Technology Recommendations to Support: Goals and Objectives for the Exploration and Investigation of the Solar System's Small Bodies

Small Bodies Assessment Group (SBAG)

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Goals and Objectives for the Exploration and Investigation of the Solar System's Small Bodies

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Revision #	Date	Notes
1.0.2016	June 28, 2016	Draft for review by SBAG Community

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Given the regularly occurring advancements that relate to technology development and innovations of novel paths to achieve the performance goals of instruments and systems to achieve the stated objectives this document, updates and reviews to this document are planned on a yearly basis, with input solicited from the entire SBAG community. The revision schedule is likely to utilize the twice-yearly SBAG meetings, which occur in January and June, with revision leads identified in January, a revised document made available for comments to the entire SBAG community in June, and the updated document finalized shortly afterwards.

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Executive Summary

The Small Bodies Assessment Group (SBAG) was established by NASA in 2008 and is composed of members with knowledge and expertise of small bodies throughout the Solar System. The term of “small bodies” refers to a wide-ranging, highly diverse, and numerous set of Solar System objects, including near-Earth objects, main belt asteroids, the Martian moons, comets, Trojan asteroids, irregular moons of the outer planets, centaurs, Kuiper belt objects, other trans-Neptunian objects, dwarf planets, dust throughout the Solar System, and meteorites and other samples of such bodies. The SBAG Goals Document captures the high priority objectives and unique exploration opportunities related to the Solar System’s small bodies.

The technology recommendations to support the SBAG Goals and Objectives represent an assessment and high level prioritization of technologies required or enhancing to the science, planetary defense and human exploration objectives. In this sense, the recommendations are all mission “pull” without advocacy of technology push. It is recognized that technology push has potential for disruptive advancements. Whenever possible, a Design Reference Mission (DRM) was the basis for technology assessment; leveraging significant investments by NASA for baseline mission concepts. A deficiency in this approach is that the mission concept studies provide viable paths to achieve the SBAG goals and objectives, but may limit the identification of technologies offering innovative approaches to achieve the same objectives. This approach typically limits itself to higher Technology Readiness Level (TRL) concepts and instruments for near-term infusion towards the achievement of new science, planetary defense and human exploration.

Just as the SBAG area of interest is broad and diverse, so is the technology set that can be used to meet its overarching goals and objectives. One of the difficulties in prioritization of technologies is the disparate applications and path for infusion. How does one prioritize an improved power density secondary battery with a laser for optical communications with a seismometer with justification? Prioritization is further complicated if missions and mission approaches are unknown and selected through a competitive process. Lastly, it is outside the scope of the SBAG to prioritize between science, human exploration or planetary defense. To overcome these challenges, an approach for this initial technology assessment was followed based on the process of Strategic Prioritization and Planning (SP2)[1] previously implemented by NASA.

The SP2 approach can provide insight into the merit of focused investments. The approach leverages qualitative relationships mapped to quantitative scales for prioritization based on the desired level of abstraction. The process is based on Quality Functional Deployment (QFD) with dynamics aspects that allow for understand the sensitivity to the input. All technology prioritization methods have known shortfalls. This approach for this assessment was used to perform high level sensitivities and provide some traceability while informing recommendations.

The technology assessment effort performed explicitly separated science instrument technologies from general systems technologies that enable the instruments to collect and return the relevant data. The priority technology recommendations for general systems include optical communication systems, high performance solar arrays for moderate power, improved guidance, navigation and control systems, higher performance batteries, low power and low power iodine electric propulsion, proximity operations and pinpoint landing technologies and completion of the high power Hall thrusters. The priority technology recommendations for instruments include survey detectors, landing proximity sensors, a long-wave infrared camera identified for human exploration mission needs, cosmic dust acquisition, orbital radar, deep drilling, lander payload, imbedded instruments, small satellite instrument and seismometer instrument technologies.

Technology Assessment Methodology

The Small Bodies Assessment Group (SBAG) was established by NASA in 2008 and is composed of members with knowledge and expertise of small bodies throughout the Solar System. Membership in SBAG is open to all interested individuals of the interdisciplinary small bodies' community. The term of "small bodies" refers to a wide-ranging, highly diverse, and numerous set of Solar System objects, including near-Earth objects, main belt asteroids, the Martian moons, comets, Trojan asteroids, irregular moons of the outer planets, centaurs, Kuiper belt objects, other trans-Neptunian objects, dwarf planets, dust throughout the Solar System, and meteorites and other samples of such bodies. The SBAG Goals Document captures the high priority objectives and unique exploration opportunities related to the Solar System's small bodies. The methods to achieve those objectives include ground observations, potential balloon / airborne science, computer modeling, and missions to fly-by, rendezvous, land, and return samples from a diverse set of targets.

In previous technology prioritization efforts for the SBAG, a consensus approach of working with technology and implementation subject matter exports to identify technology and instrument gaps to enable science objectives. Also, it was observed that enhancements to state-of-the-art (SOA) options can significant increase mission value. Additionally, it was noted that significant return on investment potential exists for the cross-cutting technologies. Finally, the previous efforts were focused on addressing the needs of the planetary sciences decadal survey, while this version is looking forward towards the next decadal survey and driven from the broader SBAG goals documents for planetary defense, human exploration and science relevant for the small bodies' community.

Given the broader scope of the SBAG beyond simply planetary science, and a desire to increase traceability into the technology prioritization, the process of Strategic Prioritization and Planning was employed. The use of SP2 can provide insight into the merits of focused investments. The approach leverages qualitative relationships mapped to quantitative scales for prioritization based on the desired level of abstraction. The process is based on Quality Functional Deployment (QFD) with dynamics aspects that allow for understand the sensitivity to the input. All technology prioritization methods have known shortfalls. This approach for this assessment was used to perform high level sensitivities and provide some traceability while informing recommendations. The output provides a Pareto assessment to understand how some technologies are enabling, but may only be applicable to a few infusion opportunities while other investments may only be enhancing yet broadly applicable to a wide range of missions.

The SP2 method was used separately for general technologies and for instruments. The SP2 scoring also always for weighting to be applied for sensitivity trades at various levels. At the highest level, the default is for an equal weighting for goals (science, planetary defense and human exploration). Options to assess the prioritization if the funding source is only science or planetary defense or human exploration is available and insightful. A second order of weighting is included in the SP2 tool for the size of the mission in four categories: Large, Medium, Small and Very Small. Large missions are roughly over a $1B including missions such as the major human exploration missions such as crewed missions to the moons of Mars or asteroids, the asteroid redirect and rendezvous mission, and a comet cryogenic nucleus sample return. Medium missions are comparable to New Frontiers planetary science mission categories. Small missions are comparable to Discovery planetary science missions and very small includes anything less than Discovery including, Small Mission Explorer Class science missions, Advanced Explorations

Systems (AES) and SIMPLEX SmallSat missions, ISS experiments, balloon based observations, ground based radar observations, etc. with no further distinction (e.g. between a $200M mission and a $10M balloon campaign). Again, the default is for all mission classes to be weighted equally.

Subject matter inputs are also difficult to eliminate from a technology prioritization activity. For this document, the SBAG prioritization leveraged the 2015 NASA Technology Roadmaps developed by the Office of the Chief Technologist (OCT). The OCT roadmaps included both a broad and deep assessment of technology paths for the 15 distinct Technology Areas with over 2000 pages of material on specific technologies needs and development paths. Each technology area included a team of SMEs for the specific area. During the OCT Roadmap effort, "Technology Candidate Snapshots" were developed within deep dives of each area. For the SBAG effort, the OCT inputs were augments by SBAG SME "Snapshots". The Snapshot information included the state-of-the-art, the Technology Readiness Level (TRL), specific performance metrics for capability and metrics for technology development efforts in addition to potential mission application information and need dates. Some of the OCT Snapshots included technology push activities, but the SBAG augmented snapshots were only limited to mission pull technologies. An example Snapshot is shown in figure 1.

2.1 Chemical Propulsion
2.1.1 Liquid Storable

2.1.1.1 Monopropellants

TECHNOLOGY

Technology Description: Monopropellant thrusters use a single Earth- and space-storable propellant decomposed to generate high-temperature gas for thrust.

Technology Challenge: More development of higher thrust classes needs to occur to be comparable to the current regime of hydrazine thrusters. Scaling may need alternate ignition developments as preheat power will grow. Development of catalysts with extended life and operational regimes is also needed. The developed propellants generally require preheat and do not cold start. Some candidates may need a reduction of freezing point without compromising performance.

Technology State of the Art: European: flight test demonstration of 1 N (1st generation propellant).

U.S.: pending flight test demonstration of 1 N and 22 N 1st generation propellant, ground (sea level and altitude) demonstrations of up to 445 N (the High Perfomance Green Propellant (HPGP)).

Parameter, Value:	**TRL**
European 1st generation: 1 N flown, 0.5 N to 22 N ground demo, density specific impulse (I_{sp}) = 278 to 309 s*kg/m³, preheat = 350° C; U.S. 1st generation: 0.5 N to 22 N ground demo, density I_{sp} = 350 to 375 s*kg/m³, preheat = 370° C; Nitrous oxide fuel blend: 0.44 N to 445 N ground demo, density I_{sp} = 291.4 s*kg/m³	3

Technology Performance Goal: High-achieved density, I_{sp}, long-life catalysts, and increased thrust level.

Parameter, Value:	**TRL**
Density-I_{sp} increase of 50% for 1st generation and 70% for 2nd generation; Thruster operating life: > SOA for a given application; Thrust: > 445 N	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High density-I_{sp} with reduced toxicity and low preheat requirement for reaction control and main propulsion.

Capability Description: Reaction control thrusters provide small accelerations to maintian or adjust a spacecraft's attitude or provide spacecraft orbit manueviering. For primary propulsion engines, provide spacecraft orbit manueviering, orbit insertion, or ascent propulsion with high I_{sp}.

Capability State of the Art: Reaction control/main propulsion systems utilizing hydrazine decomposition.

Parameter, Value: Hydrazine:

< 1 N thrusters: I_{sp} = 200 to 230 s (SmallSat);

1 N to 22 N thrusters: I_{sp} = 200 to 235 s (SmallSat attitude control system (ACS)/reaction control system (RCS)/Primary);

> 22 N thrusters: I_{sp} = 200 to 245 s ("Traditional"/Manned Scale ACS/RCS/Primary)

Capability Performance Goal: Achieve better-than-state of the art (SOA) hydrazine performance (e.g., improved I_{sp} or density-I_{sp}, greater storage temperature range, longer catalyst life, etc.) with lower operational handling and transport requirements (e.g., no Self-Contained Atmosphere Protective Ensemble (SCAPE) suits required, with less restrictive transportation methods); goals are 50% improvement in density-I_{sp}.

Parameter, Value:

Propellant with improved (less costly, safer) ground handling versus the SOA.

Propulsion system with equivalent or reduced overall system mass versus the SOA.

Density-I_{sp}: increase of 50% for 1st generation and 70% for 2nd generation.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	3-5 years
New Frontiers: New Frontiers 5 (NF5/~2022 AO Release)	Enhancing	--	2029	2021	3-5 years

Figure 1: Example Technology Candidate Snapshot.

The implementation of SP2 is a variant of a quality functional deployment (QFD) scoring method through the layers of abstracted relationships. The mapping between levels is done quantitatively through qualitative input. The layers of the SBAG SP2 calculator trace from the top level goals, to the objectives and sub-objectives explicit in the "Goals and Objectives for the Exploration and Investigation of the Solar System's Small Bodies", to the implementation method (e.g. Sample Return Mission, balloon observations, radar observations, comet rendezvous, crewed mission to the moons of Mars, etc.), and then to either the technologies or instruments to support the missions and objectives. The scoring for each layer between relationships was 0, 1, 3 and 9 for the qualitative inputs of zero, low, medium, high, no benefit, potential benefit, enhancing and enabling, etc. The layers of the SP2 SBAG calculator are shown in figure 2. In addition to the explicit layers, the calculator includes weightings on the goals and mission size, all default to equal weighting, but available for sensitivity trades.

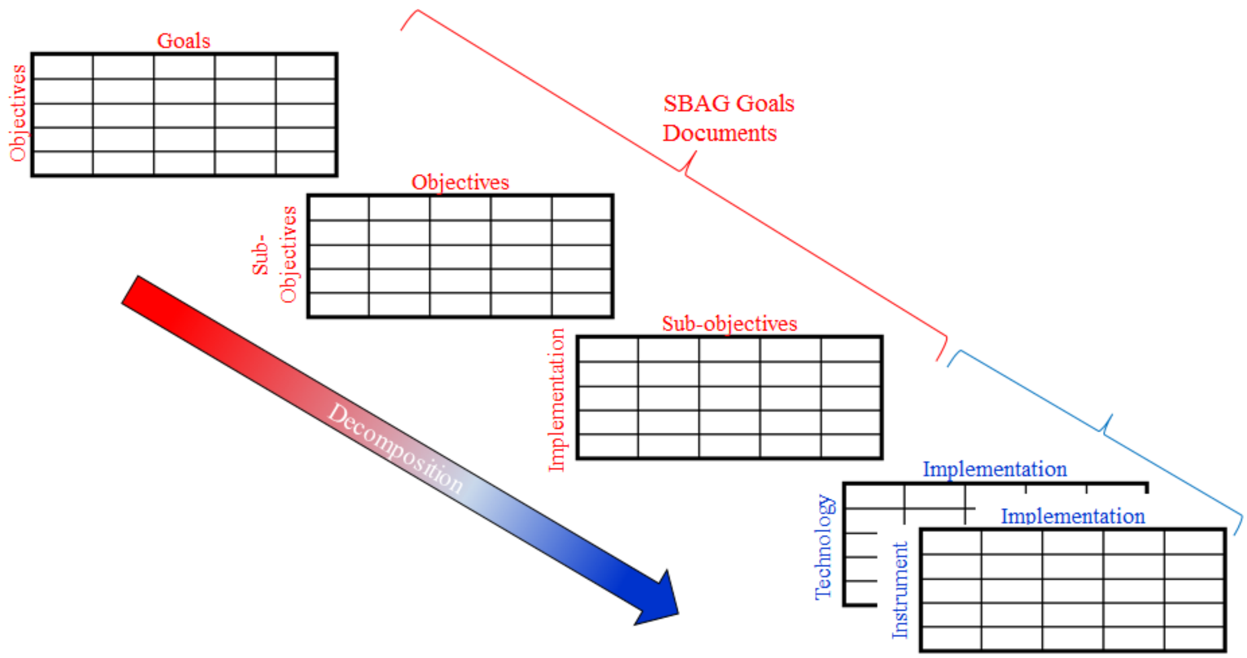

Figure 2: Decomposition of the SBAG SP2 calculator.

System Support Technologies:

TA-1: Launch Propulsion Systems

To complete both science and planetary defense objectives, based on the existing design reference missions, commercial launch propulsion systems are available to meet the planned missions / mission objectives. However, to meet the needs for the crewed missions to small body targets, the baseline vehicle is the space launch system (SLS) with several technologies required to complete its enabling performance. SLS technologies are a priority for human exploration, but a lower priority for science and planetary defense. Several studies have been performed to highlight the capability that the SLS would provide for planetary defense purposes, but none have been baseline to date.

TA-2: In-Space Propulsion Technologies

Over the past 15 years, NASA has made significant investments for in-space propulsion for science mission needs. Electric propulsion technologies is both enabling and enhancing to a wide range of small body missions. The lack of appreciable gravity wells results in electric propulsion mission design solutions with often lower cost and higher science return. The great diversity and celestial locations also often necessitate the use of electric propulsion. Pending target selection, mega-multi flyby, inclined target rendezvous, multi-rendezvous, main belt asteroid sample return, multi-asteroid sample return, comet surface sample return, comet nucleus sample return, Phobos and Deimos sample return, etc. are all enabled through the use of electric propulsion.[2] Investments have included gridded ion and Hall electric propulsion thrusters, including both NASA specific and commercial thrusters applicable for future NASA missions. The recent focus of electric propulsion investments have been on lower cost solutions for electric propulsion missions. The most recent round of Discovery class missions included an incentive for the use of NASA's Evolutionary Xenon Thruster (NEXT) and one mission selected for study included the use of a commercially available SPT-140 Hall thruster. Very long life low power thrusters have also received small investments, primarily through Small Business Innovation Research (SBIR) contracts, to develop Hall thrusters applicable to very distant rendezvous missions such as centaurs, trans-Neptunian Objects, and Kuiper Belt Objects leverage radioisotope power systems. NASA has also invested in higher performance chemical propulsion options applicable to a subset of CSSR mission targets and an option for the Trojan Tour. Investments continue for "green" propulsion options, with a promise to reduce costs, but have not been found enabling or a high priority yet for the design reference missions to small bodies.

Planetary defense goals are largely independent of in-space propulsion technologies. Planetary defense demonstrator options range of slow methods such as gravity tractors to fast methods just as kinetic impactors. The methods define propulsion needs from high specific impulse low-thrust solutions to additive divert high thrust solutions, but none have been identified technologies beyond state-of-the-art or that would drive the need for specific planetary defense in-space propulsion technology needs.

In-space propulsion technology needs for small body human exploration goals are typically enhancing with the exception of the Hall Effect Rocket with Magnetic Shielding (HERMeS). The HERMeS is required to support the Asteroid Redirect Mission (ARM) and enabling for the return of a massive target to final lunar orbit. There is a desire for crewed missions to have less toxic chemical propulsion options. Also, CubeSat propulsion investments such as solar sails, electrospray and iodine electrostatic thrusters are enabling and enhancing for human exploration scout missions.

TA-3: Space Power and Energy Storage

In general, the power system requirements are small body missions are not inherently unique. However, there are several notable exceptions for future small body missions.

For solar arrays, the requirements for several of the small body missions are driven by the enabling and enhancing nature of electric propulsion options. Due to the large number of small body missions that could benefit from the use of electric propulsion systems, solar array advancement can yield significant delivered mass advantages. It has been anticipated for more than a decade that NASA would already have >120W/kg for modest solar arrays. Of highest interest to the science community, would be modest (~7.5kW) high specific power wings. The UltraFlex array was selected for flight validation by the science mission directorate under the Space Technology 8 demonstration mission as a part of NASA's New Millennium Program (NMP). This mission was to flight validate 175W/kg system performance. The UltraFlex array was also selected as the baseline for the Constellation's Program Orion Module. ST-8 completed preliminary ground testing before cancelation, and the manned rated systems development has specific structural requirements such that the system is only expected to achieve 100 W/kg for a 7-7.5kW wing. Several planetary science and exploration missions continue to baseline the UltraFlex solar array because of its performance characteristics, but the higher performance system still carries risk until flight validation or additional ground testing can be completed. Small body missions would benefit from the decadal survey recommendations to mature a high specific power technology for planetary science missions. The solution is not required to be a specific implementation, such as Ultraflex versus a rolled out array or other configurations, but the performance goal should be similar to that of ST-8. Additionally, there is a strong desire for small body missions to have solar arrays that can be stowed and redeployed to reduce risk on small body landed operations. For small body human exploration goals, the unique solar array systems requirement is driven by the Asteroid Redirect Missions. NASA's Space Technology Mission Directorate (STMD) has matured two options to achieve improved specific power and packaging efficiency. One of these options is required to be matured to enable the ARM.

Nuclear power systems, such as Radioisotope Power Systems (RPS), are enabling to a wide range of missions, including those to the small bodies. There are no known nuclear power requirements for the small body human exploration or planetary defense objectives. For planetary science, a nuclear power system with performance goals of 8W/kg was found enabling through the Discovery Scout Mission Capabilities Enhancement (DSMCE) studies. Larger building blocks lend themselves well for high AU rendezvous missions using Radioisotope powered Electric Propulsion (REP). Missions evaluated showed that a larger power unit (>500W) could potentially enable flagship Kuiper Belt Object orbiter missions or New Frontiers class Centaur orbiter missions. A handful of Centaur orbiter targets are enabled with the 6-8W/kg, but many high interest target, e.g. Chiron, Chariklo, etc., require an improved specific mass performance. A long term technology need is a higher specific power system with an integrated system performance of > 5 W/kg; analogous to an RPS with a specific power of ~10 W/kg. Despite significant resources devoted to the restart of ^{238}Pu, the RPS program is no longer projecting near-team paths to achieve these performance goals with ^{238}Pu radioisotope systems. International efforts are exploring ^{238}Am RPS options. STMD has begun investing in a "kilopower" project for power systems in the 1-10kWe range with small fission reactors, but those are unexpected to meet the SBAG mission needs. If the community prioritizes an REP mission in the 2020s, such as a centaur orbiter, a high performance nuclear option must be prioritized.

Battery technology is a power system need with potential benefit a wide range of missions, though only offering a minor enhancement to the majority of applications. A major exception is the battery requirement for the comet Cryogenic Nucleus Sample Return (CNSR). The batteries are expected to drive the overall design of the return capsule and influence the spacecraft design. The requirements for CNSR are > 600W-hr/kg and >1.4W-day/D-cell for specific power and density based on reference systems with lithium thionyl chloride cells as a potential path forward.

TA-4: Robotics and Autonomous Systems

Robotic and autonomous systems are both enhancing and enabling to mission for human exploration and science small body goals. Overall, both human and robotic missions benefit greatly from improved sensors, object recognition, manipulators, terrain mobility, autonomous sample handling and acquisition, etc. The ARRM mission also requires robust and safe autonomous rendezvous and docking. Increased autonomy had potential to reduce mission operations and increase science return. Multiple reference missions and reports highlight the need for the development of new surface manipulators, and robotic sample collection, characterization and processing. Specific technology gaps include small body systems for anchoring, vacuum rated low power drilling systems, down-hole sensors, health monitoring, autonomous operation, thermal challenges, preventing the loss of volatiles, and multi-string systems for various depths and material properties.

The largest technology gap remains for obtaining an uncontaminated cryogenic nucleus sample that will remain unaltered through the sampling and transfer process. Concepts range from a pre-lander impactor to reduce the drilling requirement to drilling more than 20 meters autonomously at a comet. Deep icy body sample collection concepts have yet to be developed, and should be initially studied for potential solutions in preparation for the cryogenic sample return mission. While the cryogenic nucleus sample return remains a high priority for science return, the flagship mission has several high risk elements based on low maturity technology; investments are necessary to add fidelity to mission estimates and risk reduction prioritization. Risk reduction may allow the mission to gain near-term traction.

TA-5: Communications, Navigation, and Orbital Debris

Today's communication and navigation capabilities, using Radio Frequency technology, can support our spacecraft to the fringes of the solar system and beyond. Data rate range from 300 Mbps in LEO to about 6 Mbps at Mars. Further advances in communications and navigation systems with reduced SWAP (size, weight, and power) and increase performance will enable future missions, including small body missions, to implement new and more capable science instruments, greatly enhance robotic exploration and enable entirely new mission concepts. A recent analysis of NASA's likely future mission set indicates that communications performance will need to grow by an order of magnitude every 15 years to keep up with robotic mission requirements. In terms of bits per second, history has shown that NASA missions tend to return more data with time according to an exponential "Moore's Law." Missions are constrained by allocated spectral band-width; NASA's S-band is already overcrowded and there are encroachments at other bands. Future small body missions also include a diverse set of navigational challenges that cannot currently be met. Precision position knowledge, trajectory determination, cooperative flight, trajectory traverse and rendezvous with small bodies are just a few. However, proper technology investment is anticipated to solve these changes and enable new mission concepts.

Communication and navigation are technology areas needing investments for future science, exploration and planetary defense systems. Planetary defense mitigation methods include kinetic interceptor final navigation, through the technology is relatively mature. Navigation and timing investments are required for more accurate vehicle tracking and trajectory error reduction, autonomous trajectory maneuver planning and more accurate and stable time or frequency references for timekeeping to facility precise navigation and autonomous operations. Improved navigation can be particularly beneficial for proximity operations at small bodies.

There is also a need for a position, navigation and timing (PNT) focus area addresses the key technology efforts necessary to improve navigation through investments in timing accuracy and distribution as well as make autonomous navigation available for precise maneuvers, such as rendezvous and docking, anywhere in the solar system. PNT technologies that will be critical for Small Body missions will be guidance, navigation and control technologies for small body landing capabilities. There may be advantages to integrating technologies to provide greater mission flexibility, such as the integration of communications, navigation and science technologies to enable multi-functional systems at a reduced burden to the mission due to lower size, weight and power requirements. For example, a hybrid optical com and navigation could be realistically developed for a flight demonstration in 2021 in order to allow pinpoint landing capability and enable missions not possible today.

Large NASA investments are being made for ultra-stable oscillators (USO) and optical communication systems to meet these future needs. Development of photon counting detector technology focuses on new materials and attempts to raise the operating temperature for use in spacecraft. Laser power efficiency improvements will help pave the way for higher power lasers needed for communication from deep space. Also, addressing spacecraft induced jitter will improve laser beam pointing capability. Optical communications may not be driven by the needs of small body missions, but it is anticipated to benefit a large number of future missions. Specifically, one variant of a NEO survey mission includes transmitting terabytes of raw data to the ground for analysis rather than onboard detection and characterization. A NEO survey mission helps meet objectives supporting all the goals of science, human exploration and planetary defense.

TA-6: Human Health, Life Support and Habitation Systems

The human health, life support and habitation systems technology area is only applicable to the human exploration small body goals. While few of the systems are unique to the small body missions, they are required and can feed forward beyond the small body crewed missions. The mission and technology requirements increase from the rendezvous with the redirected asteroid to the crewed mission to an asteroid beyond lunar orbit and then to the crewed mission to the moons of Mars. For example, in short-duration missions lasting days or weeks, such as the ARRM crewed portion, open-loop life-support systems, in which stored consumables like water and oxygen are used once by the crew and discarded in various forms of metabolic wastes, typically offer the best combination of simplicity, reliability, and mission mass. As mission durations increase to months and years, for rendezvous beyond the moon and in the vicinity of Mars, the mass of consumables grows until, depending on specific mission parameters, it becomes more advantageous from a life-cycle cost perspective to recover water and oxygen from metabolic byproducts for subsequent re-utilization by the crew. Onboard the International Space Station (ISS), water is recovered from wastewater and oxygen is recovered indirectly from carbon dioxide. The physical-chemical processes that are employed provide safe water and oxygen that meet the metabolic and basic hygiene needs of the crew. However, less than 90% of the available water and less than half of the potential oxygen that could be is actually recovered. Furthermore, the reliance on expendable items like filters and sorbent beds, and the complexities of the systems themselves, create a dependence on the re-supply of equipment and materials from Earth. For missions beyond LEO, such re-supply chains will become stretched to the point of limiting the potential for extended-duration human space exploration. It is critically important to evolve and supplement today's Earth-reliant systems and prove their readiness to support the deep space exploration goals.

TA-7: Human Exploration Destination Systems

This technology area dominated by the needs for human exploration goals. However, this technology area includes planetary protection and sample containment systems. The OCT roadmap DRM 5 for the crew to an asteroid in a distant retrograde orbit has the fewest new technology requirements including systems for pneumatic excavation from the asteroid, regolith modeling tools, tools for the crew to collect and analyze samples during extravehicular activity (EVA), systems to store the samples and anchoring technologies. The OCT DRM 6, the crewed mission to a Near Earth Asteroid, adds the need for more autonomous crew and ground support systems for execution of procedures with limited ground interaction. Finally the OCT DRM 8 for the crewed mission to the moons of Mars requires systems to grow food, cleaning systems, active sterilization, etc.

TA-8: Science Instruments, Observatories and Sensor Systems

This technology area is covered in the more detailed instrument prioritization section.

TA-9: Entry Descent and Landing Systems

Traditional EDL systems are not applicable to small body missions. While crew entry systems are required for any crewed mission, there are no unique drivers anticipated for small body missions and therefore unnecessary for the SBAG community to prioritize. However, small body sample return missions can have specific earth entry system requirements. Just as identified in the CAPTEM report, a Multi-Mission Earth Entry Vehicle (MMEEV) is likely the most cost effective method for sample return through multiple missions. Even the heritage Stardust and Genesis entry systems are not simply build-to-print options for future small body sample return missions. Also, if sample are to be returns from small bodies with potential for life, a higher reliability must be achieved.

It is unlikely that small body sample return missions will drive the capabilities of curation facilities other than the potential cryogenic sample return. The Mars Sample Return mission, presuming it occurs in the 2020s, will likely drive initial curation facility requirements due to biological containment requirements. Regardless, the curation facilities will likely be upgraded from the existing lunar, stardust, and genesis curation facilities. Temperature sensitive samples will require curation under cold, clean lab environments.

Cryogenic samples present a unique and challenging requirement for sample recover and transfer. Cryogenic sample will have a limited time available for retrieval due to the inherit limitations for environmental control that available within the EEV. GPS and entry prediction capabilities should allow for recovery within minutes, but the samples must quickly be transferred to a controlled environment before the sample can be delivered to the curation facility. The curation facility must be able to analyze the cryogenic samples without alteration of the sample.

TA-10: Nanotechnology

For the purpose of this document, it is assumed that nanotechnology improvements are noted in their application under other technology areas. For example, areas where nanotechnologies have the greatest potential to impact NASA mission needs include: a) engineered materials and structures, b) power generation, energy storage and power distribution, c) propulsion and propellants, and d) sensors, electronics, and devices. In these applications, nanotechnologies are projected to replace state of the art materials used in aerospace vehicle components, including primary and secondary structures, propulsion systems, power systems, avionics, propellant, payloads, instrumentation, and devices.

TA-11: Modeling, Simulation, Information Technology and Processing

Mission design tools and trajectory optimization capabilities are valuable to the small body community. Today's mission design tools enabled the Dawn mission, but also enable potential future missions such as mega-flyby missions. Many of the mission design tools relevant to small body missions have included low-thrust trajectory optimization because of the applicable of electric propulsion to a wide range of small body targets. Tool development has not only focused on high fidelity mission design, such as Mystic, but also rapid mission design for mission concept development with MALTO. A gap in mission design tools for small body missions still exists for proximity operations. Many small body missions require constraints for observations, shadowing, communication, and low thrust maneuvers in unique gravity field environments. Tool development needs include proximity trajectory design with the ability to automate and optimize mission design in high fidelity dynamical systems applicable to any small body rendezvous mission, in addition to landers, and multi-asteroid systems. Also, there is a desire for tool enhancements to allow multiple encounter tour designs for lower integrated mission ΔV for a more rapid design and broader range of science opportunities. With recent pressure from launch vehicle costs and increased mission complexity, there is also a desire for tools that can perform multiple spacecraft trajectory optimization such as missions with landers/probes or multiple independent asteroid missions from a single launch.

In addition to near-term tool development for the community, there is also a desire to gain understanding into small body system dynamics and mission design for complex gravity fields at a more fundamental level. For example, Dawn used "gravity surfing" at Vesta; a better understand of the dynamics can lead to better mission design. Small body dynamics can range from very low understanding of basic dynamics through converting that knowledge into design techniques, capabilities, and tools. There is no dedicated funding for astrodynamics research for these types of problems relevant to small body missions. The recent decadal survey has highlighted the enabling ability of mission design tools and has provided a strong recommendation for tool development and astrodynamics research be included within the planetary science technology portfolio. As primarily software development and testing, mission design tools have demonstrated a high return for low on-going investments.

In addition to mission design tools, modeling and simulation is critical for planetary defense analyses and response planning, ground computer infrastructure to support solar system formation and evolution modeling, and modeling and simulation tasks to increase autonomy, performance, and the velocity of data across the science, engineering and mission data lifecycle. Finally, this technology also includes radiation hardened general purpose flight processor, high capacity memory, high performance flight computer data processing, etc. with enhancing benefits to a wide range of future missions.

TA-12: Materials, Structures, Mechanical Systems and Manufacturing

Materials are the enablers behind the structures, devices, vehicles, power, life support, propulsion, entry, and many other systems that NASA develops and uses to fulfill its missions. New materials are required as are materials with improved properties, combinations of properties and reliability. The computational techniques for designing, improving, and understanding materials behavior require continued enhancement. The combination of computation and experiment is powerful and will accelerate the next step in materials development.

Structures represent the design and analysis content to apply materials in a manner that results in certification for the intended environments. NASA's vision to extend exploration into deep space requires challenging structural innovation. NASA must do much more with much less. In order to succeed, NASA must engage in multifunctional combined system capability and smart structural designs. Certification and sustainability throughout the mission are often some of the most cost and time-consuming efforts in spacecraft development. Many of the structures technology advancements described herein are critical enablers to send humans into deep space.

Mechanism systems are essential to performing the functions required at virtually every stage of spaceflight operations in order to achieve specified mission objectives. Since mechanisms dictate the lifetime of a given mission, they must be designed to be robust, long-lived, and capable of performing in the harsh environments encountered in space. Embedded sensors in mechanisms will enable the acquisition of real-time data and the ability to monitor system performance, improving system reliability, and leading to improved designs. Health monitoring will give us real data from mechanisms operating in their environment, which will lead to improved confidence in analytical tools and ultimately digital design certification. As with TA-10, the technology needs for the TA are considered to be captured under the applications noted in other TAs. For example, the technology pull for a lower cost propulsion system is noted under TA-2, but the research and develop for an additive manufactured thruster with reduced cost would fall under TA-12. The SBAG document is intended to highlight the technology needs and not specify the method to meet the need beyond acknowledging a viable path exists.

TA-13: Ground and Launch Systems

This technology area includes support systems and infrastructure to reduce risk and costs of future mission launch readiness. Most applicable to future small body missions includes meeting the needs of curation facilities, planetary protection when appropriate, lower cost clean rooms, etc. The goals of the technologies in this TA include reducing operations and maintenance costs by 50% while reducing ground mishaps by 50%. Investments in this area are beneficial to all space based missions, but none are unique to small body missions.

TA-14: Thermal Management Systems

This technical area focuses on the technology needs for cryogenic systems, thermal control systems and thermal protection systems. Most of the technologies in this area, such as improved heat rejection systems are enhancing to a wide range of future missions. Phase change materials and efficient cryocoolers may be enabling for the CNSR mission. Entry vehicle thermal protection systems for the MMEEV should be sufficient for future small body mission needs, but high AU comet sample return could have higher entry velocities than returns from the moon or Mars.

TA-15: Aeronautics

This technology area does not applicable to small body mission objectives. It is noted that balloon technologies or SOFIA technologies are not captured in either TA-15 or TA-8. Relative to SBAG, no unique balloon or aircraft related technologies have been identified as unique to only the small body community. Detectors for air based observatories are captured in the instrument needs.

Instrument Technologies:

General Instruments

The assessment of instrument technology needs for future small body missions included an assessment of available small body instruments. Some of the small body missions that have been completed recently, ongoing, or in development include: Rosetta, Dawn, New Horizons, Hayabusa, Stardust, Genesis, NEAR, Deep Impact, Osiris-Rex, etc. These and previous missions have developed a suite of instruments that can be leveraged for future small body missions. Standard instruments such as a Wide Angle Cameras, Narrow Angle Cameras, Spectrometers over wide ranges, dust analyzers, etc. SOA instruments exist with minimal design changes necessary for most small body remote sensing instrument requirements. While heritage instruments exist, there are a few instruments that could add significant science return for remote sensing operations. As initial assessment was performed to identify instrument needs, if existing flight heritage instrument could meet the mission objectives and gaps where technology investment is required to enhance or enable increase progress towards the mission goals. The results are shown in figure 3.

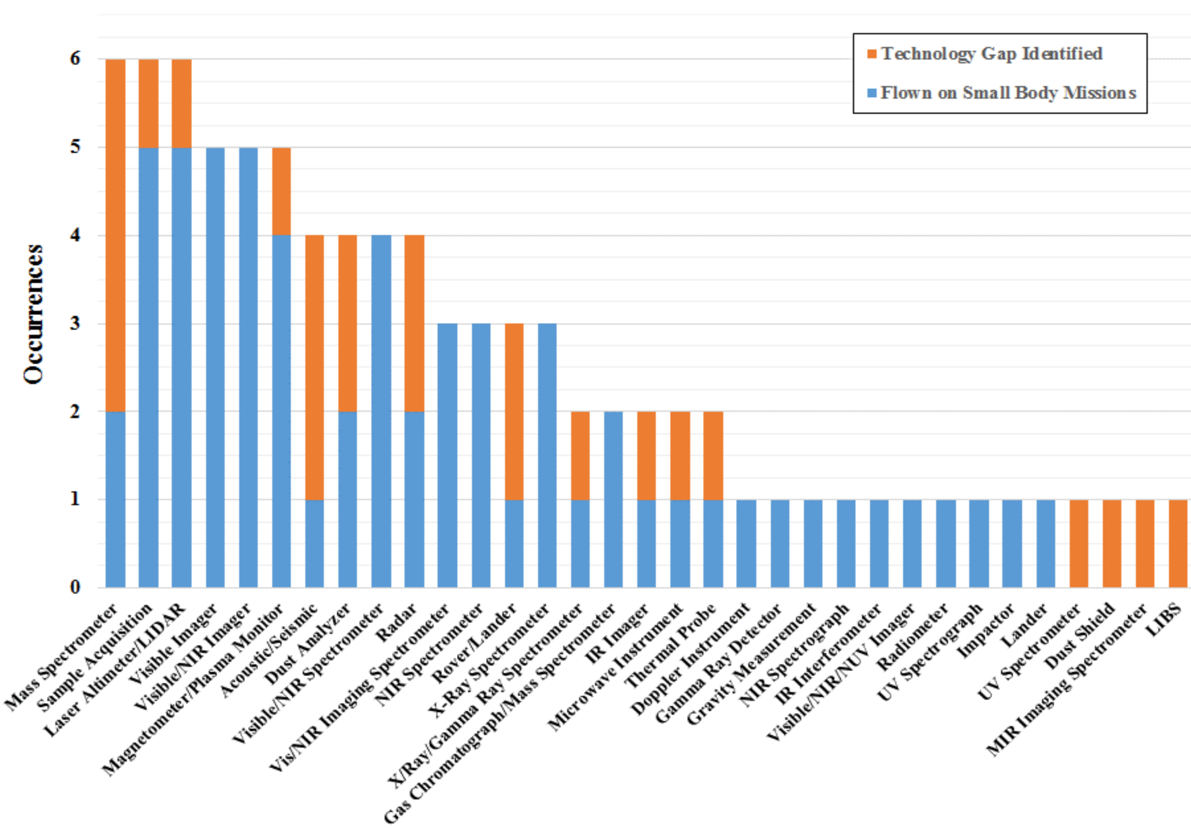

Figure 3: Initial assessment of available instruments and gaps to meet SBAG objectives.

From the preliminary assessment, a detailed look at the mission pull helped refine a list of needed instrument technologies for future small body activities. The prioritized recommendations are noted below.

Dust analyzer

An instrument is necessary for cosmic dust sample capture with a challenge to capture and preserve the samples at typical small body orbital velocities; less than 300s m/s for compositional analyses. The desired capabilities is to perform elemental composition and molecular special from sub micrometer grains. The state of the art is the European COSIMA instrument from Rosetta.

Small Body Lander System

There is a need for low-cost, even short duration, access to surface of small bodies for in-situ operations. The specific objectives would be a 10kg payload capacity and >8 hours of surface operations for <$10M applicable to future small body missions. The state of the art would be MASCOT and Philae.

Seismometer

Small body seismic science is a high priority for the community. Seismic science for small bodies can be accomplished through various techniques. Most techniques involve deployable systems, may include anchoring systems, and must have some network communications. New technology is required for packaging, delivery, and communication. A system demonstration should also be completed for various potential surface types. A seismic system development and demonstration is too costly for development under the standard solicitations for instrument development, but would have a high payoff for several small body targets answering science questions regarding internal structure and augment hazard mitigation simulations.

Initially an assessment is recommended for the design optimization of a small body seismometer. The assessment should include the optimum frequency and resolution comparison to radar technology capability. The desired capability is to measure mean dielectric properties, detect large scale structures and discern the interior of small bodies with better than 20m resolution. The state of the art is CONSERT.

Heterodyne Radiometer

There is need for a lower cost, mass and power sub millimeter heterodyne radiometer. Existing systems can achieve 100 kHz spectral resolution with 20kg and 43 watts of power, but viable paths exist to reduce the resources required by half to only 10kg and 20 watts of power while maintaining 100 kHz spectral resolution.

Laser Proximity Sensor

There remains a technology gap for smaller, lower cost and lower power landing proximity sensors applicable for small body approach and landing missions. The state of the art would be OSIRIS-Rex proximity operations sensors and radars for MSL with 30W, 30kg and $20M solutions, but increasing environmental capabilities or increasing range of 25W, 10kg and $10M solutions could enable infusion on lower cost missions.

Sample Acquisition Technology

As noted in the CAPTEM report and previous small body technology gap assessments, there are still a wide range of sample return technologies with insufficient maturity for low-risk implementation. Technology development is needed for surface manipulation, drilling or coring technologies, in-situ sample handling, hermetically sealing sample systems, systems to preserve stratigraphy, and environmental control of samples.

Radar Technologies

Radar technology investments are recommended, including a flexible radar, improved radar data processing software, and ground penetrating radar for landers and small body rovers. The flexible radar systems would likely include multiband solutions for penetration depths between meters to kilometers with resolutions from 10s of centimeters to meters. The SOA would include SHARAD or MARSIS, but few systems have high TRL at wavelengths >50cm and have a single band pass. SOA radar analysis options such as Seisware have limitations and the ability to perform tomography with mixed material types, including the extraction of dielectric properties for irregular objects is desired. Finally, there is a recommendation to develop ground penetrating radar technology to support science and human exploration objectives of subsurface profiling at depths of 100s of meters with 10s of centimeters resolution.

Small Sat Instruments

The capacities of very low cost small satellites continue to increase. SmallSats and CubeSats are demonstrating relevant communication, power, propulsion, etc. systems for future small body missions. Human exploration, science and potentially planetary defense objectives can benefit from CubeSats such as NEA Scout to flyby a small asteroid. A CubeSat may also offer a low-cost method to characterize accretion in low-Earth orbit. However, while technologies to improve capabilities of SmallSats are pursued through multiple programs throughout government, limited dedicated investments have been made to mature instruments most applicable to future small body Small Sat missions. SmallSat missions require unique investments as in most cases, some instrument capability or functionality must be reduced in order to meet the restrictive constraints of the SmallSat volume, mass and power limitations.

Prioritization Results and Sensitivities:

Systems Support Technologies

The baseline results for system support technology prioritization is provided in figure 4. However, understanding why the technologies are prioritized as they are and their sensitivities is also critical to recommendations. The technology with the highest benefit is the optical communication technologies. The optical communication payoff is driven by the increasing data anticipating for several future missions, but also the approach for the Near Earth Asteroid (NEA) survey telescope assumes sending back raw data sets rather than on-board processing of the data and only sending back detection ephemeris data. The ST-8 solar array performance is ranked high because low mass solar arrays are applicable to such a wide array of missions, but also because a large number of missions benefit from electric propulsion, increasing the value of the solar arrays. Another priority gap for small body missions is improved small body navigation technologies including high accuracy star trackers, smaller star trackers, optometric data for navigation, proximity operations development and even pinpoint small body landing for human missions to the moons or Mars, the crewed asteroid mission and robotic landing and sample return missions. Propulsion investments are also recommended for low power and low power iodine technologies for enabling lower cost missions, green propulsion technologies to reduce mission life cycle cost and the completion of the higher power Hall thruster required for the Asteroid Redirect Mission.

Rank	Technology Name	Rank Change	
1	Optical Communications Technologies	0	0.992
2	Lightweight moderate power solar arrays (ST-8)	0	0.267
3	Autonomous High-Accuracy Star Tracker	0	0.132
4	Optimetric Data for Navigation	0	0.132
5	Miniature, High-Accuracy, Multi-Function Star Tracker	0	0.132
6	Long-Life Lithium (Li)-Ion Secondary Batteries	0	0.124
7	Miniature Hall Thruster / Iodine Hall	0	0.109
8	Primitive Body/Lunar Proximity Operations andPinpoint Landing	0	0.107
9	Small-Body/Microgravity Navigation	0	0.105
10	Electrospray Propulsion	0	0.067
11	Hall Thrusters / Electric Propulsion	0	0.065
12	Prototype software and algorithmic framework to support rapid explorati	0	0.058
13	Reliably Retractable Solar Arrays	0	0.051
14	25-150 kWe-class Solar Array Structures	0	0.041
15	Higher Thrust Green Propellant	0	0.037
16	High Rate Spacecraft Guidance, Navigation, andControl (GN&C)	0	0.029
17	High-Specific-Energy, Human-Rated Lithium (Li)Secondary Batteries	0	0.026
18	SLS Technologies	0	0.023
19	High-Temperature, High-Voltage Capacitors	0	0.018
20	Onboard Real-Time Fault Detection, Isolation, andRecovery (FDIR)	0	0.018

Figure 4: Baseline technology priorities.

Technology advocacy might be associated with mission directorate funding sources. Of interest is the potential for change in priorities if science is prioritized over human exploration or planetary defense, or planetary defense first, etc. Note that some science is achieved from human exploration missions, so eliminating all human exploration objectives does not completely eliminate the benefit of a human exploration mission as a whole. Figure 5 indicates the priority shift by emphasizing science. The top 10-20 (out of more than 400) technologies assessed generally stay the same regardless of the prioritization placed on the overall objectives. For example, optical communication only drops to #2 if science objectives are the priority, and solar panels which are enhancing to nearly every mission becomes #1. If human exploration or planetary defense objectives are the highest importance, the optical communication system become #1 again because the data intensive survey mission approach achieves key objectives for finding human exploration targets or potential impact threats respectively.

Rank	Technology Name	Rank Change	
1	Lightweight moderate power solar arrays (ST-8)	1	1.000
2	Optical Communications Technologies	-1	0.959
3	Primitive Body/Lunar Proximity Operations andPinpoint Landing	5	0.538
4	Small-Body/Microgravity Navigation	5	0.530
5	Miniature Hall Thruster / Iodine Hall	2	0.444
6	Hall Thrusters / Electric Propulsion	5	0.298
7	Prototype software and algorithmic framework to support rapid explorati	5	0.284
8	Reliably Retractable Solar Arrays	5	0.249
9	Autonomous High-Accuracy Star Tracker	-6	0.227
10	Optimetric Data for Navigation	-6	0.227

Figure 5: Increased science weighting.

Technologies below the top 10 can change significantly based on the mission class trade. For example, if smaller class missions are prioritized over large missions, technologies that improve packaging and cost move up in the priority. Technologies such as Space Launch System and human extravehicular activity technologies increase in priority if the weighting are placed on higher cost missions.

Rank	Technology Name	Rank Change	
1	Optical Communications Technologies	0	1.000
2	Lightweight moderate power solar arrays (ST-8)	0	0.240
3	Long-Life Lithium (Li)-Ion Secondary Batteries	3	0.121
4	Autonomous High-Accuracy Star Tracker	-1	0.112
5	Optimetric Data for Navigation	-1	0.112
6	Miniature, High-Accuracy, Multi-Function Star Tracker	-1	0.112
7	Miniature Hall Thruster / Iodine Hall	0	0.099
8	Primitive Body/Lunar Proximity Operations andPinpoint Landing	0	0.075
9	Small-Body/Microgravity Navigation	0	0.073
10	Electrospray Propulsion	0	0.057
11	Hall Thrusters / Electric Propulsion	0	0.033
12	Prototype software and algorithmic framework to support rapid explorati	0	0.023
13	Higher Thrust Green Propellant	2	0.022
14	Reliably Retractable Solar Arrays	-1	0.017
15	Onboard Trajectory Planning and OptimizationAlgorithms	8	0.011
16	Cold Atom Lattice Optical Clocks	25	0.010
17	25-150 kWe-class Solar Array Structures	-3	0.009
18	Landing Dynamics Prediction Method	17	0.008
19	Fast Light Optical Gyroscopes for Precision InertialNavigation	15	0.008
20	Deployable Antennas	29	0.006
21	Embedded Optical Tracking for Spacecraft Navigation	44	0.005
22	Reduced-Cost Photovoltaic Blankets	26	0.002
23	High Specific Energy and Power, Wide TemperatureSupercapacitors	29	0.002
24	High-Specific-Energy, Human-Rated Lithium (Li)Secondary Batteries	-7	0.002
25	Battery Physics-Based Models	-3	0.001

Rank	Technology Name	Rank Change	
1	Optical Communications Technologies	0	1.000
2	Lightweight moderate power solar arrays (ST-8)	0	0.533
3	Autonomous High-Accuracy Star Tracker	0	0.437
4	Optimetric Data for Navigation	0	0.437
5	Miniature, High-Accuracy, Multi-Function Star Tracker	0	0.437
6	High Rate Spacecraft Guidance, Navigation, andControl (GN&C)	10	0.327
7	Hall Thrusters / Electric Propulsion	4	0.308
8	SLS Technologies	10	0.279
9	25-150 kWe-class Solar Array Structures	5	0.274
10	Small-Body/Microgravity Navigation	-1	0.271
11	Primitive Body/Lunar Proximity Operations andPinpoint Landing	-3	0.264
12	High-Temperature, High-Voltage Capacitors	7	0.241
13	Onboard Real-Time Fault Detection, Isolation, andRecovery (FDIR)	7	0.241
14	Human EVA Sample Storage and Curation, Low Mass, Low Power	7	0.241
15	Prototype software and algorithmic framework to support rapid explorati	-3	0.213
16	Reliably Retractable Solar Arrays	-3	0.197
17	Miniature Hall Thruster / Iodine Hall	-10	0.188
18	Dynamic Simulation	6	0.183
19	EVA - Space Suit Technologies	6	0.183
20	EVA Power, Avionics, and Software	6	0.183
21	Long-Life Lithium (Li)-Ion Secondary Batteries	-15	0.173
22	Very High-Voltage, High-Power Semiconductors	7	0.167
23	High-Specific-Energy, Human-Rated Lithium (Li)Secondary Batteries	-6	0.161
24	Liquid Oxygen (LO2), Liquid Hydrogen (LH2) Reaction and Attitude Control	6	0.151
25	Ground-Based Fault Detection, Isolation, and Recovery(FDIR)	6	0.150

Figure 6: Impact of mission class weighting for small (left) and large mission bias (right).

Also, of interest is the Pareto front for investments; though not necessary the highest priority. Some investments are may be enabling for a few missions, while others may only be slightly enhancing for nearly every mission. Funding priorities must consider the likelihood a new technology will be infused in future missions versus a required technology for potentially only one or few missions. Figure 7 shows the priority of investments relative to infusion potential and impact. Ideally investments would be for the top-right quadrant, technologies that are enabling and would be used on nearly every mission. An example technology might be solar cells if they did not yet exist. However, technologies both critically enabling and enabling for nearly every mission are already available. The technology needs remaining are either focused enabling investments for specific or few missions (top left quadrant) or enhancing technologies for a wide range of missions. (bottom right quadrant). Most technologies fall into the category of enhancing and only for a few missions (bottom left quadrant) and are unlikely to receive technology advocacy. This may be one of the reasons that there has been little success in sufficient funding to small body proximity operation systems, it is assumed to be a go-do activity and existing systems may be sufficient for most small body missions; though additional investments are needed, it can be difficult to advocate that the community cannot perform small body proximity operations after multiple rendezvous, landed and sample return small body missions.

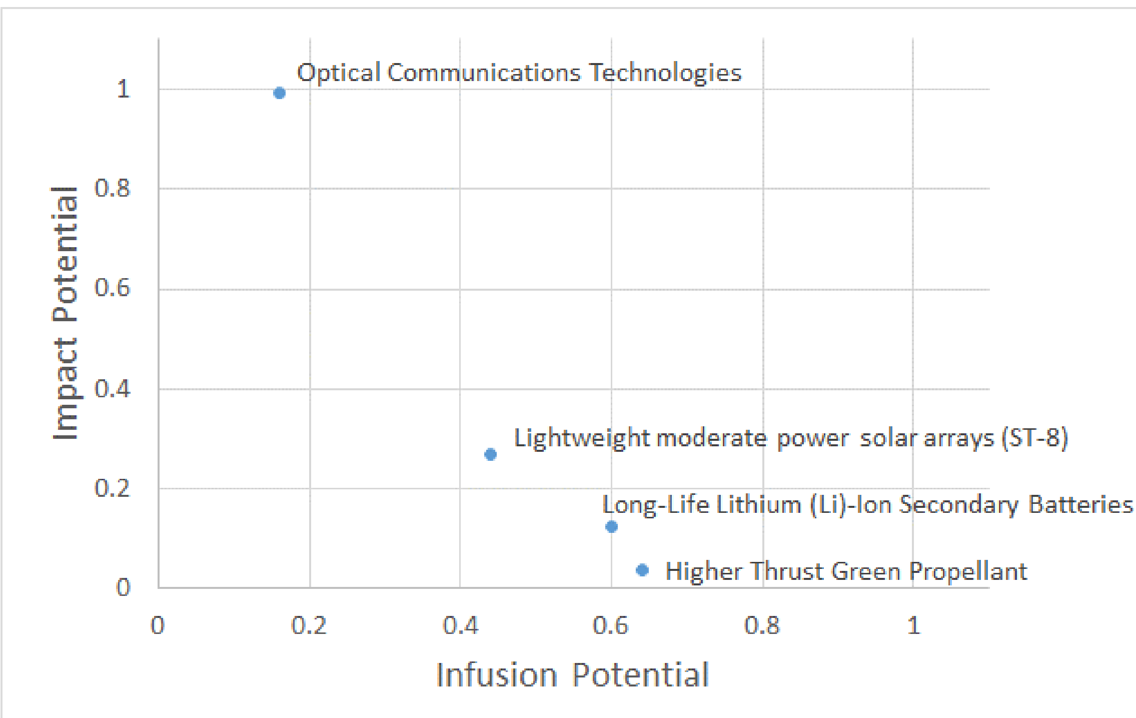

Figure 7: Pareto front of technology needs.

Instrument Technologies

As illustrated in figure 3, there is a large suite of instruments already available for a wide range of small body missions. The priority recommendations include advanced detectors for survey missions, including missions such as space based Near Earth Asteroid survey, Kuiper belt body survey space based or balloon based and ground survey assets. This specific technology recommendation is based on the survey's value to planetary defense, solar system formation and human target identification goals and objectives. Following the survey detectors, landing proximity sensors, a long-wave infrared camera identified for human exploration mission needs, cosmic dust acquisition, orbital radar, deep drilling, lander payload, imbedded instruments, small satellite instrument and seismometer instrument technologies.

Rank	Instrument Name	Rank Change	
1	Next Gen IR / Vis Low-Noise Detectors for Survey	0	1.000
2	Landing Proximity Sensor	0	0.140
3	Longwave Infrared (LWIR) Camera	0	0.095
4	Cosmic Dust Sample Acquisition Technology	0	0.061
5	Flexible orbital radar for subsurface sounding	0	0.055
6	Deep drill / Coring technology	0	0.045
7	Small Body Lander Payload	0	0.043
8	Drill Embedded Physical Instruments (Resistivity,Thermal, Shear, etc.)	0	0.042
9	General SmallSat Instrument Investments	0	0.041
10	Seismometer	0	0.036
11	ISRU Penetrometers, Shear Gauges, Compaction, DensityInstruments	0	0.035
12	ISRU Regolith Flow Instruments	0	0.035
13	Mass Spectrometer Electronics Reduction	0	0.031
14	Mass Spectronmeter Detector System Resource Reduction	0	0.031
15	Software for radar data analysis	0	0.024
16	Instruments to Measure Chemical Compositions	0	0.020
17	Drill Embedded Chemical Instrument – Laser InducedBreakdown Spectrosc	0	0.017
18	Drill Embedded Chemical Instrument – Neutron Spectrometer	0	0.017
19	Ground Penetrating Radar for landers/rovers	0	0.015
20	Submillimeter Heterodyne Radiometer	0	0.012
21	Gamma Ray Instrument Technologies - Lander	0	0.009
22	Fluid process control technology	0	0.007
23	Gamma Ray Instrument Technologies - Orbiter	0	0.005
24	In-situ X-ray micro imaging technology	0	0.003
25	Rugged Laser for Landers	0	0.003

Figure 8: Baseline instrument priority recommendations.

The need for instruments for small body CubeSat and SmallSat missions is well documented for capability push. There are limited instruments available that fit within the CubeSat form factor or that are optimized for reduced mass, power and volume while sacrificing performance for the enabling potential. However, there are few design reference missions for CubeSats or SmallSats that highlight the potential for these lower cost missions to augment or make progress towards the Goals and Objectives for the Exploration and Investigation of the Solar System's Small Bodies. A SmallSat (ESPA Class) DRM completed highlighted the potential to approach Discovery class science with significant cost reduction. It is recommended that additional mission studies be completed to better understand the capability of cost enabled low cost missions to meet SBAG objectives and generate the appropriate mission pull for specific instrument prioritization of SmallSat instruments. Cameras, spectrometers, miniaturized avionics, advanced packaging technologies, etc. are desired for future CubeSat missions. DRMs are desired for more focused recommendations. For example, if the most viable missions with meaningful progress towards the stated goals and objectives are low velocity flyby missions, then perhaps dust analyzers for the applicable velocities may become a priority.

Summary:

In summary, a method has been developed for a traceable prioritization of general technologies and instruments to meet the "Goals and Objectives for the Exploration and Investigation of the Solar System's Small Bodies." The technologies that are both critically enabling and broadly applicable are already available to the community. Therefore, remaining investments are generally either enabling for specific mission implementations or only enhancing for broadly applicable technologies. Of notable interest is that the scoring and weighting has minimal impact to the highest priority technology recommendations. Outside of the top 10 technologies, prioritization becomes more dependent on the mission class and/or goal weighting of science, human exploration or planetary defense. The priority technology recommendations for general systems include optical communication systems, high performance solar arrays for moderate power, improved guidance, navigation and control systems, higher performance batteries, low power and low power iodine electric propulsion, proximity operations and pinpoint landing technologies and completion of the high power Hall thrusters.

For instrument technologies, again the SBAG community is fortunate in that a suite of instruments already exists for a wide range of future small body missions. Most of the recommendations for technologies are either high value instruments for specific missions or enhancing investments for incremental improvements in performance or reduction in resource requirements (mass, volume, power and cost). The priority technology recommendations for instruments include survey detectors, landing proximity sensors, a long-wave infrared camera identified for human exploration mission needs, cosmic dust acquisition, orbital radar, deep drilling, lander payload, imbedded instruments, small satellite instrument and seismometer instrument technologies.

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