DESIGN OF LANDER PODS FOR ADDRESSING SMALL BODIES STRATEGIC KNOWLEDGE GAPS

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ABSTRACT

Boeing has been developing the concept and preliminary design for a set of small landing Pods that could be deployed from a spacecraft bus orbiting a Near Earth Asteroid (NEA) to address the set of "Strategic Knowledge Gaps" (SKG) that would address the specific goals for investigation prior to crewed missions to NEAs or the moons of Mars.

1. INTRODUCTION

Strategic Knowledge Gaps (SKG) represent gaps in knowledge or information required to reduce risk, increase effectiveness, and improve the design of robotic and human space exploration missions. The National Aeronautics and Space Administration (NASA) uses SKGs to help inform research and investment strategies, and prioritize technology development for human and robotic exploration.

NASA enlisted the expertise of three analysis groups:

- The Lunar Exploration Analysis Group (LEAG).
- The Mars Exploration Program Analysis Group (MEPAG).
- The Small Bodies Assessment Group (SBAG).

We focus on the SKGs being developed by SBAG, in a team led by Andrew Rivkin of the Johns Hopkins University/Applied Physics Laboratory (JHU/APL) and Mark Sykes of the Planetary Science Institute (PSI) [1]. The lists of SKGs will remain a "living documents," to be updated as needed based on ongoing efforts by the analysis/assessment groups requested by NASA.

The Small Bodies Assessment Group conducted a study in 2012 to identify critical SKGs for Exploration of Small Bodies, primarily near-Earth objects (NEO) and Phobos and Deimos. This SBAG study was motivated by the 2011 Global Exploration Roadmap, by the International Space Exploration Coordination Group, which focuses on the "Asteroid Next" scenario in the context of enabling Human Mars Exploration.

Small Body (SB) SKGs were divided into four categories:

I. Human Mission Target Identification for Small Bodies (NEOs or Phobos and Deimos).
II. Understanding How To Work on or Interact With the SB Surface.
III. Understand the SB Environment and Its Effect on Human Life (potential risk and benefit to crew, systems, and operational assets).
IV. Understand the SB Resource Potential.

We present a mission design for *in situ* exploration of small bodies that can address the majority of these SBAG SKGs.

Many of the SBAG SKGs may be addressed by orbiting the small body (either NEO or Phobos/Deimos) and deploying small surface landing "Pods." These Pods would not have an active propulsion system; rather, they would be deployed by springs to cancel the orbital velocity of the spacecraft.

Several Pods, each of ~20-kg mass, would slowly descend to the surface over a period of a couple of hours. The impact velocity would be small, about equivalent to a laptop computer sliding off its owner's lap, and the Pods would be ruggedized to withstand such an impact. The Orbiter would then provide relay of Pods data back to Earth (Fig. 1). PODS would be flat, pancake shaped, and symmetrical, so that it would not matter which side faces up (Fig. 2).

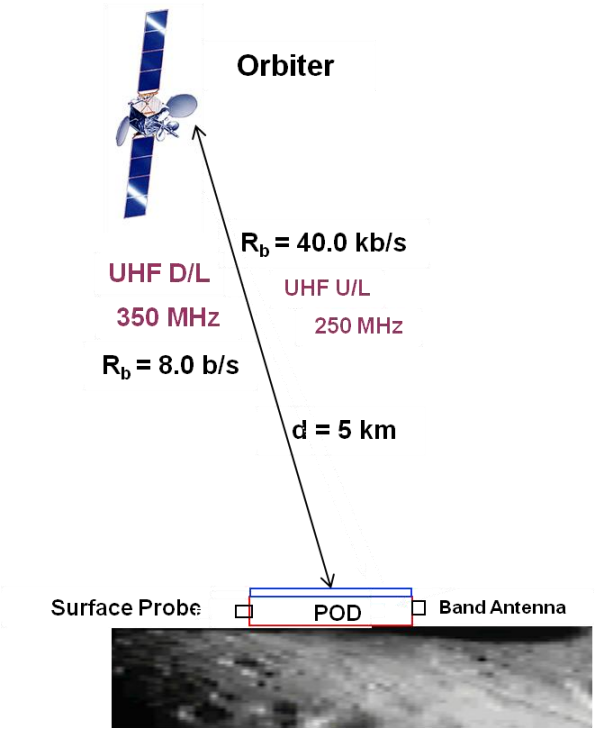

Fig. 1. Communications link for PODS and Orbiter

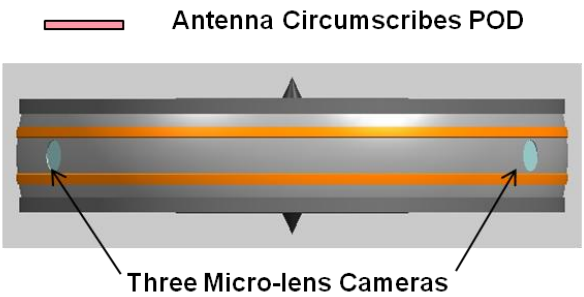

Fig. 2. Edge-on view of the PODS

2. DESCRIPTION OF THE PODS

One of the main science goals from the seismic experiment is to determine the interior structure of the asteroid, whether as a solid body or a "rubble pile." Another goal is to expose fresh unweathered regolith from the cratering for spectrographic mineralogical mapping. The third goal is to characterize surface dust and plasma. The orbiting spacecraft would provide radio relay for a 40-kbps signal from the Pods.

The Pods would have instrumentation to investigate both the interior structure and the regolith of these asteroids. Three cameras with micro-lens would obtain microscopic images of the regolith particles; a Langmuir probe would investigate the electric field and plasma environment at the surface, and the mechanism of electrostatic charging and levitation of dust particles. Each Pod could carry ~12 kg of Pentaerythrite Tetranitrate (PETN) explosive material. The detonation would send seismic signals through the interior of the asteroid, to be recorded by sensitive accelerometers on the other Pods. The orbiting spacecraft would then observe the resulting crater for spectroscopic images of the freshly exposed regolith.

3. INSTRUMENTATION

The following science instruments are being considered for this mission.

3.1 On the Orbiter

- Narrow angle (NA) and wide angle (WA) imaging camera.
- Infrared (IR) imaging spectrometry (mineralogy).
- X-band carrier for radio science.
- Transponder for data relay of Pods data to Earth.

3.2 On the PODS

- Three micro-lens cameras per Pod.
- Langmuir probe (electric field, electron density, and dust levitation).
- Thermal probe.
- PETN explosive (to create a small crater).
- Accelerometers for seismic mapping of the interior of the Small Body.

4. SEISMIC EXPERIEMENT

The cratering experiment uses 12 kg of PETN per Pod, placed in the torus of the Pods (Fig. 3). The detonation would send seismic signals through the interior of the asteroid, to be recorded by sensitive accelerometers on the other Pods.

The orbiting spacecraft would then observe the resulting crater for spectroscopic images of the freshly exposed regolith. Seismic waves travelling through the SB would be measured by Endevco 7290A-2 Low-Level Accelerometers in the other Pods,. to measure to 250 Hz and detect variations of 10^{-4} g (0.2 mv). This would use an analog-to-digital (A-to-D) convertor with 16 bits, with a 24-Kbps real-time data rate (Table 1).

5. MICRO-LENS CAMERA

The micro-lens camera could utilize the concept of:the Camera, Hand-lens, And Microscope Probe (CHAMP) [2]. CHAMP is a new high-spatial-resolution, multi-band field camera/microscope with variable working-distance/magnification.

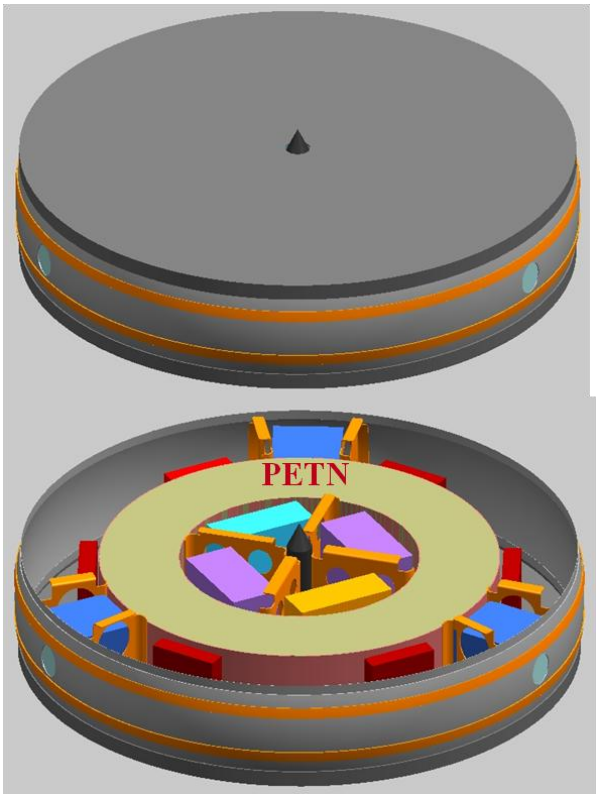

Fig. 3. Internal and external view of the Pods.

Table 1. Characteristics of the Seismic Measuring System.

Space Qualified Endevco 7290A-2 Low-Level Accelerometer	
Survives Delta Launch Vehicle Vibrations	Survives Shock of Pod Impact on Surface (at 60 km/sec)
Input Voltage: 10 V	
Output Voltage: 1 V per g, 2-g Limit (hits the stops) 3.5-V Bias: Output Voltage Range is 3.5 to 5.5 V	
Seismic Event of nearby Pod explosion may register 10^{-4} g (0.1 mv) To measure up to 250 Hz and detect variations of 10^{-4} g (0.2 mv), A-to-D conversion should be at 500 Hz, with 0.0002 V per Data Number (DN) 16,000 DN in voltage range, and 216 = 16,384, requiring 16 bits per sample and 500 samples per second per accelerometer. With tri-axial accelerometers, data rate would be 24 kbps.	

CHAMP is capable of imaging across a wide range of spatial scales from km.s to m.s for context imaging (Pancam analog) down to 3 mm/pixel at peak magnification for microscopy. CHAMP can acquire in-focus images from almost any working distance relative to a target (~7 mm out to infinity). The resultant image resolution is directly correlated with the working distance—the closer the instrument is placed to the target, the higher the resolution/magnification of the captured image at the cost of a smaller field-of-view (FOV). The mass of the 2004 version of CHAMP is about 1 kg. (See Fig. 1A of [2].) It could be miniaturized for these Pods.

6. LANGMUIR PROBE

The surface of an asteroid is subject to several charging currents: solar wind ions and electrons, and photoelectrons. On the dayside, photoemission results in a positively charged surface, whereas on the nightside, collection of the lighter and therefore faster solar wind electrons charges the surface negative.

Strong electric fields can be generated near the surface, perhaps particularly strong near the terminator where photoemission disappears. Small dust particles in the regolith of the asteroid will accumulate some charge as a result of these currents and may be transported in near-surface electric fields. Such transport can lead to sorting of the regolith by size or net transport of small grains to topographic depressions.

A Langmuir probe is an electrode that may be placed into a plasma environment. The current to the electrode is measured to provide a diagnostic of the potential on the probe that is determined by the currents of electrons and ions to the probe. We would place a Langmuir probe on each face of each Pod, because it is undetermined which side faces down.

Each probe could be spring-deployed to swing out from the body of the Pod to place the probe tip approximately one pod diameter away from the pod edge and at an angle of about 30 deg above the horizontal. Table 2 gives a typical plasma environment on an asteroid that could be measured by the Langmuir probe. Having Langmuir probes on three Pods could give simultaneous global coverage for plasma characterization, including measured effects of the terminator.

Table 2. Typical Plasma Environment on Asteroid Surface

Dayside Environment
Electron density within 10 cm of surface = 10^4 electrons per cm^2. Surface Potential: Positive 10 V. Electric Field: E = 10 V per meter gradient.
Nightside Environment
Charge density within 10 cm of surface = 0.01 ion per cm^2. Surface Potential: Negative 100 V. Electric Field: E = 1 V per meter gradient.
Operations Requirements
Step between –20 V to +20 V, at intervals of 0.5 V. Measure current at each voltage setting (8 bit for each measurement, 10 measurements per sec). Dwell at each voltage step for 1 sec, make measurements at 10 Hz. Take average and sigma for each step for inclusion in telemetry.

7. POD AVIONICS

Fig. 4 shows an avionics block diagram of the Lander Pods, including three micro-lens cameras, Langmuir probe, thermal probe, PETN detonator, data collection, communications, and Digital Signal Processor (DSP).

Table 3 lists the software modules for the DSP in the Pods as well as some of the necessary ground processing software modules. Ground processing and display software could be prepared in LabView. This paper is not focusing on the orbiting bus avionics, as that is more standard

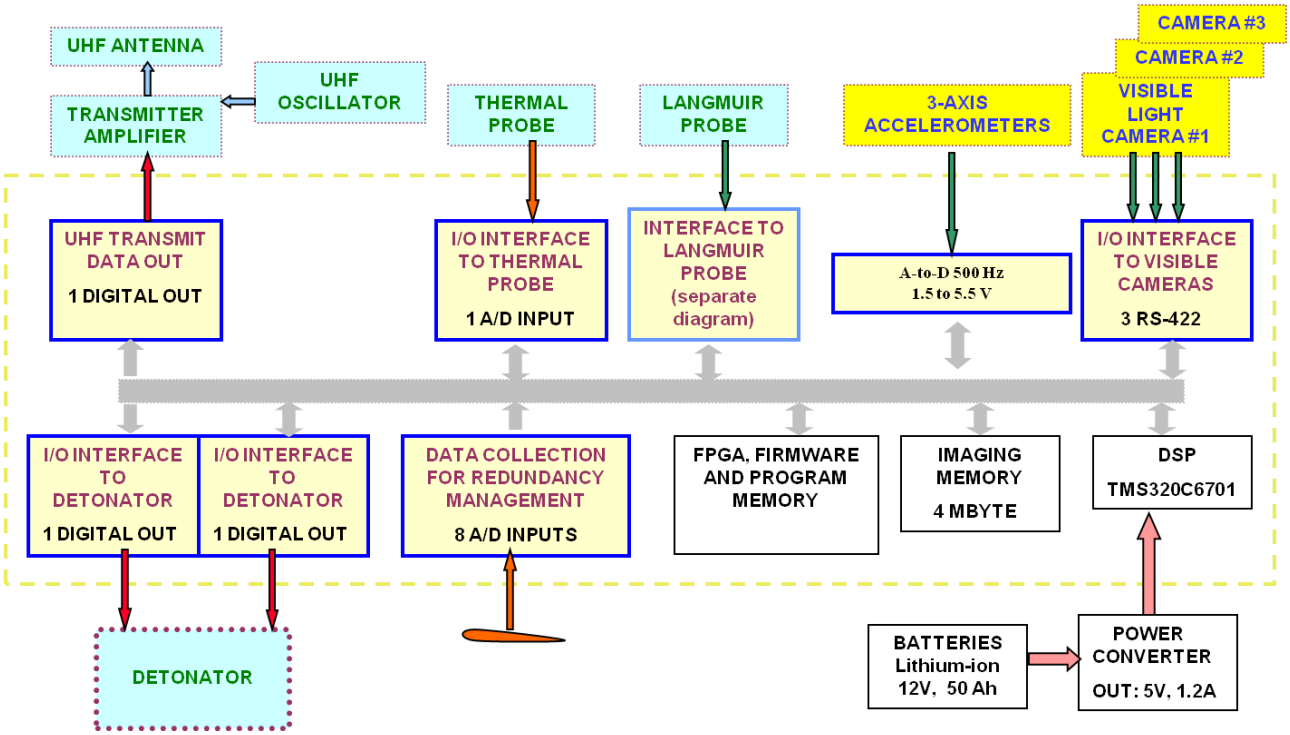

Fig. 4. Lander Pods —avionics block diagram.

Table 3. Software Modules Required for Lander Pods and Ground Data Processing and Display.

Deep Interiors—DSP Embedded Software Modules
1. Software integration, input/output (I/O) management, memory management, timing, and real-time operating system (RTOS). 2. Redundancy management and vehicle health management. 3. Camera image acquisition and formatting. 4. Langmuir probe control software. 5. Accelerometer pre-processing. 6. Telemetry formatting and encoding. 7. Command detector and router. 8. Detonation safety, timing, and signal. 9. Power management.
Deep Interiors—Ground Software LabView Modules
1. Accelerometer data processing and display. 2. Langmuir probe data processing and display. 3. Thermal probe data processing and display. 4. PETN detonation control.

8. ADDRESSING THE SBAG SKGs

The set of instruments described in section 3 can address many of the SBAG Strategic Knowledge Gaps (SKGs) for near-Earth asteroids, Phobos and Deimos. The visible and IR imaging instruments on the Orbiter (NA and WA cameras and IR imaging spectrometer) can give topography and mineralogy. If far IR imaging were included, then thermal inertia mapping could also be obtained, which could distinguish between solid rock and regolith.

On the PODs, the micro-lenses (three per Pod) will give a close-up view of the fine structure of the regolith, which could be correlated with the Orbiter imaging. The Langmuir probe will measure the plasma environment, as described in section 6. The plasma measurements could be correlated with possible micro-lens detection of dust levitation. Thermal sensors placed on the two faces of each Pod would result in one of the thermal probes being underneath the Pod, to measure surface temperature, and one on top, to measure the diurnal temperature variation of the top surface. These measurements could be conducted for several weeks to fully characterize the small body surface, prior to detonating the PETN.

The PETN detonations would be measured seismically by accelerometers on the other Pods, to potentially characterize the interior of the small body, whether it is solid or a rubble pile. The detonations will also create a small crater (perhaps several meters in diameter), which exposes fresh unweathered material. The orbital cameras, by measuring the size and shape of the crater, can determine something about the structure of the surface material (solid or fine grained), which can be correlated with the seismic data. The IR imaging can obtain mineral mapping of the crater once the weathered surface material is removed. The detonation will of course be timed so that the Orbiter is safely on the opposite side of the small body at the time of the detonation. These observations will be able to address the SKGs, as described in the following tables.

Tables 4 through 7 at the end of this paper describe the mission instrument used in addressing relevant SKGs in the four SKG categories described in section 1, Introduction, and outlined in [1]. Thus, this mission concept can address three SKGs from Category I, six SKGs from Category II, six SKGs from Category III, and two SKGs from Category IV.

Finally, Table 8 lists the SBAG SKGs that are not able to be addressed by this mission concept. Many SKGs listed in Table 8 are best addressed by laboratory or telescopic observations. However, six SKGs in Table 8 could be addressed by a larger follow-on mission that has a more extensive payload, including such equipment as a drill and an X-ray diffraction spectrometer.

The authors wish to acknowledge valuable discussions with Eric Asphaug and Josh Colwell in shaping this mission concept.

9. CONCLUSION

This paper describes a small Discovery-class mission concept that can address 17 of the SBAG SKGs. Such a mission would be valuable as a precursor to a manned mission to the same or similar small body. Phobos and Deimos are particularly interesting small bodies that could be investigated by this mission concept. It should be noted that the SBAG SKG description from [1] is likely to be revised and updated by SBAG in the very near future, to further align them with the upcoming crewed Asteroid Redirect Mission (ARM). At that time, this mission concept utilizing small landing Pods could be updated also.

10. REFERENCES

1. Rivkin, A. and Sykes, M, “NEO/Phobos/Deimos Strategic Knowledge Gaps,” presentation to the Small Bodies Analysis Group (SBAG), January, 2013.
2. Boynton, J., et al., *CHAMP: Camera, Hand lens, And Microscope Probe*, IEEE paper, IEEEAC paper 1510, ver. 5, updated December 27, 2004.

Table 4. SBAG Category I SKGs—Human Mission Target Identification for Small Bodies

SKG Addressed by PODS and Orbiter	Description of SKG	Instruments to address the SKG
C-1: Small Body size	Knowledge of SB size	Imaging by Orbiter camera on approach to the SB
C-2: SB albedo	Albedo in both visible and IR regions is desired	Imaging by Orbiter camera and IR imaging spectrometer
C-3: SB rotation state	Rotation rate provides information on interior structure and accessibility for human access to surface	Imaging by Orbiter camera on approach to the SB

Table 5. SBAG Category II SKGs—Understanding How To Work on or Interact With the SB Surface

SKG Addressed by PODS and Orbiter	Description of SKG	Instruments to address the SKG
B-1: Mechanical and electrical Effects of SB surface particles	Surface dust may create challenges for astronauts and hamper their surface experiment packages	Mechanical properties observed by PODS micro-lens cameras (three cameras give 360-deg view, focusing within a few meters of the Pod). Electrical field is measured by the Langmuir probe
C-1: Macro-porosity of SB interior	Requires *in situ* measurement using ground-penetrating radar or seismic studies	Pod "cratering experiment," exploding PETN, and measuring seismic waves by accelerometers on the other Pods
C-2: Geotechnical properties of SB surfaces	Requires *in situ* measurement of porosity, gravity, cohesion, shear strength, etc. to design optimal crew surface activities and recognize potentially hazardous crew activities	This diverse set of surface properties may be measured by orbital dynamics (gravity), micro-lens imaging, and orbital observation of crater after PETN detonation
D-1: Anchoring for tethered activities	Design of anchoring mechanisms requires knowledge of surface and subsurface morphology	Regolith morphology properties determined by micro-lenses and "cratering experiment"
D-2: Non-contact close-proximity operations for detailed surface exploration and surveys	*In situ* experiments and observations for study of particle levitation and reaction to disturbances	Orbital imaging of regolith disturbance by Pod landing; Langmuir probe for particle-levitation mechanisms
E-1: Expanding habitat volume to SB Interior for shielding and human factors	Shielding would require knowledge of specific asteroid composition, internal fractures, porosity, etc.	SB interior structure determined by seismic sensors on other Pods during "cratering experiment"

Table 6. SBAG Category III SKGs—Understand the SB Environment and Its Effect on Human Life

SKG Addressed by PODS and Orbiter	Description of SKG	Instruments to address the SKG
A-1: Expected dust environment due to ejecta from micrometeor impacts	Dust environment in near-vicinity of the SB may act as hazard or nuisance, especially given cohesive forces in low-g environment. *In situ* observations preferred	Orbital imaging of regolith disturbance by Pod landing and from cratering events
A-2: Observe the population of a dust torus around the Phobos and Deimos orbits	Obtain *in situ* observations of dust in the vicinity of Phobos and Deimos, and along their orbital tori	Back-scattering observations from Orbiter camera, and possible dust impact acoustic detector
A-3: Possible dust environment in the asteroid exosphere due to charged particle levitation following surface disturbances	Obtain *in situ* observations of dust in the vicinity of the small bodies	Observation by Orbiter during Pod landings and during cratering events

Table 6. SBAG Category III SKGs—Understand the SB Environment and Its Effect on Human Life (continued)

SKG Addressed by PODS and Orbiter	Description of SKG	Instruments to address the SKG
B-1: Local environment effects from solar flare activity	Solar flares may lead to enhanced dust levitation due to enhanced ultraviolet intensity, producing ionization of surface material	Langmuir probe to measure near-surface electric field and ionization products. Orbital camera observation of dust cloud around SB during flare activity, through imaging back-scatter of sunlight
B-2: Small Body surface as a source of radiation	SBs may have enhanced radiation return during solar flares. Laboratory measurements have not provided good modeling, so *in situ* measurements are necessary	Langmuir probe to measure near-surface electric field and ionization products. Also, need sensor to detect γ-ray flux from surface
D-2: Global structural stability	Remote observations of rotation period, and changes in period provide insight, but *in situ* measurements are necessary	Seismic measurement during cratering events provides some information on the global structural stability

Table 7. SBAG Category IV SKGs—Understand the Small Body Resource Potential

SKG Addressed by PODS and Orbiter	Description of SKG	Instruments to address the SKG
A-1: Remotely identify resource-rich SB	Low-albedo SBs are more likely than high-albedo SBs to have water/OH-bearing minerals. Laboratory work is needed to better understand how to spectroscopically identify those dark SBs that are water-rich	This mission may serve as a truth-test for laboratory modeling of spectra. IR spectral imaging from orbiter of surface regolith and of fresh material exposed by the cratering event
B-1: Do resource materials exist beneath the surface of Phobos or Deimos?	Requires a mission to Phobos/Deimos with capability of drilling and making observations beneath the surface	(Rather than drilling), IR spectral imaging from Orbiter of fresh material exposed by the cratering event

Table 8. SBAG SKGs Not Addressed By This Mission Concept

SBAG SKGs Not Addressed Pods Mission Concept	
I-A-1.	Laboratory radiation studies on radiation risk to tissue—could be conducted on ISS
I-A-2.	Survey of reachable SB targets within planned architecture (ground-based)
I-B-1.	An IR telescopic survey of long-synodic period small bodies having multi-mission opportunities
I-B-2.	An IR telescopic survey of number of SB targets available at a given time—building a database
II-A-1.	Laboratory experiments to address biological effects of SB surface particles (e.g., toxicity to crew)
III-C-1.	Modeling SBs as shields for crewed missions against solar storms
III-D-1.	Investigating local structural stability
IV-A-2.	Techniques tested on Earth and on ISS to provide knowledge of how to excavate and collect SB regolith material to be processed
SBAG SKGs That Could be Addressed by a Follow-on Mission With a Larger Lander Equipped With More Sophisticated *In Situ* Investigations (e.g., drilling, etc.)	
III-D-1.	Investigating local structural stability
IV-A-3.	Techniques tested on Earth and then on SB mission to provide a demonstration excavation and collecting water from regolith material by heating
IV-A-4.	Caching and pre-positioning regolith material
IV-A-5.	Refining, storing, and using H and O from regolith material
IV-B-2.	Demonstrate knowledge on how to access resource material from SB at depth (e.g., from drilling)
IV-B-3.	Refining, storing, and using H and O in a usable state on Phobos and Deimos