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Planning Multi-Year Solar Powered Missions on Mars : The Challenge of Dust

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Abstract

The energy available per Sol on Mars is a fundamental constraint on lander and rover operations, and for solar-powered missions results from three principal factors, only one of which is fully deterministic (the orbital cycle of insolation at the top of the atmosphere, via the orbital eccentricity and the obliquity). This makes mission planning a particular challenge.

While the experience to date does not permit confident long-term prediction of available power on Mars, there is at least a reasonable statistical basis for estimating the atmospheric dust loading (optical depth 'tau', a quasi-global property) as a function of solar longitude (Ls). The occurrence of dust cleaning events, however, seems much more to be a function of local properties – wind, the intensity of vortex activity, and perhaps the availability of sand (which may act as an abrasive agent to dislodge dust from spacecraft surfaces). It may also be a strong function of the vehicle construction and operation ; rattling movements associated with wheeled locomotion may help mobilize dust, the surface coatings on the arrays may influence adhesion. Similarly, the height of arrays above the ground, and their tilt, may also be important factors in allowing saltating sand to remove dust. Until a definitive understanding of dust removal mechanisms and their dependencies on terrain and vehicle factors is developed, Mars solar missions are hostage to uncertainty.

Keywords: Mars, Solar Arrays, Dust, Mission Planning

1. Introduction

The first successful landed missions at Mars were the Viking landers in 1976, each powered by two small radioisotope thermoelectric generators. These supplied constant electrical power (albeit only about 76 W) but also waste heat. Not only does such internal power generation avoid the uncertainties of the Martian environment, but the 'waste' heat also reduces the need to expend valuable electrical power to maintain benign equipment temperatures. However, radioisotope power is expensive and introduces programmatic complications with respect to launch approval and planetary protection; to date it has been used only on 'Flagship' missions at Mars – Viking, Curiosity and Perseverance (although the Mars rovers Spirit and Opportunity, and Sojourner, benefited from radioisotope heater units).

Solar arrays permit much higher BOL (Beginning of Life) power levels for a given mass, and have been used on most Mars missions to date. But the power output varies with time, due to the changing solar geometry (insolation at Aphelion is some ~40% less than at Perihelion), as well as absorption and scattering by dust in the atmosphere. The dust in the atmosphere settles out, forming an absorbing/scattering layer on the solar arrays that increases steadily with time. A survey of landed solar mission power histories indicates a typical loss of 0.2% per Sol, which is in fact in good accord with an estimate calculated [2] prior to the first solar-powered Mars lander mission, Pathfinder.

The Mars Exploration Rovers, Spirit and Opportunity, operated for some 2208 and 5352 Sols respectively, even though (on the basis of the Pathfinder/Sojourner experience) their initial lifetime expectation and requirement was only 90 Sols. Their exceptional longevity arose because natural events episodically removed the accumulated dust from the arrays, restoring the power output [3] : although the rovers were not equipped with meteorological instrumentation, an analysis indicated that dust devil vortices were responsible [4].

The submission date of the present paper is poignant, in that it occurs only a few weeks after the end of the InSight mission (figure 1) was declared, after 1440 Sols on the surface. The InSight mission had a requirement to operate for just over one Martian year, and it was equipped with especially large solar arrays in order to have adequate power margin to do so, even allowing for no natural clearing events. This proved prudent.

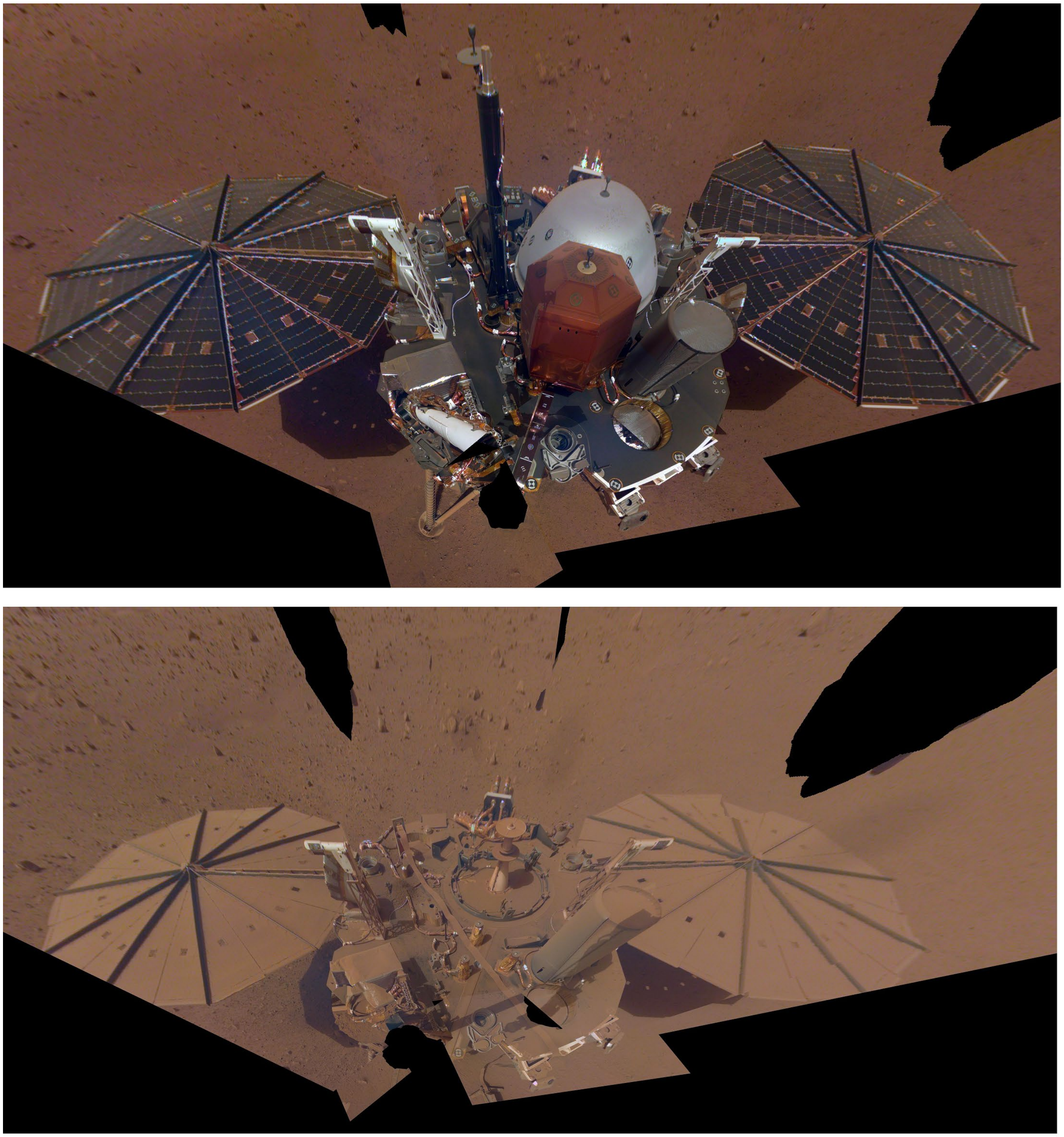

Fig. 1. "Selfie' image mosaics from the arm-mounted camera on InSight, at the beginning of the mission (about 20 Sols after landing) and near the end (Sol 1222). Notice the obliteration of contrasts on the solar arrays, due to the thick covering of dust. Note also that three deck-mounted payload elements seen in the first image are not visible in the later image, having been deployed onto the ground.

2. Solar Power on Mars

The predictable element in solar power is that the eccentric Martian orbit around the sun modulates the solar flux both by distance (such that even at the equator there is an appreciable annual cycle) as well as via the subsolar latitude. A second factor ('tau') is quasideterministic, namely the optical depth of dust in the atmosphere. This follows an annual cycle that is strikingly regular in timing, with the onset of global dust increases recurring on particular dates (Solar Longitudes, Ls) one year to the next. Southern summer (Ls=180-360°) generally has dustier conditions. Although the timing is rather reliable, the intensity of global dust storms varies dramatically from one year to the next; similarly, regional dust storms can occur that affect local conditions substantially. Lisano [5] developed a database of dust storms, to assess the probable values of tau as a function of Ls.

The third element, the 'dust factor' (figure 2), is the ratio of the generated power to that expected from a clean solar array, indicating absorption due to dust that has accumulated on the array surface. A review [1] found that a loss of 0.2% per Sol is typical. This degradation has been episodically reversed on some missions by cleaning events due to dust devils and gusts. The enduring success of the Spirit and Opportunity missions may have given an impression of the long-term viability of solar power on the Martian surface that should not be considered to be globally-applicable: the occurrence of cleaning events with an operationally-useful frequency seems contingent upon local meteorological circumstances that are not yet fully understood. The conditions for significant cleaning events are apparently not met on the InSight mission, although some artificial cleaning was performed by drizzling sand on the arrays to scrub off the dust [6].

The outstanding question, then (and one discussed at some length in [1]) is why no cleaning events occurred at InSight. In fact, the lack of such events was not altogether surprising, if the formation of dust devil tracks on the surface is taken as a proxy for solar array cleaning (there may of course be some differences, due to the different interaction heights and the impermeability of an array compared with a regolith surface). A survey [7] of dust devil tracks prior to InSight's arrival indicated about a factor of 10 lower area formation rate at Elysium (km^2 of track formed per km^2 per Sol) than at the Gusev crater site explored by Spirit. It would follow that the interval between dust devil cleaning events would be about an order of magnitude longer for InSight, namely several thousand Sols, a prediction sadly not contradicted by the mission's experience. It is notable also that while Spirit's cameras recorded many dust devils, some of which were quite large, InSight did not detect a single one in over a thousand images that were acquired.

Global Circulation Models (GCMs) can yield a parameter called the 'Dust Devil Activity' index, a combination of surface convective heat flux (which drives dust devils) and the planetary boundary layer height, which influences their thermodynamic efficiency in converting heat into motion. The comparisons in [1] show that this appears not to be an effective predictor of cleaning events (or indeed, dust devils!) in that the value at InSight was not particularly lower than for the rover missions. It is possible that dust is simply less available at Elysium to yield visible devils – vortices are abundant (although possibly not the largest ones that may be associated with dust lifting and cleaning) [8,9]. One possibility is that the background winds at Elysium are stronger, shearing out the largest devils and thus suppressing cleaning events. This topic remains one of active investigation, and is critical to understand in order to enable long-term solar-powered surface operations.

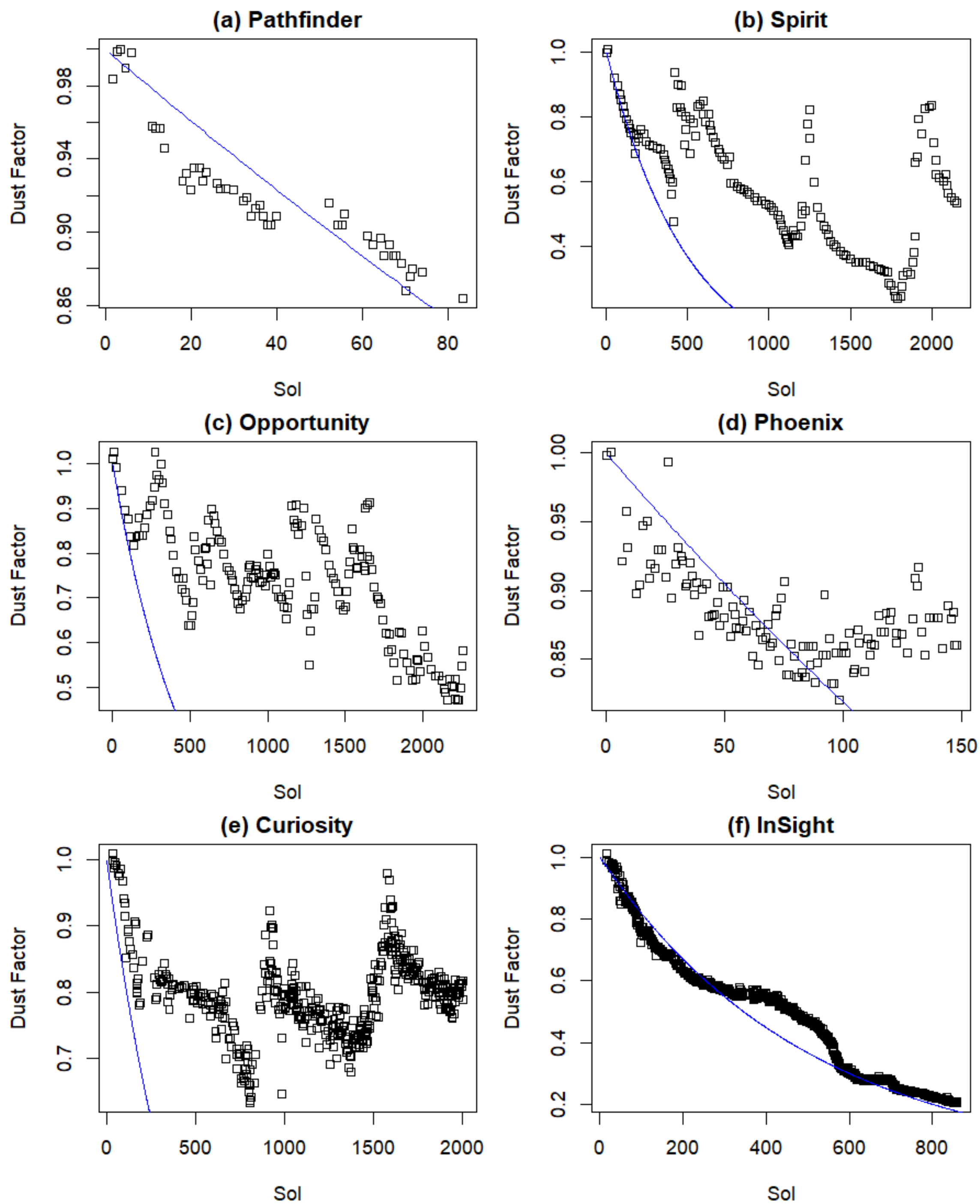

Fig. 2. Dust Factor evolution on several landed missions, from [1] (the Curiosity data is for an ultraviolet light sensor, rather than a solar array, but the situation is very similar). The blue line indicates a constant 0.2% per Sol decrease. Whereas Spirit and Opportunity (and Curiosity) saw seasonal reverses in the decline, the decay of InSight's solar array output has been unremitting.

3. Mitigation Techniques

If the occurrence of natural cleaning events with a desired frequency is not expected, or uncertainty cannot be tolerated, hardware or operations mitigations can be introduced. Similarly, some features may enhance the likelihood of natural cleaning events, assuming that saltation bombardment is an effective mechanism (as the InSight experiment suggested is the cate). All of these mitigations have penalties, either mass or complexity, and uncertainties : some were considered quite extensively in the early 2000s, after the Pathfinder experience but before the unexpected encounter of natural cleaning events by Spirit and Opportunity (e.g. [10]), and related investigations have taken place in support of other mission contexts, such as human exploration (e.g. [11]) or dust fouling of camera windows (e.g. [12,13]).

3.1 Arrays Low to the Ground

The saltation length of sand on Mars is of the order of 10-20m, and sand can reach of the order of 1m above the ground. However, the frequency of grain hops falls off strongly with height, thus lowering the arrays may increase their likelihood of being scrubbed : the arrays of Pathfinder and Beagle 2 were quite close to the ground (but did not last long enough for cleaning events to be observed), Spirit and Opportunity a little less so (with many cleaning events) and InSight's arrays were over 0.7m off the ground. Low array height increases the likelihood of sand deposition causing array obscuration, and possibly abrasion of cell coverglasses and/or damage to conductors : low array height also increases the probability of rock strike during landing or array deployment.

3.2 Tilted Arrays

Tilted arrays may enhance the motion of sand across the array surface by sliding/rolling. It will likely not significantly reduce dust deposition itself, since the gravity force on small dust grains is small relative to adhesion and electrostatic forces (which cause dust to be deposited and remain on vertically-oriented surfaces on Mars landers and rovers). Clearly, the tradeoff of tilt with array output depending on latitude and season needs to be taken into accout.

3.3 Array Vibration

Vibration can remove attached objects inertially, if the adhesion force is unable to match the product of grain mass and array acceleration. However, these inertial forces are very small for fine dust grains – macroscopic 'shaking' of the array will do no good (as evidenced by the attempts to shake InSight's panels by operating the deployment motors [1]). The only practical way to achieve high enough accelerations is with very high frequency oscillations – typically in the ultrasonic realm (10s of kHz) : some dust mitigation systems for consumer digital cameras operate this way.

3.4 Non-Stick Coatings

Depending on the properties of the dust, certain coatings on the array may reduce the dust adhesion via lowering the surface energy (e.g. fluorosilanes [11]) and/or by increasing the electrical conductivity of the surface to reduce electrostatic cling (e.g. transparent Indium Tin Oxide coatings, already used on some windows or arrays to produce effective surface grounding).

3.5 Electrostatic

Dust transport can be effected by a set of electrodes to 'sweep' dust with an alternating field pattern. Although this technique has been demonstrated in the laboratory, it should be recognized that electrostatic effects on Mars may be complicated. The photoelectron emission from surfaces exposed to ultraviolet light during daytime may be a significant effect, and the electrical conductivity of the Martian atmosphere will be higher than Earth (and the breakdown potential is low).

3.6 Mechanical Brushes

A common question in the general public is why InSight was not equipped with a brush to remove the dust. Leaving aside overall issues of design-to-requirements (InSight met its mission duration requirement) it should be noted that InSight's robot arm (an inherited design from Phoenix) could only reach a small fraction of the array area. A mechanical brush (or rather, a blade) was tested for the Beagle 2 imagers [14], but of course ensuring an effective sweep across a ~2cm fixed camera window is a much more straightforward proposition than a several-meter wide deployed array. It should be noted that brushes are not foolproof – the removal of lunar dust from the battery radiators of the Apollo lunar roving vehicles was only partly successful (e.g. [15]), despite astronauts operating them in-situ with the dexterity of the human arm coupled with zero-latency high-quality image views.

3.7 Blowers

A high-pressure jet of gas (either stored, or compressed ambient atmosphere) can apply strong shear stress to remove dust, as evidenced by the use of 'shop air' to clean hardware during assembly. The Perseverance rover carries a dust removal device [16] using high pressure gas (and though often forgotten, the Viking lander cameras had a CO_2 gas jet cleaning system, although it was not needed). In principle gas flows, which may be limited by boundary layer effects, can be augmented by blown particles (CO_2 snow is a useful abrasive for cleaning applications at terrestrial pressure, since it sublimes without residue). A gas jet system suffers the same difficulty as a brush, namely that an effector must be brought by some arm or other device to the surfaces to be cleaned.

3.8 Sacrificial Films

In principle a transparent polymer film covering an array could be removed (with the dust adhering to it) after some period, much as protective plastic films are used to protect various products such as computer screens. Removal could be effected by a relatively simple mechanism like a lanyard/winch.

3.9 Protected Arrays

One approach, apparently being considered by the Mars Sample Return project, is to simply keep one or more arrays 'in reserve'. By retaining an array in a stowed configuration (rolled or folded up) it is not exposed to dust deposition, and it therefore has its full capability when delayed deployment occurs (e.g. once an initially-deployed array has lost much of its capability). Although inelegant, and requiring substantial resources (finding real estate on the lander body to mount the arrays, as well as the mass of the arrays themselves), the approach has the advantage of not requiring new hardware designs.

3.10 Sand-blasting

The use of InSight's arm and scoop to drizzle regolith (mixed sand and dust) near the arrays was somewhat successful [8] enabling operation of InSight's seismic instrumentation through and after the power-tight aphelion period, which turned out to be exceptionally valuable scientifically (the largest events recorded were after this time). These operations required weeks of planning, and were performed at times of day predicted (from previous in-situ wind data and GCM's) to have wind that would sweep sand grains across the arrays. The winnowed sand grains produced an improvement of some improvement of 35 W hr sol^{-1} on the first attempt, although subsequent attempts were less lucky with wind conditions and yielded smaller but nonetheless beneficial effects. While this counterintuitive approach yielded good results, it must be conceded to have been a somewhat desperate improvisation and might not be the first choice of mitigation.

6. Conclusions

A variety of techniques may be considered to mitigate dust accumulation on solar arrays on Mars. The validation and introduction of such techniques, or the incorporation of large margins in array design, may be necessary unless the mechanism of natural cleaning is understood and the frequency of such cleaning events can be predicted.

Acknowledgements

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References

[1] Lorenz, R., G. M. Martínez, A. Spiga, A. Vicente-Retortillo, C. E. Newman, N. Murdoch, F. Forget, E. Millour, T. Pierron, 2021. Lander and Rover Histories of Dust Accumulation on and Removal from Solar Arrays on Mars, Planetary and Space Science, 207, 105337. https://doi.org/10.1016/j.pss.2021.105337

[2] Landis, G. A., 1996. Dust obscuration of Mars solar arrays. Acta Astronautica, 38(11), 885–891

[3] Herman, J.A., Wood, E.G. and Chin, K.B., 2021. Power Operations of the Mars Exploration Rovers. In AIAA Propulsion and Energy 2021 Forum (p. 3255).

[4] Lorenz, R. D. and D. Reiss, 2015. Solar Panel Clearing Events, Dust Devil Tracks, and in-situ Vortex Detections on Mars, Icarus, 248,162–164

[5] Lisano, M.E. and Kallemeyn, P.H., 2017, March. Energy management operations for the Insight solar-powered mission at Mars. In *2017 IEEE Aerospace Conference* Big Sky, MT March 2017. doi:10.1109/AERO.2017.7943965

[6] Golombek, M. et al., in preparation.

[7] Reiss, D. and R. Lorenz, 2016. Dust Devil Track Survey at Elysium Planitia, Mars : Implications for the InSight landing sites, Icarus, 266, 315-330

[8] Lorenz, R., A. Spiga, Ph. Lognonne, M. Plasman, C. Newman, C.Charalambous 2021. The Whirlwinds of Elysium : Dust Devil Vortex Catalog and Meteorological Characteristics Observed by InSight on Mars, Icarus, 355, 114119, https://doi.org/10.1016/j.icarus.2020.114119

[9] Lorenz, R., M. Lemmon and J. Maki, 2021. First Mars Year of Observations with the InSight Solar Arrays : Winds, Dust Devil Shadows, and Dust Accumulation, Icarus, 364, 114468 https://doi.org/10.1016/j.icarus.2021.114468

[10] Landis, G.A. and Jenkins, P.P., 2002, May. Dust mitigation for mars solar arrays. In Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, 2002. (pp. 812-815). IEEE.

[11] Hartzell, C.M., Farrell, W. and Marshall, J., 2018. Shaking as means to detach adhered regolith for manned Phobos exploration. Advances in Space Research, 62(8), pp.2213-2219.

[12] Benkoski, J.J., Luedeman, W.L., Teehan, J.O., Hörst, S.M., He, C. and Lorenz, R.D., 2019. Experimental investigation of surface adhesion of Titan analog materials: Mitigation by dust-repellent coatings. Planetary and Space Science, 179, p.104721.

[13] Benkoski, J.J., Montalbano, T.J., Luedeman, W.L., Teehan, J.O. and Lorenz, R.D., 2023. The effects of airflow velocity and particle size on dust accumulation for Titan dust simulants on transparent windows. Planetary and Space Science, 225, p.105599.

[14] Griffiths, A. and A. J. Coates, Dust Removal Techniques for the Beagle 2 Stereo Camera System External Optics, 33rd Annual Lunar and Planetary Science Conference, March 11-15, 2002, Houston, Texas, abstract no.1012

[15] Lorenz, R., The Dirty Secrets of Planetary Exploration: Lessons from Interactions with Regolith, AIAA 2022-0672, AIAA SciTech Forum, San Diego, CA & Virtual, 3-7 January 2022

[16] Jens, E., Tarantino, P., Preudhomme, M., Hinchman, R., Nakazono, B. and Vaughan, D., 2017, March. Precision cleaning samples for science analysis using a gas-based dust removal tool. In 2017 IEEE Aerospace Conference (pp. 1-12). IEEE.