



Overview of the lunar surface environment for exploration systems

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SLS-SPEC-159 Cross-Program DSNE

- The **Cross-Program Design Specification for Natural Environments** *defines the natural environment for crewed, deep-space NASA programs*
- Maintained by MSFC/Natural Environments Branch
- Baselined for SLS, Orion, Gateway, and HLS
- Latest revision (Rev I) available through the NASA Technical Reports Server (NTRS)
 - <https://ntrs.nasa.gov/citations/20210024522>
 - When searching, latest revision is not always the first result
 - Best to filter by Report Number using “SLS-SPEC-159”

SLS-SPEC-159 Cross-Program DSNE



3.4	Lunar Surface Operational Phases
3.4.1	Lunar Surface Geological and Geomorphological Environment
3.4.2	Lunar Regolith Properties
3.4.3	Lunar Surface Plasma Environment
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National Aeronautics and
Space Administration

SLS-SPEC-159
REVISION I

EFFECTIVE DATE: OCTOBER 27, 2021

**CROSS-PROGRAM
DESIGN SPECIFICATION FOR
NATURAL ENVIRONMENTS (DSNE)**



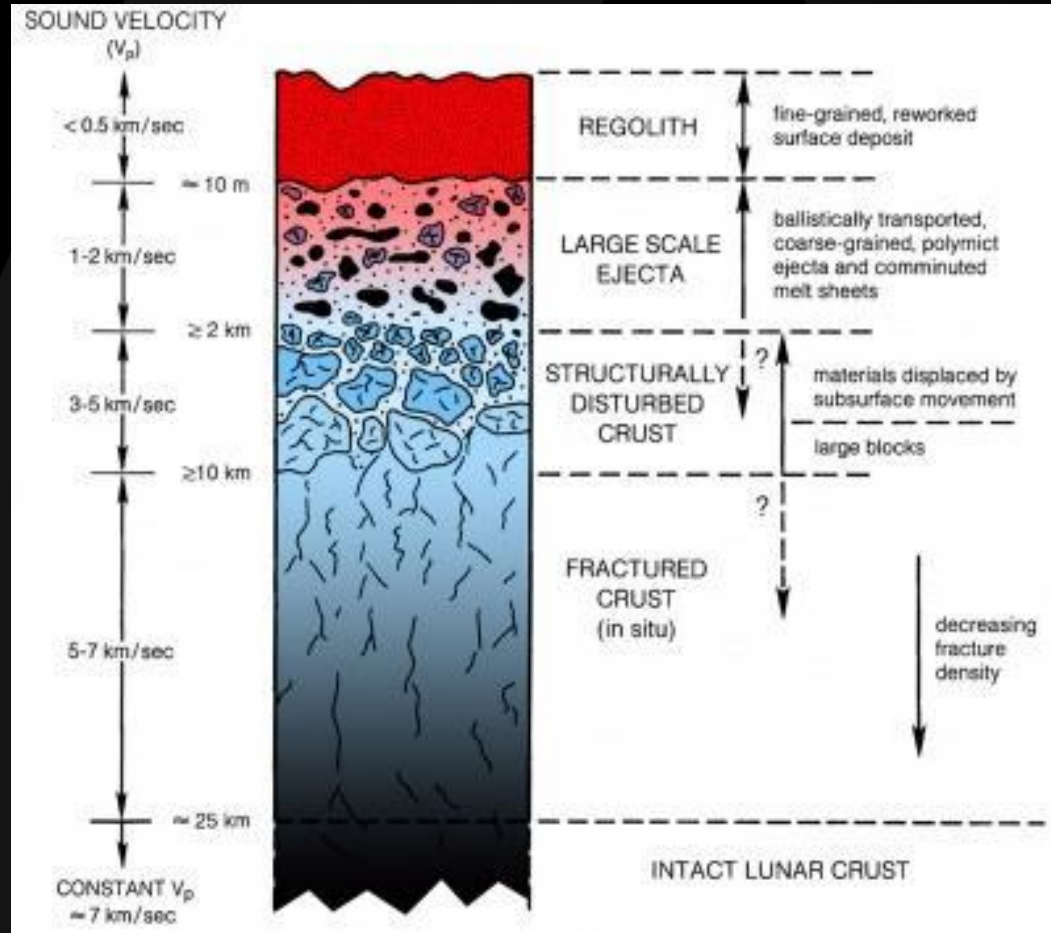
Requirements and Verification

- The Design Specification for Natural Environments is not a requirements document
- Programs must have a requirement pointing to the specification
 - Example: *The spacecraft shall meet all safety, performance, utilization, and mission objectives during and after exposure to the natural space environments as defined in SLS-SPEC-159, Cross-Program Design Specification for Natural Environments (DSNE).*
 - Allows each program flexibility in applying environments to meet program specific objectives while still maintaining a consistent set of environments across all programs
- Environments flow to each design partner/developer; reviews must be performed to ensure component level definitions are consistent with DSNE
- Verification is performed by reviewing subsystem verifications



Geological Environment and Regolith Properties

Lunar Regolith vs. Depth (Section 3.4.2.1)



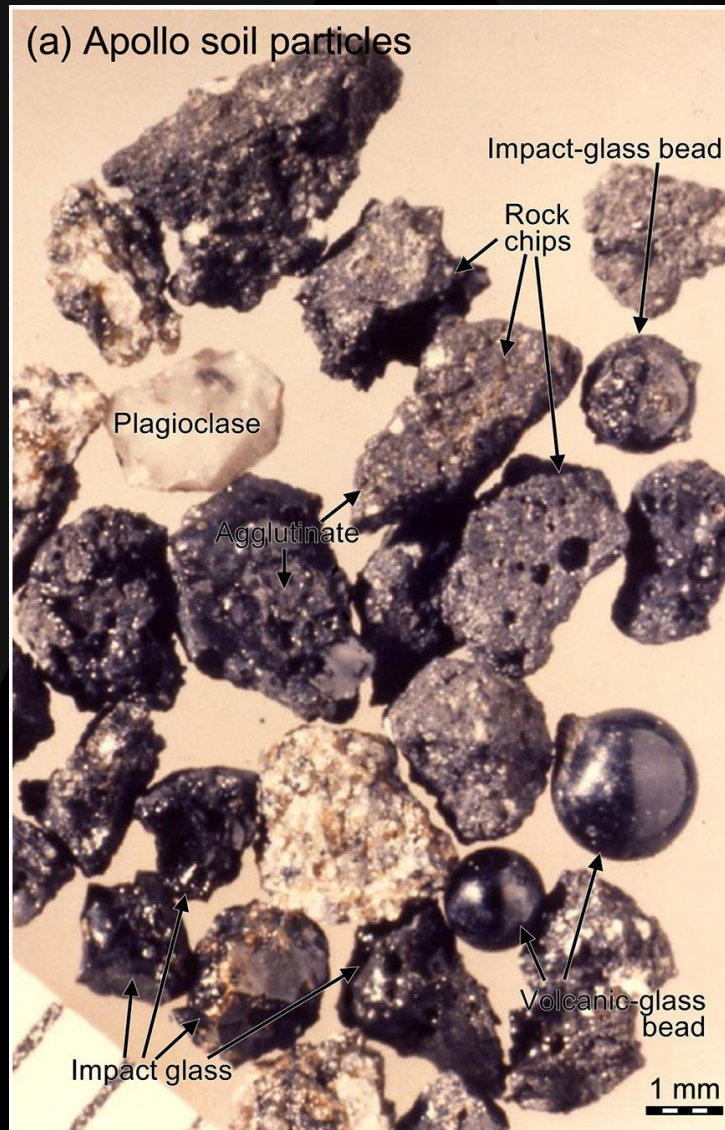
“The lunar regolith is the surficial layer of fragmented material (rocks, soil, and dust) that covers virtually the entire surface of the Moon.”

–DSNE Section 3.4.2.1, General Description of the Lunar Regolith

Median Regolith Depth	
Mare	3 – 5 m
Highlands	10 – 15 m

DSNE Figure 3.4.2.1-1, modified from Lunar Sourcebook/Heiken et al. 1991/LunaRef/LPI

Lunar Regolith Particle Shapes (Section 3.4.2.2.2)

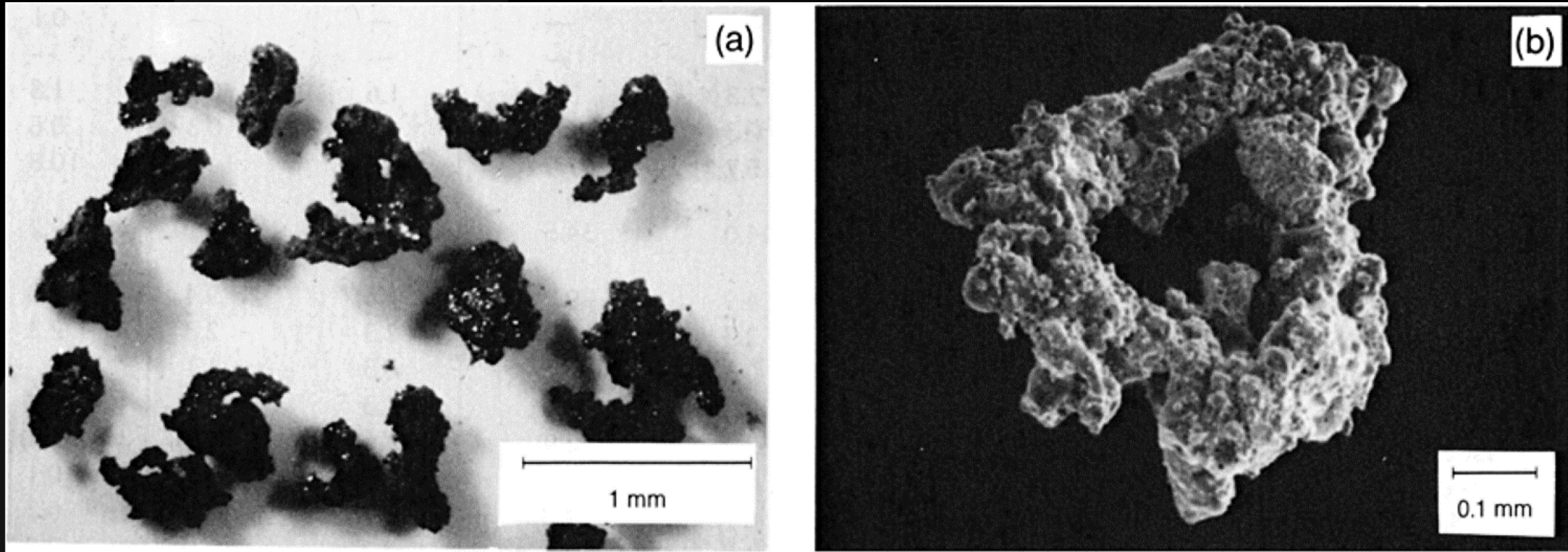


Lunar regolith particles have angular, irregular shapes due to impact processes

Figure from Zeng et al. 2019.

<https://doi.org/10.1029/2019JE006237>

Lunar Regolith Agglutinates (Section 3.4.2.2.2)



DSNE Figure 3.4.2.2.2-1: Typical lunar soil agglutinates. Optical microscope photograph (left), scanning electron photomicrograph (right). Modified from Carrier et al., 1991.

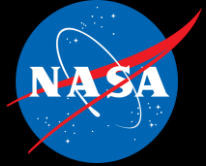
These processes also form agglutinates: glassy particles welded by hypervelocity impacts



Regolith Particle Properties (3.4.2.2.2)

Table 3.4.2.2.2-1 Summary of grain-specific properties (<1mm size-fraction)

Property	Value	Units	Notes	Section	Sources
Sorting	$\sigma_{\phi} = 1.99 - 3.73$: range	ϕ	Very poorly sorted	3.4.2.2.2.1	Heiken et al. 1991
Elongation	1.32 - 1.3835: range; 1.35: avg	-	Somewhat elongated	3.4.2.2.2.2	
Aspect ratio	0.3 - 0.9: range; 0.55: avg	-	Slightly to medium elongation	3.4.2.2.2.3	
Roundness	0.19 - 0.29: range; 0.21: avg	-	Subangular to angular	3.4.2.2.2.4	
Volume Coefficient	0.32 - 0.35: range; 0.3: avg	-	-	3.4.2.2.2.5	
Specific Surface Area	0.4 - 0.78: range; 0.5: avg	$\text{m}^2 \text{g}^{-1}$		3.4.2.2.2.6	



Particle Size Distributions, < 10 mm (Section 3.4.2.2.2)

Table 3.4.2.2.1-2 Average geotechnical particle size distribution from middle curve of figure 3.4.2.2.1-1 (Carrier 2003).

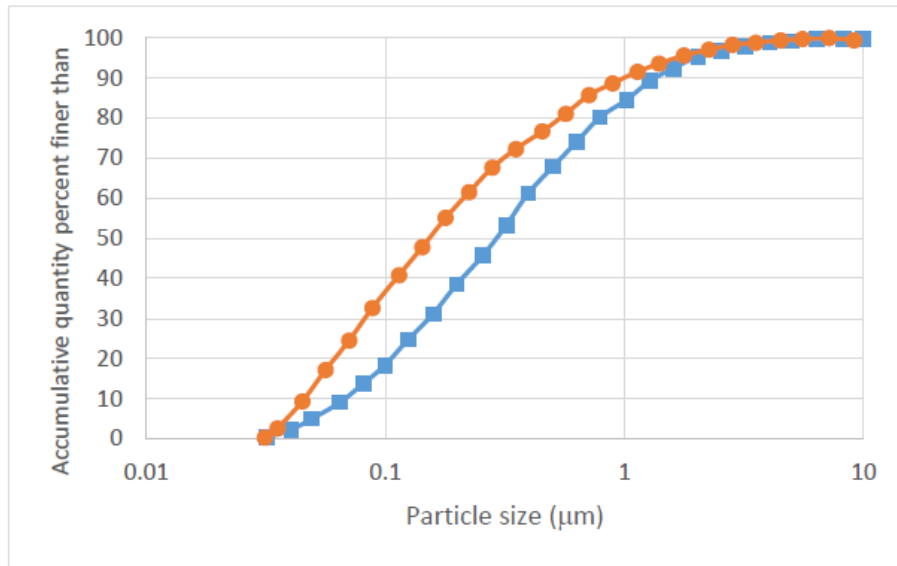
Size mm	Percent passing (smaller than)
1.3	94.9
1.0	91.8
0.4	83.5
0.3	78.7
0.2	72.1
0.1	58.0
0.07	50.5
0.05	40.8
0.04	35.0
0.03	30.2
0.02	23.6
0.01	13.9
0.005	7.8
0.003	4.8



Particle Size Distributions, < 10 μm (Section 3.4.2.2.2)

“ ... smaller particles, particularly those smaller than 20 microns, are most susceptible to electrostatic forces because of their higher charge-to-mass ratios.” (Section 3.4.2.2.2)

Table 3.4.2.2.3.1-1 Cumulative percentile of dust particles (less than 10 microns) smaller than the plotted size for Apollo 11 (sample 10084) and Apollo 17 (sample 70051) Park et al., 2008.



	Apollo 11 #10084	Apollo 17 #70051
Particle diameter (μm)	Percent finer	Percent finer
0.03	0.3	0.3
0.04	2.6	2.3
0.04	9.3	5.0
0.06	17.2	9.0
0.07	24.5	13.7
0.09	32.7	18.4
0.11	40.8	24.8
0.14	47.8	31.2
0.18	55.1	38.5
0.22	61.5	45.8
0.28	67.6	53.4
0.35	72.3	61.2
0.45	76.7	67.9
0.57	81.0	74.1
0.71	85.7	80.2

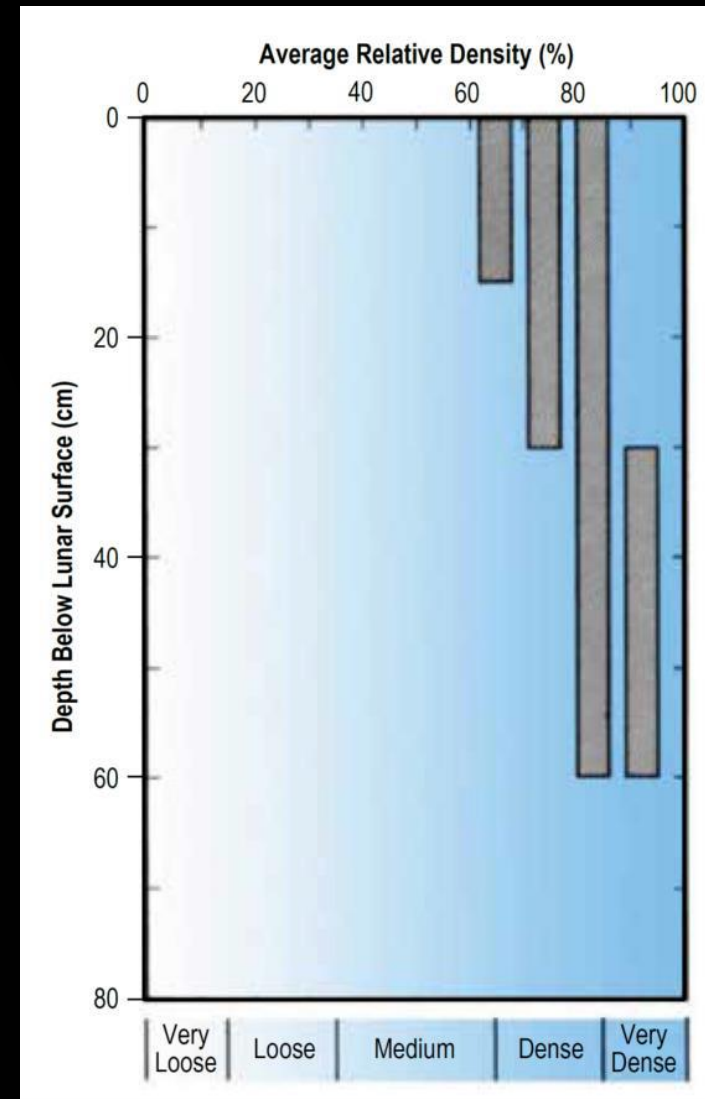
Figure 3.4.2.2.3.1-1 Cumulative percentile of dust particles (less than 10 microns) smaller than the plotted size for Apollo 11 (sample 10084, orange line) and Apollo 17 (sample 70051, blue line) after Park et al., 2008.

Regolith Properties



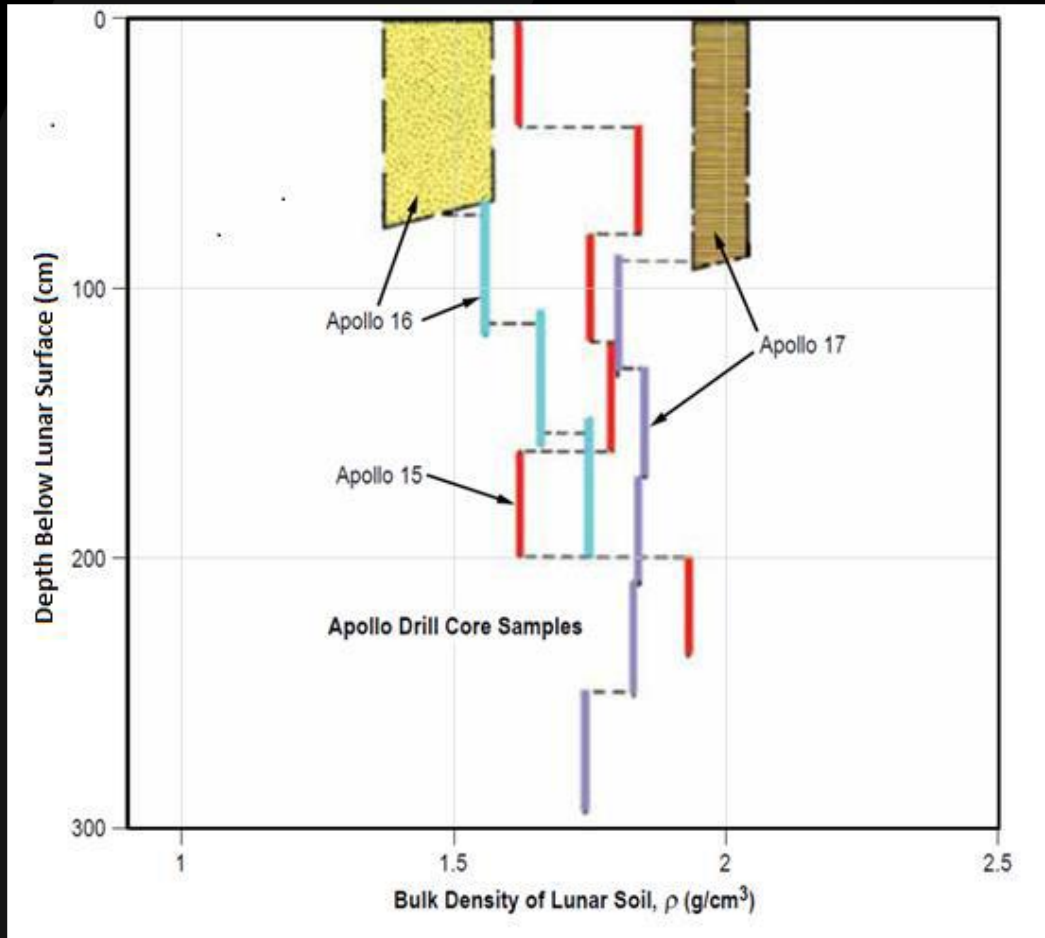
Table 3.4.2.3.4-1 Porosity for various depths.

Depth Range cm	Average Porosity, n %	Average Void Ratio, e
0 - 15	52 ± 2	1.07 ± 0.07
0 - 30	49 ± 2	0.96 ± 0.07
30 - 60	44 ± 2	0.78 ± 0.07
0 - 60	46 ± 2	0.87 ± 0.07

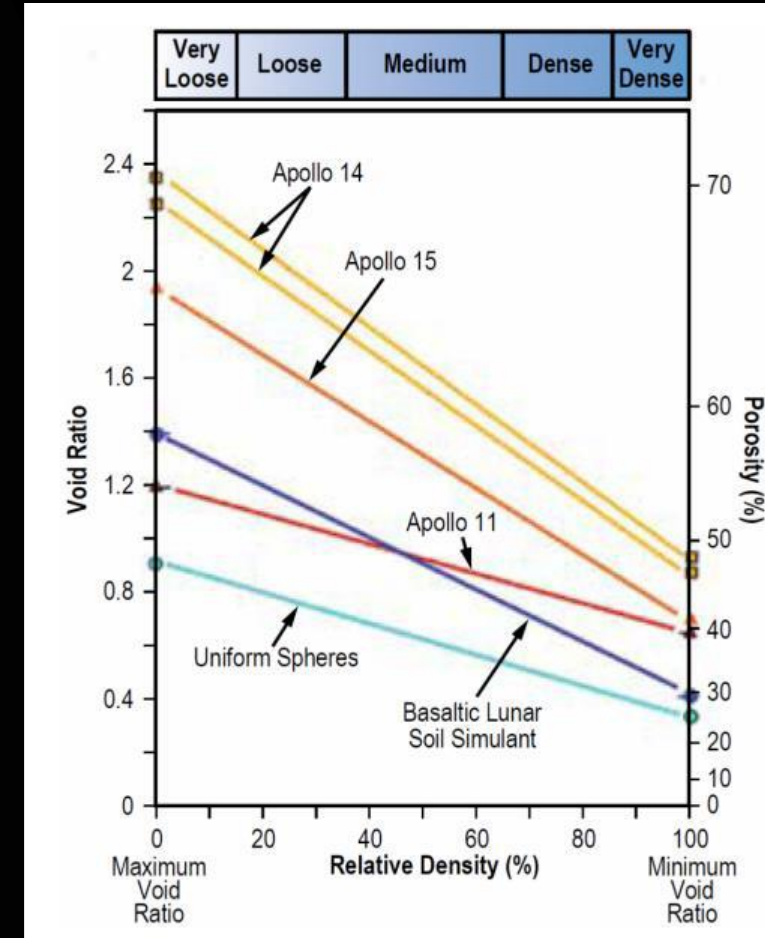


DSNE Figure 3.4.2.3.2-1: Relative density as a function of depth. Modified from Lunar Sourcebook.

Regolith Properties



DSNE Figure 3.4.2.3.1-1: In situ bulk density based on drill core samples from Apollo 15, 16, and 17. From Lunar Sourcebook.



DSNE Figure 3.4.2.3.3-1: Porosity and void ratio as a function of relative density for lunar samples. Modified from Lunar Sourcebook.

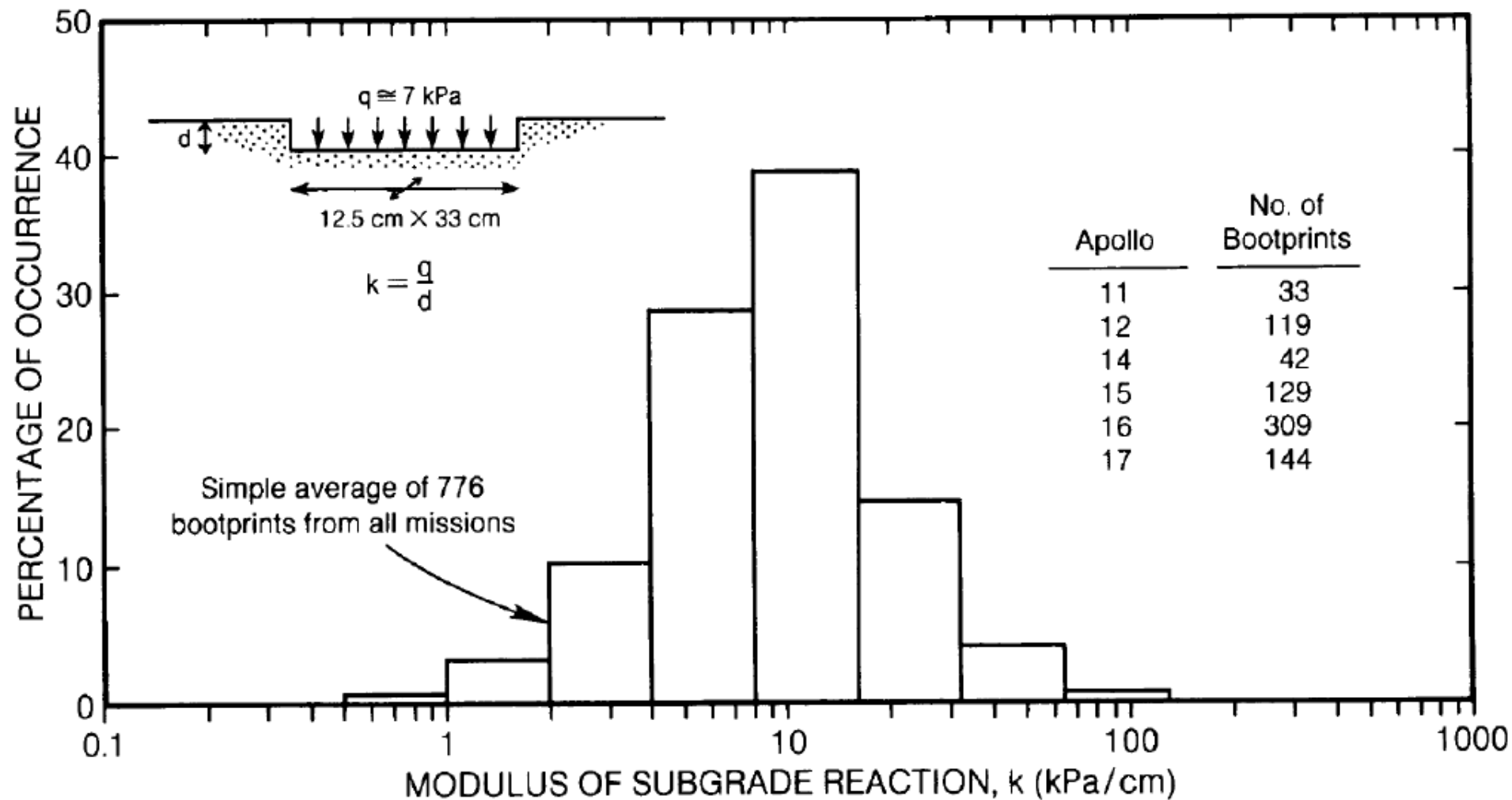


Figure 3.4.2.4.5-1 Distribution of modulus of subgrade reaction as determined from analysis of lunar bootprints (Figure 9.37 in Lunar Sourcebook).

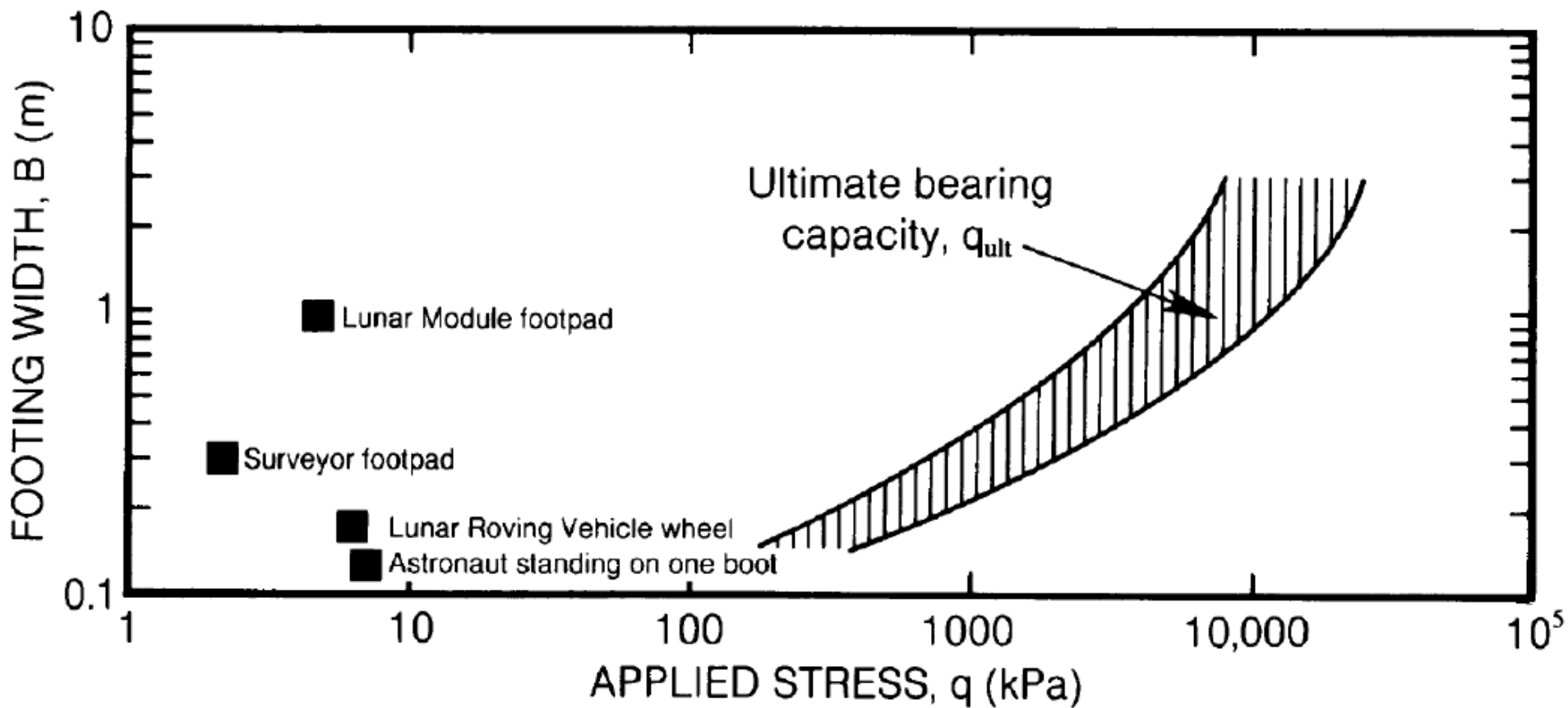


Figure 3.4.2.4.5-2 Comparison of applied stress from crew and vehicles with the ultimate bearing capacity of lunar soil vs. footing width. (Figure 9.36 in Lunar Sourcebook).

Rock distributions

DSNE 3.4.1.4

- Rocks are relatively rare on lunar surface; fractional area of rocks $\geq 1\text{ m}$ typically $< 1\%$.
- Rocks are not randomly distributed, fractional area can be high (10% – 20%) in certain regions.
- Rock abundance should be locally assessed during site characterization; size-frequency distribution may be used for sizes $< 2\text{ m}$.

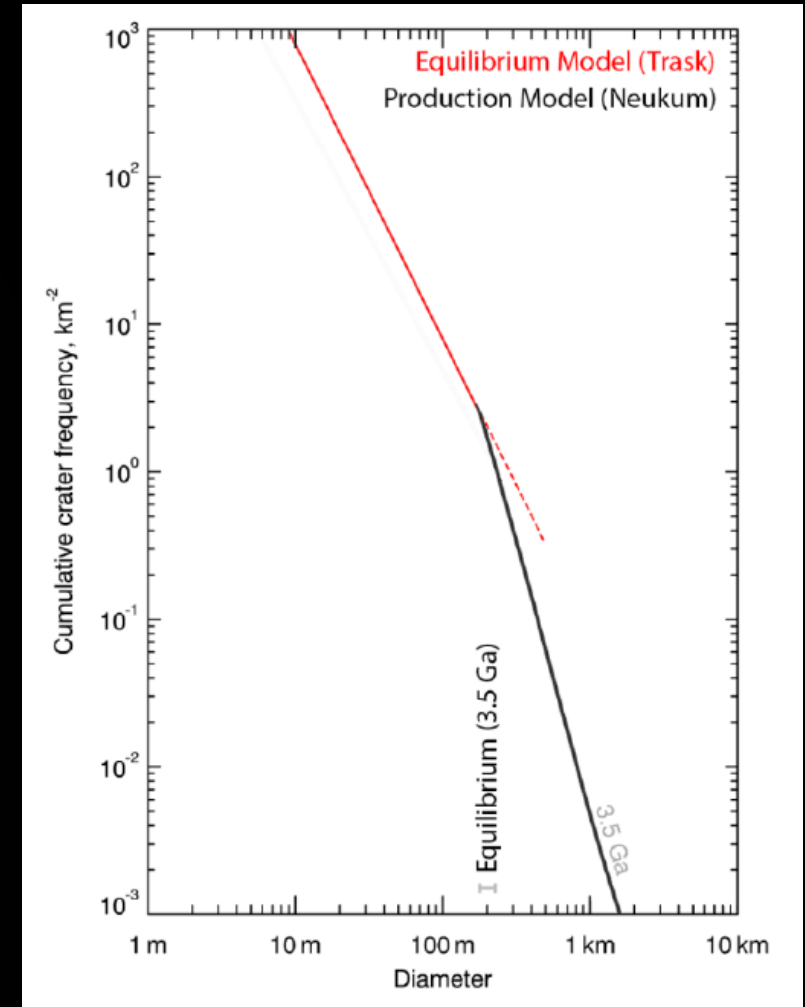


Crater size-frequency distributions, topography

DSNE 3.4.1.1, 3.4.2.2, and 3.4.1.3



- Global slope distributions
- Generalized crater statistics
 - Larger craters using Neukum production function
 - Smaller craters using Trask equation
- Site analysis should be performed as local distributions may differ
- Descriptions of crater morphology, features, depth/diameter ratios provided



DSNE Figure 3.4.1.1-1



Regolith Electrical Properties

Regolith Particle Charging (Section 3.4.2.2.3.3)

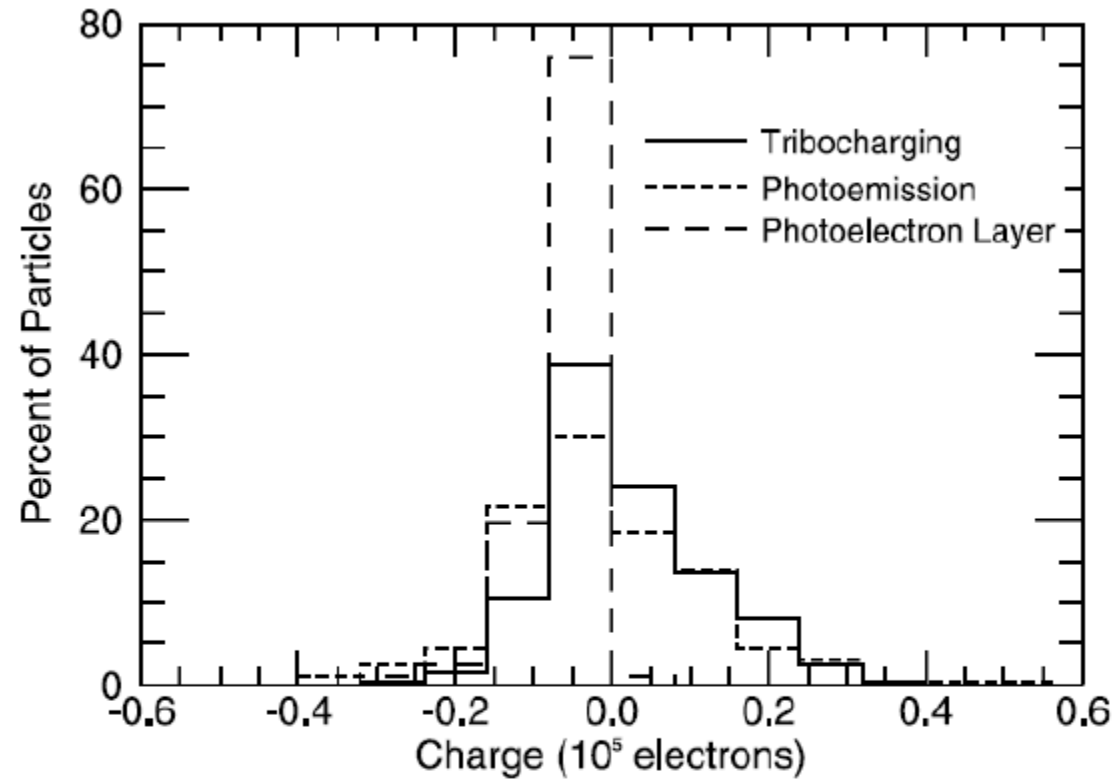


Figure 3.4.2.2.3.3-1 Experimental results using JSC-1 simulant for a 1) Tribocharging, 2) Photoemission, and 3) Photoelectron Layer (From Colwell et al., 2007 and Sickafoose et al., 2001)



Regolith Electrical Properties (Section 3.4.4)

- Bulk regolith is an electrical insulator, resistivity is temperature dependent
 - Temperature-dependent function included in subsection
- More detailed descriptions for permittivity, loss tangent in subsections

Table 3.4.4-1 Regolith electrical properties

Parameter		Units	Notes	Section	Reference
DC Electrical Conductivity	$<10^{-10}$ @ 400 K	Mho/m	For rocks; values will be lower for soil. Temperature dependent lab analysis and in situ	3.4.4.1	Carrier et al. 1991
	$<10^{-25}$ @ 100 K				Dyal et al. 1974
	$<10^{-9}$ @ upper 5 km				
Relative Dielectric Permittivity (k)	2.8 @ 1.58 g cm^{-3}	-	Function of density, temperature, and frequency	3.4.4.2	Carrier et al. 1991
	3.11 @ 1.58 g cm^{-3}				Olhoeft and Strangway, 1975
Loss Tangent	0.0057 @ 1.58 g cm^{-3} 0.0066 @ 1.58 g cm^{-3}	-	Function of density, temperature, frequency, and chemistry	3.4.4.3	Langseth et al. 1973



Natural Dust Transport

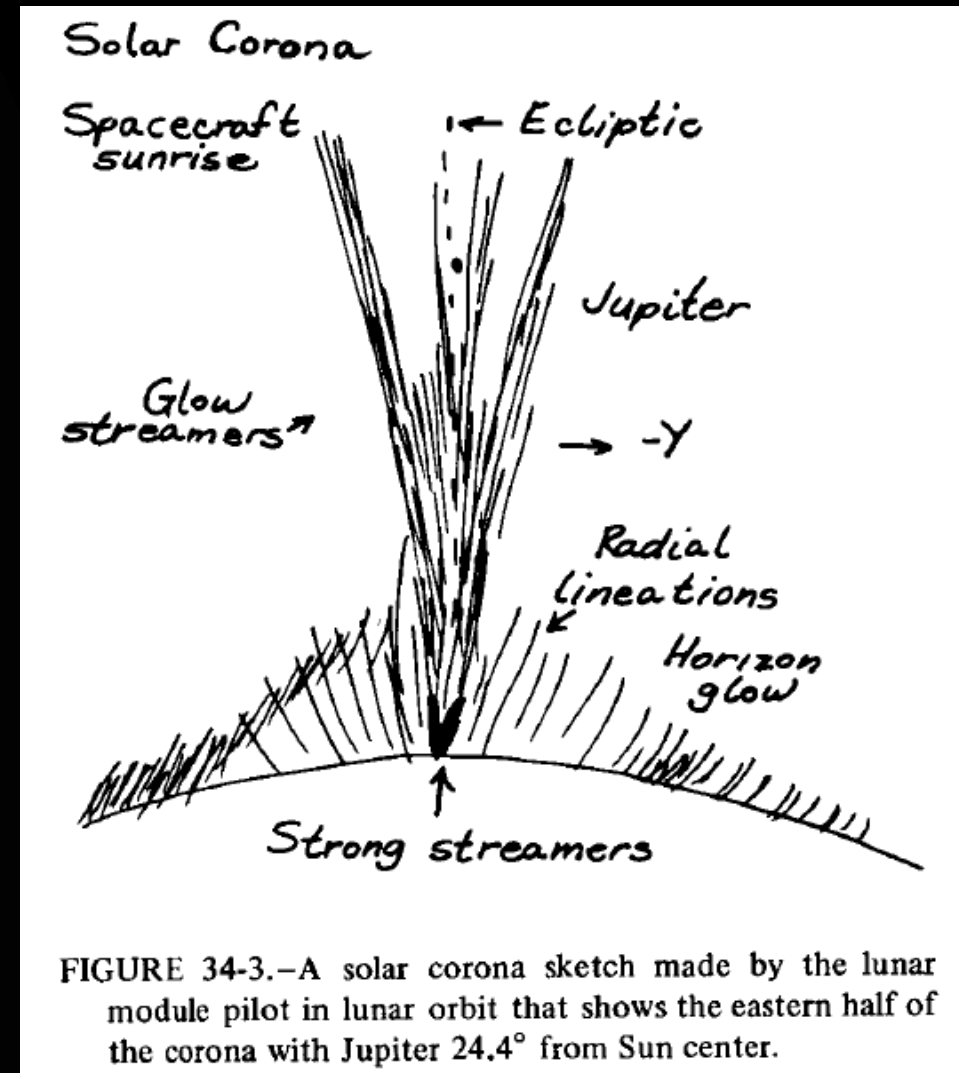


Historical Background

- Electrostatic dust lofting historically proposed as a mechanism for two distinct observations
 - Very-near-surface
 - Lofted height < 1 meter (Surveyor)
 - Orbital altitudes
 - ~ 1 km to ~ 100 km (Apollo)

Historical Background

- Astronauts on Apollo missions observing the solar corona and zodiacal light reported unexpected variations in brightness and streamers of light
 - Light scattering from high altitude lofted dust was proposed to explain these observations, with electrostatic lofting again a prime candidate mechanism
- Additional Apollo-era data
 - Apollo Lunar Ejecta and Meteorites (LEAM) Experiment first purported to show enhanced dust activity near local sunrise, sunset (Berg et al., 1975); recent analysis discounts this (Grun & Horanyi, 2011)





Near-surface Dust Environment

- No observations following Surveyor have confirmed near-surface dust transport
- Experimental work demonstrates dust lofting < 1 meter plausible (Wang et al. 2016)

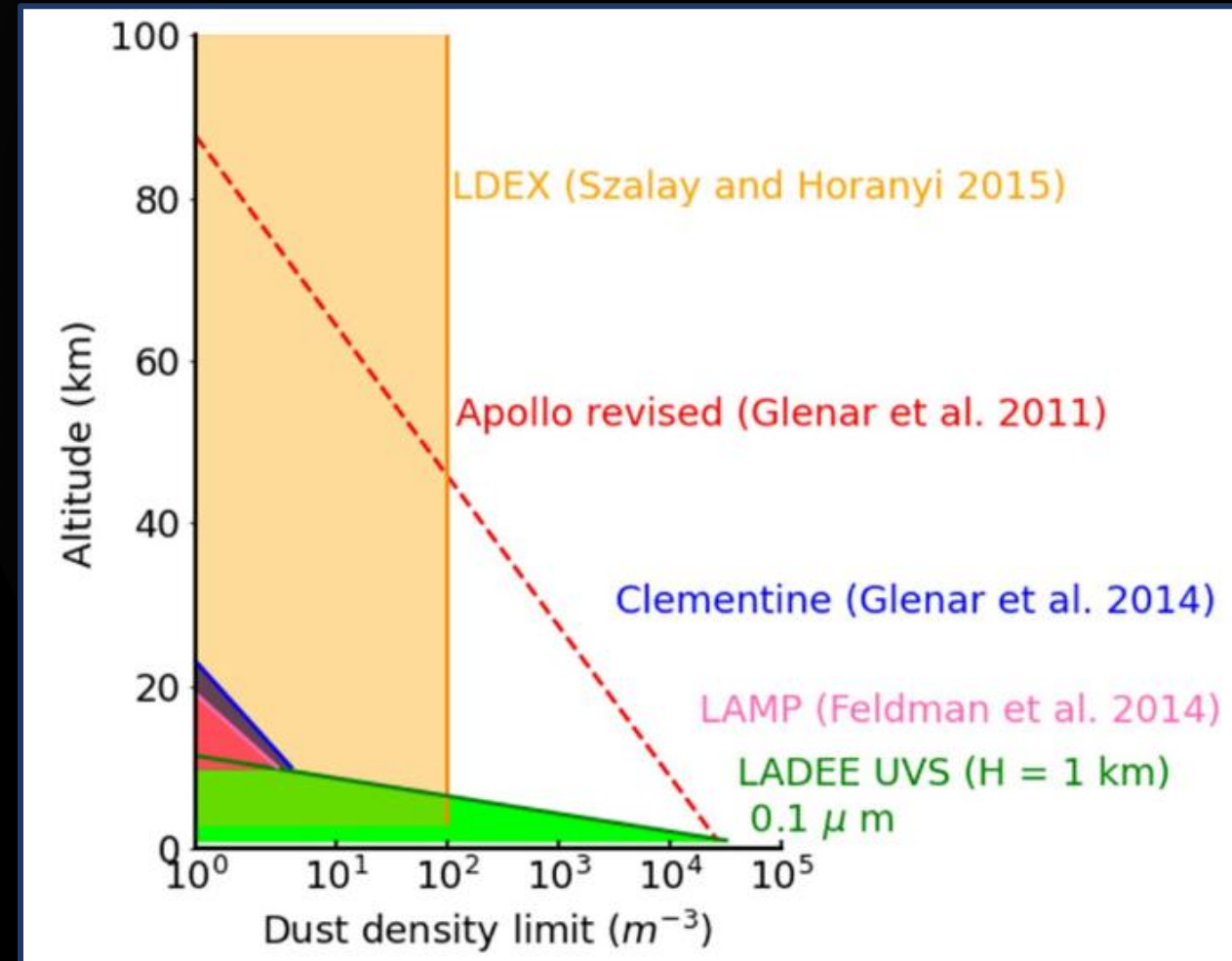


1/23/1968 Surveyor VII

Horizon Glow 1-1/2 hours start 7m camera at sunset

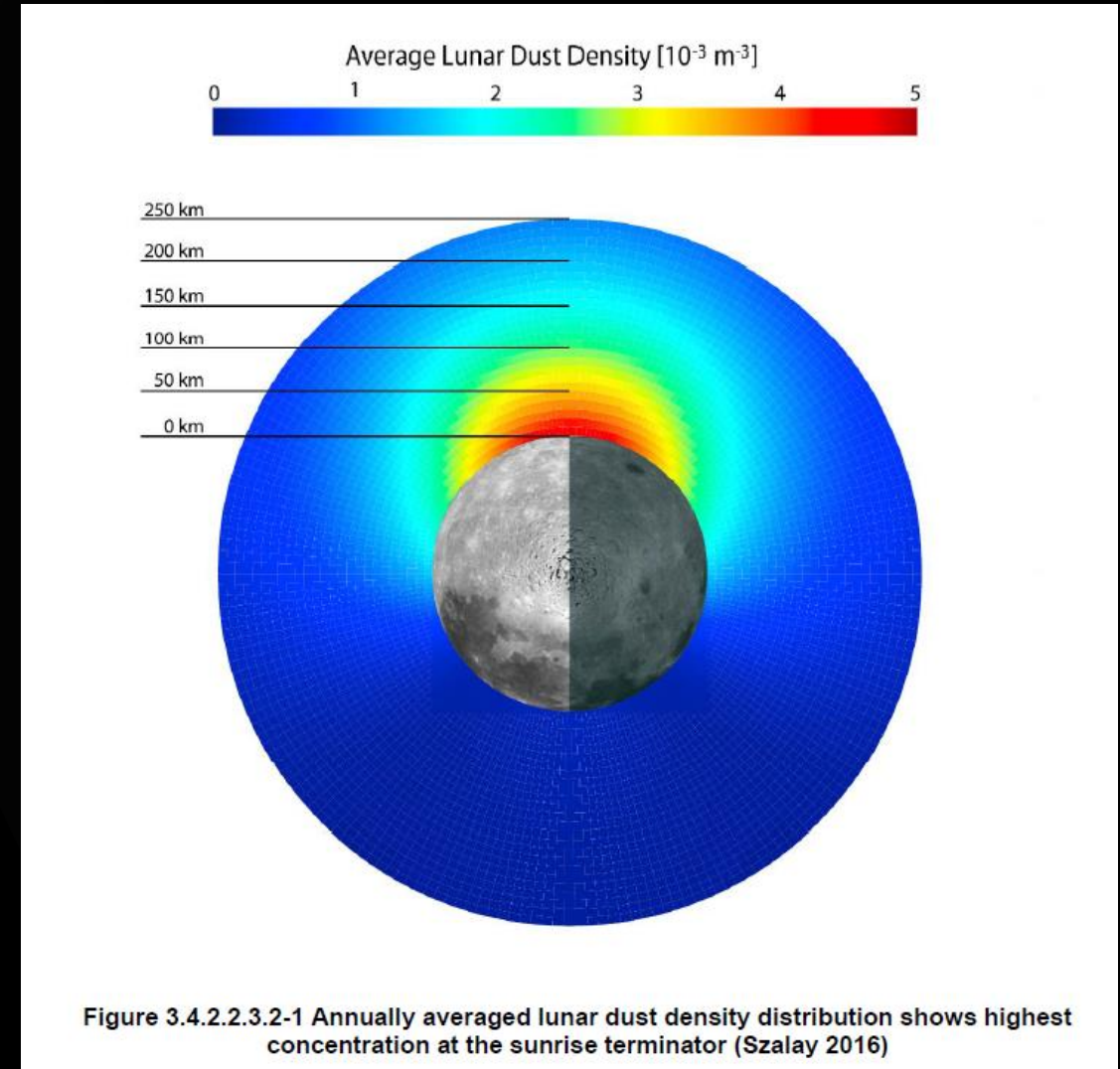
Recent Orbital Observations

- Orbital measurements bound possible natural lofted dust environment
 - In general, measured environment significantly lower than Apollo-era estimates and Apollo data bounds
 - Apollo data recently re-analyzed (Glenar et al. 2011)
 - Meteoroid ejecta accounts for lofting to orbital altitudes



High-altitude Dust Environment (3.4.2.2.3.2)

- On-orbit dust environment measured by LDEX experiment aboard LADEE
- Peak concentration measurement: $\frac{5 \text{ particles}}{1000 \text{ m}^3}$ for particle diameters $> 0.3 \mu\text{m}$





Meteoroid and Ejecta Environment



Meteoroid Environment (Section 3.4.8.1)

- Defined by Meteoroid Engineering Model, version 3 (MEM 3)
- Models mass ranges from 10^{-6} grams to 10 grams; mass range considered a threat to spacecraft
- Can be used for environments at the lunar surface

Meteoroid Ejecta Environment (Section 3.4.8.2)

- Current environment defined by NASA SP-8013
- Updated ejecta environment in-work and will be included in next revision of DSNE



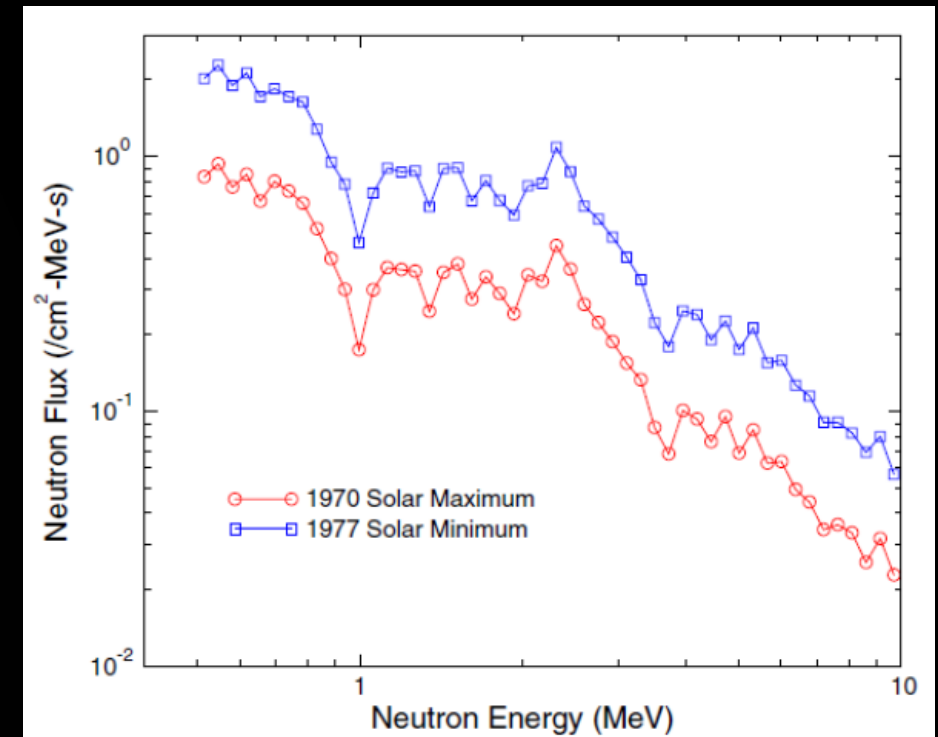
Lunar Surface Radiation Environments

Modifications/differences for the lunar surface



Lunar Ionizing Radiation Environment (3.4.7)

- In general, environments for interplanetary space can be used and divided by 2
 - Solar energetic particle/galactic cosmic rays that contribute to total ionizing dose and single effect effects
- The lunar neutron environment is an additional consideration, produced when energetic particles interact with the regolith



DSNE Figure 3.4.7.3-1: Differential neutron flux for solar maximum and minimum conditions (Adams et al. 2007).

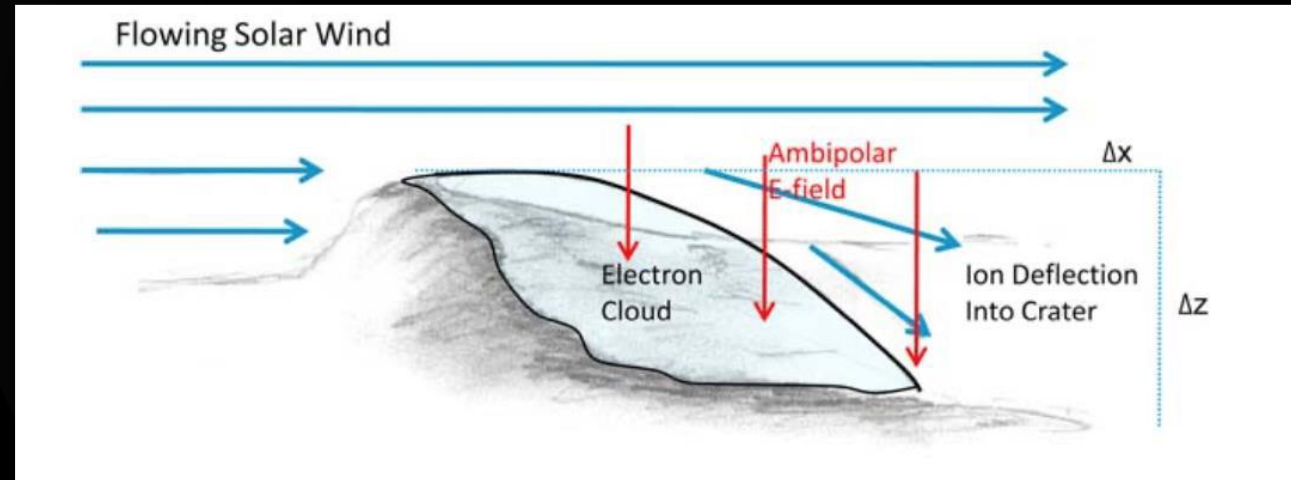


Surface Plasma Environment

Lunar surface plasma environment (Section 3.4.3)



- Lack of ground truth data, environment primarily based on modeling
- Environment complex due to interactions with the surface
- Recommend consultation with EV44 subject matter experts to determine worst-case environment
- Plasma parameters recorded in DSNE Table 3.4.3-1



DSNE Figure 3.4.1 – An illustration of the trailing plasma expansion behind a topographic feature at the lunar south pole and terminator region (Farrell et al., 2010)



Thermal Environment



Lunar Surface Thermal Environment (Section 3.4.6)

- Reflected sunlight contributes to the thermal environment near the lunar surface; relevant formulas given in DSNE section
- Lunar reflectivity is phase dependent due to lunar surface texture/regolith properties

Table 3.4.6.1.1-1 Albedo and emissivity extremes for global and south polar regions. Since the south polar region is essentially highland regolith, we use highland equatorial values for a and ϵ . The infrared emissivities are taken from Vasavada et al. 2012 and Hayne et al. 2017 and the global albedo is from Williams et al. 2017.

Location	Albedo a	Emissivity ϵ
Highland mean (0° lat)	0.16	0.95 – 0.98
Mare mean (0° lat)	0.07	0.95 – 0.98
South Pole (84-90 $^{\circ}$ S) nominal	0.16	None available. Use 0.95 – 0.98



Lunar Surface Thermal Properties

Table 3.4.6.2-1 Nominal values of thermal parameters for lunar regolith.

Parameter	Value	Units	Notes	Section	Reference
Thermal Conductivity (<i>k</i>)	35-234cm deep: $1.4 \times 10^{-2} - 2.5 \times 10^{-2}$ (Apollo 15) $1.72 \times 10^{-2} - 2.95 \times 10^{-2}$ (Apollo 17)	W/m-K	-	3.4.6.2.1	Langseth et al. 1973a Table 9-VI
	2-15cm deep: $1.0 \times 10^{-2} - 1.5 \times 10^{-2}$ (Apollo 15 & 17)				Langseth et al. 1973b
	0-2cm deep: $0.9 \times 10^{-3} - 1.5 \times 10^{-3}$ (Apollo 15 & 17)				
Thermal Diffusivity (<i>K</i>)	1.1×10^{-5}	cm ² /s	Temperature and density dependent	3.4.6.2.3	Cremers 1972
Heat Capacity (Specific Heat)	See Table 3.4.6.2.2-1	J/kg-K	Temperature dependent	3.4.6.2.2	Woods-Robinson et al. 2019



Lunar Surface Temperature (3.4.6.3)

Table 3.4.6.3-1 Lunar surface temperature extremes for various latitudes and solar illumination conditions from Williams et al. 2017. Mean temperatures are the plotted value with the max or min extremes taken from the error bars. Temperature for coldest permanently shadowed crater is from Paige and Siegler, 2016.

Location	Mean Temperature K	1 Sigma Max or Min Temp K	Solar conditions
Equatorial maximum	391	394	Local noon
Equatorial minimum	96	94	Before sunrise
45 degree latitude maximum	350	357	Local noon
45 degree latitude minimum	89	83	Before sunrise
85 degree latitude maximum	182	224	Local noon
85 degree latitude minimum	61	41	Approx. 3am equivalent
Coldest permanently shadowed crater	18		



Surface Illumination and Optical Properties

Surface Illumination (Section 3.4.10)

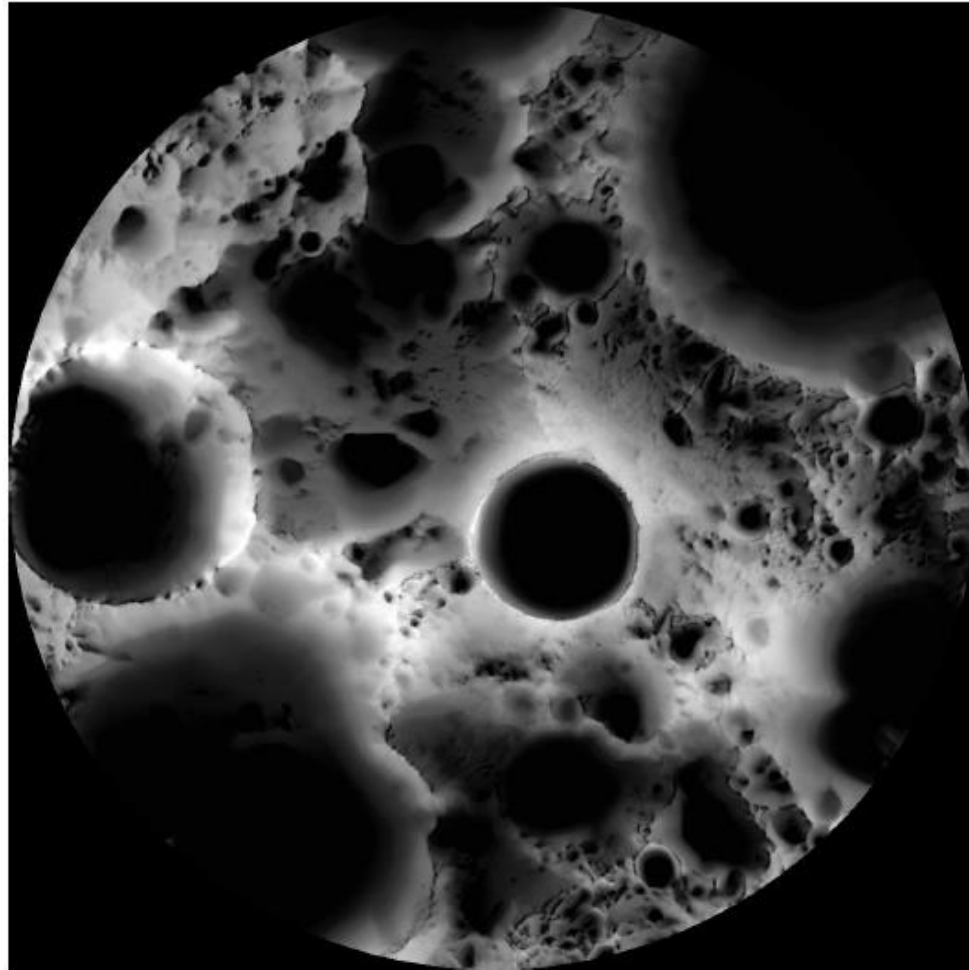


Figure 3.4.10-1 Multi-temporal illumination map of the lunar south pole, Shackleton crater (19 km diameter) is in the center, the south pole is located approximately at 10 o'clock on its rim. Mapped area extends from 88°S to 90°S [NASA/GSFC/Arizona State University].



Natural light sources

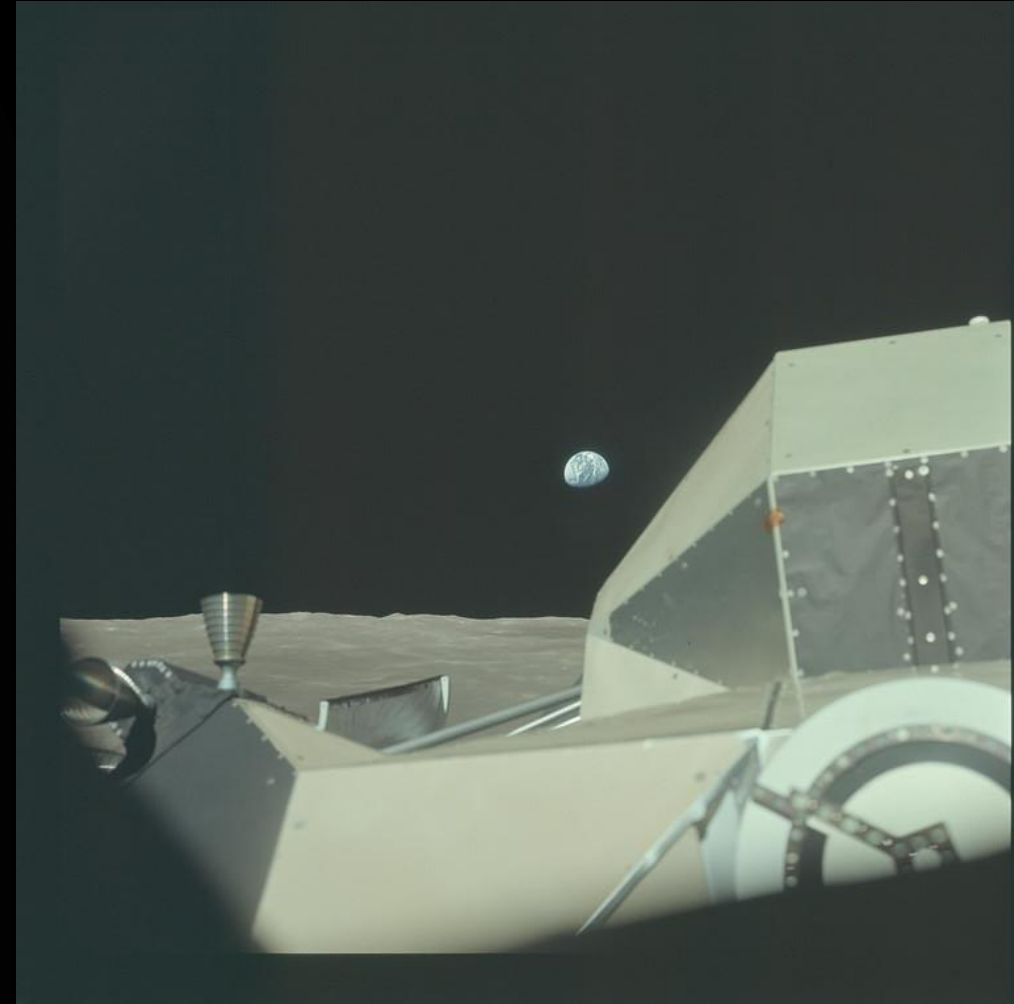
- Solar illumination
 - Average solar flux at Moon same as that at Earth
 - Maximum and minimum affected by lunar orbit
 - Incident light nearly collimated (angular diameter $\approx 0.5^\circ$)
 - Lunar day, or synodic period, is 29.5 Earth days

Solar Flux at Lunar Orbit	
Maximum	$1421 \pm 5 \frac{W}{m^2}$
Mean	$1367 \pm 5 \frac{W}{m^2}$
Minimum	$1315 \pm 5 \frac{W}{m^2}$

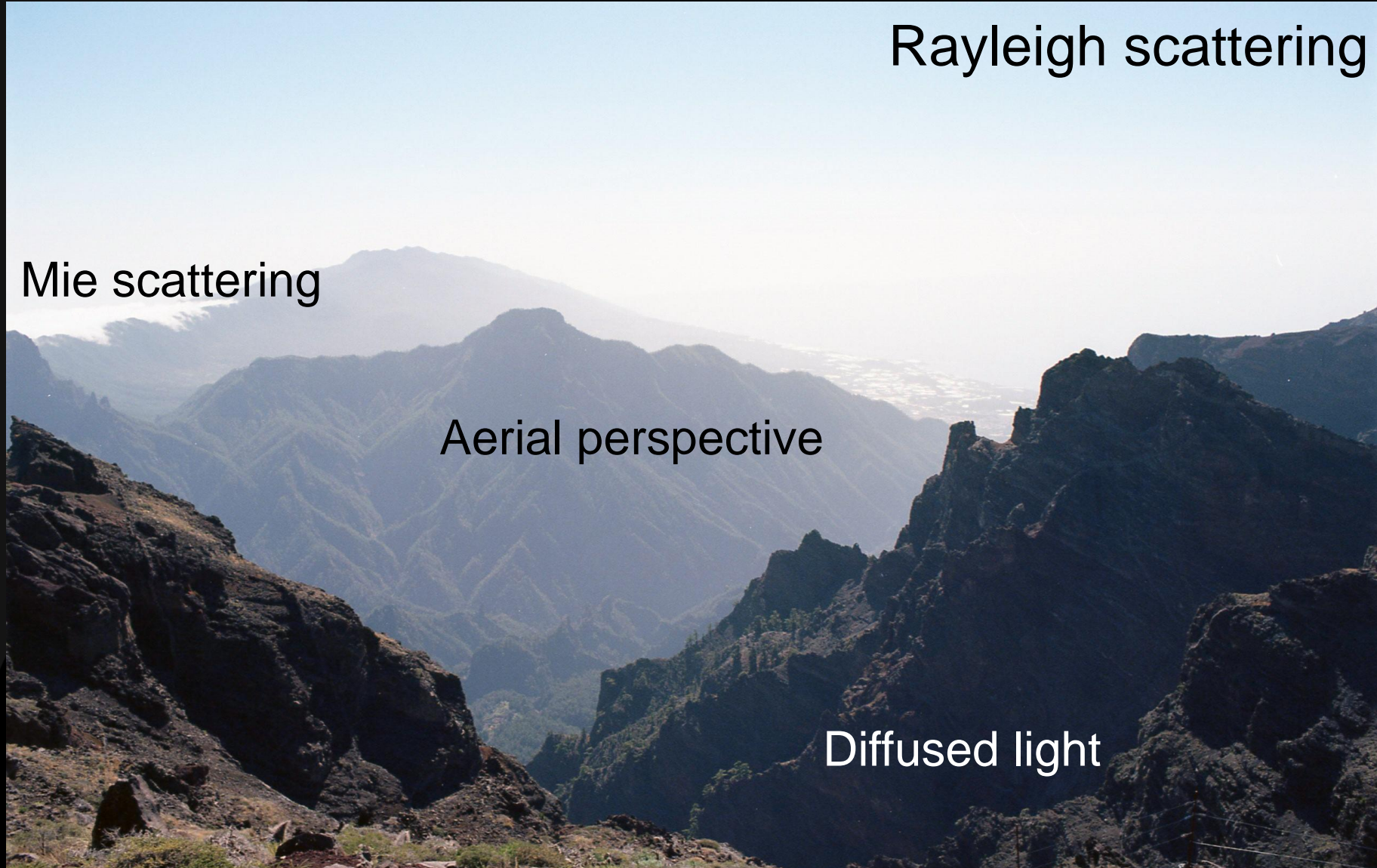
DSNE Section 3.3.9.1.1

Natural light sources

- Earthshine as illumination source studied by Glenar et al. 2019
 - Broadband flux ranges from approximately $60 \frac{mW}{m^2}$ (thermal) up to $150 \frac{mW}{m^2}$ depending on phase angle
 - Earth “would appear some 20–30 times brighter at visible wavelengths than would the Moon at similar phase over a terrestrial landscape” (Glenar et al. 2019)
 - Possible use for science/exploration
 - May affect lighting/thermal environment of PSRs



Earth's lighting environment



Rayleigh scattering

Mie scattering

Aerial perspective

Diffused light



Earth's lighting environment

1807 m (5928 ft) elevation
17 km (11 mi) distant

1844 m (6050 ft) elevation
6.6 km (4.1 m) distant

W.A. Chambers

(distances/elevations measured with Google Earth)



AS15-87-11793
NASA/scanned by Kipp Teague

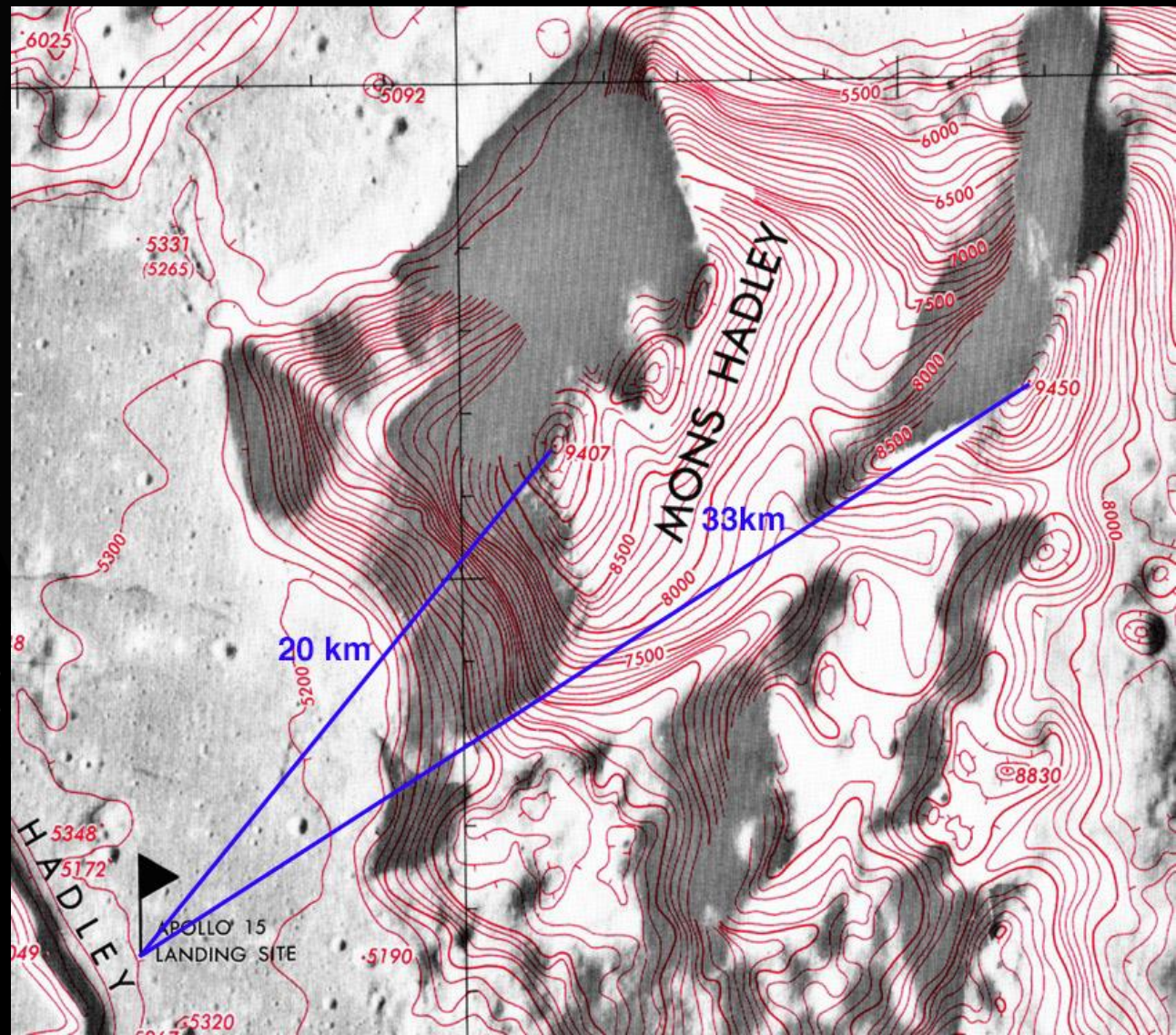




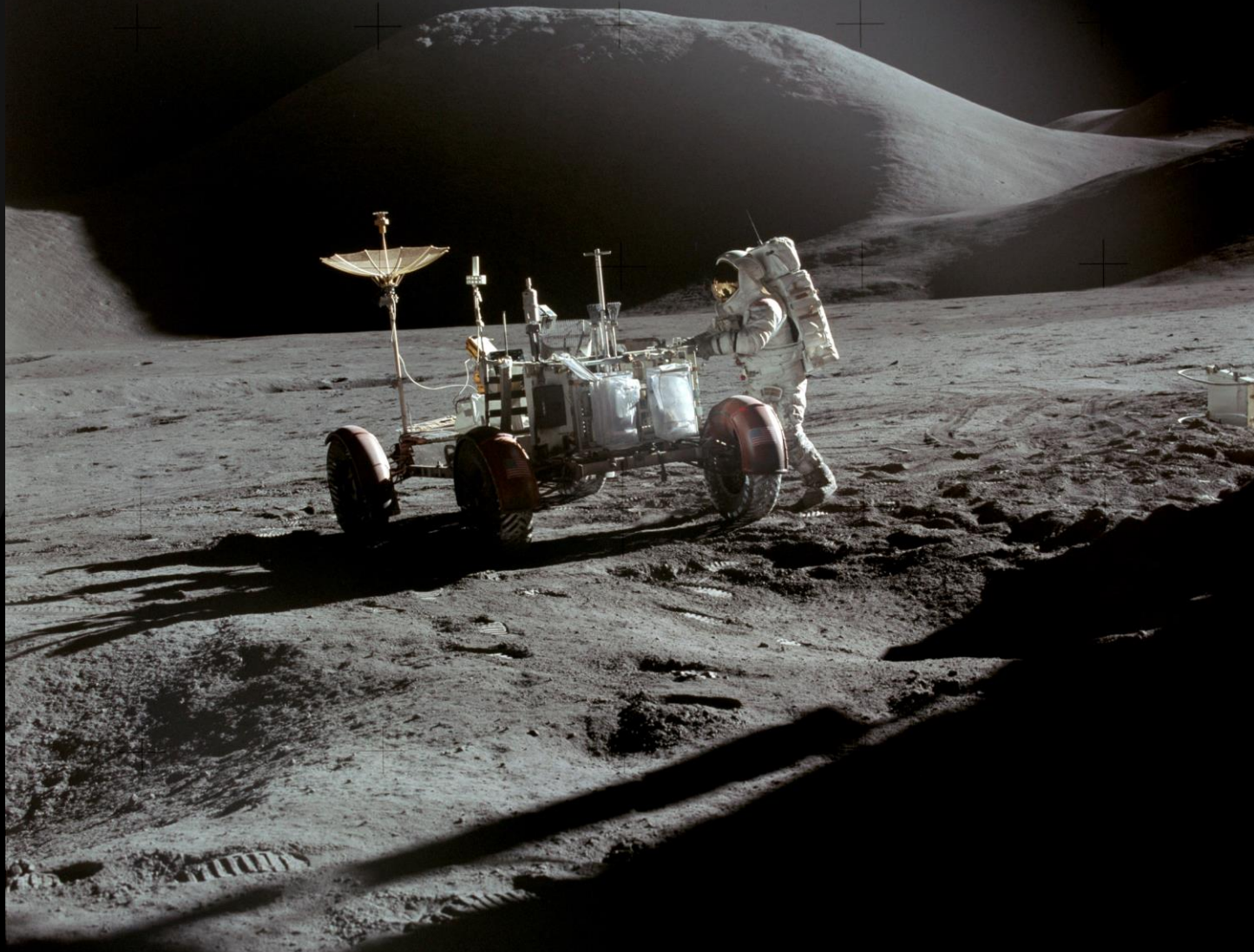
Mons Hadley

4100 m (13,000 ft) elevation change

20 km (12 mi) distant



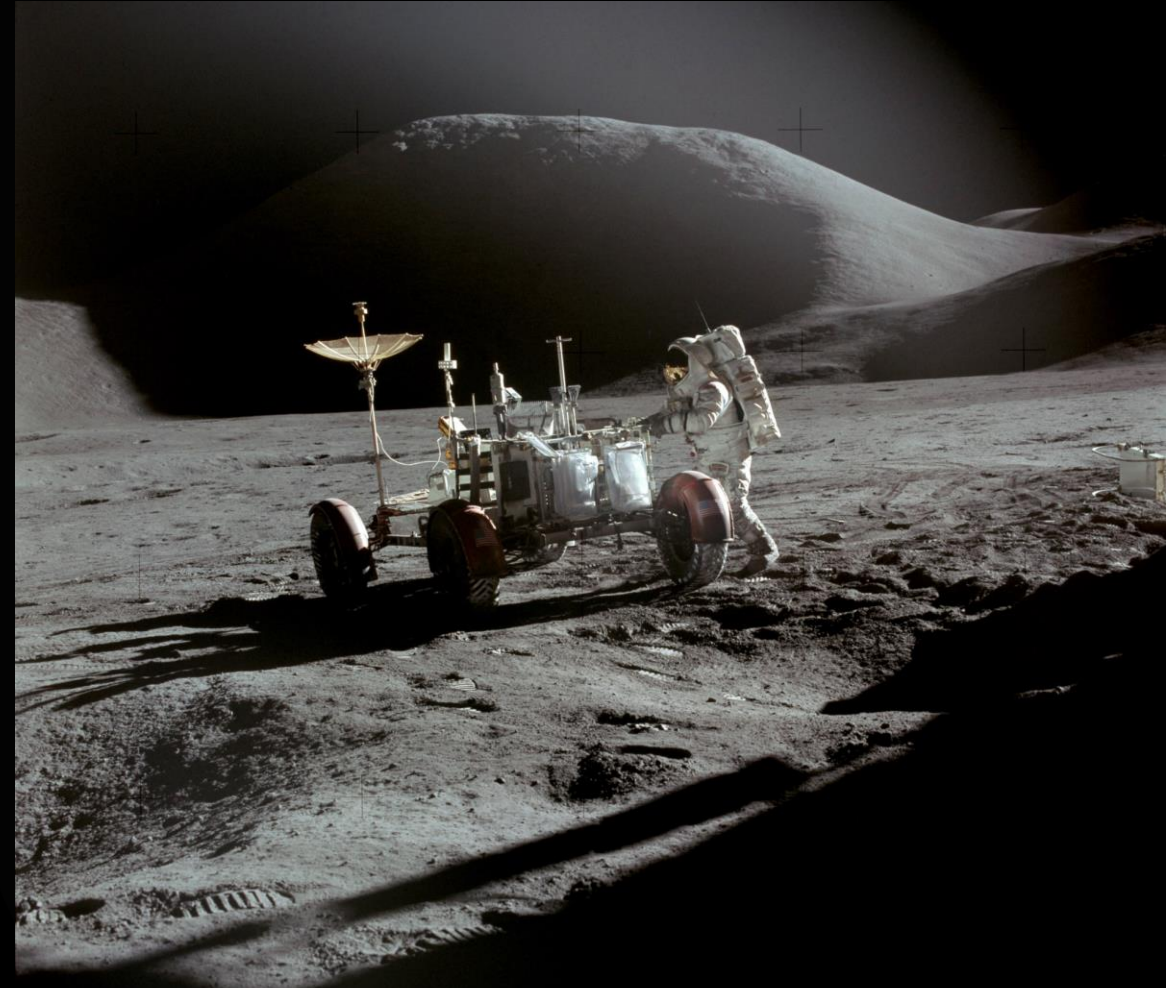
Labeled detail from LTO41B4
NASA/U.S. Defense Mapping Agency/scanned by LPI



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NASA/scanned by Kipp Teague

Lunar lighting environment

- Lack of lunar atmosphere has a significant effect on lighting environment, and therefore on human perception
 - No atmospheric scattering
 - Solar flux nearly a point source
 - No atmospheric distortion
 - Ground: no heat haze, mirages
 - Sky: stars do not twinkle or blur
 - Perfect “seeing”
 - No atmosphere → no clouds or trees for visual scale
 - Lack of familiar visual cues





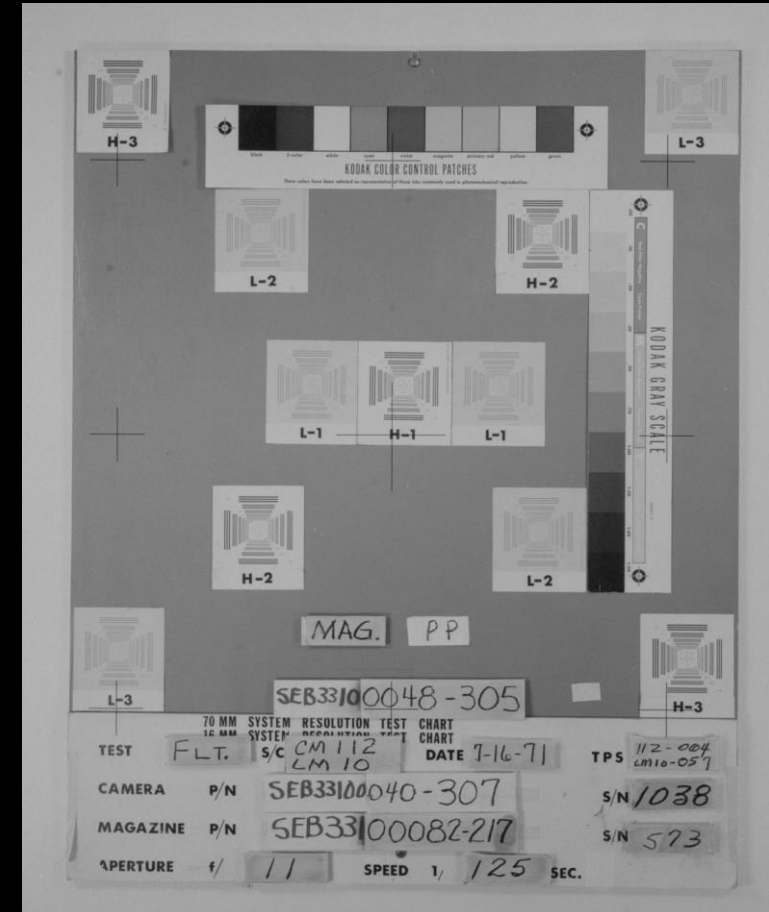
Lunar regolith properties

- Lunar albedo varies with terrain type
 - Highlands/South Pole albedo = 0.16
 - Mare albedo = 0.07

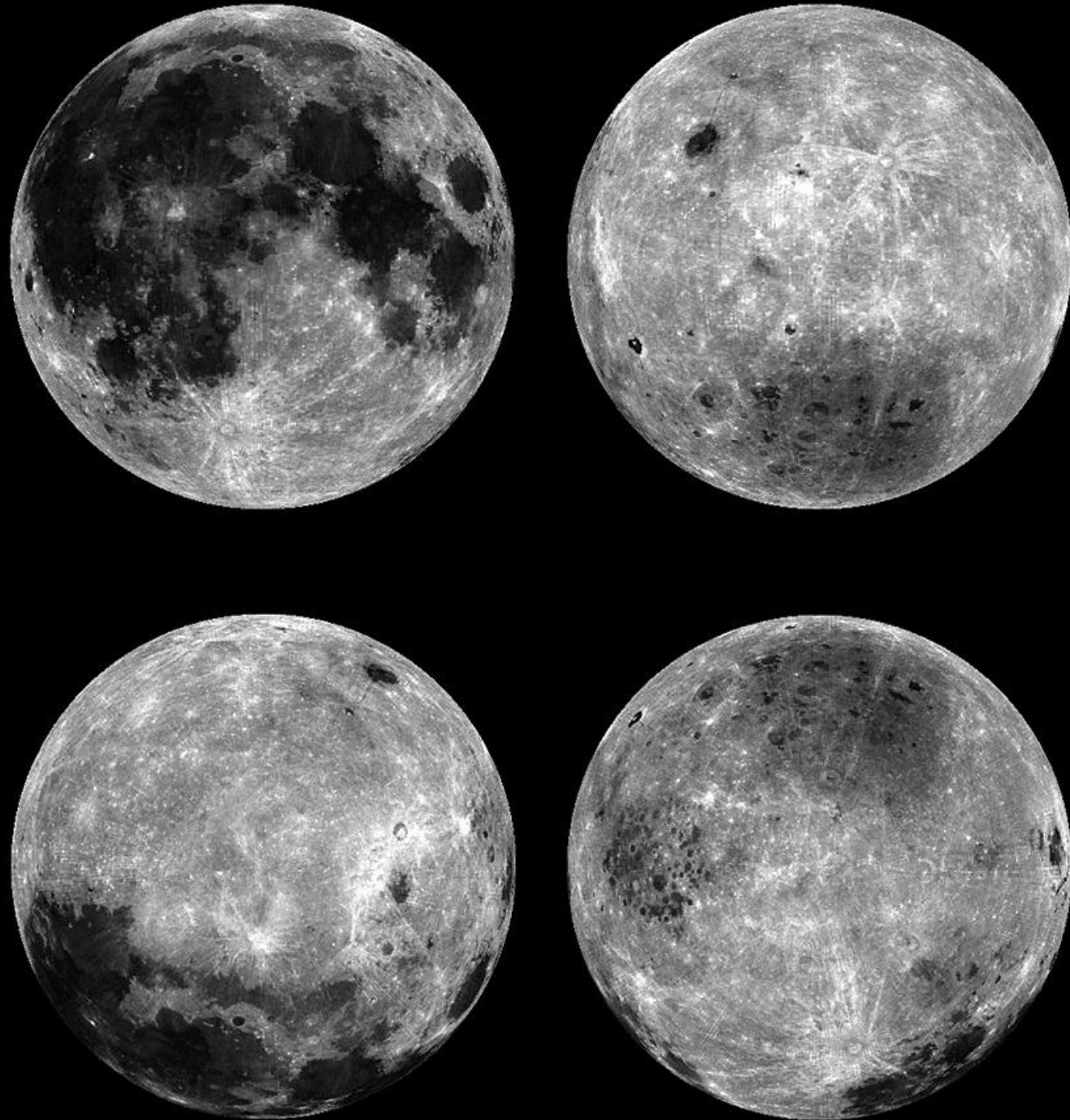
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South Pole ($84\text{-}90^\circ\text{S}$) nominal	0.16	None available. Use 0.95 – 0.98

DSNE Table 3.4.6.1.1-1



Lunar albedo



Four views of the normal albedo of the Moon at 1064 nm in orthographic projection: (top left) Earth-facing view, (top right) farside view, (bottom left) north pole view, and (bottom right) south pole view.

Figure and caption source: Lucey, P. G., et al. (2014), The global albedo of the Moon at 1064 nm from LOLA, *J. Geophys. Res. Planets*, 119, 1665– 1679, doi:[10.1002/2013JE004592](https://doi.org/10.1002/2013JE004592).

Phase-dependent reflectivity

- Reflectivity of the lunar regolith increases for phase angle (g) approaching 0°
 - Zero phase angle = looking directly away from the Sun
 - Increased backscatter

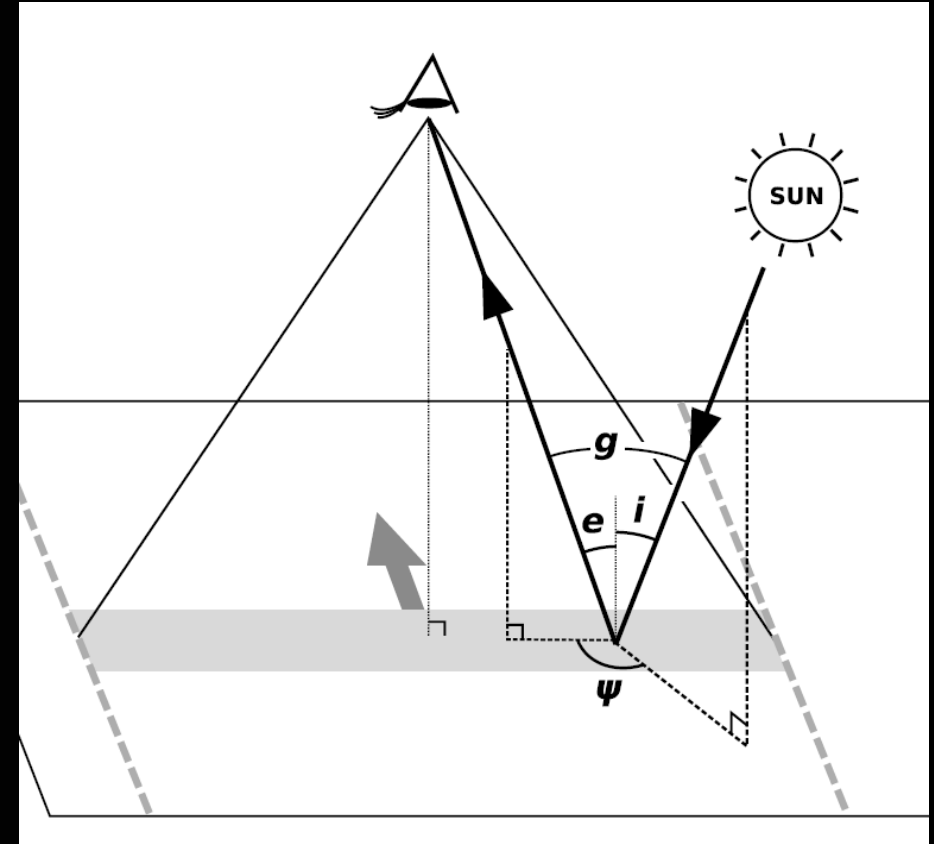
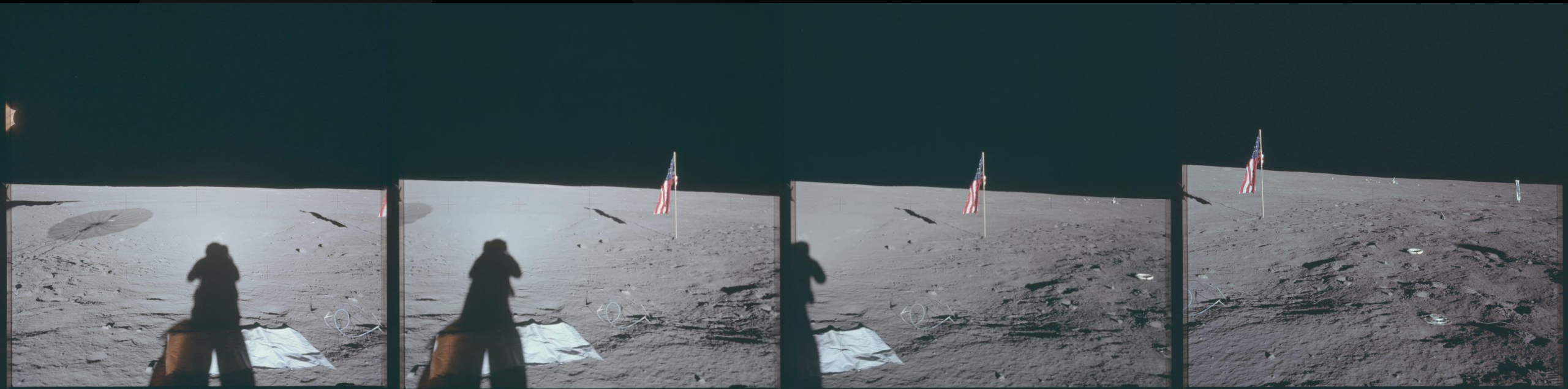
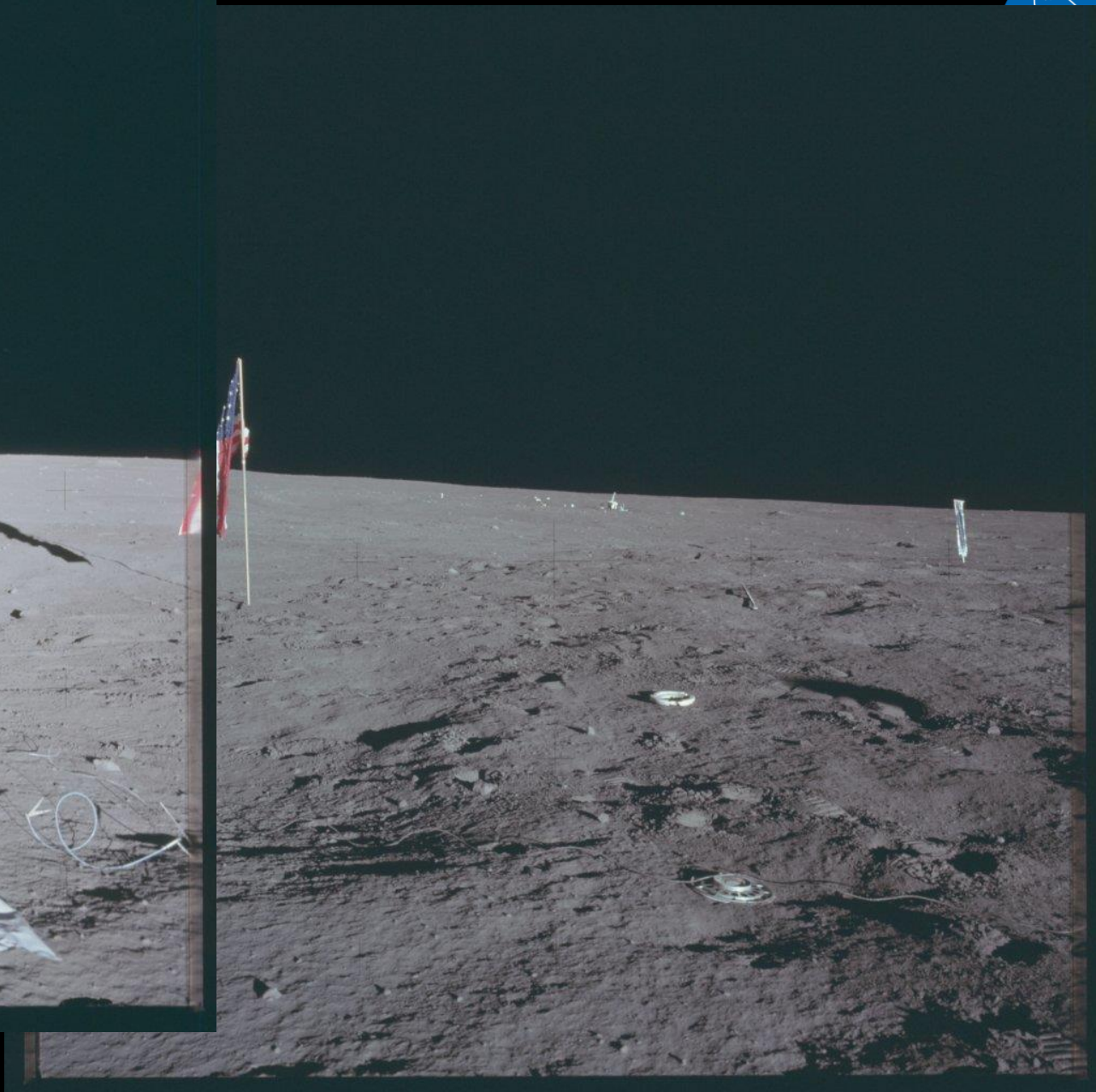
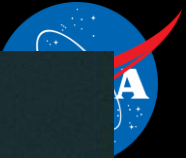


Figure source: Sato, H., Robinson, M. S., Hapke, B., Denevi, B. W., and Boyd, A. K. (2014), Resolved Hapke parameter maps of the Moon, *J. Geophys. Res. Planets*, 119, 1775–1805, doi:[10.1002/2013JE004580](https://doi.org/10.1002/2013JE004580).



AS12-47-6982 through AS12-47-6985
NASA/JSC

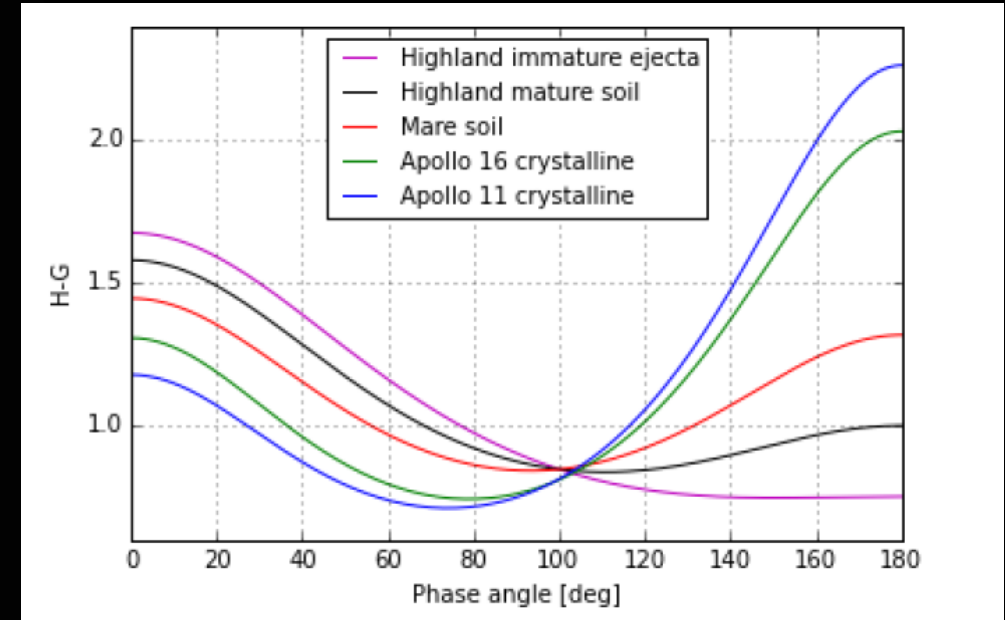


AS12-47-6982 and AS12-47-6985
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Phase-dependent reflectivity (Section 3.4.5.1)

- Light scattering from regolith modeled in detail by the Hapke function (Sato et al. 2014)
- The simpler Henyey-Greenstein (H-G) phase function is sufficient for engineering analyses
 - H-G function and parameters provided in DSNE section 3.4.5.1
- For simulation purposes, full Hapke function from Sato et al. 2014 may be preferred



DSNE Figure 3.4.5.1-1 Henyey-Greenstein phase functions using the parameters listed in DSNE Table 3.4.5.1-1.



South Pole Considerations



South Pole Considerations

- South Pole is a highlands environment
 - Regolith evolution and history relatively consistent across lunar surface
 - Geotechnical properties not expected to deviate significantly
 - Analysis of orbital data supports this conclusion
 - Unknowns/gaps related to volatile content
 - Bigger differences expected in permanently shadowed regions
- Lighting, plasma environment more complex due to low sun angles
 - Lighting environment changes more drastically with time and in space



Questions?

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