



Lunar Dust Considerations for Vertical Solar Arrays

Volume 1: Lunar Environment and Dust Interactions

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Summary

Lunar dust can complicate nearly every aspect of operations on the lunar surface. Jagged surface asperities, electrostatic charge, chemical reactivity, and interactions resulting in high-velocity motion enable a myriad of potential interaction pathways for lunar dust to adversely affect any exposed surface. Optimization of solar array energy collection efficiency, which will be important for a sustained lunar presence, will require overcoming many challenges presented by lunar dust. In this work, the fundamental properties of lunar dust, natural aspects of the lunar environment that influence the properties of lunar dust, and lunar exploration activities that will contribute to problems associated with lunar dust exposure are discussed. Aspects of the lunar environment that could contribute to reducing the operational efficiency of vertical solar arrays, which will be required for the lunar south pole region, are also identified.

Acronyms

AIAA	American Institute of Aeronautics and Astronautics
ASCE	American Society of Civil Engineers
BOL	beginning of life
ConOps	conceptual operations
DDE	Dust Detector Experiment
DSNE	Design Specification for Natural Environments
ISRU	in-situ resource utilization
LADEE	Lunar Atmosphere and Dust Environment Explorer
LDEX	Lunar Dust Experiment
MLI	multi-layer insulation
MLS-1	Minnesota Lunar Simulant 1
PSR	permanently shadowed region

UV	ultraviolet
VSAT	Vertical Solar Array Technology
XTJ	NeXt Triple Junction

Introduction

Power is a critical resource that is necessary to enable a sustained lunar presence (Ref. 1). Several approaches are being considered for power generation (Ref. 2), with the capture of solar energy being one of the most technologically advanced approaches due to its extensive use in space exploration and terrestrial applications. NASA's Vertical Solar Array Technology (VSAT) project is focused on enabling robust, reliable power generation through solar energy capture in support of the Artemis program's objective to return humans to the Moon and maintain a sustained presence near the lunar south pole (Refs. 3 and 4). The lunar surface is an extreme environment with a myriad of challenges to system design and deployment, including space radiation exposure, significant temperature fluctuations, lack of atmosphere, and the composition and dynamic nature of lunar dust. For VSAT to be successful, these environmental challenges and challenges introduced through lunar surface operations will need to be overcome. Design and integration of novel technologies on the deployable solar array system and environment-driven logistics will be critical to retain nominal operation of a VSAT (e.g., sufficient power generation efficiency) for an extended period of time.

In this work, lunar regolith refers to all the material present on the lunar surface, from nanometer-sized particles to boulders. The portion of lunar regolith approximately 50 μm in diameter and smaller is considered lunar dust. As will be described in the Lunar Dust section, lunar dust will pose a daunting challenge for nearly every aspect of lunar habitation. This challenge arises from the ubiquitous pathways for interaction with surfaces, mechanisms, instrumentation, and more. Significant portions of the lunar dust are jagged due to micrometeoroid bombardment and the lack of an atmosphere, which will further complicate removal. The sharp asperities on lunar dust particles result in stronger mechanical interlocking and embedding in incident surfaces, especially when the lunar dust is moving at high velocities (e.g., ejecta from a lander). The lunar dust can be electrostatically charged, with the magnitude varying depending on location and the time of the lunar day. Without an atmosphere, the lunar dust can be chemically reactive. Collectively, these interaction pathways resulted in the many challenges the Apollo astronauts faced, including abraded visors, compromised seals, clogged mechanisms, reduced lunar rover range, and potentially adverse health conditions.

The focus of this work is the impact that lunar dust will have on a VSAT architecture considering natural and anthropogenic (i.e., originating from human activities) phenomena. A brief overview of the VSAT technology is provided, followed by a review of the nature of the lunar dust. Natural phenomena resulting in dust generation, motion, and accumulation are described. Anthropogenic interactions with lunar dust, including walking, lunar rover activity, and launch vehicle landing and takeoff, are described. The final section describes a series of lunar dust environmental concern matrices for progressive phases of lunar habitation.

Although the purpose of this work is to provide a comprehensive review of factors contributing to lunar dust interactions with VSAT architectures, this content is not exhaustive. Several excellent resources provide further information:

- Lunar Sourcebook: A User's Guide to the Moon, 1991 (Ref. 5)
- NASA Standard 1008: Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments (Ref. 6)
- The Impact of Lunar Dust on Human Exploration (Ref. 7)

- NASA Technical Publication 20220018746: Lunar Dust Mitigation: A Guide and Reference (Ref. 8)
- NASA Technical Memorandum 2010–216446: Lunar Regolith Simulant User’s Guide (Ref. 9)
- Space Launch System (SLS) Specification 159: Cross-Program Design Specification for Natural Environments (DSNE) (Ref. 10)
- Human Landing System User’s Guide 001: Human Landing System Lunar Thermal Analysis Guidebook (Ref. 11)
- NASA Handbook 4002: Mitigating In-Space Charging Effects—A Guideline (Ref. 12)
- NASA Standard 5017: Design and Development Requirements for Mechanisms (Ref. 13)

Vertical Solar Array Technology Overview

This section summarizes VSAT technology, including VSAT architecture, performance metrics, and potential interactions with lunar dust. The effect of dust on solar cells and operational efficiency is discussed, and thermal management requirements are described.

VSAT Architecture and Performance Metrics

Several configurations of solar cell arrays have been designed, built, and evaluated for application on the lunar surface. The most appropriate solar array architecture will largely depend on the power requirements of the facilities it is supporting. In this work, a solar array capable of generating 10 kW of power on the lunar surface is considered. The system is designed to be fully deployed and retracted multiple times for relocation. The VSAT architecture must be freestanding and vertical, with the solar cells separated from the lunar surface by at least 10 m. Further details regarding the conceptual design of the vertical solar array can be found in the work of Pappa et al. (Ref. 3). System deployment, retraction, and relocation require mechanical components that may be adversely impacted by lunar dust exposure. Additionally, requirements for stability on potentially uneven ground and rotation of the array to track the Sun necessitate the location of sensitive mechanisms near the lunar surface.

VSAT Interactions With Lunar Dust

Evaluation of the risks posed to VSAT architecture by lunar dust must account for the distance between the solar array and the lunar surface and the requirement for multiple deployment/retraction cycles. Any component close to the lunar surface will have a high probability of experiencing critical levels of lunar dust exposure. That probability decreases with separation distance from the surface, as will be discussed further in the Determination of Lunar Dust Deposition Rates From Natural Phenomena and the Anthropogenically Originated Lunar Dust Motion sections. To evaluate risks from lunar dust exposure at different separation distances from the lunar surface, the VSAT architecture was divided into three regions (Figure 1): the lowest region, including the base and thermal radiator surfaces; the middle region, including the VSAT mast; and the upper region, including the solar arrays. The environmental concern matrices provided in the final section of this work delineate lunar dust concerns for each of these three regions.

Lunar dust exposure could be very disruptive to two major elements of the VSAT architecture: solar cells and radiator surfaces. Beyond these components, anything that rotates, extends, or moves in any manner could also be adversely impacted. These impacts will play a significant role in the conceptual

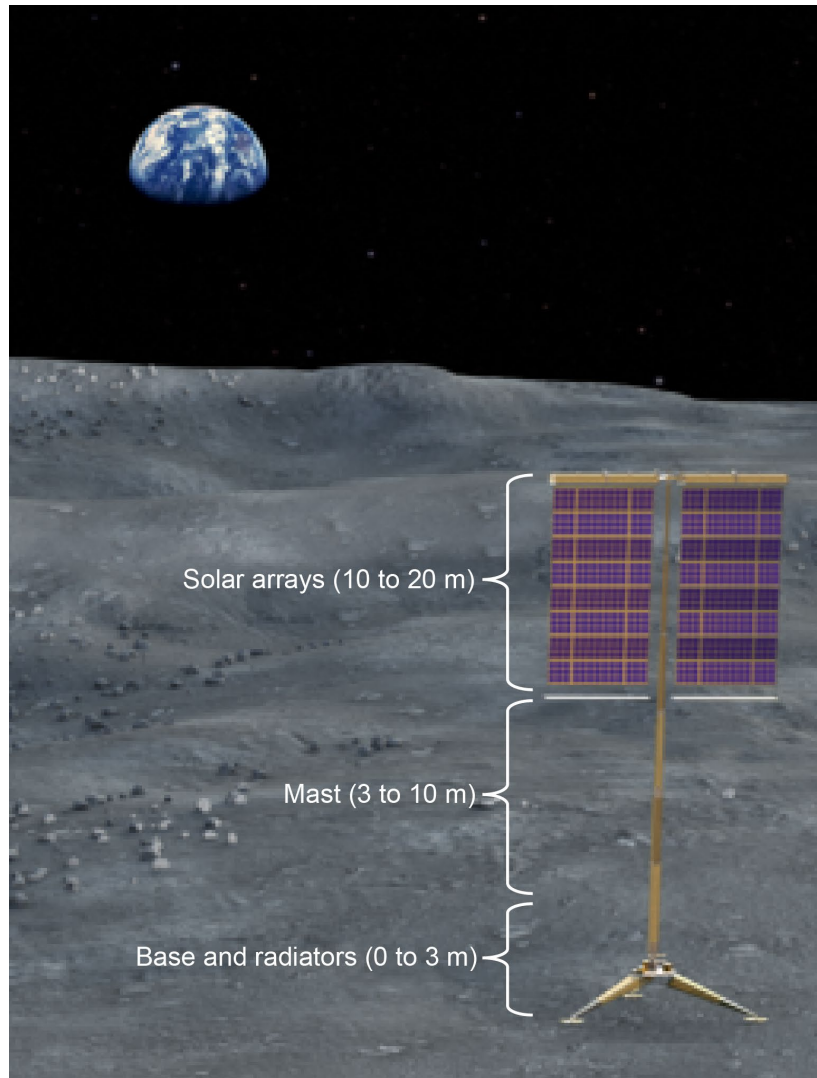


Figure 1.—Regions of consideration for VSAT architecture.

operations (ConOps) of the VSAT. For example, solar array illumination (and power generation) is probably highest when the mast is fully extended, but if rotational components are exposed to dust when the mast is retracted, the mechanism may be compromised. Consideration should be given to both activation timing and protections for vulnerable systems near the lunar surface.

Human-related activities on the lunar surface also play a role in the risk of lunar dust exposure for VSAT. In the early stages of a lunar settlement, energy generation will likely need to occur near where it will be consumed. The power generated will support activities such as habitat construction, infrastructure development, and in-situ resource utilization (ISRU). Likewise, landing and launch activities will occur nearby, resulting in significant lunar dust displacement, as described in the Lunar Lander Operations section. Once critical infrastructure, habitable space, and power distribution systems have been developed, energy generation, such as from a VSAT architecture, can be physically distanced from many hazardous activities associated with lunar dust exposure. In the final stages of lunar outpost development, solar-energy-generating equipment will likely be located at a safe distance from any activities that will increase dust exposure.

There are three different interactions between lunar dust and VSAT architecture components that should be considered: infiltration, adhesion, and abrasion. Infiltration of lunar dust particles can negatively impact the operation of mechanisms by limiting range, increasing torque requirements, and reducing the mechanism lifetime. The accessibility and cleanability of these mechanisms, in addition to Earth-based evaluation, will play a critical role in the lifetime of the VSAT architecture. Adhesion is relevant when lunar dust accumulation on a stationary surface impacts performance (e.g., solar cells and thermal radiators). Lunar dust adhesion could also impact communications equipment that will be needed to maintain reliable autonomous operations. Adhesion issues should be differentiated from infiltration concerns because the presence of lunar dust may be of no consequence on a moving part until that mechanism is activated. Active dust mitigation devices (i.e., technologies requiring an external energy source to operate) that remove lunar dust immediately before mechanism activation can be a means to overcome infiltration challenges. These technologies may also be effective on surfaces where adhesion presents a challenge by identifying an optimized operational periodicity. Finally, abrasion concerns arise when high-velocity lunar dust interacts with sensitive surfaces. Abrasion can be detrimental even when the lunar dust does not adhere to the surface. Scratching of solar cell surfaces, abrasion of thermal protection coatings, and roughening of structural component surfaces could all contribute to reduced operational efficiency and lifetime of a VSAT architecture. High-velocity lunar dust originating from vehicle landing and launch operations can be mitigated by geographic separation. Interaction with micrometeoroids and secondary ejecta, however, cannot be mitigated and will need to be evaluated in Earth-based experiments.

VSAT Solar Cells and Operational Efficiency in the Presence of Lunar Dust

Solar cells come in a variety of chemistries and architectures that will determine the overall power output of a solar array. Cells with lower efficiencies, such as silicon solar cells, require a larger active cell area to achieve the same power but are typically much less expensive than their multijunction solar cell counterparts. Currently, the VSAT program is utilizing three different solar cell technologies. Spectrolab's NeXt Triple Junction (XTJ) solar cell is a space-qualified triple-junction solar cell with a 30.7-percent beginning-of-life (BOL) efficiency (Ref. 14). The SolAero Z4J (SolAero by Rocket Lab) is a four-junction solar cell with a 30-percent BOL efficiency (Ref. 15). Both cells are space qualified according to American Institute of Aeronautics and Astronautics (AIAA) S-111 (Ref. 16) and AIAA-S-112 (Ref. 17) standards. The DS200 DragonSCALES™ silicon cell from mPower Technology, with a BOL efficiency of 20 percent (Ref. 18), is in the process of being space qualified. mPower's DS100 cell, the precursor to the DS200, is AIAA-S-111/S-112 qualified. There is some uncertainty as to how these cells will react in a dusty environment, much less a dusty plasma environment as is found on the lunar surface.

Lunar dust occlusion on the surface of solar arrays negatively impacts power generation by blocking out sunlight that could otherwise be absorbed by the cell. Dust occlusion on solar panels has been a noted issue since the Apollo era. The Dust Detector Experiment (DDE) was developed for Apollo 11 and was included on numerous subsequent missions (Ref. 19). Early ground-based studies for lunar dust impacts on solar cells found that dust accumulation resulted in an exponential loss in maximum cell power, with smaller particles causing greater loss. Since smaller particles create a near-monolayer of dust coverage on the surface of the cell, they more thoroughly block out light than larger particles (Ref. 20). As dust accumulates on the cells, it will limit power generation by blocking out light reaching the absorbing region of the cells. This is largely seen in a reduction of the short circuit current of the solar cell, which is

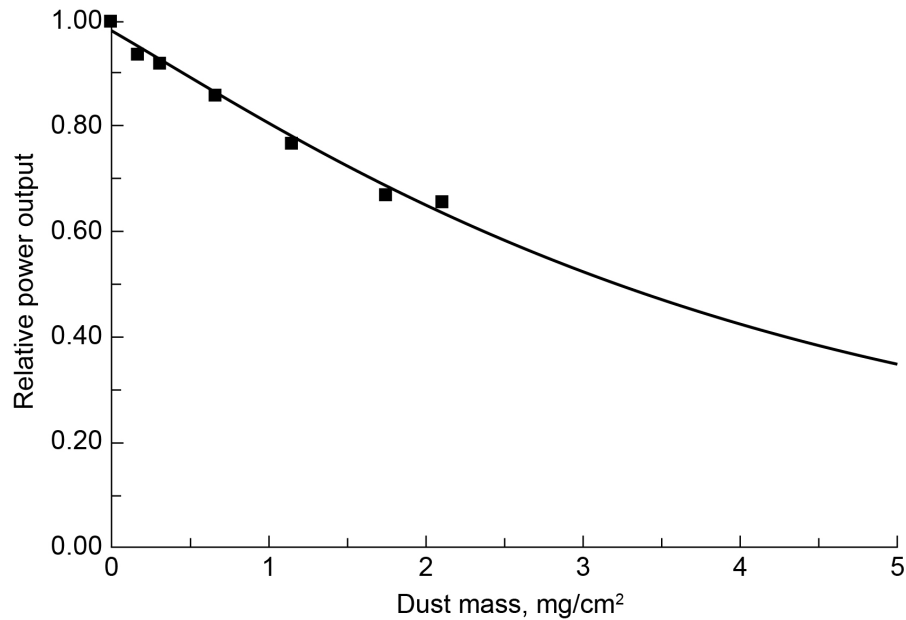


Figure 2.—Relative power output as determined from current–voltage (*I/V*) curves of dust-covered silicon cells. Illumination by solar simulator; dust materials, MLS–1, 20 to 38 microns (Ref. 20).

directly related to the intensity of incident light. Less photons reaching the absorber reduces the number of electron-hole pairs being generated, limiting the photogenerated current in the solar cell. Early studies by Katzan, Brinker, and Kress (Ref. 20) showed that increasing dust mass caused an exponential decrease in the relative power output of a silicon solar cell. Shown in Figure 2, even a relatively small 2 mg/cm² coating of Minnesota Lunar Simulant 1 (MLS–1) resulted in an almost 40 percent reduction in power. This testing was only done on silicon solar cells; it is recommended that dust impacts of specific cell technologies be determined via experimentation or simulation when generating power predictions for lunar surface solar arrays. This is particularly important for multijunction solar cells that consist of multiple layers of semiconductors, each with their own solar absorption profile.

Lunar dust also has thermal optical properties that impact its interactions with incident light; these properties are dependent on the chemistry and morphology of the dust, which is in turn largely dependent on its location on the Moon (Refs. 21 and 22). The reflectivity, emissivity, and solar absorptance of the dust will impact not only the wavelengths of light being reflected (so the light is not able to be absorbed by the solar cell) but also the heat of the regolith particles that are now accumulating on the cell. Lunar dust is an insulator that will negatively impact the ability of surface power systems like radiators and solar cells to reject heat due to added thermal resistance of the dust layer; for radiators with low solar absorptance coatings, the accumulated dust layer's high solar absorptance will also increase the absorbed solar heat load (Ref. 23). Solar cell efficiency decreases as temperature increases, so additional heat loading will negatively impact the overall power generation of the system (Refs. 24 and 25). Lunar dust chemistry and morphology differs somewhat across locations on the Moon, so the exact impact of these thermal optical properties will depend on the location of the solar array.

The risk of lunar dust accumulation on arrays is exacerbated by the charging environment found on the lunar surface. As electrons impinge on the surface of solar arrays, solar cells will build up a negative charge (Refs. 26 to 29). Lunar dust will charge either positively or negatively due to ultraviolet (UV) radiation during the lunar day or electrons during the lunar night (Refs. 26, 30, and 31). This increases the electrostatic forces attracting dust to the arrays, making it more difficult to remove by gravity or mitigation technologies. Dust can also cause mechanical damage to the cells if improperly removed, as its sharp edges can easily scratch surfaces. For systems like VSAT that are designed to retract and redeploy, dust remaining on the surface of the arrays may damage the cells during retraction. For this reason, and to reduce the risk of triboelectric charging, it is not recommended to manually brush dust off arrays. Dust mitigation technologies must overcome these forces that will vary throughout the lunar cycle.

To summarize, lunar dust presents a definite risk to solar power generation systems through efficiency degradation and mechanical damage. Understanding the behavior of dusty plasma, the impacts on power generation systems, and how best to protect these systems is crucial for a sustained presence on the lunar surface.

VSAT Thermal Management in the Presence of Lunar Dust

The VSAT thermal management system will keep batteries, avionics, and power management equipment warm through the lunar night, and during the day it will radiate waste heat to the environment, allowing these components to operate within their specified temperature range. Environment (regolith) temperatures at highly illuminated locations near the south pole will range from 80 K in darkness to 220 K in direct sunlight (Ref. 32). The thermal management system will consist of one or more enclosures to house batteries, avionics and power management systems, an external radiator, and a variable conductance pathway between the electrical components and the radiator.

The enclosure will be designed to minimize heat loss. This is to reduce the size of the component heaters that will be necessary for night survival. The insulating material will be multi-layer insulation (MLI). MLI has a low solar absorptance and effective emissivity. These properties limit solar heating during periods of illumination and minimize heat loss during periods of darkness.

The Moon has a small equatorial tilt with respect to the ecliptic plane (Ref. 33) of approximately 1.5°. Therefore, near the south pole the solar vector is nearly parallel to the lunar surface. During daytime, any vertical surfaces facing the Sun will be nearly perpendicular to the solar vector and will receive between 1,365 and 1,410 W/m² of solar heating (Ref. 34). The energy exchanged between the MLI, surroundings, and avionics is shown in Figure 3. The system shown ignores heat generated by the equipment and heat conducted away to a radiator and radiated to space. The system is used to evaluate the impact of dust on the heat flow through the MLI. For this analysis, the temperature of the equipment is chosen and remains constant.

The steady-state energy balance on the MLI is shown in Equation (1):

$$\alpha \dot{q}_{\text{solar}} - F_{MLI-\text{space}} \sigma \epsilon (T_{\text{outer}}^4 - T_{\text{space}}^4) - F_{MLI-\text{regolith}} \sigma \epsilon (T_{\text{outer}}^4 - T_{\text{regolith}}^4) = \sigma \epsilon^* (T_{\text{outer}}^4 - T_{\text{equipment}}^4) \quad (1)$$

Here, the right-hand side of Equation (1) represents the heat flow through the MLI, $\dot{q}_{MLI}$. The parameters used to solve for T_{outer} , which is the temperature of the outermost layer of MLI, and to determine the heat flow through the MLI are given in Table I.

Equation (1) is used to investigate the difference in heat flow between clean MLI and MLI that is completely coated with dust. Using Equation (1), and the parameters in Table I, the temperature of the outermost MLI layer and the heat flow through the MLI is determined. The results are shown in Table II.

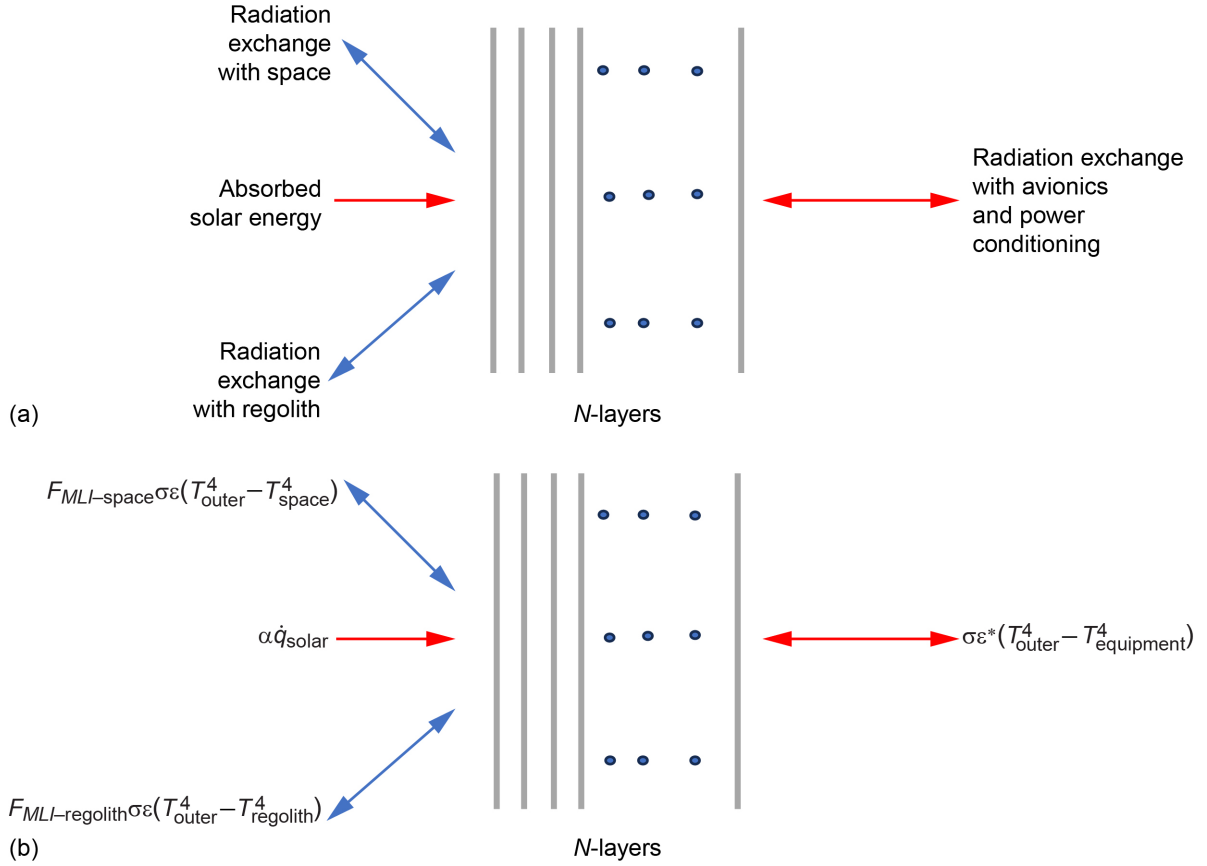


Figure 3.—Energy exchange between multi-layer insulation (MLI), surroundings, and electronics. Here, N -layers refers to number of layers. (a) Diagram of energy exchange. (b) Equations describing energy exchange.

TABLE I.—PARAMETERS USED FOR THERMAL ANALYSIS OF CLEAN AND DUSTY MLI

Parameter	Clean MLI	Dusty MLI
Solar flux, $\dot{q}_{solar}$, W/m ²	1,367	1,367
Absorptivity, α	0.15	0.76
MLI outer surface emissivity, ϵ	0.8	0.93
MLI effective emissivity, ϵ^*	0.015	0.015
T_{space} , K	3	3
$T_{regolith}$, K	220	220
$T_{equipment}$, K	270	270
View factors, $F_{MLI-space}$, $F_{MLI-regolith}$	0.5	0.5
Stefan–Boltzmann constant, σ , W/m ² ·K ⁴	5.67×10^{-8}	5.67×10^{-8}

TABLE II.—OUTERMOST MLI LAYER TEMPERATURE AND HEAT FLOW THROUGH CLEAN AND DUSTY MLI

	Clean MLI	Dusty MLI
T_{outer} , K	287.53	384.16
$\dot{q}_{MLI}$, W/m ²	1.29	14.00

A coating of dust on the MLI protecting avionics or electronics can have a significant impact on the heat flow through the MLI. The increase in solar absorptivity caused by the dust on the surface of the MLI increases the temperature of the outermost layer of MLI, increasing the heat flow through the insulation. This is offset slightly by an increase in surface emissivity caused by the dust. For the example shown, the heat flow increases by a factor of nearly 11 due to the coating of dust on the MLI. This increase in heat flow may impact the design of conduction paths between the equipment and radiators as well as the radiator sizing, as more heat will need to be rejected to keep equipment within a desired operating range when the avionics enclosure is exposed to sunlight.

Lunar dust is a poor heat conductor, with an average thermal conductivity of approximately $5 \times 10^{-4} \text{ W/m}^2 - \text{K}$ (Ref. 35). During darkness, the higher emissivity of the MLI surface due to dust may be inconsequential because the multiple insulation layers, including the dust itself, will minimize the amount of heat reaching the radiating surface. Equation (1) can be modified to illustrate this. At night the solar absorptivity will be zero and the surrounding regolith temperature will drop. Heat will flow from the avionics and equipment through the MLI and to the surrounding regolith and space. Equation (2) describes the heat flow from the equipment to the external surroundings during periods of darkness.

$$\sigma \epsilon^* (T_{\text{equipment}}^4 - T_{\text{outer}}^4) - F_{\text{MLI-space}} \sigma \epsilon (T_{\text{outer}}^4 - T_{\text{space}}^4) - F_{\text{MLI-regolith}} \sigma \epsilon (T_{\text{outer}}^4 - T_{\text{regolith}}^4) = 0 \quad (2)$$

Table III shows the resulting outermost MLI layer temperature and the associated heat flow out of the equipment enclosure for clean MLI and MLI completely coated with dust when the regolith temperature is 100 K. During darkness, the presence of dust has little impact on the MLI's thermal performance in minimizing heat loss for the equipment enclosure. The outermost MLI layer temperature is slightly lower due to the higher emissivity of the dust layer, but the resulting heat flow is nearly the same for the clean and dusty MLI.

A radiator removes waste heat from the electronics enclosures. The radiator is connected to the electronics by a variable conduction pathway. The pathway is typically a heat strap, thermal switch, or heat pipe. These devices decrease their thermal conductivity when the environment temperature is cold and increase conductivity when the external temperature is hot. Therefore, heat is maintained inside the electronics enclosure during darkness and removed during daylight to prevent overheating.

Like MLI, radiator performance changes due to the presence of dust. VSAT radiators will be placed horizontal or nearly horizontal to maximize the view of deep space, which has a temperature of 4 K. This will minimize the exposure of the radiator to solar heating and maximize the temperature difference between the radiator surface and the environment.

TABLE III.—NIGHT OPERATION: OUTERMOST
MLI LAYER TEMPERATURE AND HEAT FLOW
THROUGH CLEAN AND DUSTY MLI

	Clean MLI	Dusty MLI
$T_{\text{outer}}, \text{K}$	118.32	116.28
$\dot{q}_{\text{MLI}}, \text{W/m}^2$	4.35	4.36

A clean radiator has a surface emissivity between 0.83 and 0.88. As mentioned previously, dust has an emissivity of approximately 0.93. Lunar dust is a better emitter than a clean radiator, so for a very thin layer of dust, a dusty radiator may radiate more energy than a clean radiator. As the thickness of the dust layer increases, the poor thermal conductivity of the dust causes the surface temperature of the radiator to increase. The radiator temperature will increase as the dust layer becomes thicker; this will decrease the amount of heat that can be conducted from the electronics to the radiator and cause the electronics to operate at higher temperatures. Dust will inhibit the radiator's ability to remove waste heat and may lead to overheating of the batteries, avionics, and power management components. Development of a dust mitigation strategy for the thermal management system will be necessary for the longevity of the VSAT system. Analytical methods to evaluate dust interactions and potential mitigation strategies are outside the scope of this report and will be discussed in future volumes.

Lunar Dust

This section discusses the fundamental properties of lunar dust, natural aspects of the lunar environment that influence its properties, and lunar exploration activities that contribute to lunar dust perturbation.

Lunar Dust Composition and Physical Properties

The following discussion will be centered around properties determined from the samples returned during the Apollo missions. It should be noted that VSAT assets will most likely be in polar regions where the lunar regolith properties could be significantly different. Therefore, the information provided here should be understood as an approximation of what may be present in the local environment, and greater understanding of the actual lunar regolith properties will be achieved once lunar exploration missions in the polar regions have occurred.

The surface depth of the lunar regolith has been determined to range in thickness from 3 to 20 m and consists of all lunar soil particles, from very fine dust to boulders (Ref. 36). Up to 50 percent of the regolith consists of particles less than 50 μm (Figure 4) (Ref. 37); this subset is known as lunar dust. The mineralogy of lunar dust mainly consists of familiar basaltic components: plagioclases (e.g., anorthite and olivine) and pyroxenes with an average density of approximately 2.65 g/cm³ (Ref. 5). Comparisons of the mare regions with the elevated, highly cratered highlands regions have revealed variations in lunar dust composition, as shown in Table IV (Ref. 38). Basalt flows covering the maria resulted in the soil there being enriched in Fe, Ti, and Mg, mostly from ilmenite (FeTiO_3), olivine ($(\text{Mg,Fe})_2\text{SiO}_4$), and other minerals. Highland regions can contain as much as 60 percent anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$), whereas maria contain only approximately 35 percent (Ref. 39). Even with these differences in mineralogy, significant differences in particle size were not observed in comparisons of the maria and the highlands.

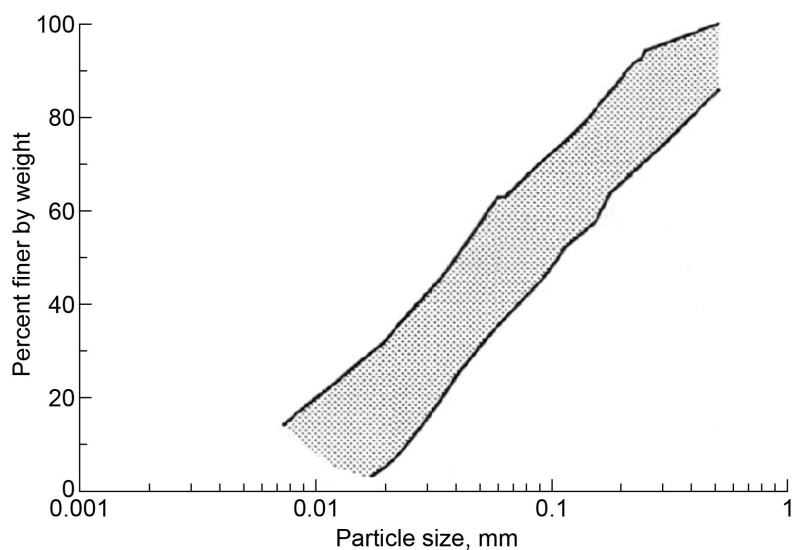


Figure 4.—Lunar regolith particle size distribution (Ref. 36).

TABLE IV.—LUNAR MARE AND HIGHLAND MINERALOGICAL COMPOSITION (REF. 38)

Chemical species	Maria, wt% ^a	Highlands, wt% ^b
SiO ₂	40.1	44.2
TiO ₂	9.2	0.3
Al ₂ O ₃	10.7	29.4
Cr ₂ O ₃	0.5	-----
FeO	17.9	2.96
MnO	0.2	0.6
MgO	9.9	16.3
CaO	10.6	0.7
Na ₂ O	0.4	0.1
K ₂ O	0.1	-----

^aSoil 71060, Apollo 17.

^bSoil 67710, Apollo 16.

Particles smaller than 10 μm tend to be enriched in Al₂O₃ due to the susceptibility of feldspars (anorthite) to comminution, the mechanical breaking of rocks and minerals, relative to olivine and pyroxenes (Ref. 40). Al₂O₃ content decreases over the particle size range of 10 to 90 μm ; increases above 100 μm are largely due to an abundance of agglutinates, individual particles consisting of smaller particles that are stuck together. These two processes, comminution and agglutination, are a result of meteoroid impact, thermal cycling, creep, and solar wind erosion, and they account for the size and shape variation of lunar dust (Ref. 38). Although glassy spheres account for approximately 20 wt% of the lunar soil, agglutinates make up as much as 50 to 60 wt%, with each particle typically containing three to four different mineral types. The average surface area of an agglutinate particle is typically 60 times greater than that of a spherical particle of the same mass (Ref. 5). Examples of different lunar dust particles are shown in Figure 5.

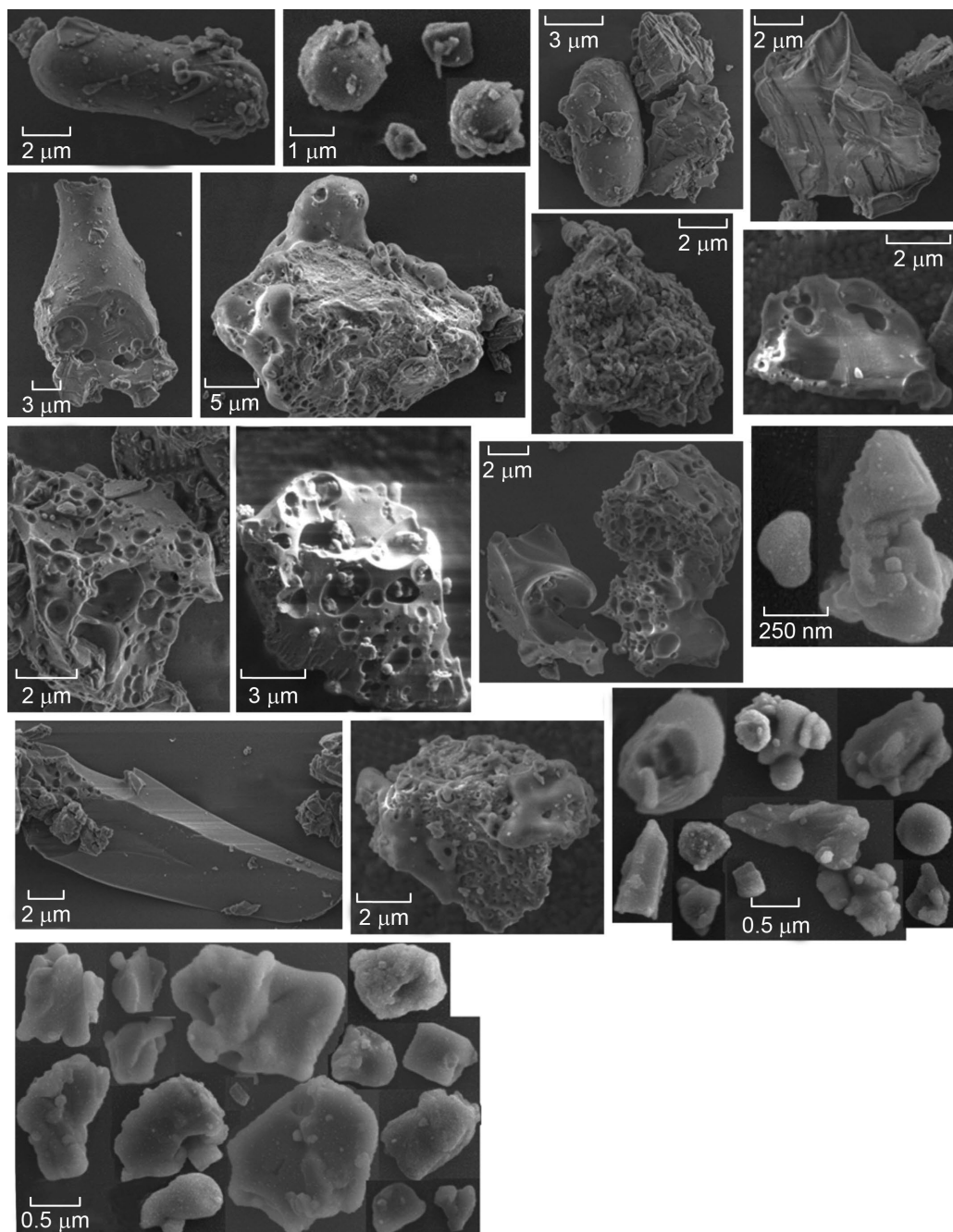


Figure 5.—Images of lunar dust particles retrieved during Apollo missions (Ref. 35; reproduced with permission from American Society of Civil Engineers (ASCE)).

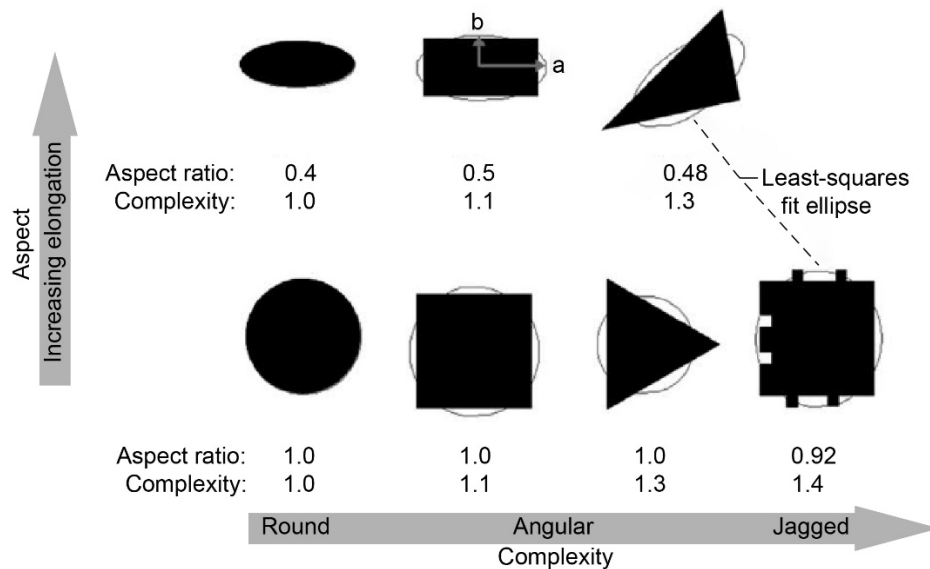


Figure 6.—Graphical representation of projection image approach for characterizing lunar dust particles (Ref. 35; reproduced with permission from ASCE).

With this significant variation in particle shape, general characterization of the morphology of the lunar dust is difficult. Liu et al. used two-dimensional projection images to characterize the aspect ratio and shape complexity of lunar soil samples (Ref. 35). The aspect ratio was calculated as the ratio of the major and minor axes of an ellipse generated from a least-squares fit of the particle area. A perfect circle would have an aspect ratio of 1, and lower values would be indicative of less circularity. Complexity values were calculated from the ratio of the actual perimeter to the perimeter of the ellipse. Increasing complexity values indicated greater angularity. A graphical description of this projection approach is shown in Figure 6, and results determined for lunar soil samples and a lunar simulant are shown in Figure 7.

Environmentally Originated Lunar Dust Motion

Beyond size and shape, two intrinsic properties of lunar dust contribute to its propensity to be released from the lunar surface and moved: electrical conductivity and cohesion. Lunar dust is electrically insulating, with conductivity values determined to be from 10^{-13} to 10^{-16} $1/\Omega\cdot\text{m}$ (Ref. 41). As a result, dust particles that are charged may undergo strong repulsion forces with the surrounding environment due to the generation and variation of electric fields on the lunar surface, discussed in greater detail in the Plasma Sheath Interactions section. Further, the cohesion force between lunar dust particles (the force keeping dust particles together) is very small, 0.035 to 0.05 N/cm^2 (Ref. 42). For comparison, a volcanic ash soil considered to exhibit weak cohesion forces (Kashima soil) was determined to have a minimum cohesion force of 1.9 N/cm^2 in a water saturation study; this value increased with lower water content (Ref. 43). Therefore, relatively small disruptive forces would be needed to separate lunar dust particles. Those disruptive forces arise from two main sources: natural and anthropogenic interactions. In the following sections, natural sources, including micrometeoroid bombardment and solar illumination, will be discussed with regard to their role in lofting lunar dust particles. Finally, anthropogenically instigated dust motion will be described.

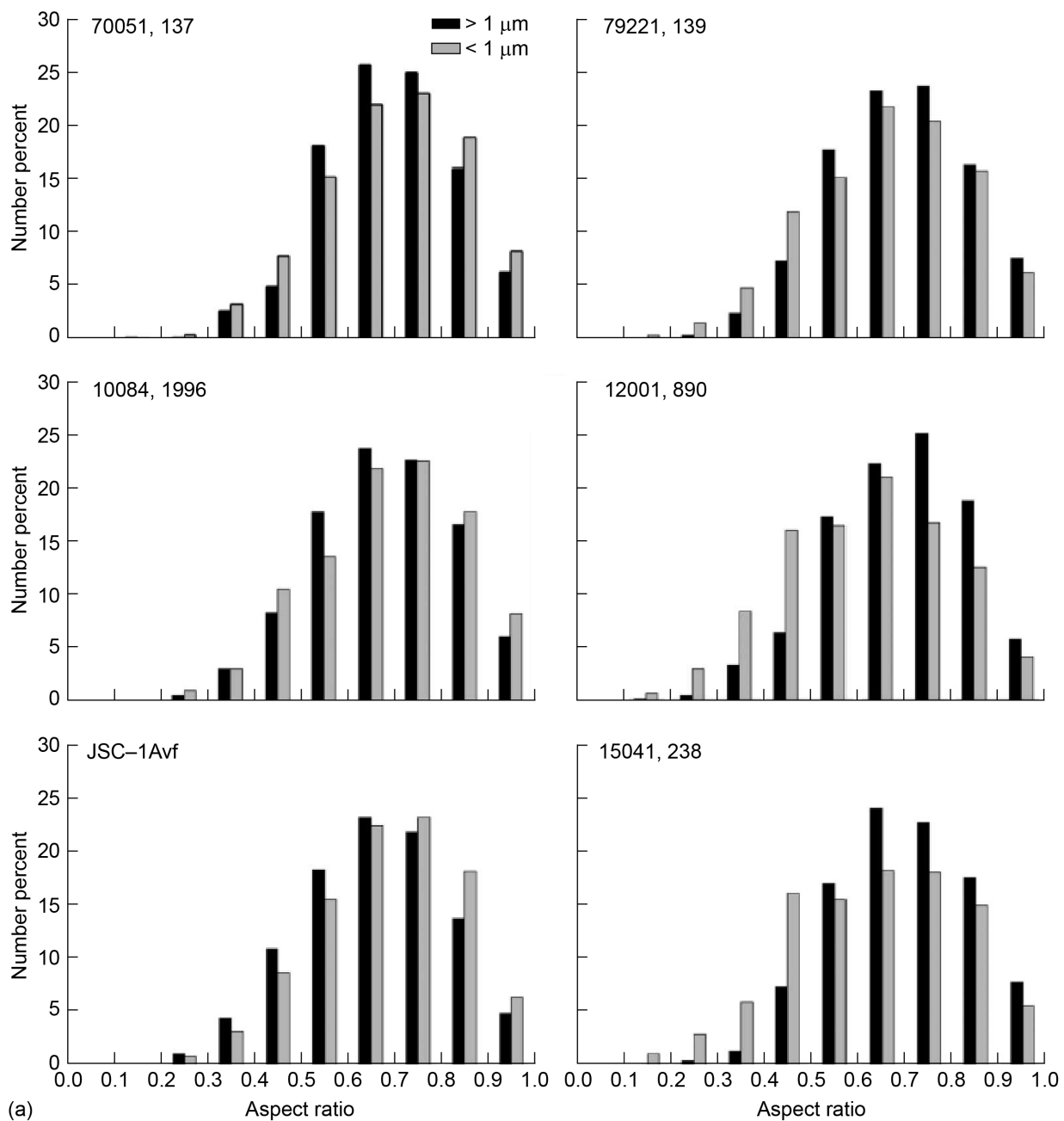


Figure 7.—Values determined for five lunar soil samples and lunar simulant JSC-1Avf calculated from particle number count data (Ref. 35; reproduced with permission from ASCE). (a) Aspect values. (b) Complexity values.

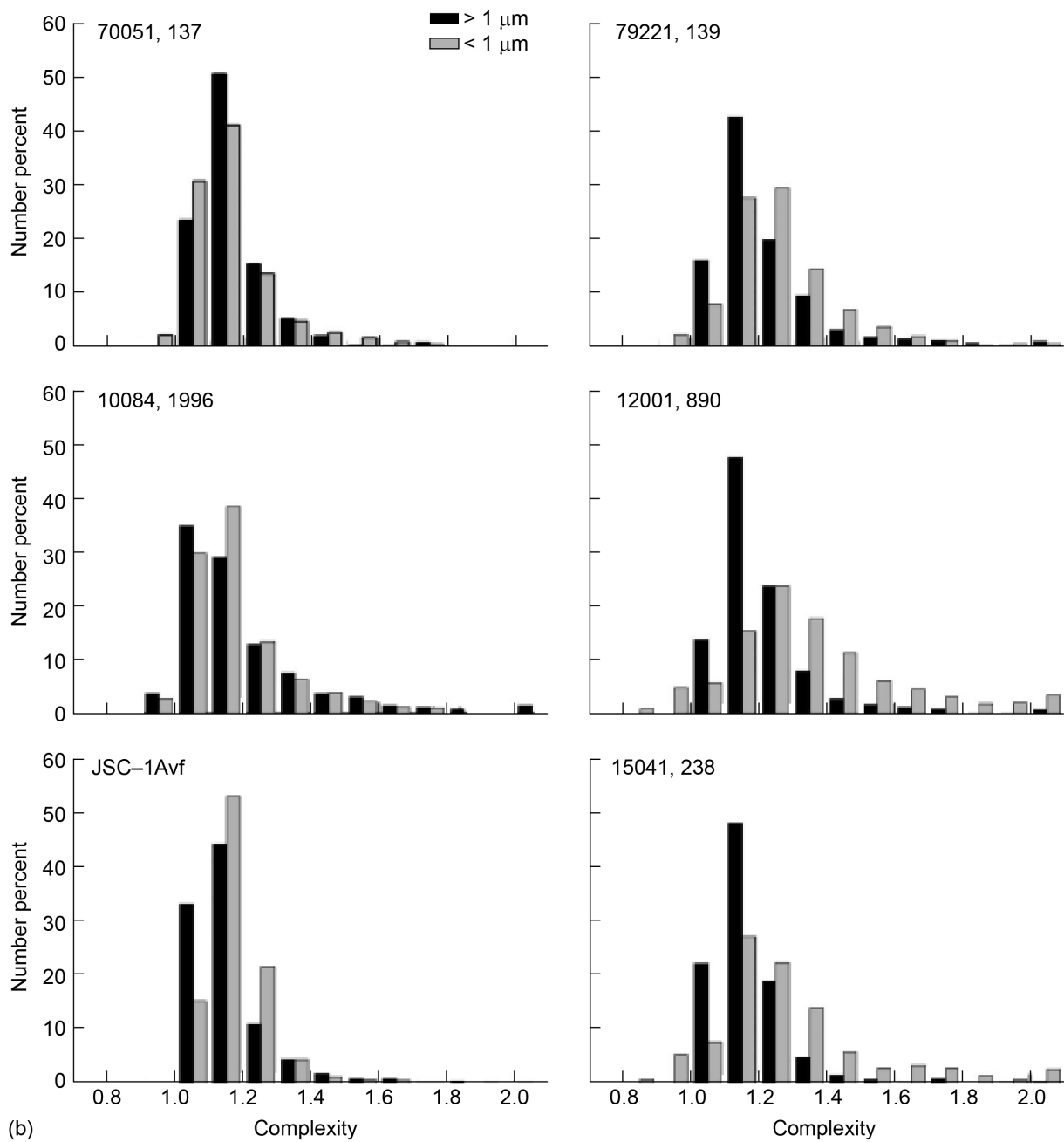


Figure 7.—Concluded.

Lunar dust particles have been detected at significant separation distances from the lunar surface. One of the most comprehensive studies to make such observations was carried out by the Lunar Atmosphere and Dust Environment Explorer (LADEE). LADEE was launched on Sept. 3, 2013, and reached lunar orbit on Oct. 6, 2013, with one of its primary objectives being the study of the lunar dust environment (Ref. 44). One instrument on LADEE, the Lunar Dust Experiment (LDEX), collected detailed information on the particle mass of impacting particles at altitudes ranging from 3 to 250 km. On average, one particle impact event occurred per minute, with increases during meteor showers. A total of over 14,000 impacts were detected over 80 days. Analysis of the altitude, mass, and frequency of impacts indicated the presence of a permanent dust cloud in the lunar atmosphere that was asymmetric with a slight tilt toward the Sun (see Fig. 3 in Ref. 45). Particles within the lunar dust cloud ranged in size from 0.3 to 100 μm and followed a power law distribution (x^a) with an exponent (a) of 0.9. Electrostatic migration heights were determined to depend on particle size with 100-nm particles capable of migrating to tens of kilometers away from the lunar surface (Ref. 46). Ejecta density distribution plots were generated by Yang et al. based on the LDEX data with consideration of the interplanetary impactor environment of the Earth–Moon system (Ref. 47). Yang et al. calculated an enhanced particle ejecta generation rate on the dayside of the Moon and attributed this to exposure to UV light and solar wind, as well as an increased surface temperature, relative to the Moon’s night side. However, measurement of particle charge by LDEX indicated that smaller particles had a larger surface potential (see Fig. 5 in Ref. 44). These large surface potentials were determined to indicate that the particles became charged from impact events, not from exposure to UV and plasma currents. It was also determined that particles ejected from the lunar surface at ≥ 4 m/s will follow purely ballistic trajectories with nominal influence from the presence of local electric fields regardless of particle size (Ref. 48).

Micrometeoroid Bombardment

Micrometeoroid bombardment, one of the primary contributors to ejected lunar dust, is sporadic and can be divided into six groups: Helion, Antihelion, Apex, Antiapex, and Northern and Southern Toroidal meteoroids. Yang et al. provide a thorough analysis of how meteoroid impacts from each of these sources influence localized ejected dust concentrations (Ref. 47). Approximately 95 primary meteoroids with a mass of at least 1 ng impact every square meter of the lunar surface annually. This results in a mass accumulation of approximately 18 tons daily, or 0.2 kg/s when averaged over the entire lunar surface, with slightly higher mass production rates on the dayside (Ref. 49). Hypervelocity impacts are bombardment occasions that occur at approximately 20 km/s; these high-energy events can eject as much as 100 to 1,000 times the impactor mass, depending on the impact angle. This ejecta manifests as secondary particles (Ref. 50). The average particle ejecta velocity was calculated to be 0.1 km/s, indicating that a majority of this ejecta will return to the lunar surface based on a lunar escape velocity of 2.3735 km/s (lunar gravitational acceleration rate: $1.67 \text{ m}^2/\text{s}$).

Plasma Sheath Interactions

The influence of solar irradiation on lunar dust ejecta, especially as it relates to dust particle densities closer to the lunar surface, was investigated by Poppe et al. (Ref. 51). The work of Li et al. provides a detailed analysis of the interactions between solar irradiation and the lunar surface from a global perspective (Ref. 52). Generation of a photoelectron sheath occurs at small solar zenith angles due to the photoemission current being greater than the ambient plasma collection current. This photoelectron sheath has a typical potential of 5 V, with a strength of 5 V/m arising from the thickness (typically approx. 1 m). As the solar zenith angle increases, the photoelectron sheath is anticipated to weaken and eventually transition to a negative plasma sheath near the lunar terminator. Although the maximum strength of the

electric fields on the lunar surface is currently open for debate, the implications of the field strength relative to topographical features can be evaluated. Because the Debye length (a measure of a charge carrier's net electrostatic effect and how far its electrostatic effect persists) on the dayside of the Moon is roughly 1 m, topographical features greater than 1 m should not affect the plasma environment; the influence of exposed regions (as compared to shadowed regions) on the local electrostatic environment would be negligible on this length scale. This is particularly relevant when considering whether a VSAT structure would have local influence on the electrostatic fields. On the nightside, the plasma sheath becomes negatively charged and can extend up to 1 km or more from the lunar surface (Figure 8) (Ref. 26).

The horizontal glow observed at the terminator has been attributed to the presence of a low cloud of lunar dust particles being lofted due to the transition from a positively charged plasma sheath to a negatively charged one. Initial estimates suggested that the lofted, positively charged dust particles were levitated from 3 to 30 cm from the lunar surface with migration densities of 300 g/m² (Ref. 20). This equates to 2×10^5 times more mass than secondary ejecta from meteoroid impacts (Ref. 53). Light brightness measurements by the Lunokhod-2 rover estimated a dust cloud to consist of, on average, 5- μ m dust particles that scattered sunlight from about 260 m above the lunar surface (Ref. 47). More research is needed to ascertain the origin of these particles, since it is possible that the dust particles present at this height could have originated from micrometeoroid impact instead of dust lofting.

Poppe et al. modeled a three-dimensional dayside, near-surface lunar plasma environment at several solar zenith angles that included a 7-m-diameter, 1-m-deep crater (Ref. 51). At noon—that is, at a solar zenith angle of 0°—the photoelectron sheath was determined to have a maximum field strength of 5 V and extended up to 15 m. As the solar zenith angle was increased, the electric potential within the sunward side of the crater diminished, becoming zero at approximately 45° (Figure 9). At 60°, the sunward side reached a negative potential. This region is adjacent to a region of positive charge and significant horizontal electric fields appeared. Poppe et al. also conducted net dust transport simulations predicting that crater regions with similar dimensions (i.e., a diameter of 7 m), would exhibit a pronounced increase in lunar dust relative to the surrounding surface. They also predicted a size dependence on dust trapping, with the accumulations being greater for particles 100 nm to 10 μ m and diminished trapping for particles less than 100 nm.

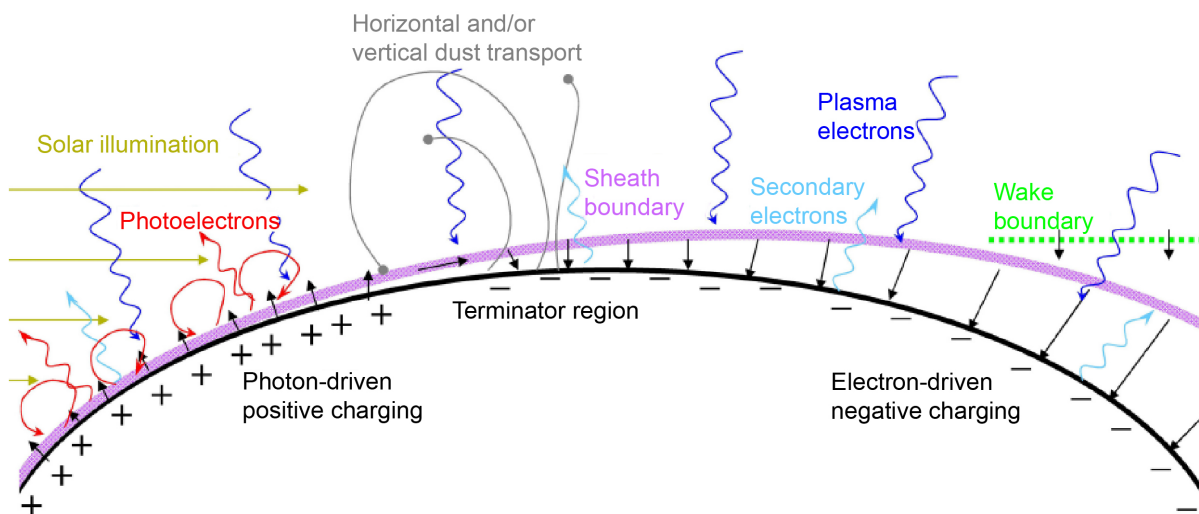


Figure 8.—Lunar surface charging and electric fields (adapted from Ref. 26).

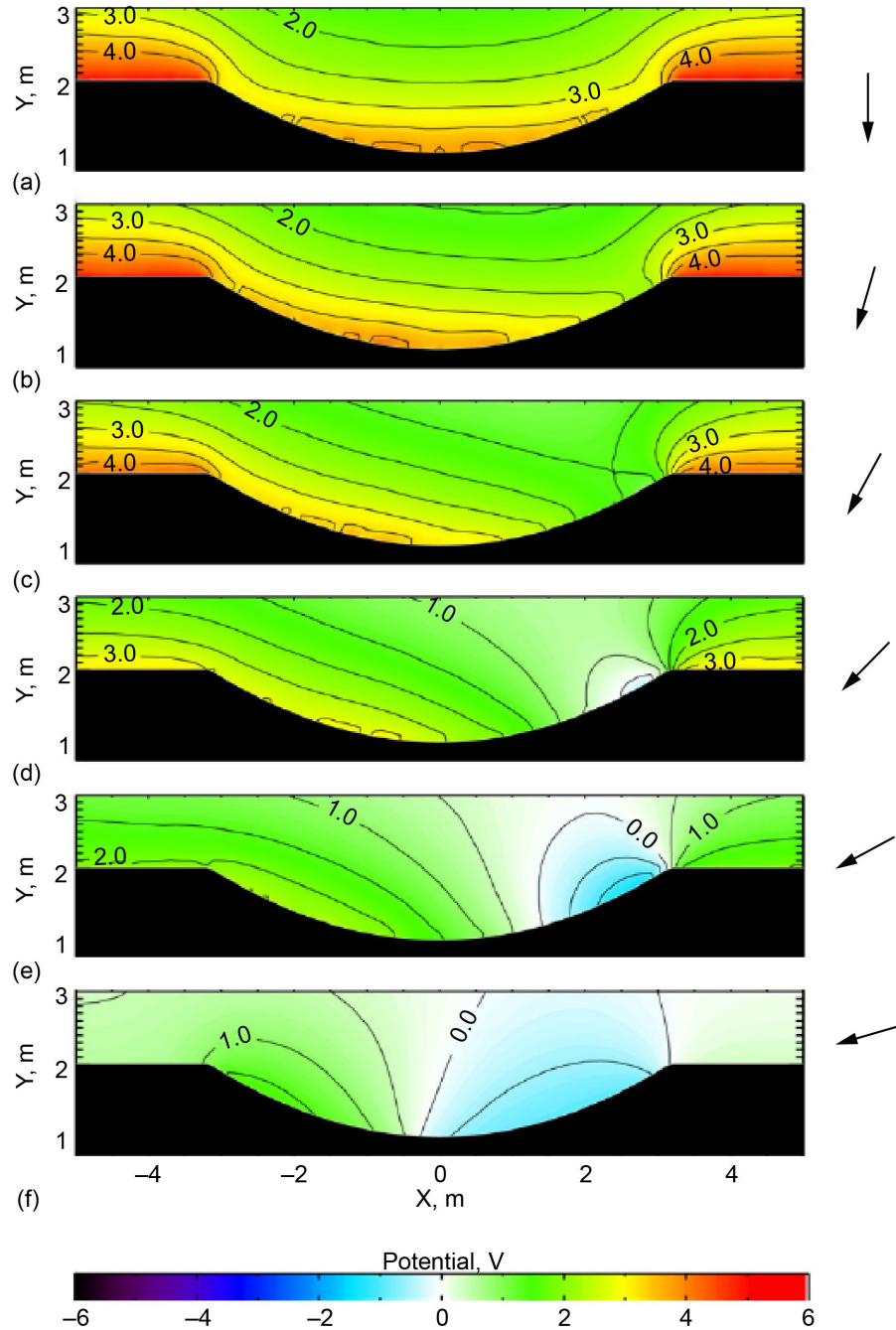


Figure 9.—Electric potential plots of lunar surface containing 7-m-wide crater feature at various solar zenith angles (Ref. 51; reproduced with permission from Elsevier). (a) 0°. (b) 15°. (c) 30°. (d) 45°. (e) 60°. (f) 75°.

Permanently Shadowed Regions

Electric field variations are even greater in polar regions, where very small distances can separate permanently shadowed regions (PSRs) from regions with nearly continuous solar illumination. Zhao et al. generated a model to simulate lunar dust behavior in polar regions considering two scenarios: a raised surface and a pit (Ref. 54). These two geographical features were placed at the lunar terminator with a

latitude of 80° , resulting in a solar wind impingement angle of 10° relative to the lunar surface (Figure 10). The plasma environment included solar wind ions and electrons, photoelectrons, and a plasma sheath. Three dust-generation locations were evaluated for each scenario, with two different dust sizes considered, $1\ \mu\text{m}$ and $10\ \mu\text{m}$. The initial charge sufficient to result in an initial upward force was considered for each particle.

For the raised topographical feature (Figure 10(a), referred to as the “convex surface” in Ref. 54), photoelectron emission from the surface and the raised topographical feature generated positive potentials on the front and top surfaces of the feature and the lunar surface. Conversely, shadowed regions developed a negative potential. Plots of dust distribution in this environment were generated for each case (Figure 11). As can be seen, most of the dust lofted for case 1 concentrated at a height of approximately 10 m, although there are significant dust densities as high as 80 m from the lunar surface. For the shadowed region, represented as case 2, lofted dust concentrated at approximately 20 m from the lunar surface. There was little evidence to suggest that dust lofted in case 2 would migrate to the region defined as case 1. Case 3 was similar to case 1, with little dust observed to migrate to the regions defined by case 1 or case 2.

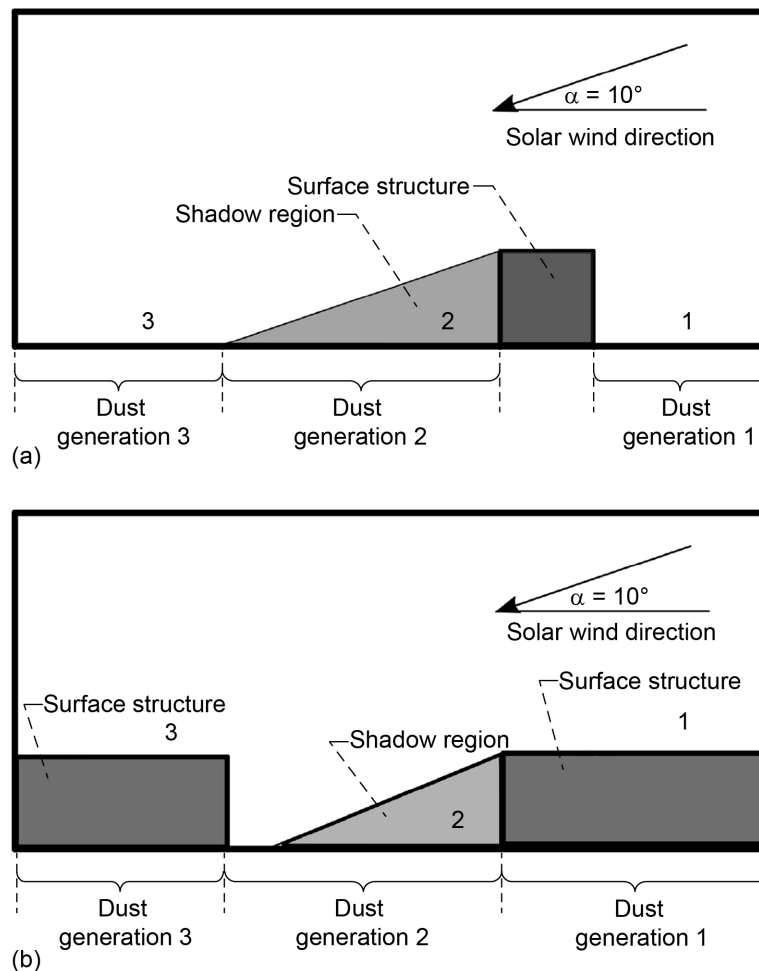


Figure 10.—Models of features positioned in polar region on lunar surface (Ref. 54; reproduced with permission from ASCE). Angle, α .
(a) Raised topographical feature. (b) Pit.

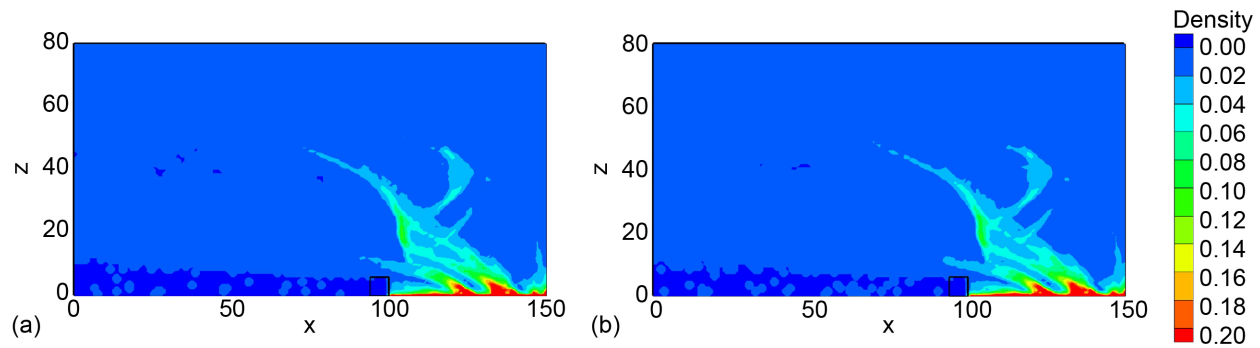


Figure 11.—Dust concentration plots generated from raised topographical feature scenario considering dust generation case 1 in Figure 10(a); X and Z coordinates normalized to 1.38 m, Debye length of photoelectron at 90° solar zenith angle (Ref. 54; reproduced with permission from ASCE). (a) Particle size = 1 μm . (b) Particle size = 10 μm .

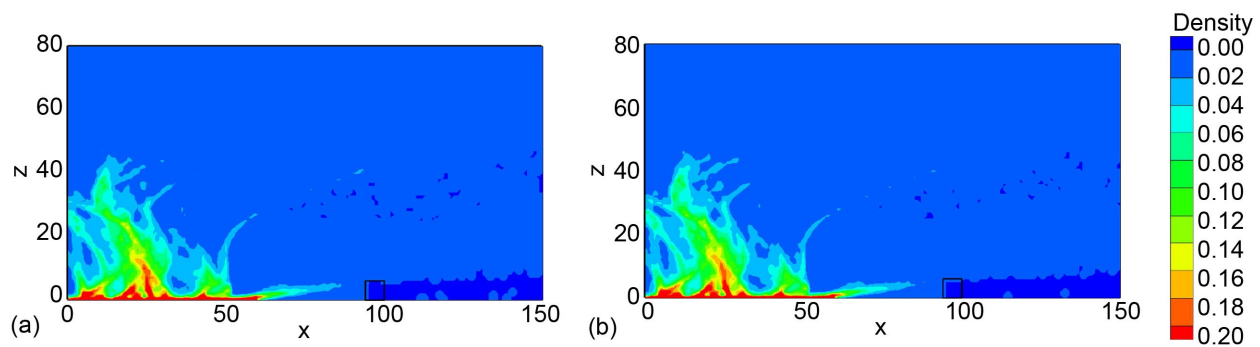


Figure 12.—Dust concentration plots generated from pit topographical feature scenario considering dust generation case 3 in Figure 10(b); X and Z coordinates normalized to 1.38 m, Debye length of photoelectron at 90° solar zenith angle (Ref. 54; reproduced with permission from ASCE). (a) Particle size = 1 μm . (b) Particle size = 10 μm .

For the pit topographical feature (Figure 10(b), referred to as the “concave surface” in Ref. 54), the potential in most areas above the surface was nearly neutral due to the neutrality of the total charge. The magnitude of the electric potential inside the pit, up to tens of volts, was dependent on the size of the shadowed region. Results from cases 1 and 3 were similar to those described for the raised topographical feature, with nearly no dust transport into the pit (Figure 12). For case 2, dust was determined to concentrate within the shadowed region of the pit. Dust particles with greater charge were observed to migrate farther.

These pit features modeled by Poppe and Zhao, also referred to as “twilight craters,” are shadowed craters near the terminator. Experimental evidence suggests that these regions exhibit particularly high levitated dust densities (Ref. 46). Analysis of LDEX measurements determined that there were “dust fountains” originating from interactions between solar wind and twilight crater walls (Figure 13), specifically at the Copernicus and Plinius craters, where solar wind and magnetic anomalies were determined to have no influence on the detected particles. These highly localized phenomena, arising from large secondary electron production within this environment (Ref. 55), resulted in 100-nm particles detected at heights tens of kilometers from the lunar surface.

There is significant interest in PSRs due to the possibility of these regions being enriched with resources, especially water (Ref. 56). Observation of dust ponds on the asteroid Eros suggested that PSRs could have greater amounts of loosely compacted lunar dust arising from electrostatic transport (Ref. 57). However, this was contradicted by the previously discussed simulations by Zhao et al. (Ref. 54) and the calculations by Cheng et al. (Ref. 58), who created a seismic agitation model suggesting that impact events on Eros generated these pond features. Given the differences in size and surface gravity between Eros and the Moon, it is unlikely that similar features would form on the lunar surface (Ref. 58).

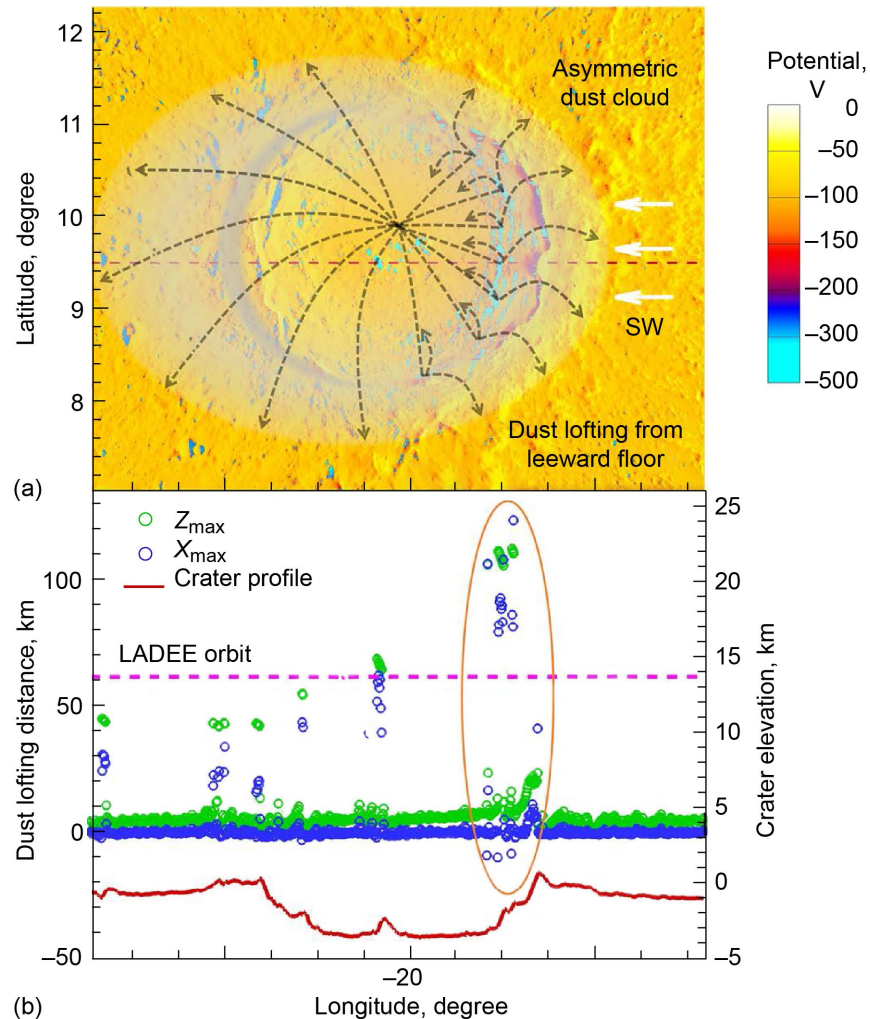


Figure 13.—Observed dust fountain originating from twilight crater wall (Ref. 46; reproduced with permission from American Geophysical Union). (a) Surface potentials, dust lofting trajectories (black arrows), solar wind direction (white arrows), and area of anticipated lunar dust cloud (gray region). (b) Maximum altitude, $Z_{\max}$ (green dots), and maximum horizontal distance, $X_{\max}$ (blue dots), of 100-nm-diameter lofted dust. Orange oval highlights increase in lofted dust close to crater wall. Crater profile (red line) and altitude of LADEE orbit (pink dashed line) are also indicated.

Determination of Lunar Dust Deposition Rates From Natural Phenomena

Lunar Dust Detector Experiments (DDEs) placed on the lunar surface during Apollo 12, 14, and 15 were used to ascertain lunar dust deposition rates arising only from natural phenomena (Ref. 59) (Figure 14.). The detectors, both covered and uncovered, were placed 1 m from the lunar surface and consisted of three silicon solar cells in different orientations. The reduction in the astronomically normalized counts, where normalization was used to remove seasonal variation, was attributed to several phenomena, including accumulation and removal of lunar dust, discoloration, darkening, and exposure to energetic particle irradiation (Figure 15). Contributions from lunar dust accumulation were derived from the average long-term degradation of the covered solar cells (a 7-percent count loss over 5 years). Utilizing count losses determined in a controlled experimental environment using MLS-1 (Ref. 20), an upper estimate for the lunar dust accumulation rate was determined to be 100 $\mu\text{g}/\text{cm}^2$ annually. This suggests that it would take 1,000 years to accumulate a 1-mm-thick layer on an exposed surface. As will be discussed in the next section, human interactions with the lunar surface are likely to contribute significantly higher dust deposition rates, which will make logistics, especially around VSAT architectures, critical to retain high power-generation efficacy.

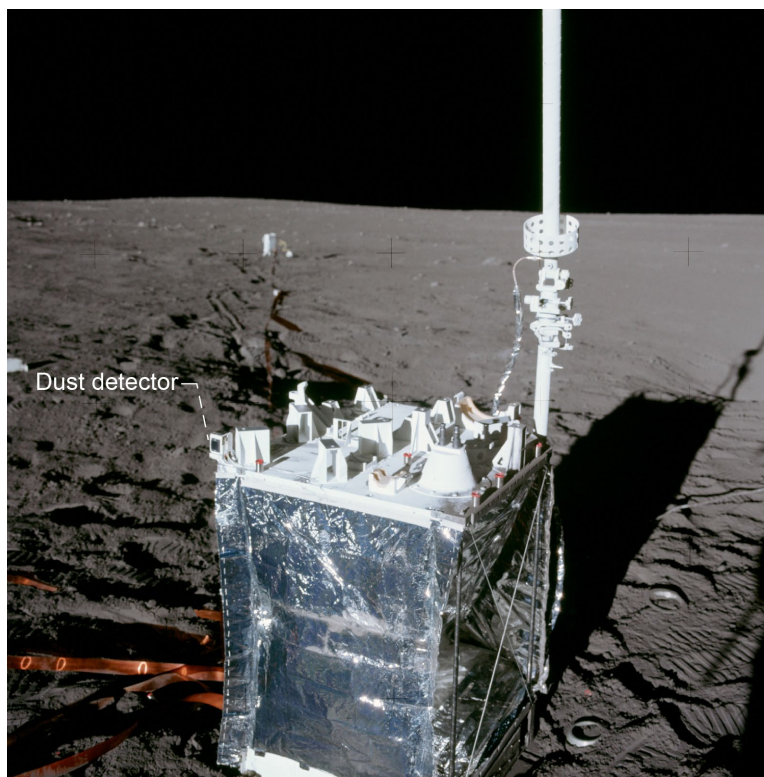


Figure 14.—DDE detector placed on lunar surface during Apollo 12 (Ref. 60; NASA Apollo 12 Image Library, NASA AS12-47-6927).

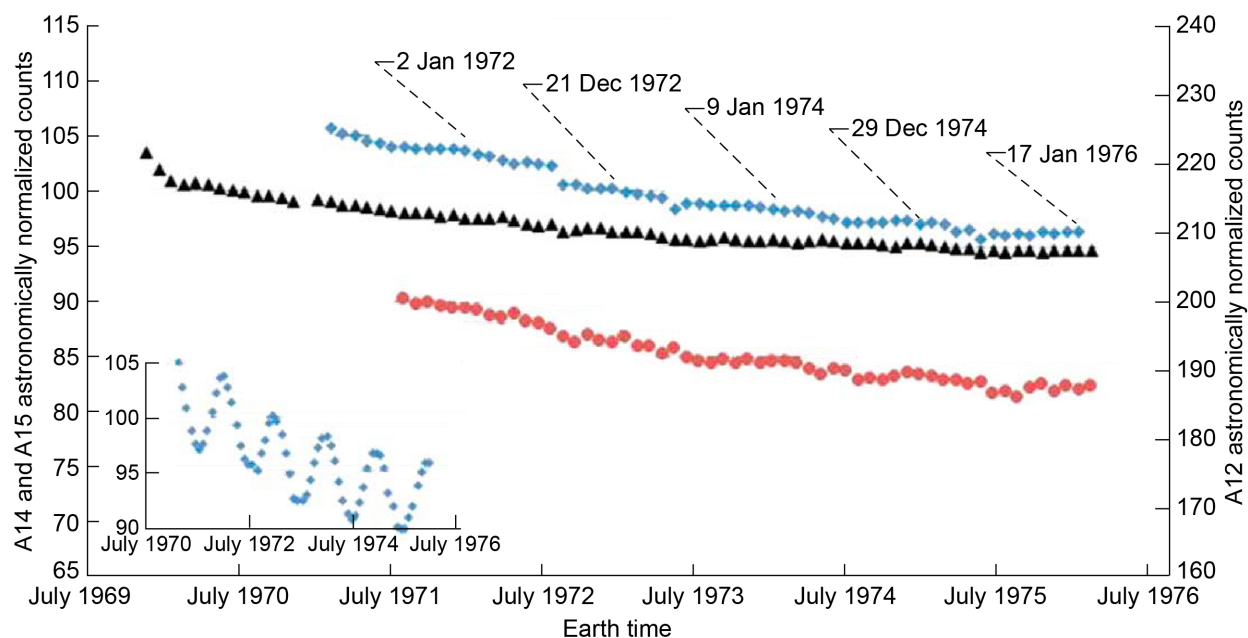


Figure 15.—Results from DDE detectors from Apollo 12 (black), Apollo 14 (blue), and Apollo 15 (red); A14 covered cell raw counts (inset). (Adapted from Ref. 59; reproduced with permission from American Geophysical Union.)

Anthropogenically Originated Lunar Dust Motion

Sources for lunar dust disruption arising from human interactions are relatively straightforward. They include astronauts walking on the lunar surface, lunar terrain vehicles, mining and construction, and lunar landers during both landing and takeoff operations. Katzan and Edwards considered the unique side-to-side gait of the Apollo astronauts and determined that the maximum dust range extending from the astronaut would occur when dust particles were disrupted at an initial orientation of 45° (Ref. 37). Dust that was disturbed with an initial orientation of 90° relative to the lunar surface was calculated to reach a height of 4 m. With the significant changes in spacesuit designs for the Artemis III explorers, these dynamics may change, potentially reducing dust disruption due to improvements in mobility (Ref. 61).

Lunar Terrain Vehicles

Lunar terrain vehicles will be critical to increase lunar mobility range, especially considering the latter stages of a sustained lunar presence, where it is likely that lunar facilities will be spread over a significant distance. During the Apollo missions, it was observed that lunar dust was cast out behind the lunar rover, as well as being carried over the wheels, sprayed out of the side of the wheels, and piled up in front of the wheels (Ref. 20). Dust ejected from the front of the wheels was calculated to have a maximum speed of up to 7.12 m/s based on Apollo rover velocities. The maximum particle displacement distance (20.4 m) was reached when the dust was ejected from the wheel surface at 120° (Figure 16.). Particles ejected at angles $<90^\circ$ (i.e., behind the lunar rover) were determined to continue to move forward due to both the forward momentum imparted by the lunar rover motion and the lack of atmosphere at the lunar surface.

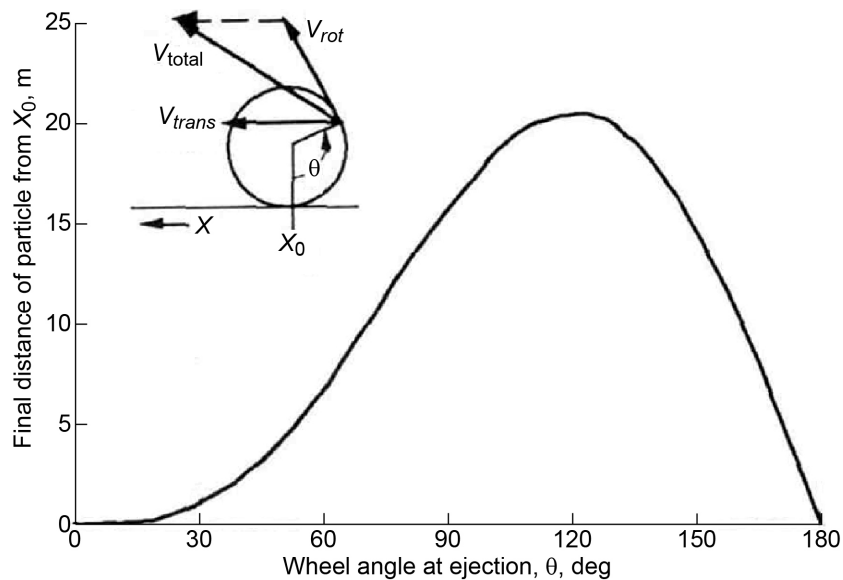


Figure 16.—Calculated maximum displacement distance of lunar dust ejected from a lunar terrain vehicle based on ejection angle (Ref. 37). X is the final distance of particle travel from the wheel's point of contact with the lunar surface, X_0 . V_{total} is the vector sum of the rotational, V_{rot} , and translation, V_{trans} , velocity vectors.

Lunar Construction Activities

Mining and construction operations are likely to cause high, very localized disruption of lunar dust. Considering the breadth of activities that fall into this category (Ref. 62), it is unclear how best to quantify dust velocities, maximum displacement distances, and accumulation rates. It is anticipated that there will be significant variability in dust velocity, especially close to the active zone (e.g., a drilling operation), with accumulation rates being greatest closest to the activity and diminishing as the separation distance increases.

Lunar Lander Operations

Interactions arising from human activities are of the greatest complexity when considering landing on and taking off from the lunar surface. During Apollo 12 and 14, astronauts observed dust as high as 37 m from the lunar surface upon descent, and the dust cloud was calculated to be approximately 300 m in diameter. Based on the dust that accumulated on Surveyor III as a result of the Apollo 12 spacecraft landing 155 m away, it was determined that significant accumulations can occur as far as 2 km away from a landing site (Ref. 37). Alignment of the screwhead shadows on Surveyor III (i.e., portions of the surface that were not contaminated by lunar dust arising from the lunar lander due to being “shadowed” by the protruding screwhead) with the lunar module was used to estimate the velocity of the lunar dust that impacted the Surveyor III surface. This was determined to be at least 40 m/s, with estimates as high as 100 m/s also reported (Refs. 63 and 64). Images captured during the landing of Apollo 14 showed that significant lunar soil was removed by the thrust from the descent engine, which remained engaged until 2 s after contact. More than 600 kg of soil was estimated to have been removed from the landing site and subsequently deposited over a nearly 150-m radius at approximately 9.6 g/m². Katzan and Edwards generated three models based on these observations to ascertain dust accumulation amounts as a function of the distance from an Apollo-era lunar module (Figure 17) (Ref. 37). Model 1 considered a broad particle velocity range up to 2,000 m/s to account for pitting damage observed on the Surveyor III's reflective glass. Model 2 was developed with the greatest fraction of particles traveling at velocities

from 40 to 100 m/s, which was the closest representation to the actual particle velocity distribution experienced on the lunar surface arising from the Apollo 12 landing. Model 3 was similar to model 2 except that 50 percent of the particles had velocities in the range of 40 to 100 m/s. The predicted accumulation levels at 1 km away from the lunar landing site for models 1, 2, and 3 were 0.83 mg/cm², 0.14 mg/cm², and 1 µg/cm², respectively. This 1-km separation distance will be used later in the work as the separation distance from a VSAT structure and a landing pad during the habitat construction phase of sustained lunar presence development.

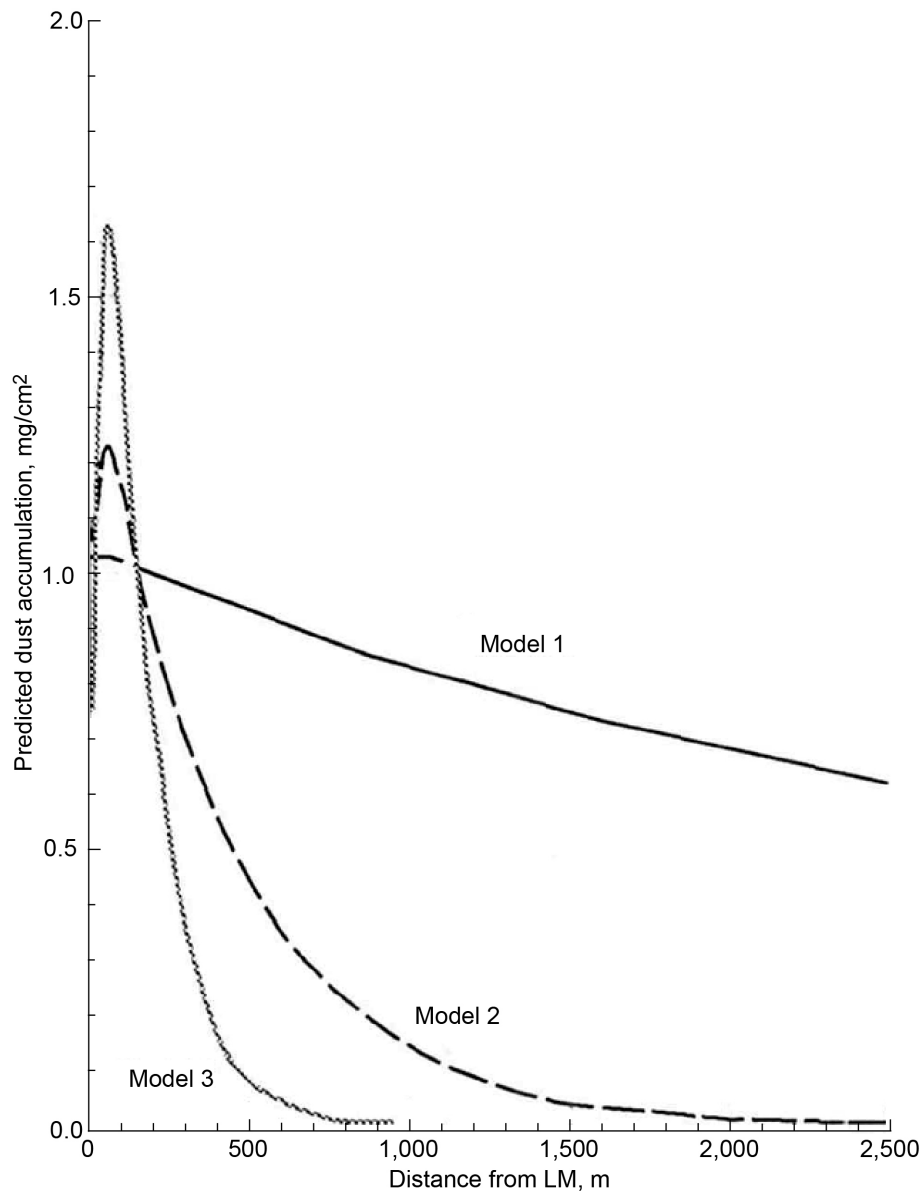


Figure 17.—Model results of lunar dust accumulation rates arising from lunar module (LM) landing (Ref. 37).

The degree of dust perturbation arising from lunar module landing may depend on local lunar environment properties. Lower dust deposition amounts (0.83 mg/cm^2) were observed upon landing of China's Chang'e-3 vehicle, which was attributed to the landing site consisting of younger mare basalts relative to the Apollo landing sites (Ref. 65). Observations made from the Lunar Reconnaissance Orbiter, however, suggested that the local perturbation region scaled with dry lander mass (Figure 18) (Ref. 66). Averaging the area for all observed lander sites generated a quadratic relationship, suggesting that heavier landers should land farther from sensitive lunar surface facilities to minimize interactions with disrupted lunar dust. Wittal et al. used dry lander mass, M_{lander} , scaling for determination of regolith mass displacement, M_{regolith} , to ascertain the risk to orbital assets arising from high-velocity plume ejecta (Ref. 67) (Eq. (3)).

$$M_{\text{regolith}} = 0.762M_{\text{lander}}^{1.77} \quad (3)$$

They determined that particles significantly smaller than $10 \text{ }\mu\text{m}$ were negligible, as most of these particles would be carried away by solar wind. Larger particles were calculated to reimpact near the landing site, with particle density decreasing exponentially as distance from the landing site increased. These calculations suggest that high-velocity plume ejecta would present a risk to nearby infrastructure and have negligible influence on orbital assets, such as the lunar Gateway. The scaling factor used by Wittal et al. was found to accurately predict the ejecta mass from the Chandrayaan-3 Vikram lander (Ref. 68).

The lunar dust detector aboard the Chang'e-3 lander was oriented 205 cm above the lunar surface and was used to detect lunar dust accumulation. It detected increased dust deposition from initial landing and then from a rover, Yutu, that was released from the lander on the first lunar day (Ref. 67). Estimated lunar dust deposition masses collected from the solar cell probe detector for the first two lunations (a lunar month, consisting of approximately 29.5 Earth days) were approximately 0.83 and 0.3 mg/cm^2 , whereas the remaining 10 lunations resulted in an additional mass deposition of only 0.15 mg/cm^2 (Figure 19) (Ref. 69).

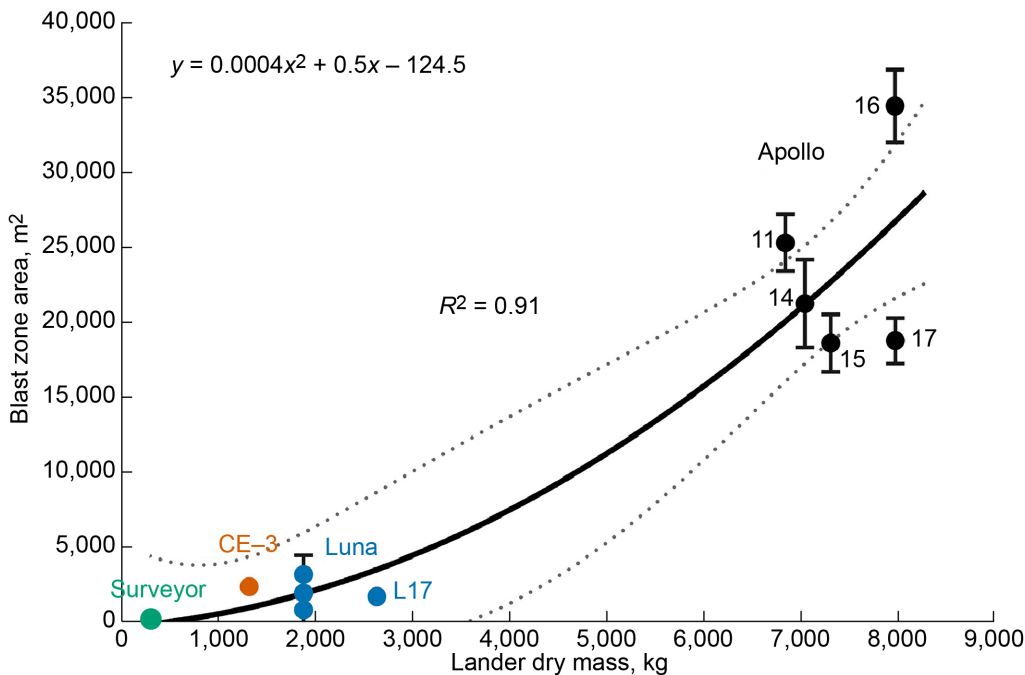


Figure 18.—Surface area disrupted by landing events compared to lander mass (Ref. 66; reproduced with permission from Wiley). Correlation coefficient $R^2 = 0.91$; CE-3 is Chang'e-3; L17 is Luna 17.

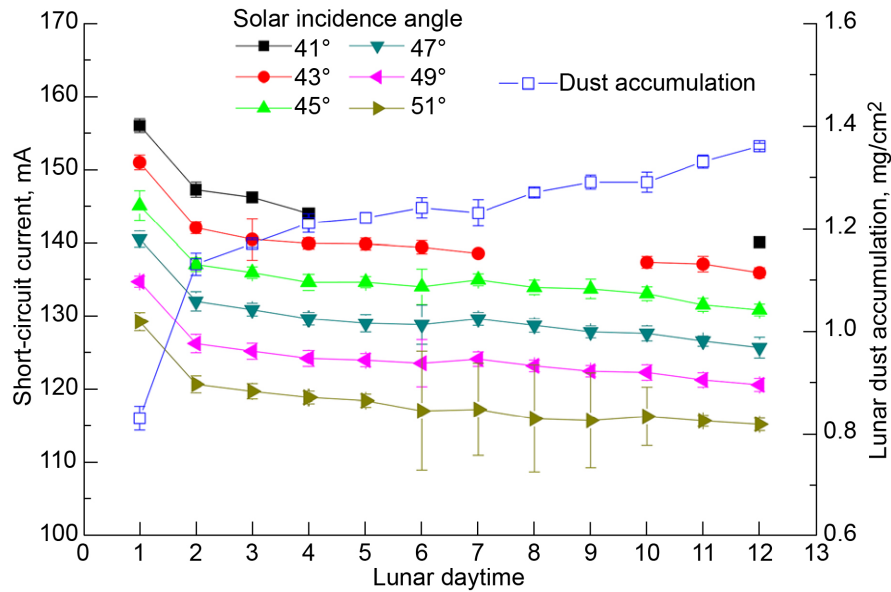


Figure 19.—Short-circuit current values and calculated lunar dust accumulation densities from solar cell probe aboard Chang'e-3 lander (Ref. 69; reproduced with permission from American Geophysical Union).

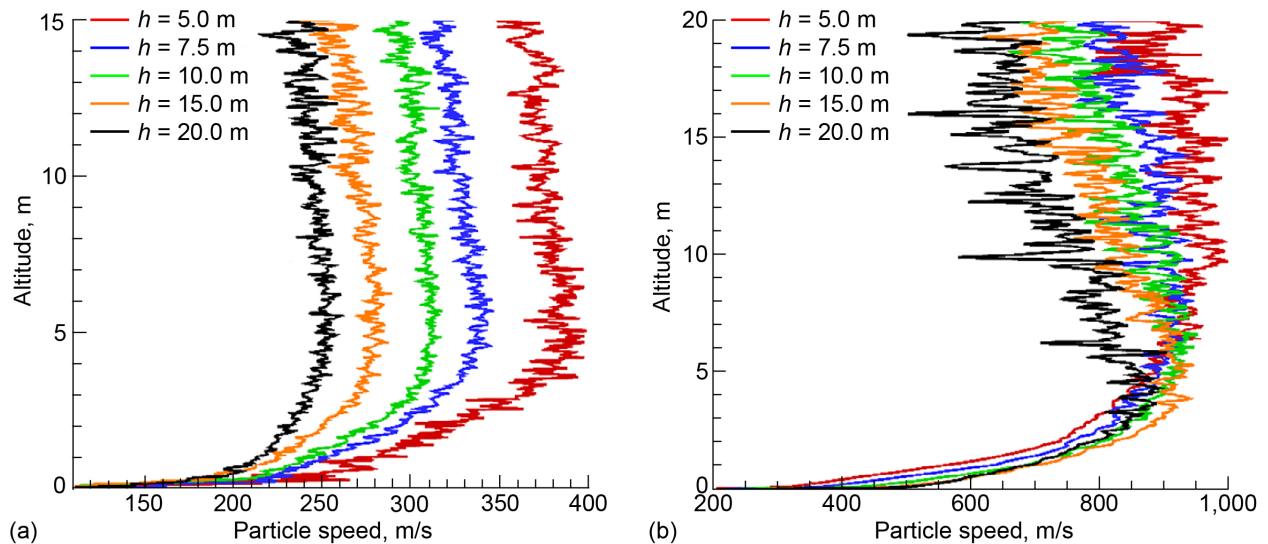


Figure 20.—Calculated velocities for particles displaced by single-engine lander hovering at various altitudes. Lunar lander–surface separation distance, h ; radial distance from plume centerline, $r = 70$ m (Ref. 70; reproduced with permission from AIAA). (a) 11- μ m particles. (b) 800-nm particles.

Simulations have been performed for some of the anticipated lander engine configurations proposed to support the Artemis missions, including single-engine and four-engine configurations. From single-engine simulations, the gas flow fields were determined to be similar in value to each other near the lander at heights of 2.5 m and higher, suggesting that entrained dust particles would be traveling at similar velocities (Ref. 70). As can be seen in Figure 20, these velocities were calculated to be as high as 1 km/s for 800-nm particles, reducing as particle size increased (e.g., 11- μ m particles were determined to travel

at velocities approaching 400 m/s). Particles traveling at these velocities would be anticipated to cause significant abrasion to a nearby surface. This is based on the observations of Surveyor III surface abrasion arising from the nearby landing of Apollo 12, discussed previously, where the upper limit of the estimated particle velocity was 100 m/s. From the four engine simulations, formation of a recirculating gas bubble was predicted as the lunar module approaches due to several complex interactions arising from the proximity of multiple exhaust plumes. Entrainment of dust in this recirculating bubble was predicted, which could cause erosion of the bottom surface of the lunar module. Greater particle density was predicted for particles entrained in the gas flow moving away from the lunar module, with trajectories directed slightly upward relative to the surface, which differs from the single-engine simulation results, at lunar-module-to-lunar-surface separation distances of 5 m and less.

Launch activities may perturb less dust overall than landing activities because of the rapid separation rate of the module from the lunar surface upon launch. This is contrasted to the gradual descent experienced during a landing event. However, the greater thrust experienced during a launch may result in greater dust perturbation rates in the initial launch activity.

Lunar Dust Environmental Concern Matrices

Although the influence of natural environmental factors on lunar dust properties, especially as relates to VSAT operational efficiency, will be constant, the proximity of lunar surface exploration and construction activities will likely evolve as the timeline for lunar surface habitation extends. Anthropogenic activities have been determined to contribute much more significantly to lunar dust accumulation rates and can present hazardous conditions to exposed surfaces relative to natural phenomena. Both natural and anthropogenic concerns have been compiled into a series of matrices that consider different hypothetical phases of lunar surface habitation. In the earliest phase, it is anticipated that lunar lander events and lunar surface mobility activities will occur in very close proximity to a VSAT asset (i.e., within 100 m), so a greater frequency of high-velocity impacts and increased dust deposition rates shall be considered (Table V). In the second phase, an initial infrastructure has been developed and surface operations can be shifted farther from VSAT architectures (i.e., 1 km of separation distance from a high-velocity or large-magnitude dust disruption activity) (Table VI). Local activities arising from habitat construction, increased energy harvesting and distribution, and (potentially) upgrades to VSAT equipment will still be frequent and will contribute to higher lunar dust exposure rates relative to those associated with natural environmental factors. In the final phase, when there is an established lunar outpost, it is anticipated that all surface operations that could adversely impact VSAT operation will be well removed from these assets (i.e., at least 2 km of separation distance from a high-velocity or large-magnitude dust disruption activity) (Table VII). Therefore, the primary considerations will return to those associated with natural phenomena with infrequent, yet relevant, human interactions. For each table, footnotes are provided to connect parameter values to literature sources where appropriate.

The level of concern for each entry in the matrices has been divided into three different categories. The lowest level, green, was assigned to factors that will likely not need to be directly addressed. The next level of concern, yellow, was assigned to factors that can likely be resolved through appropriate materials technologies and engineering solutions. The lighter shade of green is for instances that are likely somewhere between these two levels. The highest level of concern, orange, was assigned to factors that will likely need active dust mitigation strategies to reduce the risk that they would severely adversely impact VSAT operational efficiency.

TABLE V.—VSAT ENVIRONMENT CONCERN MATRIX FOR EARLY STAGES OF
LUNAR EXPLORATION WITH HEAVY LOCAL SURFACE ACTIVITIES

[Cell shading indicates anticipated level of dust remediation required. Dark green = no direct remediation; yellow shading = remediable through materials technologies and engineering solutions; light green = between green and yellow; orange = requires active dust mitigation strategies.]

Region of consideration/ Environmental aspect		0 to 3 m from surface Base and radiators	3 to 10 m from surface Mast	10 to 20 m from surface Solar arrays	>20 m from surface Not specified
Particle count		Not enough available empirical data at this level of resolution			
Particle size		10^{-9} to 10^{-2} m	10^{-9} to 10^{-2} m	<1 mm	$\sim 2 \mu\text{m}^a$
Deposition rate	Natural phenomena	0.1 mg/cm ² per year	<0.1 mg/cm ² per year	<0.1 mg/cm ² per year	<0.1 mg/cm ² per year
	Human activity ^b	>1 mg/cm ² per landing	>1 mg/cm ² per landing	>1 mg/cm ² per landing	>1 mg/cm ² per landing
Particle velocity	Micro- meteoroids ^c	20 km/s	20 km/s	20 km/s	20 km/s
	Human activity	100 to 1,000 m/s	100 to 1,000 m/s	100 to 1,000 m/s	100 to 1,000 m/s
Lunar surface potential		Day: 5 V ^d Night: -150 V ^e	Day: 5 V ^d Night: -150 V ^e	Day: 5 V ^d Night: -150 V ^e	Day: <5 V ^d Night: -150 V ^e
Thermal considerations, lunar south pole ^f		Day: 310 K Night: 80 K	Day: 310 K Night: 80 K	Day: 310 K Night: 80 K	Day: 310 K Night: 80 K

^aValues from Horanyi and Szalay (Ref. 44).

^bAssuming 100 m from landing site. Values from Katzan and Edwards (Ref. 37).

^cConsidering 95 primary meteoroids of 1 ng or bigger every year per square meter. Values from West, Wright, and Euler (Ref. 49).

^dAt a solar zenith angle of 0°, the electric field strength was determined to be 5 V and extended 15 m from the lunar surface (Ref. 50).

^eValues from Figure 4 in the work of Li et al. at a solar zenith angle of 180° (Ref. 52).

^fThese values were calculated as the median values for an epoxy mast from Table B2 in the work of Pappa et al. (Ref. 3). The actual temperature variation will be material dependent.

TABLE VI.—VSAT ENVIRONMENT CONCERN MATRIX FOR SUSTAINED
HABITAT CONSTRUCTION OPERATIONS PHASE

[Cell shading indicates anticipated level of dust remediation required. Dark green = no direct remediation;
yellow shading = remediable through materials technologies and engineering solutions; light
green = between green and yellow; orange = requires active dust mitigation strategies.]

Region of consideration/ Environmental aspect		0 to 3 m from surface Base and radiators	3 to 10 m from surface Mast	10 to 20 m from surface Solar arrays	>20 m from surface Not specified
Particle size		10 ⁻⁹ to 10 ⁻² m	10 ⁻⁹ to 10 ⁻² m	<1 mm	~2 µm ^a
Deposition rate	Natural phenomena	0.1 mg/cm ² per year	<0.1 mg/cm ² per year	<0.1 mg/cm ² per year	<0.1 mg/cm ² per year
	Human activity ^b	~0.2 mg/cm ² per landing	~0.2 mg/cm ² per landing	~0.2 mg/cm ² per landing	~0.2 mg/cm ² per landing
Particle velocity	Micro- meteoroids ^c	20 km/s	20 km/s	20 km/s	20 km/s
	Human activity	7 m/s	<7 m/s	<<7 m/s	Negligible
Lunar surface potential		Day: 5 V ^d Night: -150 V ^e	Day: 5 V ^d Night: -150 V ^e	Day: 5 V ^d Night: -150 V ^e	Day: <5 V ^d Night: -150 V ^e
Thermal considerations, lunar south pole ^f		Day: 310 K Night: 80 K	Day: 310 K Night: 80 K	Day: 310 K Night: 80 K	Day: 310 K Night: 80 K

^aValues from Horanyi and Szalay (Ref. 44).

^bAssuming 1 km from landing site. Values from Katzan and Edwards (Ref. 37).

^cConsidering 95 primary meteoroids of 1 ng or bigger every year per square meter. Values from West, Wright, and Euler (Ref. 49).

^dAt a solar zenith angle of 0°, the electric field strength was determined to be 5 V and extended 15 m from the lunar surface (Ref. 50).

^eValues from Figure 4 in the work of Li et al. at a solar zenith angle of 180° (Ref. 52).

^fThese values were calculated as the median values for an epoxy mast from Table B2 in the work of Pappa et al. (Ref. 3). The actual temperature variation will be material dependent.

TABLE VII.—VSAT ENVIRONMENT CONCERN MATRIX FOR ESTABLISHED LUNAR OUTPOST
[Cell shading indicates anticipated level of dust remediation required. Dark green = no direct remediation;
yellow shading = remediable through materials technologies and engineering solutions; light green = between green
and yellow; orange = requires active dust mitigation strategies.]

Region of consideration/ Environmental aspect		0 to 3 m from surface Base and radiators	3 to 10 m from surface Mast	10 to 20 m from surface Solar arrays	>20 m from surface Not specified
Particle size		10 ⁻⁹ to 10 ⁻² m	10 ⁻⁹ to 10 ⁻² m	<1 mm	~2 µm ^a
Deposition rate	Natural phenomena	0.1 mg/cm ² per year	<0.1 mg/cm ² per year	<0.1 mg/cm ² per year	<0.1 mg/cm ² per year
	Human activity ^b	<0.1 mg/cm ² per landing	<0.1 mg/cm ² per landing	<0.1 mg/cm ² per landing	<0.1 mg/cm ² per landing
Particle velocity	Micro- meteoroids	20 km/s	20 km/s	20 km/s	20 km/s
	Human activity	7 m/s	<7 m/s	<<7 m/s	Negligible
Lunar surface potential		Day: 5 V ^d Night: -150 V ^e	Day: 5 V ^d Night: -150 V ^e	Day: 5 V ^d Night: -150 V ^e	Day: 5 V ^d Night: -150 V ^e
Thermal considerations, lunar south pole ^f		Day: 310 K Night: 80 K	Day: 310 K Night: 80 K	Day: 310 K Night: 80 K	Day: 310 K Night: 80 K

^aValues from Horanyi and Szalay (Ref. 44).

^bAssuming >2 km from landing site. Values from Katzan and Edwards (Ref. 37).

^cConsidering 95 primary meteoroids of 1 ng or bigger every year per square meter. Values from West, Wright, and Euler (Ref. 49).

^dAt a solar zenith angle of 0°, the electric field strength was determined to be 5 V and extended 15 m from the lunar surface (Ref. 50).

^eValues from Figure 4 in the work of Li et al. at a solar zenith angle of 180° (Ref. 52).

Conclusions

Characterization of the lunar environment and a determination of what will be necessary to enable a sustained lunar presence will continue to evolve as our exploration of this extreme environment progresses. Lunar dust's influence on surface operations, equipment operational efficiency and lifetime, and inhabitant health will be extensive and will require a range of mitigation and management technologies. As indicated in the environmental concern matrices, an increased lunar presence will not change the risks associated with natural phenomena. Risks arising from anthropogenic activities can evolve with the limitation of activities that would disturb significant amounts of lunar dust around sensitive assets, such as Vertical Solar Array Technology (VSAT) architectures. For VSAT architectures and any aspect of lunar activities that will harvest energy from solar cells, the information compiled here can be used to identify materials technologies, engineering solutions, and conceptual operations that will provide the greatest risk reduction regarding lunar dust interactions. Coupling those efforts with targeted ground-based testing may provide the greatest opportunity to realize reliable solar power generation on the lunar surface.

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