The American Astronomical Society's Committee on Light Pollution, Radio Interference and Space Debris (AAS LPRISD) submits the following response to Request for Information; Cislunar Science and Technology Subcommittee, 40282 Federal Register / Vol. 87, No. 128 / Wednesday, July 6, 2022

> *Q1. What research and development should the U.S. government prioritize to help advance a robust, cooperative, and sustainable ecosystem in cislunar space in the next 10 years? And over the next 50 years?*
>
> *Q2. What key technical standards are most useful to develop in support of activities in cislunar space, and how could these standards enable and support a vibrant and sustainable cislunar ecosystem?*

The submission consists of two contributions: *Protection of Unique Astronomical Sites on the Moon* by Dr. Martin Elvis, following on this page, and *Needs for Assessment of Impact on Astronomy from the Moon - A Specific Example* by Dr. Patrick Seitzer on page 6. References follow in an Appendix on page 8.

AAS LPRISD also calls your attention to the submission by Dr. Harvey Liszt for the National Radio Astronomy Observatory on the measures required for the protection of lunar radio science.

Protection of Unique Astronomical Sites on the Moon

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Summary

Astronomers were caught unprepared for the challenge of massive internet constellations in low Earth orbit. A similar situation could soon arise on the Moon. There are a limited number of special sites on the Moon that could host breakthrough astronomical telescopes. Those identified to date include a handful of special regions on the lunar far-side and a subset of the cold traps in the Permanently Shadowed Regions (PSRs). Astronomers need these sites to be conserved against "harmful interference" while active peaceful exploratory and commercial developments proceed at an accelerating pace. In accordance with the 1967 Outer Space Treaty (OST), a prudent course to creating a sustainable cis-lunar ecosystem for astronomy will include both R&D into ways of minimizing damage to the scientific value of these sites and standards adhered to by all players in cis-lunar space for avoiding "harmful interference" to scientific sites, in particular those for astronomy.

1. The Challenge for 21st Century Astronomy

The first image releases on July 12 this year from the James Webb Space Telescope dramatically demonstrate how much we have still to learn about the Universe and our place in it. Even as Webb begins its outpouring of wonders, some astronomers are asking how we can go far beyond its abilities. Utilizing some very special places on the Moon could enable science that is as far beyond Webb as Webb is beyond its 20th century predecessors.

Like many rare environments, these special sites for astronomy can be easily ruined for scientific use. Astronomers have gone to the ends of the Earth to place their most sensitive telescopes on a mere handful of cloudless mountaintops far from light pollution. Yet these sites proved vulnerable to a new source of light pollution: reflections of sunlight off thousands, soon to be tens of thousands, of satellites launched into low Earth orbit to enable fast global internet coverage [2]. One of the most affected telescopes is the new, NSF-funded, billion-dollar Vera Rubin Observatory nearing completion in Chile. Caught on their back foot by this rapid and unexpected development, astronomers are now rallying to mitigate this problem through working with both satellite manufacturers and the UN COPUOS[1].

On the Moon we have an opportunity to look ahead to how similar surprises can be prevented and effectively nullified, preserving these sites as sustainable resources for humanity. As with internet constellations, ensuring this outcome will require both *research and development* into mitigation techniques that manufacturers can apply, and international *technical standards* to limit sources that interfere with the science value of these sites.

This response outlines first the locations of value to astronomy, then the challenges they face, and lastly some possible actions for both R&D and Standards.

2. The Moon as a Unique Location for 21st Century Astronomy

In early 2021 a volume of the Philosophical Transactions of the Royal Society was devoted to astronomy from the Moon [1], with further ideas for new classes of lunar-based telescopes emerging in just the subsequent 18 months. The realization that the Moon is rapidly becoming accessible has ignited astronomers' creativity.

The Moon astronomy concepts developed so far, and their preferred, rare locales, include:

1. <u>Far-side Radio Telescopes for Cosmology and SETI.</u> The far-side of the Moon is shielded from radio interference from Earth's radar, radio, and TV emissions better than anywhere else in the Solar System [3]. This quiet environment allows the faint signal of hydrogen atoms from a time before there were any stars or galaxies to be detected. This signal can test the inflation model of cosmology. The same quiet radio environment is needed for sensitive searches for techno-signatures of alien civilizations, to see if we are alone in the Galaxy, or not [4].

   There are only some 3 sites on the lunar far-side that are both large and smooth enough to be a site for the ultimate "Epoch of Recombination" telescope [5].

2. <u>Infrared Telescopes for Searching for Life on Exoplanets</u>. The signatures of life can be discerned in the infrared spectra of planets outside our Solar System ("exoplanets"). Most of these signatures are very faint. While Webb may find one or two, and its proposed successor may find two dozen, to really know if we are alone or in diverse company in our Milky Way galaxy, a much bigger telescope will be needed. An infrared

telescope must be cryogenically cold to keep its own emission low so that the weak cosmic signal can be discerned. In space this requires complex heat shields – Webb deployed 5 tennis-court sized reflective shields to keep the telescope and instruments cold enough. The Moon, instead, has craters near the poles that are in permanent shadow and are always at the temperatures needed. They may be ideal places from which to conduct a broad search for life in the Universe [6].

Only a few craters will be old, cold, and well located enough for this use [7]. They must be far from human activity to avoid dust coating the mirrors.

3. Radio interferometers to Image the Event Horizon of Black Holes. The release of the first image of the shadow of a giant black hole by the Event Horizon Telescope team made headlines around the world in 2019 [8]. Impressive as that image and its 2022 successor are, they lack the detail to test deeply either Einstein's General Relativity or theories for how black holes accelerate tight jets of plasma to near light-speed. And without sharper images, we are limited to just these two black holes. Getting off-Earth is the only path, and even one antenna placed on the Moon (with a view of the Earth and in almost continuous sunlight) would pick out the effects of General Relativity cleanly [9].

There are only a few locations suitable for such an antenna.

4. Gravitational Wave Antennas to see Mergers of Black Holes Throughout the Universe. The dramatic birth of gravitational wave astrophysics in 2016 has led to strong new tests of General Relativity and the realization that the range of black hole masses is much broader than we knew. Between the few kilometers long Earth-based antennas (e.g. NSF's LIGO) and the million kilometer long European LISA instrument planned for the 2030s, there is a gap. Several teams have realized that the Moon offers a path to bridging that gap (e.g. [10].) Gravitational Wave Antennas are exquisitely sensitive to vibrations; they need a good vacuum, cold temperatures, and low seismic activity: the Moon supplies all three - at present.

The limited number of large enough polar craters in permanent shadow and isolated from human activity are the prime locations.

3. Challenges to Lunar Astronomy Sites.

Radio Interference threatens the radio quiet environment of the lunar far-side. Future sources of radio interference would come from communication satellites in lunar orbit, any future lunar-GPS system, and ground operations communications both human and robotic. Side-lobes and harmonics at even very low levels could swamp the cosmic signals being sought.

Water mining the large, possibly billion ton [11] water deposits in the permanently shadowed regions near the lunar poles is the motivator for much of the recent interest in the lunar surface, as it opens up the possibility of a sustained human presence. Mining of any kind produces dust, tailings, and vibration due to both extraction and transport of ore.

Large landers will necessarily fire their rockets at the lunar surface to slow down for a safe "soft" landing and to accelerate for lift-off. If they land on and take off from the unaltered rocky surface of the Moon – the regolith – they will kick up tons of material. A study of the Apollo 12 landing found baseball-sized rocks ejected at 60 mph and smaller dust ejected at orbital speeds [12]. Apollo landers also produced detectable plumes of water and other volatiles in their exhaust, and studies have shown that such exhaust plumes can disperse around the entire Moon and might persist over geologic timescales [13], potentially impacting astronomical observations from the lunar surface. The planned lunar landers for humans are larger than the Apollo Lunar Excursion Modules and will create more debris without mitigation.

Major Human and Robotic Activity will inevitably produce seismic noise and dust from almost any major activity, including but not limited to driving around, construction of habitats (including covering them with meters of regolith for radiation protection), etc.

4. Actions and Approaches to Mitigate and Limit Threats to Lunar Astronomy Sites.

While astronomers were unprepared for the sudden emergence of internet constellations of thousands of satellites in low Earth orbit (LEO) [Lawrence], on the Moon we have the chance to anticipate the threats to scientific, astronomical, sites.

Potential actions fall into the two categories called out by the RFI: research and development, and technical standards.

R&D approaches: For each of the relevant areas, specific research and development topics may include:

Radio Interference: techniques to suppress side-lobes, harmonics, and electronics noise both in the vicinity of the astronomical site and from orbit; optical (laser) communication as an alternative. Accurate prediction of orbits for temporal mitigation could be developed (see Seitzer, this response, p.6.

Water mining techniques to minimize dust, vibration; surveys for "dry" cold traps in PSRs suitable for science but not mining.

Large landers – ways to manufacture landing pads to eliminate regolith debris. Sites for landing pads may be quite restricted at the high illumination regions (the "Peaks of Eternal Light") near the lunar poles. Investigating their preferred locations and spacing will be essential. Can landers be movable to allow others to use the same pad? Are there other ways to reduce regolith debris?

Major Human and Robotic Activity – develop automated systems to alert instruments to imminent activity. Develop wheels and suspension systems that transmit less vibration to the lunar surface.

Technical Standards Approaches: Organizations developing technical standards should work in coordination with the International Astronomical Union (IAU) Centre for the Protection of the Dark and Quiet Sky, hosted at the NSF's National Optical-Infrared Research Laboratory (NOIRLab) to establish well-vetted technical standards that would protect these lunar sites. One critical aspect is provision of accurate positional predictions for all satellites in the cislunar regime, as discussed in more detail in the following contribution.

For each of the relevant areas specific standards may include:

Radio Interference: As with the ITU allocation of orbital slots and frequencies for satellites in geosynchronous orbit (GEO), allocation of radio transmission frequencies will help. These allocations may include well-defined limits on allowable side-lobes, harmonics, and stray noise from electronics.

Water mining: Establish limits to dust and vibration levels observed at the astronomy sites. These will depend on the level of disturbance they pose to the scientific activity. The limits may be temporal – i.e. certain mining activities (e.g. drilling) are only allowed at certain times.

Large landers: Landing pad activities will need an allocation mechanism, including landing times and time on each pad (rather like gates and time slots at airports.)

Major Human and Robotic Activity: Advance notification could prevent damage to delicate instruments; after-the-fact notification could allow identification and editing out of lunar created noisy data. Limits to vibration measured at the astronomical sites may be needed.

Policy Standards Approaches: Treaties establishing appropriate standards of behavior that include all active lunar players appear to be a remote possibility, given the geopolitical situation, at least on the roughly decade timescale on which action is needed. The 1967 Outer Space Treaty[2] has wording that could form the basis for further elaboration that may include the protection of scientific sites on the Moon (OST Article IX[3]). On the other hand, restricting access to others is not allowed by the OST, so long as "reasonable advance notice" is given (OST Article XII[4]). The ITU Radio Regulations are an applicable treaty with the US as signatory, and they include protection of lunar radio-quiet zones.

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[1] United Nations Committee on the Peaceful Uses of Outer Space. https://www.unoosa.org/oosa/en/ourwork/copuos/index.html. (Accessed 18 July 2022.)

[2] Formally the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies". (http://www.unoosa.org/oosa/SpaceLaw/outerspt.html, accessed 2022 July 18.)

[3] OST Article IX: "*A State Party to the Treaty which has reason to believe that an activity or experiment planned by another State Party in outer space, including the moon and other celestial bodies, would cause potentially **harmful interference** with activities in the peaceful exploration and use of outer space, including the moon and other celestial bodies, may request consultation concerning the activity or experiment. (Emphasis added.)*

[4] OST Article XII: *"All stations, installations, equipment and space vehicles on the moon and other celestial bodies **shall be open** to representatives of other States Parties to the Treaty on a basis of reciprocity. Such representatives shall give reasonable advance notice of a projected visit, in order that appropriate consultations may be held and that maximum precautions may be taken to assure safety and to avoid interference with normal operations in the facility to be visited." (Emphasis added.)*

[5] United Nations International Telecommunication Union. https://www.itu.int (Accessed 18 July 2022.)

Although the United States is not a party to the Moon Agreement (because of specific language not relevant here), the Moon Agreement nonetheless contains useful conceptual language to apply for purposes of protecting sites of the Moon and including lunar orbits within this protection (see Art. I, § 2). More importantly, the United States' efforts to protect certain aspects of the Moon for scientific research would be consistent with the much more recent United Nations Long-Term Sustainability Guidelines.
A useful further step would be for the United States-led Artemis Accords to explicitly cover protection of special lunar sites for science. The Artemis Accords would then set "community standards" for those countries signing onto them. The Artemis Accords would not, however, include important State Parties China and Russia in this community - at least in the current state of affairs.

There do exist laws that govern resolution of certain disputes in space - though more focused on Earth and its orbit. As such, we have a foundation for addressing and resolving conflicting uses of resources through adoption of "customary laws" applicable to signatories [14]. Recently, tentative arguments have been advanced toward explicitly expanding this approach to establish a lunar "customary law" regime [11,15].

Some form of authority that licenses lunar activities will be needed. This may well be more like the ITU[5] than any more general "lunar government"; indeed a heavier regulatory regime may encourage violations and defections.

5. Conclusions

The promise of the Moon as a location for breakthrough telescopes for astronomy is becoming clear, as is the realization that the specific sites for these telescopes are surprisingly few. Sustained human activity on the Moon and the infrastructure that presence will demand threatens these rare sites if we do nothing. Fortunately, there are prudent steps we can take to mitigate, or eliminate, many and perhaps all of these threats. A dual-pronged approach is needed, encompassing both research and development and technical standards.

Needs for Assessment of Impact on Astronomy from the Moon
A Specific Example

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There is major interest [1] in using the lunar surface for astronomy at all wavelengths. A small telescope is scheduled for launch in December 2022 as a precursor to a more substantial facility at the lunar pole [2]. Astronomers are concerned about the number of satellites in lunar orbit, and their potential effect on astronomical observatories on the lunar surface or in lunar orbit. This issue has been extensively studied for observatories on the Earth's surface

[3][4][5][6]. To assess and mitigate the impact of lunar orbiting satellites on lunar astronomy operations, it will be necessary to calculate the number of satellites above the lunar horizon at any time, and for any lunar location. Example: a radio observatory on the back side of the moon - what is the potential for radio interference from satellites, even if there are zones intended to be protected as radio-quiet under ITU-R Radio Regulations Articles 22.22 to 22.25?

The RFI asks for research and development to be pursued by the US Government over the next 10 and then 50 years. What technical standards are most useful?

For astronomy, research and development should lead to the cislunar equivalent of space-track.org, maintained by the 18th Space Defense Squadron. Astronomers use the following from this web site and underlying databases:

1. Public catalog of orbital elements (usually Two Line Element (TLE) sets) to determine location of satellites with respect to ground based observatories and space telescopes in low Earth orbit (LEO).
2. Ephemerides provided by the operators themselves, which can be considerably more accurate and precise than the information in TLE sets.
3. Description of the algorithms used for predicting orbital positions using TLE sets.

A high priority should be the creation of a cislunar equivalent of space-track.org with:

1. A catalog of all objects currently in the cislunar regime, and their up-to-date orbital elements or state vectors. Technical standards for representing these orbital elements need to be developed, as the orbital motion in the cislunar regime is considerably more complex than in LEO and geosynchronous orbits (GEO).
2. Public domain propagators for objects in cislunar space. This can be used to predict the future (and past) positions and velocities of objects in the cislunar catalog for studying the visibility of objects from observatories on the lunar surface and in space. One propagator will not suffice, since the orbital motion depends now on both the Earth and the Moon, and for orbits close to the moon strong lunar perturbations such as mascons.
3. Ability for operators to deposit their own ephemerides into the databases on this site.

With this information astronomers can study the effect of satellites in the cislunar regime on telescopes on the lunar surface and elsewhere. The development of technical standards for cislunar orbital elements and propagators will enable theoretical studies of proposed cislunar constellations and their effect on astronomical facilities.

All three components suggested above will also be essential to space situational awareness (SSA), space domain awareness (SDA), and space traffic management (STM) in the cislunar regime. Such a cislunar web site will benefit all users of cislunar space, not just astronomers.

Appendix - References

References for M. Elvis Contribution

[1] Silk, J., Crawford, I., Elvis, M., and Zarnecki, J. (eds), 2021, Astronomy from the Moon: the Next Decades, *Phil. Trans. Roy. Soc., A*, 379, Issue 2188.

[2] Lawrence, A., 2021, *Losing the Sky*, Photon Productions, ASIN**:** B08W9NR7DX

[3] Burns, J.O., et al., 2021, "Low Radio Frequency Observations from the Moon Enabled by NASA Landed Payload Missions", *The Planetary Science Journal*, 2, 44.

[4] Heidmann, J., 1998, SETI from the moon: an invitation to COSPAR, Advances in Space Research, Volume 22, Issue 3, p. 347-351.

[5] LeConte, Z., Gläser, P.C., and Elvis, M., 2022, Lunar Far-Side Radio Arrays: A Preliminary Site Survey, in prep.

[6] Schneider, J., Silk, J., and Vakili, F., OWL-Moon in 2050 and beyond, *Phil. Trans. Roy. Soc., A*, 379, Issue 21880187.

[7] Elvis, M., 2022, Environmental Considerations for Lunar Astronomy, in preparation.

[8] Event Horizon Telescope Collaboration, 2019, "First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole", *Astrophysical Journal Letters*, Volume 875, L1.

[9] Johnson, M.D., et al., 2020, "Universal Interferometric Signatures of a Black Hole's Photon Ring", arXiv:1907.04329v2. Johnson, M.D., et al., 2019, "Studying black holes on horizon scales with space-VLBI", Astro2020: Decadal Survey on Astronomy and Astrophysics, APC white papers, no. 235; *Bulletin of the American Astronomical Society*, Vol. 51, Issue 7, id. 23.

[10] Amaro-Seoane, P., et al., 2021, "LION: laser interferometer on the Moon", *Class. Quantum Grav*. 38 125008

[11] Elvis, M., Krolikowski, A., and Milligan, T., 2021, Concentrated lunar resources: imminent implications for governance and justice, *Philosophical Transactions of the Royal Society A*, Volume 379, Issue 2188, article id.20190563

[12] Metzger, P.T., 2021, Cratering of Soil by Impinging Jets of Gas, with Application to Landing Rockets on Planetary Surfaces, eprint arXiv:2104.05195.

[13] Prem, P. et al, 2020, "The Evolution of a Spacecraft-Generated Lunar Exosphere," *J Geophys Res Planets,* Vol. 125, Issue 8, doi: 10.1029/2020je006464.

[14] Ostrom, E., 2015, *Governing the Commons*. Cambridge University Press.

[15] Johnson-Freese, J., and Weeden, B., "Application of Ostrom's Principles for Sustainable Governance of Common-Pool Resources to Near-Earth Orbit," *Global Policy*, vol. 3, no. 1, pp. 72–81, Feb. 2012. Schingler, J.K. et al., 2022, Res Lunar: Resource Systems and Governance Approaches, *OpenLunar Foundation*, https://uploads-ssl.webflow.com/5e4b77413a237e44acc573ac/62328b385b107173fe68448b_Res%20Luna.pdf. (Accessed 18 July 2022.) Krolikowski A. & Elvis, M., 2022, Space Resources and Prospects for

Contested Governance, *The Oxford Handbook of Space Security*, eds. Saadia Pekkanen, and P.J. Blount, Oxford University Press.

References for P. Seitzer Contribution:

1. Silk, J., Crawford, I., Elvis, M., and Zarnecki, J. (eds), 2021, Astronomy from the Moon: the Next Decades, *Phil. Trans. Roy. Soc., A*, 379, Issue 2188.
2. https://iloa.org/
3. Walker, Constance ; Hall, Jeffrey ; Allen, Lori ; et al., Impact of Satellite Constellations on Optical Astronomy and Recommendations Toward Mitigation, 2020, Bulletin of the American Astronomical Society, Vol. 52, No. 2, id. 0206.
4. Hall, Jeffrey ; Walker, Constance ; Rawls, Meredith ; et al., SATCON2: Executive Summary, 2021, DOI: 10.3847/25c2cfeb.4554c01f
5. Walker, Connie ; Di Pippo, Simona ; Aubé, Martin ; et al., Dark & Quiet Skies I, 2020, DOI:10.5281/zenodo.5898785
6. Walker, Connie ; Di Pippo, Simonetta ; Aubé, Martin ; et al., Dark & Quiet Skies II, 2021, DOI: 10.5281/zenodo.5874725