

## THE SEARCH FOR NATURAL LANDING PADS ON THE MOON AND MARS.

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**Introduction:** Landing a spacecraft on the lunar or martian surface without a pre-built landing pad presents specific challenges concerning damage to the lander and risk to mission. Landing plume interactions with the surface can result in high velocity regolith ejecta and surface cratering which can cause lander structural pitting or uneven landing/tipping, respectively. Future mission planning should justify regions of the Moon and Mars that minimize these risks associated with natural landing pad touchdowns.

**Background:** Rocket plume-surface interaction (PSI) describes the lander environment as it applies to the impingement of rocket exhaust on the surface of planetary bodies. Plume-induced erosion and ejecta physics led to an approximate 12° tilt of the Apollo 15 lander. Regolith ejecta led to serious visibility issues during all lunar landings, and ejecta impacts from the Apollo 12 lander pitted/sandblasted the Surveyor 3 lander 525 feet away [1]. Due to its atmosphere, Mars does not present the same regolith ejecta threat as the lunar surface. However, atmospheric presence collimates the lander plume, resulting in a more directed force at the surface and significant cratering [2]. This leads to an uneven landing surface which could increase lander tipping risk.

We can develop confidence equations to isolate geographic locations that minimize landing risk. This is not without precedent. The Planetary Science Institute has been working to develop and refine an equation to infer high confidence in the consistency of subsurface water ice on Mars with a full suite of remote sensing datasets [3]. The initial Subsurface Water Ice Mapping (SWIM) equation calculated consistency of ice,  $C_i$ , as:

$$C_i = (C_N + C_T + C_G + C_{RS} + C_{RD})/5$$

Each subscript in the equation refers to an ice characteristic technique tied to a remote sensing dataset. The values of each term are ranged from -1, entirely inconsistent with presence of ice, to +1, wholly consistent with the presence of ice [3].

Using remote sensing datasets for the Moon and Mars, we can parameterize and isolate the data to determine locations on the lunar and martian surfaces that minimize the risks associated with plume-surface interaction on natural landing pads to a level of high confidence using equations similar to SWIM. We construct these Surface Hydrodynamic Interaction Efficiencies Limiting Damage (SHIELD) equations at both global and localized scales for the Moon and Mars. Global SHIELD equations account for global, lower resolution remote sensing data to map locations with high densities of natural landing pad candidates.

The local SHIELD equations use higher resolution data on the candidates produced from the global equation map for more precise landing locations.

**The Lunar SHIELD Equations:** For the lunar surface, we are trying to find large, flat regions with a thin/dense layer of regolith. This optimal landing surface will have a low slope and roughness, low abundance of large rocks on or near the surface, and a high thermal inertia consistent with dense regolith. The initial global confidence equation, calculated for  $L_{global}$ , is:

$$L_{global} = (L_T + L_S + L_R + L_{RA})/4$$

The subscripts in the above equation reflect the following: T, thermal analysis from Diviner at 10ppd; S, slope analysis from LOLA/SELENE Terrain Camera (TC) hybrid DEM (SLDEM 2015) at 128ppd; R, roughness analysis from SLDEM 2015 at 128ppd; RA, rock abundance analysis from Diviner at 128ppd.

High values from the global equation indicate a higher density of local-scale natural landing pads that meet our optimal criteria while low values from the equation indicate fewer candidates. In these high-density areas, we can use higher resolution imagery at a local scale to discern the relative safety of a landing location using the local confidence equation, calculated for  $L_{local}$ :

$$L_{local} = (L_T + L_S + L_R + L_{RA})/4$$

T, h-parameter (dense regolith thickness) [4] from Diviner at 128ppd; S, slope analysis from LRO WAC at 100mpp; R, roughness analysis from LRO WAC at 100mpp; RA, rock abundance analysis from Diviner at 128ppd. Incorporation of high-resolution data for the local equation is in progress.

**The Mars SHIELD Equations:** For the martian surface, we are seeking large, flat regions with exposed bedrock and minimal dust; low slope and roughness, high thermal inertia consistent with bedrock, and a high value on the Dust Cover Index (DCI) consistent with dust-free surfaces. The initial global confidence equation, calculated for  $M_{global}$ , is:

$$M_{global} = (M_T + M_S + M_R + M_{DO})/4$$

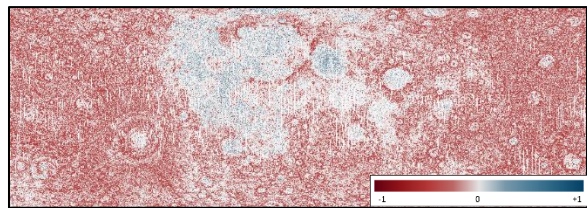


Fig. 1. Global Lunar SHIELD map (60S60N000360)

The subscripts in the global equation reflect the following: T, thermal analysis from TES at 20ppd; S, slope analysis from MOLA DEM at 128ppd; R, roughness analysis from MOLA DEM at 128ppd; DO, dust opacity analysis from TES Dust Cover Index (DCI) at 16ppd.

Once areas with a high density of natural landing pad candidates are mapped from the global equation, we can use higher resolution imagery at a local scale to discern the relative safety of a landing location using the local confidence equation, calculated for  $M_{local}$ :

$$M_{local} = (M_T + M_G + M_S + M_{BD} + M_R)/5$$

T, thermal analysis from THEMIS at 100mpp; G, geomorphological analysis from CTX at 5mpp; S and R, slope and roughness analysis from HRSC/CTX/HiRISE at 3-25mpp; BD, boulder density analysis using Martian Boulder Automatic Recognition System (MBARS) [9] with CTX imagery at 5mpp or HiRISE imagery at 1mpp.

**Methods:** We parameterize the individual datasets for the global SHIELD equations such that each variable ranges between +1 and -1, where +1 indicates the best/safest landing parameter and -1 indicates the worst/least safe landing parameter. The equation results in an average between +1 and -1 for each pixel, representing the overall possibility of damage to a lander from a landing location.  $L_T$  values range between  $55 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$  and  $75 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$  [4].  $L_S$  values range between  $0^\circ$  and  $20^\circ$  based on current height/width specifications for the Starship HLS.  $L_R$  and  $M_R$  values range between 0m and 8m, with the median value of 4m representing the peak roughness value of proposed landing sites on Mars [5].  $L_{RA}$  values range between 0% and 10%, representing a range of locations where the areal coverage of 1m rocks is less than 10% [6].  $M_T$  values range between  $350 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$  and  $1200 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$  [7].  $M_S$  values range between  $0^\circ$  and  $8.6^\circ$  based on current height/width specifications for the SpaceX Starship.  $M_{DO}$  values range between 0.95 and 1.00 on the Dust Cover Index, corresponding to locations of dust-free surfaces on Mars [8]. These parameters are integrated into the SHIELD equations and mapped using QGIS software.

**Preliminary Results:** When we map the global lunar SHIELD equation results, the optimal landing

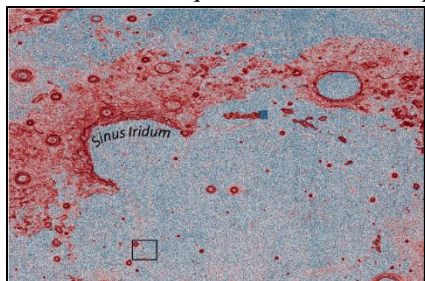


Fig. 2. Mare Ibrum vicinity Sinus Iridum

locations correspond with the lunar mare regions, as expected (Fig. 1). As a proof of concept, we localize our search to just south of Sinus Iridum (Fig. 2). Local SHIELD maps show stretches of potential landing areas kilometers long within the mare region near Herschel Crater (Fig. 3).

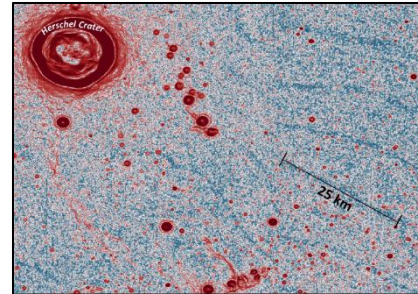


Fig. 3. Local Lunar SHIELD map vicinity Herschel Crater

Global SHIELD mapping of Mars results in sparse optimal landing locations with most values ranging between -1 and +0.5 (Fig. 4). Possible locations for further localized analysis are the Acadalia Planitia, Solis Planum, and Daedalia Planum regions. These areas have substantial surface areas with SHIELD confidence levels near +0.5 given the current global parameters.



Fig. 4. Global Mars SHIELD map (60S60N000360)

**Conclusions:** Using low resolution remote sensing datasets and global confidence equations, we can determine general locations for optimal natural landing pad selection that minimizes risk to the lander. From there, we can use higher resolution datasets and local confidence equations to further minimize the risk associated with plume-surface interaction. Ongoing work using local SHIELD equations, to be presented, will compare confidence levels with known bedrock locations on Mars and shallow regolith locations on the Moon.

**References:** [1] Mehta, M. (2019) NASA – DLR Technical Interchange Meeting. [2] Metzger P.T. et al. (2009) 47<sup>th</sup> AIAA ASM, 1-19. [3] Morgan, G.A. et al. (2021) Nature Astronomy, 5, 230-36. [4] Hayne, P.O. et al. (2017) J. Geophys. Res., 122(12), 2371-400. [5] Putzig, N.E. et al. (2014) J. Geophys. Res., 119(8), 1936-49. [6] Bandfield, J.L. et al. (2011) J. Geophys. Res., 116(12), 1-18. [7] Edwards, C.S. et al. (2009) J. Geophys. Res., 114(11), 1-18. [8] Ruff, S. & Christensen, P. (2002), J. Geophys. Res., 107(12), 1-22. [9] Hood, D.R. et al. (2019) 50<sup>th</sup> LPSC, 2132, 1-2.