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SMALL BODIES ASSESSMENT GROUP

NEO/Phobos/Deimos Strategic Knowledge Gaps SAT Report Summary

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Human Exploration Contexts

The human mission contexts from which SKGs flow are assumed to be the study of, interaction with, and exploitation of Small Bodies.

The Global Exploration Roadmap considers the “Asteroid First” scenario in the context of enabling Mars Exploration. The SKGs identified, with the exception of ISRU potential, do not require Small Body targets and could be addressed by a mission to open space. Therefore, they are not considered here.

Target Scenarios

Small Body targets for human exploration consist of NEOs, Phobos and Deimos. SKGs unique to human missions to Phobos and Deimos include understanding the atmosphere of Mars. Martian atmosphere SKGs in human exploration is left to MEPAG.

The SBAG SKG SAT Charter (Reduced)

Identify, assess, and refine the basic knowledge / data sets / technologies that are required to safely, effectively, and efficiently implement asteroid mission scenarios and architectures for human exploration.

Identify the gaps that need to be filled in order to implement, enable or enhance those missions and architectures.

Of particular note is use of NEO In-Situ Resource Utilization (ISRU).

Identify specific robotic precursor missions that could fill these gaps.

The SBAG SKG SAT Charter Tasks

1. List required knowledge / data sets / technology, traced to human exploration needs.
2. Identify gaps in that knowledge / data sets / technology relative to our current understanding and capabilities.
3. Create a timeline of when the missing knowledge / data sets must be acquired or technology developed.
4. Provide a list of existing and potential missions, experiments, modeling activities, technology, or any other activity that would fill the knowledge gaps (linking to prior studies).
5. If additional measurements are required to fill knowledge gaps, identify the fidelity of the measurements needed, and if relevant, provide examples of existing instruments capable of making the measurements. Any ISS role in filling the gaps should be identified.

The SBAG SKG SAT Charter

The group will assemble the information and findings into an appropriate set of power point charts and back up materials. It will also create a spreadsheet with the individual knowledge elements and whether that information is lacking, and if so how it could be filled.

Schedule and Updating

A final set of findings was delivered to NASA on November 28, 2012.

It is recognized that these findings will be improved and expanded with broader engagement of the small bodies community and as our knowledge from research and missions continuously expands.

Proposed: The SBAG SKG report will be formally updated and delivered to NASA annually (after the January meeting beginning in 2014). A standing Special Action Team, chaired by Rivkin, will collect specific recommendations for modifications/additions. Those recommendations will be distributed to the SBAG community and posted for discussion/comments. Prior to integration, they will be subject to open discussion at the January SBAG meeting.

SB SKG Themes and Categories

SB SKGs can be organized into several themes, which can be further divided into categories:

I. **Human mission target identification (NEOs).** The identification of multiple targets for human exploration is fundamental.

II. **Understand how to work on or interact with the SB surface.** Human presence may disturb the environment in non-intuitive ways. We need to understand how best to perform sample acquisition and handling, instrument placement, and proximity operations.

III. **Understand the SB environment and its potential risk/benefit to crew, systems, and operational assets.** The small body environment may include dust emitted periodically (for instance via levitation) or episodically (after impact or spin-up events). It may enhance or screen solar radiation. It may be gravitationally metastable.

IV. **Understand the SB resource potential.** ISRU is considered a “game changer” in how humans explore the Solar System by enabling an infrastructure that allows a sustainable human presence in space. The short-stay missions likely to be in the first wave of NEO or Phobos/Deimos visits may test or prepare that infrastructure but are unlikely to take advantage of it.

SB SKG Themes and Categories

SKG Themes	SKG Categories	Examples of SKGs
I. Human mission target identification (NEOs)	A. Constraints on targets B. NEO orbit distribution C. NEO composition/physical characteristics (population/ specific targets)	I-A-1. Round trip limitations due to radiation exposure. I-A-2. Reachable objects within planned architecture I-B-1. Long-synodic period NEOs having multiple mission opportunities. I-B-2. Number of available targets at a given time. I-C-1. NEO sizes. I-C-2. NEO albedos. I-C-3. NEO rotation state.

SB SKG Themes and Categories

SKG Themes	SKG Categories	SKG Examples
II. Understand how to work on or interact with the SB surface.	A. Biohazards and mitigation B. Hazards to equipment and mitigation C. SB surface mechanical properties D. Mobility around and interaction with surface in microgravity conditions E. Habitat expansion options	II-A-1. Biological effects of SB surface particles. II-B-1. Mechanical/electrical effects of SB surface particles. II-C-1. Macro-porosity of SB interior. II-C-2. Geotechnical properties of SB surface materials. II-D-1. Anchoring for tethered activities. II-D-2: Non-contact close proximity operations for detailed surface exploration and surveys. II-E-1. Expanding habitat volume to SB interior for shielding and human factors.

SB SKG Themes and Categories

SKG Themes	SKG Categories	SKG Examples
III. Understand the SB environment and its potential risk/benefit to crew, systems, and operational assets.	A. The particulate environment in the proximity of Small Bodies. B. The ionizing radiation environment at Small Body surfaces, including contributions from secondary charged particles and neutrons produced in the regolith.	III-A-1. Expected particulate environment due to impact ejecta. III-A-2. Possible dust/gas emission via sublimation from volatile-rich objects III-A-3. The population of a particulate torus around the Phobos/Deimos orbits from micrometeoroid impacts and material ejected from Mars. III-A-4: Possible particulate environment in the asteroid exosphere due to charged particle levitation following surface disturbances. III-B-1. Local effects on plasma and electrostatic environment from solar flare activity. III-B-2. SB surfaces as a source of radiation.

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SB SKG Themes and Categories

SKG Themes	SKG Categories	SKG Examples
III. Understand the SB environment and its potential risk/benefit to crew, systems, and operational assets.	C. Mitigation strategies to preserve human health. D. Local and global stability of small bodies.	III-C-1. SBs as shields against solar storms. III-D-1: Local structural stability based on remote measurements. III-D-2: Global structural stability based on remote measurements

SB SKG Themes and Categories

SKG Themes	SKG Categories	SKG Examples
IV. Understand the SB resource potential.	A. NEO resources B. Phobos/Deimos resources	IV-A-1. Remotely identifying resource-rich NEOs. IV-A-2. Knowledge of how to excavate/collect NEO material to be processed. IV-A-3. Knowledge of extracting and collecting resources in micro-g. IV-A-4. Prepositioning and caching extracted resources. IV-A-5. Refining, storing, and using H & O in micro-g.

SB SKG Themes and Categories

SKG Themes	SKG Categories	SKG Examples
IV. Understand the SB resource potential.	A. NEO resources B. Phobos/Deimos resources	IV-B-1. Phobos/Deimos subsurface resource potential. IV-B-2. Knowledge of how to access resource material at depth IV-B-3. Refining, storing, and using H & O in a usable state on Phobos/Deimos.

Venues/Contexts for Addressing SKGs

Venue/ Context	Description
R&A	**Research and Analysis Programs** that support basic research, field work, and mission data analysis supported by PSD and HEOMD but in a broad programmatic context.
Earth-based	**Terrestrial** location for specific development and testing, including ground-based telescopes.
ISS	**International Space Station**
Robotic	**Space-based robotic missions** which can be telescopic or a precursor mission to a small body target.

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Venue/Context Relevancy

Relevance	Description
🔴	**Preferred Location/Context:** Provides the best location or context to obtain knowledge, including actual or flight-like conditions, environments, or constraints for testing operational approaches and mission hardware.
●	**Highly Relevant:** Provides highly relevant location/context to obtain knowledge, including flight-like conditions, environments, or constraints for testing operational approaches and mission hardware. This venue can serve as a good testing location with less difficulty and/or cost than anticipated for the preferred location.
⊙	**Somewhat Relevant:** Provides some relevant testing or knowledge gain (including basic analytical research and computational analysis). Conditions are expected to be not flight-like or of sufficient fidelity to derive adequate testing or operational performance data.
○	**Not Relevant:** Not an adequate location/context for testing or knowledge gain.

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Strategic Knowledge Gaps

I. Human mission target identification (NEOs)

SKG	R&A	Earth-Based	ISS	Robotic Missions	Specific Target?	Narrative
A-1. Round trip limitations due to radiation exposure.	⊙	🔴	⊙	🔴	N/A	Laboratory radiation studies on tissue etc., determination of cancer risk, sensitivity of results to weightless conditions are testable on ISS. Such work is not supported by PSD R&A. Finding additional targets through survey also helps to close this gap.
A-2. Reachable targets within planned architecture	🔴	🔴	○	○		Energetics of rendezvous mission is calculable given a target orbit. Cost constraints are a separate policy issue. Propulsion technology development increases number of possible targets
B-1. Long-synodic period NEOs having mult. mission opportunities.	○	●	○	🔴	N/A	An infrared survey space telescope in a stable environment with wide instantaneous visibility is best used to identify long-synodic targets in a timely fashion. These are not efficiently observable from Earth-based telescopes because they are in twilight or daytime skies.

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Strategic Knowledge Gaps

I. Human mission target identification (NEOs)

SKG	R&A	Earth-Based	ISS	Robotic Missions	Specific Target?	Narrative
B-2. Number of available targets at a given time.	⊙	●	○	🔴	N/A	An infrared survey space telescope in a stable environment with wide instantaneous visibility is best used to identify long-synodic targets in a timely fashion. These are not efficiently observable from Earth-based telescopes because they are in twilight or daytime skies.
C-1. NEO sizes	●	●	○	🔴	N/A	Knowledge of NEO sizes is determined by observations by the mission supporting B-1 and B2, but also can be estimated by inferring albedo from spectroscopic classification (if available) and absolute magnitude determined from ground-based or space-based observations.

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Strategic Knowledge Gaps

I. Human mission target identification (NEOs)

SKG	R&A	Earth-Based	ISS	Robotic Missions	Specific Target?	Narrative
C-2. NEO albedos.	●	●	○	🔴	Yes	Albedo knowledge is critical for calculating accurate diameters, and also contains some compositional information. Depending upon the visibility of NEOs from different assets, different assets with infrared capabilities need to be engaged.
C-3. NEO rotation state.	🔴	🔴	○	🔴	Yes!	Rotation rate provides information about interior structure. In addition, some objects rotate sufficiently quickly that astronaut surface activities may be difficult or impossible. The datasets from which rotation rates are calculated also give information about target shape and pole position. Depending upon the visibility of NEOs from different assets capable of making lightcurve observations, all such assets should be engaged. Lightcurve-measuring capability as part of a robotic survey would ensure “no asteroid left behind”.

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Strategic Knowledge Gaps

II. Understand how to work on or interact with the SB surface

SKG	R&A	Earth-Based	ISS	Robotic Missions	Specific Target?	Narrative
A-1. Biological effects of SB surface particles.	🔴	○	○	●	No?	Laboratory experiments using meteoritic analogs and simulants, but exposure to Earth atmosphere may change dust properties (charging/activated surfaces). May need to do some toxicity measurements in situ.
B-1. Mechanical/ electrical effects of SB surface particles.	●	○	○	🔴	Early: Yes? Later missions: No?	Particles may interfere with experiments or critical life-support systems. Laboratory experiments using meteoritic analogs and simulants useful, but not demonstrated to be an adequate stand-in for in-situ observations.
C-1. Macro-porosity of SB interior.	○	⊙	○	🔴	Yes	Necessary for proximity operations. In-situ measurements using radar or seismic studies, plus radio science. Depending on specific case, constraints possible from Earth-based observations
C-2. Geotechnical properties of SB surfaces.	○	○	○	🔴	Early: Yes Later: No?	In-situ measurements of porosity/gravity/ cohesion/shear strength/etc. to design optimal surface activities, and recognize less fruitful approaches.

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Strategic Knowledge Gaps

II. Understand how to work on or interact with the SB surface

SKG	R&A	Earth-Based	ISS	Robotic Missions	Specific Target?	Narrative
D-1. Anchoring for tethered activities.	○	●	●	🔴	Yes	Technology development on Earth. Testing on ISS. Lab environment not demonstrated to be adequate stand-in for in-situ measurements. Without knowledge of surface/sub-surface morphology, can't design anchor/tether for surface elements.
D-2 Non-contact close proximity operations for detailed surface exploration and surveys.	●	⊙	🔴	⊙	Yes?	Anchor/tether not necessarily needed for astronauts, but more work needed on proximity non-contact techniques. In-situ experiments/observations useful for study of particle levitation/reaction to disturbances.
E-1. Expanding habitat volume to SB interior for shielding and human factors.	○	🔴	●	⊙	No?	Long-term visits may take advantage of local material for safe, cost-effective shielding. Technology development on Earth. Testing on ISS. Shielding would require some knowledge of specific asteroid composition/porosity/etc.

Strategic Knowledge Gaps

III. Understand the SB environment and its effect on human life.

SKG	R&A	Earth-Based	ISS	Robotic Missions	Specific Target?	Narrative
A-1. Expected dust env. due to ejecta from micrometeor. impacts.	●	○	○	🔴	Yes?	Dust environment around object may act as hazard or nuisance (especially given cohesive forces in low-g environment). Modeling and impact laboratory experiments, in-situ and remote observations.
A-2. The pop. of a dust torus around the Phobos/ Deimos orbits.	●	○	○	🔴	Yes	Rationale same as A-1, though unique position in Mars orbit exacerbates problem due to ejecta re-collection. Develop models based on remote and past in-situ observations by spacecraft, obtain in-situ observations in the vicinity of Phobos/Deimos.
A-3. Possible dust environment in the asteroid exosphere due to charged particle levitation following surface disturbances.	●	○	○	🔴	Yes?	Consistency with III-A-2.

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Strategic Knowledge Gaps

III. Understand the SB environment and its effect on human life.

SKG	R&A	Earth-Based	ISS	Robotic Missions	Specific Target?	Narrative
B-1. Local environmental effects from solar flare activity.	🔴	○	○	🔴	No?	Solar flares may lead to enhanced dust levitation or other hazards/nuisances. Modeling and monitoring by existing space-based solar observatory assets.
B-2. SB surfaces as a source of radiation.	●	○	○	🔴	No?	SB surfaces may have enhanced radiation return during solar flares. Laboratory measurements. Lab not shown to be fully adequate stand-in for in-situ measurements. Robotic mission preferred.
C-1. SBs as shields against solar storms.	🔴	○	○	🔴	No	Modeling In-situ measurements of shielding by "hiding" in shadow of target small body, even without storms, would be useful.
D-1. Local structural stability	⊙	⊙	○	🔴	Yes	Emplacement of experiments etc. may lead to mass wasting, especially on metastable rapid rotators. In-situ measurements required. Some relevance of modeling of whole-body measurements to local scales.
D-2. Global structural stability	⊙	⊙	○	🔴	Yes	Emplacement of experiments etc. may lead to large-scale reorientations, especially on metastable rapid rotators. Observations of rotation period, change of period provide some insight but in-situ measurements required

Strategic Knowledge Gaps

IV. Understand the SB resource potential

SKG	R&A	Earth-Based	ISS	Robotic Missions	Specific Target?	Narrative
A-1. Remotely identifying resource-rich NEOs.	●	●	○	🔴	No	Low-albedo NEOs are more likely than high-albedo ones to have water/OH-bearing minerals. Laboratory work may be needed to better understand how to spectroscopically identify those dark NEOs that are water-rich. More observations, particularly from space where Earth's atmosphere doesn't interfere, are also needed. NEOs with known resources are more attractive targets, other things being equal.
A-2. Knowledge of how to excavate/collect NEO material to be processed.	🔴	⊙	●	🔴	No	Techniques can be developed and tested on Earth and optimally tested in the zero-gravity of ISS.

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Strategic Knowledge Gaps

IV. Understand the SB resource potential

SKG	R&A	Earth-Based	ISS	Robotic Missions	Specific Target?	Narrative
A-3. Knowledge of extracting and collecting water in zero-g.	🔴	⊙	🔴	●	No	Techniques can be developed and tested on Earth preparing and heating meteorite analog and simulants, then optimally tested in the microgravity of ISS.
A-4. Caching and prepositioning and extracted resources.	○	○	⊙	🔴	No	Techniques best tested in microgravity
A-5. Refining, storing, and using H & O in micro-g.	🔴	⊙	🔴	●	No	Refinement testing starting with extracted water from meteorite analogs and simulants to test processes on Earth, then deploy for testing at ISS. In-situ demonstration needed.

Strategic Knowledge Gaps

IV. Understand the SB resource potential

SKG	R&A	Earth-Based	ISS	Robotic Missions	Specific Target?	Narrative
B-1. Do res. materials exist beneath the surfaces of Phobos/Deimos	⊙	⊙	○	🔴	Yes	This might be determined via remote observation (neutron spectrometer), but may requires a mission to Phobos/Deimos with the capability of drilling and making observations beneath their surfaces. Better understanding of P/D composition, modeling of evolution would also help close this gap.
B-2. Knowledge of how to access resource material at depth.	○	⊙	●	🔴	No?	This will require the developing of techniques on Earth and their testing in the micro-g environment of the ISS, and require in situ knowledge about subsurface (and so testing at an NEO).
B-3. Refining, storing, and using H & O in a usable state on Phobos/ Deimos.	🔴	⊙	🔴	●	Yes	Refinement testing starting with extracted water from meteorite analogs and simulants to test processes on Earth, then deploy for optimal testing at ISS.

Determining a Timeline

Ranking Priorities

Rank	Description
Critical	Human exploration cannot proceed without closing of SKG.
High	Important for maximizing human safety and/or meeting mission objectives.
Enhancing	Enhances mission objective return.

Timeframe

Time	Description
Near	Needs to be addressed immediately or in the near-term: A target cannot be chosen without it.
Mid	Needs to be addressed in the mid-term: Must be completed before launch to human mission target,
Long	May be addressed in the longer term: May be completed after first launch.

Critical Items

Timescale	SKGs: Number and Name
Near	1. I-A Constraints on targets: Reachable targets within architecture and radiation exposure limits 2. I-B NEO orbit distribution
Mid	1. I-C-3: NEO rotation state 2. II-C-2: Geotechnical properties of SB surface 3. II-D-1:Anchoring for tethered activities 4. II-D-2:Non-contact proximity operations development 5. III-A-1: Particle environment, undisturbed 6. III-A-3: Particle environment post-disturbance 7. III-B-1: Local effects post-solar flare 8. III-B-2: Small body surfaces as secondary radiation sources 9. III-D-1: Local structural stability 10. III-D-2: Global structural stability
Long	1. III-A-2: Phobos/Deimos torus characterization

High Importance Items

Timescale	SKGs: Number and Name
Near	None identified at this time
Mid	1. I-C-1: NEO sizes 2. I-C-2: NEO albedos 3. IV-A-1:Remotely identifying resource-rich NEOs 4. III-C-1: Small Bodies as shields against solar storms 5. II-C-1: Macroporosity of SB interior
Long	1. II-A-1:Biological effects of particulates 2. II-B-1:Mechanical/electrical effects of particulates 3. IV-B-2:Accessing resource material at depth

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Enhancing Items

Timescale	SKGs: Number and Name
Near	None identified at this time
Mid	1. IV-A-5: Refining, storing, and using H&O at NEOs 2. IV-B-1: Phobos/Deimos subsurface resource potential
Long	1. II-E-1: Expanding habitat to SB interior 2. IV-A-2: Excavate/collect NEO material to be processed. 3. IV-A-3: Extract/collect resources in micro-g 4. IV-A-4: Prepositioning and caching extracted resources 5. IV-A-5:Refining, storing, and using H & O in micro-g. 6. IV-B-3:Refining, storing, and using H&O at Phobos/Deimos

Supporting Items

- Closing some SKGs listed here may be of greater importance enabling visits or long stays on the Moon or Mars than for small body missions per se. These are usually ISRU-related.
- These SKGs are:
  - IV-A-5: Refining, storing, and using H&O at NEOs
  - IV-B-2:Accessing resource material at depth
  - IV-B-1: Phobos/Deimos subsurface resource potential
  - II-E-1: Expanding habitat to SB interior
  - IV-A-2: Excavate/collect NEO material to be processed.
  - IV-A-3: Extract/collect resources in micro-g
  - IV-A-4: Prepositioning and caching extracted resources
  - IV-A-5:Refining, storing, and using H & O in micro-g.
  - IV-B-3:Refining, storing, and using H&O at Phobos/Deimos

Critical Measurements: Part 1

Measurement	SKGs: Number and Name	Notes
Orbit/Size/Frequency of NEOs in accessible orbits to 30 m size	I-A-1, I-A-2, I-B-1, I-B-2	Survey where possible, modeling as necessary. Size from HQ.
Biological Research	I-A-1, I-A-2, I-B-1, I-B-2	Better defined by bio experts
Propulsion Research	I-A-1, I-A-2	Better defined by propulsion engineers
Shielding Research	I-A-1, I-A-2	Better defined by engineers
Radiation dosimetry in asteroid milieu	I-A-1, I-A-2, III-B-1, III-B-2	Details better defined by bio experts. CRaTER, RAD example instruments
Measure rotation rate of target asteroid to 15 minute precision	I-C-3, III-D-1, III-D-2	After target is selected; combination of Earth-based, spacecraft, in-situ study as necessary.
Measure rotation rates in NEO population for ensemble properties	I-C-3	Combination R&A, spacecraft study
Model sparsely-sampled lightcurves to understand biases	I-C-3	Some data will be available from LSST/Pan-STARRS, but optimized for discovery not lightcurve collection.
Studies of “how quickly-rotating is TOO quickly-rotating” for target.	I-C-3, II-D-2	Details better defined by bio experts (human factors) and engineering experts (operations issues)
Measurement of mass (in-situ radio science)	II-C-2, III-D-1, III-D-2	If multiple system, remote measurements also possible. Sufficient precision to support 5% precision on density.
Measurement of volume/shape model (in-situ imaging/LIDAR)	II-C-2, II-D-1, II-D-2, III-D-1, III-D-2	Radar (if observable), lightcurve observations also applicable. Sufficient precision to support 5% precision on density, understand local gravity to factor of 10.
Calculation/constraint on mass/ density, thermal properties via measurement of Yarkovsky drift (astrometry)	II-C-2	Ground/Earth-based. Enhanced by in-situ data. Not obtainable in all cases.

Critical Measurements: Part 2

Measurement	SKGs: Number and Name	Notes
Calculation/constraint on mass/density, thermal properties via measurement of YORP (long-term lightcurve/radar observations)	II-C-2, III-D-1, III-D-2	Ground/Earth-based. Obsoleted by in-situ data Not obtainable in all cases.
In-situ measurement of cohesion/shear strength/etc. (imaging, surface disturbances)	II-C-2, III-D-1, III-D-2	Impactor? Observation of plume impingement?
Near-surface porosity of target	II-D-1	In-situ or ground-based radar.
Engineering research	II-D-2	Including thruster contamination threshold for science
Measurements of dust density at target	III-A-1, III-A-3, III-A-2 (at Phobos/Deimos)	In-situ observations.
High phase angle, long-duration imaging at target	III-A-1, III-A-3, III-A-2 (at Phobos/Deimos)	Search for dust/dust levitation. In-situ. Also insights from Rosetta/Hayabusa 2/OSIRIS-REx/completed mission data
In-situ radiation monitoring	III-B-1, III-B-2	Also data mining of XGRS/GRS from NEAR/Hayabusa?
High phase angle, long-duration imaging at target	III-A-1, III-A-3	Search for dust/dust levitation. In-situ.