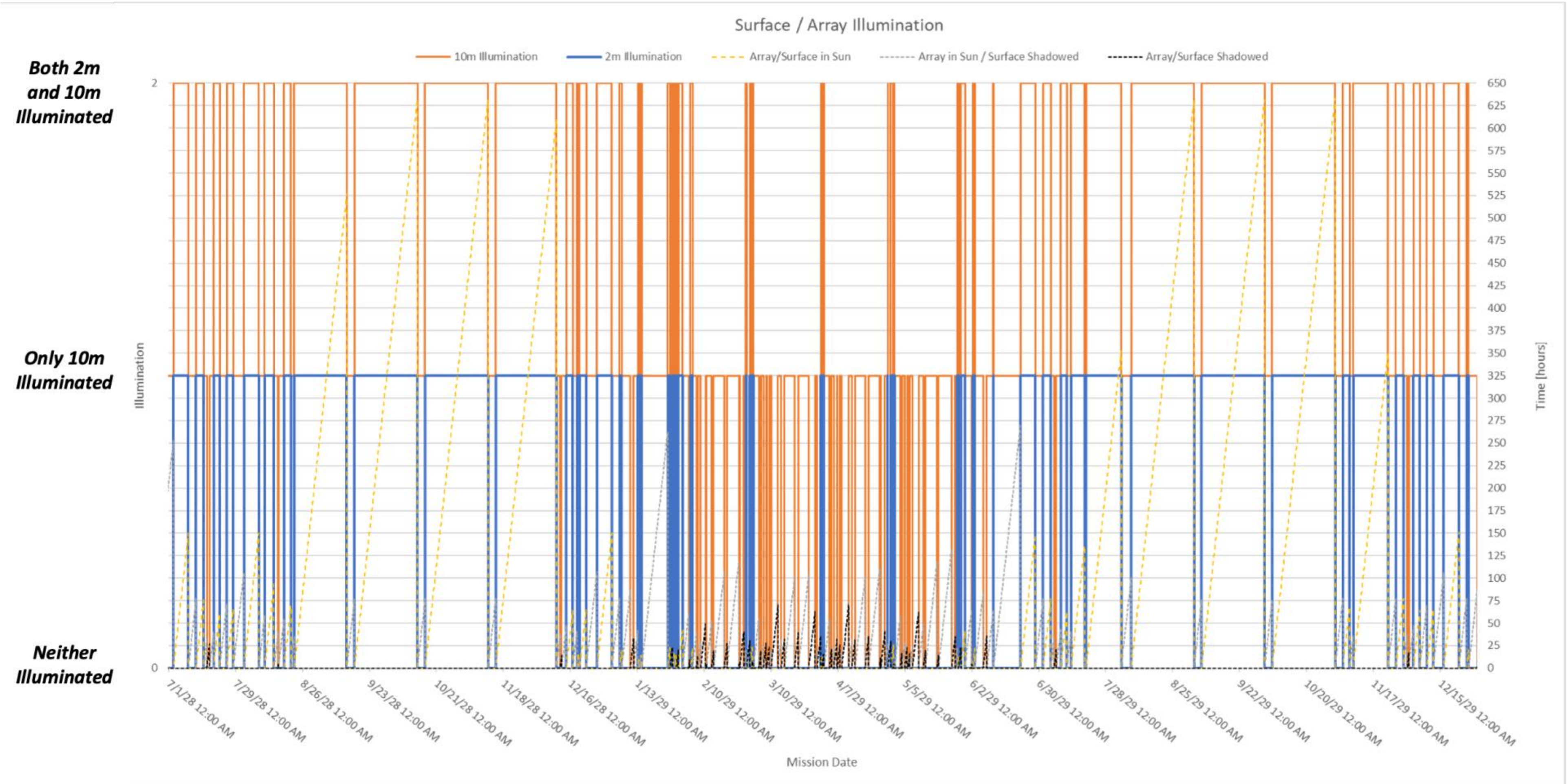

Fig. 5 18-Month Profile for Shackleton Ridge Landing Site.

The VSAT and laser beaming power system will be capable of supporting up to four users, including the LTV and science rovers or landers. The single laser would power users serially. The mission is designed to operate in three distinct modes. These modes include both surface and elevated array illuminated, only the elevated array illuminated, and neither illuminated. These modes are shown throughout a sample 18-month period in Fig. 5. Each potential site on the moon would have different operational periods, but the Shackleton Ridge location promises to be one of the better illuminated sites, at least above 10 m to clear the surface irregularities. The 18-month illumination profile for the Shackleton Ridge landing site (Fig. 5) assumes that sun visibility greater than 50 percent is full illumination for both 2 m and 10 m elevations.

During periods of the year where the surface is illuminated, primarily occurring during the lunar summer, only relay services should be required by the users. The 3GPP relay system will enable data transmission from science elements, and a link to HLS user equipment will be established with data relay to LCRNs or Earth using the 1m antenna. To minimize data loss due to orbiter or Earth outages, a storage capacity of 4 TB using a 3U card, which could store up to 56,000 images at 5 MP resolution was added to the BEACON avionics system.

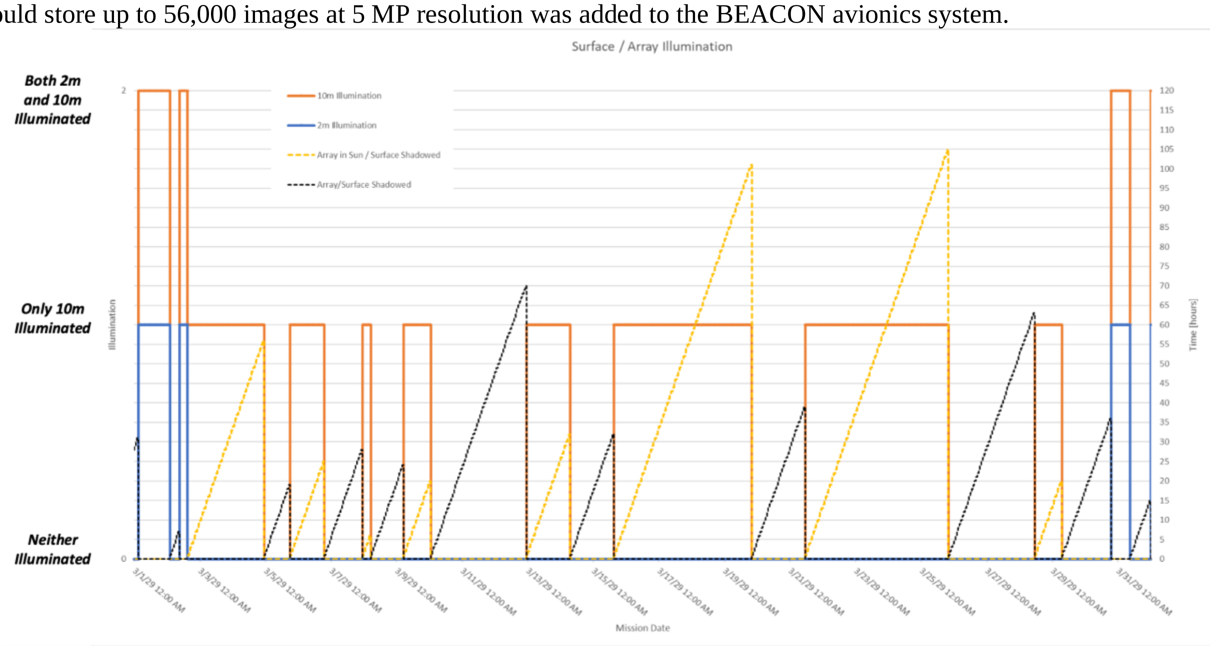

Fig. 6 Worst Case Shadowing Month.

Night operations will occur during the winter months when the surface is in darkness, but the VSAT remains illuminated. This mode will last for approximately 17 days cumulative per month. BEACON can support the 3GPP relay and data transmission capabilities during these times. Power beaming would be demonstrated with the goal of delivering 500W useful power to a user located up to 10 km away. When both the surface and VSAT are shadowed, which occurs for about 12 days on and off each winter month (with a maximum continuous shadow of 70 hrs), the BEACON provides only a minimal relay capability, and no power is available to other users. The worst-case month shadow periods shown in Fig. 6 assumes sun visibility greater than 50 percent as full illumination. A final redeployment test may be conducted at the end of the 18-month mission, allowing for a thorough assessment of the impact of cold and dust on the VSAT tower during the winter.

The mission is planned for an 18-month duration (Class D), which includes surviving through a full lunar winter. There is also the potential for an extended mission, depending on the system's performance and condition at the end of this period.

C. Beaming CONOPS

For beaming the power from the BEACON lander to the user, the user asset (rover) is assumed to remain stationary, establishing a communication link with the 3GPP system. The asset then provides its location to the BEACON lander in one of two ways. In the first, a beacon-based closed loop, the power optic itself is used to locate the user. A laser diode on the user asset with an 850 nm wavelength (different than the power laser wavelength) and

150 mW power output provides its location through a wide 10-degree angle beam. This method operates continuously, correcting any disturbances, such as those caused by boom or array movements on the BEACON lander. The acquisition phase involves a search pattern using spiraling search methods. The laser's pointing mechanism relies on a two-axis gimbal, modeled after the LUSTR beam director [3]. A graphical representation is shown in Fig. 7. A future option would be to use this user asset laser beacon beam as a high-rate communication link, capable of transmitting at gigabit per second (Gbps) speeds. The second option involves an RF loop, where the user photovoltaic (PV) array senses a defocused main laser power beam and relays an RF signal back to the BEACON lander, which then focuses the laser beam on the user PV array, ensuring optimal energy transfer.

The elevation angle from the BEACON lander to the user remains unrestricted in azimuth, though the laser optic can only point down at a maximum of 10 degrees over the solar arrays. This configuration assumes a minimum user distance of 1 km, though precise beam focusing is required across a range of 1 to 10 km. The system also assumes that the user's PV array is approximately 1.5 m in diameter and tuned to the laser frequency.

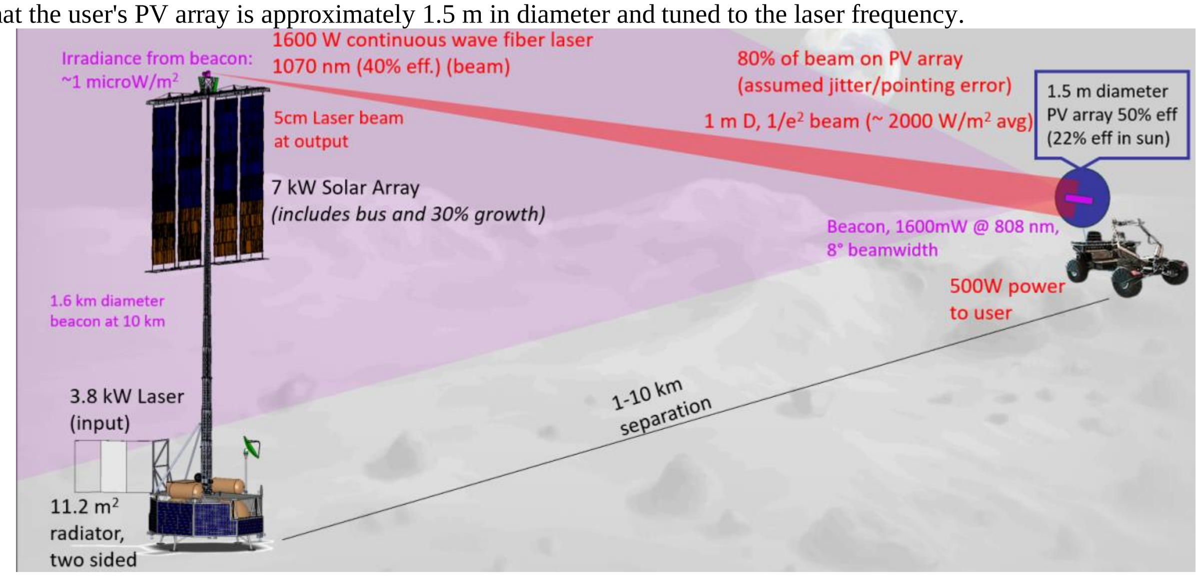

Fig. 7 Laser Power Beaming Demonstration.

Environmental factors, particularly lunar dust, must be mitigated. One approach involves pointing the optic downward when not in use, and a dust cover may be added if necessary. The optic is designed to survive extreme temperatures, down to 60 K, in standby mode for up to 70 hours, with heaters applied before use once the solar array is illuminated. Waste heat from the PV array could potentially be used to warm the user bus, although this introduces additional system complexity and would require future trade studies.

To minimize vibrations, the VSAT boom may be stopped during transmission, creating a 'quiet boom.' Since the sun moves once around the horizon during a month the stopped array will not incur noticeable cosine illumination losses. Once the user is located, the optic or mirror is pointed, and the system waits for vibrations induced by the gimbal to settle before beaming begins. The divergence angle of the laser beam is designed at 10^{-4} radians, requiring a pointing precision of 10^{-5} radians. Consideration must also be given to the potential for disturbances on the lunar surface, including rare but impactful moonquakes. Magnetic hysteresis damping or similar technology could reduce disturbances down to one-tenth of the divergence angle, controlling vibrations in the range of 100 milliradians at 100 Hz.

The beam director is placed above the 3GPP 180-degree antennas, with enough height for the beam to clear the solar array wings. Power input to the laser is limited to 3.8 kW, based on previous VSAT designs, while the laser output is approximately 1.6 kW. Of this, around 500 W instantaneous power is delivered to the user, assuming 80 percent of beam on the array, 84 percent of the array covered with cells, 50 percent PV cell efficiency and 95 percent PMAD efficiency. This results in sufficient power for 300 W operations with the additional 200 W used to charge the rover battery as required when VSAT power is unavailable.

Sequential power beaming to multiple users is possible with the power beam moving between users as needed. It is assumed that each asset has at least a 70-hour battery for shadowed operations, with the laser beam recharging this battery while also providing some operational power. Potential users include CLPS landers, which require approximately 50 W of continuous power, and VIPER-class rovers, which average around 300 W per user [4]. The

Lunar Terrain Vehicle (LTV) requires 300 W for shadow survival alone and would be the sole user during this phase of operations.

D. System and Layout

The BEACON concept is compatible with a representative medium-class CLPS lander. Such landers promise to provide an inexpensive way to place demonstration payloads onto the lunar surface. While some of the subsystems of the CLPS lander (e.g., power, communication, data storage, etc.) will be used to get the BEACON to the surface and support commissioning, it was assumed these systems are not designed for lunar night and they would not be available for BEACON lunar operations. A system schematic shows the main subsystems of the BEACON (Fig. 8.) Integration of these systems in a pallet which is integrated into the top payload section of the lander is shown in Fig. 9.

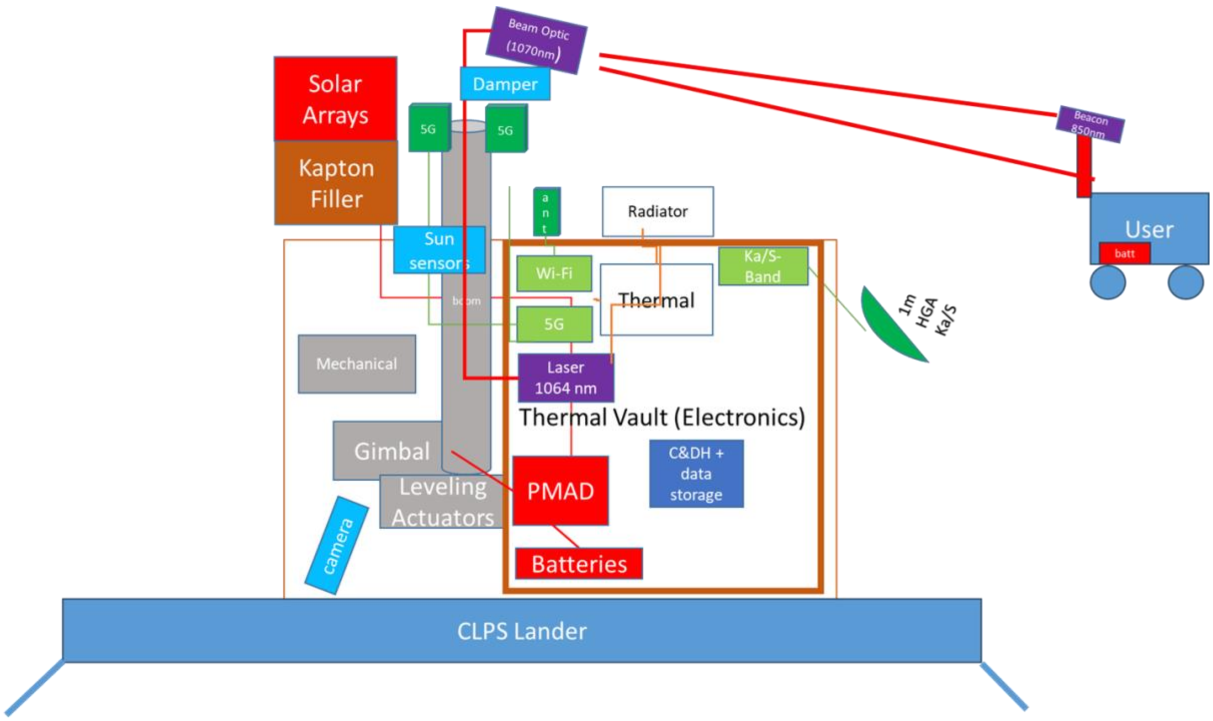

Fig. 8 BEACON System Schematic.

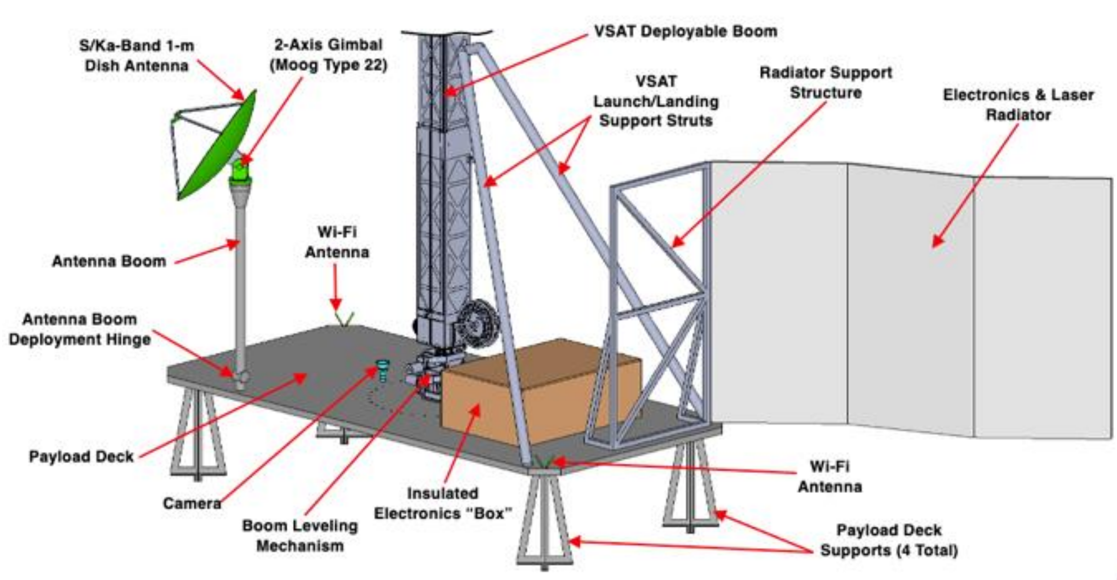

Fig. 9 BEACON Platform.

E. Systems and Subsystems

Table 1. BEACON Mass Breakdown

MEL Summary: Case 2_VSAT_Beamed_Power_LSR CD-2023-203	VSAT_LSR
Main Subsystems	**Basic Mass (kg)**
Science	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 Dry Mass (no prop,consum)	456.7
Element Propellant	0.0
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*

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%**

The mass of the BEACON system will fit within the 625 kg landed limit as shown in Table 1. Both growth and margins are carried at the subsystem and system level per AIAA guidelines for pre-phase A concepts [5]. The mass of the system is dominated by the structures (which includes the VSAT ~70 kg boom) and the power system which includes the solar arrays, PMAD, and batteries. The Thermal control system is significant as it must insulate the BEACON electronics through the lunar darkness periods to minimize the electrical heat loss and thus reduce battery requirements. The science package in this case includes all the laser beaming demonstration equipment including the laser, beam director, and fiber optic cable to connect them. Ironically, the relay system mass is relatively small and easily carried by the BEACON platform. Each of these subsystems are described in the following sections.

E.1 Power Collection and Storage System

The BEACON demonstrator is designed to serve dual purposes, functioning as both a communications relay and a beamed power source for nearby payloads and vehicles on the lunar surface, specifically at the lunar south pole. The power system, optimized for polar operation, accounts for environmental conditions to determine solar array size and energy storage needs. The system must operate under both sunlit and shadow conditions, storing energy to maintain functionality during periods when the solar array is shadowed. Major power loads include communications, the beamed power laser, heaters, and avionics, all of which require sustained operation over multiple day/night cycles as tallied in the power equipment list (Table 2). Only during VSAT array sunlit periods will the laser beam actively power user payloads, eliminating the need for energy storage to operate the laser itself. As mentioned previously, during shadow periods, the BEACON power beaming ceases and the system enters a low-power standby mode, with energy storage requirements scaled to support this reduced power state.

The BEACON power system design incorporates a deployable VSAT tower and solar array panels with a single axis tracking mechanism, following the sun's path across the lunar horizon throughout the day. The single-axis tracking system is sufficient to optimize power output due to the sun's relatively low and consistent path near the pole. To save mass in this demonstration mission, a Kevlar blanket simulates part of the solar array area, showing the full deployment capability while maintaining enough functional array area to meet power needs. For shadow operation, energy storage is provided by a Li-Ion battery pack, sized specifically for the minimal power demand during these low-power standby periods. Table 3 outlines the power system attributes and Table 4 provides the components and masses.

Table 2. BEACON Power Equipment List

Description	Power Mode 1	Power Mode 2	Power Mode 3	Power Mode 4	Power Mode 5	Power Mode 6
Case 2_VSAT_Beamed_Power_LSR CD-2023-203	Deployment (VSAT and Antenna)	Sunlit Operations	Sunlit VSAT-Shadow Surface Ops	Shadowed Operations	Retraction and Redeployment Test	Shadowed Health Check
	45 minutes	Full time Summer / 72 hours cumulative March (representative)	min of 24 hours / 15 days cumulative March (representative)	100 hours / 12 days cumulative March (representative)	37.5 hours	30 mins per day (max 120 mins per shadow period)
	(W)	(W)	(W)	(W)	(W)	(W)
VSAT_LSR	101.7	4431.3	4433.3	19.6	179.2	166.1
VSAT_LSR	101.7	4415.3	4417.3	19.6	179.2	166.1
Science	1.0	3988.0	3988.0	1.0	1.0	1.0
Attitude Determination and Control	13.6	0.1	0.1	0.1	13.7	0.1
Command & Data Handling	37.5	60.5	60.5	1.5	37.5	38.5
Communications and Tracking	0.0	182.0	182.0	0.0	75.0	75.0
Electrical Power Subsystem	49.6	184.7	186.7	5.0	52.0	51.5
Surface Users	0.0	16.0	16.0	0.0	0.0	0.0
Electrical Power Subsystem	0.0	16.0	16.0	0.0	0.0	0.0
(User load not included)						
Bus Power, System Total	102	4415	4417	20	179	166
30% growth	31	1325	1320	6	54	50
Total Bus Power Requirement	132	5740	5738	26	233	216
Total System power with growth	132	5740	5738	26	233	216

*Array was sized for the maximum required output power including 30% growth margin.

Table 3. BEACON Power System Attributes

Specifications	Value/Description
Mission Requirements	Provide power for the BEACON for an 18-month mission
PMAD	120 VDC Output 28 VDC Output
Array Output Power Level	5760 W at 120 VDC Solar Cell Fill Factor: 0.85 Temperature adjusted efficiency: 24% Specific Mass: 1.65 kg/m^2
Energy Storage	Li-Ion Battery 28 VDC 3737 Whr Capacity (27 W Output Power for 100 Hours, note includes inefficiencies) Charge & Discharge Efficiency 0.85 Depth of discharge: 0.85 Specific Energy: 200 Whr/kg Dimensions: 0.23 m X 0.23 m X 0.18 m
Environment	Operation on the Lunar South Pole Array: 267 K to 136 K sink temperature range on the surface Battery & Electronics: Within Enclosure ~300 K day/night temperature Solar Flux, Earth Orbit Yearly Minimum: 1309 W/m^2

Table 4. BEACON Electrical Power Subsystem Equipment List

Description	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Case 2_VSAT_Beamed_Power_LSR CD-2023-203						
		(kg)	(kg)	(%)	(kg)	(kg)
Electrical Power Subsystem			**106.7**	**30%**	**31.6**	**138.4**
Power Generation			**39.5**	**20%**	**7.9**	**47.4**
Solar Array - Active Area	1	36.3	36.3	20%	7.3	43.6
Solar Array - kevlar/kapton	1	3.1	3.1	20%	0.6	3.8
Power Management & Distribution			**49.9**	**41%**	**20.3**	**70.2**
PMAD	1	28.6	28.6	15%	4.3	32.9
Harness	1	21.3	21.3	75%	16.0	37.3
Energy Storage			**17.3**	**20%**	**3.5**	**20.8**
Battery	1	17.3	17.3	20%	3.5	20.8

E.2 Laser Power Delivery Subsystems:

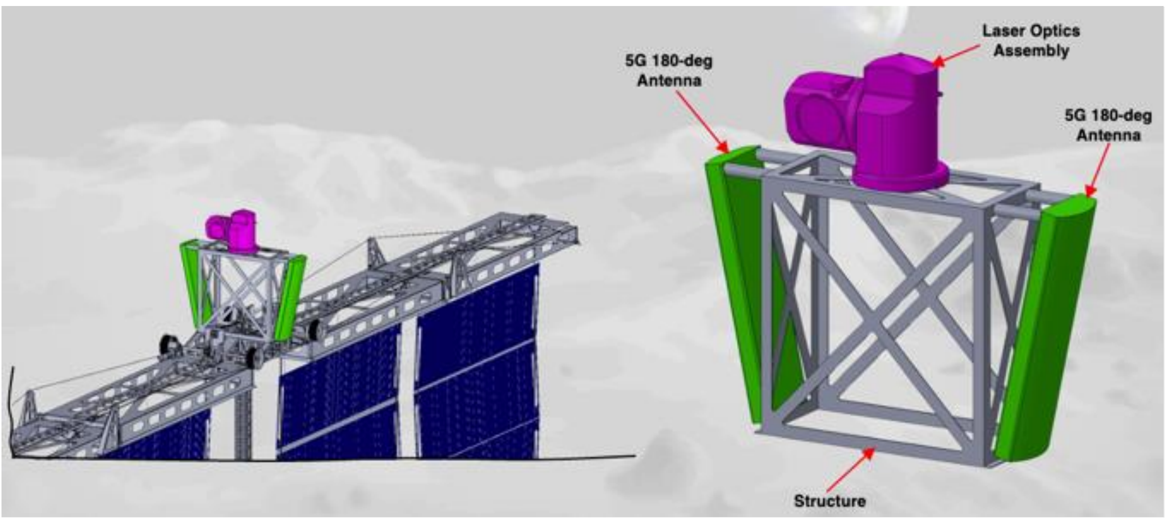

Fig. 10 BEACON Laser Director and 3GPP Antennas atop the VSAT boom.

To represent the BEACON laser source, a commercially available laser (IPG model YLR-2000-U multimode laser [6]) laser was chosen for its relatively high efficiency. This laser system features hermetically sealed industrial pump diode packaging, though it currently lacks space qualification. Liquid cooling is employed to maintain operational stability, with connectivity options including analog, RS-232, or Ethernet, and built-in self-diagnostics enable real-time performance monitoring. Operating at a 1080 nm central wavelength, the laser can modulate up to 50 kHz and utilize a 3.8 kWe input. The output beam of the laser is about 1.6 kW given the devices ~40 percent efficiency. This system is representative of the type BEACON would employ.

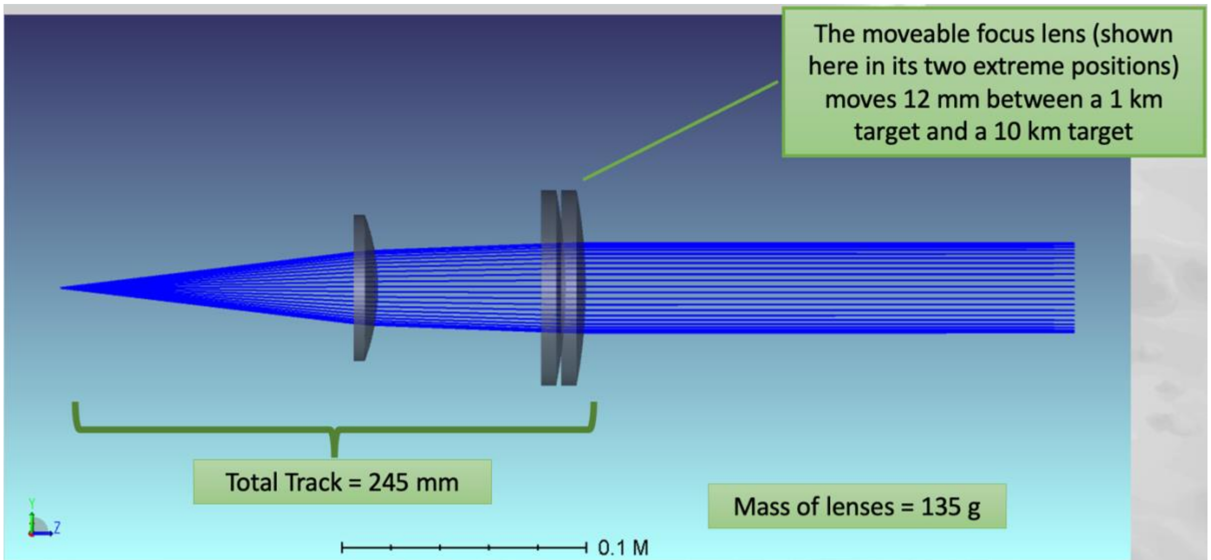

Fig. 11 Laser Director optics train.

The beam director optic design concept was optimized for user distances ranging from 500 m to 10 km. Although a top-hat converter would be preferred for more uniform beam distribution across this range, the current design operates with a Gaussian distribution. The system features a 5 cm main beam diameter and a 10 cm primary aperture, ensuring effective beam propagation over the required distances. With a length of 23.6 cm, the beam director can achieve focal distances from 1 to 10 km, accommodating varying user needs. This beam director design is based on a prototype developed by the University of California, Santa Barbara, specifically for the NASA Space Technology Mission Directorate (STMD) Lunar Surface Technology Research (LuSTR) project [3].

The beamed power transfer system for the current design leverages a fiber optic cable for routing, following a trade-off analysis between fiber optics and periscope methods. The fiber optic routing is integrated into a dust sock that extends up the mast, providing a protected path for the cable. Approximately 32.5 m of fiber optic cable is required, running from the lander deck to the aiming optics positioned on the mast. Stored within the dust sock at the platform, the fiber is coiled in a structure roughly 30 cm or larger in diameter, allowing flexibility during deployment and retraction. Key attachment points along the exterior mast structure aid in smooth fiber deployment. The fiber optic cable must be axially adjustable, enabling it to extend and retract as the mast moves. With a nominal pitch angle of 30 degrees and a deployment strategy that includes a 20-spiral wrap around the mast, this setup provides ample slack to accommodate rotation and deflection. The mounting scheme was inspired by deployable/retractable systems used in terrestrial camera and cell towers. Table 5 shows the masses of the components of the power beaming subsystem.

Table 5. BEACON Power Beaming Equipment List

Description Case 2_VSAT_Beamed_Power_LSR CD-2023-203	Basic Mass	Growth	Growth	Total Mass
Supporting hardware	(kg)	(%)	(kg)	(kg)
Science	**35.9**	**6%**	**2.2**	**38.0**
Science Package Group One	**35.9**	**6%**	**2.2**	**38.0**
Laser	32.0	3%	1.0	33.0
Beam Director	2.0	20%	0.4	2.4
Fiber Optic Cable	1.5	50%	0.8	2.3
Fiber Optic Spool	0.4	20%	0.1	0.4

E.3 Notional User Power System

In order to assess the end-to-end performance and technology needs, a concept for the user laser receiver was developed. Table 6 shows the main attributes of the subsystem.

Table 6. User Rover Power System Attributes

Specifications	Value/Description
Mission Requirements	Provide power for the lander/rover from the transmitted laser beam.
PMAD	Array string output: ~3.0 V DC to DV converters 94 converters going from 3 VDC to 28 VDC Output
Array Specifications	Diameter 1.5 m Solar Cell: 1080 nm InGaAs Input from Laser: 1594.9 W Solar Cell Fill Factor: 0.85 Beam Spill Factor: 0.80 Cell Efficiency 0.50 (1080 nm tuned cell) Specific Mass: 1.65 kg/m^2
Energy Storage	Li-Ion Battery 28 VDC 102 kWhr Capacity (300 W continuous output during shadow periods) Charge & Discharge Efficiency 0.95 Depth of discharge: 0.85 Specific Energy: 200 Whr/kg
Environment	Operation on the Lunar South Pole Array: 267 K to 136 K sink temperature range on the surface Battery & Electronics: Within Enclosure ~300 K day/night temperature Total Operating time: 744 hr / cycle, Laser Input Time: 421 hr, Battery operation time: 323 hr.

The PV cells on the user rover were assumed to be tuned to the laser beam at 1080 nm [7]. The laser wavelength of can be converted with high efficiency by a receiving array populated with these single-junction InGaAs photovoltaic cells. During the daytime, the same array will also produce power from solar illumination, although at somewhat lower efficiency.

The laser beam intensity has a gaussian distribution, highest intensity at the center and decreasing outward. To maximize the array output and minimize the effects of the uneven power distribution a series of short array strings were used to populate the array.

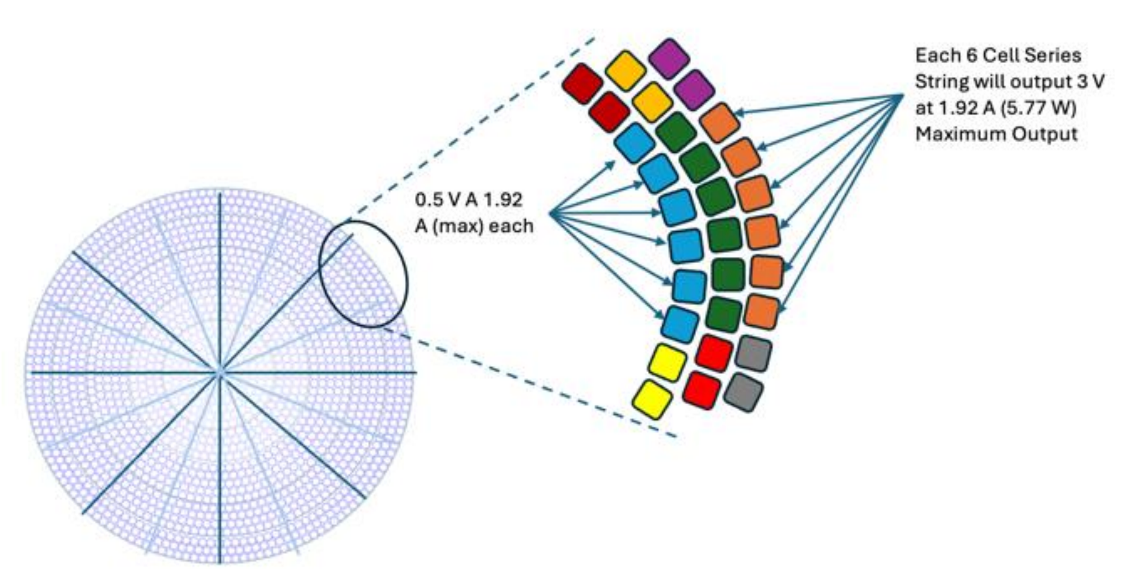

Fig. 12 Laser PV receiving cells wiring approach.

The array consisted of 6 cells in series per string and 94 strings in parallel with a total of 564 cells at 26.6 cm^2 per cell. Each string max current is 1.92 A. The current output of the series string of cells will be the lowest output of each of the cells in the string. This will be the cell receiving the lowest flux from the laser. Utilizing a short string of cells minimizes the effect that the gradient of the laser power has on the output of the array. This is shown conceptually in Fig. 12 and Fig. 13, while Table 7 outlines the power system components for the user system.

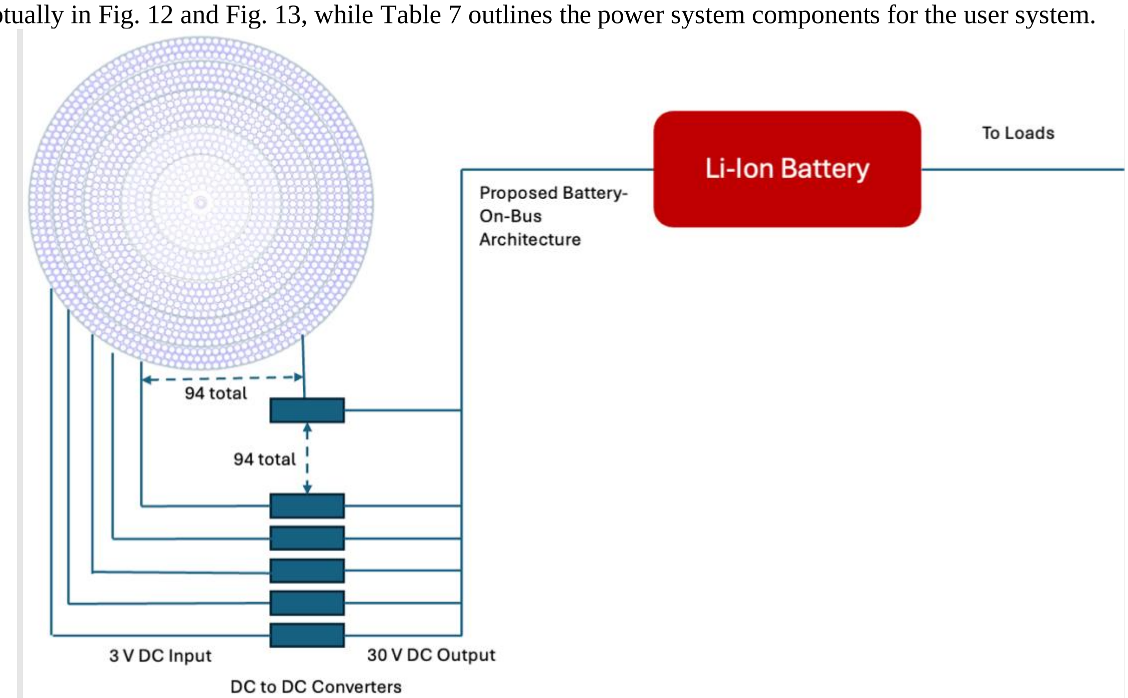

Fig. 13 User Rover Receiving PV Array and Power System.

The user laser beacon system is designed to enhance tracking and pointing accuracy of the power beam on the user asset. By employing a beacon mounted on the user rover, this setup relaxes the stringent requirements associated with open loop pointing and absolute positional accuracy, compensating for potential misalignment issues caused by micro-vibrations within the BEACON mast. The laser beacon is assumed to be mounted perpendicular to the user rover's PV array, providing a stable reference for tracking. Localization of both the user rover and

BEACON is maintained within the lunar surface coordinate frame with an error margin of less than 100 m RMS per axis, utilizing a combination of onboard sensors (e.g., positioning, navigation, and timing (PNT) radio, clocks, optical sensors) or external systems (e.g., narrow field-of-view cameras on lunar orbiters, Earth-based telescopes, Deep Space Network tracking). The user rover will also need to carry sensors, such as sun sensors and inclinometers, to ascertain its orientation within the lunar surface coordinate frame with accuracy well below 0.8° per axis. Additionally, it is assumed that the user rover can actuate its PV array with a pointing error of less than 0.8° per axis.

Table 7. Users Electrical Power Subsystem Equipment List

Description Case 2_VSAT_Beamed_Power_LSR CD-2023-203	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
		(kg)	(kg)	(%)	(kg)	(kg)
Surface Users			**6**	**20%**	**1**	**7**
Electrical Power Subsystem			**5.9**	**20%**	**1.2**	**7.0**
Power Generation			**5.4**	**20%**	**1.1**	**6.4**
Laser Array	1	2.9	2.9	20%	0.6	3.5
Low Voltage Power Converters	94	0.0	0.7	20%	0.1	0.8
gimble	1	1.3	1.3	20%	0.3	1.6
Wirre Harness	1	0.5	0.5	20%	0.1	0.6
Power Management & Distribution			**0.5**	**20%**	**0.1**	**0.6**
Beacon Laser	1	0.5	0.5	20%	0.1	0.6

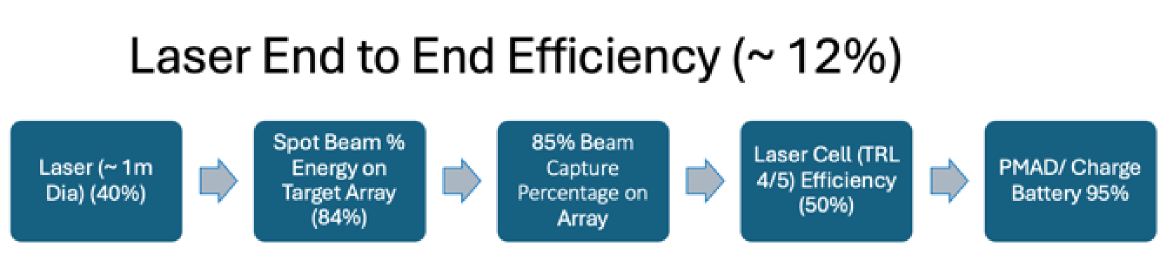

Fig. 14 Laser end-to-end efficiency.

Based on the laser system from BEACON to the user an estimate of system efficiency could be calculated. The end-to-end efficiency of the power beaming system, as expected, was fairly low. Figure 14 shows the end-to-end efficiency with the main contributors to efficiency being the laser source and the laser cell receiver. Efforts to increase these efficiencies, especially for the sample laser source, could produce improvements. The flexibility, robustness and reach of powering users up to 10 km without requiring a cable run might offset this low efficiency performance.

E.4 Thermal Systems

Two unique thermal systems are required for the BEACON system. The first is a large radiator to reject the waste heat from the low efficiency laser source (~40 percent). While this is a common system to cool systems, there are periods of time when the laser is not running and must be 'disconnected' from the laser so as to not continue to cool it down to lunar night temperatures. A pump loop cooling system would typically be utilized for cooling the laser but for this application the pump loop was not selected do to the extended shadow period and the corresponding need to either maintain the coolant in a liquid state or provide a means for it to freeze and recover from a frozen state to operate during the next daylight period. To avoid these issues a heat-pipe system was selected which is capable of freezing and thawing allowing it to function over the day/night cycles.

Concerns with the heat-pipe system include integrating to and removing head from the laser which is a compact system with a high heat load and integrating heat pipes with a deployable radiator.

Table 8. Heat Loss estimates for the Thermal Vault

Item	Dimensions Electronics	Material	Thermal Conductivity	Insulated Length	Number Electronics	Heat Loss to Surroundings (Day, Pole) Electronics	Heat Loss (Night, Pole) Electronics
Insulation (direct heat loss)	Surface Area 3.52 m^2	Aluminized Mylar	0.0009 W/mK (effective thermal conductivity)	NA	25 Layers	0.76 W	1.02 W
Insulation Seams and Passthrough Heat Loss	Surface Area with 0.5% seam and passthrough effected area	Aluminized Mylar	0.0009 W/mK (effective thermal conductivity)	NA	25 Layers	4.81 W	11.03 W
Box Standoffs	5cm long, 1.5cm Diam, .5cm wall thickness	Ti	6.75 W/mK	5 cm	7 per box	0.53 W	3.63W
Power In Wires	Diameter (16 gauge)	Copper	401 W/mK	1 m	12	0.23 W	1.53 W
Data Wires	Diameter (24 gauge)	Aluminum	177 W/mK	1 m	50 (70)	0.37 W (0.52 W)	0.93 W (1.30 W)
Power Out Wires	Diameter (18 gauge)	Copper	401 W/mK	1 m	36 (22)	0.98 W (0.60 W)	2.47 W (1.51 W)
Comm Feeds	Effective Diameter 16 gauge	Copper	401 W/mK	1m	8 (5)	0.39 W (0.24 W)	0.97 W (0.61 W)
Heat Pipes	OD: 1 cm, Wall 0.5 mm	Titanium	6.7 W/mK	0.5 m	8	0.05 W	0.35 W
Fiber Optic Line	3 mm Diameter	Quartz	1.4 W/mK	1 m	1	0.0006 W	0.002 W
					Total	8.11 W (7.73 W)	21.93 W (20.98 W)

The other unique thermal system was the ‘thermal vault’ which contains the electronics, laser source, and batteries which must be kept warm during the lunar night. For these calculations the assumed maximum operating temperature in the daytime was 310 K with a sink temperature of 251 K. At nighttime the minimum operating temperature was assumed to be 273 K with a sink temperature of 64 K.

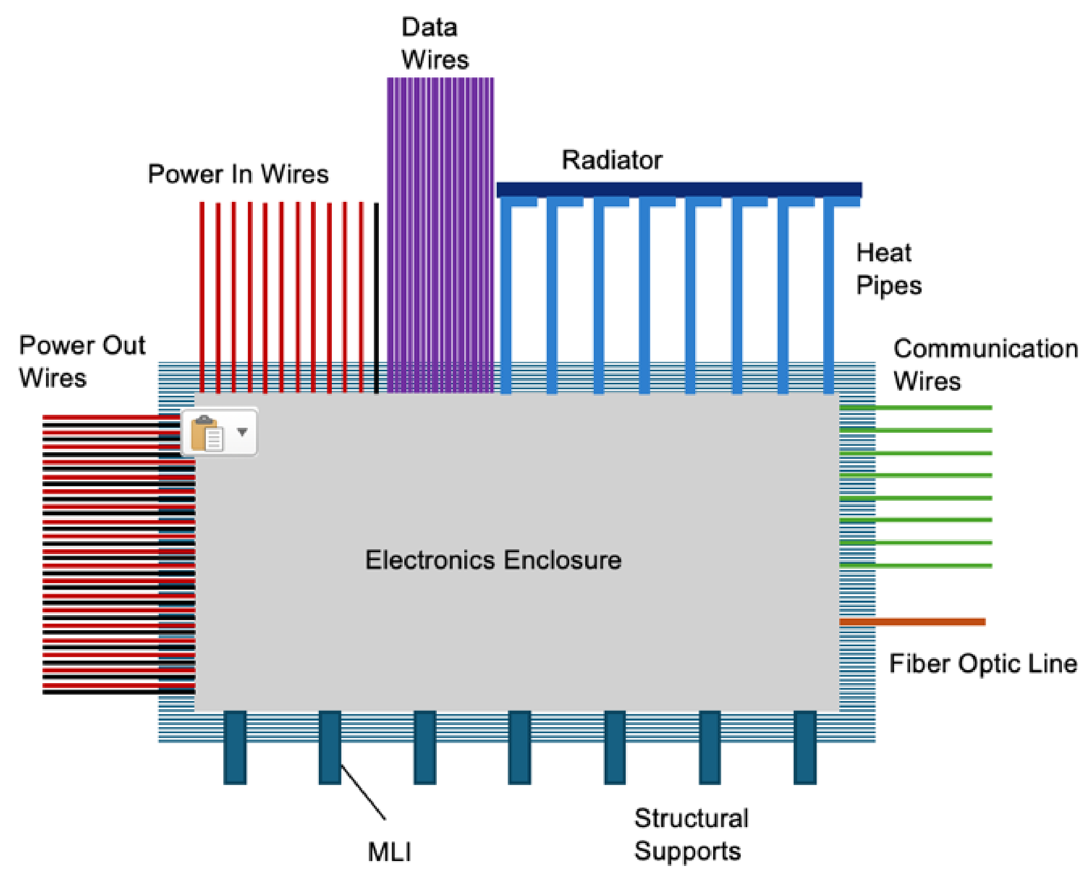

Fig. 15 Electronics enclosure ‘thermal vault’ schematic.

This 'keep alive' heat was provided by a battery for 100 hr periods enabled by the tall solar array. Heat leak from the thermal vault was minimized by placing the sensitive components in a well-insulated box and minimizing the structural heat leak using low conduction standoffs (Fig. 15 and Fig. 16). A preliminary assessment of heat leaks from various sources (insulation seams, wiring, variable conductance heat pipes, etc.) was found to be around 20 Wth, as shown in Table 8. This required the battery system to provide ~2000 Wh of energy to the thermal vault during its shorter ~70-hr shadow periods (100 hr periods carried for margin).

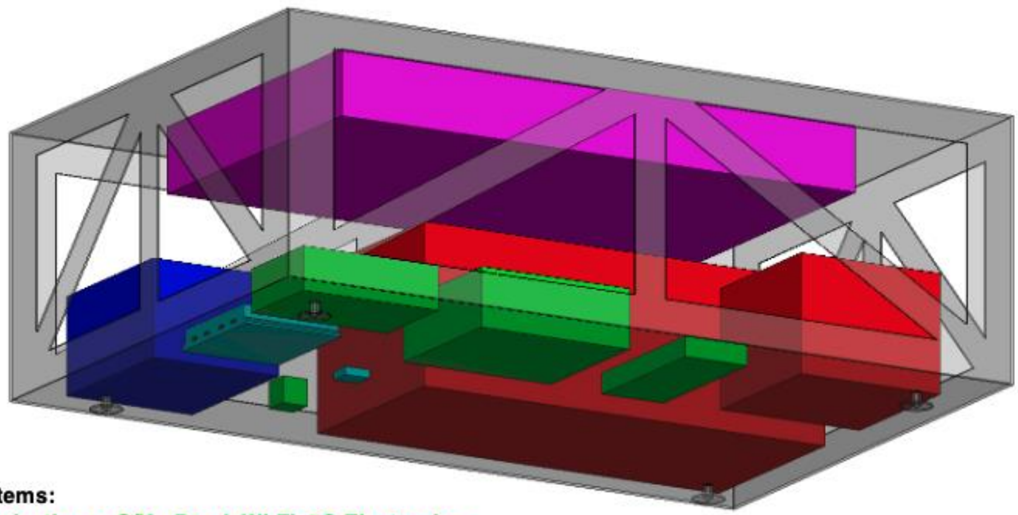

Fig. 16 Thermal Vault and Internal Components.

Table 9. BEACON Thermal Control System Equipment List

Description Case 2_VSAT_Beamed_Power_LSR CD-2023-203	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
		(kg)	(kg)	(%)	(kg)	(kg)
Thermal Control (Non-Propellant)			**70.9**	**18%**	**12.8**	**83.6**
Active Thermal Control			**2.3**	**18%**	**0.4**	**2.7**
Heaters	8	0.1	0.4	18%	0.1	0.5
Thermocouples	12	0.0	0.1	18%	0.0	0.1
Data Acquisition	4	0.3	1.0	18%	0.2	1.2
Switches	8	0.1	0.8	18%	0.1	0.9
Passive Thermal Control			**68.6**	**18%**	**12.3**	**80.9**
Electronics Cold Plates	8	0.1	1.1	18%	0.2	1.3
Electronics Heat pipes	16	1.3	20.2	18%	3.6	23.8
thermal paint	1	0.1	0.1	18%	0.0	0.1
Radiator	1	36.9	36.9	18%	6.6	43.5
Mast Cover	1	3.8	3.8	18%	0.7	4.5
MLI Electronics	1	6.6	6.6	18%	1.2	7.7

E.5 Communications

The communication system is designed to prioritize demand-based links, enabling efficient connectivity for various user requirements on the lunar surface. Key connections include relay services for lunar surface users and links from the lunar surface to the Lunar Communication Relay Network System (LCRNS) or directly to Earth.

For communication link requirements, a single co-feed 1 m dish provides S/Ka-band capability for both LCRNS/Relay and direct-to-Earth links. The S-band link operates at 36 kbps with offset quadrature phase-shift keying modulation and ½ forward error correction (FEC), supported by transmitter with a power demand of approximately 10 WDC. The Ka-band link can reach a peak data rate of 60 Mbps, using the same modulation and FEC scheme, and is powered by a 4 WRF solid state power amplifier with an additional power requirement of ~10 WDC. The associated radio equipment operates at a power level of 80 WDC. Fig. 17 shows the communications system schematic and Table 10 shows the associated equipment list.

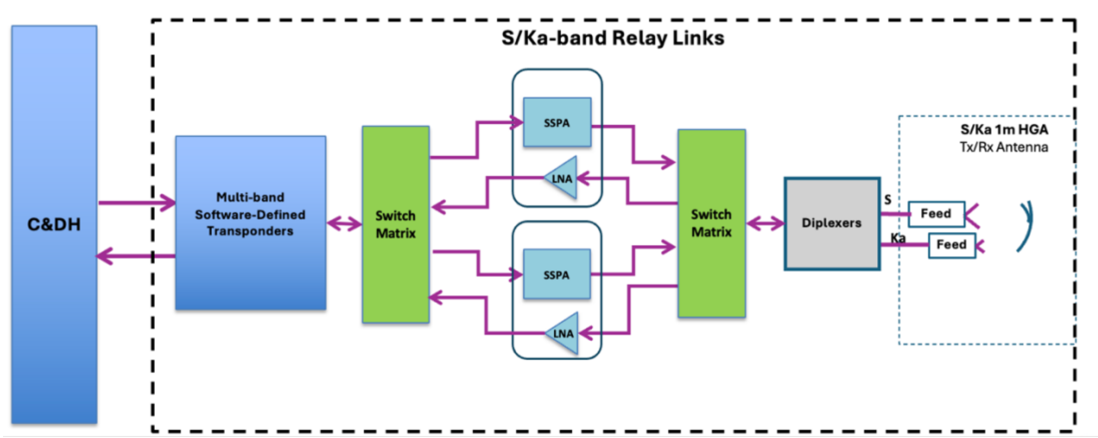

Fig. 17 Relay with LCRNS Schematic.

For lunar surface users, Wi-Fi-based communication is provided up to 300 m away and 3GPP band offers data rates of up to 60 Mbps up to a 10 km range. This setup provides continuous relay communication while the VSAT tower array is illuminated. Minimal, periodic, 'checkup' housekeeping comms are provided for 30 minutes per earth day during VSAT array shadowing to minimize BEACON energy storage needs but still provide health checks and small science data streams.

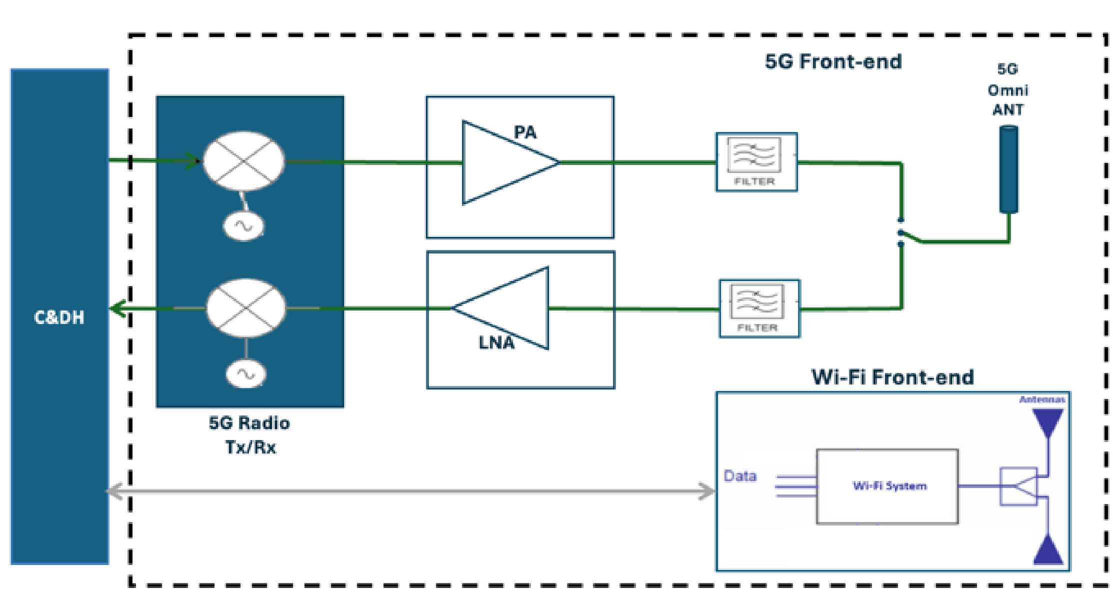

Fig. 18 Surface 3GPP and Wi-Fi Schematic.

Table 10. BEACON Communications System Equipment List

Description Case 2_VSAT_Beamed_Power_LSR CD-2023-203	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
		(kg)	(kg)	(%)	(kg)	(kg)
Communications and Tracking			**22.5**	**31%**	**6.9**	**29.4**
S/Ka Band System			**5.5**	**10%**	**0.6**	**6.1**
S/Ka-band SDR-radio	1	2.5	2.5	10%	0.3	2.8
Cables/WGs/Switches	1	1.0	1.0	10%	0.1	1.1
Moog 22 gimbal	1	2.0	2.0	10%	0.2	2.2
Lunar Surface Comm			**11.0**	**28%**	**3.1**	**14.1**
5G 180-Deg Wi-Fi Antenna	2	2.5	5.0	25%	1.3	6.3
5G base station	1	4.5	4.5	30%	1.4	5.9
Wi-Fi IEEE 802.11a/b/g/n	1	1.4	1.4	30%	0.4	1.8
Wi-Fi antennas	1	0.1	0.1	30%	0.0	0.1
Antennas and Cables			**6.0**	**55%**	**3.3**	**9.3**
S/Ka-band 1m HGA	1	3.0	3.0	10%	0.3	3.3
Boom Cables	1	3.0	3.0	100%	3.0	6.0

E.6 Command and Data Handling

The Command and Data Handling (C&DH) system is designed for the harsh lunar environment. Avionics are radiation-hardened and radiation-tolerant, but with zero fault tolerance. The system incorporates non-volatile data storage, with a capacity of 4 terabytes, providing approximately 18.5 hours of data buffering at a transfer rate of 60 Mb/s.

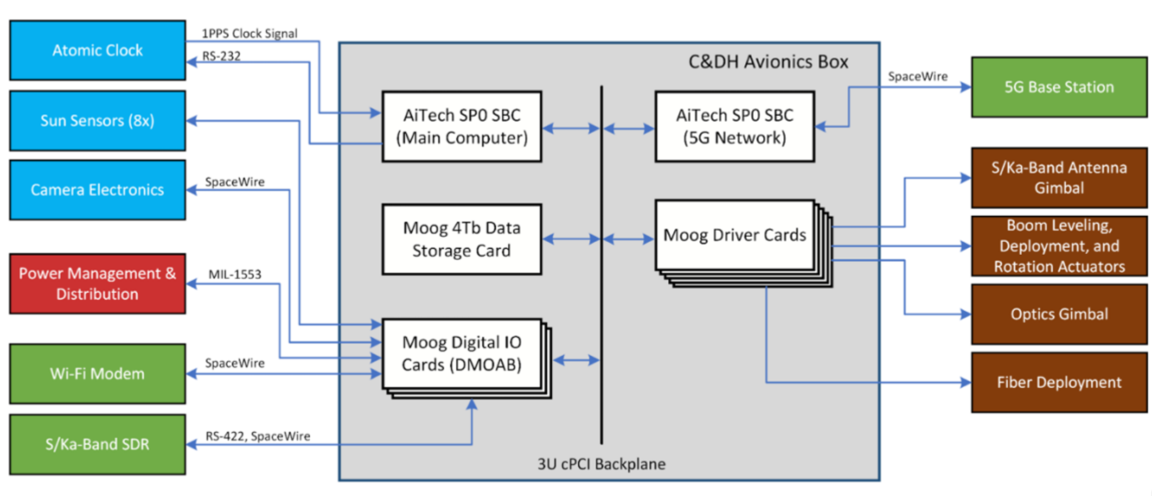

Fig. 19 Command and Data Handling Schematic.

The avionics architecture is based on commercially available, military/space-grade components ensuring high reliability and a technology readiness level of 9. The digital components are housed on 3U cPCI form factor cards within a card cage and backplane structure, including a Power-PC class processor, data storage, input/output cards, and driver cards. The enclosure package includes necessary DC-DC converters, filters, and electromagnetic interference shielding, ensuring stable and secure operation within the lunar environment. Fig. 19 shows a schematic of the system and Table 11 list the components and masses.

Table 11. BEACON Command and Data Handling System Equipment List

Description Case 2_VSAT_Beamed_Power_LSR CD-2023-203	Basic Mass	Growth	Growth	Total Mass
Supporting hardware	(kg)	(%)	(kg)	(kg)
Command & Data Handling	**13.0**	**56%**	**7.4**	**20.4**
C&DH Hardware	**8.1**	**30%**	**2.4**	**10.5**
SP0 SBC	0.4	30%	0.1	0.5
Data Storage Card	0.4	30%	0.1	0.5
Digital IO Cards	1.2	30%	0.4	1.6
Driver Cards	3.5	30%	1.1	4.6
RAD750 Watchdog	0.2	30%	0.1	0.3
SP0 SBC (5G)	0.4	30%	0.1	0.5
Avionics Box	2.0	30%	0.6	2.6
Instrumentation & Wiring	**4.9**	**100%**	**4.9**	**9.8**
Harness	4.9	100%	4.9	9.8

E.7 Position, Navigation, Timing Demonstration

The position, navigation, and timing demonstration includes a space-rated Chip Scale Atomic Clock (CSAC) integrated within the C&DH box. This clock serves as a demonstration of low-mass, low-power, and low-volume atomic clocks and showcases their capability to maintain precise timing relative to a reference source, whether Earth-based or LunaNet [8]. The CSAC is disciplined by an external source and remains powered as consistently as possible to monitor clock drift over time, providing valuable insights into its long-term stability. Initial clock disciplining may require several hours to achieve synchronization [9].

The CLPS lander is assumed to incorporate retroreflectors positioned on opposite sides of its deck, serving as key components for ranging operations. These retroreflectors enable orbiting assets to determine relative range to the lander's known position, facilitating accurate spatial measurements. This capability enhances the overall navigational and positional accuracy for lunar orbiters and assists in precise lunar surface localization, contributing to the broader objectives of lunar exploration and mapping.

E.8 Mechanical

The mechanical system includes all the structures and mechanisms to support and point the power collection, distribution and relay systems. A single, honeycomb Al pallet provides a surface for installation of most of the subsystems with the rest installed atop the VSAT boom. The boom is a deployable, telescoping device from past government development efforts but is only meant to be representative of the current VSAT booms under development by several vendors [1]. In lieu of laying the boom down for launch and delivery and then rotating it up, a two strut, separable bracket was used to steady the boom through landing – after which it would be separated as the boom will be able to withstand lunar gravity conditions on its own (see Fig. 9.). Mechanisms included deployment systems of the boom, power and fiber optic cables, along with the VSAT and 1m dish pointing gimbals. A mass breakdown is in shown in Table 12.

Table 12. BEACON Structures and Mechanisms Equipment List

Description Case 2_VSAT_Beamed_Power_LSR CD-2023-203	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
		(kg)	(kg)	(%)	(kg)	(kg)
Structures and Mechanisms			206.1	18%	37.1	243.2
Structures			173.0	18%	31.1	204.1
Primary Structures			153.8	18%	27.7	181.5
15m Deployable Boom	1	65.7	65.7	18%	11.8	77.5
Payload Deck	1	54.3	54.3	18%	9.8	64.0
Payload Deck Stand	4	2.6	10.6	18%	1.9	12.5
Multiband Dish Ant. Boom	1	0.8	0.8	18%	0.2	1.0
Solar Array Upper Support Boom	2	7.3	14.7	18%	2.6	17.3
Solar Array Lower Support Boom	2	3.9	7.8	18%	1.4	9.2
Secondary Structures			19.1	18%	3.4	22.6
Electronics Box Lunar Surf. Beam Pwr	1	7.9	7.9	18%	1.4	9.4
Top of Arra Boom Struc Lun Surf Beam Pwr	1	0.8	0.8	18%	0.1	0.9
Launch Support Strut	2	3.2	6.4	18%	1.2	7.5
Launch Support Strut to Boom Connector	1	0.1	0.1	18%	0.0	0.1
Radiator Support	1	3.9	3.9	18%	0.7	4.6
Mechanisms			33.2	18%	6.0	39.1
Power System Mechanisms			24.7	18%	4.4	29.1
Deployable Boom Drive	1	3.0	3.0	18%	0.5	3.5
Boom Alignment Gimbal	1	15.7	15.7	18%	2.8	18.5
Boom Rotation Gimbal	1	6.0	6.0	18%	1.1	7.1
Adaptors and Separation			0.7	18%	0.1	0.8
Boom Support Strut Release	1	0.2	0.2	18%	0.0	0.2
Boom Support Strut Hinge	1	0.5	0.5	18%	0.1	0.5
Installations			7.8	18%	1.4	9.3
C&DH Installation	1	0.3	0.3	18%	0.1	0.4
Comm. & Tracking Installation	1	0.9	0.9	18%	0.2	1.1
Electrical Power Installation	1	3.8	3.8	18%	0.7	4.5
Thermal Control Installation	1	2.8	2.8	18%	0.5	3.3

III. Conclusion

A. Lessons Learned

Integrating a VSAT power system and a lunar surface relay (LSR) system offers considerable synergies and benefits. The LSR, requiring a certain tower height and power, combines well with the VSAT system which gains a reliable communications link and a primary power consumer on the deck. This dual system, while primarily a demonstrator, could notably provide a useful relay capacity of around 60 Mbps and up to 500 W of power to distant mobile users in science and HLS sectors.

The inclusion of this system into a medium-class CLPS could significantly reduce both launch and lander costs. This integration strategy eliminates the need for additional off-loading and mobility and ensures a stable platform. Site selection is crucial, focusing on optimizing both power and relay capabilities. This reduces the need for HLS users to carry extensive nighttime power capabilities while addressing concerns about HLS landing ejecta. It provides approximately a 10 km relay for HLS and science users back to Earth through either LCRNS relay or direct transmissions.

It should be noted that the addition of an overnight battery for purposes other than survival is considered too heavy for the CLPS lander, given current mass limitations. The VSAT power system is capped at about 7 kWe due to these payload mass constraints. The balance of the 10 kW-class area is only blanket without cells. Nevertheless, this system could significantly shorten the night-time duration for users in polar winters from roughly 700 hrs to about 70 hrs. Additionally, the VSAT's power could be utilized to charge HLS and science users during extended shadow periods, providing an extra 16 days of operational charge during these darker surface times—enabled by the height of the arrays.

Landing with precision within a 100 m x 100 m area, as some CLPS vendors intend, is critical to position the VSAT in an optimally illuminated location, with Shackleton Ridge chosen as a representative site for this study. Although a mobile BEACON configuration is too heavy for the selected CLPS lander class, it would otherwise alleviate this constraint.

Adding to this framework, demonstrating beamed power from a VSAT tower to users 1 to10 km away is not only feasible but effective. Powers up to 500 W can be provided to users when they are in darkness, despite an end-to-end efficiency of less than 10 percent. This efficiency is offset by the flexibility and convenience of remotely powering mobile assets to either operate or survive through the night. Users, including CLPS, small rovers, and potentially LTV (for survival only), can benefit from beamed power, allowing for significantly reduced battery sizes—from approximately 700 hrs to just 70 hrs of operations during most polar winters. Additionally, a beacon from the user to the BEACON lander allows accurate pointing of the power beam. However, there is a challenge as the necessary laser, optics, beacon, and photovoltaic technologies may not be ready by the projected 2028 launch date.

B. Next Steps

This conceptual design study has identified several areas of study to further mature the concept.

B.1 Evaluation of Charging Systems and Integration with CLPS Lander

A more detailed assessment of the charging requirements and supporting systems is needed for mobile users, considering potential needs and anticipated technological advancements. This evaluation will address the development of charging solutions that accommodate future users, including the LTV and scientific payloads likely to require power and communication support. Integration with the CLPS lander must be explored to maximize the compatibility and efficiency of power and relay functionalities. This includes examining potential physical and operational interfaces with the CLPS lander.

B.2 Site Selection and Alternative Power Locations

Identifying and evaluating potential sites for additional power and relay installations—especially those in proximity to prospective HLS sites—could enhance mission flexibility and coverage. Locating these installations strategically will support broader mission needs, extending relay capabilities for communications and power across key lunar surface areas.

B.3 Power Beaming Technology Development

Power beaming technology demonstration for the 2028 target launch date would require rigorous evaluation to ensure readiness and compatibility. Key tasks include refining the laser-to-optic and beacon designs to improve performance, as well as establishing the operational procedures and user equipment requirements to facilitate power beaming. The PV cell's many-string approach could be optimized to mitigate the effects of off-pointing and jitter, while the structural impact of a tall, lightweight tower on jitter and pointing accuracy will be assessed to ensure beam stability. Reuse of the PV cells for use with the sun needs to ensure that the lower efficiency is sufficient for rover use. For fiber optic routing, strategies for restowing the fiber optic feed during VSAT retraction tests must be developed.

B.4 Thermal and Communication Enhancements

Thermal management options, including deployable heat pipe radiators and a pump loop to prevent freezing at night, will be investigated to maintain sufficient operating conditions for all lunar surface components. Additionally, an optical communication link option will be explored to add redundancy and enhance the communication capabilities, ensuring consistent data transmission.

Ideally, by addressing these areas, the BEACON concept can be more thoroughly defined for potential lunar use. This could establish a resilient and adaptable lunar power *and* communications infrastructure capable of supporting various lunar surface users and evolving mission needs well into the next decade.

Acknowledgments

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