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Overview of Instruments for Investigating Dust Interactions on Small Solar System Bodies by Landers and Rovers

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Small Solar System bodies such as asteroids, comets and Mars' moons Phobos and Deimos have relatively unknown regolith environments. It is hypothesized that dust preserved in the regolith on the surfaces will have similar mechanical properties to lunar dust because of similar formation processes from micrometeorite bombardment, low relative gravity for slow settling times, and virtually no weathering because there is no atmosphere. This combination of processes infers that small-body dust particles will be highly angular and retain abrasive properties. The objective of this paper is to provide a comprehensive overview of science instruments that could be utilized by landers and rovers on Small Bodies. The paper uses a specific mission architecture example and engineering design entailing the deployment of "spacecraft/rover hybrids" from a mother spacecraft, which are minimalistic, internally-actuated surface mobility platforms capable of achieving both large surface coverage and fine mobility. Specifically, we first summarize regolith properties are summarized in order to identify technologies that may be useful for exploration in terms of scientific return and spacecraft design. Then, we provide an overview of past, current, and proposed scientific instruments that potentially could be deployed on the aforementioned spacecraft/rover hybrids. Finally, opportunities for instrumentation and hardware payloads are highlighted that include low mass solutions or dual-purpose instruments that can measure regolith or dust properties. Understanding the regolith can help answer many key questions about our solar system's age, how it was formed, and how we may be able to use its resources to explore further.

I. Introduction

Exploration strategies are constantly being reinvented to maximize scientific output while minimizing the time it takes for a new idea to go from the back of a napkin into space. By examining a specific Rover/Hybrid mission architecture (Section III), this paper focuses on the dust interactions that would occur on small solar system bodies, such as asteroids. The paper describes the expected regolith environment of small bodies; a novel mission architecture that capitalizes on the low gravity of these targets; the measurable properties of small body regolith; past, current, and proposed instruments especially relating to dust; and unique opportunities and technologies outlined for consideration.

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II. Small Body Regolith

Although small-bodies such as asteroids, comets, and Mars' moons Phobos and Deimos have relatively unknown regolith environments, to a first order one may hypothesize the silicate dust on these bodies may have similar mechanical properties to lunar dust. This hypothesis is further supported by common factors such as: limited mineralogy; a history of micrometeorite bombardment and space weathering processes; low gravity regime; and lack of atmospheric weathering. This suggests that small-body dust will include a high percentage of angular particles and retain abrasive properties. There is likely to be considerable differences in mineral composition between the moon and these small bodies (small bodies can be considered to have a relative diameter or primary dimension up to 20 km). Hardness of particles and adhesive ability will vary with the mineralogy, but high levels of three-body abrasion can be expected even if the particles are friable.[1-6]

What little is known about asteroids shows they can have a wide range of internal structures. The transition between a gravitationally bound rubble piles from ~100m to 100km in average diameter[7] to a self-welded monolith with discrete superficial regolith is an important distinction. For example, a rubble pile may dynamically change shape as a result of a rocket-propelled hopper's contact forces. For asteroids dominated by silicate minerals, it is reasonable to hypothesize that asteroid regolith will be similar to lunar regolith. The rubble piles may be dominated by cohesive van der Waals forces over gravitational forces up to component sizes less than a few meters[8], which needs to be considered for rover contact interactions (soft landing, hopping) or purposeful impacts (high velocity to observe from a secondary spacecraft like the LCROSS mission). Scheeres et al.[9] summarized asteroid ejecta literature, which has progressed from smaller asteroids predicted to retain little regolith to modeled estimates that relate regolith thickness and spatial distribution as a function of asteroid size, shape, and rotation state.

Another factor of regolith formation is proximity to other celestial bodies. For example, Phobos and Deimos are in the gravitational field of Mars. There is potential regolith exchange between these three bodies that needs to be part of any regolith modeling. The Martian moons are also partially shielded by Mars-facing bombardment (the Moon is less cratered on the Earth facing side potentially for this reason, but the maria are only present on the Earth facing side due to volcanic activity, so there are several Earth-Moon models).

Specific to the moons of Mars, there are conflicting sets of data describing their regolith. Images from the Mars Global Surveyor suggest regolith a meter deep covering the entire surface of Phobos[10]. Kuzmin and Zabalueva[11] calculated and modeled the thermophysical properties of Phobos surface regolith derived from observations made with the Mariner 9 orbiter, the Viking orbiter, the Fobos-2 spacecraft, and the Mars Global Surveyor orbiter. An analogy with lunar soil was used to estimate the surface regolith density of Phobos at 1100 kg/m^3 (agrees well with the values obtained for finely crushed basalt, with particles of 37–62 μm in size placed in vacuum at 150–250 K) to 1600 kg/m^3. The Kuzmin and Zabalueva model uses a 40-cm-thick regolith layer, which is divided into sub layers, the first being 0.08 mm thick. The thickness of the subsequent sub layers increases progressively with a geometric ratio of 1.26 [Ref. 11].

Particles from the one asteroid from which we have samples, Itokawa, have been interpreted as being autogenousously ground, meaning the content of the rubble pile has been grinding against itself.[12] The temporal stability of the asteroid is questionable given it's morphology and obvious spatial variation in particle sizes[13]. The parent bodies of stony meteorites have been repeatedly broken and then re-consolidated, which is immediately apparent in a sawn slab, but the age dating shows this to have happened billions of years ago.[14] Possibly, the breaking and coalescence process continue but the decay of ^{26}Al has stopped the melting process or may be attributed to another mechanism.

III. Novel Rover/Hybrid Mission Architecture

To explore small bodies in the solar system, a novel mission architecture was developed with funding by the NASA Innovative Advanced Concepts (NIAC) program.[15,16] The design, which was to enable affordable, in-situ sampling, included a mother spacecraft that would deploy one or more spacecraft/rover hybrids over the surface of a small body. Each remote vehicle would be multi-faceted with several symmetric spikes and internal actuation, with the primary design having a central 'spherical' core about 1-foot in diameter. These remote scouts would be capable of different synergistic operation modes coordinated with the mother spacecraft including: hopping for long distances; short controlled tumbles for precise science locations; or high-altitude ballistic flight (as shown in Figure 1). The key design feature of the robotic platform is that it directly exploits the low gravity environment for mobility with three orthogonal internal flywheels (as seen in Figure 2), which spin to create internal reaction torques leading to attitude-controlled hops.

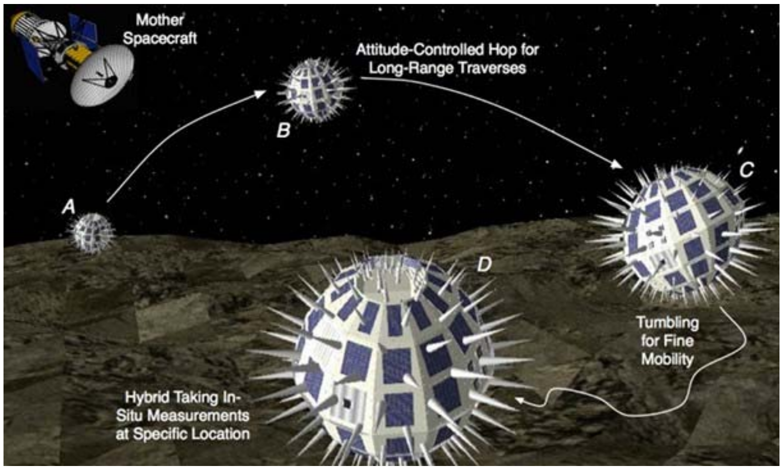

Figure 1. Mission architecture. Mother spacecraft deploys one (or more) spacecraft/rover hybrids (from dm- to m-scale). The hybrids perform attitude-controlled hops for long-range traverses (on the order of 10 m per hop, steps A to B to C in the figure) and would tumble to reach specific locations (steps C to D in the figure).

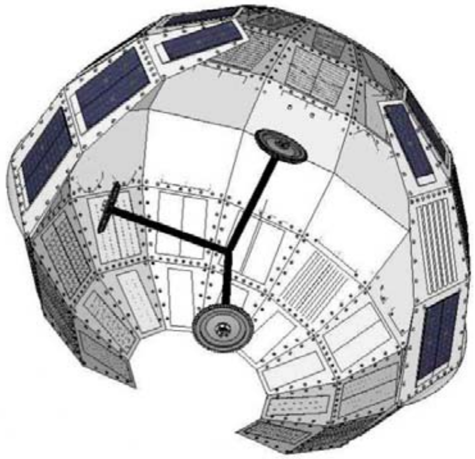

Figure 2. Internal view of the deployed spacecraft/rover. Each hybrid is sealed in an enclosure and internally actuated through three mutually orthogonal flywheels.

Phobos was targeted as a reference mission destination, but the applications of this novel system could be used to enable several of the missions recommended by the Planetary Science Decadal Survey. The lower cost of deploying several simplified spacecraft/rovers, analogous to commercial cubesats versus large satellites, means these vehicles are better choices for higher risk measurements such as geophysical dust dynamics and electrostatic charging. They could be considered expendable in future exploration missions and make measurements in dangerous terrain as probes or precursors to human exploration. This paper will now examine science investigations that this specific architecture and vehicle configuration could accomplish with respect to the regolith environment, and unique design features and potential payloads to characterize the expected dusty environments.

IV. Measurable Regolith Properties

Characterization of a celestial body's environment is both an objective and a requirement to achieve successful missions. Measuring topography changes of planetary bodies is important for both mobility and unlocking the history of the terrain, which can lead to mapping early solar system activity. Interactions by small spacecraft on the surface will primarily be with the regolith that occupies the upper layer and consists of unconsolidated rocks, pebbles, soil (< 1 cm), fines (<1 mm) and dust (effective particle radius < 20 or 50 μm depending on definition).[17-19] Theoretical models based on remote sensing and orbital mechanics can be used to estimate the characteristics of an environment including micrometeorite bombardment, temperature ranges, electrostatic charging via photoelectric effects, radiation, gravity or mass, and estimated atmospheric density. But in order to understand the elemental makeup and history of an object, further measurements would be required in near proximity or directly on the surface.

Some of the mechanical properties of regolith will change with depth if sufficient gravity is present. Examples include: average bulk density (g/cm^3); void ratio; relative density (percentage); average cohesion (kPa); and average friction angle (degrees). Other physical properties that may vary with depth would be related to spatial variation in mineralogy, such as: hardness, cleavage angles and other properties related to the mineral crystal properties. Generally speaking, the relative density will increase with depth as the regolith becomes more compacted primarily due to self-weight,[17] while crater rims or sloped terrain features will be less dense and dependent on the cohesion and friction angle properties.[20,21] The inspection of individual grains can reveal size and shape properties, such as angularity and surface area, which could help develop planetary surface exploration models such as abrasive wear predictions [see Kobrick, et al. publications for lunar dust abrasion research] that would be important for risk mitigation for hardware, instruments and potentially humans in subsequent missions (see Ref. 22 for issues identified during the Apollo missions). A list of regolith properties that could be measured by this architecture are summarized in Table 1, which is a reduced list adapted from the NASA Dust Management Project work at NASA Glenn Research Center conducted by Ryan Kobrick, PhD (a more complete list is given in Table 2 of Rickman and Schrader[23]).

Table 1. Summary of regolith physical properties of interest to spacecraft/rover mission architecture.

Properties Affecting Mission	Properties Potentially Measureable by Mission
Particle size and shape distributions	Particle size and shape distributions
Soil compaction	Soil compaction
Adhesion	Tribocharging
Abrasion	Mineral Identification
Tribocharging	

Furthermore, the chemical composition and mineralogy are important properties to investigate as they will reveal the building blocks of the planetary object and directly influence the physical environment. For example, the mineral hardness could be an indicator of how much abrasive wear can be expected [Rickman, 2008]. Also, discovering the composition of the planet could be a gateway for further missions studying astrobiology or extracting planetary resources for in-situ resource utilization or commercial endeavors.

V. Past, Current and Proposed Instrumentation:

The following lists from various online sources are used to demonstrate examples of atmosphere, regolith and dust measurement, and global properties instruments that are from past, present or future concepts. This list illustrates the range of possible instrumentation and motivating science questions a lander or probe may be asked to address and serves as a reference for future work. The instrumentation list is by no means comprehensive but includes a survey of payloads from the following selected Missions: Lunar Atmosphere and Dust Experiment Explorer (LADEE); Chandrayaan-1 (C1); Luna-Resource and Luna-Globe (LR/LG) [LR is an upcoming Russian-Indian mission]; Apollo Lunar Surface Experiments Package (ALSEP) [Apollo 11, 12, and 14 - 17 missions (A11-A17)]; Mars Global Surveyor (MGS); Mars Pathfinder's Lander (MPL) and its Sojourner rover (MPS); Phobos-Grunt [Russian Federal Space Agency] (PG); Yutu rover, Chang'e 3 (Yutu) [China National Space Administration]; Curiosity Mars Rover (CMR); Mars Exploration Rovers Sprit and Opportunity (MERS and MERO); Viking Landers 1 and 2 (VL); Venus Express Orbiter (VE) [European Space Agency, ESA]; Rosetta Spacecraft (RS) and Philae Robotic Lander (PRL) [ESA]; Mars Express Orbiter (MEO) [ESA]; and Exomars Rover (ER) [ESA]. Proposed Instrumentation (PI) in various stages of completion are also included to broaden the scope of consideration.

The regolith physical properties measured are divided into three proximity categories: A) exosphere down to near surface; B) near surface to shallow depths; and C) planetary interior. Sensors in key subsystems may be in any surface vehicle and may include accelerometers, load cells, thermocouples, magnetometers, or other off-the-shelf components. Ideas of how these may be incorporated are outlined in the next section. Photography/imaging in various wavelength regions of the spectrum has been used on most missions and for a wide range of applications, but only some of these instruments are discussed.

A. Exosphere Down to Near Surface

Atmospheric and Meteorological packages including: Anemometer to detect wind speed; Pressure sensor to detect atmospheric pressure; and temperature sensor to monitor temperature. (MPL and VL)

Electron reflectometers measure ionic particles and gamma rays within the plasma of the solar wind by collection of ions within multichannel plates that convert and amplify the particulate strikes to electrical signal. High-energy photons, gamma rays, have sufficient energy to cause ionization within the plates with enough efficiency to be detected as well (MGS).

Thermal Emission Spectrometer (TES) is an infrared spectrometer, typically of the Michelson Interferometer type (Fourier Transform Infrared Spectrometer, FT-IR), capable of measuring ice, dust clouds and surface composition at a distance from the thermal emission spectrum of the surface. The TES is included here due to the high altitude positioning (elliptical orbit ranged between 258 and 54,000 km) of the instrument also reading all materials between the surface and the instrument orbiting the body (MGS).

Lunar Dust Detector measures dust layer deposition by monitoring the power output from a set of solar cells. This experiment was also used to monitor long-term degradation of solar cells from radiation and thermal effects (ALSEP; A11, A12, A14 and A15).

Lunar Dust EXperiment (LDEX) is an impact ionization detector designed to provide information on the size and speed of the lunar dust particulates in atmospheric clouds at an altitude of 50 km (LADEE).

Lunar Dust Monitor (DML) contains two sensor types to study levitated particles and ejecta production including a piezo ceramic impact sensor and an electrostatic field sensor 20 and 90 cm from the surface (LR/LG).

Suprathermal Ion Detector Experiment (SIDE) measured ions incident on the lunar surface with a stepped electrostatic mass analyzer and stepped crossed-field (Wien) velocity filter package (ALSEP, A12, A14 and A15).

E-parallel-B / Thomson-parabola device measures charge-to-mass ratio and momentum of individual particles incident on the lunar surface (PI - University of Colorado at Boulder and the Laboratory for Atmospheric and Space Physics (LASP)).

Plasma analyzers are typically a collection of other instruments such as electron reflectometers and mass spectrometers. The combined information provides atmospheric information regarding the distribution of plasma and neutral gas, and energetic neutral atoms, ions and electrons (VE, MEO).

B. Near Surface to Shallow Depths

Investigations in this section include measurement of properties that occur from the surface to a depth of 1 meter.

Soil mechanics investigations have been performed on most missions (including orbital surveyors), which are nominally done by photographic observations (Yutu and almost all ground missions).

Near infrared, infrared (MEO, ER), visible, ultraviolet (MEO), low and high-energy X-ray (C1), radiowave and microwave spectrometers (RO) are used for remote chemical and mineralogy identification. The radiowave, microwave, near infrared and visible spectrometers operate by detecting the loss of photons in a given wavelength region of the spectrum to identify chemical bonding. The photons can be supplied by either a light source associated with the instrument or by natural reflected light and are quantitative. X-ray spectrometers may operate the same way or by monitoring the shift in wavelength of an exciting x-ray (or gamma ray) beam due to interaction with the sample. X-ray spectrometers provide quantitative elemental information for mineral identification. The Moon Mineralogy Mapper (M3) is an imaging spectrometer containing all of the aforementioned instruments for chemical mapping of the lunar surface, including lunar mineralogy at high spatial and spectral resolution from an altitude of 100 km.

Nanosecond excitation and relaxation fluorescence/phosphorescence spectroscopy in the visible and ultraviolet wavelength range has been proposed for mineral identification. The luminescence can be from the primary chemical composition or by ions entrapped as an impurity during solidification and uses energies between those of ultraviolet and visible light. In addition to wavelength specificity, the luminescence process is in a rate range now within the reach of commercial instrumentation (PI).

Mössbauer spectroscopy (MIMOS II) is specifically designed to identify iron-containing minerals. The Mossbauer principle is based on gamma ray absorption where the frequency of the gamma rays is monitored by Doppler shifting the frequency of a standard Fe source, ^{57}Fe, to tune its energy to that of the atoms within a sample. This instrumentation can see oxidation states and chemical bonding information specific to the element providing the gamma ray source, iron in this unit (MERS, MERO and PG).

Gamma Ray spectrometers detect gamma rays and analyze them by their energy, which is characteristic of individual elements. The intensity of the gamma rays specific to each element provides a quantitative elemental analysis of the sample (PG).

X-Ray Powder Diffraction (XRD) is a form of spectroscopy that measures the diffraction angle, or pattern, for X-Rays produced by impinging a collimated beam of X-rays on a sample. The resulting pattern is unique to the molecular structure of crystalline materials such as minerals (CMR).

Alpha Particle X-Ray Spectrometer (APXS) is used for determining elemental composition of soils by using alpha particle excitation of the sample followed by measuring emitted X-rays which are characteristic of individual elements. By monitoring the intensity of the X-ray emission the technique is quantitative for elemental composition and can thereby be used for mineral, rock and glass identification (MERS, MERO, Yutu, and numerous other missions).

Alpha Proton X-Ray Spectrometer (similar to APXS) is used for determining elemental composition of soils by using alpha particle excitation of the sample followed by measuring emitted protons, which are characteristic of individual elements. By monitoring the intensity of the proton emission the technique is quantitative for elemental composition and can thereby be used for mineral, rock and glass identification (MPS).

LASER Induced Breakdown Spectroscopy (LIBS) is a method of chemical analysis where a laser micro-probe vaporizes a small volume of material into a plasma containing excited state atoms. The atoms excited decay by emission of light characteristic of individual elements, thus providing an elemental analysis of the minerals, rocks and glassy materials vaporized (CMR).

Dynamic Albedo of Neutrons (DAN) is a pulsed sealed-tube neutron source and detector for measuring hydrogen or ice and water (CMR, ER). A Neutron Spectrometer was constructed to examine soil neutron radiation (PG).

LASER Raman Spectroscopy – With the advent of solid state lasers, photo detectors and high-resolution non-moving monochromators, it is now possible to construct miniature Raman spectrometers capable of identifying minerals by chemical bond structure rather than elemental analysis such as is done by X-ray fluorescence spectroscopy. The technique is performed by exciting the molecular sample components with a LASER and analyzing the emitted photons having wavelengths shifted from that of the LASER, which are characteristic of chemical bonds. The technique is quantitative by measuring the intensity of the emitted photons (ER). With the large spectral databases already developed for mineral identification, it should be possible to obtain rapid identification of minerals, based on spectroscopic studies of lunar samples (PI).

Miniature Thermal Emission Spectrometer (Mini-TES) is a mini-FT-IR, capable of mineral identification at a distance by measuring the thermal emission spectrum (MERS and MERO).

Infrared Microscopy is the combination of an FT-IR with a microscope and can be used for mineral identification (PG).

Gas Chromatography (GC) is performed by injecting a sample into a column packed with beads having selectivity that varies for each different molecular species injected. The sample is swept through the column by a carrier gas and the isolated species are detected as they emerge from the column. The column selectivity is used to identify the species and the detector signal intensity gives a quantitative determination of amounts of individual species in a sample (CMR and PG).

Mass Spectrometry (MS) is performed by ionizing molecules and sending the ions into a magnetic field, which separates the various ions by charge to mass ratio. Not only do the molecules (e.g. water, carbon dioxide, methane, etc.) have different masses but the technique is sensitive enough to differentiate between molecules containing different isotopes of various elements, such as hydrogen vs deuterium in water or methane. The technique is quantitative for determination of amounts of individual species in a sample (CMR, RO, PRL). Samples may also be ionized by LASER desorption (ER), pyrolization or by collision with an atomic ion beam produced by the instrument, known as secondary ion mass spectrometry, SIMS (PG), or collected vaporized from atmosphere (VE).

Gas Chromatograph-Mass Spectrometer (GC-MS) is a two-stage instrument. The GC separates volatile organic molecules as well as oxygen, carbon dioxide, nitrogen, hydrogen, and methane, which are then fed into a MS, which identifies them (VL, ER).

Atomic Force Microscopy (AFM) provides high resolution (nanometer scale) imagery of samples by mechanical approach of the sample by a small probe (RO). The AFM probe can also be used as an indenter or if conductive, can yield electronic structural information.

Wheel Abrasion Experiment (WAE) studied abrasive surface wear of Martian soil on different materials and coatings on a rover wheel by using a photodetector to measure reflected light from the reflective material applied as a thin coating of various thicknesses (MPS).

Materials Adherence Experiment (MAE) measured adhesive properties of the soil by two sensors operating under independent mechanisms. A photosensor measured output, which was inversely related to dust deposition on its surface, and a quartz crystal microbalance measured the mass of deposited material over time (MPS).

Electrostatic Lunar Dust Analyzer (ELDA) detects the charges on dust particles levitated from the surface by micrometeorite impact or electrostatic repulsion released with low velocity. The measurement technology is based on an array of wire electrodes in combination with an electrostatic deflection field region, which measures the mass, charge, and velocity vector of individual dust grains (PI - University of Colorado at Boulder, LASP, Texas A&M Associates, and University of Stuttgart)

Magnets attract magnetic particles for subsequent observation and analysis by visual inspection, which allows tentative identification of magnetic minerals in the soil. The technique can be made qualitative by analysis of the materials collected by the magnet using a technique like APXS (MERS, MERO and numerous other missions).

C. Planetary Interior

Investigations in this section include measurement of properties that occur below a depth of 1 meter.

Magnetometers detect magnetic field magnitudes and directions at scales ranging from planetary to microscopic. Magnetometers were used to provide evidence as to whether Mars contained an iron core (MP, MGS, VE, PRL).

Gravimeter Experiments measure variations of the gravitational acceleration. For subsurface structure this can be done by a Vibrating String Accelerometer (VSA), which precisely measures electrical current passing through a vibrating pair of strings (A17) and for measuring gravity and its variation over time, a one-axis seismometer consisting of a sensitive spring balance was developed (A17). Other missions such as PG include gravimeters.

Lunar Seismic Profiling was performed by two different experiments, the Active Seismic Experiment (A14 and A16) and the Lunar Seismic Profiling Experiment (A17) to determine the detailed structure of the upper kilometer of the lunar crust. Both experiments involved a geophone network monitoring of the seismic waves and/or ground motions resulting from detonation of a series of small explosives. Seismometry has been done on numerous missions and can be done using external impacts to provide the initial stimulation (VL, PG and others).

Long Wave Radar can be used to study structure to a depth on the order of 100 m (PG, Yutu). Ground penetrating radar can also be used to characterize underground stratigraphy for location of, for example, water deposits as a screening tool for sampling selection (ER).

VI. Unique Opportunities on Spacecraft/Rover Hybrid

There are endless concepts for dust measurement payloads that could be integrated into the featured mission architecture of this paper. The following short list is to highlight low mass solutions or dual-purpose instruments that can measure regolith or dust properties. These sensors or payloads would fit inside (or externally mounted) to the featured architecture, of which the deployed spacecraft/rover core is about 1-foot in diameter with spikes approximately 1-foot long (size, spike length, and number of spikes were examined in the NIAC work). This could be scaled up, but then less of the scouts could be deployed or the mothership would have to be scaled up as well. The instrumentation should fit inside a sphere 1-2 feet in diameter. Some of these ideas are dependent on technology advancement and miniaturization, while others are commercial off the shelf solutions. The regolith physical properties measured and the function of potential devices on the spacecraft/rover are underlined.

- Force feedback load cells on spikes, like a cone penetrometer. This would help give impact telemetry and could help give information on soil compaction and density. The spikes could have retractable spike tips, like a pogo stick, to take measurements.
- Spike tips could be hollow or scoop-shaped to allow regolith to be collected. When the spacecraft/rover tumbles, the sample could be fed through a particle size analyzer.
- Atmospheric and meteorological packages similar to previous missions could be used. Thermocouples could be placed at various parts of the spacecraft/rover to measure regolith and surrounding environment temperature variations. Anemometers can be used to detect wind speed and pressure sensors for atmospheric pressure, which are less likely to be used for missions on small bodies, but may be a good addition for scout architectures on larger planetary bodies. This concept leads to the modular design of the central core or hub, with packages that can be swapped out for various missions.
- Remote sensing measurements of the thermal inertia of a surface, the resistance of a material to temperature change, could determine the approximate soil composition by examining the temperature changes of a region over time during a heating/cooling cycle (usually driven by orbital mechanics with respect to the sun).
- Piezo sensors and micro voltage meters on the spacecraft/rover could be used to measure the relative electrostatic environment.
- Optical (microscopes and cameras) could be used to observe the regolith for particle shape and size. They could also be used to look at dust adhesion directly on the spacecraft/rover. The outer surface of the spacecraft/rover could have a variation of material types for optical observations of adhesion, and/or magnets of varying strength could be used directly on the regolith for simple observations.
- LIDAR instruments could be used to measure dust aloft and settling times of the impact ejecta from the spacecraft/rover motions and be dual purposed as a landing hazard avoidance system.
- The spacecraft/rover could remain static to take seismic, temperature and radiation measurements over time.
- A mechanical gear could be placed on spike tips to drive three body abrasion measurements and to determine approximate particle size distribution (flow rate through system).
- XRF or similar methods could be used to measure mineral composition as well as particle size and shape. The hardware would need to reduce its physical size to make it practical for a small spacecraft.
- A miniature LASER Raman spectrometer may be capable of identifying minerals by chemical bond structure from databases.
- Magnetometers can be used for close proximity operations such as docking and rendezvous to mothership or other spacecraft/rovers in the absence of interference sources. They can be used for iron detection on surfaces and magnetic fields on surfaces or in orbit.

There are many additional instruments that could be considered from the past, current and proposed list in Section V for this architecture including:

- Thermal Emission and Imaging Spectrometers: These can be made very small and would be used through an observation window on main body. The largest part is the interferometer which could be as small as 6 x 6 x 1 inches. The detectors are small and solid state.
- Dust, Ion and Impact Detectors: these are small and may be useful for Phobos where there may be levitated soil.
- Fiber optic technology: these involve the use of fiber optic cable through spikes directly to the surface. For LASER spectrometer technologies, such as Raman and FT-IR, this may lead to a smaller laser requirement, less power required, and have more potential for multidirectional sampling without moving internal parts. Overall this could lead to LASER based instrumentation reduced in size.

VII. Conclusion

Dusty environments can be harsh on spacecraft and it is important to consider how technology can exploit these properties to return scientific data rather than be subject to degradation. Simple, low-mass technology can be easily added to any mission architecture to aid in efficient exploration and act as a precursor for follow-on activities. The novel rover/hybrid mission architecture has many potential configurations (number of scouts deployed, sizing, and modes of operation) and can be expected to churn up regolith and initiate a variety of measurements regolith properties. Understanding the regolith can help answer many key questions about our solar system’s age, how it was formed, and how we may be able to use its resources to explore further.

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