# 3GPP Mobile Telecommunications Technology on the Moon

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*Abstract*— **Under NASA's Artemis program, NASA is planning to send astronauts back to the Moon in the next couple of years. Near term missions will be analogous but much more sophisticated versions of the last couple of Apollo missions. However, unlike Apollo, this time NASA intends to put the infrastructure in place to support long term human presence and eventual industrialization of the Moon. To make this vision a reality, NASA plans to collaborate with commercial and international partners as much as possible as opposed to developing, building, and operating equipment on its own. Lunar infrastructure will eventually be built over time by many organizations, public and private, to support sustained human exploration, science, and industrial activities. Obviously, this vision for the future will be impossible without a robust lunar communications and navigation system that can support many users with varying degrees of services. On Earth, most people are very familiar with the 3rd Generation Partnership Project (3GPP) 5G mobile telecommunications technology. NASA's Space Technology Mission Directorate and NASA's Space Communications and Navigation office would like to see a lunar communications and navigation network with similar capabilities to the cellular communication networks most of us enjoy today. Building such a network will require participation by many organizations. This paper will provide an overview of NASA's interest in using 5G and beyond on the lunar surface; it will also describe current work based on 3GPP standards within NASA or funded by NASA, such as Nokia's upcoming Tipping Point demonstration of 4G / LTE on the lunar surface.**

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## 1. INTRODUCTION

With the Artemis program, NASA will establish a long-term human presence on the Moon. Lunar activity will also include scientific research and eventually commercial operations. This sustained growth in lunar activity will require robust communications, navigation, and networking capabilities. NASA's Space Communications and Navigation (SCaN) office has developed the LunaNet [1] architecture to meet these needs.

LunaNet will leverage innovative networking techniques, standards, and an extensible framework to rapidly expand network capabilities at the Moon. This framework will allow industry, academia, and international partners to build and operate LunaNet nodes alongside NASA. These nodes will offer four distinct services to missions: networking, navigation, detection and information, and radio/optical science services.

LunaNet does not represent a specific implementation of an architecture but rather a set of ground rules by which each provider or user of services can interface within that set framework. These users and providers of services include U.S. and international governments, universities, and commercial partners. For example, NASA's Lunar Communication Relay and Navigation System (LCRNS) [2] intends to provide navigation and communication services at the Moon with an architecture and implementation which is different from the European Space Agency's (ESA) Moonlight program [3]. However, both systems will be compliant with the overall LunaNet architecture and standard, and thus users will be able to interface with and benefit from services from both programs. In addition, LunaNet includes standards for service provider-to-service provider interfaces as well as time and reference frames. These are crucial building stones to ensure that missions at the Moon have a common language by which they communicate information akin to the standards we now have on Earth.

For lunar navigation, the LunaNet architecture will provide missions with access to key measurements necessary for onboard orbit determination and guidance system operations or surface positioning. A key element of the navigation component of LunaNet is a constellation of satellites in lunar orbit providing position, navigation, and timing (PNT) services. The number of satellites needed at the Moon can be built up over time as needed to meet navigation and position locating requirements. Various NASA studies have indicated that lunar PNT satellites are absolutely required, though questions remain as to how many and in what orbits.

Some of those PNT satellites could be enhanced with communications relay services. This capability will be critical for exploring and operating in areas where direct communications to Earth are not possible, such as the Moon's far side and large portions of the polar regions. Furthermore, hills, mountains, and craters can also block line-of-sight communications. A network of lunar relay satellites will be a critical component of any robust lunar communications infrastructure. As in the case of satellites providing PNT service, the exact number of communications relays and their orbits still needs to be determined.

While it is technically possible that surface-to-surface communications could be provided via lunar relay satellites for a small number of users, that solution does not scale well as the number of users increases dramatically. Scalability is a very important factor and is specifically called out in the Lunar Infrastructure (LI) Objectives in the "Moon to Mars Objectives" [4] released by NASA in September 2022. These are high level objectives to guide NASA in making architectural decisions. LI Objectives 2 and 3 are germane to this paper:

> LI-2: Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs
>
> LI-3: Develop a lunar position, navigation and timing architecture capable of scaling to support long term science, exploration, and industrial needs

With these high-level objectives in mind, the LunaNet architecture thus calls out the need for a lunar surface wireless network to augment the orbital communications and navigation infrastructure. NASA can take advantage of technologies in use on Earth for this lunar surface wireless network. Specifically, 3GPP cellular technology and standards would meet NASA's needs today and for the foreseeable future [5]. The first step is a demonstration of the technology on the Moon.

## 2. ARTEMIS INFUSION

The Nokia Bell Labs Lunar LTE Tipping Point mission scheduled for 2023 will operate a non-critical, 4G/LTE system (release 12) in a lunar south pole environment. The system will radiate in a 20 MHz channel in Band 3 (1710-1785 MHz uplink, 1805-1880 MHz downlink), and it will demonstrate communication from a 4m-tall base station (BTS) mounted on an Intuitive Machines (IM) lander (Figure 1) to user equipment (UE) on each of a 1m-tall rover from Lunar Outpost (Figure 2) and a free-flying "hopper" provided by IM as part of a companion Tipping Point project. The system itself has been hardened for operation in the lunar environment, including lunar radiation levels, but it is not considered "rad hard" for high-criticality applications. Indeed, reset counts due to radiation-induced errors inform one of the key performance parameters governing success of the Lunar LTE TP project.

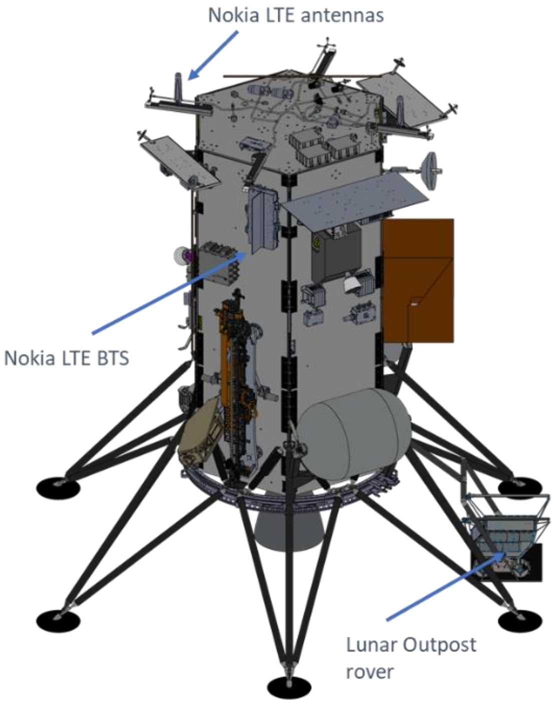

**Figure 1. Intuitive Machines lander with Nokia LTE BTS and Lunar Outpost rover (stowed configuration).**

In addition, the BTS and UEs are not designed to live through the lunar night. This limits overall mission duration to a single lunar day, imposing a maximum ~2km traverse distance for the rover. Moreover, long-term spectrum approval for Band 3 use on the lunar surface is not likely given radio astronomy concerns below 2 GHz. Any future system fielded in support of Artemis missions would probably necessitate a change of band to align with recommendations from the Space Frequency Coordination Group (SFCG), described further in Section 4.

Therefore, while the Tipping Point experiment will raise the overall Technology Readiness Level (TRL) for 3GPP solutions on the lunar surface, it will not produce a hardware solution that can be directly ported to meet Artemis mission requirements for high-criticality wireless traffic, such as extra-vehicular activity (EVA) crew audio. Further work must be done on lunar 3GPP solutions to harden them for the lunar environment (including radiation), modernize them to a more recent 3GPP release (e.g., 5G) to ease the long-term maintenance burden, characterize system operation at longer distances and frequencies on a path to regulatory approval, and begin demonstration 3GPP infusion into Artemis EVA concepts of operation. Critically, data gathered on system performance must be analyzed to build models for RF propagation on the lunar surface to inform development of an emulation capability necessary for infusion of 3GPP into mission-critical Artemis applications (Section 3).

**Figure 2. Lunar Outpost rover with Nokia UE and deployed rover antennas.**

We envision an onboarding process for lunar 3GPP that begins gradually, starting with non-critical uses in ambulatory EVAs and building toward more critical applications in rover-assisted EVAs, approaching the point where 3GPP could be used as the primary communications architecture for all EVA activities. It should be emphasized that this path is notional and may vary greatly based on programmatic needs, timelines, and budgets. This path also begins with an understanding of the Artemis Exploration Extravehicular Activity Services (xEVAS) suits as instantiated in the government reference design – the Exploration Extravehicular Mobility Unit (xEMU). xEVAS vendors are under no obligation to adhere to the xEMU design and may propose alternative solutions. Under the xEMU design, critical EVA audio is handled with a custom, legacy five-user time division multiple access (TDMA) radio operating in a UHF band. The UHF audio radio allows users to communicate with each other and a host vehicle - either the Human Landing System (HLS) lander or the Lunar Terrian Vehicle (LTV) unpressurized rover. Non-critical video is provided by a 5 GHz Wi-Fi radio which is hosted by a wireless access point (WAP) on either the HLS or LTV. As currently understood, walking EVAs have a range limit of 2 km from HLS, and LTV-assisted EVAs have a range limit of 10 km. Depending on final HLS and xEVAS configurations, it is unlikely that Wi-Fi coverage will extend 2 km radially around the HLS, and UHF audio coverage may be incomplete as well. Neither will cover the 10 km radius available to LTV traverses at the maximum range from HLS. This presents an opportunity for an early, non-critical infusion of 3GPP as a range extension option for walking EVAs. Presuming solid UHF audio coverage out to the maximum walking EVA limit, crew can carry a small 3GPP/Wi-Fi hotspot in their toolkit. If their xEVAS Wi-Fi radios are configured to access the hotspot as an alternative to the HLS WAP, this would allow them to continue sending non-critical video via the 3GPP network when they have exceeded the range of the HLS WAP. The system could further be used as a backup to the critical UHF audio system – either by relaying suit audio through the xEVAS Wi-Fi radio in a contingency situation or adding a UHF audio client radio to the 3GPP/Wi-Fi hotspot (necessitating a more custom hotspot implementation).

The latter approach has the advantage of providing more TRL advancement for the envisioned first operational infusion of 3GPP into the Artemis architecture: providing a surface link between the HLS and LTV. Under the current paradigm, the LTV will host xEVAS audio/video when the crew have left the range of HLS during an LTV traverse. As the LTV moves across the lunar surface, it will be responsible for relaying that data back to Earth. It is not currently expected that lunar orbital relays or direct-to-Earth paths from the LTV will be able to support voice and video traffic for all phases of the LTV's operation – for example, sending video from the LTV when it is driving between waypoints. There is therefore an opportunity for 3GPP to provide a pipe to transport LTV data – both non-critical video and mission-critical audio – over the lunar surface back to a BTS located either on the HLS or on a dedicated communication terminal in the operational area.

The ability to provide this 3GPP relay service to LTV also provides another immediate opportunity to address an open communication issue: providing crew member audio and video during a walk-back from a malfunctioning LTV. The 10 km traverse limit for LTV is set such that crew members can safely walk back to HLS before depleting their consumables should their rover break down at the edge of its range envelope. But since the LTV hosts all crew member communications in the current model, an alternate means of encapsulating this traffic for transport back to earth will be required. Again, relay through orbital assets is likely to be limited (and may require equipment too large to carry in a contingency EVA), so 3GPP could provide an alternative path for that data. Though we would anticipate the link to be more challenging to close at range to an EVA crew member than to a rover, 3GPP is well suited to prioritizing certain kinds of traffic (e.g., critical audio) to use available capacity, so we should be able to design a contingency capability that maintains crew audio while filling any additional capacity with crew video to enhance situational awareness.

This approach, should it provide a successful add-on solution to an xEMU-like architecture, could be migrated over time to a native-3GPP EVA suit design that eschews the legacy UHF radio.  Details of suit-to-suit side link still need to be worked out, and they may lean on vehicle-to-everything (V2X) / Proximity Services (ProSe) in the 3GPP architecture or a mission-critical implementation of the Wi-Fi radio we would still expect to reside in xEVAS.  Re-architecture of EVA audio in an Internet protocol (IP) framework will also be required, though this follows 20 years of terrestrial audio trending to all-IP solutions.

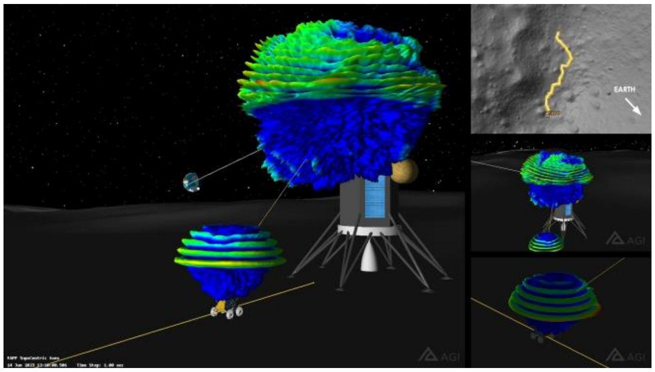

**Figure 3. Simulation of lander-to-rover link shown in AGI STK with incorporated electromagnetic scattering analysis from Ansys HFSS.**

Finally, as described, this initial infusion describes a single-BTS deployment designed to provide the desired service to an LTV at a 10 km cell edge.   Our analysis to date (Section 5) has focused on determining that this network design will provide adequate coverage, given that a single BTS integrated into the HLS or a single, standalone lander will be less complex to field than a multi-BTS network.  Given time, though, we would expect the network to evolve in the direction of multiple, standalone BTS units deployed on fixed or mobile platforms on the lunar surface that remain even when no HLS or crew are present.  Further expansions of the system may be considered, including adding BTS components to the LTV itself to enhance local coverage to native-3GPP EVA suits.  We may also consider enhancing the coverage provided by surface BTS deployments through emerging 3GPP non-terrestrial networking (NTN) applications.  NTN distributes components of the BTS on coordinated, orbiting assets to provide coverage to ground assets that are not in the field of view of permanent surface infrastructure.

## 3. MODELING, SIMULATION & EMULATION LAB

NASA's Glenn Research Center (GRC) is supporting the agency's 3GPP initiatives through the development of a modelling, simulation, and emulation lab to characterize communications system performance in complex environments such as the Lunar surface. This facility, the Multiple Asset Testbed for Research in Innovative Communications Systems (MATRICS), is a modular emulation environment enabling the operation of a real communications system or its digital twin in an accurately recreated, complex, and dynamic RF environment. Through a combination of reconfigurable hardware, channel emulation, electromagnetic simulation, and historical mission data, testing in the MATRICS is intended to reduce mission risk by providing end-to-end link analysis, hardware test and evaluation, verification and validation, model refinement, anomaly investigation, and an overall improved understanding of performance in complex radiofrequency environments. A complementary effort to develop the regolith propagation models for the MATRICS and use them to characterize Lunar 3GPP links is also ongoing under the Lunar LTE Studies (LunarLiTES) project.

Both efforts are strengthened by coordination with closely related agency initiatives, such as those detailed herein, not only to share capabilities between relevant users but to leverage the variety of experience across the agency, industry, and academia.  The MATRICS is envisioned as an accessible and evolving knowledgebase that can utilize the latest research and flight data to refine modelling and simulation. This coordination is particularly essential considering the imminent influx of Lunar propagation data from Artemis and other Commercial Lunar Payload Service (CLPS) missions, which is expected to greatly increase the fidelity of surface propagation modeling as soon as CLPS missions begin landing this year.As a first milestone for the development of its surface emulation models, LunarLiTES is targeting the NASA-funded Nokia Tipping Point demonstration of LTE on the lunar surface mentioned earlier in this paper. Using analogous LTE hardware in conjunction with the emulated Lunar surface environment, the MATRICS will be used to predict and assess performance of the mission's LTE links, and, in turn, flight data from the Nokia demonstration will be used after the conclusion of the mission to refine the Lunar models in the MATRICS and inform future surface network architectures.

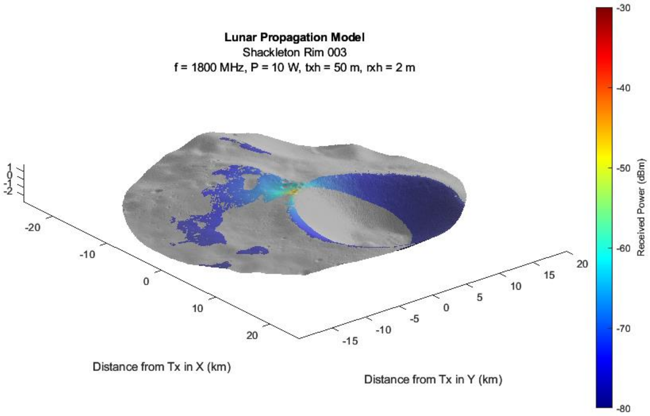

**Figure 4. Example raytracing simulation for a 50 m tall base station on the rim of Shackleton to a 2 m tall user.**

The modeling and simulation capabilities of the MATRICS utilize a variety of commercial tools in combination with custom models. Antenna performance is characterized either by simulation or measurement, then combined with vehicle geometry to simulate as-installed performance using Ansys High Frequency Structure Simulator (HFSS). Measurements as-installed can also be incorporated if necessary using the 7-meter planar near-field range of GRC's new Aerospace Communications Facility. The effects of local terrain are also considered in the scattering analysis for surface elements, utilizing high resolution digital elevation maps (DEM) from the Lunar Reconnaissance Orbiter (LRO) and dielectric models of Lunar regolith. LRO DEM data are also used for pathfinding to generate rover paths consistent with slope and illumination requirements. Path gain and delay spread are used to define the RF channel model and are characterized through a combination of HFSS, Wireless Insite, and MATLAB propagation model simulations. The orbital dynamics and relative motion of the systems are determined in STK, which is also used to incorporate the simulations of antenna performance and the RF channel.

From STK, the complete model is translated into the channel emulator, a Keysight Propsim F64, which drives the emulation environment for the radios and other hardware under test. In the case of the Nokia Tipping Point emulation, LunarLiTES is using an LTE Band 3 (1.8 GHz) Nokia Digital Automation Cloud (NDAC) edge computing platform as the closest available commercial, terrestrial analog of the flight hardware. Emulated results of the surface-to-surface LTE link are planned in early 2023, with emulation of direct-to-Earth and orbiting relay backhaul links also targeted for completion in advance of the planned IM-2 launch date of June 2023.

## 4. LUNAR SPECTRUM

Spectrum use of lunar surface 3GPP and Wi-Fi communication networks is a key focus area for NASA working groups. There are currently very few bands allocated for space-to-space use (which lunar surface activity would fall under), let alone space-to-space bands that overlap with commercial 3GPP bands. Therefore, new space-to-space allocations need to be established for lunar mission use. The initial approach towards allocation is to select a modest set of bands that are spread across a wide frequency range to achieve spectrum use diversity in support of exploration, habitation, and industrialization of the lunar surface. NASA fully expects that this initial spectrum allocation for lunar surface communications will expand with future requests as lunar infrastructure grows, more international partners/users become active, and more commercial vendors and service providers become involved. This section describes the approach to this activity, current status, and future work.

3GPP technology is designed to expand into, and utilize, any spectrum band that becomes available in the terrestrial market, and this approach of targeting any frequencies could be extend to the lunar regime as well. However, commercial implementation cost will be the lowest if terrestrial 3GPP bands are available to use on the lunar surface, and modification to the 3GPP standard is avoided. Band selection also needs to be balanced with protecting existing bands for space communication, space navigation, and radio astronomy, which are critical to lunar operations.

3GPP Release 16, which is the current baseline for LunaNet [6], has many frequency bands specified for use. Teams at Simon Fraser University and University of Colorado Boulder have cataloged these bands and ranked them by important specifications and features such as channel bandwidths, carrier aggregation properties, functional attachment like V2X/Sidelink, and more, as well as ranked them by commercial and government usage matching with the lunar environment and mission set. The latter is very important since the 3GPP specification itself is vast in implementation options and features. Choosing bands or weighting them based upon items that are not used regularly in commercial networks (ProSE is an example of a feature not well developed by industry to date) should be avoided. This prioritized listing was then overlayed with FCC/ITU space-to-space frequency bands (especially those specified by LunaNet), ITU-R RA.479-5 [7] for Shielded Zone of the Moon (SZM) considerations, and ITU-R RA.314-10 [8] for specific radio astronomy bands of interest. The non-overlapping 3GPP bands of interest were then taken to the Lunar Spectrum Management Team, and a compromise was reached. The resulting list was proposed and mostly accepted by the SFCG, which is captured in SFCG Recommendation 32-2R4 [9]. The general 3GPP band listing is extracted here to Table 1.

**Table 1. Summary of SFCG 32-2R4 recommended bands for 3GPP use**

| Ref. # | 3GPP Band | Frequencies (MHz) |
|---|---|---|
| SFCGb1 | N7/38/41 | 2.5035 – 2.6550 |
| SFCGb2 | N48/77/78 | 3.5000 – 3.8000 |
| SFCGb3 | N46 | 5.1500 – 5.8350 |
| SFCGb4 | N47 | 5.8550 – 5.9250 |
| SFCGb5 | N258 | 25.2500 – 25.5000 |
| SFCGb6 | N257/258 | 27.2250 – 27.5000 |
| SFCGb7 | N257/261 | 27.5000 – 28.3500 |
| Note: Ref. # labels will be used to state bands for simplicity in text below. | | |

Overall, this recommendation has a very large amount of total bandwidth. However, SFCGb3 is shared use with Wi-Fi, and SFCGb5/6/7 are not expected for use until larger networks and more complex use cases demand very high rate user links and multicellular backhaul crosslinks. The technology being developed to operate in these high frequency bands is also less mature. The band recommendations also need to accommodate a variety of implementations and international users, which will likely lead to more spectrum use for redundant and protected channels. It is also important to note that the SFCG frequency ranges do not exactly match the 3GPP band frequency ranges, and therefore will have a reduced number of channels within the recommended bands. Band subsets was one part of the spectrum compromise.

An important omission to this listing is a low band below 2 GHz, as these bands are typically used for search and rescue, long range cells, and cells in rough terrain similar to the lunar south pole. This was done because the initial spectrum request was targeted to the whole lunar surface, including the SZM which *limits*, not prohibits, band use below 2 GHz. Part of the 2023 NASA effort in preparation for the next SFCG meeting will be preparing an additional request for a UHF band of operation stipulated for use outside of the SZM. Further thoughts on protection of the SZM with a notional Radio Restricted Zone of the Moon which still allows a robust surface wireless network are contained in Appendix A.

Initially for near term mission deployments, primary use is expected in SFCGb1. SFCGb1 was selected to fit within SZM restrictions of 2-3 GHz communication use, and because it is the largest available contiguous 3GPP band in this spectrum region. N7 and N41 also have good 3GPP carrier aggregation specifications within their bands, and with the other bands in Table 1. Also, N7 uses frequency division duplexing (FDD) and N38/41 use time division duplexing (TDD). This dual technology coverage of SFCGb1 allows a mission to select implementations with different SWaP-C and performance balances to meet their mission needs.

Unfortunately, most of the N7 FDD downlink band channels overlap with an important radio astronomy band from 2.655-2.7 GHz, and a LunaNet navigation band at 2.484-2.5 GHz has restricted the bottom frequency of B1 to protect sensitive navigation receivers which will likely be collocated with 3GPP equipment. This only yields 30 MHz of usable channels. The NASA Lunar Spectrum Management Team will be running studies leading up to the next SFCG meeting to review interference issues with these neighboring waveforms and suggest band updates, channel usage restrictions, or out of band emissions restrictions. The authors of this paper are working directly with this team, and the LunatNet navigation team, to provide analysis input and work out any compromises needed. Hopefully this study will lead to band expansion supporting 35 MHz of bandwidth in N7 and produce clear guidance on out of band emissions and rejection.

As these spectrum recommendation items are analyzed and studied, we will also support the Lunar Spectrum Management Team in developing materials to support the national and international request for spectrum allocation. The ultimate goal is to have the SFCG recommendations become space-to-space allocations before Artemis V operations (which is expected to be the earliest *operational* use of 3GPP on the moon). To be timely and successful in the spectrum allocation process an ITU World Radio Conference (WRC) 2023 action item is being developed. The action proposes to study and analyze the SFCG recommended bands, so that specific allocations can be given at WRC 2027. Concepts of link, network, and mission operations will be developed to support these specific frequency band requests, as well as support the large bandwidths. Spectrum needs for precision position, navigation, and timekeeping (PNT) functions over 3GPP will also be included to support mission needs. University activities under this program have looked at single link scenarios, up through small single cell networks with multiple user scenarios, over the past two years. These findings and additional work in 2023 are discussed in the next section.

## 5. UNIVERSITY ACTIVITIES

### *SFU & CU-Boulder*

Teams at Simon Fraser University (SFU) and University of Colorado Boulder (CU-B) have been providing information and analyses for the 3GPP lunar surface actives, in parallel with their significant efforts in supporting CCSDS books for 3GPP and Wi-Fi technologies via standards analysis, laboratory testing and multi-kilometric mountain terrain field testing [10]. SFU expertise in 3GPP field deployments supporting both US and Canadian government agencies for spaceflight studies and for first responders have been crucial in lunar surface networking efforts. The deployment environments of the Canadian Rockies and a Shackleton-class Arctic Circle impact crater mimic the lunar south pole topography and provide critical field experience and data to their analyses. This experience in the field and with vendor equipment was invaluable in this past year of effort in providing information and recommendations on 3GPP bands used to support the spectrum requests to the SFCG as discussed above. Underlying these spectrum band recommendations is an analysis of the lunar regolith based upon historical and new (Lunar Reconnaissance Orbiter (LRO) [11] and Chang'E [12]) lunar surface measurement data, and link analyses that include these conditions under multiple 3GPP equipment configurations.

The lunar surface structure has been known to behave very differently than situations we see on Earth, due to high regolith transparency underlaid by complex reflective topography not captured by lunar terrain models. This has been known since Apollo missions and looks to be more extreme than previously expected given new LRO and Chang'E data recently collected, especially at the south pole location of interest. Transparency goes as 1/loss tangent, and, due to low conductivity vs. permittivity, loss tangent is very small on the Moon compared to Earth. This means that lunar RF paths do not see the surface as a distinct transition, but as a "dirty glass" tens of meters deep, including embedded objects with different RF properties. Quasi-static models such as 2-ray, DEM LR, ray-tracing, and other models breakdown under these conditions, because the surface interaction region is extended over more than a wavelength and cannot be modelled via a simple solid surface. Regolith RF paths are better conceptualized and modeled as a volume of particulate oscillators.

SFU has developed a statistical link modeling approach which includes these different lunar regolith properties, along with Doppler spread conditions (example in Figure 5) and multipath fading and delay spread effects (example in Figure

6) supported by the extensive field testing. Various example conditions are pointing towards trends which help the spectrum selection process (e.g. subcarrier spacing of 15 kHz and channel bandwidths ≤20 MHz may yield better multipath performance), but the largest impact is bounding the various link margin allocations for the unknown highly variable conditions and better informing the use of modeling tool input and results as discussed in the next section. Until more measurement data is available from the Nokia TP mission, regions of transition between line of site (LOS) and non-LOS (NLOS) need to be treated very conservatively, and not as a high reliability coverage area, for these ray trace modeling tools.

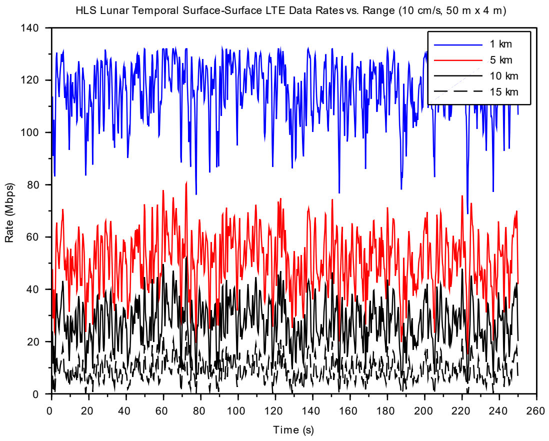

**Figure 5. Example link data rate impacts of Doppler spread at 10 cm/s motion over different UE ranges with 50m and 4m antenna heights.**

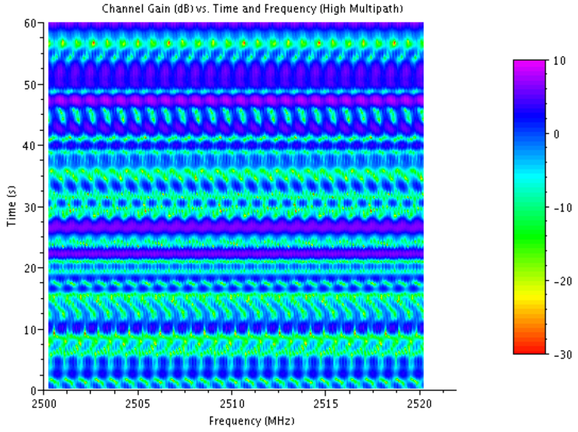

**Figure 6. Example link gain variation for multipath effects under lunar surface conditions.**

SFU used their statistical link model to create estimates for link capacity over a cell range for different spectrum and equipment configurations, shown in Figure 7. These links do not include specific *surface* terrain, which is modeled as the lunar radius sphere. Links capable of supporting two or more video channels for a *single user* out to 10 km of range are very reasonable given good terrain. Beyond that point, given the antenna heights and surface curvature, the link effects discussed above begin to dominate over free-space path loss.

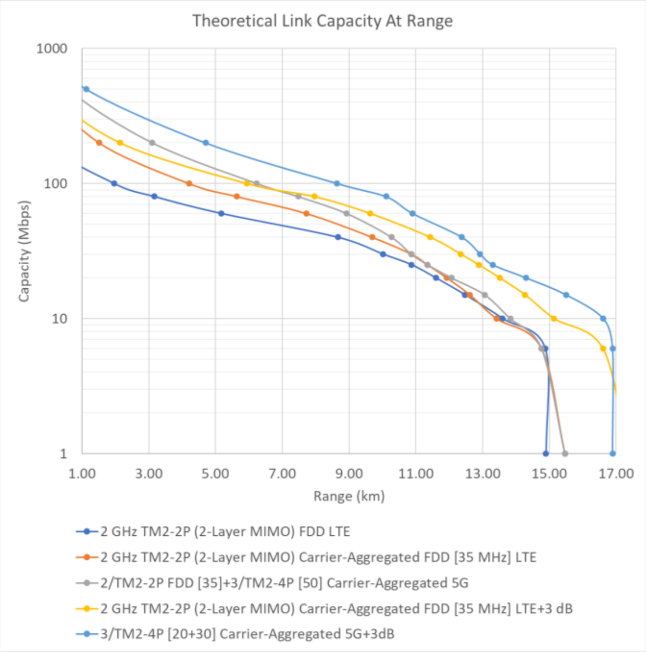

**Figure 7. Theoretical mean link capacity over cell range for different 3GPP equipment configurations.**

Given this limited set of configurations, several trends were observed from the results. Additional uplink path gain (antenna gain or UE Tx power) and more spectrum usage (via wider channels or through carrier aggregation) does increase LOS capacity, but it has diminishing returns in total coverage range and enhancing capacity outside of LOS conditions. Cases beyond the ones shown in Figure 7 were modeled, and as expected configurations with beam forming and/or UHF carrier aggregated with 2.5 or 3.5 GHz outperformed others. This yields options for throughput and coverage improvements beyond adding more BS cells to the network. However, the diminishing returns for SWaP-C and spectrum applied, and uncertainty in RF propagation, all point to the need for a multicellular network to achieve high quality of service reliability, and coverage.

Related to the surface RF propagation link analyses efforts is a recommendation to prevent contamination of the SZM discussed in Appendix A. Given these results, including the wide variety of spectrum, power, and antenna height considerations, there is no concern of SZM contamination from 3GPP network activity at the lunar poles.

### *JHUAPL*

A team at the Johns Hopkins University Applied Physics Laboratory (JHUAPL) has also been providing information and analyses based upon their experience in fielding deployable single-cell networks in contested spectrum environments for the Department of Defense and building upon earlier lunar study work for NASA [13]. Their effort started with supporting the Lunar Spectrum Management Team with basic information on 3GPP5G waveforms, links, and operations in relation to spectrum use. Laboratory testing of high-tier 3GPP equipment has shown out-of-band emissions well below 3GPP specifications in lunar recommended bands. These measurements, as well as equipment capability testing, have supported the SFCG expansion of spectrum use by reducing interference concerns in neighboring bands (SFCGb1 discussion in the Spectrum section). Unit testing of gNodeB/BTS and user equipment (UE) will continue at APL to support spectrum allocation request activities, until NASA obtains more 3GPP equipment.

The primary work that JHUAPL performed is setting up a lunar surface propagation model and fusing it with expected link models/budgets for the physical and data-link layers of the 3GPP protocol stack. The latest high-resolution LOLA topography data from the NASA Planetary Geodesy Data Archive was imported into Wireless InSite (a 3GPP ray-tracing Vertical Plane Model tool from Remcom Inc.) for a 27.5 km square area of the Shackleton Crater connecting ridge. The import resolution was set to 55 m for reasonable processing time, and lunar parameters were set for atmosphere (off), curvature, and regolith electrical properties. As better information develops from missions like Nokia's Tipping Point, these electrical parameters can be adjusted. The resulting path loss results yield maps like the one shown in Figure 8, which was generated with 30 m BTS height and 3.5 m UE height as a reasonable representation of a lunar lander tower and Lunar Terrain Vehicle (LTV) user. Note that this site was not chosen for optimal network coverage, and more work is needed to select these sites for single or multiple mission needs.

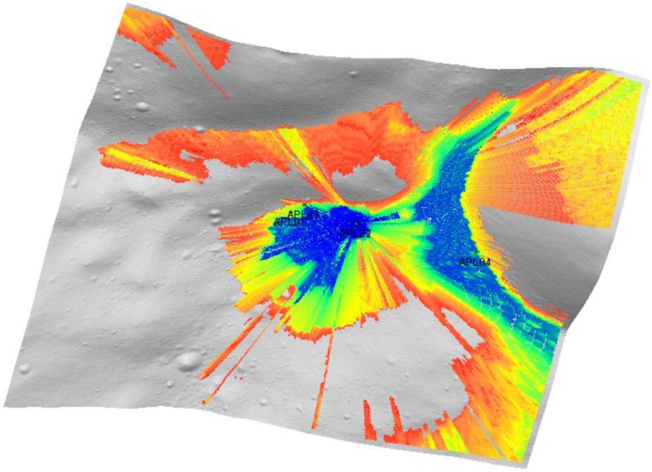

**Figure 8. Example path loss heatmap overlay of lunar terrain given a possible BTS site.**

The path loss data was then run through a Matlab script to estimate the link throughput. The key link parameters for this model are listed in Table 2, and can easily be adjusted as needed for different equipment configurations. The resulting throughput result estimates are displayed in Figure 9. It is very important to note that this estimate is calculated for a single UE topology, and the addition of other uses will reduce these estimates accordingly.

**Table 2. Link parameters used in representative scenario to estimate of throughput capabilities**

| Parameter | Scenario Value |
|---|---|
| Noise Temperature | 250 K |
| Channel BW | 20 MHz |
| TDD UL/DL split | 80/20 % |
| BTS Tx Power | 50 dBm |
| BTS & UE Antenna Gain | 0 dBi |
| BTS & UE Noise Figure | 2.5 dB |
| UE Tx Power | 23 dBm |

Given the uncertainty in the lunar regolith electrical properties, margin was allocated to each of these parameters/items: Wireless InSite inaccuracies, low terrain resolution, surface roughness, electrical conductivity, and commercial equipment application to the space environment. The largest allocated margin (~8 dB) is applied to the Wireless InSite estimates which have been compared to real world measurements over various site field tests on programs. Total margin represented in the throughput plot of Figure 9 is 18 dB. Note that these margins have been estimated based upon statistical analyses, and more work is needed to combine these items into a reasonable margin value given a specific probability threshold. For this effort these values were chosen and combined in the most conservative methods, so the throughput estimates in Figure 9 are conservative and will most likely be much higher on average. It is important to mention again that these estimates do not account for aspects of the networking layer and above, which will reduce single UE throughput depending upon the network topology and specific vendor core implementation.

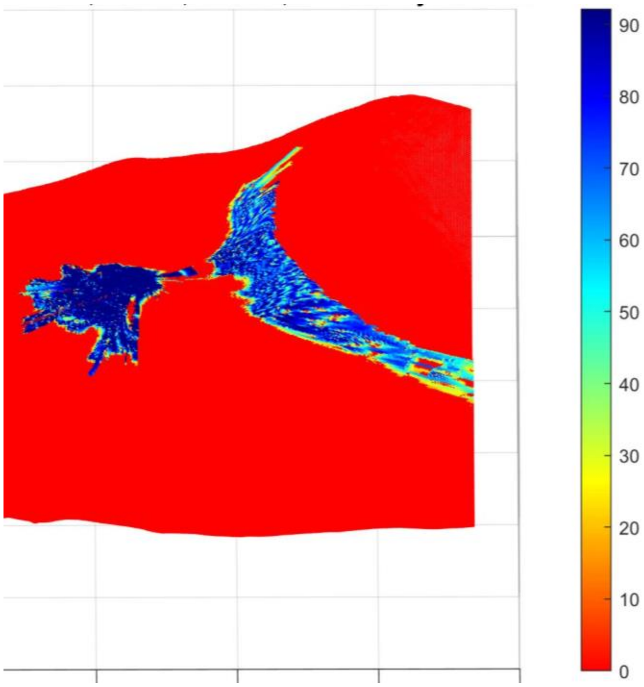

**Figure 9. Example uplink throughput heatmap overlay of lunar terrain given a possible BW site (scale in Mbps).**

Results from different configurations (BTS/UE locations and parameters) show that a very wide area of coverage is not possible with a single BTS given the lunar south pole terrain. However, this throughput data has not yet been quantitively overlaid with topographical data to highlight terrain areas that are inaccessible via LTV or walking, or not of primary interest. Broadly speaking, known and estimated areas of interest for near-term missions should achieve a very high percentage of coverage from a single BTS with basic 3GPP equipment. The important benefit to this 3GPP link/network, as Figure 9 shows, is the high throughput when coverage is available, allowing support for multiple video, audio, and data streams, even with multiple users.

Using different link parameters demonstrates that there are ways to improve throughput, and marginally increase areas of coverage. These findings align with the SFU findings above. Note that the NASA use case is opposite of the typical terrestrial case in terms of UL/DL data traffic, hence the ratio setting in Table 2. UE Tx power, and BW/UE antenna gain all have a large impact on throughput but show diminishing returns on the edges of the coverage area, and little to no expansion of the coverage area itself. BTS and UE height show significant impact on coverage area, with a steep loss in coverage below 20 m of BTS height for the terrain and locations modeled. Under these same conditions, there is not much improvement in coverage area with BTS heights above 50 m.

JHUAPL has also been capturing position, navigation, and timing (PNT) aspects of the 3GPP specification and vendor capabilities. It is quite clear that a single BTS solution like the example shown above will not be able to provide a 2D/3D fix sufficient for lunar navigation. However, PNT capabilities are built into the 3GPP standards, and as equipment is added to the network (within a BTS or with multiple BTSs) the PNT measurement capability and standalone 2D/3D fix capability improves without the need to modify existing equipment (standard navigation measurement techniques like TDOA, AOA, and RTT are built in). There are also options available within the standard for addition of beacons and/or receivers to the network, that are much lower complexity than a full BTS, that can dramatically enhance the PNT capabilities. This area of lunar 3GPP network capability needs more study to select reasonable implementation solutions that best enhance the LunaNet architecture in a phased approach as lunar infrastructure develops, without driving deployment or mission cost too high.

Near-term missions using single BTS topologies will not be able to achieve standalone 2D/3D fix solutions with the 3GPP link(s), but these links will be able to contribute to the larger navigation solution for each UE. In the example scenario shown above in Figure 8 and Figure 9, when a UE is in the covered areas, time can be synchronized between BTS and UE with a precision similar to ethernet PTP (<1 us), and ranging measurements can be made with precision of ~10 meters. This level of measurement and synchronization contributions is impactful to the total navigation solution. Future work in this area will include a modeling overlay of the lunar surface, similar to the throughput heatmap of Figure 9, with ranging accuracy/precision estimates.

## 6. SUMMARY

In the not-so-distant future, there will be a sustained human and robotic presence on the Moon. As called out in NASA's "Moon To Mars Objectives" that was recently published, a robust communications and navigation infrastructure will be required to support and enable this vision. Like the Earth's internet, this infrastructure will need to increase in size and probably complexity as the number of users and applications grow. This "Lunar Internet of Things" will be a combination of networks and services with multiple provider systems, owned and operated by a combination of international and commercial entities. LunaNet is NASA's overall architecture that envisions this robust communications and navigation infrastructure. A key component will be a lunar surface wireless network to support this upcoming sustained human and robotic presence. The authors believe that 3GPP cellular technologies and standards provide the ideal solution for this lunar surface wireless network. A space qualified lunar 3GPP network provides increased sustainable data rates, range, mobility, reliability, and scalability over other wireless technologies such as Wi-Fi, and fills a crucial role in the overall LunaNet architecture to bring the lunar surface closer to Earth.

# APPENDICES

## A. RADIO RESTRICTED AREA OF THE MOON

Given the interest of using 3GPP transmission sites at the lunar south pole and beyond the Earth observable limb, there has been concern with protection of the Shielded Zone of the Moon (SZM). The SZM is defined by the ITU Radio Regulations (RR) Article 22 Section V as:

> *“The shielded zone of the Moon comprises the area of the Moon’s surface and an adjacent volume of space which are shielded from emissions originating within a distance of 100 000 km from the centre of the Earth.”*

100,000 km from Earth allows a significant angle of lunar latitude and longitude to be visible from the potential RF emitters zone into the lunar surface far side, and thus to be excluded from the surface portion of the SZM. The Earth-Moon (centre to centre) distance during the Moon’s orbit around the Earth varies during the year due to the influence of Sun’s gravity on Earth-Moon orbital dynamics and corresponding orbital parameters, ranging from 356,400 km to 406,700 km, which results in an instantaneous (largest 100,000-km zone parallax) angle of 16.00° from the polar lunar limb at closest perigee down to 13.98° at the equatorial limb at furthest apogee, into the far side, that is not shielded by the Moon if the sub-Earth point was at 0°N, 0°W. However, the libration of the Moon, 7.90° in longitude due to orbital eccentricity and 6.68° in latitude due to the Moon’s orbital obliquity, increases the area excluded from the lunar surface portion of the SZM by shifting this parallax shadow during orbital dynamics. If these effects are taken into account, a geometric mean fraction of 30.2% to 31.0% of the lunar surface area is within the SZM, in a roughly ellipsoidal region of the lunar far side within a maximum angle of approximately 66.1° to 68.1° (within limits of modelling presently used in this study) of longitude and 67.3° of latitude of the antipodal point on the Moon from Earth (0°N, 180°W in selenographic coordinates). The full cone-like SZM in space is the prism formed by surface SZM by rays up a point located less than 4,660 km from the lunar centre over the antipodal point.

ITU-R RA.479-5 [7] aligns with this analysis as described in Annex 1 Introduction, where it states the SZM boundary to be “*23.2° beyond the mean limb of the Moon as seen from the centre of the Earth*”. The Figure 10 cross-sectional diagram shows this SZM boundary.

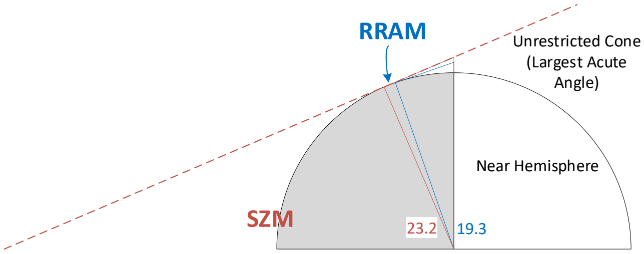

**Figure 10. Diagram of SZM and proposed RRAM.**

The lunar poles are well outside of the SZM, as are 100% of near-side locations that can support direct-to-Earth (DTE) communications. Indeed, the lunar poles, important for human and robotic missions, are over 687 km from the SZM, and even with potential realistic extreme maximum lunar surface line-of-sight of 264 km (5-km mountain to 5-km mountain), it is possible to position transmitters 423 km or more into the far side from the lunar poles, approximately the distance from Pittsburgh to Philadelphia, with no line-of-sight into the surface portion of the SZM. Additionally, no transmitter at 264 km from the surface SZM at an altitude below approximately 20 km above the lunar reference ellipsoid can be received by a spacecraft in the full SZM volume.

To better protect the SZM, and to better understand the impacts of surface network transmitters upon this area, we propose the concept of a RF Restricted Area of the Moon (RRAM). The RRAM range corresponds to anywhere south of 76°S and north of 76°N on the lunar surface on the lunar far side (and anywhere on the lunar near side). Therefore, this allows for wireless surface communications for near-term human exploration-class missions to the Moon in a wide range of frequencies with no impact on radioastronomy in the SZM. Wireless surface communications in the SZM and RRAM can then be restricted to limited bands, with a potential reduction in communications range, data rates, and reliability, to avoid radioastronomy impacts. These restrictions would currently flow from the SFCG Recommendation 32-2 [9].Note that none of the ITU defining documents, nor this analysis, take into account specific surface terrain. This is a reasonable approach for a general guiding surface allocation. Mountains, craters, and trenches do impact RF propagation boundaries, and should be taken into account upon planning specific missions (transmission sites and radio astronomy sites) on the boarders of these areas.

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## BIOGRAPHY

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