Expected Science Return of Spatially-Extended In-Situ Exploration at Small Solar System Bodies

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Abstract—**The recent decadal survey report for planetary science (compiled by the National Research Council) has prioritized three main areas for planetary exploration: (1) the characterization of the early Solar system history, (2) the search for planetary habitats, and (3) an improved understanding about the nature of planetary processes. A growing number of ground and space observations suggest that small bodies are ideally suited for addressing all these three priorities. In parallel, several technological advances have been recently made for microgravity rovers, penetrators, and MEMS-based instruments. Motivated by these findings and new technologies, the objective of this paper is to study the expected science return of spatially-extended in-situ exploration at small bodies, as a function of surface covered and in the context of the key science priorities identified by the decadal survey report. Specifically, targets within the scope of our analysis belong to three main classes: main belt asteroids and irregular satellites, Near Earth Objects, and comets. For each class of targets, we identify the corresponding science objectives for potential future exploration, we discuss the types of measurements and instruments that would be required, and we discuss mission architectures (with an emphasis on spatially-extended in-situ exploration) to achieve such objectives. Then, we characterize (notionally) how the science return for two reference targets would scale with the amount (and type) of surface that is expected to be covered by a robotic mobile platform. The conclusion is that spatially-extended in-situ information about the chemical and physical heterogeneity of small bodies has the potential to lead to a much improved understanding about their origin, evolution, and astrobiological relevance.**

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1. INTRODUCTION

The main objective of this paper is to study the expected science return of spatially-extended in-situ exploration at small bodies[2] as a function of surface covered and in the context of the key science priorities identified by the survey report *Vision and Voyages* for planetary science (compiled by the National Research Council, [1]). Specifically, the decadal survey report has prioritized three main areas: (1) the characterization of the early Solar system history, (2) the search for planetary habitats, and (3) an improved understanding about the nature of planetary processes. Certain small bodies are ideally suited for addressing some of these key priorities. Many small bodies have probably migrated and reached their current locations due to large dynamical events that shaped the early Solar system; therefore, the characterization of their chemical and mineralogical compositions would likely allow the validation (or confutation) of current dynamic models for the evolution of the Solar system (especially the Nice model introduced in [2], [3], and [4]). Furthermore, a variety of recent observations have recently shed new light on the astrobiological relevance of small bodies, as a source of organics to Earth and/or as potentially habitable objects [5].

To date, small bodies have been mostly observed with ground-based telescopes and, to some extent, by space observatories. While astronomical observations offer a powerful means to identify and characterize the dynamical and physical properties of a large population of objects, the information they offer about the nature of small bodies is limited due the fact that most of them are covered by a thick regolith layer. Hence, unambiguous observations about their spectral types[3] (both in terms of chemical and mineralogical composition) are almost unavailable, and this severely limits our understanding about their origin and evolution. In terms of close-range observations, a handful of comets have been the target of dedicated space missions (e.g., *Stardust*, *Deep Space 1* [6], *Stardust-NEXT* [7], *Deep Impact* [8], and *EPOXI* [9]), while

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[2] The term "small bodies" covers all Solar system objects that are not planets.

[3] Spectral types are established based on the slope of the reflectance spectrum of the surface measured in the visible and near-infrared.

only seven asteroids have been flown by, with the *Dawn* [10] mission being the only one to target asteroids large enough to qualify as protoplanets (Vesta and Ceres). Irregular satellites and regular satellitesimals[4] have been studied in the frame of large flagship missions, with Saturn's irregular moon Phoebe as a notable example. These missions have shed new light on the scientific significance of small bodies, by unveiling the large diversity of landscape exhibited by their surfaces at a scale that can not be resolved by ground-based and space observatories.

All these observations are raising a number of novel science questions, which are currently driving the development of a new generation of space missions whose main goal would be to obtain *ground truth* constraints on the origin and nature of small bodies. Mars' moon Phobos is an outstanding example in this regard: it has been observed by five different spacecraft, in the course of three decades, but its nature and origin are still poorly constrained. (The *Phobos-Grunt* mission, launched in November 2011, had the potential to resolve these questions by combining remote sensing observations, a static lander, and a sample return, but it failed shortly after launch.) Other sample return missions have been launched or are proposed for launch (e.g., *OSIRIS-REx*, target: C-type asteroid, [11]). These missions all include a stage of reconnaissance via remote sensing observations. Only a few of them also include a surface mobility platform, such as *Hayabusa* (target: S-type asteroid Itokawa, [12]) and *Hayabusa Mk2* (target: D-type asteroid, [13]).

This paper is motivated by the recent progress and ongoing development of new technologies enabling surface exploration, such as micro-gravity rovers, penetrators, and MEMS-based instruments[5]. Some of these technologies will likely be infused in future planetary missions planned in response to the decadal survey. In this paper we discuss how these various technologies can help achieve key science by offering the opportunity to sample *multiple* locations on a specific object and *multiple* targets within a given system (e.g., a satellite system). Our analysis is built on the wealth of information provided by past and current missions.

Specifically, the contribution of this paper is threefold. First, in Section 2 we show that the exploration of a selected subset of small bodies would collectively address all of the three cross-cutting themes presented in the decadal survey report; furthermore, it would also be instrumental to the future human exploration of the Solar system. This is in contrast with the long-held idea that small bodies are "primitive" and mainly relevant to constrain the origin of the Solar system. Second, in Section 3 we focus on three classes of small bodies (asteroids and irregular satellites, comets, and near-Earth objects (NEOs)) for which spaceborne observations are available. For each class of targets, we identify the corresponding science objectives for potential future exploration, we discuss the types of measurements and instruments that would be required, and we discuss mission architectures (with an emphasis on spatially-extended in-situ exploration) to achieve such objectives. Third, in Section 4 we review several concepts for micro-gravity rovers, and we discuss (notionally) how the science return of a mission would scale with the extent of surface explored by an in-situ platform, by focusing on two reference targets. Our conclusions are presented in Section 5.

2. SCIENCE OBJECTIVES OF SMALL BODIES EXPLORATION

In March 2011 the National Research Council (NRC) has released the planetary science decadal survey 2013-2022 *Vision and Voyages* [1]. The NRC committee has organized the basic motivations for next-decade planetary research into three cross-cutting themes:

Building New Worlds: i.e., understanding Solar system beginnings.
Planetary Habitats: i.e., searching for the requirements for life.
Workings of Solar Systems: i.e., revealing planetary processes through time.

In this section we discuss how the exploration of a subset of small bodies would collectively contribute to all of the three aforementioned objectives. This is in contrast with the traditional view whereby small bodies are objects whose exploration would mainly fulfill the objectives in the *Building New Worlds* theme [14]. Furthermore, we discuss the relevance of small bodies exploration in the context of future Human Exploration programs (also highlighted in the exploration roadmap recently published by the Small Bodies Assessment Group [15]). Figure 1 shows the relevance of some selected targets in the context of the decadal survey report and the vision for future human exploration. Key science priorities driving the scientific and human exploration of small bodies in the frame of the *Vision and Voyages* report are summarized in Table 1.

Small Bodies and "Building New Worlds" Theme

Most small bodies, being building blocks of the Solar system, are clearly of pivotal importance within the *Building New Worlds* theme. Recent observations have also dramatically highlighted the relevance of small bodies for the understanding of Solar system's dynamical evolution. In fact, small bodies bear clear markers of their origin that can help reconstruct the dynamical paths that led to the current Solar system architecture. The current state of the art (known as "Nice" model) is that resonances between Jupiter and Saturn led to the redistribution of planetesimals throughout the Solar system during its first million years (My), and then later during the "late cataclysm" (also know as "late heavy bombardment") about 700-800 My ago [2], [3], [4]. Key aspects of the models that may be testable are that (a) all asteroids in Jupiter's Lagrangian points come from the outer Solar system [4]; (b) wet asteroids throughout the main belt and Hilda group of asteroids share a genetic link with Jupiter's Trojan asteroids and outer planet irregular satellites [16]; (c) most of the volatiles accreted in the Solar system were supplied by outer Solar system planetesimals [17]. Therefore, small bodies play a central role in the validation (or confutation) of the Nice model, and more in general for understanding the origin of volatiles and organics on Earth (and on Mars). Within this context, recent measurements of the deuterium to hydrogen ratio (D/H) measured for the Hartley 2 comet confirms the long-suspected role of comets in supplying volatiles to Earth and, as a corollary, to other inner Solar system bodies [18]. This in turn tends to support the suggestion of a genetic link between outer Solar system planetesimals and inner Solar system suggested by the Walsh model in [17]. However, additional sampling of the D/H and other isotopic ratios (e.g., $^{13}C/^{12}C$ and $^{14}N/^{15}N$) across the Solar system would be necessary in order to fully understand the relationships between the various classes of planetary bodies. Another recent progress on this theme is how the

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[4] Small regular satellites, like Janus and Epimetheus in the Saturnian system, or Amalthea in the Jovian system.

[5] MEMS stands for "Micro-Electro-Mechanical Systems"

Themes	Key Science Priorities	Key Observations	Key Instruments	Key Targets
Building new worlds	What were the initial stages, conditions and processes of Solar system formation and the nature of the interstellar matter that was incorporated?	Elemental, mineralogical, isotopic composition	NIR, mid-IR, TIR, UV, GR&ND, MS, XRD/XRF; Sample Return	Comets, NEOs, Phobos, Deimos, Main belt and Trojan Asteroids, Irregular Satellites
	How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?	Isotopic composition, dynamical properties	MS, high-resolution imaging; Sample Return	Irregular satellites, inner planetesimal satellites
	What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?	Isotopic composition, nature and abundance of volatiles (elemental and mineralogival composition), venting	MS, mid-IR, NIR, UV, GPR; Sample Return	NEOs, C- and D-asteroids, comets
Planetary habitats	What were the primordial sources of organic matter, and where does organic synthesis continue today?	Search for organics, signature of hydrothermal environment	mid-IR, NIR, XRF, APXS; Sample Return	C-asteroids, Trojan asteroids, NEOs, comets
	Beyond Earth, are there contemporary habitats elsewhere in the Solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?	Organics, temperature, water bio-signatures, endogenic and geological activity, presence of a deep ocean, surface environments, (temperature, radiations, etc.)	Thermal mapper, GPR, gravity, mid-IR, RPWS, High-res imaging	Icy satellites, TNOs, Comets, Large wet asteroids, Phobos
Workings of Solar Systems	How do the giant planets serve as laboratories to understand Earth, the Solar system, and extrasolar planetary systems?	Collision processes, dust distribution	High-res imaging, Dust Analyzer	Satellites (inner, medium/large, irregular)
	What Solar system bodies endanger and what mechanisms shield Earth's biosphere?	Population survey, dynamical properties characterization	Mid-IR, TIR, NIR, UV, High-res imaging	NEOs, comets
	Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth?	Surface morphology, search for cryovolcanic activity	High-res imaging, Thermal Mapper	Comets, Enceladus
	How have the myriad chemical and physical processes that shaped the Solar system operated, interacted, and evolved over time?	Regolith properties, global physical structure, surface chemistry	Gravity, GPR, High-res imaging, RPWS	Any object
Human exploration	Risk reconnaissance	Surface morphology at all scales, dynamical properties, mechanical properties, electrostatic charging, dust dynamics	Dust analyzer, High-res imaging, rover motion	NEOs, Phobos, Deimos
	In situ resource utilization	Search for water abundance and distribution, physical structure	GPR, GR&ND, gravity; Sample Return	NEOs, Phobos, Deimos
	Reconnaissance of scientific significance	Heat flow and thermal structure, deep interior properties, dynamics		NEOs, Phobos, Deimos

Table 1. Traceability matrix for the key science priorities highlighted in the decadal survey report and for possible exploration approaches. Acronyms used: APXS := Alpha-Particle-X-Ray; GPR := Ground-Penetrating Radar; GR := Gamma Ray; MS := Mass Spectrometry; ND := Neutron Detection; NIR := Near Infra-Red; RPWS := Radio and Plasma Wave Science; TIR := Thermal Infra-Red spectroscopy; UV := Ultra-Violet Spectroscopy; XRD := X-Ray Diffraction; XRF := X-Ray Fluorescence; High-Res := High-Resolution.

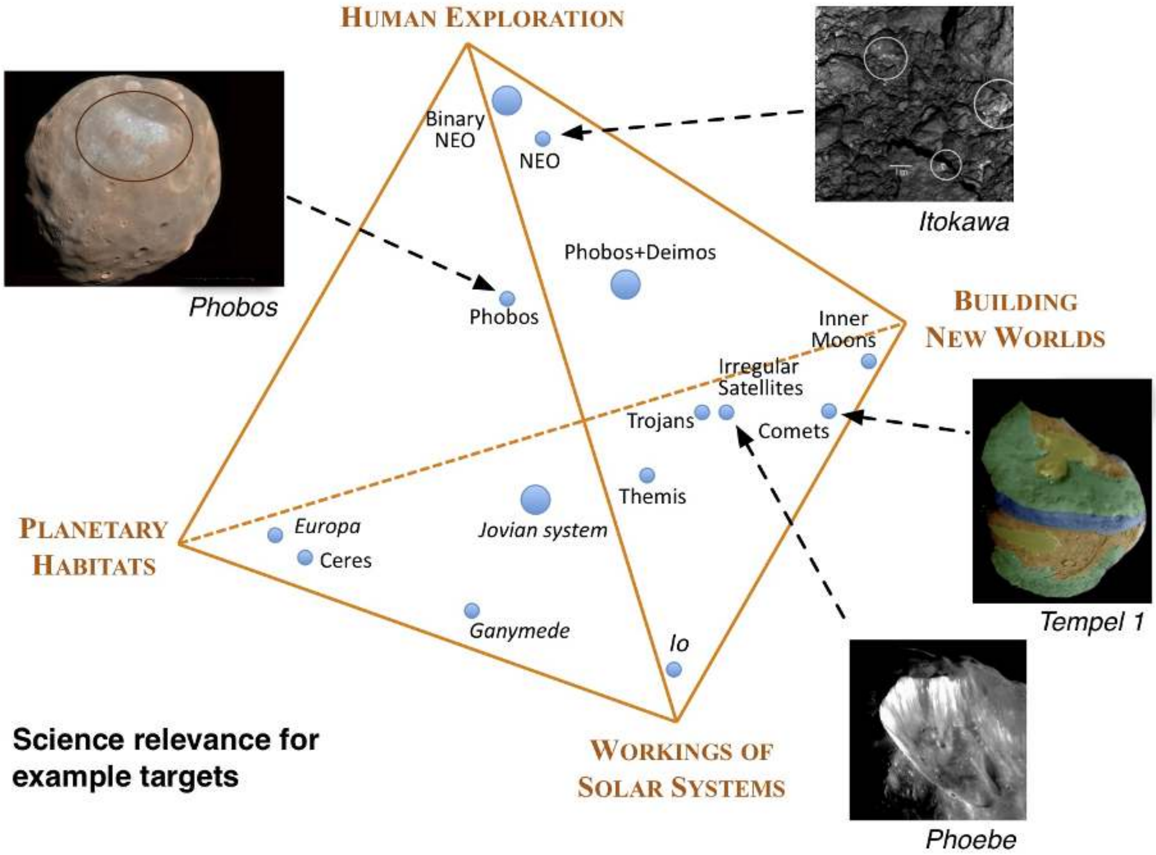

Figure 1. Relevance of different small bodies with respect to the three cross-cutting themes of the decadal survey report and to the vision for future human exploration (represented as corners of the polygon). The position of a target within the polygon represent its relative relevance with respect to the science themes and vision for human exploration. For example, comets are expected to be among the most primitive objects in the Solar system although space observations indicate that they also exhibit a large variety of landscapes that result from long-term geological activity. Another example is Phobos whose surface exploration would pertain to all four themes, as detailed in the text. The exploration of several components of a multinary system is expected to increase the overall science return of a mission, which is symbolized by bigger circles.

satellites of giant planets originated. A recent theory, based on the observation of propellers in the rings of Saturn [19], suggests that Saturn's inner moons accreted inside its rings and then evolved outward as a consequence of tidal interaction with the ring material [20]. This is in contrast with the long-held belief that satellites accreted in a subnebula from transneptunian planetesimals (see, e.g., [21]). Solving this mystery would be a cornerstone in the understanding of the origins of the Solar system; constraining the origin of these satellites (in particular the largest ones) would also help evaluate their potential for hosting a liquid layer over the long term, possibly until present [22] (an aspect relevant to all three cross-cutting themes).

Small Bodies and "Planetary Habitats" Theme

A variety of recent observations have shed new light on the astrobiological relevance of small bodies. For example, ground-based observations have led to the identification of water ice at the surface of large main belt asteroids 24 Themis ([23] and [24]) and 65 Cybele [25]. The detection of crystalline ice and ammonia hydrates at Charon [26] and of carbonates at the surface of Ceres [27] suggest that these two dwarf planets present recent or ongoing endogenic activity [28], [29]. Albedo variations at the surface of Pallas [30] indicate that this large asteroid is differentiated and the regions excavated by impacts are rich in organics [29]. NASA's proposed *New Frontiers* mission *OSIRIS-REx* (currently in development) would sample the surface of a Near Earth Object and collect organics that would help understand the role played by small bodies in seeding life molecules across the Solar system. The analysis of comet Wild 2 samples collected by the *Stardust* [7] mission has revealed a watery past in that object, as evidenced by the existence of cubanite produced in hydrothermal environments [31].

Small Bodies and "Workings of Solar Systems" Theme

The relevance of small bodies to this theme is multifold, since they are subject to a variety of processes (some of them unique, e.g., cryovolcanism, see Figure 4). Many of these processes tend to smooth out the surface; examples include a) flow of regolith and dust material along cliffs and in consequence to seismic activity, b) chemical weathering (that causes the darkening of surface material), and c) weathering due to solar wind (that happens on a scale of just a few My) [32]. The result is that most small bodies are characterized by an albedo less than 0.1. However, pictures of surface

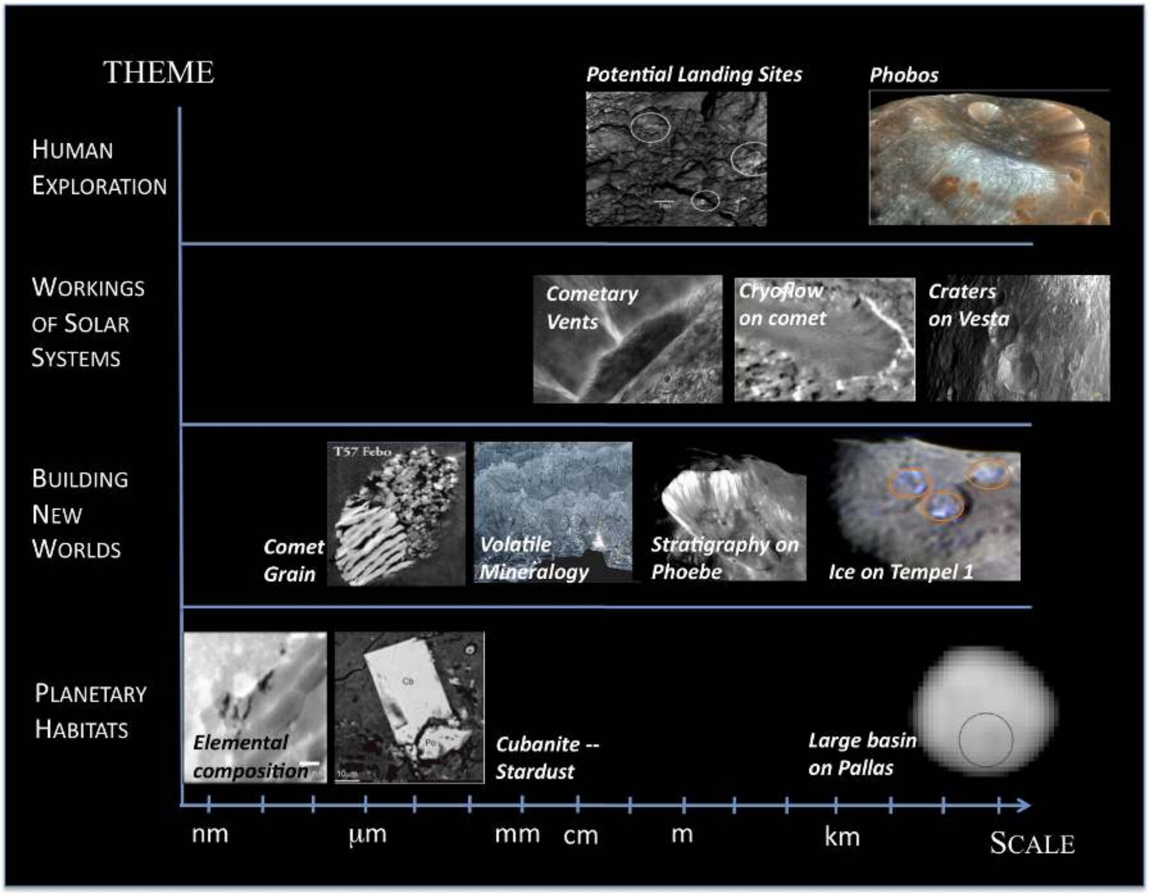

Figure 2. Illustration of the type of observations to be achieved by space missions in order to successfully address the key science pertaining to the three cross-cutting theme highlighted in *Vision and Voyages*. Note that in general we lack high-resolution observations at the mm to the meter scale that can be best obtained by in-situ exploration.

overturn and landslides indicate that the dark layer is only a few microns to a few meters thick (see Figure 3a, 5) [33].

Another important process is cometary outgassing, whose driving mechanism has not been fully elucidated. This process depends in part on the nature of volatiles present on comets, and in particular on the way such volatiles are trapped: either encaged in clathrate hydrates or adsorbed in amorphous ice.

In giant planet systems, small bodies represent satellitesimals (inner regular satellites) or captured outer Solar system planetesimals (irregular satellites); the observation of their dynamical interactions have allowed to contrain the dissipative properties of giant planets [34] and the accretional mechanisms in planetesimal belts [20]. In this regard, an important process (subject of intense research) is represented by tidal dissipation in icy satellites; understanding the nature of the mechanisms driving this process would help better constrain the evolution of these satellites and of the planetary system as a whole. Furthermore, in the outskirts of giant planet systems, irregular satellites offer a natural laboratory for the observation of collisional processes.

Small Bodies and Human Exploration

Small bodies (especially NEOs) are also central to the President's Vision of sending humans to Mars within the next decades. In fact, given their vicinity (for NEOs) and low gravity, they represent ideal targets for precursor missions. Besides NEOs, Mars' moons Phobos and Deimos are also envisioned as key targets for Human exploration (see Table 1).

3. MEASUREMENTS AND INSTRUMENTS TO FULFILL SCIENCE OBJECTIVES AT SMALL BODIES

As discussed in the previous section, small bodies are, *collectively*, ideal exploration targets to address all of the themes of the decadal survey report. On the other hand, small bodies represent a vast and varied class of planetary objects, and each subclass is particularly relevant for a subset of the objectives summarized in the traceability matrix in Table 1. In this section, we consider three classes of small bodies: 1) asteroid and irregular satellites, 2) comets, and 3) near-Earth objects (NEOs). Key science to be achieved at these bodies is summarized in Table 2 (for asteroids and irregular satellites), Table 3 (for comets), and Table 4 (for NEOs). These science objectives have been formulated based on the wealth of data provided by past space missions; these missions have demonstrated that small bodies present a significant diversity in surface properties, whose exploration is the obvious next step.

For each science objectives we discuss the types of measurements and instruments that would be required (with an emphasis on in-situ measurements). Note that the results in this section are based on our state of knowledge for the limited number of objects that have been visited by spacecraft so far. Hence, as new close-range information becomes available, these results should be updated accordingly. A key finding from our analysis is that *in-situ* exploration (especially at several key designated locations) is *pivotal* to constrain the characteristics of small bodies. Indeed, part from sample return architectures, the in-situ exploration of small bodies is in its "technological infancy", but is poised to become a major science enabler in the near future.

Measurements

Essentially, constraining the origin of a small body is achieved with three different types of observations:

- density of the object,
- dynamical properties of the object,
- characterization of volatile composition and isotopic ratios.

In many cases, a basic information such as the object's density is indicative of its origin. For example, in [35] the authors inferred from Phoebe's relatively large density (1.67 g/cm^3, against 1.24 g/cm^3 that is the average for Saturn's medium-sized moons) that this irregular satellite is a captured transneptunian object. Then, in [20] and [36] the discrepancy between the densities of Saturn's inner moons and that of Titan has been reconciled by suggesting, respectively, that the former formed from Saturn's ring material and that the latter formed from Phoebe-like planetesimals. However, in general, *the information contained in the density observation is limited*. For example, Phobos' relatively large density is puzzling scientists and cannot be unambiguously interpreted in terms of chemistry.

A more advanced and informative type of observation concerns the dynamical properties of an object. For example, captured objects are likely to present extreme orbital properties (compared to the orbital properties of regular bodies). In particular, the various populations of small bodies can be identified (see, e.g., [37]) as a function of their Tisserand parameter[6]. Astronomical observations (ground-based and space observatories) are particularly suited for characterizing the orbital properties of large populations of objects. However, *observations purely relying on orbital measurements could not be sufficient to constrain the origin of an object*, since resonances can also dramatically alter orbital properties. In this regard, the situation of the large main belt asteroid Pallas is particularly insightful. With a comet-like Tisserand parameter of just about 3, Pallas has the dynamical characteristics of a captured asteroid. However, capturing such a large object would have been extremely difficult, and an alternative explanation may be that Pallas has gone through a recent resonance that pumped up its inclination [29]. Conversely, Phobos' eccentricity and inclinations are small and are difficult to reconcile with the long-held scenario that this irregular satellite is a captured asteroid as suggested by its spectral properties [38].

Arguably, the most direct approach for determining the origin of migrated and captured bodies is characterizing their volatile composition and isotopic ratios. Volatiles and organics may be identified by searching for signatures of hydration and by measuring the C-H and C-C spectral bands in the near infra-red (NIR) and mid infra-red (mid-IR). Other techniques require sampling the material, either from an orbiter or in-situ. As examples of these techniques, gamma-ray and neutron detection provide elemental composition and are particularly suited for detecting the presence of deep water. On the other hand, isotopic ratios can be determined with the use of a mass spectrometer sampling outgassing material. However, most small bodies are not outgassing and do not present enough exospheric density to allow such measurements. As a consequence, *the measurement of isotopic ratios for a large class of small bodies requires in-situ exploration*; current techniques include the aforementioned mass spectrometry (MS), laser-induced breakdown spectroscopy (LIBS), and tunable laser spectroscopy (TLS).

In Situ Sampling Driving Science Return

The science objectives summarized in Tables 2, 3, and 4 have been formulated based on the wealth of data provided by past space missions; these missions have demonstrated that small bodies present a significant diversity in surface properties, whose direct exploration is the obvious next step. This implies that for a given science objective the exploration of *designated* and *multiple locations* should be an integral component of a mission. Also, it is important to note that the nature of the heterogeneity to be sampled depends on the exploration goal: some bodies may be chemically homogeneous but very heterogeneous when it comes to devising Human exploration strategies.

The importance of sampling mutiple (diverse) and designated locations is illustrated by a few examples presented in Figures 3, 4, and 5.

Multiple Location Sampling—For example, Comet Hartley 2 exhibits two regions: very granular areas with vents and smooth areas that have been interpreted as wasting areas (Figures 4a, 4b). While these areas would be easier to sample (less risk), they are probably less interesting since they result from the accumulation of fine surface material ejected from the active areas. Comet Tempel 1 presents four distinct geological units; in particular, it exhibits cryoflow features (that are products of geological evolution) near areas that appear to be less evolved and may be more representative of the original material. Hence, a spatially-extended exploration of Tempel 1 would be key to capture information on the accretional environment of that object as well as on its long-term evolution. Additionally, spatially-extended coverage may also imply sampling the various components of a planetary system, for example, the two components of a binary asteroid system, or a subset of asteroids within the main belt (to probe the chemical gradient, which plays a special role in the Nice model [39]), or several NEOs during the course of one mission in order to evaluate the diversity of physical properties). In situ exploration of Phobos would most probably solve the

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[6] Tisserand's parameter is defined as

$$T := \frac{a_P}{a} + 2 \cdot \sqrt{\frac{a}{a_P}(1-e^2)}\cos i,$$

where a is the semi-major axis, e is the eccentricity, and i is the inclination relative to the orbit of a perturbing larger body with semimajor axis a_P (the perturbing body could be, for example, Jupiter). Pallas's Tisserand parameter relative to Jupiter is stable at 3.01 (against, e.g., 3.65 for Ceres), while anything below 3 is considered "cometary".

Objectives	Observations	Measurements	Architecture
Constrain accretional environment	Density, volatile composition, isotopic ratios	Radio science, NIR, mid-IR, TIR, MS, TLS/LIBS, Raman	Orbiter, in-situ
Constrain dynamical evolution	Orbital properties, cratering properties, rotational properties	High resolution imaging (WAC+NAC), gravity	Orbiter, surface beacon
Characterize surface environment	Fields and waves	MAG, RPWS	Orbiter
Evaluate astrobiological potential	Geological activity, biomakers, outgassing, magnetic field	High-resolution imaging, NIR, mid-IR, UV, MS, MAG	Orbiter, in-situ

Table 2. Asteroids and irregular satellites.

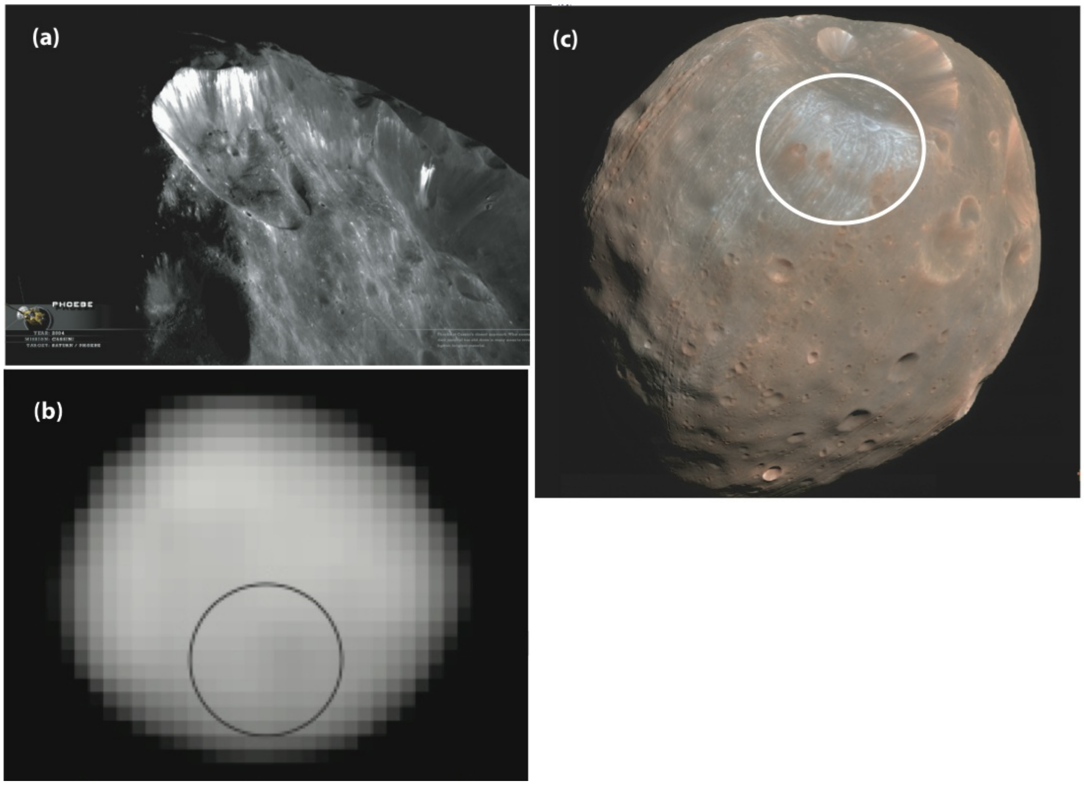

Figure 3. These pictures capture the chemical and physical diversity observed at asteroids and irregular satellites. (a) North pole of Saturns satellite Phoebe obtained by the Cassini-Huygens mission; while the satellites albedo is less than 0.1, high-albedo material can be seen on crater walls, which suggests that the dust cover is only a few tens of meter thick (Credit: NASA/ISS/CICLOPS). (b) Pallas surface as seen by the *Hubble* Space telescope [30]; the circle indicates a low-albedo area associated with a large impact basin. (c) Phobos by HiRISE on the Mars Reconnaissance Orbiter; lateral variations in color properties suggest that Phobos material has different origins (Credit: NASA/University of Arizona).

Objectives	Observations	Measurements	Architecture
Distinguish signature of accretion environment from evolution processes, identify sampling sites	Quantify diversity and relationship between units	High resolution imaging and spectral mapping, fine chemical properties (APXS, Raman, UV, XRD)	Mapping from orbiter followed by sampling at multiple selected areas
Identify genetic relationship with other volatile-rich bodies	Volatile and isotopic composition	High resolution imaging (WAC+NAC), gravity	Reconnaissance of water-rich areas by orbiter followed by in-situ measurements
Understand the processes driving cometary activity	Study venting area and relationship with the environment	UV imaging, high-res imaging	Orbital identification of venting features followed by in-situ measurements of dynamic events by multiple redundant surface assets (in order to decrease risk)
Characterize astrobiological significance	Characterize environment, search for hydrothermal signature	Raman/LIBS, APXS, mid-IR, XRF/XRD	In situ measurements at multiple locations since orbital reconnaissance is difficult

Table 3. Cometary science and relevant instruments and architecture.

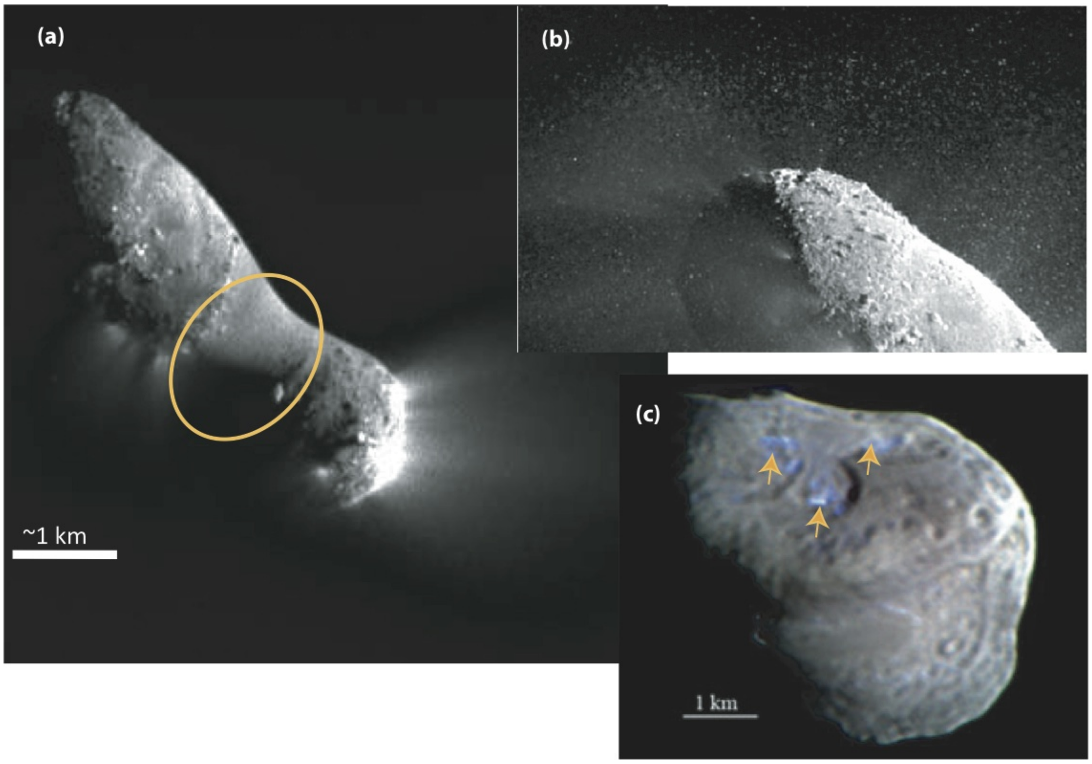

Figure 4. Illustration of the variety of landscapes found at comets. (a) Picture of Hartley 2 obtained by EPOXI showing a contrast in surface roughness between active and waste areas. (b) This close up shows the variations of physical properties, especially roughness, at all scales. (c) In this close-up picture of Tempel 1 observed by Deep Impact lateral variations in chemistry (ice and dust) occurs on short spatial scales.

Objectives	Observations	Measurements	Architecture
Determine surface mechanical properties	Soil competence, granularity at all scales, gravity	High resolution imaging, gradiometer, mechanical tester	Reconnaissance with orbiter, track rover's motion and interaction with dust
Search for in-situ resources	Chemical and mineralogical composition	NIR, GRaND, APXS	Remote sensing from orbiter, in-situ characterization at selected sites
Characterize risk and search for mitigation approaches	Waves and fields (e.g., electrostatic field), dust dynamics	UV imaging, high-res imaging	In situ
Understand and simulate human activities in low-gravity environment	Simulate digging, sampling	Performance	In situ

Table 4. Near Earth Objects.

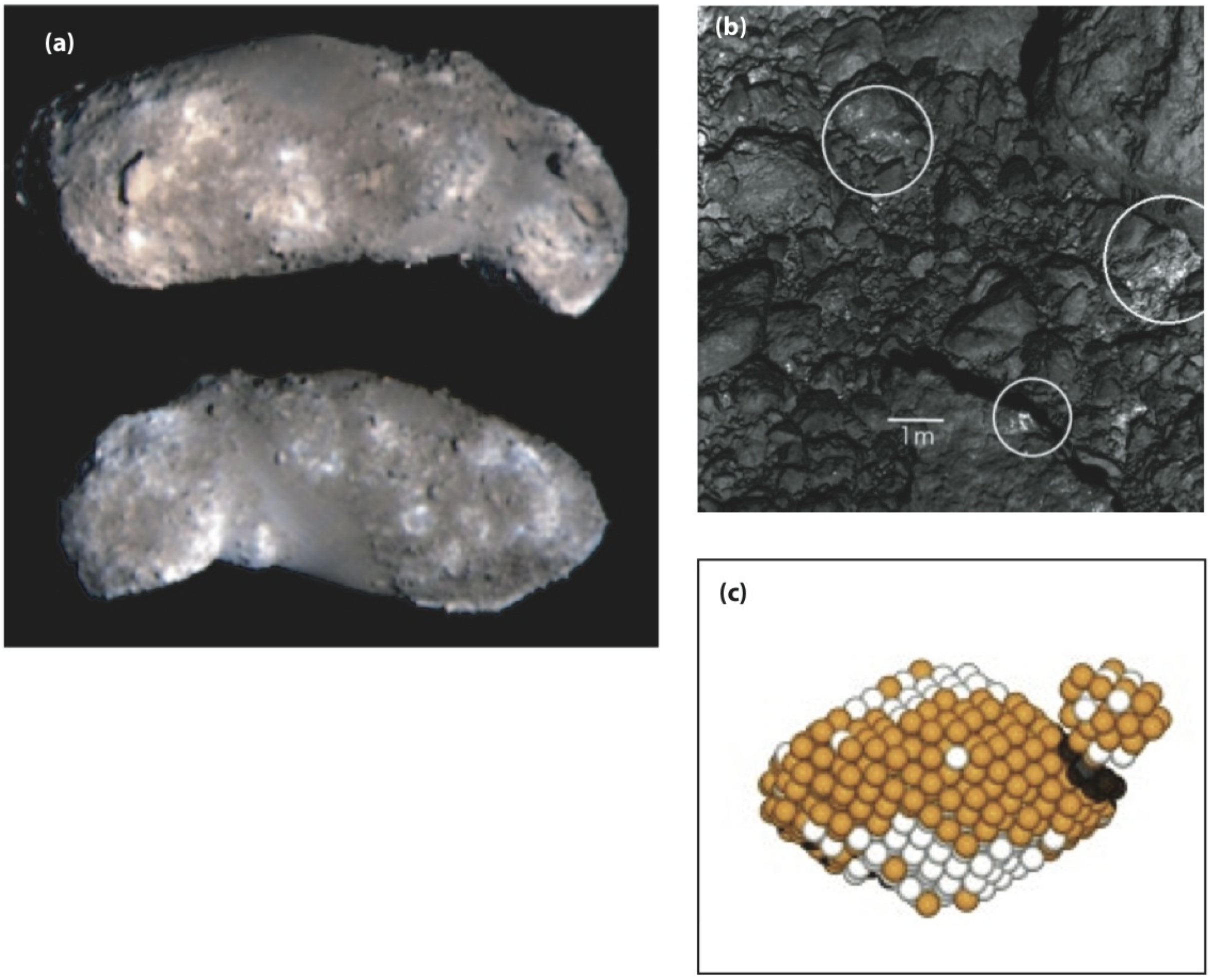

Figure 5. (a) Chemical and physical property variations observed at the surface of Itokawa by the *Hayabusa* mission. The surface shows significant lateral variations in roughness determined in large part the gravity field. Local surface overturn (due to landslides or impacts) has exposed fresh material whose high albedo significantly contrasts with the overall dark color of the asteroids weathered surface. (b) High-resolution view of the surface illustrating the hazardous conditions presented by that type of bodies to Human exploration. (c) Result of the simulation of binary asteroid formation [39] as a consequence of high-velocity spinning of the original parent body; spinning results in the redistribution of material from the equator to the poles and the exposure of pristine material (orange) buried below the regolith layer (white).

mystery of the origin of that satellite. However, the combined exploration of both Phobos and Deimos would lead to a far more fundamental understanding of the early history of the Martian system, the origin of Mars volatiles, and the genetic relationship between Mars and Earth.

Sampling Designated Locations—The capability of mobile elements to achieve specific, short-scale features (which would require fine mobility) would be of primary importance. An example is represented by craters; they are generally interesting locations to study because they present excavated material, which can represent either the bulk of the object near to a lag deposit or regoliths resulting from space weathering [40]. The latter is generally dark and is responsible for the low-albedo and spectral types observed from the ground (Figures 3c, 5a, 5b), hence the interest to study "fresh" material exposed by overturning of the surface. Other features of scientific importance are represented by ice-rich and/or organic-rich features (Fig. 4c), outstanding features such as ejecta, boulders, tectonic faults (e.g., Enceladus' Tiger stripes). In situ *reconnaissance* would also be an important component of potential future sample return missions, such as the *Comet Surface Sample Return*[7] and the *Cryogenic Comet Nucleus Sample Return* (CCNSR) [8] proposed in *Vision and Voyages*. Specifically, the decadal survey has identified very specific requirements on the nature of the material to be returned by the prospective CCNSR mission, which must contain at least 20% of water ice [1]. A possible strategy to ensure this requirement would be to analyze the samples onboard the spacecraft (or within the sampling device, if this could be equipped with analytical instruments). However, such a strategy implies that several sites would have to be sampled prior to selection, with very high risk associated. An alternative would be to send one or multiple landers to identify compelling sample sites of the surface prior to sampling. When examining mission trades, it is important to note that high science return may imply high risk. For example, crater slopes exposing fresh material (Fig. 3a) or comet outgassing areas where chemistry is expected to be relatively pristine (one could measure volatiles directly at the source) are extremely hazardous areas for an hypothetical rover. Rovers could also help assess the risk posed by certain environmental conditions, such as electric charging and dust levitation.

Discrete vs. Continuous Sampling— When talking about spatially-extended measurements, it is important to recognize the distinction between discrete sampling over a broad scale and continuous sampling (in other words, it is important to specify the sampling frequency). Understanding the origin of certain geological features requires continuous sampling at the regional scale in order, for example, to understand the nature of the interface between two spectral or geological units.

4. SCALING OF SCIENCE RETURN AS A FUNCTION OF SURFACE COVERED BY IN-SITU PLATFORMS

As discussed in the previous sections, in-situ and spatially-extended exploration would be instrumental to fulfill the objectives of the decadal survey. In this final section we exclusively focus on in-situ exploration, and we aim at characterizing (at least notionally) how the science return would scale with the amount (and type) of surface that is expected to be covered by a robotic mobile platform (i.e., by a rover). To this purpose, we first describe available concepts for in-situ exploration of small bodies, and then we discuss with two examples the scaling for science return.

Mobile Platforms for In-Situ exploration

Even though no mission so far has landed a mobile platform on the surface of a small body (the hopper onboard the *Hayabusa* mission, in fact, failed during its deployment), several concepts have been proposed in the recent past. Mobility platforms can be divided into four class, depending on the type of actuators.

Thruster Mobility—Mobility via thrusters is the key actuation mechanism for the Comet Hopper (CHopper) mission concept, which has been recently preselected for a NASA Discovery-class mission to comet 46P/Wirtanen [41]. If selected, the mission is baselined to be launched in 2016. CHopper would land multiple times (4-5 times) on the surface of the comet to investigate changes with heliocentric distance. Specifically, the spacecraft would descend to the surface and subsequently hop twice. Each landed operations campaign would last a few days, collecting science from all instruments. The sortie would conclude when the spacecraft lifts off the surface and resumes far operations. Possible drawbacks of this architecture include the risk of damaging the orbiter during landing, the limited number of locations that could be visited, and the limited mobility once on the surface (which, combined with the uncertainty in the landing ellipse, implies that the visited locations could be fairly nonspecific).

To overcome such limitations, it has been suggested to have a mother spacecraft deploy hopping rovers that would use thrusters for mobility [42]. The main drawback of this architecture is its mechanical and operational complexity, and the fact that hovering at very low gravities can be extremely challenging.

Wheeled Mobility—Wheeled vehicles have been extremely successful for the exploration of Mars. However, because of the very low traction, wheeled vehicles do not allow for fast and precise mobility on small bodies. An example of wheeled vehicle for small bodies exploration is represented by the MUSES-CN rover [43], which was designed by NASA-JPL and planned to fly onboard the Hayabusa mission (this project was however cancelled before flight). The MUSES-CN rover, a 4-wheel vehicle, was a direct descendant of the Sojourner rover used in the Mars Pathfinder mission. Because of low traction, the MUSES-CN rover was bound to speeds less than 0.0015 $\mathrm{m/s}$; for this reason, a hopping capability was also envisioned.

The main issues with wheeled vehicles are that they are bound to very low speed, it is fairly complicated to maintain the wheels in contact with the surface (and, hence, to ensure fine mobility to selected targets), and they are sensitive to dust contamination (since the wheels could become "stuck").

Legged mobility— Legged systems are probably the least suited for the exploration of small bodies, at least in the near (10-20 years) future. The main drawback of legged systems is that they are mechanically complex and they require some form of anchoring system. However, since the soil properties are largely unknown before launch, designing legs with good

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[7] This mission is prioritized by the decadal survey as one of the possible New Frontiers missions for this decade.

[8] This flagship mission has been identified as a key priority by the small bodies community [14]; however, it can not be accomplished with the existing technology.

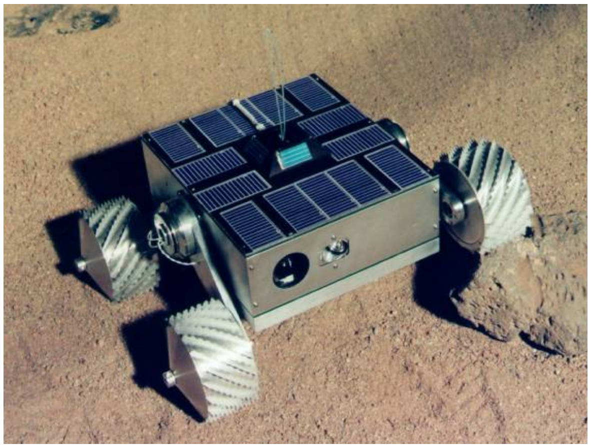

Figure 6. MUSES-CN rover [43].

grasping properties is challenging.

Hopping mobility—There are two basic principles of hopping:

1. The hopper uses a sticking mechanism (thus jumping away from the surface).
2. The hopper moves an internal mass.

Two missions so far have included a robotic hopper as part of their payload: Phobos 2 [44] and Hayabusa [12]. Phobos 2 was a Soviet mission aimed at studying Mars and its moons Phobos and Deimos. The plan was to deploy in close proximity to the surface of Phobos a 41 kg robotic hopper (called PROP-F, see Figure 7). Its actuation was based on a spring mechanism sticking the surface (according to principle 1)). Unfortunately contact with Phobos 2 was lost shortly before the deployment of PROP-F. The Hayabusa mission, instead, carried a robotic hopper actuated according to principle 2). Specifically, Hayabusa's robotic hopper, called MINERVA, was actuated through a spinning flywheel mounted over a turntable, and was considered capable of achieving speeds as high as $0.1\ \mathrm{m/s}$. Unfortunately, the deployment of MINERVA failed as well. NASA-JPL has developed in the past several generations of robotic hoppers actuated by sticking the surface [45]. ESA is currently developing a small hopper rover (called MASCOT [46]) meant to be the payload of the Hayabusa Mk2/Marco Polo mission. MASCOT is actuated by spinning two eccentric masses. All of these platforms are designed for exploring extended areas, however they do not include an option for fine mobility.

The key advantage of hoppers is that, with a fairly simple actuation mechanism, they are capable of large surface coverage. Moreover, they are fairly insensitive to the soil characteristics. Indeed, one can recognize that hoppers exploit the low gravity to their advantage, rather than facing it as a constraint. One advantage of hoppers moving according to principle 2) is that all actuation is internal, which significantly reduces the problem of dust contamination and thermal control. For these reasons, if one is able to include the option of fine mobility, hopping robots with internal actuations could represent a good trade-off between performance and complexity (see also an analogous conclusion in [47]).

Summary— Even though no mission so far has landed a mobile platform on the surface of a small body, the development of a rover for spatially-extended in-situ exploration should be possible with current technology. Most likely, this rover would use some form of hopping, which should ensure horizontal speeds in the order of $0.1\ \mathrm{m/s}$ (mobility accuracy is a current research topic). Assuming a lifetime of about 10 hours (as scheduled, for example, for MASCOT [46]), surface coverage in the order of 1-2 km should be possible.

Figure 7. PROP-F Phobos hopper [44] .

Scaling of Science Return as a Function of Surface Mobility

In the previous sections we have discussed several options for in-situ exploration, and we have argued that surface exploration in the order of, at least, 1-2 km should be possible. In this final section, by considering two example targets, we explicitly discuss how the projected science return would scale with the amount and type of surface that is covered (in other words, with the amount and type of mobility). Note that, in the following, the relative contribution of each platform is notional, based on the expected capability of each architecture to achieve the observations described in Figure 2.

The first example concerns the exploration of Phobos (see Figure 8 for the scaling of the science return). In the case of Phobos, in-situ exploration should aim at characterizing the nature of the four (or five) spectral units identified from observation with the *Mars Express* Planetary Fourier Spectrometer [48]. The red material covering most of Phobos' surface may be of exogenic origin, while the blue spectral unit (exposed around the Stickney crater) may represent the bulk of the material. However, at this stage, the chemical composition of these materials is not constrained, despite a large number of remote sensing observations obtained with a variety of instruments. At this stage, it seems that ground truth measurements would be necessary to constrain the nature and origin of these materials.

The second example focus on the exploration of a comet, namely Tempel 1 (see Figure 9 for the scaling of the science return); we chose Tempel 1 since its surface properties have been extensively studied by the *Deep Impact* mission. This object is particularly interesting due the presence of water

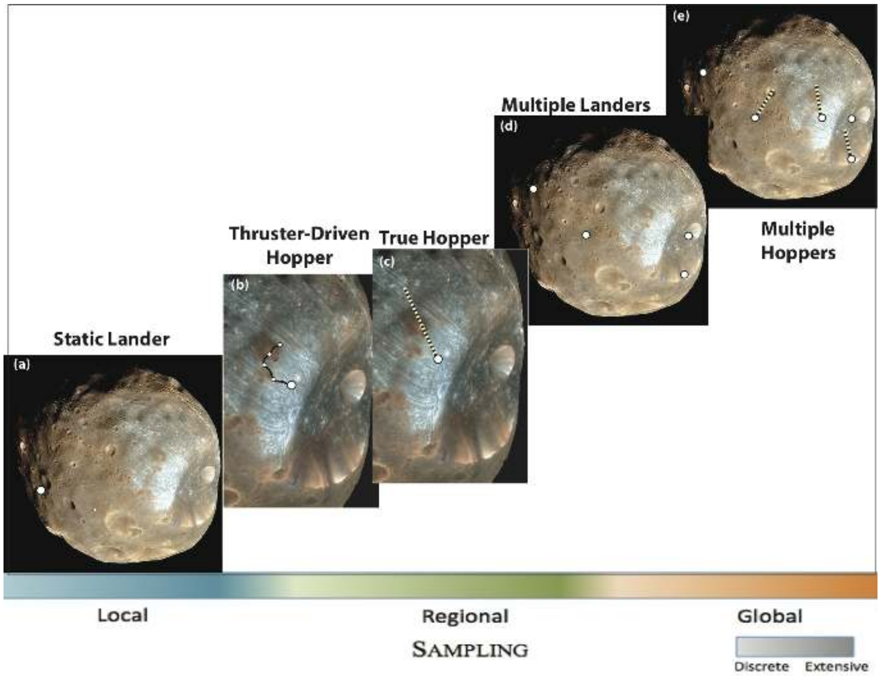

Figure 8. Schematic representation of the surface coverage offered by the different in-situ architectures discussed in Section 4. (a) One of the landings sites considered for *Phobos-Grunt*, which was planned to sample the red dust, whose origin (endogenic or exogenic) is unknown. (b) Discrete sampling by a hopper that would randomly travel from one area to another. (c) Continuous sampling by a rover that would be able to observe in detail the relationship between the red and blue material. (d) Exploration of the various spectral units observed on the Phobos' surface by multiple static landers; if these landers are properly instrumented (e.g., mass spectrometer, LIBS), the origin of each unit and their genetic relationships may be constrained. (e) Same as (d), but now considering mobile rovers that could capture the relationship between different materials at various scales.

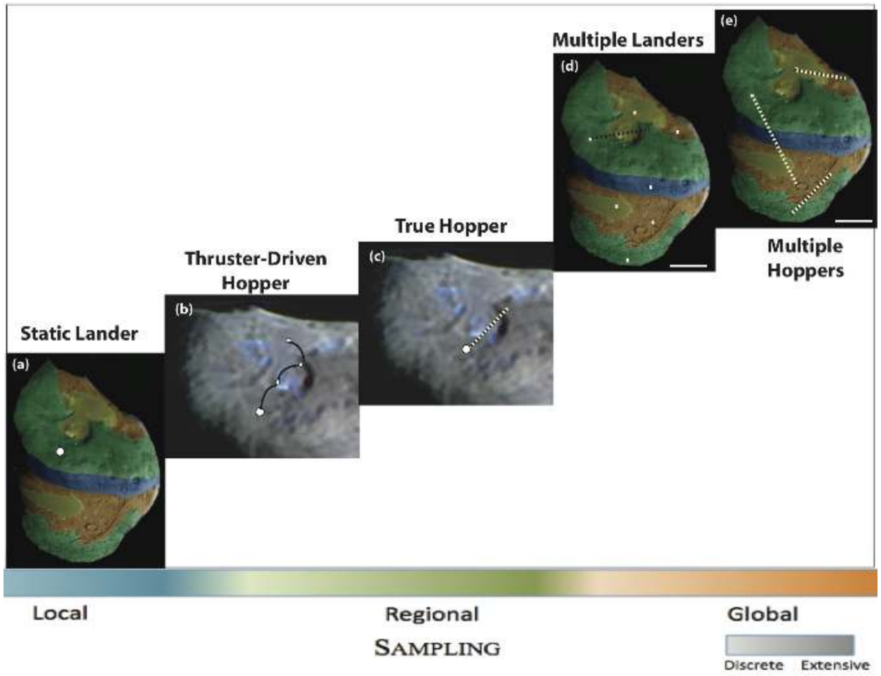

Figure 9. Same as Fig. 8 but for the case of comet Tempel 1.

ice on or near the surface in several areas; also, remote observations show a ridge and outstanding geological features, such as cryoflow-like features (see image in Figure 2) that are the signature of long-term evolution processes. Hence, in-situ exploration of comets should strive to access several sites in order to capture the complexity of these objects and constrain the processes that led to their formation and evolution. Random sampling from one region to another may help capture this complexity. However, continuous sampling from one region to another would lead to deciphering the stratigraphic relationships between these regions, thus significantly increasing the science return of the in-situ mission.

5. CONCLUSION

In this paper we have presented an initial study of the expected science return of spatially-extended in-situ exploration at small bodies, as a function of surface covered and in the context of the key science priorities identified by the decadal survey report. The conclusion is that spatially-extended in-situ information about the chemical and physical *heterogeneity* of small bodies has the potential to lead to a much improved understanding about their origin, evolution, and astrobiological relevance.

This paper leaves a number of important extensions open for future research. For example, it would be interesting to characterize the scaling of science return with respect to surface covered for a larger set of objects. Also, in-situ science is a function of available instrument technology (validated for small bodies environment), a point that we barely touched upon in this paper. Finally, the results of this paper prompt for further technology advancements toward the development of affordable and versatile mobility platforms for in-situ exploration.

ACKNOWLEDGMENTS

This study was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA, and supported by NASA under the Innovative Advanced Concepts program. Government sponsorship acknowledged.

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