Developing Sample Return Technology using the Earth's Moon as a Testing Ground

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Introduction

Sample return missions provide a unique perspective not offered by either orbital or surface missions – the opportunity to study the returned material in well equipped Earth laboratories. Compared to most analyses done on a planetary surface, this unique perspective is based on scale (down to angstroms), precision, sample manipulation capability, and the ability to modify analytical experiments as logic and technology evolves. Sample return provides fundamental chronological and geochemical ground truth that enhances the value of both orbital and surface observations far beyond their stand-alone importance. Further, sample return is a vital necessity for the human exploration program for resource identification as well as human health and safety issues. The price paid for this unique and valuable information is increased cost and risk relative to other types of missions. To conduct sample return missions from a wide range of planetary bodies (asteroids, comets, small moons, Moon, Mars, Venus) on a regular basis these two factors must be minimized. Rather than looking at sample return as single point missions, each requiring their individual technology development, it would be much more advantageous to examine sample return technologies as threads linking simple missions (both sample return and non-sample return missions) to more complex missions and include them at the onset or early in the development of an exploration strategy. This approach, which is not planetary body specific, would result in an evolving technological heritage and thereby reduce cost and risk in each subsequent sample return mission. However, the proximity and scientific importance of the Earth's Moon makes it an ideal testing ground for many robotic sample return technologies that will also enable science for generations to come.

The Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) was requested by the NASA Director of Planetary Science, Science Mission Directorate in 2007 to organize an analysis of potential linkages between simple and complex sample return missions and to identify those critical investments that would best reduce risk and cost for increasingly complex sample return missions over the next 20 years. This white paper represents a summary of the full document, which can be found at **http://www.lpi.usra.edu/captem/analysis.shtml**.

Returning samples from other planetary bodies to Earth is a complex endeavor requiring careful planning and execution. This begins with the mission objective(s) and the type of planetary body under investigation. Broadly speaking, planetary bodies can be subdivided into those with atmospheres and those without, with each type requiring a different sampling strategy. At the next level is the type of sample that will be collected and returned to address the science mission objectives. Such samples are broadly defined as solid, liquid, or gas. Each sample type requires specific technologies for sampling, caching, storage, and, once on Earth, curation to maintain them in a pristine state (i.e., unaltered from the condition the samples were in at the time of sampling). Each of the three broad sample types can be further subdivided. For example, solid samples include coherent rocks, dust, and ices, as well as unconsolidated regoliths; liquid samples could include water, methane, ammonia, etc.; and gas samples include different planetary atmospheres as well as volcanic gases. While this perceived complexity may lead one to conclude that each sample return mission requires an individualized technological approach to be successful, this white paper demonstrates that there are common technologies that link different sample return targets and strategies. Furthermore, many of the technologies (except atmospheric sampling via flyby) can be tested on the Moon.

Sample Return Missions Styles

Sample return missions are generally more complex than other robotic planetary exploration missions because they need to return safely to their body of origin (Earth) with a "payload" of collected planetary materials. The materials thus returned can be collected via a number of mission styles. The term "mission style" refers to different ways of implementing the sample acquisition. As with planetary bodies and sample types, sample return styles can be defined by general categories – flyby, touch-and-go, and surface collection. While these three differ widely in the equipment required to prepare and to execute the sample collection phase, the following (equally important) phases - sample preservation and curation – are in principle identical in all.

Flyby Missions. Here samples of material from the planet (or comet, or asteroid) are collected without touching its surface. The spacecraft flies over the planet, a single time or repeatedly, at an orbit sufficiently low so that the material sought crosses its trajectory. Such a mission was proposed, but not selected, to collect dust from the martian atmosphere. In fly-by missions a special collection device opens to collect dust/atmosphere particles. The sample collection unit proper can be essentially two-dimensional, something equivalent to a sticky paper that captures the particles, or a more complex three-dimensional collector. This type of mission is perfect for collecting samples of a planet's atmosphere or a comet's tail. A variant of this mission is one that creates a plume of material from an airless body that the spacecraft can fly through by impacting a probe into the surface.

As no landing is required, the only specialized technology needed is the sample collection unit, a relatively simple passive device. While being the simplest and therefore least expensive among the sample return mission styles, flyby missions are ranked noticeably lower than other styles in terms of scientific information they can yield. It may be a preferable style for a first exploratory mission, or if other sample return styles are not feasible. Table 1 illustrates several examples of flyby missions. The impact plume is the flyby mission type that could be tested on the Moon.

Table 1. Examples of Flyby, Touch-and-Go, and Surface Collections Missions.

Type	Planetary Body or Process	Sample type
Flyby	Mars, Venus	Atmospheric sample (dust, gas)
	Impact or volcanic plumes	Plume (dust, gas)
	Comet	Cometary dust
	Planetary Rings	Dust
	Solar Wind	High-energy particles
Touch-and-go	Moons	Regolith
	Asteroids	Regolith, organics
	Comets	Regolith, ices, organics
Surface Sampling		
	Comets	Regolith, ices, organics
	Asteroids	Regolith, rocks
	Moon/Mercury	Regolith, rocks, ices
	Mars, Phobos, Deimos	Regolith, rocks, ices, organics
	Venus	Regolith, rocks, atmosphere
	Moons of the outer planets	Regolith, rocks, atmosphere, organics

Touch-and-go Missions. In this type of mission the spacecraft briefly touches the surface of the space body, quickly collects the sample, and takes off, to move to another sample collection site or to return to Earth. This type of mission is ideal for asteroids or small moons, where the gravity force is negligible, obviating the need for elaborate expensive descent and ascent systems, or whether the environment to be sampled is extreme requiring the sampling space craft to spend as little time as possible exposed to those surroundings. On the Moon this could mean polar cold traps (although the integrity of the sample may be impaired) or the sampling of lunar rilles.

The virtual absence of gravity on asteroids brings about a problem opposite to that faced by a spacecraft landing on a planet: forces produced during the sample collection push the touch-and-go craft away from the asteroid, necessitating a special means to hold the craft in place – say, an anchor run into the ground or a thruster generating a balancing force.

The touch-and-go sample collection can be achieved with a relatively small and light craft. The Japanese sample return craft Hayabusa (spacecraft mass = 510 Kg) is an example of a touch-and-go mission: it made a touch-and-go stop on the asteroid Itokawa. Hyabusa illustrates an important technology development needed for this and all styles of sample return, namely verification of sample acquisition; there is no assurance that Hyabusa collected a sample. Table 1 illustrates several examples of touch-and-go missions.

Surface Collection. Obtaining soil samples from moons and planets (our Moon, Mars, Venus, etc.) requires the safely landing on the surface and spending sufficient time on it. This is the most complex of sample return mission styles, since the operation requires sufficient technical means to descend to the surface, reliably collect and preserve the sample, and then ascend from the planet in order to rendezvous with the waiting orbiter vehicle or to head directly toward Earth. Soft landing is critical to guarantee the right conditions for the sample collecting equipment. Besides the need for sufficient fuel for safe landing, the landing vehicle needs to carry an ascent stage. This increases the craft's mass considerably: typical mass estimates of the sample collection lander for Moon and Mars are in the range of 1,000-1,500 Kg. For comparison, the on orbit dry mass of the Luna 16 spacecraft was 5600 kg.

The sample collection equipment can appear in a great variety of designs, from a simple shovel or scoop to a torpedo device shot, during the descent, into the ground and used to acquire samples from under the surface, to producing an artificial explosion and then collecting the resulting debris. Other devices include a robotic manipulator arm to "grab" rock samples to coring devices that can return cores of uniform size from more substantial outcrops. The particular choice depends on many considerations, including the mission's science goal, budget, the desire to minimize complexity and maximize reliability, etc. The reduction in system complexity must be balanced by the need to provide sufficient sensing information to the device itself and to the ground operator (e.g., for teleoperation control of the task). Adding various sensors and cameras, or placing the sample collection tool in the hand a robot arm manipulator quickly adds to complexity and cost. Placing the sample collection device on a mobile robot rover adds much flexibility in the choice of specific sites of sample collection, but this also adds to system complexity and may, in turn, require additional complex hardware for transferring samples from the rover to the ascent vehicle. Table 1 illustrates several examples of surface sampling missions.

Linkages

The variety of sampling missions styles range from simple flyby to a more complex "touch-and-go" sampling that does not involve direct landing on the surface to very complex landed sample return missions (with or without rovers; at one locality or several). Within these different mission styles are numerous sample types (Table 1), some of which need specialized collection tools and caching capabilities. The commonalities of sampling technologies are highly dependent upon science goals and materials needed to fulfill those goals. An analysis of linkages between sampling technologies and missions is illustrated in Table 2.

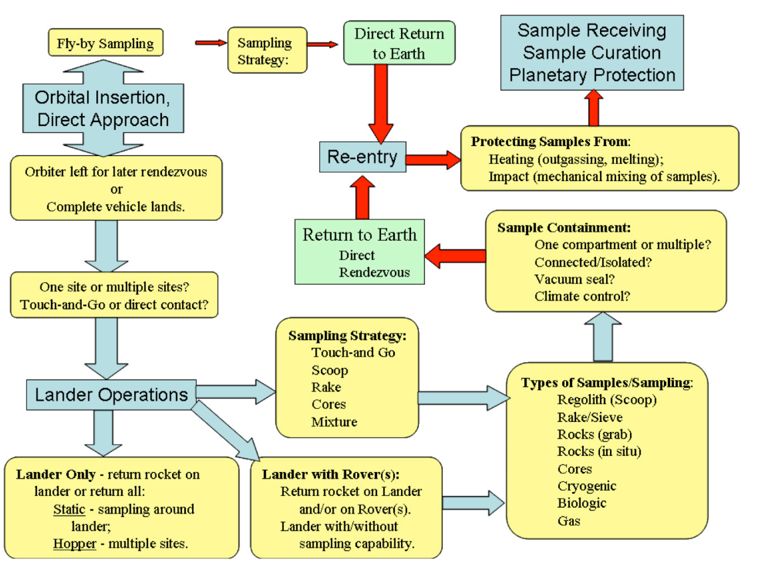

Figure 1: Flow diagram illustrating technologies and capabilities required to fulfill the objectives of a sample return mission.

Technologies and Capabilities Required for Sample Return

Perhaps, relative to other robotic missions, sample return missions are the closest approximation to human flight in overall goals. Further, in many cases a sample return has to perform a series of interrelated, complex tasks. Each stage of a sample return mission must accomplish its task and be integrated with follow on stages of the mission to be successful. The stages required to accomplish a generic sample return mission (regardless of mission style) and their relationship to one another during a mission is illustrated in the flow diagram in Figure 1. This diagram not only illustrates some of the similarities among all sample return missions, but also illustrates differences among flyby, touch and go, and surface collection with regards to the complexity in technology and coordination among technologies. Using this flow diagram, we identified required technologies within each sample return mission stage, identified potential technology linkages (and distinct uniqueness) among and within flyby, touch and go, and surface collection style missions, and ranked the technologies with regards to their potential for investment for lowering overall cost and risk of sample return missions. These are summarized in the following tables and findings.

Table 2: Simple, Intermediate, and Complex Mission Concepts

	SIMPLE	INTERMEDIATE	COMPLEX
FLYBY SAMPLING			
Spacecraft	Orbiter	Orbiter	Orbiter
Sample Type	Dust	Dust	Atmospheric/volcanic gases and dust
Mode	Fly through upper atmosphere Fly through volcanic plume	Fly through plume produced by projectile fired from spacecraft	Fly through plume/atmosphere
Sampling Mechanism	Aerogel (or equivalent) capture	Aerogel (or equivalent) capture	Canister+aerogel (or equivalent) capture
TOUCH-AND-GO SAMPLING			
Spacecraft	Orbiter	Orbiter	Orbiter
Sample Type	Regolith	Regolith	Regolith+Rock. Ice
Mode	1 descent & grab	>1 descent & grab	>1 descent & grab at different sites
Sampling Mechanism	Tether & Scoop	Tether & Scoop	Tether, scoop, mechanical "hand"
LANDED SAMPLING			
Spacecraft	Lander (no rovers)	Fetch Rover	Sampling rover or hopper
Sample Type	Regolith	Regolith + rocks	Regolith, rocks, ices, gases
Mode	Sampling from lander - one site	Sampling from lander - multiple sites	Sampling from lander - multiple sites
Sampling Mechanism	Scoop/Rake/Sieve	Sampling Cache	Scoop. "mechanical hand" corer, rake, or sieve.

Table 2 summarizes the different types of sample return missions defined in terms of "simple", "intermediate", and "complex". Table 3 shows the technologies and linkages across the difference mission types. Table 4 highlights the enabling technologies for sample return.

FINDINGS

Finding 1. Sample return from a wide range of planetary bodies provides valuable insights into the origin and evolution of the solar system. It is a valuable exploration tool, as it increases the value of both orbital and surface observations. It should be an important component in NASA's overall solar system exploration strategy.

Finding 2. Higher risk and cost is commonly associated with sample return missions relative to other types of solar system exploration missions. This is a result of a sample return mission commonly being more complex and the necessity for the spacecraft to return to its point of origin. However, sample return has many important attributes. First, it is the closest approximation to a human exploration mission. Second, samples provide a unique perspective of a planetary body that cannot be obtained by any other mission approach. The mitigation of cost and risk with a mission puts an even higher priority on early technology development for sample return missions than for more conventional mission types.

Table 3: Technologies and Capabilities with Significant Linkages across Mission Types.

MISSION STAGE	MISSION TYPE			
	Flyby	Touch-&-Go	Surface (Static)	Surface (Mobile*)
PRE-LAUNCH:				
Sterilization protocols & verification procedures	X	X	X	X
SAMPLING:				
Autonomous Positioning/ Hazard Avoidance		X	X	X
Pin-point landing capability			X	X
Multiple Sample Acquisition		X	X	X
Multiple sites sampled		X	X	X
Sample acquisition & transfer mechanisms		X	X	X
Sample acquisition verification procedures	X	X	X	X
Environmental control on sampling and storage	(X)	(X)	(X)	(X)
SAMPLE CONTAINMENT:				
Separation/isolation of separate samples to prevent cross contamination	(X)	X	X	X
Unreactive, strong sample containers	X	X	X	X
Environmental monitoring (and control if appropriate)	(X)	(X)	(X)	(X)
Abrasion between samples and the container needs to be minimized		X	X	X
Sealing/resealing of sample container - verification of seal		X	X	X
Encapsulation: regular cores vs. irregular rocks vs. loose regolith samples vs. ice samples vs. biological samples vs. gas/atmospheric samples			X	X
Development of non-silicate aerogel	X			
Gas containment at pressures different to 1 bar	(X)	(X)	(X)	(X)
SAMPLE RETURN:				
Low mass lander/ascent vehicle infrastructure			X	X
Autonomous vertical alignment of ascent vehicle for return			X	X
Environmental monitoring and control	(X)	(X)	(X)	(X)
Hard-landing vehicle & sample preservation	X	X	X	X
CURATION:				
Development of cold/cryogenic (ice) curation and storage protocols	(X)	(X)	(X)	(X)
Development of gas sample curation and storage protocols	X	(X)	(X)	(X)
Development of biological sample curation and storage protocols	(X)	(X)	(X)	(X)

(X) = sample dependent

Table 4: Enabling Technologies for Sample Return.

1. Technologies that impact all sample acquisition types and all sample return mission scenarios:	
Pre-Launch	Sterilization protocols and verification procedures.
Sampling	Autonomous Positioning/Hazard Avoidance; Multiple sample acquisition; Sample acquisition and transfer mechanisms; Sample acquisition verification procedures.
Sample Container	Separation/isolation of separate samples to prevent cross contamination; Unreactive, strong sample containers; Sealing/resealing mechanisms for sample container; Sealing verification procedures.
Sample Return	Low mass lander/ascent vehicle infrastructure.
2. Technologies that impact the majority of sample types and majority of mission scenarios:	
Sampling	Pin-point landing capability.
Sample Container	Environmental monitoring (and control if appropriate) during time on the surface and during return; Abrasion between samples and the container needs to be minimized; Gas containment at different pressures to 1 bar;
Sample Return	Low mass lander/ascent vehicle infrastructure.
Curation	Development of cold/cryogenic curation and storage protocols; Development of gas curation and storage protocols.
3. Technologies required for specialized sampling/sample targets.	
Sampling	Ability to sample multiple sites.
Sample Container	Encapsulation: regular cores vs. irregular rocks vs. loose regolith samples vs. ice samples vs. astrobio samples vs. gas/atmospheric samples; Development of non-silicate aerogel for dust sampling.
Sample Return	Autonomous vertical alignment of ascent vehicle return.

Finding 3. There are technology linkages among different types of planetary missions that provide feed forward to increasingly complex sample return missions. Investing in developing and flying these technologies will increase the rate of success of sample return missions and lower the overall cost.

Finding 4. There are several types of technology/capability linkages that either are appropriate for several missions with minor modifications or feed forward to more complex missions: (1) Linkages between sample return and non-sample return missions such as precision landing and hazard avoidance. (2) Linkages among different styles of missions (flyby, touch-and-go, surface landing) such as hard-landing on Earth and preserving environmentally sensitive samples. (3) Linkages with a single style of mission to a variety of planetary bodies such as sample collection, manipulation, and storage on a planetary surface or sample collection and verification of success during a touch-and-go mission, or inert collection material on a flyby mission. (4) Linkages between sample return and human exploration such as rendezvous around a distant planetary body and return to Earth.

Finding 5. Several priority investments were identified. These priorities are placed within the groupings noted in Findings 4:

Between non-sample return and sample return missions:
- Precision landing and hazard avoidance
- Robotic arm
- Autonomous robotic capabilities

Among all sample return mission types:
- Hard-landing and sample preservation during such a landing
- Environment control of sample containment for future generations of sample return missions
- Curation of environmentally sensitive samples and biologic-organic samples

Among Flyby missions: Inert sample collection material
- Gas collection and storage capability

Among Touch-and-go missions:
- Sample collection and verification
- Robotic manipulation of sample for collection and transfer to container

Among surface landing missions:
- Variety of sample collection tools (drill, rake)
- Robotic manipulation of sample for collection, transfer to container, and final selection or discard.
- Adaptable sample containment

Feed forward from sample return to human exploration:
- Mars Ascent Vehicle
- Rendezvous around distant planetary body

Finding 6. There are many technologies that are specific to a single planetary body (i.e. Mars Ascent Vehicle, Mars rendezvous). Investment in these technologies will substantially reduce risk to a single sample return mission and perhaps will provide feed forward technology to more complex missions to the sample planetary body (i.e. human missions) to reduce both cost and risk.

Finding 7. A Sample Return Technology Program (SRTP) would reduce the cost to individual missions, provide the technology in a more timely and cost effective way than could be provided if one had to depend solely upon mission-specific development, enable missions possibly otherwise unachievable within cost and schedule constraints, and provide an evolutionary path from simpler to more ambitious sample return missions. As shown, investments in technologies with commonalities across numerous missions would be beneficial to sampling of a variety of planetary settings. The success of such a program would be aided by (1) developing clear, prioritized goals with demanding yet achievable schedules, (2) Coordinate the Sample Return Technology Program (SRTP) with on-going mission-specific technology development programs and with prospective mission acquisitions, (3) Develop a clear, precise understanding of the current and desired end-point TRL of the selected technologies, (4) Provide a dedicated budget sized to the goals and schedule, (5) Use competitive procurements for technology developments, (6) Require a full technology development plan , and (7) Annual program/project assessment.

Over the next decade, NASA should be encouraged to embark on a sample return technology development program. The scientific reasons for sample return have been outlined above. Also, while robotic sample return has been achieved from the Moon, NASA is yet to do this. In fact, NASA has not yet conducted a successful robotic sample return from any planetary surface. What we emphasize in this white paper is that the scientific benefits of sample return should facilitate sample return technology development and testing. We have identified cross cutting technologies that enable simple, intermediate, and complex sample return missions and these technologies can be used on a variety of planetary surfaces. We feel that the Moon offers a close planetary body to test such technologies (except gathering an atmospheric or volcanic plume sample through a flyby) and is a target that has high scientific value for Solar System exploration. Therefore, such "testing" would have significant scientific benefit while getting the technology to a high TRL level.