INTERNATIONAL COORDINATION AND COOPERATION ON LUNANET SPECTRUM

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Abstract

LunaNet is planned to be the network of networks operated by a set of cooperating organizations to provide interoperable Communications, networking, Position, Navigation, and Timing (CPNT) services to users on and around the Moon based on a framework of mutually agreed-upon standards, protocols, frequency bands and interface requirements. LunaNet follows a service-oriented architecture that is agnostic about the types of organizations that provide services, e.g., government, industry, or academia. LunaNet is open, scalable, resilient, secure, and extensible. To achieve these goals, LunaNet Service Providers (LNSP) must coordinate with each other to define and develop the architecture, to plan initial and evolved capabilities, and to operate their networks. One of the central LunaNet tenets is the use of shared spectrum. For example, the Lunar Augmented Navigation Service (LANS) acts like a Global Navigation Satellite System (GNSS) such as the US Global Positioning System (GPS) or European Galileo but the LNSPs' contributions to LunaNet must use the same frequency band (2483.5 MHz-2500.0 MHz) and transmit the same waveform synchronized by highly accurate clocks so that Users 'see' one virtual network and use the same multilateration algorithm to determine their positions. This necessitates a high degree of spectrum coordination.

NASA's Lunar and Human Spaceflight Spectrum Management Team has been actively supporting development of the LunaNet Interoperability Specification (LNIS), soliciting inputs from spectrum policy and planning experts across NASA, ESA and JAXA. Cislunar spectrum use considerations have been studied and adjudicated within the Space Frequency Coordination Group (SFCG) and inform the ongoing discussion of a lunar communication and navigation architecture within the existing radio regulatory framework of the International Telecommunication Union, leading to the 2027 World Radiocommunication Conference (WRC-27). The frequency plan contained in the publicly released draft of the LunaNet Interoperability Specification reflects the initial phase of exploration (roughly to 2030) defining an optimal set of radio frequencies in appropriately allocated services consistent with WRC-23 decisions for use by known or planned CPNT applications, while striving to maximize coexistence and compatibility amongst cislunar systems and other systems within the near-Earth regime (< 2 million km from Earth). Important considerations include: protection of extremely sensitive receive-only radio astronomy systems on the lunar far side, known as the Shielded Zone of the Moon (SZM); compatibility between Direct with Earth (DWE) communications links and links needed to support relay satellites in lunar orbit with their customer systems on orbit or on the lunar surface; compatibility between multiple lunar surface communications systems and capabilities over varied and challenging terrain and distances; as well as ensuring compatibility and interoperability between navigation systems which either leverage Earth-based or in-situ lunar systems. In addition, the lunar CPNT architecture is envisioned to be the basis – with adjustments – of the future Mars CPNT architecture as we expand into the solar system using Interplanetary Networking (IPN). The second phase of lunar spectrum definition will address planned international capabilities for the next decade that will require action at WRC-27 and beyond. This paper will discuss each of these considerations in more depth and how the current LunaNet frequency plan addresses them.

Introduction

Radio frequency (RF) spectrum is a natural resource of the universe that is used by numerous wireless technologies such as mobile phones, radar systems, and scientific instruments. However, spectrum access is a challenge, as these disparate wireless applications must often share limited portions of the RF spectrum to support their respective operations. This means that spectrum planning decisions (and individual missions' spectrum use decisions) have implications for other users. The conclusion is that users cannot make their plans and architectures unilaterally. The International Telecommunication Union (ITU) is the United Nations (UN) specialized agency for information and communication technologies that, among other functions, allocates global radio spectrum and satellite orbits and develops technical standards that ensure networks and technologies connect seamlessly [1]. The Radiocommunication Sector of the ITU (ITU-R) was established "to ensure the rational, equitable, efficient, and economical use of the RF spectrum by all radiocommunication services, including those using satellite orbits, and to carry out studies and approve Recommendations on radiocommunication matters" [1]. The objective of the ITU-R is to "ensure interference free operations of radiocommunication systems… through implementation of the Radio Regulations (RRs) and Regional Agreements" [2]. The ITU RRs are treaty obligations and are binding for ITU member states. Modifications to the ITU RRs by ITU member states and administrations are only possible through actions at a WRC, which occurs every 3-4 years.

The 2020s have seen exploding interest in multinational lunar campaigns led by the American Artemis program and the Chinese International Lunar Research Station (ILRS) program. NASA has released the Moon to Mars Architecture Definition Document describing the myriad elements constituting the Artemis Base Camp on the surface, Gateway orbiting space station, and ancillary systems from the US and its partners. [3] This has resulted in enormous growth in spectrum use and the number of links for missions traveling to and from the Moon, in lunar orbit, descending to and ascending from the lunar surface, and operating on the lunar surface. A high degree of interoperability is targeted across the multinational infrastructure to provide a large set of CPNT services to the many missions that not only minimizes the RF interference (RFI) potential but enables shared use of capabilities, capacity, and coverage. Counterpart terrestrial systems exhibit a high degree of interoperability in the telephony and networking industries but with a much lower degree of compatibility amongst the major space-based navigation systems. The opportunity exists today to establish lunar infrastructure with increased interoperability that will confer benefits onto lunar vicinity activities by all countries and missions.

Established in 2013, the SFCG's Lunar Martian Spectrum Group (LMSG) [4] currently maintains the recommended spectrum, vetted and agreed by SFCG member agencies, for use at the Moon [5]. The recently concluded WRC-23 issued resolutions [6] on lunar spectrum with direction to:

- Complete studies in time for WRC-27 on the spectrum needs of systems in the Space Research Service (SRS) which may operate on the lunar surface, or systems in lunar orbit communicating with systems on the lunar surface, in the frequency ranges 390-406.1 MHz, 420-430 MHz and 440-450 MHz, limited to outside the SZM and frequency ranges 2 400-2 690 MHz, 3 500-3 800 MHz, 5 150-5 570 MHz, 5 570-5 725 MHz, 5 775-5 925 MHz, 7 190-7 235 MHz, 8 450-8 500 MHz and 25.25-28.35 GHz;
- Complete studies in time for WRC-27 on propagation considerations for lunar surface systems and lunar-orbiting systems;
- Complete studies in time for WRC-27 on sharing and compatibility related to systems in the SRS to ensure protection of radiocommunication services and the Radio Astronomy Service (RAS) on the Earth and in the SZM in the same, adjacent or nearby bands; and
- Complete studies in time for WRC-27 on potential new or modified frequency allocations and/or identifications to the SRS with appropriate regulatory provisions, for communications on the lunar surface or in lunar orbit communicating with systems on the lunar surface.

Within the Artemis ecosystem, the LunaNet Interoperability Specification (LNIS) is being developed to "define the standards and interfaces for LNSPs to administer interoperable services to meet the needs of missions operating in the lunar vicinity" [7]. Originally codeveloped by NASA and ESA, JAXA has been added to the team to finalize version 5 which defines the capabilities for LunaNet 1.0, the initial version of LunaNet. LNIS and its companion documents are planned to evolve to encompass future services that will need expanded bandwidth as well as expanding membership to include other countries in coordination with the Interagency Operations Advisory Group (IOAG) [8] and other international forums. Figure 1 illustrates the current envisioned LunaNet interoperability frequency plan including expansion options that may be utilized in the 2030s.

In addition to the LNIS, the International Communication System Interoperability Standards (ICSIS) has been developed for the Artemis users to "define the minimum set of functional, interface and performance standards necessary to support interoperable and compatible communications and position, navigation, and timing (PNT) between human exploration spacecrafts, lunar and earth ground infrastructure, and other space and surface systems. The ICSIS document also identifies a set of recommended functional and interface standards beyond the minimum set for interoperability." [9]

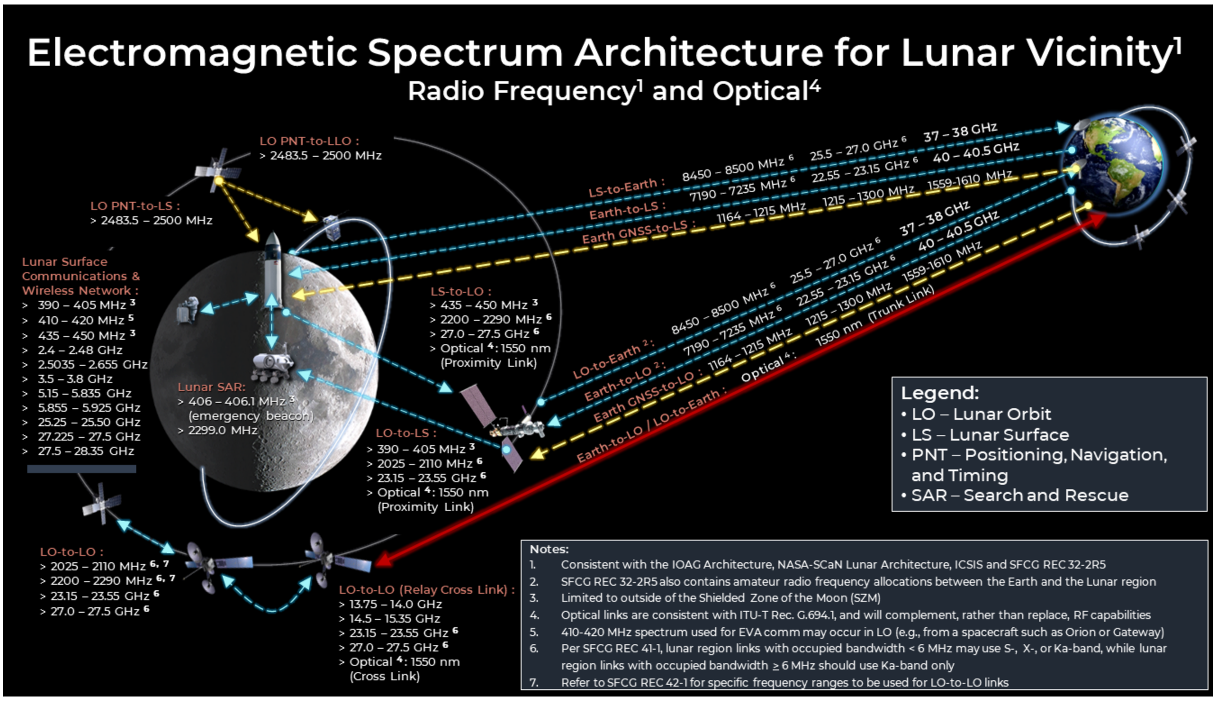

Figure 1. LunaNet Interoperability Frequency Plan

The authors of this paper include the chairs of the SFCG's LMSG and the IOAG as well as members of the LMSG technical team. The concepts discussed in this paper are consistent with the consensus achieved on lunar spectrum and architecture within the IOAG and SFCG.

Architectural Principles

Key principles incorporated into the architecture of the cislunar spectrum plans affect spectrum allocations and are affected by them. Key principles and associated spectrum impacts include:

- **Openness:** LunaNet is based on open international standards like the Internet and internationally agreed-upon use of spectrum via the ITU-R Radio Regulations.
- **Scalability:** Planned deployment of cislunar capabilities envisions introducing early capabilities focused on providing regional near the south pole that are designed to accommodate expansion of coverage, capacity, and other qualities as new mission elements and CPNT service providers come online. The architecture must be capable of a very small initial configuration with limited performance while accommodating orders of magnitude increases in capabilities over the next several decades of establishing a sustainable lunar presence. Spectrum planning must recognize these growth plans with allocations that allow limited early occupancy yet accommodate graceful long range future expansion. For example:
    - Dedicated DWE links for each lunar vicinity system is not a scalable approach to supporting CPNT needs of missions since the available frequency bands become saturated as the number of spacecraft and ground stations grow. Lunar in-situ networks and relay services that enable interoperable services across different LNSPs and users are scalable, but only achievable if principled architecting and planning is applied as recommended in this paper.
    - The 37/40 GHz band has been identified in SFCG Recommendation 32-2R5 [5] to support higher data rate trunk links for future lunar relay services. Although there is no existing infrastructure, this band provides an additional path for future expansion to accommodate a growing number of missions and increasing demand.
- **Resilience:** As lunar infrastructure grows into many networks and users, performance requirements are expected to increase in terms of reliability, availablity and overall resilience to offnominal conditions and events. Spectrum planning should consider frequency diversity and other means of supporting enhanced resilience of the infrastructure amongst cooperating countries and companies while continuing to protect frequency bands for scientific use.

- **Extensibility:** The LunaNet architecture is intended to be sufficiently general-purpose that it is adaptable to other celestial bodies such as Mars. However, the Moon uses near-Earth frequency bands while Mars and other bodies will require use of deep space frequency bands. The architecture must accommodate flexible assignment of functions to bands.
- **Evolvability:** Plans are being formulated that will require decades of investment to realize. Technology investments over this period will continue to introduce new and improved capabilities and place continuing demands on spectrum management. Early planning for assured spectrum access supports long-term investment in space technology efforts. For example, the International Space Station was designed to use S-band and Ku-band without consideration for growth of uplink and downlink demand and testing of technologies using different frequency bands. Adding Ka-band payloads in the US and European modules required additional electromagnetic environmental effects studies and operational conditions to ensure other systems onboard would not be affected.

To support this long-range evolution concept, LunaNet is conceived as the first instance of a *planetary network*. By treating the combined space and ground architecture across multiple LNSPs as a template for planetary networks, this approach can be applied elsewhere with local modifications leading to the eventual concept of the Solar System Internet (SSI) [10]. The SSI definition is nascent and may not anticipate all the spectrum issues that will arise but raises awareness that the lunar spectrum architecture sets a precedent for Mars and other future planetary networks.

One of the technologies under evaluation for the Moon is cellular telephony based on standards established by 3GPP, the 3rd Generation Partnership Project [11]. Satellite constellations are already being launched into Earth orbit by companies such as Lynk [12], AST SpaceMobile [13], and SpaceX Starlink [14] that implement unmodified 4G/5G service from satellite to unmodified cell phones under a paradigm referred to as Direct-to-Cell. New frequency allocations for the SRS are being considered for use on the lunar surface at the ITU-R level, which would enable re-use of hardware built for terrestrial cellular networks on the Moon. Initially, only major elements of the Artemis Base Camp may carry base station equipment supporting smaller fixed and mobile surface systems including space suits acting as user equipment. As size and power shrink, we anticipate that this will proliferate to more complex networking between the surface and orbit.

Spectrum Drivers

The LunaNet architecture is being developed taking into consideration the following spectrum drivers, some of which were discussed in a previous Ka-Band Conference paper [15]:

- The SZM establishes a radio-quiet environment for radio astronomy observations that are not possible from Earth-based observatories due to RFI.
- DWE links between Earth and the lunar vicinity and Earth and Earth-orbit share the same set of frequency bands for communication, as both regimes are within the near-Earth domain as defined by the ITU.
- Lunar in-situ communications and navigation relays will lighten the demand for DWE support by many lunar vicinity missions.
- Additional frequency ranges above 27 GHz that are allocated in the ITU RRs to SRS and Inter-Satellite Services and are reflected in SFCG Recommendation 32-2R5 can support future extension and scaling of the LunaNet framework.

Protection of the SZM: The SZM, illustrated in Figure 2, is defined in Article **22**, No. **22.22.1** of the ITU RR [16] as the area of the Moon's surface and an adjacent conical volume of space which are shielded from emissions originating within a distance of 100,000 km from the center of the Earth.

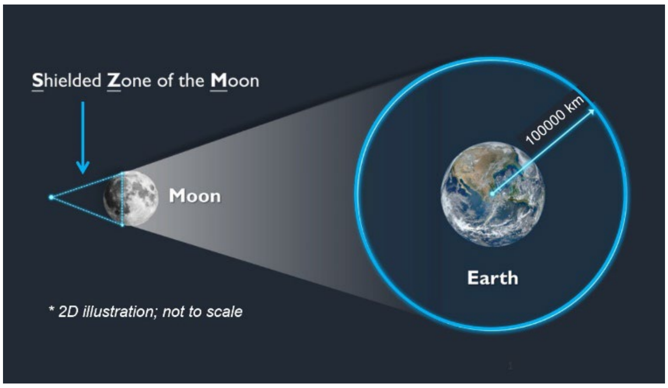

Figure 2. Illustration of Shielded Zone of the Moon (SZM)

Due to its isolation from radio emissions from the Earth as well as satellites orbiting the Earth, the SZM is an ideal physical location from which to conduct radio astronomy observations of celestial objects and phenomena that are not observable by Earth-based radio astronomy systems. The

ITU RRs Article **22**, Nos. **22.22** through **22.25**, which prohibit harmful interference to radio astronomy observations in the SZM [16]. Additionally, the frequency ranges in SFCG Recommendation 32-2R5 [5] and leveraged by the LunaNet spectrum architecture have been selected to conform with these ITU provisions.

DWE Services between Earth and Lunar Vicinity: The Moon and cislunar space are well within the 2 x 10^6 km distance from Earth that marks

the beginning of deep space, as defined in Article **1**, No. **1.177** of the ITU RR [16]. Therefore, missions to the lunar surface and in the lunar vicinity share the same spectrum as other near-Earth systems including Earth orbiting satellites and terrestrial users. Specifically, the use by Earth-orbiting missions of the 2025-2110 MHz and 2200-2290 MHz frequency bands ("2 GHz") allocated in the ITU RRs for space research, space operation, and Earth-exploration satellite services for telemetry, telecommand, and control (TT&C) as well as data downlink and return uses has proliferated over the past few decades. As a result, the 2 GHz bands are already very congested and require careful coordination to address potential RFI concerns amongst users. Furthermore, higher transmit power and antenna gain are required by supporting Earth stations and by lunar surface and orbiting systems to close their respective communications links, thus exacerbating the interference environment in the 2 GHz bands. While it is recognized that there are several currently active and planned near-term lunar missions that are using the 2 GHz bands for DWE communications support, the LunaNet spectrum architecture limits DWE communications support to the 7/8 GHz and 23/26 GHz bands to help alleviate congestion in the 2 GHz amongst near-Earth systems. In anticipation of an increase in lunar systems using the 7/8 GHz and 23/26 GHz bands for DWE communications support, the SFCG in 2023 achieved consensus on Recommendation SFCG 41-1 [17], which recommends that the 7/8 GHz bands only be used for DWE communications links with occupied bandwidths less than 6 MHz and 23/26 GHz bands be used for DWE communications links with occupied bandwidths greater than or equal to 6 MHz.

Lunar In-Situ Relay Services: The LunaNet spectrum architecture includes the 2 GHz and 23/27 GHz bands for use by in-situ lunar relay services to lunar orbiting and lunar surface users. Transitioning away from 2 GHz for DWE support for lunar vicinity systems as discussed above will help improve the interference environment experienced by in-situ lunar relay links and also reduce the size, weight, and power (SWaP) burden for lunar systems as a result of the shorter link paths. Recognizing that a combination of legacy and recently planned lunar systems are using 2 GHz for DWE support, the SFCG developed SFCG Recommendation 42-1 [18] to identify an initial, limited set of frequency ranges for use by lunar in-situ relay systems. This recommendation is expected to evolve over time as lunar in-situ relay service offerings mature.

Future Extension and Scaling of LunaNet: SFCG Recommendation 32-2R5 identifies the 37-38 GHz and 40-40.5 GHz frequency ranges for space-to-Earth and Earth-to-space communications support to lunar orbiting systems, respectively. As mentioned earlier, while there is currently no satellite communications infrastructure on Earth that operates in these frequency ranges, an expansion of the LunaNet architecture is possible in this portion of the RF spectrum, particularly as lunar in-situ relay services see an increase in demand from lunar vicinity systems, which, in turn, will require higher-bandwidth backhaul links between lunar orbit and Earth.

Issues for WRC-27

To meet the ever-evolving uses of the RF spectrum, the ITU-R periodically convenes a WRC to consider proposed modifications to the ITU RRs. During the recently concluded WRC-23, ITU member administrations reached consensus on several ITU-R Resolutions related to lunar spectrum to create agenda items for consideration at future WRCs.

One of these resolutions is ITU-R Resolution 680 (WRC-23) [6], which invites ITU-R members to study spectrum allocations to support select lunar surface and lunar orbit communications and navigation applications as part of the next four-year study cycle leading up to WRC-27. The ITU-R has tasked its Working Party (WP) 7B, which performs studies pertaining to space radiocommunication applications, to lead efforts to address the work outlined in this Resolution. The studies in progress will evaluate RFI impacts to incumbent services in select frequency ranges proposed to be additionally allocated to the SRS for lunar vicinity links between systems on the lunar surface and between the lunar surface and in lunar orbit. Currently, any in-situ lunar communications activities, such as NASA's upcoming Tipping Point demonstration of Long-Term Evolution (LTE) communications between a lander and other platforms on the lunar surface [19, 20], are being authorized to operate on a temporary basis. Among other limitations, such systems are not entitled to protection from harmful RFI and are required to cease transmissions if they cause harmful interference to other fully authorized operators. This approach is adequate in the current lunar environment with very few lunar vicinity communications links. However, attaining SRS allocations and regulatory protection for in-situ lunar communications and navigation applications in the frequency ranges being considered under ITU-R Resolution 680 is critical as the number of platforms in the lunar environment is expected to rise drastically in the near future, increasing the likelihood of interference impacts between different operations.

Among the frequencies under consideration in ITU-R Resolution 680, the 7190 – 7235 MHz and 8450 – 8500 MHz frequency ranges (referred to as X-band) are currently allocated to the SRS on a primary basis for Earth-to-space and space-to-Earth links, respectively. Pending the results of spectrum sharing studies within ITU-R WP 7B and the relevant decisions at WRC-27, use of these X-band frequency ranges for space-to-space applications may be reflected in alternate lunar network architectures such as the China-led ILRS.

Another WRC-27 agenda item is studying additional spectrum for terrestrial broadband applications in several frequency bands including the 7125 – 8400 MHz and 14.8 – 15.35 GHz ranges. Within the 7125 – 8400 MHz frequency band, there are existing DWE systems that provide critical support to Earth orbiting and deep space operations. Furthermore, the 14.8 – 15.35 GHz band is currently used by NASA's Tracking and Data Relay Satellites (TDRS) and planned for future use by lunar orbiting relay systems for crosslink support. The work being done during the WRC-27 study cycle is important to ensure that these incumbent operations are able to take place without experiencing harmful RFI impacts or operational constraints.

Issues for the 2030s

Continued Cislunar Spectrum Planning Beyond WRC-27: The scope of the WRC-27 Agenda Item set out in Resolution 680 described above, now designated as WRC-27 Agenda Item 1.15 [6], is intentionally limited. These studies will address the immediate spectrum needs of cislunar activities in the near-term, which mostly fall within the scope of the service definition of SRS, which is defined by Article **1**, No. **1.55** of the ITU RR as a service "in which spacecraft or other objects in space are used for scientific or other technical research purposes" [16]. These studies are also limited in scope to consider only links in the cislunar vicinity (referred to as 'space-to-space' links).

Of course, NASA's Artemis Program, China's ILRS, and proposed commercial ventures have described activities which will require spectrum applications that stretch or even fall well outside the definition of SRS. For example, a long-term human presence in cislunar space will entail communications and data transmission which have nothing to do with science or technology research, such as data streaming services that astronauts will use to call their families, consult their doctors, or watch a movie during their rest and relaxation periods.

NASA's Human Health & Performance (HH&P) Directorate identifies several risks dependent on the availability and use of appropriately protected spectrum that can meet the link requirements of the relevant applications. The risk of over work has motivated strict work schedules with designated rest periods [21]. During these rest periods crew may wish to read a book, watch a movie, interact with others via social media, or even correspond with friends and family on Earth. Such activities, in our modern age, may necessitate connectivity with servers and data sources on Earth (e.g., e-book libraries or stores, streaming services, and internet-based video call platforms). The risk of adverse cognitive or behavioral conditions stemming from isolation and confinement [22], and the closely related risks of deteriorating individual and team performance [23] can both be affected in part by factors related to the crew's ability to communicate with Earth – both with Mission Control for mission-related issues, and with friends, family and healthcare providers for personal or medical issues. As the distance from Earth increases, the transmission and reception delay of such communications increases, which could contribute to both a sense of isolation, and stress in time-sensitive or emergency situations. Such communications may be more effective if both voice and video are available, and the sensitive nature of these communications will require encryption (both for mission security and for the personal privacy of the crew). These both increase the bandwidth requirements. These uses of spectrum are clearly not related to science or technology research, and therefore would need to use service allocations other than the SRS that is under study during the WRC-27 cycle.

The international space spectrum planning community has already acknowledged this reality in ITU-R Resolution 680, which in addition to calling for studies under AI 1.15 for decision at the WRC-27, also has an eye towards spectrum needs studies beyond 2027. As the Resolution further notes, current and near-term science and technology research efforts lay the groundwork for further space activities, which may require other relevant radiocommunication services and links between Earth as well as the cislunar links currently under study. For example, current science activities can collect data that will inform our understanding of the cislunar environment leading to improved communications protocols, informed by the terrain, free-space path loss, and other propagation characteristics including studying alternative frequency bands. Future studies will also need to consider whether existing service definitions or new or revised service definitions are needed to best recognize such applications to enable communication, navigation, and health and safety, while continuing to enable RF-dependent science data collection in the cislunar environment, Mars and beyond.

Alternatives to RF Spectrum to Alleviate Congestion: NASA conducted its first test of optical communications between Earth and Moon in 2013 with the Lunar Laser Communications Demonstration (LLCD) that successfully uplinked data at an error-free rate of 20 Mbps and downlinked data at 622 Mbps at the specified bit error rate. [24] NASA plans to conduct a second demonstration on Artemis II called the Orion Artemis II Optical Communications System (O2O) capable of downlinking data at 260 Mbps. [25] These optical systems are based on the ITU-T G.694-1 standard for Dense Wavelength Division Multiplexing (DWDM) based on the optical C-band around 1550 nm (193 THz). [26] These optical frequencies are beyond the authority of the ITU-R Radio Regulations and do not fall under the same governance process that applies to the use of RF spectrum. The extremely narrow beamwidth of optical links makes them ideal for point-to-point communications and optimetrics for PNT capabilities with almost unlimited frequency reuse with little risk of RFI.

Applicability to Future Mars Spectrum Architecture and Management

The feasibility of adopting the lunar frequency plan, or portions thereof, for use in the Mars vicinity is currently being studied by the SFCG. One advantage is that RF hardware developed for LunaNet surface-to-surface and surface-to-orbit communications could potentially be adopted to support Mars human and robotic exploration, with benefits in increased reliability, reduced mission risk, and lower costs. Due to the large distance between Mars and Earth, re-use of the near-Earth frequency bands for Mars proximity links is unlikely to cause RFI to Earth orbiting satellites. In addition, the Moon can facilitate Mars analog testing on the lunar surface that will be used to determine how to best support astronaut health and performance during the long duration Mars missions, and develop and validate feasible countermeasures for exploration-class missions to Mars. NASA HH&P has noted that although effective countermeasures have mitigated the cognitive and behavioral performance risks, exploration missions beyond low Earth orbit will have constrained resources limiting implementation of these validated countermeasures. [22]

The SFCG has developed Recommendation 22-1R4 [27] with guidelines on the frequency bands to be used for communications between elements on the Martian surface, and for communications between elements on the Martian surface and in Martian orbit. The Recommendation includes a number of the frequency bands for use on the Mars surface that are also recommended for lunar surface communications in SFCG Recommendation 32-2R5; e.g., the 410-420 MHz, 2400-2480 MHz, 2503.5-2620 MHz, and 5150-5835 MHz bands. In addition, the near-Earth frequency bands 2025-2110 MHz and 2200-2290 MHz are recommended by the SFCG for surface-to-orbit communications in both the Mars and lunar regions. Additional modifications to SFCG Recommendation 22-1 will be considered based on further developments in the lunar frequency plan and the outcome of WRC-27 AI 1.15.

For Mars-Earth communications, the ITU-R frequencies allocated for SRS (deep space) are used. These frequency bands are different than those allocated for near-Earth SRS communications (including lunar). The 7145-7190 MHz and 8400-8450 MHz SRS (deep space) frequency bands used for Earth-to-Mars and Mars-to-Earth communications, respectively, are already quite congested. Mars missions using the 8400-8450 MHz frequency band (space-to-Earth) are limited to a maximum of 8 MHz bandwidth by SFCG Recommendation 23-1 [28]. Missions requiring higher bandwidth, including trunk links for Mars data relay satellites, can use the 31.8-32.3 GHz or 37-37.5 GHz allocations. Additional studies are considering optical frequencies to support Mars high-rate relay applications.

Frequencies allocated for Inter-Satellite Service can be used for orbiter-to-orbiter communications in both the lunar and Mars regions. Current Mars surface-to-orbit and orbit-to-surface relay communications are conducted using 390-405 MHz and 435-450 MHz UHF bands, respectively. With planned human exploration of Mars, the existing UHF and SRS (deep space) bands used for Mars TT&C will be insufficient to support all the human exploration spectrum needs. Human exploration missions will drive the need for much higher uplink bandwidth requirements. Current deep space

TT&C uplink data rates are on the order of tens of kilobits per second driven by commands and software uploads, whereas human exploration missions will require uplink data rates on the order of tens of megabits per second driven by crew interaction with Mission Control and psychosocial needs. Future study of new additional SRS allocations for communications on Mars surface, and communications between the Martian surface and Mars orbit, are expected within the ITU-R.

Propagation effects [29] also need to be considered when adapting the lunar spectrum plan for Mars. RF communications on the Mars surface need to contend with atmospheric attenuation, which is less than the atmospheric attenuation seen on Earth but considerably higher than the attenuation on the Moon which has a negligible atmosphere. In addition, there are frequent dust storms on Mars which can cause additional RF attenuation at high frequencies.

Conclusions

Taken together, the sum of the existing plans and envisioned capabilities for the longer-term force us to consider the Moon as a new RF spectrum ecosystem. It parallels the terrestrial ecosystem and decisions which led to the current frequency arrangements. NASA studies have shown new lunar exploration mission concepts require extended ranges and higher data capacity which can leverage investments being made (e.g., wideband transceivers capable of interfacing with a variety of service providers operating in frequency bands spanning several gigahertz of spectrum that implement a standard set of communications protocols for services with the ability to interoperate or *roam* across multiple networks). The LunaNet spectrum architecture aims to accommodate the initial capabilities needed for the breadth of early Artemis missions and other lunar activities planned in the coming decade. Additional features are envisioned or implicit in anticipation of the needs of missions in the next 20 years. Comprehensive, long-range spectrum management is needed to enable that future while efficiently using (and reusing) our limited access to RF spectrum and wisely enforcing those special provisions essential to enable scientific investigations that will yield a deeper understanding of the universe. The slow pace of global spectrum decision-making dictates that we identify candidate frequency bands and coordinate the process for approval far in advance of their operational use.

With limited spectrum allocated to space radiocommunication, intentional design, implementation, and coordinated operational approaches to lunar vicinity systems are essential and foundational to enable equitable access of spectrum operating in proximate geographical footprints. Furthermore, infusion of advanced technologies into space telecommunication and navigation systems is key to assure long term spectrum availability for future generations.

While work is underway to study regulatory recognition of cislunar activities consistent with the SRS definition, the ITU-R is laying the groundwork for this work to continue beyond WRC-27 and consider other activities beyond science and technology research. This work is critical to enable development and execution of well-informed business ventures as well as sound government investments to grow the lunar economy, that rely on the LunaNet community implementing the principles discussed here.

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