

# Lunar Surface Network Relay Terminal: A Lunar Communications Platform

*Maximilian C. Scardelletti<sup>1</sup>, Michael R. Gasper<sup>1</sup>, Richard C. Reinhart<sup>1</sup>,  
Michael J. Zemba<sup>1</sup>, Jennifer L. Rock<sup>2</sup>, Steven R. Oleson<sup>3</sup>, and Elizabeth R. Turnbull<sup>3</sup>*

*1. Communications and Intelligent Systems Division*

*2. Space Communications & Spectrum Management Office*

*3. Mission Architecture and Analysis Branch*

*National Aeronautics and Space Administration, Glenn Research Center, Cleveland, Ohio, USA*

*\*Maximilian.C.Scardelletti@nasa.gov*

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## Abstract

This paper will discuss the development of a Lunar Surface Relay that will serve as a central terminal for lunar surface wireless communications (e.g., 3GPP, Wi-Fi) for surface assets to transmit and receive data back-and-forth with Earth through lunar orbital relays or direct with Earth. Four variations of a wireless surface terminal were designed with varying concepts of operation to assess mass, power, cost drivers, and trade-offs. The designs entailed one stationary platform and three mobile which provided interesting trade-offs. The terminals are powered for operation with either a radioisotope/solar/battery power system or solar array/battery power system.

## 1. Introduction

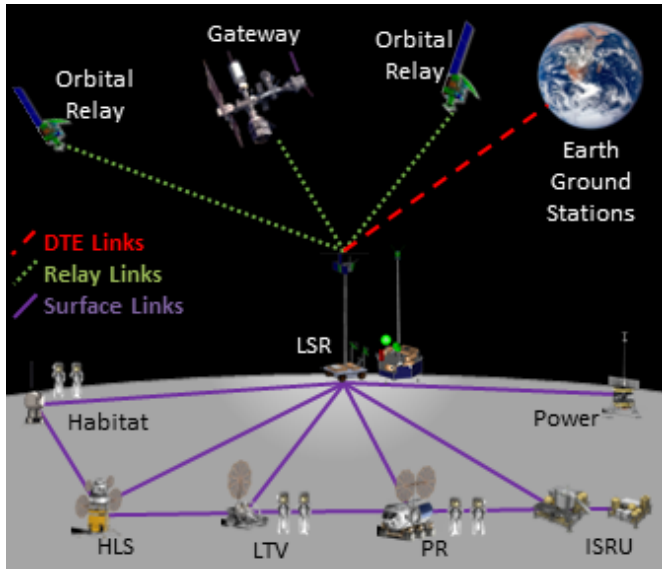
The National Aeronautics and Space Administration (NASA) along with commercial industry and other international space agencies such as the European Space Agency (ESA) and the Italian Space Agency (ASI) are planning for humans to go back to the Moon in the near future and eventually Mars. The U.S. Artemis missions are designated under NASA's Moon-to-Mars program [1] which is the first step in the next era of human space exploration. NASA plans to establish a sustainable presence on the Moon to prepare for human missions to Mars and beyond. A sustained presence on the Moon will require habitats, rover vehicles, power stations, and communication and navigation systems so astronauts can live and explore for long periods of time.

The Artemis missions to the moon require a robust and secure communication system for the lunar community to exist safely and sustainably. Connection with Earth, an essential aspect, includes a Direct-to-Earth (DTE) link and links to lunar orbital relays; Gateway (GW) and Lunar Communications Relay and Navigation System (LCRNS). A surface communication network will enable communication among lunar surface landing spacecraft, astronauts, and science assets.

In the near term, Lunar surface assets will consist of six types of users. 1) The Human Landing System (HLS) which is the spacecraft to transport the astronauts to the surface of the Moon. 2) Extra Vehicular Activity (EVA) spacesuits, allowing

astronauts to perform functions outside the landing spacecraft or surface habitat. Early Artemis missions will involve two EVAs with later missions having as many as four EVAs at a single time, or more as the program evolves. 3) Lunar Terrain Vehicle (LTV), a surface rover used to transport astronauts or science payloads while on the surface of the moon. 4) Surface Habitat (SH) which provides long duration indoor, pressurized living and working quarters for astronauts. 5) Pressurized Rover (PR) providing additional short duration habitation, and which allows astronauts to travel greater distances than with the unpressurized LTV alone and lastly, 6) Fission Surface Power (FSP), which will provide the power required to operate the SH and other surface assets when solar illumination is not sufficient to power needed systems. There will also be science missions and instrumentation that will operate on the surface and receive operational commands and instructions and transmit experimental data to other surface elements, the Lunar orbitals and/or eventually Earth. All of the surface elements and systems will have a communication system for command, control, and telemetry for monitoring from Earth and likely use some type of navigation service. Many of the surface assets will have cameras for streaming live, high-rate video back to Earth.

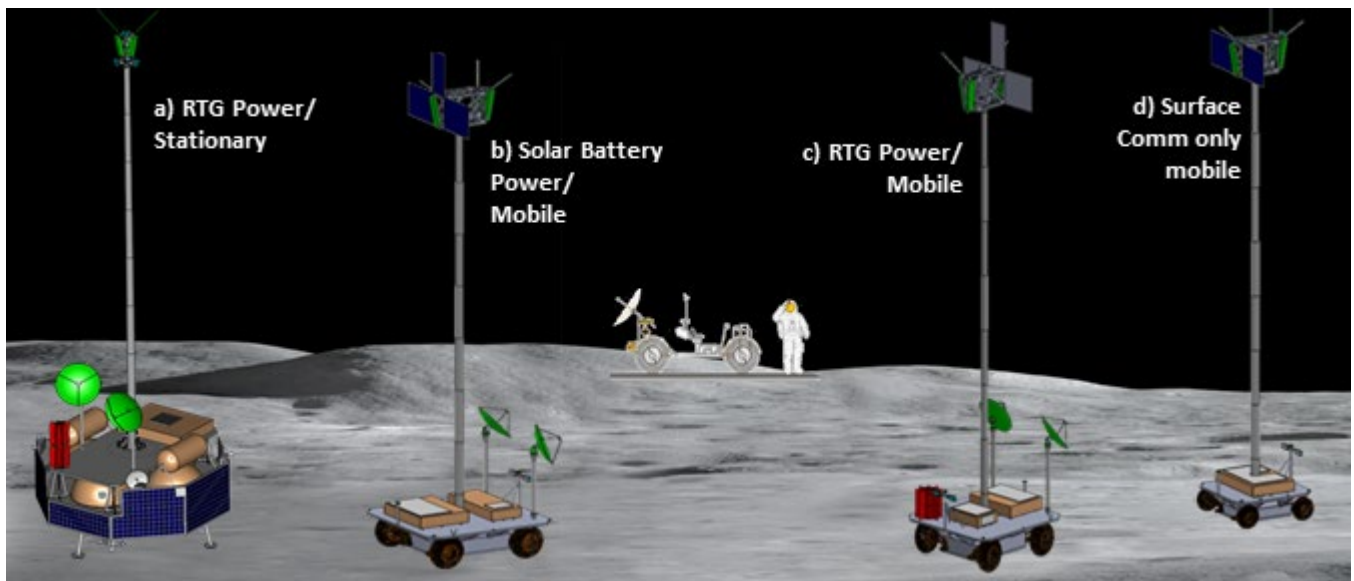
A Lunar communication architecture will enable proximity communications among surface assets and trunk links to Earth. Links to Earth will include relay through orbiting assets (GW, and LCRNS) and DTE. In this paper we describe the development concept of a Lunar Surface Network Relay (LSR) platform that provides the proximity communication links between lunar assets and links to the orbital relays and Earth. The concept highlights the use of terrestrial standards for the surface network and promotes interoperability among service providers and is shown in Figure 1. The relay terminal serves as a base station for the surface assets thus alleviating each asset (EVA, LTV, PR and FSP) of costly size, mass, volume, and power requirements for long range communications and instead only requires communication with the LSR for connectivity with Earth.



**Figure 1: Lunar Surface Relay Context Diagram showing LSR as the central base station for all surface and trunk links.**

There are four conceptual designs which consist of 1) radioisotope thermoelectric generator (RTG) powered stationary terminal (with battery storage for all concepts), 2) solar array powered mobile terminal, 3) Multi-Mission RTG (MMRTG)/solar array powered mobile terminal and 4) solar array powered mobile with surface communication system only. The design requirements and assumptions evolved to emphasize different operational concepts throughout the process, resulting in different designs. The four concepts allow comparison of power generation, mobility, and communication and navigation functions. The four concepts are shown in Figure 2.

The self-reliant LSR contains its own power source and thermal management solution which enables the LSR to not only have the capability to survive the lunar night but have an operational design life of 10 years allowing multiple Artemis missions to benefit. The mobile versions of the LSR platform can be remotely operated and driven to locations to optimize coverage of Artemis sites of interest. Furthermore, the LSR provides positioning, navigation, and timing services serving as a reference site on the moon as well as providing timing information for orbital and surface assets.



**Figure 2: Four LSR conceptual designs: a) RTG power/stationery LSR, b) solar power/mobile LSR, c) MMRTG power/ mobile LSR and d) solar power/mobile LSR with surface communication only.**

## 2. Lunar Surface Relay

### 2.1 LSR Orbital Relay and Direct-to Earth Communications

The LSR is a stationary or mobile platform that provides the communication and navigation services between surface assets and Earth, using either lunar orbital relays and/or direct with Earth.

The DTE links consists of X- and Ka-band links, compliant with the International Communications Systems Interoperability Standards (ICSIS) [2]. The X-band link provides voice, telemetry, tracking, and control (TT&C) and

data and the Ka-band link provides more bandwidth and higher rate service for the video applications including HD 720p, HD 1080p and 4K Ultra HD 2160p. The DTE trunk links will send/receive information to the Earth through NASA's Space Communications and Navigation Program (SCaN) ground stations, primarily via the Lunar Exploration Ground Stations (LEGS) which are expected to be located in White Sands, New Mexico, USA, Matjiesfontein, South Africa and Canberra, Australia. Each LEGS site will be equipped with an 18 m class high gain dish antenna. During the time Earth is not visible from the lunar south pole (nominally for 14 days every month), both Gateway and LCRNS can provide orbital relay service to

route data to Earth from the LSR. Links through Gateway and LCRNS send/receive data from the LSR using S- and Ka-band frequencies according to ICSIS [2]. The S-band link provides voice, TT&C and data and the Ka-band link supports the high-rate data and video. Gateway will transmit and receive data via LEGS while LCRNS will be dependent upon commercial Earth ground stations, yet to be decided.

Note that the Surface Comm Only mobile terminal concept differs from the first three by removing the trunk link capability to relays and Earth and only provides surface communications and reduced accuracy PNT to reduce mass, and power.

## 2.2 LSR Surface Communications

The LSR provides 3GPP-based/Wi-Fi network services to the surface assets, supporting voice, data, and video communications. The LSR serves as a central terminal (e.g., base station, access point) for the surface assets such as EVA, LTV, PR and FSP to communicate with Earth, thus relieving them of additional communication hardware needed to send and receive data to the lunar relay orbitals and/or direct with Earth. Both the stationary and the mobile LSRs are equipped with a 10 m deployable/retractable boom. The top of the boom supports the 3GPP sector antennas which provide optimum lunar surface communication coverage. The 3GPP network on the LSR will provide coverage out to 10 km, depending on local terrain effects. The 3GPP system can be a simplified version of a terrestrial system with a limited number of surface users on the moon in the early Artemis missions. The complementary Wi-Fi network will support a range of approximately 300 m. The LSR concept can also support a legacy Space to Space Communication System (SSCS) on the UHF-band.

## 2.3 Positioning, Navigation and Timing

The LSR concepts are equipped with high accuracy clocks, synchronized with the orbital relay satellite reference, to provide positioning, navigation, and timing (PNT) services to surface assets. Two rubidium clocks, operating continuously, provide lunar timing to surface elements and orbital relays. The LSR will also be equipped with two retroreflectors to provide positioning and ranging sources for the orbital relays and Earth.

## 2.4 Mobility

Mobility on the surface enables the LSR to remotely move from its initial landing site to other locations that could potentially provide both improved surface communication network coverage and optimize illumination for longer, higher power operations. A mobile LSR can also relocate to other Artemis sites of interest prior to the astronaut's arrival to support infrastructure build-up, thus making more efficient use of the astronaut's time while on the surface.

The LSR mobility system is based on NASA's Volatiles Investigating Polar Exploration Rover (VIPER), with a scaled-up chassis with four-wheel modules. Each wheel module is equipped with independent steering, suspension and drive motors allowing the LSR to self-level up to 10 degrees while stationary and traverse 20-degree slopes while mobile. The LSR has a nominal roving speed of 0.8 km/hr and can rove 100

km in a single lunar day with the capability of roving over 1000 km over its lifespan. The LSR moves on battery power but stops to recharge the batteries using the solar arrays (with boom deployed or retracted).

The navigation camera of the mobility platform provides real-time or near-real-time visualization of the lunar terrain allowing operators from GW or Earth to send commands and remotely navigate the LSR lunar traverse. The waypoint navigation system concept is similar to the system used on NASA's VIPER rover.

## 2.5 Surviving the Night

Surviving the lunar night is essential for surface assets to be used and relied upon for multiple missions over an extended time. If the surface asset cannot survive the lunar night, it is limited to single mission use, requiring expensive replacement for subsequent missions, and limiting its ability to be prepositioned. A lunar day/night cycle is approximately 29.5 Earth days (708 hrs) which results in a lunar day equivalent of approximately 14.75 days (354 hrs) and the same for the lunar night. The 14.75-day lunar night is a worst-case scenario used in the LSR design analysis. Depending on the location at the lunar south pole, and boom height, future designs could reduce the night cycle to as little as 100 hours. It is worth noting night periods can extend beyond the 354-hour case, especially in the lunar winter periods, but careful positioning could allow the rover to avoid these locations.

All four conceptual LSR designs have thermal management systems which allow them to survive the lunar night with differing capabilities during night operation. The thermal management systems consist of radiator panels for removing heat from electronics (during sunlit operations), heat pipes and cold plates, thermal paint, thermal sensors, heaters, thermocouples, and insulation. Waste heat from the electronics (or power source in the RTG cases) is used to maintain internal operating temperatures for the LSR electronics during night periods. In cases where this waste heat is insufficient, heaters can be used.

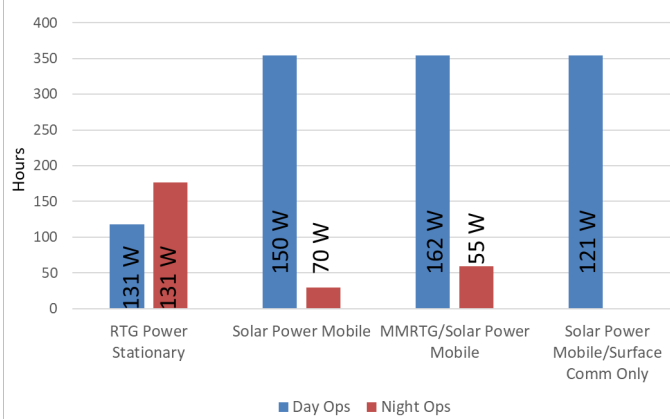
## 2.6 Power and Mass

The LSRs are powered by a solar/battery power system, a radioisotope/solar/battery power system (RPS), or a combination of both. The solar/battery system's solar arrays are mounted at the top of the 10 m boom to provide longer duration illumination and power to the batteries which are positioned on the deck of the LSR. The MMRTG/Solar version consists of a MMRTG mounted to the deck of the LSR with solar arrays. The amount of power needed to operate the various systems on the LSR depend on the duty cycle of the operational concepts which varies with each LSR design.

Figure 3 shows the required communication sub-system power to provide the high data rate (HDR) services for both lunar day and night operation for the four LSR design concepts. The process and drivers to size the power systems are directly impacted by the requirements and assumptions of each study. Each design has slightly different operation concepts and attributes (e.g., throughput, memory capacity, power).

The use of solar arrays instead of an RTG allowed the power generation system to be sized directly by the peak power needs of the system and the battery to then be sized by the shadow operations and hibernation periods. The MMRTG version of the mobile relay system allowed the reduction of battery mass with the addition of constant RTG power and was able to perform comparatively substantial shadowed operations to the solar array design. Finally, the surface comm only case was able to independently size the solar array and battery to meet its unique surface communication requirements.

The three mobile LSR concepts are all capable of continuous HDR Day Ops (354 hrs), but the power requirements differ due to marginal differences in data throughput design. Night Ops for the Solar Mobile requires 70W for 2 hrs per 24 hrs for surface communications and MMRTG power of 55W for 4 hrs per 24 hrs for surface communications. There are no high-rate Night Ops for the Surface Comm Only LSR. Each maintains power to the onboard clocks to ensure reference stability.



**Figure 3: Graph illustrating communication subsystem power requirements for day/night operation for the four LSR design concepts.**

The RTG Stationary Day Ops can run for 118 hrs over one lunar day (8 hrs every 24 hrs), with a power requirement of 131 W. The Night Ops can operate for 177 hours over one lunar night (12 hrs every 24 hrs) with the same power requirement of 131 W. The RTG Stationary allows for enhanced Night Ops since the RPS is thermally more efficient during the night resulting in greater power generation than during the day. The figure illustrates the design outcomes of the other LSR concepts in a similar manner.

While the Solar Mobile and MMRTG Mobile LSR's are capable of continuous operation (although reduced throughput compared to RTG Stationary), during the lunar day, the MMRTG Mobile provides more power for Night Ops. During Night Ops, the solar powered systems operate solely off stored battery energy and does not generate any additional power. The batteries charge during sunlit periods using excess power generated from the solar arrays. The Surface Comm only concept removes much of the functionality and is only capable of Day Ops and limited to keep-alive at night.

The total and the major sub-system contributors of the mass for the four LSR designs are listed in Table 1. The RTG Stationary is the lightest of the four LSR concepts. This is due to the RTG power system which is roughly 70 kg, lower battery capacity, and absence of a mobility system compared to the Mobile LSRs. Note also that this mass does not include the mass of the lander on which the LSR is mounted. The Solar Mobile LSR is the heaviest of the LSR concepts due to the battery and mobility sub-systems. The mobility unit is approximately 190 kg which is a mass driver of the LSR mobile designs. The MMRTG Mobile is second heaviest due to a 20% decrease in battery mass which is offset by the MMRTG power system. The Surface Comm Only LSR offers a lighter mobile version than both the MMRTG mobile and even more so when compared to the Solar Mobile. The mass reduction is due to the overall decrease in communication payloads, removing DTE and Lunar Relay communication capabilities as well as reduced PNT functions, and an associated reduction in the mobility platform mass.

**Table 1. Mass Comparison with Baseline Design**

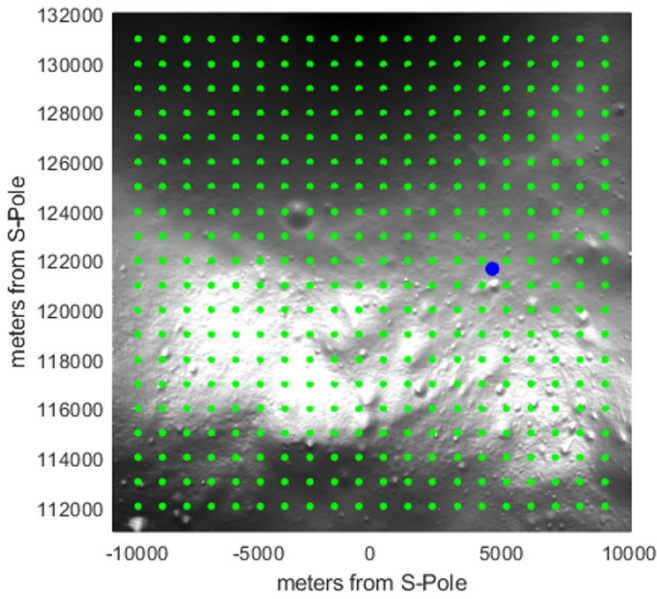
|                   | Total Mass (kg) | Mass Driver                                    |
|-------------------|-----------------|------------------------------------------------|
| RTG Stationary    | 547             | Baseline                                       |
| Solar Mobile      | 700             | + Mobility                                     |
| Surface Comm only |                 | + Battery<br>- DTE Comm & PNT clocks (removed) |
| MMRTG Mobile      | 1003            | ++ Mobility<br>+ Structures<br>+ Battery       |
| Solar Mobile      | 1218            | ++ Mobility<br>+ Structures<br>++ Battery      |

### 3. Lunar Surface Communication Coverage

The terrain of the Lunar surface offers a challenging environment to provide constant communication among assets. To illustrate the challenges to provide surface coverage, we examine the process to analyze a notional scenario to place a communication tower that provides the best line-of-sight (LOS) coverage to the Lunar surface. We begin with a 20 km by 20 km region of interest, Malapert Massif, near the Lunar South Pole [4] with a notional habitat/landing site at highest point within the region. In order to determine an optimized tower placement for LOS coverage, a grid of tower locations (20×20, ~1 km spacing) is placed over the region. The viewshed (i.e., line of sight coverage) over the Malapert Massif region is calculated from each of these points (considering and comparing transmitter tower heights of 20 m and 4 m from the surface) to receiver points 2 m above the surface.

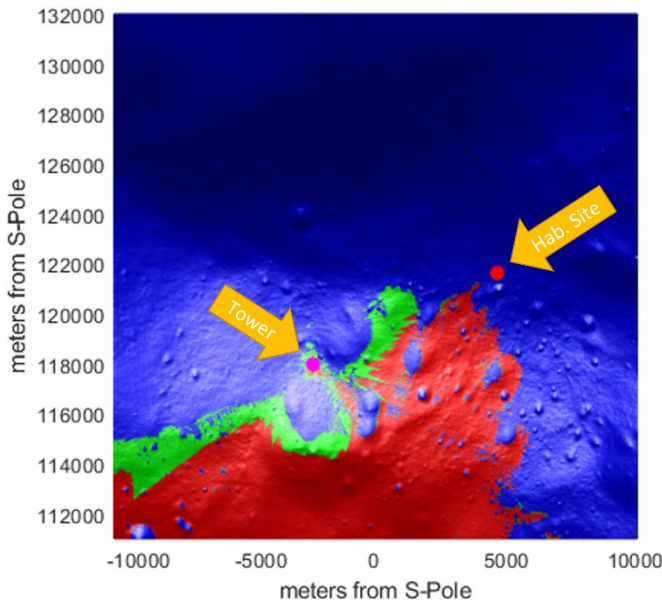
The best coverage of the area is evaluated by the percentage of the total area that has LOS to the tower locations. The examined tower locations and notional habitat/landing site are shown in Figure 4. The large blue point indicates the habitat/landing site and green points illustrate the grid of potential tower locations over the region of Malapert Massif.





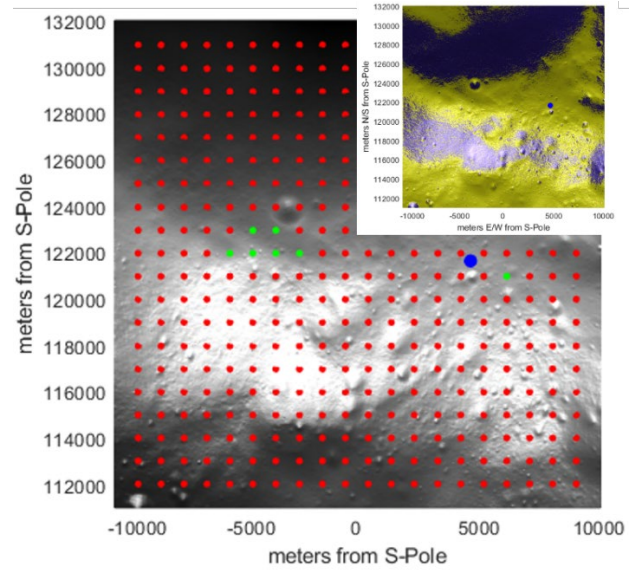
**Figure 4: Notional habitat/landing site and tower locations.**

For this case, the tower location with the best coverage covers 29.2% (green) of the Malapert Massif region with a 20 m tower and 23.7% of the region with a 4 m tower (red). The coverage viewsheds are shown in Figure 5. The tower is located approximately 8.3 km from the notional habitat site. Note that the tower location while having the largest area of coverage does not have line-of-sight coverage to the notional habitat/landing site. Also, the increase in tower height only provides modest improvement to overall coverage for this specific scenario and terrain characteristics. The use of maximum coverage of a region does not always equate to the best coverage for mission needs. Examined locations must be constrained by mission requirements.



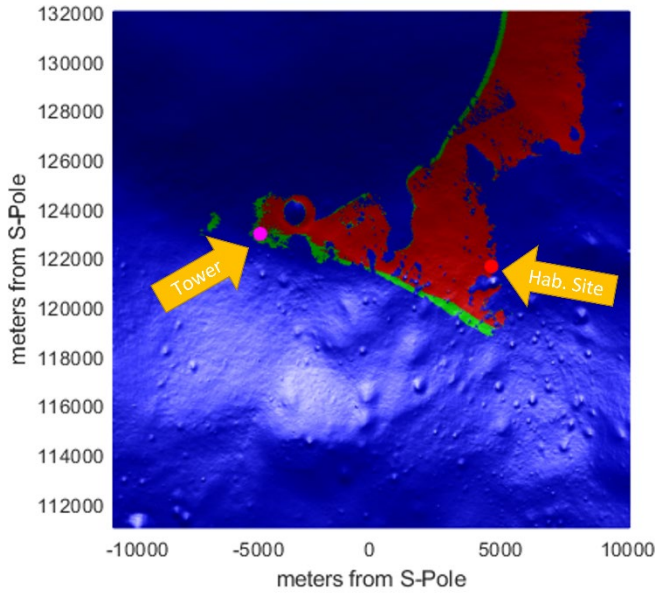
**Figure 5: Viewshed of the Malapert Massif region.**

We now impose that the tower must have line-of-sight to the habitat/landing location as well as lie on a point on the Lunar surface that has a slope less than 20 degrees (i.e., is traversable by the LSR). These are only two of many possible constraints on tower positioning; solar illumination, DTE link availability, lunar orbit link availability, and surface RF link quality are other constraints one could consider. Figure 6 shows the reduction in potential tower locations to consider accounting for line-of-sight and terrain slope, the number of tower locations decreases from 400 to only seven in this analysis. Green points indicate tower locations that meet the LOS and slope constraints, red dots indicate potential tower locations that do not meet the criteria (e.g., line of site to the habitat). The inset figure shows the terrain slope of the region, gold indicates slope less than 20 degrees, small blue dot indicates the habitat site.



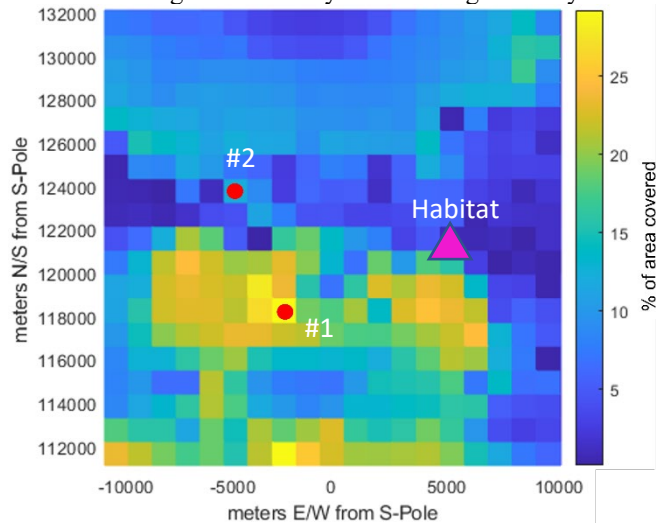
**Figure 6: Reduced tower locations accounting for slope and LOS.**

Figure 7 shows the tower location with the best coverage, while meeting the imposed constraints. Red indicates coverage by both a 20 m and 4 m tower. Green is coverage by 20 m tower only. The tower is located approximately 9.5 km from the notional habitat site. The site covers 12.1% of the Malapert region with a 20 m tower and 10.6% of the region with a 4 m tower.



**Figure 7: Viewshed of the best examined coverage of the Malapert Massif region considering tower location constraints.**

Further analysis of each tower location's coverage (regardless of constraints) was compared to examine the sensitivity of surface coverage to the exact tower placement. Figure 8 illustrates by color coding each tower location with the total % of coverage from that tower (all 400 locations). Tower #1 indicates the location with best coverage of the region (results from Figure 5). Tower #2 indicates the location with best coverage that also includes line of site to the habitat (results from Figure 7). One will notice that the tower location color corresponds to coverage percentage of the region; tower site #2 is light blue or approximate 12%, while tower location #1 is yellow or 29% (higher coverage % but does not have line of site to habitat). Since landing inaccuracies may have significant impacts on the specific landing site, overall coverage from a tower will be dependent upon the locations and could change considerably with landing accuracy.



**Figure 8: Location coverage sensitivity for a 20 m tall tower.**

Due to rough terrain, movement of a tower  $\pm 1$  km could have severe impacts to tower LOS coverage, and therefore mission success. Thus, a system capable of moving and optimizing its location reduces the risk of communication coverage inaccuracies on the Lunar surface.

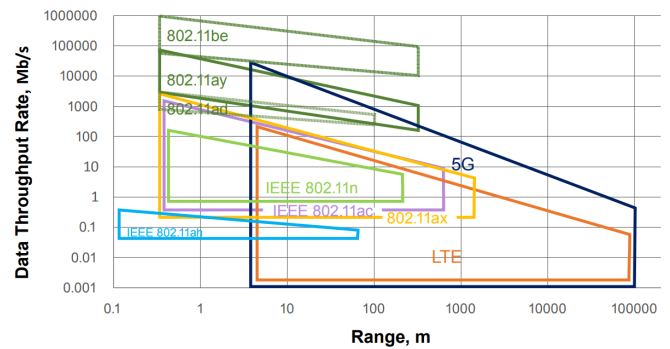
#### 4. Considerations for a Lunar Surface Network

3GPP standards-based networks, specifically 5G New Radio (NR), are viewed as a candidate option for the implementation of a Lunar Surface Network and have been a topic of research and discussion for future Artemis missions [5].

A 3GPP based network offers many options to customize, adapt, and upgrade the surface network and enhance interoperability among service providers and users. 3GPP architectures are complex and there is an open trade space available to provide optimal service for Lunar mission needs. For example, the data rate (Mbps) of a 5G NR channel is

$$10^{-6} \sum_{j=1}^J \left( v_{\text{Layers}}^{(j)} \cdot Q_m^{(j)} \cdot f^{(j)} \cdot R_{\text{max}} \cdot \frac{N_{\text{PRB}}^{\text{BW}(j),\mu} \cdot 12}{T_s^\mu} \cdot (1 - OH^{(j)}) \right).$$

The channel data rate capacity is a function of multiple system parameters, including the number of MIMO layers ( $v_{\text{Layers}}^{(j)}$ ), bandwidth (number of available resource blocks,  $N_{\text{PRB}}^{\text{BW}(j),\mu}$ ), carrier aggregation ( $j$ ), and modulation and coding ( $R_{\text{max}}$ ) [6]. The modulation and coding scheme is adaptive and dependent on the SINR of individual receivers in the network and drives the data rate vs range comparison shown in Figure 9.



**Figure 9: Data rate vs range for 3GPP and Wi-Fi systems [7].**

While 3GPP systems offer farther ranges, simpler Wi-Fi systems remain a consideration for shorter range, localized communication. Wi-Fi products are widely utilized terrestrially with a large COTS provider base, very high data rates, and can be operated at 2.4 GHz or 5 GHz [7]. An older Wi-Fi (802.11n) standard has seen heritage usage on the International Space Station.

The latest releases of 3GPP have functions defined that allow for other radio access networks to interface with a 5G core network. These are the Non-3GPP Interworking Function (N3IWF) and Trusted Non-3GPP Gateway Function (TNGF), for non-trusted and trusted networks respectively. This allows for networks, such as Wi-Fi, to integrate into a complete surface network alongside a 3GPP 5G/NR system [8].

## 5. Conclusion

As NASA and its international and commercial partners look to develop and explore the lunar surface, an interoperable surface network for communications and navigation among surface elements is essential. There are a variety of surface user communication needs including: telerobotic vehicle command and control, science instrument data, voice, and video. Navigation needs include knowledge of one's position on the surface to move about and return safely to vehicles, and to record the position of samples collected. These needs all rely on the surface network services. One approach to enhancing the surface network is adding lunar surface relays (LSR) that provide 3GPP-based surface network and relay data to Earth via orbital relays or direct with Earth.

This paper discusses an approach to provide a 3GPP/Wi-Fi surface network terminal (e.g., base stations, access point) for communication and navigation services on dedicated platforms. The study assessed stationary and mobile concepts and alternative methods for power generation including solar array and radioisotope thermoelectric generators each with battery storage. Various operational concepts were considered for both sunlit operations and shadowed operations and survival during the long lunar nights. Solar array-based terminals provided more power during sunlit operations, while RTG provided stable levels of power through the lunar night. Array-based systems relied on batteries for minimal functions throughout shadowed periods.

The analysis illustrates the challenge of the lunar terrain and coverage of the surface from terminal locations and tower heights in the vicinity of a lunar habitat. Coverage from towers within 20km of the habitat provide a maximum of 29% coverage of the region from any single tower location and only 12% coverage if coverage of a particular site (e.g., the habitat site) itself is required.

While stationary platforms had lower mass than mobile platforms and were less complex, they offer more risk to landing inaccuracy due to inability to change their location. Further, stationary terminals are best suited for single mission use. Mobile platforms, remotely operated from Earth or Gateway, offered more versatility and flexibility than stationary platforms with the ability to move and recover from missed landing locations or to optimize coverage for continued exploration over many missions.

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