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Non-Interference of Lunar Activities

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Abstract

As dozens of countries and private sector companies have expressed interest in establishing lunar operations by the end of the decade, including many in the South Pole region, it will be critical to determine how to minimize interference in lunar activities. Although lunar interference concerns have been broadly identified, and deconfliction has been identified as an area of further work in Section 11 of the Artemis Accords, there is not broad consensus in the lunar scientific or technical community on key questions such as standards and best practices for non-interference or mechanisms for mitigation. This paper seeks feedback from the scientific and technical community to determine the breadth of interference concerns and clarify community usage of the terms "interference", "contamination", and "deconfliction". The paper proposes a framework for further deconfliction activity.

Keywords: Lunar, Sustainability, Artemis Accords

1. Introduction

Dozens of countries and private sector companies are looking to establish lunar operations over the next decade. Unlike historic lunar operations which have operated in locations largely isolated from other missions, in order to achieve scientific and operational objectives, future operators will need to share information, consult, and potentially coordinate to mitigate interference for simultaneous and planned missions in proximity to one another, especially in the lunar south pole region. In order to determine what level of coordination could be needed, and what information should be shared, NASA Office of Technology, Policy, and Strategy (OTPS) explores historical and modern uses of the terms "contamination" and "interference", the extent of contamination and interference concerns, and existing or proposed mitigation mechanisms (both policy and technical).

1.1 A history of international and U.S. domestic use of "contamination" and "interference"

1.1.1 Interference in Telecommunications

The International Telecommunication Union (ITU) has acted as the primary international venue for regulations, guidelines, and arbitration surrounding radiofrequency allocation and interference, both terrestrially and in space. The international regulatory principle of non-interference in telecommunications can be traced back to the 1903 International Radio Conference, over concern of disturbing wireless stations. The concept of "harmful interference" was introduced at the International Radio Conference of 1947. Interference as defined in today's ITU radio regulations was defined at the 1979 World Administrative Radio Conference [1,2]:

> *1.166 Interference: The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radiocommunication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy.*
>
> *1.167 permissible interference: Observed or predicted interference which complies with quantitative interference and sharing criteria contained in these Regulations or in ITU-R Recommendations or in special agreements as provided in these Regulations.*
>
> *1.68 accepted interference: Interference at a higher level than defined as permissible interference and has been agreed upon between two or more administrations without prejudice to other administrations.*

> *1.169 harmful interference: Interference which endangers the functioning of a radionavigation service or other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with Radio Regulations (CS)*

These interference categories delineate the level of impact to another party, and recognize that some level of interference may be permissible either pursuant to regulatory guidance or after appropriate agreement with the affected party.

1.1.2 The Launch of Sputnik: Defining [Harmful] Contamination and Interference in Space

Shortly after the launch of Sputnik, international concern was raised regarding contamination of celestial bodies. On February 8, 1958, the National Academy of Sciences (NAS) of the United States adopted a resolution urging that "scientists plan lunar and planetary studies with great care and deep concern so that initial operations do not compromise and make impossible forever after critical scientific experiments," citing examples of possible biological or radioactive contamination [3]. Upon the urging of the NAS, the International Council of Scientific Unions established an ad-hoc Committee on Contamination by Extra-terrestrial Exploration (CETEX). CETEX explicitly noted impacts to the Moon's atmosphere, Moon dust, and biological contamination as potential areas of contamination concern. Contamination by lunar dust was incorrectly deemed to be unproblematic except in the instance of nuclear explosions, and a lack of understanding of the presence of lunar volatiles and water ice led to initial dismissal of impacts to the ability to study lunar geological history or biological contamination. CETEX noted in their recommendations that "there is a real danger that exploration attempts made within the next few years which would complicate or render impossible more detailed studies, when the technological problems of landing sensitive scientific instruments on the moon and planets have been solved," noting that "an experiment essential for one purpose may make it impossible for other types of studies to be made subsequently (e.g., the explosion of a nuclear device to provide seismic data on the interior of the moon or of the planets might make subsequent radiochemical analysis meaningless)" [3].

CETEX was formalized in 1958 through the founding of the Committee on Space Research (COSPAR). COSPAR provided contamination recommendations to the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS) in 1964, focused on "upper atmospheric pollution by rocket exhaust and chemical injection experiments," "belts of orbiting dipoles", and "contamination of planets" with particular focus on further work regarding space probe sterilization [3]. The upper atmospheric group split impacts into four categories, noting an emphasis on long-term impact in their discussion of severity:

(a) A harmless, short-term and localized alteration of the upper atmosphere that can be readily observed at the ground;
(b) A long-term and world-wide alteration of the observable characteristics of the upper atmosphere, but one which causes no identifiable interference or harmful effect;
(c) An extensive alteration of the upper atmosphere that interferes with scientific experiments or other human activities
(d) An atmospheric alteration that affects man's environment [4].

The discussion of the meaning of contamination continued through the drafting and negotiation of the Outer Space Treaty (OST). According to Gabrynowicz and Langston in "A Chronological Development of Article IX of the Outer Space Treaty" [5], the inclusion of "harmful contamination" was widely understood by negotiators to be concerned about biological contamination (as well as nuclear weapons per Article IV), while the provisions related to "harmful interference" and consultation were developed based on a U.S.S.R. proposal designed to address U.S.S.R. concerns with U.S. Project West Ford, an experiment that put 480 million dipoles 0.7 inches in length in Medium Earth Orbit [6]. The U.S.S.R. sought to make advanced international coordination for all space missions mandatory, but the United States was concerned that such required coordination could result in a veto. The full text of Article IX reads [7]:

> In the exploration and use of outer space, including the Moon and other celestial bodies, States Parties to the Treaty shall be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space, including the Moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty. States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their **harmful contamination** and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose. If a State Party to the Treaty has reason to believe that an activity or experiment

> planned by it or its nationals in outer space, including the Moon and other celestial bodies, would cause potentially **harmful interference** with activities of other States Parties in the peaceful exploration and use of outer space, including the Moon and other celestial bodies, it shall undertake appropriate international consultations before proceeding with any such activity or experiment. 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

Since the entry into force of the Outer Space Treaty, COSPAR has continued to provide guidance on planetary protection and avoidance of "harmful contamination".

Presidential Directive/National Security Council Directive-37, *National Space Policy* (1978), provides further domestic guidance on "interference," noting that "[t]he space systems of any nation are national property and have the right of passage through and operations in space without interference. Purposeful interference with operational space systems shall be viewed as an infringement upon sovereign rights." [8] This guidance has consistently remained in subsequent U.S. National Space Policies.

1.1.3 Recent interest in contamination and interference

The 2011 "NASA's Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts" provides guidance regarding the protection and preservation of lunar sites, noting that many Apollo sites are still active science sites. The recommendations define contamination as "the act of depositing chemical, biological or physical material onto artifacts at the heritage site such that the deposition reduces its historical, engineering, or scientific value. Contamination can take on several forms, including surface particulate, non-volatile residue, volatile hydrocarbons, and microbial" [9]. The recommendations specifically address physical contact, dust, un-burned/residual propellants, planetary protection, and residual biological contamination from past missions. It recommended a 2.0 km exclusion radius for heritage lander sites and 0.5 km exclusion radius for heritage impact sites to minimize the possibility of plume impingement and propellant deposition during overflight, exhaust-blown dust during near-overflight, or system failure. It additionally recommended the use of "natural lunar terrain barriers such as hills, crater rims, ridges, or terrain slopes to block spray of the landing spacecraft" [9].

NASA, with particular mindfulness to the increase in lunar missions, updated its contamination guidance in Standard 8719.27 in 2022 [10,11], differentiating between contamination and harmful contamination as shown in Figure 1. Notably, harmful contamination, according to NASA Standard 8719.27, damages the integrity of the study of chemical evolution and the origin of life at another solar system body and focuses on biological/molecular contamination, while contamination is unwanted material on the spacecraft or introduced to the environment of a solar system body, and may also include particulate contamination.

While there is no authoritative definition of "harmful interference" as that term is used in the Outer Space Treaty, Section 11 of the Artemis Accords details the notification and coordination measures to which Accords signatories have committed to avoid harmful interference, stating "[t]he area wherein this notification and coordination will be implemented to avoid harmful interference is referred to as a 'safety zone'. A safety zone should be the area in which nominal operations of a relevant activity or an anomalous event could reasonably cause harmful interference." [12]. Section 11 notes the size and scope of safety zones is dependent on activity, and should change over time to reflect the nature of operations.

1.2 Non-governmental interest in interference and contamination

In addition to international law and governmental policies related to interference and contamination, several non-governmental groups have outlined interest in further work to mitigate impact of lunar interference and contamination.

A 2010 International Academy of Astronautics Cosmic Study, *Protecting the Environment of Celestial Bodies*, looked to go beyond planetary protection to the geophysical, industrial, and cultural realms, finding present space environment protection mechanisms insufficient. In particular, they note threat to geomorphological features from space exploration, increased use of lunar and planetary orbits, and cultural and historic sites as major gaps for lunar policy. [13]

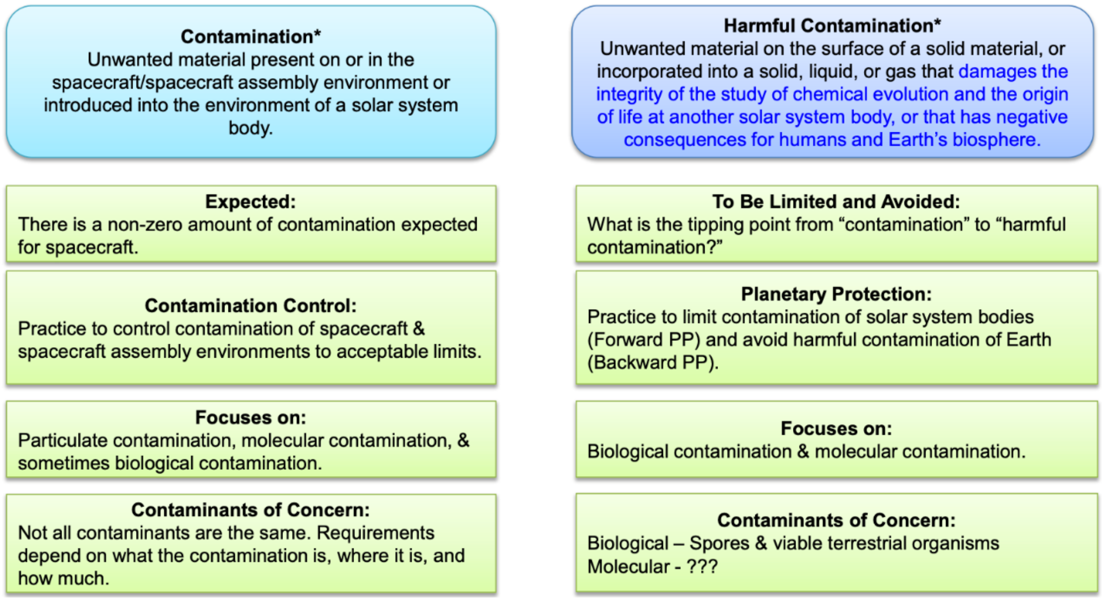

Figure 1. Contamination vs. harmful contamination in NASA Standard 8719.27 (* denotes definition in STD), courtesy of NASA Office of Planetary Protection, Office of Safety and Mission Assurance

The Lunar Exploration Analysis Group, established in 2004 by NASA to bring together academia, industry, government, and the commercial sector to discuss lunar scientific, technical, commercial, and operational issues, developed a 2016 Lunar Exploration Roadmap. This roadmap outlines scientific and technical priorities for lunar exploration. It in particular outlines the need to measure certain scientific characteristics such as the lunar exosphere before extensive contamination by lunar activity, and notes that dust will have an immediate impact on lunar surface activities. It notes that site selection may not always be optimal to meet both scientific and exploration objectives, suggesting these parties "may have differing objectives for its collaborative use suggesting both a need for balanced negotiations and the best obtainable data from the candidate locations," and suggests that in addition to getting feedback from across the lunar stakeholder community, operational considerations may drive site selection [14].

In 2020, the Moon Village Association established the Global Expert Group on Sustainable Lunar Activities (GEGSLA), including representatives from academia, industry, government, and non-governmental organizations. They released a reference framework in 2022, which defined "harmful interference" as "the result of any activity with a significant adverse effect on the lunar activity of other actors, which prevents them from carrying out their legitimate lunar activities or gaining access to an area." They additionally note that "lunar stakeholders should adopt appropriate measures to avoid harmful contamination to the environment of the Moon or adverse changes in the environment of Earth resulting from the introduction of extraterrestrial matter," including "a) Internationally agreed planetary protection policies, b) Adverse changes to designated and internationally endorsed lunar natural or cultural heritage sites, c) Adverse changes to designated and internationally endorsed lunar sites of scientific, commercial or another interest." [15]. In their 2024 report to the COPUOS Scientific and Technical Subcommittee, the Moon Village Association noted that GEGSLA working group 1 seeks to offer clarification of "harmful contamination… and consider the extent to which this concept needs to be developed to include other forms of harmful interference," and "assess aspects and locations of the lunar environment which merit protection from harmful contamination and other interference in order to preserve scientific, cultural and/or aesthetic value", in addition to making recommendations to protect these environments. They note that interpretations of Article IX generally include planetary protection but do not explicitly include physical, chemical, and radiological contamination. [16]

2. Methods

In order to receive public feedback on the scope of interference and contamination concerns, and potential mitigation measures, OTPS developed a questionnaire on lunar interference and contamination concerns, understanding site value, and mitigation mechanisms (full questionnaire in Appendix A). OTPS held two breakout sessions at the April 2024 Lunar Surface Innovation Consortium meeting in Laurel, MD, to get feedback from in-person and virtual participants on the questionnaire. The Lunar Surface Innovation Consortium is led by NASA's Space Technology Mission Directorate and Johns Hopkins Applied Physics Laboratory and brings together lunar stakeholders across academia, industry, and government. Participants were asked to break out into groups and determine their definitions of interference and contamination, ways they measured site value, and potential impacts to site value. OTPS simultaneously released the questionnaire publicly on the NASA website, social media, and relevant list-servs. Input was received from roughly 50 individuals or organizations between the workshop and questionnaire, representing both scientific and technical interests, including academia and industry. Responses to each question were qualitatively analyzed using an open coding model, which thematically grouped responses as they were digested.

3. Results

Respondents largely focused on potential impacts to mission in their discussion of interference, and the alteration of materials or the environment in their discussions of contamination. Many noted that interference could be intentional or unintentional, permanent or temporary. For the purposes of the analysis below, we consider the amalgamated definition of interference from the questionnaire to be an activity that may impact the activity of another actor to carry out a mission or objective. We include contamination as a type of interference in this analysis, and adopt the NASA STD 8719.27 definition of contamination—"Unwanted material present on or in the spacecraft/spacecraft assembly environment introduced into the environment of a solar system body" to aid in the categorization of responses. However, we note that there were a wide variety of definitions received from the questionnaire, which included non-physical materials/resources (e.g., RFI, orbits), the alteration from a natural or pristine state, and the alteration of safety or economic value.

3.1 Interference concerns

Table 1 delineates respondents' interference concerns. We break up their concerns into operational phases: orbital; entry, descent, and landing/ascent; static surface operations, and dynamic surface operations, and highlight by color which types of interference were flagged as scientific and/or operational concerns. In Table 2, we break up these interference concerns into scientific vs. operational concerns, and their spatiotemporal extent. While we do not define the delineation between short and long-term, or hyperlocal vs. regional, we hope further work will help refine the extent of these concerns.

3.1.1 Physical contact

Plume surface interactions and movement of dust were highly cited as both scientific and operational concerns, from coating solar panels/scientific instruments/habitats, to impacting geological samples. Movement or compression of lunar soil was also identified as a concern for operations and for geological sampling. The movement of soil and dust can have long-term scientific impact to lunar sites (hyperlocal for soil, regional for dust).

Additional concerns were raised about direct physical contact, both the potential for physical contact especially between crewed and uncrewed missions, and for the blocking of heavily desired corridors/locations. While the physical imprint of an object blocking a heavily utilized corridor may be small, infrastructure or other operational/scientific considerations may force a large diversion for other missions and thus have regional impact. Orbital conjunctions and occupation of highly desired lunar orbits/physical crowding in these orbits were highlighted as long-term concerns.

3.1.2 Thermal disturbance

Respondents indicated scientific concern in the potential heating and dissipation of volatiles in PSRs. Reflection of sunlight onto other elements or PSRs could additionally impact operational objectives for thermally sensitive operations. While the reflection of sunlight primarily impacts concurrent hyperlocal operations, the impact to volatiles can be regional and long-term. Additionally, any thermal instability could impact gravitational wave detectors at a hyperlocal scale.

3.1.3 EMI/RFI

Respondents expressed concern regarding the impact of radiofrequency interference (RFI) and electromagnetic interference (EMI) on astronomical observations from both orbital and surface assets. RFI was of particular concern for astronomers in in the 0.1-110 MHz range with a power spectral density above 228 dBm/Hz, due to high scientific value of observations for fundamental physics, cosmology, astrophysics (cosmic origins, exoplanet habitability), heliophysics, space physics, and plasma physics. The band is inaccessible and/or compromised from the surface of the Earth due to Earth's ionosphere, Earth's auroral kilometric radiation, and terrestrial human transmissions. EMI concerns included unshielded/ insufficiently shielded assets not only on the surface but ion propulsion engines during entry, descent, and landing/ascent. There was also concern about energy deposition into surface dust increasing charged particles on the lunar plasma and charged particle-antenna interactions, degrading passive use of radio band.

3.1.4 Contamination (biological, mechanical, chemical)

Many respondents highlighted concerns regarding the contamination by biological, mechanical, chemical and hazardous materials, especially during disposal. Improper disposal of hazardous materials, accidental disposal of material (e.g., crash landing), and astrobiological contamination including human health hazards were highlighted. Contamination of polar ice traps from water and from rocket exhaust was flagged as a contaminant that could add 20% to polar ice trap mass long-term [18]. Exospheric contamination was also flagged as a concern given the low density of the atmosphere and impact of high cadences of lunar operations, though some of this impact is likely temporary. One respondent noted that topographical changes could impact lunar processes such as water transport, energetic particle flow, and temperatures.

3.1.5 Shadowing from large structures

Respondents noted that shadowing from large structures may impact operations, particularly solar power and communications (visibility of Earth, of other lunar sites). These impacts, while hyperlocal, could have long-term effects in highly utilized corridors if there is not a disposal protocol for the structure.

3.1.6 Seismic/vibration from movement

Seismic impacts/vibrations from movement were highlighted as a particular concern for gravitational wave astronomy. Solar panel proximity to a seismic station was also flagged as a potential disturbance.

3.1.7 Aesthetic degradation

One respondent highlighted concerns regarding the visibility of lunar objects or structures from Earth with the naked eye or through small telescopes.

3.2 Mitigation mechanisms

Table 3 summarizes interference mitigation responses and existing technical or standards work on these mechanisms. Many respondents focused on broad coordination and communication to mitigate interference of lunar activities. This included the development of recommended concept of operations (CONOPS), to include information such as the activities an actor wishes to perform and their location, planned spectrum use, information to support dust ejecta predictions, and waste generation information. Astronomer respondents emphasized the need to maintain a database of transmitter frequencies used by all lunar assets, and encouragement of coordination between active/passive users during early stages of technology development. Pre-coordination of lunar trajectories, as well as a schedule of activities for long-term surface operations were also highlighted.

Multiple respondents suggested NASA or international technical bodies could provide guidance on sites of scientific interest and how to preserve their value, or even designating certain zones for specific purposes. One respondent suggested adding environmental impact guidance during procurement. Several respondents suggested defining minimum distances from gravitational wave detectors or from passive radio operations. One respondent highlighting an existing EMI standard, MIL-STD-461, which could be adopted to minimize impact of EMI on passive radio operations. Respondents also highlighted the desire for guidance on disposal of lunar waste, and how sites might be restored, if possible, after operations.

Several respondents noted that collective investments on infrastructure and data could help mitigate interference. Development of infrastructure such as roads and railways, landing pads, and regolith walls could help mitigate dust. Monitoring data and predictive tools could help assess and rectify impacts of lunar interference. Many respondents highlighted specific technologies or technological development initiatives that could help mitigate dust, provide guidance on reuse, minimize chemical contamination, improve energy efficiency, improve shielding, and more.

Respondents emphasized the need to share data on interference (e.g., plume surface interaction (PSI) data) and lessons learned publicly, and to coordinate on developing best practices to avoid interference.

4. Further Work

This report is an interim product. OTPS intends to continue to engage with government and non-governmental organizations, industry, and academia to further dialogue on mitigating interference in lunar activities. OTPS is committed to working across NASA to further understand interference data needs and both technical and policy solutions to mitigating interference.

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Appendix A

Lunar Non-Interference Questionnaire

- How do you define these terms?
    - Interference
    - Contamination
    - Deconfliction
- Understanding the Potential Value of a Site
    - What attributes/characteristics are relevant to site selection in consideration of science objectives? Attributes may include time-sensitive or physical characteristics, holds awaiting technology or science advancements, or other perspectives. Example scenarios are encouraged.
- Impacting the Potential Value of a Site
    - What human or robotic actions/events may negatively impact the value of a lunar site? Such as chemical contamination, physical contact, hardware proximity (for example Apollo hardware causing localized 'moon quakes' due to heating and cooling differences vs surroundings), waste hazards, etc.
        - How do the impacts of those actions/events alter the value of a site (e.g., unusable for certain missions, usable for certain missions but not others)?
        - What detrimental impacts are permanent, temporary, or still unknown?
    - What data, models, or information is needed to inform the value? Such as how to understand where contaminants are going, what they are doing that impacts science, computational models validated with ground and flight data, etc.
- Mitigation Mechanisms
    - What types of mitigation mechanisms exist to preserve the value of a site?
    - During what phases of operations are mitigation mechanisms needed? Examples include ascent/descent, overflight, traverse, contingency, experimental or construction phase, etc.
    - What technologies/capabilities need to be developed?
    - What types of communication and coordination efforts minimize concerns? Such as development/planned activity timelines for pre-coordination, operational timelines with time-critical communication mechanisms, list of materials, transparency, etc.

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Table 1. Summarized public lunar interference questionnaire responses regarding interference concerns during phases of operations. Red are operational interference concerns, blue scientific interference concerns, black both operational and scientific interference concerns.

Interference Concern	Orbital Operations	Entry, Descent, and Landing; Ascent	Static Surface Operations	Dynamic Surface Operations
Physical Contact	• Cislunar conjunctions • Occupation of highly desired orbits	• Movement and compression of lunar soil, movement of dust (e.g., PSIs), which may impact geological samples or impede physical movement • Dust coating scientific instruments, solar panels, or habitat surfaces • Ejection of debris into cislunar space	• Operations blocking desired path/location	• Movement and compression of lunar soil, movement of dust (e.g., PSIs), which may impact geological samples or impede physical movement • Dust coating scientific instruments, solar panels, or habitat surfaces • Operations blocking desired path/location • Threat of active physical contact, including due to uncertainty of positioning, especially between crewed and uncrewed operations
Thermal disturbance		• Heating resulting in dissipation of volatiles (e.g., in PSRs)	• Reflection of sunlight into another element or into PSRs	• Heating resulting in dissipation of volatiles (e.g., in PSRs) • Reflection of sunlight into another element or into PSRs
EMI/RFI	• RFI from satellites, with particularly sensitive impacts to lunar astronomical observatories	• RFI and EMI with particular concern for proximity to astronomical sites; unshielded electronics from ion propulsion engines flagged for EDL/Ascent • Energy deposited into surface dust increasing charged particles on the lunar plasma and charged particle-antenna interactions, degrading passive use of radio band	• RFI and EMI with particular concern for proximity to astronomical sites	• RFI and EMI with particular concern for proximity to astronomical sites • Energy deposited into surface dust increasing charged particles on the lunar plasma and charged particle-antenna interactions, degrading passive use of radio band

Contamination (biological, mechanical, chemical)		• Improper disposal of hazardous materials (e.g., batteries, lubricants) • Unplanned disposal of materials (e.g., crash landing) • Biological/mechanical waste • Astrobiological contamination including human health hazards • Topographic changes (e.g., drilling, structures) that impact processes such as water transport, energetic particle flow, temperatures • Contamination of polar cold traps from exhaust • Exospheric contamination	• Improper disposal of hazardous materials (e.g., batteries, lubricants) • Biological/mechanical waste • Astrobiological contamination including human health hazards • Topographic changes (e.g., drilling, structures) that impact processes such as water transport, energetic particle flow, temperatures	• Improper disposal of hazardous materials (e.g., batteries, lubricants) • Unplanned disposal of materials (e.g., crash) • Biological/mechanical waste • Astrobiological contamination including human health hazards • Topographic changes (e.g., drilling, structures) that impact processes such as water transport, energetic particle flow, temperatures • Exospheric contamination
Shadowing from large structures			• Operations blocking solar power • Alteration of thermal environment • Operations blocking communications (visibility to Earth, lunar-to lunar)	• Operations blocking solar power • Alteration of thermal environment • Operations blocking communications (visibility to Earth, lunar-to lunar)
Seismic/ Vibration from movement		• Seismic/vibrational impacts from operations of particular concern to gravitational wave astronomy	• Solar panels in proximity to seismic station	• Seismic/vibrational impacts from operations of particular concern to gravitational wave astronomy • Solar panels in proximity to seismic station

Table 2. Summarized public lunar interference questionnaire responses regarding spatiotemporal extent of interference concerns

Interference Concern	Scientific Impact: Concurrent, short, or long-term?	Scientific Impact: Hyperlocal, regional, global?	Operational Impact: Concurrent, short, or long-term?	Operational Impact: Hyperlocal, regional, global?
Physical Contact	Can be long-term for movement of soil/dust	Hyperlocal: Soil disturbance, blocking of transit corridors Regional: dust	Primarily concurrent for surface operations unless physically blocking highly utilized corridor; orbital debris can be long-term	Dust is regional for surface operations, global for orbital debris. Physical blocking of activity is largely hyperlocal unless blocking a highly utilized corridor
Thermal Disturbance	Long-term; thermal disturbance itself is concurrent but volatile disturbance could be permanent.	Regional for volatiles; for gravitational wave detectors hyperlocal thermal instabilities are of concern	Concurrent for sunlight reflected onto other elements	Hyperlocal
EMI/RFI	Concurrent	RFI: Global for cislunar satellites EMI: hyperlocal	Concurrent	RFI: Global for cislunar satellites EMI: hyperlocal
Contamination (biological, mechanical, chemical)	Long-term for some hazardous materials and for contamination of polar ice traps from exhaust; some exospheric impact temporary. Localized changes to surface likely permanent on human-timescales.	Can be global for exosphere short-term, long-term gases can be permanently trapped near lunar poles. Changes to surface will affect multiple processes (water transport, particle flow, temperature variation, illumination). Estimated that Starship could dump 70 T of water in the polar region and possibly a similar amount of CO_2 [17]; water may migrate into polar craters	Could be long-term for chemical contaminant health hazards	Hyperlocal
Shadowing from large structures	N/A	N/A	Long-term if no disposal protocol in highly utilized region	Hyperlocal
Seismic/Vibration from movement	Concurrent	Can be hyperlocal for some disturbances, global for others	Concurrent	Hyperlocal to regional
Aesthetic Degradation	Potentially long-term if structures are not disposed of	Depends on the extent of visible structures	N/A	N/A

Table 3. Summarized public lunar interference questionnaire responses regarding mitigation mechanisms and existing technical/standards guidance

Interference Concern	**Mitigation Mechanisms?**	**Existing Technical or Standards work?**
Physical Contact	• Infrastructure to minimize dust (roads/railways, landing pads, regolith walls) • Pre-mission CONOPS reporting requirements to include dust ejecta predictions	
Thermal disturbance	• See contamination	
EMI/RFI	• Pre-mission CONOPS to include planned spectrum use, characterization of EMI/EMC • Maintaining a database of transmitter frequencies used by all lunar assets regardless of country of origin • Coordination between active/passive users during early stages of tech development • Minimizing active band spectrum to allow for more science (particularly at bands blocked by Earth's ionosphere) • Locating missions at geographically dispersed areas away from passive users	• MIL-STD-461 for EMI • ITU working groups 7a/7d • Space Frequency Coordination Group • CITEL
Contamination (biological, mechanical, chemical)	• Designate (temporarily or indefinitely) certain regions for certain purposes. • Studies of if and how sites may be 'restored' after (say) in situ resource utilization may also be worthwhile. • Add environmental impact requirements to the NextSTEP Appendices used to procure HLS services. • NASA provide explicit guidelines on (1) what these sites are with respect to science and exploration, and (2) how lunar actors should conduct operations in their vicinity without compromising their value. These guidelines may include recommended landing site keepaway distance, recommended rover keepaway distance, discouraging certain activities in certain areas, etc. • industry best practices and standards, • Economic incentives for companies to sell NASA in situ data prior to site compromise • Expanding ITU framework and Interagency Operations Advisory Group work to consider preservation for scientific community • Cryogenic sample collection and storage prior to executing surface activities that may impact future science in that area.	• COSPAR
Seismic/Vibration from movement	• Defining minimum distances between machines and a gravitational-wave detector (dependent on machine) • Correct detector data with environmental monitoring systems measuring seismic disturbance	
Aesthetic Degradation	• Significant alteration of the Moon's surface must be prohibited to preserve its integrity as seen by Earth's inhabitants, i.e. any area of material concentration or in-situ processing must be strictly limited to a size smaller than 1 arcsecond from the Earth surface, equivalent to a disc with a radius of 2 km at the Moon's equatorial location. This ensures it remains unnoticeable to the naked eye and through amateur telescopes. Additionally, each of these areas must be at least 30 arcseconds apart to prevent the formation of visible clusters.	