SPECTRUM MANAGEMENT FOR CISLUNAR SPACE IN THE ERA OF COMMERCIAL MISSIONS

Arvind J. Aradhya[1*] and Kevin. K. Gifford[1], [1]Wireless Interdisciplinary Research Group, University of Colorado, at Boulder. (Corresponding Author: arvind.aradhya@colorado.edu)

Introduction: Electromagnetic spectrum is a consumable natural resource, and the use of the radio-frequency region of the spectrum by spacecraft is perhaps the oldest example of In-Situ Resource Utilisation (ISRU), (as well as remote resource utilisation) and an essential *sine qua non* for communication, positioning, navigation, timing (CPNT) and scientific research. Radio frequency spectrum management, however, has hitherto *not* been considered in this vein. The renewed global interest in lunar exploration has led to an unprecedented increase in missions to cislunar space, particularly through NASA's Commercial Lunar Payload Services (CLPS) program [5], wherein this expansion now confronts us with the potential for spectrum scarcity, and presents significant challenges in spectrum management. Ensuring successful co-existence and operation of missions with varied objectives will therefore be well served by the consideration of spectrum as an in-situ resource, accompanied by updated policies and technologies for co-ordination. The current regulatory approach—reliant (within the US) on experimental licenses granted by the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA)—is fragmented and unsustainable for long-term operations [2]. Furthermore, the need to protect the radio-quiet Shielded Zone of the Moon (SZM) is paramount for astronomical research, including the search for technosignatures [1]. This work reviews the current state of spectrum allocation for cislunar space missions: to solicit wider discussion and engagement for affected stakeholders to provide informed input, into future in-space spectrum sharing frameworks.

Current Spectrum Allocation Framework via Experimental Licensing and its Limitations: Most (if not *all*) spectrum allocations for lunar missions are currently managed through FCC and NTIA experimental licenses [8]. While this approach has enabled initial mission deployments, in the absence of a comprehensive, dedicated national and international policy for cislunar spectrum allocation, the patchwork nature of these authorizations results in:

1. <u>Limited Coordination:</u> Each mission operates under different authorizations, leading to potential conflicts and both economic and spectrum inefficiencies [2].
2. <u>Temporary Allocations:</u> Experimental licenses suffice for capability demonstrations, but are not intended for continuous use, facilitating missions. [8]. The absence of a dedicated regulatory framework contributes to legal uncertainty, hindering commercial & international stakeholders investing in lunar operations [3].

Emerging Regulatory Developments: The International Telecommunication Union (ITU) is considering new regulations for lunar communications, especially with incorporation of a dedicated agenda item at the World Radio Conference 2027 (WRC-27). reflecting the need for international cooperation [3]. Moving forward, a cohesive regulatory structure is required to accommodate the growing number of missions while preventing spectrum conflicts.

Challenges with CLPS Mission Proliferation Increasing Demand for Lunar Spectrum: NASA's CLPS program has encouraged numerous private entities to engage in lunar exploration [5]. Missions such as Firefly Aerospace's Blue Ghost lander and Intuitive Machines' Nova-C lander highlight the rapid expansion of commercial lunar activity [4]. However, this proliferation introduces significant spectrum management challenges:

1. <u>Spectrum Congestion:</u> The proliferation in the number of missions has transitioned the spaceflight industry to the increased use of COTS (Commercial Off The Shelf) hardware, to minimise cost, and maximise speed and agility in the delivery of missions. As a result, the communications hardware employed are close cousins of terrestrial hardware, and so are the frequency ranges, modulation and encoding schemes. Thus, the growing number of missions increases the likelihood of signal interference, particularly in key bands [7]. Notably, this trend also results in the export of the same terrestrial Radio-Frequency Interference (RFI) issues to the cislunar and deep-space environment.
2. <u>Lack of Standardisation:</u> At the same time, however, there is still enough divergence at a system level, wherein different mission operators use varying communication protocols, complicating inter-system compatibility [6]. Data back-haul is often a limiting condition for various mission concepts, and the use of a standard communication protocol would augment mission capability. The Electra bent-pipe relay for Martian missions has established precedent for such co-operative standardisation, atleast between civilian space agencies of different nations. The NASA administered Space Frequency Co-ordination Group, seeks to serve as a platform for international lunar spectrum

coordination, in order to allocate and manage frequency bands [3] prior to the ITU – and is well positioned to facilitate the development of common technical standards which would enhance interoperability [7].
3. Need for Dedicated Lunar Spectrum: Unlike Earth-based communications, lunar operations require unique spectrum allocations due to the Moon's distinct environmental conditions, [8] especially at lower frequencies. Here, the di-electric properties of the heavily insulating lunar regolith, in close proximity to a hard-vacuum, offers a unique propagation environment not seen terrestrially, or in Earth orbit.

Protecting the Shielded Zone of the Moon (SZM):

Scientific Importance of the SZM: The SZM, located on the far side of the Moon, is **uniquely** suited for radio astronomy due to its natural shielding from Earth's radio frequency emissions [9], enabling:
1. Low-Frequency Radio Astronomy: ~Ideal Observations in frequency ranges inaccessible from Earth due to ionospheric interference [6], including cosmological investigations into the highly redshifted emissions from the early universe, at the epoch of re-ionisation.
2. Searching for Technosignatures: Detection of potential extraterrestrial signals requires a radio-quiet environment, especially one that is free of anthropogenic Radio Frequency Interference [1].

Threats to the SZM's Radio-Quiet Environment: Increasing lunar infrastructure development presents various threats to quietness of the SZM [7] including:
1. Leaked Anthropogenic Radio Emissions: Signals from landers, rovers, and communication satellites could contaminate SZM observations [6], if there is unsatisfactory fencing – either spatial or temporal, due to deployment prior to comprehensive studies.
2. Insufficient co-ordination with ITU and International Partners: The absence of clear policies on radio emissions near the SZM leaves it vulnerable to interference [9]. Developing global agreements to ensure adherence to SZM protection policies between commercial entities, and sovereign civilian space agencies is time-consuming, given the extant investment in different approaches for each of these stakeholders [3].

At the same time, however, even the scientific research from the SZM would require backhaul links for data delivery, while construction and operation will require their own communication bandwidths. For instance, remote sensing of the lunar sub-surface can reveal the presence of water ice, and other ISRU conducive deposits, and habitat supporting lava tubes via Ground Penetrating RADAR (GPR).

Achieving a balance would require research with an open-minded approach, where communication systems are tested in-situ while passive observations are made simultaneously. An effort in this direction is being worked on with the Hat Creek Radio Observatory, tasking the Allen Telescope Array to first attempt targeted detection of 4G LTE transmissions on the near side of the moon (emitted by the Nokia base station on the Intuitive Machines Lander), and then subsequently to conduct a radio astronomical observation of a target in the spatial and spectral vicinity of this potential interferer, in order to test mitigation mechanisms.

Strategies for SZM Protection

To safeguard the SZM, the following strategies can be considered, both indepently and in combination:
1. Establishment of a Protected Frequency Band: Designating specific frequencies for radio astronomy, free from commercial and operational signals [3]. Given the uniqueness of the SZM in the solar system, as well as the scientific potential across the wider electromagnetic spectrum, and the nascent state of extant and proposed SZM infrastructure – approaches that consider ***licensing-in emissions***, rather than licensing-in radio astronomy might setup a favourable precedent for the passive observation community as well.
2. Lunar Spectrum Zoning: Creating exclusion zones where radio emissions are minimized or prohibited [6].

References

1. Center for Strategic and International Studies (CSIS), 2025. *Lunar Spectrum Policy*
2. Federal Communications Commission (FCC), 2022. *DA-22-954A3*.
3. International Telecommunication Union (ITU), 2025. *Lunar Communications Regulations*.
4. Lunar Surface Innovation Consortium (LSIC), 2021. *NASA Lunar Surface Innovation Consortium*
5. National Aeronautics and Space Administration (NASA), 2021. *CLPS Program Overview*
6. Schier, J., Sham, C., Lee, D., Abhyankar, K., and Clothier, K., 2024. *International Coordination and Cooperation on LunaNet Spectrum*. In: 29th Ka and Broadband Communications Conference, Seattle, WA, USA, 24-27 September 2024.
7. Nokia Bell Labs, 2025. *Networking the Moon and Beyond*.
8. National Telecommunications and Information Administration (NTIA), 2024. *Talking on the Moon: How Spectrum Research Will Shape the Next Era of Space Exploration*
9. Sham, C., 2023. Lunar Spectrum Considerations. In: International Committee on Global Navigation Satellite Systems (ICG-17) Plenary, Madrid, Spain, 16 October 2023