



NEO/Phobos/Deimos Strategic Knowledge Gaps Special Action Team Final Report

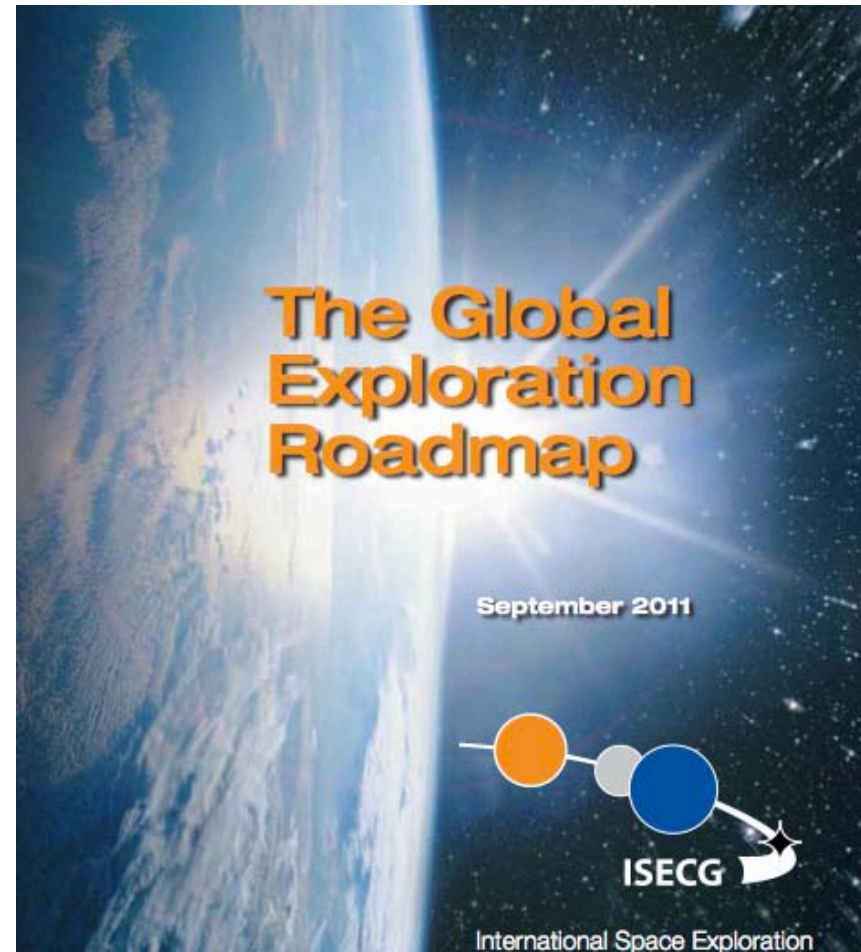
Andrew Rivkin (JHU/APL)
on behalf of the SBAG SKG-SAT

November 28, 2012



Motivation and Background

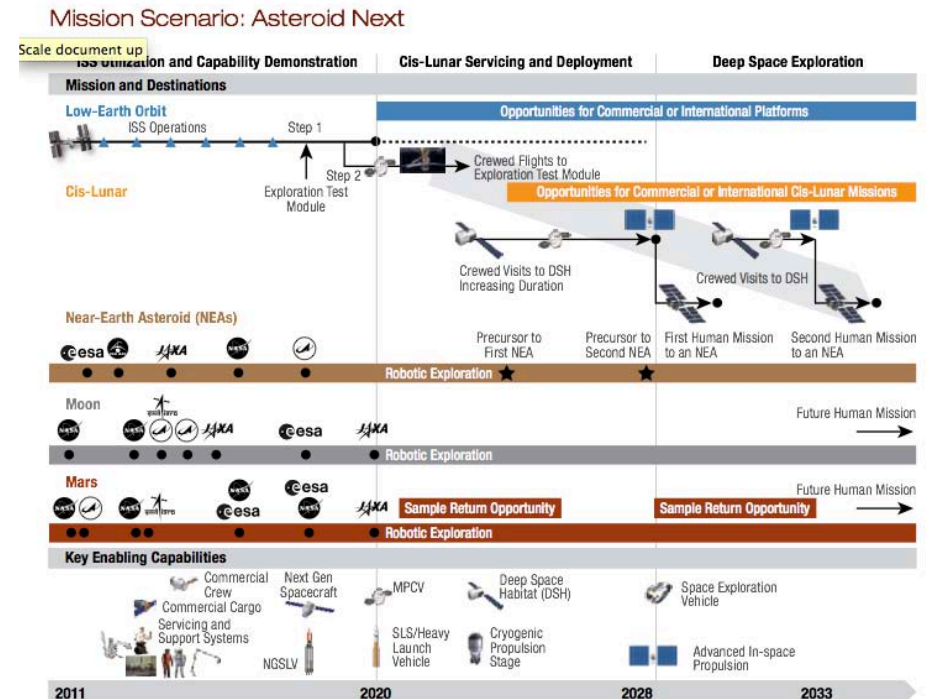
- Global Exploration Roadmap (GER) outlines multi-agency plan for human exploration
 - Includes consensus principles, notional mission scenarios, preparatory activities
- Two scenarios: Asteroid Next, Moon Next
- Intent is *not* to revisit decisions in GER





Motivation and Background

- Global Exploration Roadmap (GER) outlines multi-agency plan for human exploration
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From Global Exploration Roadmap

“Strategic Knowledge Gaps”

- “The gap between what the organization needs to know and what it knows now”
- Taking a human visit to an NEO[‡] as a given*, what don’t we know how to do, and how do we learn to do it?
- Ultimately, generate list of measurements, allowing design of precursor missions

*See previous slide

‡ Also Phobos/Deimos

262 PART III. KNOWLEDGE STRATEGIES

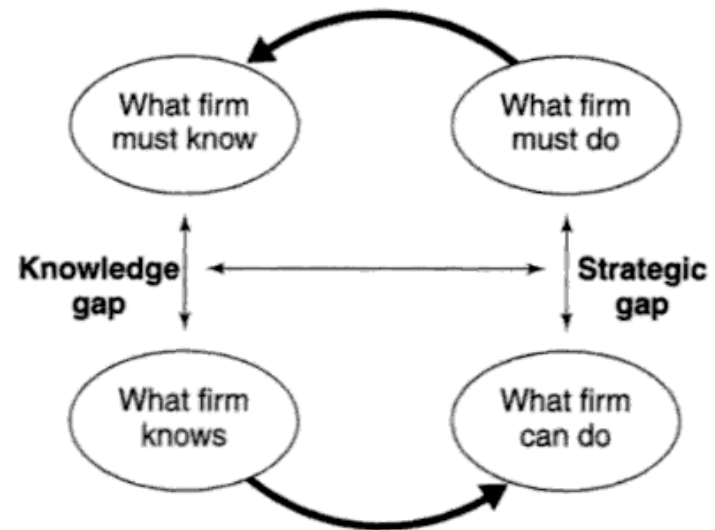


Figure 15.3

Zack, in *The Strategic Management of Intellectual Capital and Organizational Knowledge*, Choo & Bontis eds. (2002)



...for instance:

- Goal: Ensure Kryptonian race survives planetary destruction
- Path: Evacuate inhabitant(s) to intact planets
- Example SKGs
 - Fraction of planets within reach that are habitable
 - Effects of non-K/M star on Kryptonian life
 - Likely reactions of less-advanced civilizations to “first contact”



Morrison and Quitely, 2008



The SBAG SKG SAT Charter

The Small Bodies Assessment Group (SBAG) has been tasked by the Human Exploration and Operations Mission Directorate (HEOMD) to establish a Specific Action Team (SAT) to evaluate and provide findings related to NASA's draft Strategic Knowledge Gaps (SKGs) identified by NASA's Human Spaceflight Architecture Team's destination leads. **The SAT will focus on the SKGs in the context of implementing asteroid mission scenarios and architectures for human exploration.** A Near-Earth Object (NEO) (as yet unidentified) is one of the destinations being considered by NASA's Human Space Flight Architecture Team and the International Space Exploration Coordination Group's Global Exploration Roadmap (GER). In addition, NEOs concern planetary defense and offer the potential to facilitate the expansion of human presence in space beyond low Earth orbit.



The SBAG SKG SAT Charter

Based on the GER's "Asteroid first" scenario for human exploration beyond low Earth orbit (attached), as well as the broader context of NASA's Human Space Flight Architecture Team's (HAT) mission scenario development, the SBAG SAT **will identify, assess, and refine the basic knowledge / data sets / technologies that are required to safely, effectively, and efficiently implement human missions and architectures.** The group will **then identify the gaps in those knowledge / data sets / technologies that would need to be filled in order to implement those missions and architectures.** The missing knowledge could be either enabling (i.e., the absence of a particular knowledge / data set prevents the implementation of the architecture or significantly raises the technical / programmatic / schedule risk) or enhancing (i.e., that knowledge / data set significantly reduces the technical / programmatic / schedule risk). Such knowledge includes technology gaps; **the SAT should highlight any areas where investment in technology development would be enabling or game changing.**



The SBAG SKG SAT Charter

Of particular note is use of In Situ Resource Utilization (ISRU). The specific resource and its use will depend upon specific architectures for future human space activity and its objectives, including the establishment of space transportation infrastructure and planetary defense. **For each architecture scenario, the group will consider the knowledge / data / technology gaps that exist in order to determine the location, availability and viability of exploiting the resource in an effective manner.** Depending upon the scenario, a resource may include volatiles extracted from NEO material (especially H₂O), other NEO materials and solar energy.

Within the context of identifying strategic knowledge gaps, **the SAT will identify specific robotic precursor missions that could fill these gaps and thereby enable or enhance future human missions and architectures.** Potential links of this precursor missions to past National Academy studies (i.e., Planetary Science Division Decadal Survey) and the SBAG Roadmap should be explored.



The SBAG SKG SAT Charter

1. List of required knowledge / data sets / technology, traced to human exploration needs.
2. Gaps in that knowledge / data sets / technology relative to our current understanding and capabilities.
3. A timeline of when the missing knowledge / data sets must be acquired or technology developed in order to make architecture-specific decisions or in order to make subsequent measurement decisions. In the context of this timeline, the group should consider interdependencies among the acquisition of knowledge, data sets and development of technology.
4. Provide a list of existing and potential missions, experiments, modeling activities, technology, or any other activity that would fill the knowledge gaps. **Links of potential missions to past National Academy studies and the SBAG Roadmap should be explored.**



The SBAG SKG SAT Charter

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. The group should identify any ISS role in filling the gaps identified.

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.



The SBAG SKG SAT Charter

Schedule:

An initial “draft” set of findings will be delivered to NASA on or about TBD, 2012.

A final set of finding will be delivered to NASA no later than TBD, 2012.



The SBAG SKG SAT Charter

SAT MEMBERSHIP:

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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.

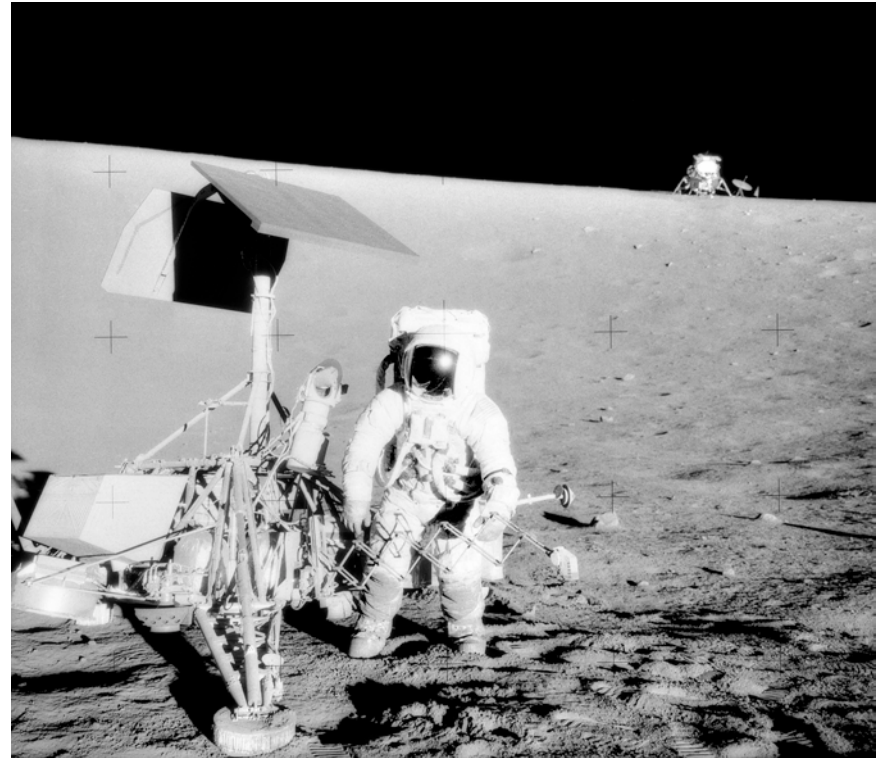
Target Scenarios

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.



Field Position on the Flexible Path

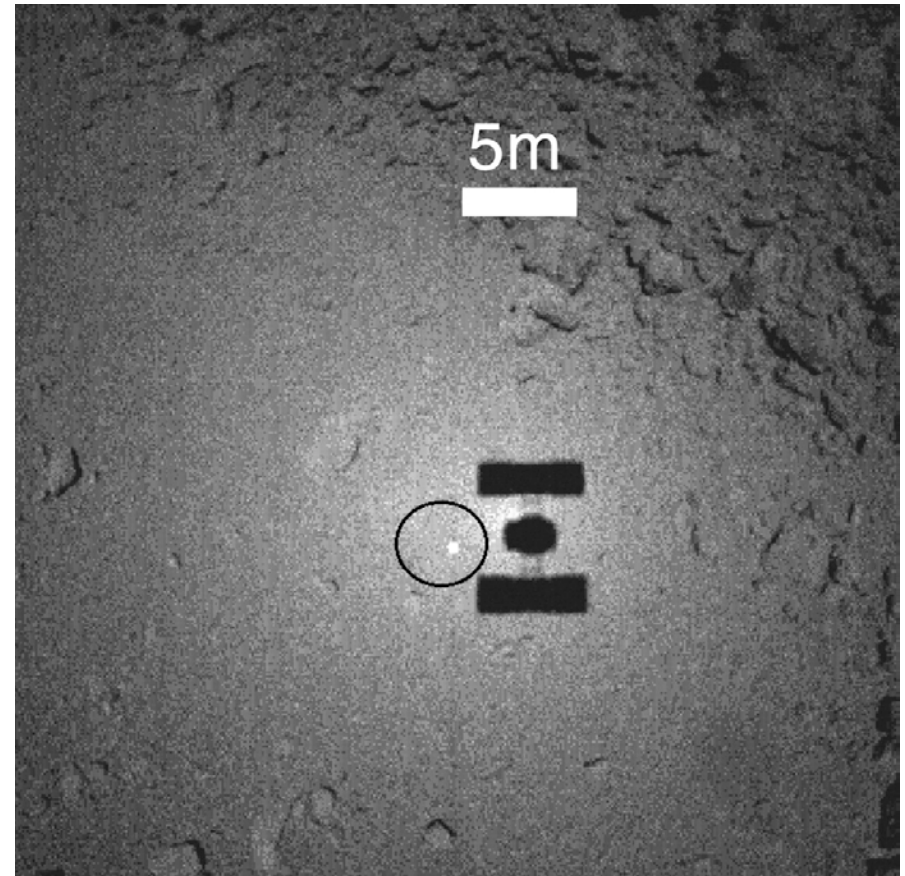
- Lunar exploration began > 50 years ago
 - Roughly 50 successful missions to date from US/ USSR/ESA/Japan/China/ India
 - Orbiters, Sample Return, Landers, Impactors
- Mars exploration began ~45 years ago
 - Roughly 20 successful missions to date from US/ USSR/ESA
 - Orbiters, Landers





Field Position on the Flexible Path

- Asteroid exploration began 20 years ago
 - Significant data return from 5 missions for eight objects (5 flyby, 3 rendezvous, 1 sample return)
 - State of knowledge similar to Mars at time of Viking or Moon at time of Surveyors
 - Note that we do not have in-depth knowledge of any viable HE targets, nor of anything in likely HE target size range
- Understanding of Phobos/Deimos in (slightly/somewhat) more advanced state
- Small bodies community needs time, resources, data to reach level of maturity long ago reached by lunar/Mars communities





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)	<ul style="list-style-type: none">A. Constraints on targetsB. NEO orbit distributionC. NEO composition/physical characteristics (population/specific targets)	<ul style="list-style-type: none">I-A-1. Round trip limitations due to radiation exposure.I-A-2. Reachable objects within planned architectureI-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.	<ul style="list-style-type: none">A. Biohazards and mitigationB. Hazards to equipment and mitigationC. SB surface mechanical propertiesD. Mobility around and interaction with surface in microgravity conditionsE. Habitat expansion options	<ul style="list-style-type: none">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.	<p>A. The particulate environment in the proximity of Small Bodies.</p> <p>B. The ionizing radiation environment at Small Body surfaces, including contributions from secondary charged particles and neutrons produced in the regolith.</p>	<p>III-A-1. Expected particulate environment due to impact ejecta.</p> <p>III-A-2. Possible dust/gas emission via sublimation from volatile-rich objects</p> <p>III-A-3. The population of a particulate torus around the Phobos/Deimos orbits from micrometeoroid impacts and material ejected from Mars.</p> <p>III-A-4: Possible particulate environment in the asteroid exosphere due to charged particle levitation following surface disturbances.</p> <p>III-B-1. Local effects on plasma and electrostatic environment from solar flare activity.</p> <p>III-B-2. SB surfaces as a source of radiation.</p>



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.	<ul style="list-style-type: none">C. Mitigation strategies to preserve human health.D. Local and global stability of small bodies.	<p>III-C-1. SBs as shields against solar storms.</p> <p>III-D-1: Local structural stability based on remote measurements.</p> <p>III-D-2: Global structural stability based on remote measurements</p>



SB SKG Themes and Categories

SKG Themes	SKG Categories	SKG Examples
IV. Understand the SB resource potential.	<ul style="list-style-type: none">A. NEO resourcesB. Phobos/Deimos resources	<ul style="list-style-type: none">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.



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.



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.



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.



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”.



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.



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.



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.



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
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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
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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	<ol style="list-style-type: none">1. I-C-1: NEO sizes2. I-C-2: NEO albedos3. IV-A-1: Remotely identifying resource-rich NEOs4. III-C-1: Small Bodies as shields against solar storms5. II-C-1: Macroporosity of SB interior
Long	<ol style="list-style-type: none">1. II-A-1: Biological effects of particulates2. II-B-1: Mechanical/electrical effects of particulates3. IV-B-2: Accessing resource material at depth



Enhancing Items

Timescale	SKGs: Number and Name
Near	None identified at this time
Mid	<ol style="list-style-type: none">1. IV-A-5: Refining, storing, and using H&O at NEOs2. IV-B-1: Phobos/Deimos subsurface resource potential
Long	<ol style="list-style-type: none">1. II-E-1: Expanding habitat to SB interior2. IV-A-2: Excavate/collect NEO material to be processed.3. IV-A-3: Extract/collect resources in micro-g4. IV-A-4: Prepositioning and caching extracted resources5. 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.