Small Body Technology Roadmap

Executive Summary: The planetary science of small bodies includes ground observations and missions to fly-by, rendezvous, and return samples from a diverse set of targets. Small bodies include asteroids, comets, small satellites, dwarf planets, centaurs, trans-Neptunian objects, and interplanetary dust. These targets offer great diversity over a wide range of heliocentric locations, however; many have similar characteristics that allow for a practical assessment of near-term technology needs. The highest priority needs include a variable focus imager, a high resolution topography instrument, affordable electric propulsion, and a large number of sample return supporting technologies. An initial roadmap of development for small body missions in provided below.

I. Introduction

This document is to serve as the initial start of an evolving technology development roadmap for small body mission instruments and systems to allow maximum science return. The missions of interest are for observations, fly-by, rendezvous, landing, and sample return from asteroids, comets, small satellites, dwarf planets, centaurs, and trans-Neptunian objects. Small body missions are diverse both in the type and class of viable missions, but also in the broad range of celestial location. Though the diversity is great, most small body mission instruments and system requirements are broadly applicable over the range of missions without overly cumbersome unique instrument requirements one would expect trying to encompass in-situ environments and science priorities at the larger bodies of planets and moons.

The original approach for developing this technology roadmap for small body missions was to develop an all inclusive science traceability matrix for all classes of small body missions, specify the instrument/systems requirements to enable the science return, identify state-of-the-art (SOA) capabilities, and advocate technology development to fill the requirements gap. However, after progressing with the science matrix, it was determined that the majority of instrument/system requirements can be met with SOA options with only engineering modifications and in general were enhancing and not enabling technologies. Instead, the technology needs identified below were based on science community input for clear technology gaps, preferably with multi-mission applicability. Technologies are identified by requirements and capabilities only and not specific solutions that have been institutionally development. Technology prioritization was then completed based on broad applicability, science return benefit, and likelihood of mission infusion. The initial roadmap is consistent with recent decadal survey recommendations.[1]

II. Technology Needs

The focus of the technology needs described below is on mission capabilities or science gaps that can be closed with technology development and/or system demonstration. However, in many cases, enhancements to SOA options can have significant science return. For example, a SOA instrument with reduction in power, mass, and volume is enhancing and desirable for any mission, but it can also be enabling for some missions that have limited performance to the desired target; e.g. Centaur Reconnaissance. There is significant payoff potential for crosscutting technologies than can reduce the power, mass, volume, and cost of existing capabilities.

One of the strengths of small body missions can also be one of its weaknesses; the fact that small body missions are well suited for Discovery and New Frontiers class missions. Because small body missions are well suited for competed missions, there are limited avenues for mission specific technology development analogous to the Mars Technology Program for Mars missions, yet limited time, budget, and risk tolerance for dedicated technology development after mission selection, as typical in a flagship class mission.

A. Power Systems

The decadal survey noted the two largest roadbloacks for primitive body missions are power and propulsion. All space missions require power systems. A small body mission, in general, does not have intrinsically unique power requirements. However, small body missions under consideration include several potential electric propulsion missions, lander missions, and sample return missions. These types of missions can place large burdens on the power system, and a large premium on specific power of solar array and battery technologies.

1) Solar Power Systems

It is expected that the power source for the majority of small body missions will be solar power systems. Today's state-of-the-art (SOA) solar power systems have cell efficiencies of 28% and resulting integrated specific powers of 100-120 W/kg; the Dawn array is 80W/kg. While improvements in solar array technology are likely enhancing to small body missions, advancements are not typically enabling for the majority of targets. 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. Regardless, large investments in solar array cells and packaging are made on behalf of commercial, DoD, and other NASA missions. Because SBAG missions can leverage outside investments, and there are no unique power requirements, the small body technology roadmap will rely on external sources to provide the available solar power systems. Of highest interest for advocating solar array technology development for SBAG, especially for relatively high power missions will be large (~6m) Ultraflex arrays.

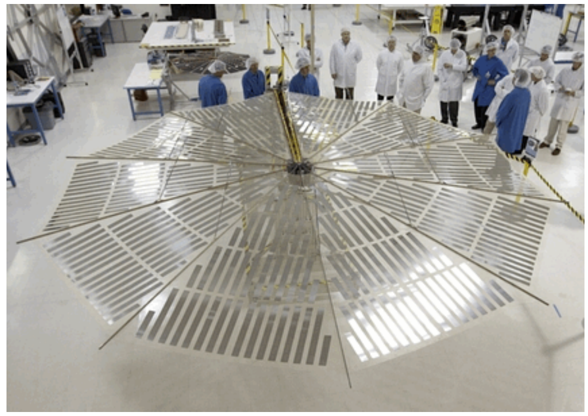

Figure 1. ST8 UltraFlex Array Structure.

UltraFlex arrays have shown packaging and specific power characteristics well suited for SBAG missions. 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 continuing Orion (MPCV) 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 system still carries risk and high first use costs until flight validation or additional ground testing can be completed. Small body missions would benefit from the decadal survey recommendations to mature the UltraFlex technology for planetary science missions.

2) Radioisotope Power Systems (RPS)

Because all deep space missions, whether small body or outer planets, are enabled by the availability of radioisotope power systems, they must be included on any technology development roadmap. The recent Discovery selections included two out of three ASRG missions and one was a small body mission to a comet. It is unknown if future Discovery missions will be allowed to propose the use of RPS, but if so; it will be a valuable option for several small body science opportunities. Based on the decadal survey, the only small body missions within New Frontiers are the Comet Surface Sample Return (CSSR) and the Trojan Tour and Rendezvous missions. The CSSR mission study did not require the use of an RPS, though it might simplify surface operations. A Trojan / Centaur reconnaissance mission would need an RPS. Based on JUNO, it may be possible for a Trojan only mission to be completed using solar power; though the decadal survey results baselined an ASRG.

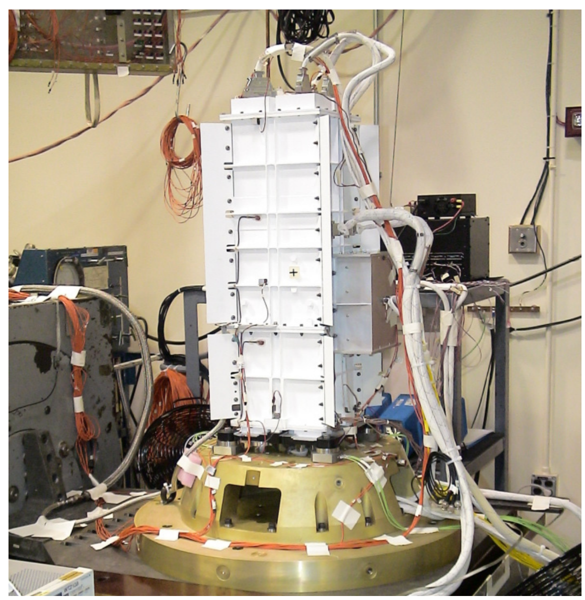

Figure 2. EM ASRG during Vibration Testing.

a) ^{238}Pu Availability

There is a concern regarding the availability of ^{238}Pu for the general purpose heat source (GPHS) necessary for any RPS. With the cancellation of manned missions' requiring RPS units, the availability of ^{238}Pu for NASA science missions is currently sufficient for the two ASRGs offered for the Discovery 2010 solicitation and the six MMRTGs that were baselined for the Jupiter Europa Explorer (JEO) mission. Because of the need for radioisotope power for at least a small body Trojan Rendezvous and Tour mission, there is a requirement to either restart ^{238}Pu production or purchase the material from foreign sources or both. Alternatively, successful ASRG risk reduction may supplant the MMRTGs for JEO and free up ^{238}Pu for future missions. The decadal survey went as far as to state that JEO should baseline the ASRG now; alleviating the demand of ^{238}Pu.

b) Stirling Radioisotope Generators

Based on both internally funded and the externally funded Discovery Scout Mission Capabilities Enhancement (DSMCE) studies, the ASRG has been shown to offer sufficient performance for missions of interest in the near term. However, the ASRG must be sufficiently matures; potential missions will benefit from risk reduction. The SBAG community is continuing to advocate for ASRG life testing and opportunities to gain flight experience.

Long-term planning has included studies for a larger, ~500W, ASRG building block; the SRG-500. The larger building block lends itself well for high AU rendezvous missions using Radioisotope powered Electric Propulsion (REP). Missions evaluated showed that a larger ASRG 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 SOA ASRG, but many high interest target, e.g. Chiron, Chariklo, etc., require an improved specific mass performance. A long term technology need is the higher specific power RPS with an integrated system performance of > 5 W/kg; analogous to an ASRG with a specific power of 9-10 W/kg. The RPS program is actively investigating in technologies to improve the system alpha, but even with dedicated development; an SRG-500 is not expected to be available for mission implementation this decade. If the community prioritizes an REP mission in the early 2020s, such as a centaur orbiter, a larger RPS building block development needs to be initiated early.

c) Component Level Technologies

The RPS program is continuing to make advancements in component level RPS technologies. These technologies include thermophotovoltaic (TPV) cells, advanced Stirling duplex, thermoelectrics, etc. None of these technologies are expected to be unique to small body missions, though they may help yield the desired specific power for future missions.

3) Secondary Power Systems

The potential for lander and sample return missions can quickly increase the demand on secondary power systems. Depending on the surface operations, surface location, body rotation, etc., the battery system may have challenging requirements. Concept studies that have been completed and they are able to close the design reference missions using SOA battery systems. Obviously, missions could benefit from improved battery system specific power, but it has not been shown to be a critical driver beyond SOA capabilities.

B. Propulsion Systems

Propulsion systems are fundamental to space missions. The propulsion systems can be very minimal, simple monoprop, bi-prop, or electric propulsion dependent on the mission class, target, and objective. In general, the propulsion systems required for small body missions can be leveraged from commercial, military, or existing NASA programs. Additionally, small body missions do not have unique requirements that are not also met by propulsion systems for general NASA science missions. However, because of the lack of appreciable gravity wells, the benefits of electric propulsion systems can be significantly more beneficial than for larger gravity well targets.

1) Chemical Propulsion

It is expected that a large number of the missions to easier small body targets to reach can be completed using a state-of-the-art chemical propulsion systems. Higher chemical ΔV missions may benefit from the recent Advanced Material Bipropellant Rocket (AMBR) engine, shown in figure 3, but additional chemical propulsion technology development efforts, e.g. pumps, exotic propellants, advanced monopropellants, etc., are not expected to yield significant benefits to solely justify their investment. Ongoing military investments in advanced monoprops may yield mission benefits, but the requirement and justification does not exist for high priority investments in chemical propulsion systems for small body missions.

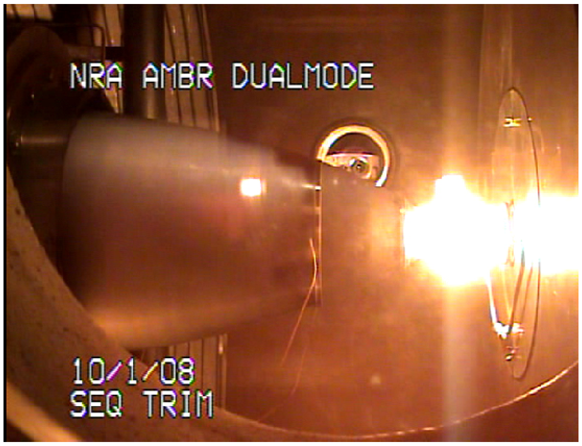

Figure 3. AMBR engine during hot-fire test.

2) Electric Propulsion

It is not surprising that the two NASA missions to use electric propulsion, the DS1 demonstrator and the Dawn Discovery missions, are both small body missions. Without an appreciable gravity well, small body missions can greatly benefit from the use of electric propulsion. 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 Diemos sample return, etc. are all enabled through the use of electric propulsion.[2] Multi-Trojan rendezvous, centaur rendezvous, and TNO reconnaissance are enabled by radioisotope powered electric propulsion.

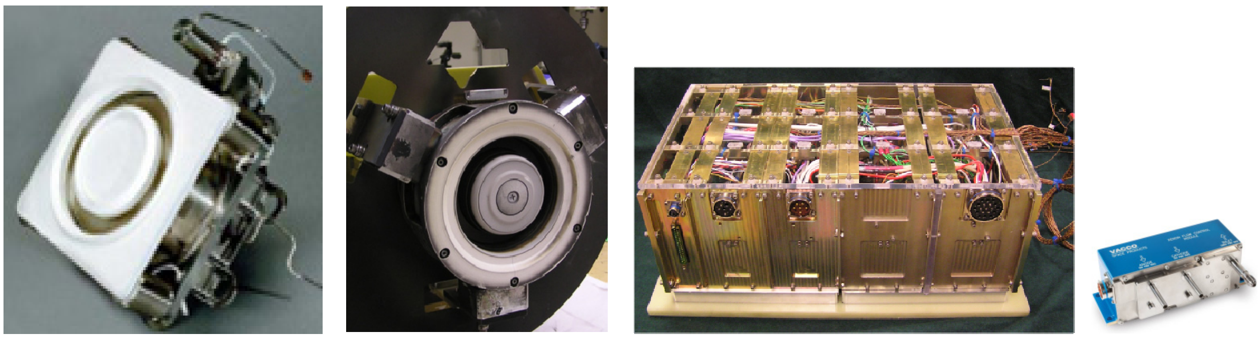

Figure 4. From left to right, BPT-4000 thruster, HiVHAC, bread-board Hall PPU, and VACCO feed system module.

a) Low-cost Electric Propulsion System

The NEXT ion propulsion system is nearing completion and has been incentivized during recent New Frontiers and Discovery 2010 mission solicitations. NEXT is cost viable for Discovery class missions, but only with additional SMD contributions for the first user; the true first use cost is nearly double typically allocated for a discovery mission spacecraft propulsion system. The enabling nature of the electric propulsion system may justify the cost, but there are alternatives that exist for lower cost electric propulsion options.

As far back as 2004, it was determined that Discovery class missions are well suited for higher thrust Hall thruster systems. During the Refocus Study, to determine the optimal propulsion system for competed PI-led missions, a Hall thruster system was recommended to potentially cost enable electric propulsion for Discovery Class missions.[3] Additional studies have continued to show the potential for Hall thruster based systems, typically either the BPT-4000 or the HiVHAC, to reduce cost approaching that of a chemical propulsion system. Because of the flight opportunities available through the Discovery and New Frontiers program, and the wide range of small body missions enabled by electric propulsion, a low-cost Hall system continues to demonstrate broad applicability and high likelihood of mission infusion once matured.

The BPT-4000 Hall thruster system has been flown for GEO operation, but requires a regulated bus or power processing unit (PPU) update for variable input voltage. The HiVHAC system remains relatively immature with an engineering model thruster and bread-board power processing unit. A PPU development for either system is not expected to receive funding until at least 2012. Ideally, development would occur to advance a Hall thruster system for a low-cost electric propulsion system to be matured for infusion during the next competed mission opportunity.

b) Radioisotope Electric Propulsion (REP) System

The use of electric propulsion powered by radioisotope power systems is not a new concept, but the system alpha of the Advanced Stirling Radioisotope Generator is now sufficient for viable REP missions.[4] While there are limited missions that will benefit from a qualified REP system, Centaur orbiters and multi-Trojan landers have been shown to be enabled by the technology. If the small body community wishes to have Centaur orbiter and/or tour the Jupiter Trojans, REP technology is required. Because of the low-power nature of the system, a system development is a relatively low cost investment, however; the duration of life testing would be several years due to the lifetime requirements of the

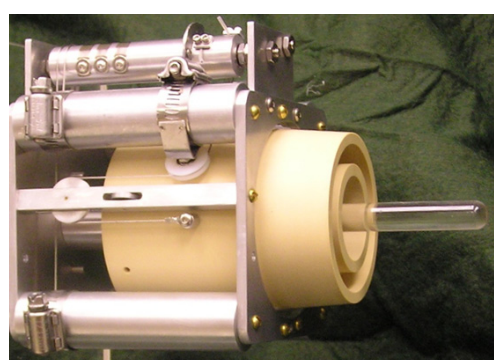

Figure 5. 600 Watt REP Hall thruster model.

individual thrusters. REP system development must be initiated shortly to be available for mission opportunities several years from now. Estimates, call for sustained funding just over $1M per year, but for over 10 yrs before the life can be sufficiently demonstrated. Figure 5 is a concept under development with Busek through the NASA SBIR program to increase the lifetime of their BHT-600, a 600W Hall thruster. If successful, the Busek Hall thruster has demonstrated sufficient performance to close the REP mission to several high science interest targets. The thruster is the highest risk element of the system; the PPU will be relatively low power and voltage compared to SOA primary ion propulsion systems. The decadal recommend developing the technologies to enable a centaur or Kuiper belt object rendezvous in the next decase.

3) Secondary Propulsion

In addition to primary interplanetary propulsion systems, some small body missions have unique requirements for additional propulsive capability during near-body operations. Maneuvering around small body systems may benefit from higher performance secondary propulsion systems. There may also be a desire to use propellants that will not produce combustion products that could interfere with instrument readings for contaminate the landing or sample sites. A relatively high performance cold gas thruster or novel propulsion system may be of interest for counterforce engine to maintain surface contact during landing and sample return operations.

C. Remote Sensing Instruments

Several small body missions have been completed recently or ongoing including: Rosetta, Dawn, New Horizons, Hayabusa, Stardust, Genesis, NEAR, Deep Impact, etc. These 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.

1) Variable Focus Distance Imager

Commercial advances in imaging technology have made high resolution images available at variable focus distances. This technology involves a moving part in the imager, but can have significant benefits to a remote sensing mission in both science return and simplified mission operations. Images can be made at preferred orbits. In many cases gray scale would be sufficient for science return, and sub-cm resolution should be achieved; mm resolution is desired for this technology. A variable focus distance images with this level of resolution and autonomous focusing can be used for both spot (meter scale sections) and global imaging. Combining mm scale resolution with a method of disturbing the surface, e.g. an impactor, can also yield significant science. This instrument can have broad applicability for all small body missions and would have a very high likelihood of technology infusion if the technology can be matured and associated risks retired. It is highly desirable for a variable focus distance imager to be developed through at least Technology Readiness Level[5] (TRL) 6, with significant lifetime testing and system demonstration in relevant environments.

2) High Resolution Topography Instrument

High resolution topography is also a high priority for future small body missions. The instrument requirements are for both cm scale vertical and spatial resolution. There are multiple concepts under development to meet these requirements such as a scanning Light Detection and Ranging (LIDAR) instrument. This technology should be developed to TRL 6 prior to the next mission solicitation. A high resolution topography instrument has broad applicability to all small body missions and has a high likelihood of technology infusion if sufficient risk can be retired.

3) Low Speed Dust Detector / Analyzer

For small body missions, there will be opportunities to leverage dust analyzers other than during heliocentric transfers with high relative velocities. A relatively low speed dust detector / analyzer can provide significant information while performing proximity operations around a comet or asteroid. Projectiles can also be used to create dust ejecta for analyses.

D. In-Situ Instruments

The in-situ environments are not expected to differ significantly within the categories of asteroids and comets. Several instruments exist at various TRLs for in-situ analysis. In-situ analyses are high priority when critical scientific issues remain unresolvable from orbit and can be resolved at a lower cost than through sample return. In situ analyses of small bodies are needed to determine their elemental, molecular, isotopic, and mineralogical compositions. Related questions include identifying the sources of extraterrestrial materials that collide with Earth, and understanding correlations between asteroids and comets, surface geology, types of carbonaceous materials in cometary nuclei, and determining the range of activity on comets.[6]

1) Seismic System Demonstration

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 or penetrators, 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. The cost viability with near-term mission opportunities is unknown. The decadal recommended technology investment for a seismic mission in the following decade.

2) In-Situ Material Dating Instrument

Another in-situ measurement that can be very beneficial for small body missions is material dating. The ability to accurately date the surface and materials at various depths can help answer key questions regarding formation and evolution of the solar system. There are concepts currently under development, but technology investments are required for packaging an in-situ dating instrument for applicability on a PI-led class mission.

3) Surface Manipulators

Small bodies do not have the protective shield of an atmosphere. Consequently, micrometeorite and solar particle damage could have significantly altered the near-surface environment. To ensure analysis of unaltered material is obtained, access must be available to subsurface (>1cm?). Surface manipulator designs can vary significantly depending on the complexity and expected environment; ranging from rakes, drills, penetrators, etc. There is a need for investment in tools that can work in a near autonomous mode with a robotic arm or lander. This would increase the scientific value of samples analyzes, or later returned. These tools must be developed for extreme cold environments and to minimize the contamination/alteration of the samples during acquisition.

4) Compositional Analyses

The goals for solar system exploration can be partly addressed through compositional analyses of small bodies. In-situ analyses can be used to determine the elemental, molecular, isotopic, and mineralogical compositions. Related science questions including identifying the sources of extraterrestrial materials that collide (or will) with Earth, determining if there are correlations between asteroids and comets, determining surface geology, the types of carbonaceous materials, and the range of activity on comets. For asteroids, a goal of any in-situ analysis will also be to correlate asteroid groups to meteorite samples to fully leverage the terrestrial database.[5] Therefore compositional discriminatory measurements along, correlated to observed spectra, are of high value. For comets, with various periods of activity, the elemental composition should be determined over time and possibly depth and be supplemented with analyses of the O and H isotope compositions of solids and ices on the comet. Compositional analyses can also be used to indicate potential heat sources. Heritage compositional analyses instruments have varying heritage, but in most cases; require modifications for small body in-situ analyses.

E. Sample Return Technologies

Aside from large flagship missions, sample return missions are expected to be small body missions. There are a suite of sample return technologies that could benefit future small body sample selection, collection, confirmation, storage, and return. Also, many of the sample return technologies could benefit non-sample return missions by collecting samples for in-situ analyses.

It should be noted that the NASA Planetary Science Division of the Science Mission Directorate requested the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) identify critical investments to best reduce risk and cost for increasingly complex sample return missions over the next 20 years.[7] The key findings were that sample return from a variety of bodies can provide valuable insights in the origin and evolution of the solar system and representation an important component of NASA's overall solar system exploration strategy, sample return missions are relatively higher risk, cost, and complexity vs. traditional planetary science missions, there are technology linkages where technology development and investment can increase the rate of success and lower the overall cost of sample return missions, sample return technologies should be development through a dedicated technology program within the SMD for multi-mission application, the technologies should be advanced to TRL 6 targeting infusion on PI-led class missions, and the key common technologies included (potentially small body relevant): robotic arm, autonomous robotic capabilities, hard-land and sample preservation during landing, environmental control of sample containment, inert sample collection materials, sample collection and verification, robotic manipulation of sample for transition and transfer, and a variety of sample collections tills including drills and rakes. The CAPTEM report was taken under consideration and focused small body technology development requirements are provided below.

As the CAPTEM report recommended, sample return technologies has enough variation that it can easily mandate a standalone technology development program within NASA. This is due to the large number or interrelated technologies, but also the fact that only a few of the required technologies are sufficiently development to a point that major new efforts are not required. Many subsystem technologies have developed at least one technical solution to the point it has been published or used as part of a mission proposal. However, the community consensus is that significant development remains to be sufficiently mature to be proposed and evaluated as low risk. For the technologies described below, about half have at least one technical solution, but nearly all have limited or no heritage. Additionally, the limited number or applicable missions that have landed or attempted sampling from a small body further adds to the uncertainly of the conditions that any proposed future sampling mission with encounter. Note that technologies are only listed once although many are redundant across mission types. The technologies are listed by category, note whether potential solutions have been identified, and if significant investment beyond standard engineering development is required.

1) Sample Collection

A great deal of work at several research organizations has already been applied to the development of the sampling mechanism itself. The sampling technologies range significantly; driven by three key parameters:

1) Surface Characteristics – Mechanisms for loose regolith vary than those for solid rock
2) Time to take a sample – Touch-and-go limited to seconds vs. full landing
3) Desired Depth of the sample – Surface, a few centimeters, meters / core sample

While the institutional investments have matured technologies to various readiness levels, the proprietary nature and variability lends itself to significant expenditures with limited infusion opportunities. An integrated sample return technology program can ensure that a solution developed for sampling can interface with the solution for sample transfer and verification and the Earth return vehicle.

a) Flyby Sample Collection

In fly-by sample collection, samples are collected without touching the target surface. Flyby sample collection was demonstrated by Stardust and Genesis. In fly-by missions, a special collection device opens to collect particles; this is viable for comet tails or a small body with a surface disturbance to eject material to be captures. While flyby missions provide the lowest science return, they are also the simplest and only require technology for the sample collection, typically passive, and in some cases an impactor. The technology required for flyby sample collection is expected to be either minimal or unique requiring only a modification to a heritage system or limited technology infusion opportunity. If NASA decides to continue with additional flyby sample collection missions, an area for improvement is to minimize the interaction between the collection material and the samples. Developing more inert collection material will decrease the overall risk to the science goals of flyby sample return missions.

	Solution(s) Identified	Work Needed
Sampling mechanisms	✔	

b) Touch-and-Go

During touch-and-go sample return missions, the spacecraft briefly touches the surface of the body, collects the sample, and takes off either for another collection or return to Earth. This type of sample return is very practical for small body missions without the need for costly and complex descent and ascent systems. A touch-and-go mission can also minimize the need for anchoring or propulsion to hold the spacecraft in place during collection. The Hayabusa mission demonstrated the concept of a touch-and-go sample collection with a very low-cost and low-mass spacecraft, but failed to return macroscopic samples. The touch-and-go sample collection only allows limits sample preferential discrimination. Approaches should be investigated to maximize sample quantity, to increase the number of potential samples collected, to isolate individual samples, to verify sample collected, and to reduce system risk. The technologies identified include:

	Solution(s) Identified	Work Needed
Identifying landing/sampling site	✔	✔
Precision terrain-relative navigation	✔	✔
G&C sensors for landing/touch-and-go	✔	✔
G&C actuators for landing/touch-and-go	✔	
Propulsion for G&C actuators for landing/touch-and-go	✔	
Sampling mechanisms	✔	✔

Some of the sampling mechanisms with laboratory testing, shown in figure 6, include tethered or rigid mounted: sticky pads[8] to collect lose particles from the surface, counter-rotating cutters[9], brushes, or paddles, gas samplers[10] to draw loose material off the surface into a container, and projectile samplers[11] to drive projectiles into the target body and collect or trap the ejecta.

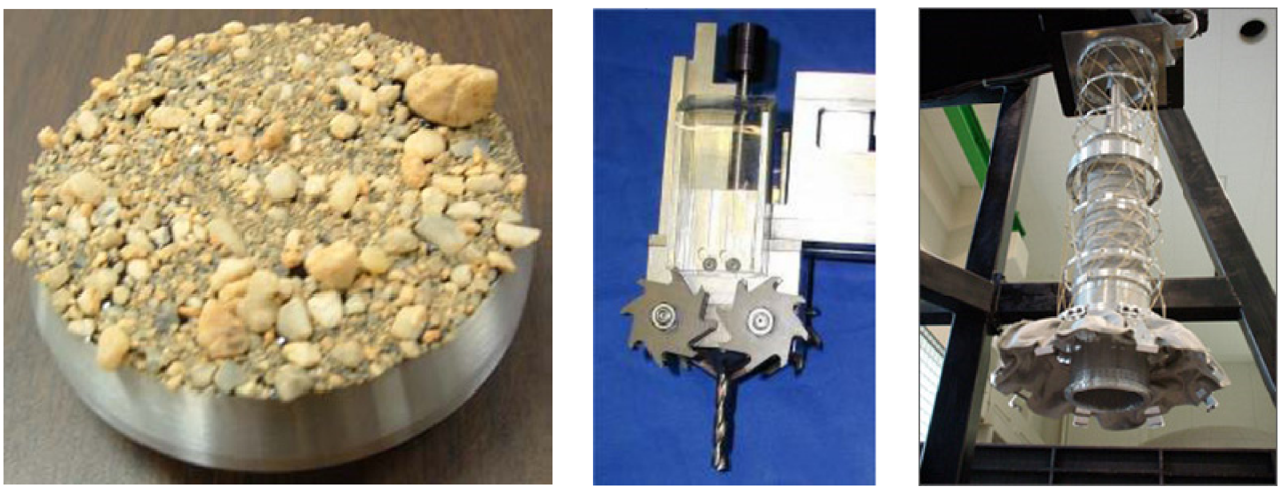

Figure 6. Sample collection mechanisms: sticky pad (left), counter-rotating cutter (center), and projectile (right).

c) Context Based - Surface Sampling

While surface collection is far simpler for small bodies than large bodies, the spacecraft must still safely land on the surface, land at the desired sampling location, and spend sufficient time at the location to obtain the desired sample. Also, many small bodies of interest have negligible gravity for performing collection and require some method of anchoring the spacecraft or operating a small propulsion system long enough to collect and preserve the sample for return. Anchoring techniques vary significantly based on the expected surface environment which may or may not be known until target arrival. Several solutions have been proposed for anchoring at a comet and some have been matured. Anchoring systems for rocky asteroids remain immature with no published demonstrated mature and reliable method for spacecraft anchoring.

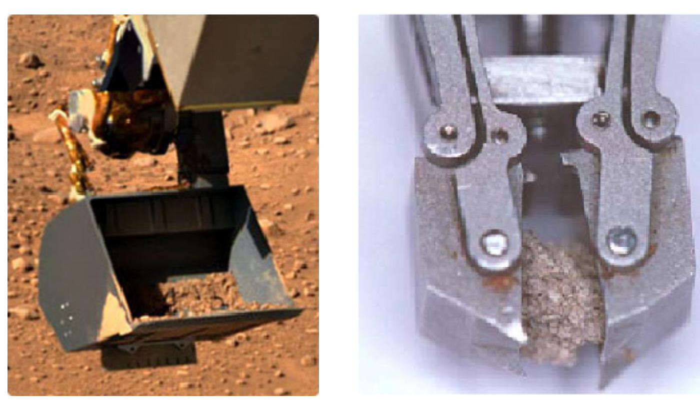

Figure 7. Surface sample collection mechanisms: Icy Soil Acquisition Device[12] (left), and pincher[13] (right).

Surface sampling also requires different sampling mechanisms than touch-and-go sample collection. While some of the methods may still work, if the spacecraft is landed, there will be a desire to select the highest valued samples and discriminately choose the returned regolith and rocks (e.g. outcrops). Sampling mechanisms have been developed to a point that several options are available mature enough for proposals including robotic arms with manipulators. Adding sensors, instruments, cameras, etc. to assist in sample collection and a small body arm could be developed applicable to classes of small bodies. However, additional capability can quickly increase the complexity and cost of a sampling mechanism.

	Solution(s) Identified	Work Needed
Sampling mechanisms	✔	
Autonomous operations	✔	✔
Anchoring techniques		✔
In cometary materials	✔	✔
In asteroids		

d) Coring / Drilling – Subsurface Sampling

Drill and coring technologies offer significant science potential looking for pristine subsurface samples to cores with stratigraphy maintained. Drilling and coring systems all require significant investments before applicability to small body missions. Investments have been made for low-gravity subsurface sampling with rotary or percussive systems, but none are raised to TRL 6. Technologies gaps remain for 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 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.

	Solution(s) Identified	Work Needed
Subsurface Sampling	✔	✔
Subsurface core sample	✔	✔
Maintain stratigraphy		✔
Drill or Worm Technology	✔	✔
cm depth	✔	✔
< 2m depth	✔	✔
> 2m depth	✔	✔
> 20m depth (Nucleus Sample)	✔	✔

3) Sample Confirmation

Assuming the vehicle has the capability for multiple collection attempts, it is highly desired to perform some assessment to confirm a sample has been obtained and ideally verify that the sample contains the material of interest; not all samples are of equal value.

	Solution(s) Identified	Work Needed
Sample verification/confirmation	✔	✔
Visible	✔	
Mass	✔	✔
Chem or physical property		✔
Confirm ice content		✔

4) Sample Transfer and Environmental Control

While the environmental control for the sample return is often discussed for the transit back to Earth, during the Earth Entry, Descent and Landing (EDL), and during transit to the curation facility, for some scientific goals, environmental control must also be maintained during the sampling process until the sample can be placed in the return capsule. Mechanisms add significant complexity and must be developed to high maturity for passing the collected sample to the return capsule. For comets, and the cryogenic sample return, thermal control will be desired throughout the sequence from collection to encapsulation. For the cryogenic nucleus sample return, the sample must transfer from the comet nucleus to the capsule without contamination or significant heating while in contact with the spacecraft; a significant development effort.

The ultimate sample containment vessel should be constructed from materials that do not contaminate the samples, allow samples to be isolated from one another, manipulated or even removed and discarded, be adaptable for a variety of missions and sample types, have the capability of being sealed without contaminating samples, and have a common interface with the Earth Entry Vehicle. Second generation containment vessels would be upgraded for environmental control and monitoring.

	Solution(s) Identified	Work Needed
Transfer from sampler to return capsule	✔	✔
Sample encapsulation	✔	✔
Thermal control for comet sampling		✔
Maintain sample cryogenic		✔

5) Entry Vehicles

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. The planetary science division has already initiated investments into an MMEEV.[14] Beginning from a single design concept ensures maximum commonality and feed-forward for all MMEEV users. By leveraging common design elements and technology development, this approach could significantly reduce the risk and associated cost for all sample return missions leveraging the MMEEV concept.

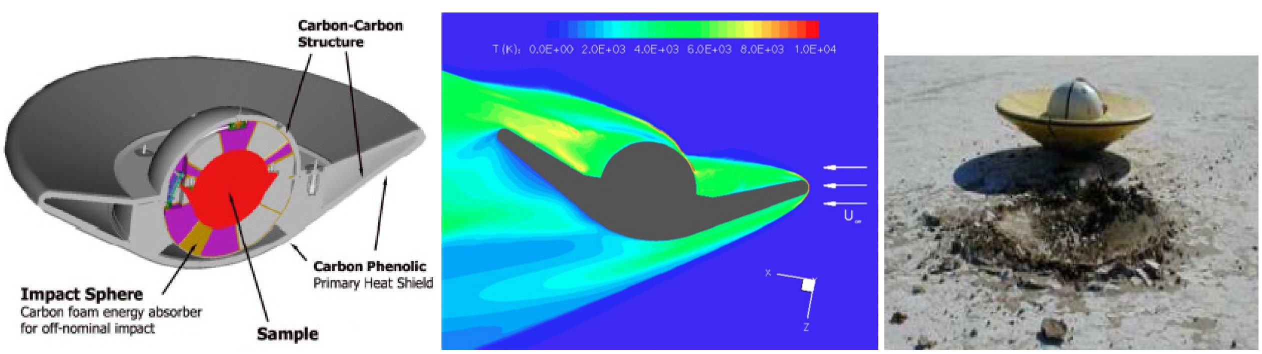

Figure 8. Concept design, CFD analysis and test model of the MMEEV.

The MMEEV concept is based on the Mars Sample Return (MSR) EEV, shown in figure 8, design originally developed at NASA LaRC in 1999-2001 and continued from 2001-2004 through focused technology development activities including impact attenuation, sample containment, and aerodynamics performance. The system is driven by probabilistic risk assessment with planetary protection and sample containment as the drivers. The design requires the need to eliminate or minimize the use of active systems; e.g. hard landing without parachutes. Earth Entry Vehicle technology developments are provided:

	Solution(s) Identified	Work Needed
General Vehicle Development	✔	✔
Aerodynamics stability	✔	✔
Thermal Protection System (TPS)	✔	✔

Impact Protection System	✔	✔
Dust mitigation / vehicle sterilization	✔	✔
Micrometeoroid protection	✔	✔
Sample reception	✔	✔
Environmental control within return capsule	✔	✔
Maintain sample cryogenic	?	✔
Prevent contamination (hermetic seal)	?	✔
Capture volatiles		✔
Sublimation, water chemical reactions		✔
Core sample in compression	?	✔
Environment control during Earth landing	✔	✔
Maintain sample cryogenic		✔
Prevent contamination (hermetic seal)	?	✔
Core sample in compression	?	✔
Transfer of sample to curation facility	✔	✔
Maintain sample cryogenic	✔	✔
Prevent contamination (hermetic seal)	✔	✔
Core sample in compression	✔	✔

Another specific need for the MMEEV is the availability of carbon phenolic TPS material. JPL has purchased all of the remaining qualified rayon material for the Mars Sample Return mission, but there may not be sufficient material for the required testing to meet the high reliability requirements. Also, additional missions must carbonize rayon supplied by a new vendor with new manufacturing processes. The lack of carbon phenolic material has the ability to impact a large number of sample return missions. Because the current MSR EEV need date is to achieve TRL 6 by 2019, the EEV technologies are likely to be developed without SBAG advocacy, however; it is critical to keep a multi-mission focus with early technology developments to address small body sample return.

6) Sample Recovery, Transfer, and Curation

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.

F. Communication Systems

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. Data rates as a function of distance for notional communication systems are illustrated in figure 9. 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.

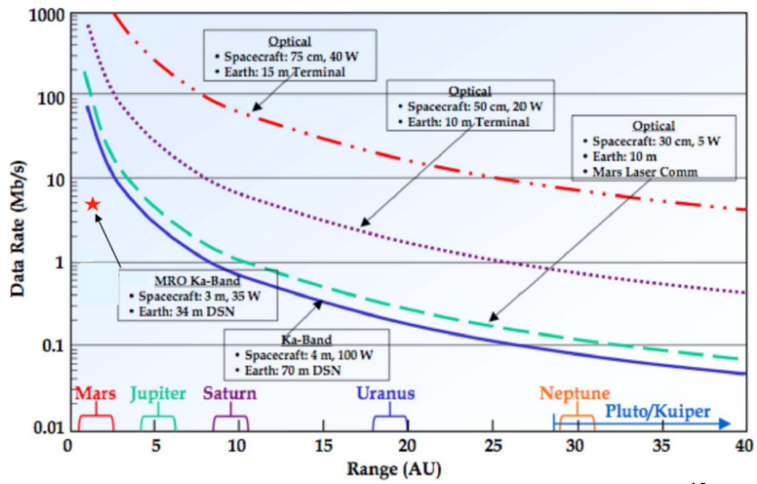

Figure 9. Data rate vs. distance of communication options.[15]

The Small Body roadmap can leverage advances that are specified in the recently drafted OCT Communications and Navigation Technology Roadmap.[16] This roadmap identifies advances in RF technology that concentrates on getting more productivity out of the constrained spectrum bands that are allocated to space users and in parallel, optical communications technology, which seeks to take advantage of the virtually unconstrained bandwidth available in the optical spectrum. In addition, the OCT Comm-Nav roadmap includes the migration of the Earth's internetworking technology and processes throughout the solar system. The expansion of internetworking will help lower operational costs of our systems by replacing manual scripting and commanding of individual spacecraft communication links with autonomous handling of data distribution similar to that of the terrestrial internet. These technologies could be of benefit in small body missions in which there may be multiple assets and instruments within the operational domain with limited relay connectivity back to earth. Internetworking technologies such as DTN (Delay/Disruption Tolerant Networking) would provide missions with greater autonomy in delivering critical science data in environments with high delay and disconnected links.

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.

A summary of enabling technologies taken from the OCT Communications and Navigation Roadmap applicable for Small Body missions are listed below:

1) Optical Communication

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. Addressing spacecraft induced jitter will improve laser beam pointing capability. Initially optical terminals on spacecraft will use Earth-based beacons but eventual beacon-less pointing will be developed.

2) RF Communication

RF communication will develop new techniques that will allow at least two orders of magnitude increase over current data rate capabilities in deep space. Cognitive radios will be developed that will sense their environment, autonomously determine when there is a problem, attempt to fix it, and learn as they operate.

3) Internetworking

Earth-based internetworking technologies will be migrated to space with protocols such as Disruptive Tolerant Networking (DTN) which will help deal with latency issues and automate distribution of data where ever our spacecraft operate.

4) Position, Navigation, and Timing

Fundamental to the improvement of our navigation capability is the improved accuracy and stability of our space clocks so significant focus will be on this area. Algorithms for autonomous rendezvous, docking, landing, and formation flying will also be developed.

5) Integrated Technologies

Development of hybrid optical and RF communication systems should reduce mass and power requirements on spacecraft. Integrating knowledge engineering with future networking radios could provide cognitive networking functionality which would further reduce dependence on manual control from Earth. Techniques will be developed to improve the use of the RF link as a science instrument (measuring perturbations along its path or in the spacecraft trajectory) and enable these kinds of measurements using optical links.

G. Ground Based Observation Technologies

Earth-based telescopic observations are the primary means of studying the large populations of primitive bodies. Space-based infrared telescopes cannot operate within specific avoidance angles around the Sun, precluding certain essential studies of comets or inner-Earth asteroids. Access to large Earth-based telescopes will continue to be needed to acquire such observations. Following discovery and orbit determination, telescopic data can probe an object's shape and size, mineralogy, orbital and rotational attributes, presence of volatiles, and physical properties of the surface material including particle size and porosity. These data can motivate scientific goals for future planetary science missions, provide context within which to reduce and analyze spacecraft data, and expand the scientific lessons learned from spacecraft observations to a much larger suite of small solar system bodies.

The 3-meter NASA Infrared Telescope Facility (IRTF) has provided significant data for studies of primitive bodies. The IRTF continues to be relevant to the study of larger or closer objects. Observations of distant objects are, however, constrained by IRTF's modest aperture. Extending the frontiers of knowledge for primitive bodies in the distant regions of our solar system will require more powerful telescopes and significant access to observing time. NASA-provided access to the Keck telescope continues to yield important new data, but the meager number of available nights each year is barely adequate for limited single-object studies and completely inadequate for large-scale surveys.

The Arecibo and Goldstone radar telescopes are powerful, complementary facilities that can characterize the surface structure and three-dimensional shapes of the near-Earth objects within their reach. Arecibo has sensitivity 20 times greater than Goldstone, but Goldstone has much greater sky coverage than Arecibo. Continued access to both radar facilities for the detailed study of near-Earth objects is essential to primitive bodies' studies. The large number of primitive bodies in the solar system requires sufficient telescope time to observe statistically significant samples of these populations to expand scientific knowledge and plan future missions. Characterization of this multitude of bodies requires access to large ground-based telescopes as well as to the Goldstone and Arecibo radars. The Arecibo radio telescope is essential for detailed characterization of the shape, size, multi-body systems, precice orbit determiniation, morphology and spin dynamics of NEOs that make close approaches to Earth. These radar observations also provide highly accurate determinations of orbital parameters for primitive bodies critical to modeling and planning future exploration. Currently only 2% of the time at Arecibo and Goldstone are used for radar activities and as of December, 2010 radar has been used to observe only 271 of 7674 known NEOs.

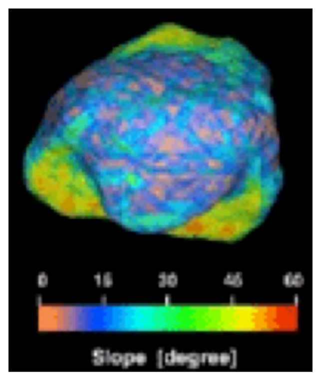

Figure 10. Goldstone observation.[17]

The recent astronomy and astrophysics decadal survey endorsed the Large Synoptic Survey Telescope (LSST) project as its top-rated priority for ground-based telescopes for the years 2011-2021.[18]In addition to its astrophysics science mission, the LSST will have a profound impact on our knowledge of our solar system by providing a dramatic increase in the number of known objects across all dynamical types such as near-Earth and main-belt asteroids, KBOs, and comets. The NRC has outlined observations with a suitably large ground-based telescope as one option for completion of the George E. Brown NEO survey of objects 140 meters diameter or greater in size.[19] The LSST will allow major advances in planetary science by dramatically extending inventory of the primitive bodies in the solar system. These facilities are primarily funded by NSF, but the small body community would benefit from the completion of the LSST and PanSTARRS in addition to increased access to existing ground based facilities.

H. Support Tools and Capabilities

1) Mission Design Tools

Mission design tools and trajectory optimization capabilities are also 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 or 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.

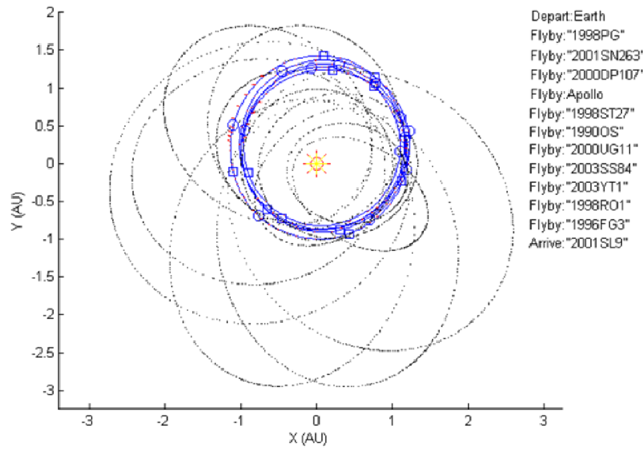

Figure 11. Mega-mult-flyby Trajectory.

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 is using "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. As of FY12, 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.

2) Simulant Materials

Small body simulant materials are required in order to further the research and development of a variety of new technologies that will enable future small body science and exploration. Improvement in instrument payloads, mobility systems, and anchoring devices will aid both robotic and human interaction at the surface of a small body under microgravity conditions. Technological breakthroughs that apply to the improved designs for anchors, tethers, sampling devices, penetrators, instruments, rovers/hoppers, etc. will be necessary to further our understanding of the near-surface environment and physical characteristics of the object. Therefore, the main objectives for creating a suitable simulant is to design, develop, test, and evaluate materials found on Earth, which provide similar near-surface mechanical and geotechnical properties to those found small body targets.

Previous planetary simulants have been developed to represent materials from Moon and Mars, and used with good success for future improvement to spacecraft and rover systems. Based on data obtained from the terrestrial meteorite collections, ground-based observations, and from the NEAR Shoemaker and Hayabusa missions, it should be possible to design, develop, fabricate and test relevant materials for small body simulants as well. Properties of targets such as particle size frequency distribution, particle shape, material strength (compressive, mechanical, and shear), bulk density, chemistry, and composition will be used to develop suitable simulants. These simulants will be used to represent the upper surface of objects in order to develop, test, and certify the hardware and systems required for small body science and exploration. Use of these materials will reduce the risk to future missions by testing materials, systems, and spacecraft components in Earth laboratories, therefore increasing the chances of success of interacting with the object and performing surface operations under microgravity conditions.

Initial appropriate feedstocks need to be identified in order to produce the required stimulants. Once a feedstock has been identified and a prototype simulant has been produced, its properties will need to be tested. Characterization of the particle size distribution, composition, and geotechnical properties of the materials will need to be performed prior to its evaluation as an adequate simulant. Hence, use of calibration instruments designed to accurately measure/estimate the geotechnical and geochemical properties of surface materials and compare them to those of the simulant(s) is another activity that will be required prior to simulant certification. Additional work will focus on the production of simulants for microgravity testing (e.g., anchoring/interaction simulations in micro-g airplane tests and/or drop tower experiments). The ability to test technologies and hardware with stimulants in specific test beds, vacuum chambers, analog sites and other environmental chambers is a risk mitigation strategy that will lead to increase mission confidence and success.

Based on previous lunar simulant development experience, it should be possible to acquire appropriate simulant materials that mimic small body compositions such as those from the ultramafic Stillwater tailings piles in Montana or other mining sites. These mining materials will be evaluated as an adequate simulant for ordinary chondritic asteroids such as (25143) Itokawa. In addition, there is the possibility that we will need carbonaceous chondrite stimulants. Such objects are already targets for future robotic sample return missions (e.g., Hayabusa 2 and OSIRIS REx) and may become future targets of choice for human exploration. For a carbonaceous chondrite object, coal-like materials such as Texas lignite may be suitable for testing and evaluation. Such materials may be available at reasonable cost and may even be already ground to appropriate grain sizes. It is expected that the costs for obtaining and transporting these mining/tailing materials will be minimal.

For each type of simulant a multi-ton supply for characterization and engineering evaluations should be procured. The actual simulants should include at least two different small body compositions (i.e., ordinary and carbonaceous chondrites) with a variety of subsets having different grain sizes and shapes. Where possible boulders of the appropriate composition and size should also be obtained/generated based upon the recent terrain findings from the Hayabusa spacecraft mission to asteroid Itokawa. These stimulants should be transported and installed in laboratories or controlled environments such as mobility rock piles, small vacuum chambers, air bearing tables, neutral buoyancy facilities, and microgravity test flights. Analyses of the appropriateness of the simulants for the envisioned engineering test programs needs to be performed given that some substitution of material may be required in order to mitigate potential damage to the facilities (i.e., free floating geologic materials within the Neutral Buoyancy Laboratory (NBL)).

I. Extreme Environments

For small body missions, there are limited needs for extreme environment technologies. In general, the only applicable extreme environment for small bodies is the low temperatures. Especially for a cryogenic comet sample analysis or return, the use of heaters would complicate the sample collection, analyses, and transfer to the return capsule. In order to operate in the extreme cold environment, mechanisms, electronics, sensors, drills, etc. need to be qualified for an operational environment down to -270^{o}C. This is a significant challenge that could require years of investment and low TRL testing before reliable systems and solutions are matured for mission application.

	Solution(s) Identified	Work Needed
Extreme cold (-270^{o}C) mechanisms, electronics, etc.	✔	✔

III. Prioritization

Based on community input, the key technology investments to benefit small body missions are improved specific power solar array system demonstration, a low-cost electric propulsion system option, a seismic science network system demonstration, a variable focus distance imager, several sampling (both for in-situ analyses and return) technologies, a sample return vehicle and environmental control technologies. The diversity of small body missions and PI competed mission opportunities can make technology prioritization difficult; e.g. a comet sample return mission will not benefit from a seismic network demonstration. However, some technologies are applicable to a wide range of small body missions.

This prioritization is not meant to represent NASA's technology priority and assumes no preference for mission class or target selection. For example, if the Decadal Survey recommends a flagship Comet Nucleus Sample Return, the solar array may become a higher priority technology, just as a recommendation for a flagship Kuiper belt object explorer may significantly raise the priority of ^{238}Pu restart or a larger ASRG unit. Scoring is based on three factors, the mission applicability, the science return compared to existing options, and the potential for infusion if sufficient risk it reduced. For mission applicability, a score of 1 was assigned if the technology was likely only to benefit a single or very few missions, e.g. a cryogenic comet nucleus drilling system, a score of 3 was assigned if the technology would be applicable to several missions such as an Earth Entry Vehicle that would benefit any sample return missions, and a score of 9 was assigned for a technology that would likely be used on half or more future small body missions if developed, like an advanced imager or topography instrument that can be used on orbiters and landers prior to touchdown. Science benefit over start of the art was scored as a 1 for slight enhancement over alternative options, a score of 3 for significant enhancements over SOA, and a score of 9 for technology that would significantly augment the science return of the mission. The third ranking, infusion potential, was scored a 1 if there was a low likelihood the technology would be infused on future missions regardless of mission type, e.g. the 500W ASRG unit would not be infused on small body missions that do not require radioisotope power. A score of 3 was assigned if there was a high likelihood the instrument would be infusion if available, and a 9 was assigned if the likelihood was high that most future missions would use the technology if matured; e.g. an advanced imager. Because the mission applicability and infusion potential are closely related, results are shown based on science return vs. total return on investment. The technology prioritization is shown in figures 12 and 13 for general technologies and for sample return technologies respectively. The technologies were separated because the mission applicability would inherently be lower for sample return missions. Detailed scores are provided in appendix A.

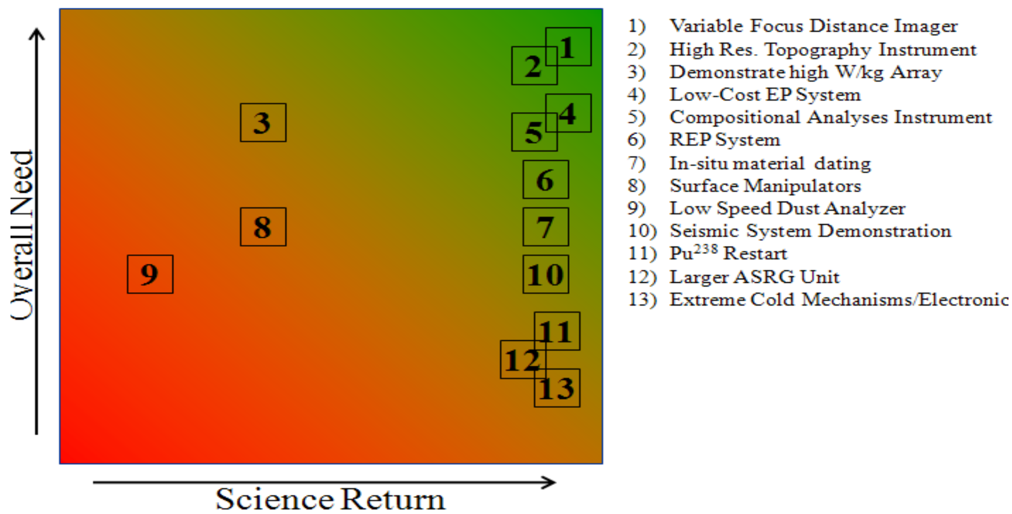

Figure 12. Prioritization of general small body technologies.

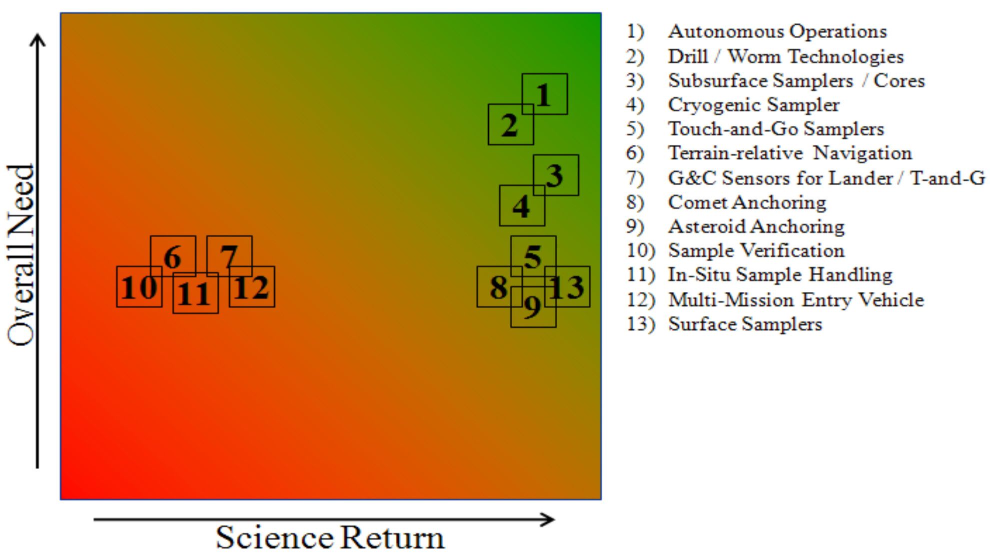

Figure 13. Prioritization of small body sample return technologies.

With any road mapping and prioritization exercise, one must also look at the practical, primarily fiscal, realities associated with technology development. The Solar System Exploration Survey initiated in 2001 and finalized in 2003 vaguely identified the "Key Enabling Technologies for Primitive Body Exploration" as drilling on small bodies to depths on the order of a meter, cryogenic sample preservation and handling including subsurface collection, transfer, encapsulation, and return from Earth where the sample is never exposed to temperatures exceeding 150K, and in-situ age determination and compositional analyses. If one refers back to the NASA Solar System Exploration Roadmap and NASA Science Plan for NASA's Science Mission Directorate 2007-2016, there is a an increased level of detail in the technology roadmap. Specific technologies identified include: solar array technology for 175 W/kg, addressing the shortage of ^{238}Pu and developing an Advanced Stirling Radioisotope Generator, affordable solar electric propulsion system for use by Discovery missions, cryogenic sample return technologies, sample acquisition and preparation technologies, small body anchoring, subsurface access, high heat flux entry return TPS, etc. With the exception of the ASRG program, these technologies and development efforts have been reduced and/or underfunded from the time these recommendations were provided. The planetary science division technology development programs are not given funding levels to succeed in fulfilling these recommendations. The New Millennium Program (NMP) Space Technology 8 mission was to flight validate solar array specific power of 175 W/kg, but after the NMP cancellation is only expected to achieve 100 W/kg as developed to meet the Orion Crew Module requirements. Efforts to restart ^{238}Pu continue to stall in congress, Discovery Mission class electric propulsion systems lack any power processing unit investments outside of SBIRs, sample return technologies are funded sporadically through institutional investments only, and the availability of carbon phenolic TPS materials required for future sample return missions remains uncertain.

IV. Technology Infusion Remarks

The goal of any technology development effort is for the technology to be infused into a mission and provide an otherwise unachievable science return. The priority of instrument development should be for instruments that will be used if sufficient risk is retired regardless of specific target or CO-I institution. NASA has initiated instrument development efforts, but has not always provided a clear path for technology infusion. Investments are made into instrument technologies, but many are not proposed in lieu of lower performance higher heritage options. If NASA continues to invest in technologies, there must be an acceptable method for risk review and acceptance prior to submission of mission proposals. Not only is it often difficult to advance technology and systems from TRL 5-6, but there are no appreciable opportunities to advance the technologies and systems from TRL 5-6-7 prior to mission selection. This was also highlighted in earlier SMD road mapping efforts; recommending a Solar System Instrument Development Program (SSIDP) to bridge the gap between programs such as PIDDP and ASTID and flight. The PIDDP program has expanded scope from target readiness levels of TRL 6, rather than 4, but an increase in funding is recommended as the cost for advancement increase at higher TRLs. Even at TRL 6, instruments and systems may have too high of a risk posture during the Technical, Management, and Cost (TMC) review. All technology investments could benefit from some method of TMC approval or familiarization prior to proposing the new technology.

Infusion challenges also exist for instruments with heritage. While instruments, such as spectrometers, exist with little need for focused technology development, engineering challenges for adapting the instruments for new environments or extending instrument capabilities pose risk potential during step one proposals. Any opportunity to increase early funding for instrument risk reduction after Step 1 mission selection may allow for increased science return with minimal cost risk.

Another challenge is for infusion of higher cost or complex small body mission systems. The NASA science planning has not indicated a high potential for a flagship class small body mission and has only identified the Comet Surface Sample Return or Trojan/Centaur Reconnaissance within the New Frontiers cap; insufficient for a Cryogenic Nucleus Sample Return. Again, the decadal survey will be updating these mission priorities, but infusing a seismic science system on a small body within a Discovery class mission is not cost viable. If the science it highly prioritized, then the system must either be allowed under New Frontiers or subsidized by NASA, similar to the ISPT Products for Discovery 2010.

V. Decadal Survey Recommendations

Relevant to small body missions, the recent decadal survey provided several explicit technology recommendations. In general terms, the decadal recommendation is for advances in:

- Reduced mass and power requirements for spacecraft and their subsystems;
- Improved communications yielding higher data rates;

- Increased spacecraft autonomy;
- More efficient power and propulsion for all mission phases;
- New and improved sensors, instruments, and sampling systems; and
- Mission and trajectory design and optimization.

Specific recommendations include the completion and validation of the ASRG, technologies to enable a flagship class primitive body cryogenic sample return mission in the following decade[20] (technologies to acquire subsurface sample from an original ice-bearing region of a comet from 0.2 to 1 meter below the surface, sample preservation capability below 125K from collection to delivery to curation facility), technologies to enable an asteroid interior composition mission (integrated penetrator systems with seismic network systems and mineralogical and/or chemical instrumentation), remote sampling and coring devices, methods to confirm samples contain and organic material, instrumentation for in situ determination of the stratigraphy, structure, thermodynamic state, chemical, and isotopic composition of subsurface materials, electric propulsion thrusters mated with advanced power systems (both SEP with UltraFlex and REP with ASRGs).

Instrument improvements were also recommended for increased resolution, mass reduction and extreme environments compatibility for imaging systems, UV, visible, infrared, Raman, laser, and gamma/neutron spectroscopy, mass spectrometers, laser ranging, radar, seismometer systems, heat flow, radio sounder, plasma analyzer, dust analyzer, magnetometer, and ultra-stable oscillators, in addition to the previously mentioned surface sample and handing, subsurface sampling, and cryogenic handling. Finally, with respect to ground based observatories, the decadal survey recommends that NASA continue support to planetary science observations of the Infrared Telescope Facility, the Keck Observatory, Goldstone, Arecibo, and the Very Long Baseline Array in addition to the completion of the Large Synoptic Survey Telescope (LSST) and the Panoramic Survey Telescope and Rapid Response System (PanSTARRS) to dramatically expand the inventory of primitive bodies in the solar system.

VI. Summary

This roadmap represents the first draft of the small body missions' technology development roadmap. Requests for input will be continuously solicited as recommendations evolve with mission opportunities and technology advancement. This technology capabilities and gap assessment is very consistent with earlier recommendations including the Solar System Exploration Survey from 2001, the SSE Roadmap for 2007-2016, the CAPTEM report, etc. The technologies identified are also consistent with the current Planetary Sciences Decadal Survey 2013 – 2022. Past planetary science missions have provided a high heritage instrument base for wide and narrow angle camera, spectrometers, etc., but science return can be significantly increased with strategic investments. Technology needs include a variable focus imager, a high resolution topographer, improved solar array alpha, a low-cost electric propulsion option, advanced communication systems, higher TRL investments for instruments for in-situ compositional analysis, in-situ material dating instruments, seismic science system demonstrations, improved alpha radioisotope power systems and fuel availability, extreme cold electronics and mechanisms, and a myriad of sample return technologies.

There are significant gaps on a large range of sample return technologies that must be addressed prior to surface and especially subsurface sample return missions. The technologies range, but most are very immature with strategic investments recommended for risk reduction. Risk reduction efforts are recommended for autonomous operations, drilling technologies, touch-and-go, surface, and subsurface samplers, landing site selection and terrain-relative navigation, small body anchoring, sample verification, in-situ sample handing mechanisms, and the sample return entry vehicle.

Investments should be balanced based on mission implementation potential and the increase in science return. Complex system demonstrations are required for seismic science, subsurface in-situ analyses, and surface and sub-surface sample return operations. Small body technology investments range, but have the advantage that many technologies would be applicable across a broad range of small body missions. If sufficient risk can be retired, small body technologies such as an advanced imager, an advanced topography instrument, and low-cost electric propulsion have a high likelihood of mission infusion with repeated application.

Appendix A: Scoring for Technology Prioritization

Instrument / System Area	Multi-mission Applicability	Science Benefit of SOA	Infusion Potential	Total Score
Variable Focus Distance Imager	9	9	9	27
High Res. Topo. Instrument	9	9	9	27
Demonstrate high W/kg Array	9	3	9	21
Low-Cost EP System	9	9	3	21
Compositional Analyses Insutrment	3	9	9	21
REP System	1	9	9	19
In-situ material dating	3	9	3	15
Surface Manipulators	3	3	9	15
Low Speed Dust Analyzer	9	1	3	13
Seismic System Demonstration	1	9	3	13
Pu^{238} Restart	1	9	1	11
Larger ASRG Unit	1	9	1	11
Extreme Cold Mechanisms/Electronics	1	9	1	11
Autonomous Operations	3	9	9	21
Drill / Worm Technologies	3	9	9	21
Subsurface Samplers / Cores	1	9	9	19
Cryogenic Sampler	1	9	9	19
Touch-and-Go Samplers	3	9	3	15
Terrain-relative Navigation	3	3	9	15
G&C Sensors for Lander / T-and-G	3	3	9	15
Comet Anchoring	3	9	3	15
Asteroid Anchoring	3	9	3	15
Sample Verification	3	3	9	15
In-Situ Sample Handling	3	3	9	15
Multi-Mission Entry Vehicle	3	3	9	15
Surface Samplers	3	9	3	15

Appendix B: Definition of Technology Readiness Levels

TRL 1 - Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

TRL 2 - Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

TRL 3 - Analytical and experimental critical function and/or characteristic proof-of-concept: Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.

TRL 4 - Component/subsystem and/or breadboard validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

TRL 5 - System/subsystem/component and/or breadboard validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.

TRL 6 - System/subsystem model or prototype demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

TRL 7 - System prototype demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.

TRL 8 - Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space): End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

TRL 9 - Actual system "mission proven" through successful mission operations (ground or space): Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

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