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Human and Robotic Mission to Small Bodies: Mapping, Planning and Exploration

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Abstract

This study investigates the requirements, performs a gap analysis and makes a set of recommendations for mapping products and exploration tools required to support operations and scientific discovery for near-term and future NASA missions to small bodies.

The mapping products and their requirements are based on the analysis of current mission scenarios (rendezvous, docking, and sample return) and recommendations made by the NEA Users Team (NUT) in the framework of human exploration. The mapping products that satisfy operational, scientific, and public outreach goals include topography, images, albedo, gravity, mass, density, subsurface radar, mineralogical and thermal maps. The gap analysis points to a need for incremental generation of mapping products from low (flyby) to high-resolution data needed for anchoring and docking, real-time spatial data processing for hazard avoidance and astronaut or robot localization in low gravity, high dynamic environments, and motivates a standard for coordinate reference systems capable of describing irregular body shapes.

Another aspect investigated in this study is the set of requirements and the gap analysis for exploration tools that support visualization and simulation of operational conditions including soil interactions, environment dynamics, and communications coverage. Building robust, usable data sets and visualisation/simulation tools is the best way for mission designers and simulators to make correct decisions for future missions. In the near term, it is the most useful way to begin building capabilities for small body exploration without needing to commit to specific mission architectures.

1 Introduction

The main goal of this study is to investigate and describe the set of mapping tools, mapping products and 3D visualization and simulation tools needed in planning, exploration and scientific discovery by near-term and future NASA missions to small planetary bodies.

These bodies include asteroids, comets and irregular satellites. The accurate determination of shape and dynamic models before or during the mission is essential for understanding the lighting conditions, direct communication between the Earth and the small body and its vicinity, and the state of debris in the vicinity of the small body. This information together with higher resolution mapping products plays a crucial role in approach, docking or anchoring, and surface operations. The required mapping products include topography, images, albedo, gravity, mass, density, subsurface radar, mineralogical, thermal maps, and associated accuracy maps for all of these. These mapping products will be used to satisfy operational, scientific, and public outreach goals. To achieve their full potential these mapping products require high accuracy at the highest achievable resolutions and accurate registration to existing maps. Real-time processing and mapping is required for local map generation, astronaut localization, and obstacle avoidance. Figure 1 illustrates the mission instruments, the mapping products that are obtained from them, and the role of these mapping products in mission operations.

Several products and tools to make them have been developed by other US or international government centers and universities using various approaches and computing platforms which makes them difficult to use in an operational way. An important objective of this study is to identify the gaps and requirements for an integrated system that will support near-term and future NASA missions to small planetary bodies.

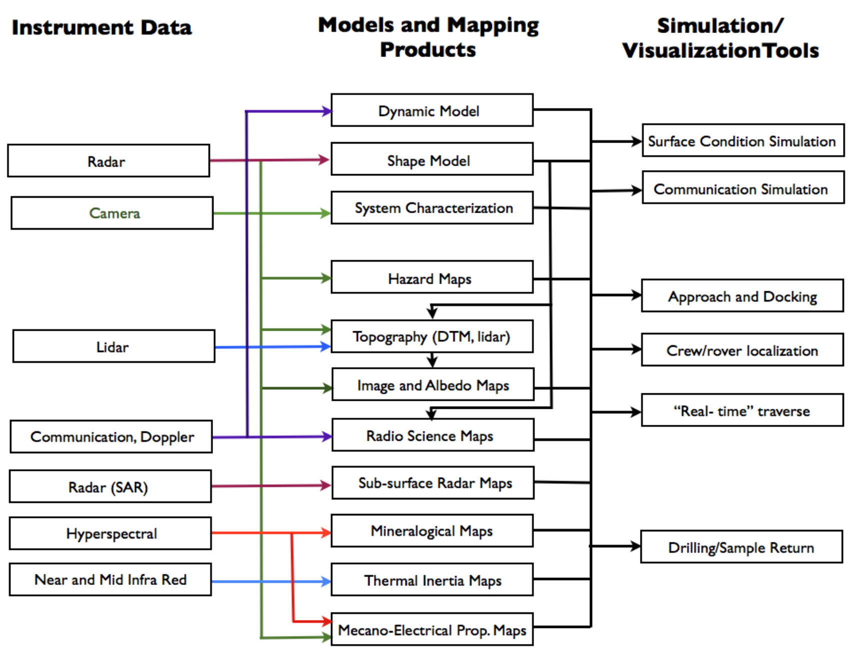

Figure 1. The mapping products in small planetary body exploration

This paper is organized as follows: Section 2 describes current and future mission scenarios; Section 3 describes the constraints and requirements for each of the discussed mission scenarios. Section 4 presents existing data products, processing and visualization tools. Section 5 and Section 6 describe a set of recommendations and gaps for data products and visualization/simulation tools required for mission operations.

2 Mission Scenarios

Human, robotic, and combined human-robotic mission scenarios drive the requirements for the mapping products and visualization tools described in this study. The mission scenarios discussed in this section are grouped in three categories based on their approach to the target body and exploration objective: rendezvous, docking/landing, and sample return. In each of these cases, due to the complex and dynamic nature of an Near-Earth Asteroid (NEA) environment, data processing may need to be done in real time (or near real time) on board the spacecraft itself.

2.1 Rendezvous

Robotic precursors would be launched prior to crewed missions in order to qualify the NEA destination(s) and obtain preliminary engineering information such as the target orbit, the spin state, debris field, and surface/subsurface electro-mechanical properties.

Figure 2. Human exploration at NEAs ([35]).

The small body environment is quite different from that of a planetary body. Variations in gravity (due to the sum of the gravitational attraction of the asteroid and centrifugal force if on the body, and the influence of other bodies such as the sun) are much larger relative to the central gravitation force than on larger bodies. These objects usually have distorted shapes, may be associated with a variety of different spin states, and may be composed of multiple bodies in contact or close orbit. In addition, comets can have outburst activities on their surface. Hence, due to the non-uniform gravity field and the importance of external forces, orbital motion may quickly transition from stable to unstable as the deviations from a nominal orbit can grow exponentially, and lead to particle impact or escape from the small body [21].

Rendezvous at small bodies is assumed to include target acquisition and approach, and multi-resolution mapping. A robotic spacecraft approaching the target would scan the system for potential debris or other smaller satellites, and then refine proximity operations plans. Low-resolution shape and system dynamical models are developed while still being located at large distances from the body. Depending on the target size, the proximity operations may include orbiting the target, hovering, or performing slow hyperbolic flybys. Characterization at low and high resolution includes remote sensing images from kilometer to centimeter scale, over the visual and infrared spectrum for shape modeling, topographic maps, gravity maps, composition, and thermal mapping. Information about the internal structure of a body can be obtained via radar imaging with transmit and receive satellites or landed stations. Additional information on surface composition and element counts can be obtained from gamma-ray and neutron spectrometers, and alpha particle x-ray spectrometers when in close proximity [73, 86]. Active remote instruments such as Laser-Induced Breakdown Spectroscopy (LIBS), raman, and fluorescent spectroscopy may be possible across distances of several NEA radii. However, integration times are limited from orbit, and hence instrument sensitivities will be likewise limited.

Crewed missions at asteroids (Figure 2) could spend between 14 and 30 days in close proximity [35]. Due to the short stay time, the NEA needs to have been well characterized and new data must be processed quickly in order for the crew to approach quickly; there won't be much time for data processing. The target orbit needs to be well known for navigating directly to it, while the small body environment needs to be clear of debris for approach and surface activities. Astronauts may perform Extra-Vehicular Activity (EVA)s in proximity of the NEA for remote observation, spacecraft maintenance, and in-orbit experiments. For this, the spacecraft can maintain a hovering state at a few kilometer distance. The crew may then deploy surface probes and perform remote experiments on the surface before reaching it themselves.

2.2 Docking and Landing

When surface activities are planned, the images returned from remote sensing instruments are processed to identify specific features for navigation, descent, and docking. Since the spin period of the small body may be on the order of hours and the spacecraft must adapt to rapidly changing dynamics, autonomy becomes essential for safe operations due to potentially long communication delays between the NEA and Earth. A robotic spacecraft will identify features from orbit, and then maneuver in the asteroid rotating frame to match the spin period of the target and dock to the surface. Simulations will have been done long in advance, and validated by rehearsals prior to the actual docking.

Past missions have revealed interesting dynamics, from the formation of ponds where small particles may be moved by surface charge and shadow regions [42], to Van der Waals forces being much stronger than cohesion forces compared to the small gravity field [24]. The compaction, density, and mechanical stability of the surface are critical parameters to know for preparing for crewed missions, as astronauts will need to anchor and interact with the surface. These properties can be roughly estimated from remote sensing prior to contact with the surface. Specific regions to be investigated will be identified from orbit.

Figure 3. Human interacting with a near-Earth asteroid, learning about the promise and risks of these primordial bodies ([35]).

Determination of the anchoring feasibility and related engineering conditions will be important prior to a human mission, as this can completely change the overall human mission operational architecture. Crewed operations (Figure 3) will have more extensive contact with the surface as multiple EVAs will be organized throughout the NEA stay time. Each EVA will last up to a few hours, and the spacecraft will stay in orbit between each surface activity. Astronauts may be tethered to the spacecraft or on the surface through anchoring devices. Extra care needs to be taken when moving surface material as any activities may shed material off the surface.

The objectives of the surface operations are to image and map the fine scale structure of the rocks and regolith, investigate the composition and resources, and prepare for sampling, necessitating a variety of tools and equipment. Both remote (e.g., impactors) and in-situ (e.g., drills) maybe be used to acquire subsurface material. As the surface material may exhibit significant space weathering, sampling at depth will be important to acquire “pristine” parent body material.

2.3 Sample Return

Collecting samples from surface (Figure 4) and subsurface layers depends heavily on the preparation done in orbit and on the surface. Specific sampling sites will generally but not in all cases have been identified long in advance, and multiple samples may be brought back. The sequence of operations and interactions with the surface will be precisely defined, and potentially planned over multiple EVAs. The samples may be brought onboard the spacecraft for further study by the crew, or kept sealed and cooled at cryogenic temperatures for Earth laboratories.

Due to the very small gravity field, any removal of rocks and regolith will disturb loose materials on the surface. As the environment is highly perturbed, the fate of these slow moving debris will be difficult to predict, although only temporarily, and at very low relative speed. Dynamic modeling and exploration tools are critical in the success of surface operations and the tracking of any newly generated debris.

Figure 4. Hayabusa sample return mission, courtesy JAXA.

3 Constraints and Requirements

Strategic Knowledge Gap (SKG)s for human missions to near-Earth asteroids have been identified by the Near Earth Asteroid User Team (NUT) and the NEA Working Group (NEAWG) [92, 93, 94]. These gaps represent an informed and systematic look at anticipated needs for human exploration, especially in terms of data or information that would reduce risk, increase effectiveness, and aid in planning and design of missions. They are further translated into requirements, listed in Table 1, which inform on strategic needs for data, mapping products, and exploration tools for human missions. Note that the SKGs and recommendations (Table 1) are currently being refined with input from the science communities, the Small Bodies Assessment Group (SBAG), the Lunar Exploration Analysis Group (LEAG), and the Mars Exploration Program Analysis Group (MEPAG). Also note that more instruments can be added in Table 1 but were not included in these first set of recommendations.

Table 1. NUT Recommendations

Target Qualification Knowledge Needs	Go, no go Criteria	Measurements Needed	Instrumentation Recommended
Required			
Orbit knowledge	OCC $= 0$ for HSF, if OCC > 0 then need OCC < 3, for precursor	OCC (U parameter)	High-res cam Radio tracking, radar obs. Space-based IR/Vis telescopes
System type characterization	No go, binary or satellites	Binarity/ternary determination	High-res cam Radar obs.
Spin state, mode Tumbling	Period (¿1.9 hr spin) Stable axis over 24 hrs	Albedo, lightcurve Measure tumbling	High-res cam Radar obs., IR telescope
Activity Debris field	Go, no go based on volatiles, outgassing, debris	Observe evidence of activity via surface interaction	WAC/NAC Vis/IR spectrometer Surface experiments
Internal structure Mechanical stability	Go, no go based on density and porosity (level tbd)	Porosity, density and mass/volume measurements Mechanical stability	WAC/NAC Radio science Surface experiments
Gravitational field	Go, no go based on internal structure Ops planning	Escape velocity Surface gravity Gravity interaction	Radio science, WAC LIDAR (3D), laser ranger Prox ops (2-4 wks, DSN, DV)
Highly Recommended			
Mineralogy Chemical composition	N/A	Surface spectrum Metallic properties	Vis/IR, neutron, X-ray Gamma Ray, APXS, FTIR
Dust properties Regolith mechanics Geotechnical properties	N/A	Particle distribution Dust levitation Compaction, shear	High-res camera UV/Vis spectr., surface exp. Dust collector, samples
Topography	N/A	Shape, slopes Surface relief	Laser ranger LIDAR (3D) High-res/stereo cam
Recommended			
Electrostatic	N/A	Electric field Electron/ion density Plasma potential	Electrostatic probes
Micrometeoroid flux	N/A	Flux measurement	High-res/IR camera Micrometeoroid exp.
Toxicity	N/A	Toxin compounds	Gamma Ray spectr. Vis/NIR spectr. Samples
Thermal properties	N/A	Thermal mapping	IR camera, radiometer Temperature probes
Illumination	N/A	Cycles, topography Pole orientation	High-res camera
Magnetic field	N/A	Magnetic field	Magnetometer

3.1 Remote sensing requirements

One of the most important operations performed with the spacecraft is radio tracking using Earth-based stations. For deep space applications, the Deep Space Network (DSN) antennas allow to retrieve the spacecraft position and velocity information, which refines the NEA orbit when the spacecraft reaches it. The Orbit Condition Code (OCC), or U parameter [13], associated with a NEA quantifies the knowledge of its orbit. It is calculated from orbital elements and errors on its position in space. In general, the OCC is correlated to the number of ground or space-based observations. Requirements are to bring the OCC down to 0 or 1, which is achievable by ground radar observation during a NEA close enough approach to Earth, but done more easily by a spacecraft tracked during rendezvous with the target.

Resolving the small body spin mode requires a high enough resolution and sampling rate. From ground-based surveys of small body spin periods, it has been shown that small bodies with diameters less than 100 m can have a rotation period between minutes and several hours [15]. A camera may need to sample images at 1-2 Hz in order to reconstruct the full motion of the body. A resolution of $\sim$1 m/pixel is enough for matching features and determining the spin axis orientation. The processing time will be longer if the body is tumbling. In certain circumstances, the spin state may be resolved a priori from the ground. However, in general it is not possible to fully resolve the body rotational direction, or spin vector, and distinguish prograde from retrograde rotation.

Determining the system type, single or multiple asteroid system, also requires high (optical or radar) image resolution. The smallest natural satellite observed to date is 60 m in diameter, for a primary body being 120 m in diameter (the Apollo NEA 2003 SS84). On the other hand, the highest small body primary to satellite size ratio observed is about 20. That is, there has been no observation of a natural satellite with diameter smaller than 20 times its primary ratio (see [45] for a list of compiled asteroids with satellites). Most ground-based radar observations obtained to date have resolution between 10 and 100 m/pixel, although in 2010 the highest resolution of 3.75 m/pixel was obtained using Goldstone [29]. For spacecraft mission, resolution in the order of meters/pixel is required for resolving any moon missed by ground-based observatories.

Due to the dynamics in the vicinity of an irregular small body being very chaotic [21], debris fields may be temporary orbiting the body at low speed. Imaging over the terminator and at high phase angles are best to determine debris hazards. High resolution camera and ultraviolet (UV)/visible (Vis) spectrometers are required.

Images obtained during approach and survey mapping activities serve in constructing shape models to high resolution when in close proximity operations. Topographic and digital elevation maps are obtained using altitude data retrieved using stereoclinometry techniques and range data using laser rangefinders or LIDAR, which can have three dimensions mapping capabilities and obtain data in dark regions. Sub-meter resolution will allow identification of rocks, craters, regolith variations, and local surface features, also critical information for surface and subsurface requirements (3.2).

Approaching the NEA also requires knowledge of the small body mass and gravity field for planning appropriate operations. This is first obtained partially through radio science techniques, using spacecraft radio tracking while in close proximity of the body. The observables are the change in velocity and bending of the trajectory as it is deflected by the gravitational field of the body. However, the resolution on the mass estimation depends on the small body overall mass. For bodies larger than a few hundred meters, 1% mass estimate accuracy is possible whereas other techniques may be needed for the very small NEAs of less than 100 m in diameter, particularly using surface probes [36]. Both mass and shape model estimates allow the determination of gravitational harmonic coefficients. For crewed missions, although the resolution needed on mass has not been clearly defined by the NUT, gravity field estimates to second degree and order are sufficient for docking operations and planning surface activities.

3.2 Surface and sub-surface requirements

As the spacecraft approaches the small body, a more refined resolution map is needed for building precise surface morphology and digital elevation terrain maps. During proximity operations, the navigation system will need to track features on the ground and match them to existing maps. The resolution has to suit both close approach operations and future terrain investigations to be performed by astronauts. Hence, image resolution of the order of tens of centimeters is needed.

A volume estimate combined with the overall mass of the small body results in a bulk density measurement, and can provide data to infer surface and sub-surface mechanical stability and properties such as compaction and porosity. Although the actual mass, density and stability resolution requirements have yet to be defined, refined measurements can lead to mapping gravity anomalies, such as Bouguer maps, and determine local-scale surface and subsurface density and geotechnical properties' variations. In addition, high-resolution observations of surface features such as craters, boulder orientation, and regolith distribution can give information on the mechanical stability and surface roughness. The regions where astronauts will dock need to be safe and have interesting features to explore, most likely on a flat terrain cleared of boulders, depressions, sharp slopes or craters where unstable soil may exist, though still in vicinity of those features for scientific measurements. Hidden buried rocks can be detected through thermal imaging and radar mapping.

In addition, astronauts may need knowledge of the potential mineral content to further investigate and then choose samples to be carried back to Earth. Hence, sub-meter to sub-cm scale imaging is required to construct those composition maps, in wavelengths from visible spectral bands to infrared due to the possibly low albedo of the small body. Chemical composition can also be obtained using neutron, x-ray and gamma-ray spectrometers and hyperspectral mapping. Past experience with the NEAR-Shoemaker mission has shown that a gamma-ray and neutron spectrometer can best be used on the surface. Other instruments such as Raman and fluorescent spectroscopy can also return composition information.

The fine scale structure and mineralogical composition of the surface need to be observed at millimeter resolution. This can only be done using surface probes or through a close-up or microscopic camera or hand lens. Similarly, the mechanical and electrical properties of the NEA can be obtained through surface and subsurface experiments, or during astronaut operations.

In the planning of operations, for both robotic and crewed missions, all these measurement requirements directly flow down to instrument and subsystem requirements.

4 Existing Data and Tools

A large amount of information is known about the population of small bodies, especially Near-Earth Object (NEO)s and Main-Belt Object (MBO)s from extensive Earth-based telescopic surveys. These ground-based data sets provide the initial information upon which more detailed missions are planned. Ground-based data can allow derivation of absolute magnitudes, light curves, dynamical properties, spin vectors, and spectroscopic identifications. Space missions have also returned a wealth of refined and new information, having either flew by or rendezvoused with these bodies. Table 2 provides a complete list, by year, of small body encounters, where a subset of those missions have or will have data products available for use in the Planetary Data System (PDS) [57]. Table 3 lists the small body corresponding data sets and derived products.

Table 2: Small body encounter and related missions (credit: NASA, ESA, JAXA).

Year	Missions	Agency	Targets	Encounter	Instruments	Objectives
1969	Mariner 7	NASA	Phobos	Flyby	Camera	Opportunity
1971	Mariner 9	NASA	Phobos	Flyby	Cam, UV spectrometer	Opportunity
			Deimos	Flyby	Cam, UV spectrometer	Opportunity
1973	Mars 5	USSR	Deimos	Flyby	electrostatic plasma sensor, spectrometer	Solar wind interaction
1976	Viking	NASA	Phobos	Flyby,	Camera, IR	Opportunity
			Deimos	Flyby	Camera	Opportunity
1985	ISEE3/ICE	NASA	21P/Giacobini-Zinner	Flyby	X/Gamma-ray spect.	Solar wind interaction
1986			1P/Halley	Flyby	X/Gamma-ray spect.	Solar wind interaction
1986	Giotto	ESA	1P/Halley	Flyby (596 km)	Camera	Image comet
1992			26P/Grigg-Skjellerup	Flyby (200 km)	Camera	Image comet
1986	Planet-A	JAXA	1P/Halley	Flyby (151 000 km)	UV, particle analyzer	Observation
1986	MS-T5	JAXA	1P/Halley	Flyby (7M km)	Plasma-wave, ion, magneto.	Solar wind study
1986	Vega 1-2	USSR	1P/Halley	Flyby (3000 km)	N/A	Science opportunity
1989	Phobos 2	USSR	Phobos	Flyby	Camera , spectrometer	Opportunity
			Deimos	Flyby	Camera , spectrometer	Opportunity
1991	Galileo	NASA	951 Gaspra	Flyby (1600 km)	Solid state imaging, NIR	Opportunity
1993			243 Ida and Dactyl	Flyby (2400 km)	Solid state imaging, NIR	Opportunity
1996			Phobos, Deimos	Flyby	Solid state imaging	Opportunity
1997	NEAR-	NASA	253 Mathilde	Flyby (1800 km)	X, G-ray, NIR, LRF, multispect.	1st NEA RV

Year	Missions	Agency	Targets	Encounter	Instruments	Objectives
2001	Shoemaker		433 Eros	RV, landing	X-ray, G-ray, NIR, LRF, multispect.	1st NEA RV
1997	MPF	NASA	Phobos	from Mars	Imager	Opportunity
			Deimos	from Mars	Imager	Opportunity
2000	Cassini	NASA	2685 Masursky	Flyby (1.5M km)	Saturn payload	Opportunity
2000	Mars Global Surveyor	NASA	Phobos	Flyby	Camera	Opportunity
1999	Deep Space 1	NASA	9969 Braille	Flyby (15 km)	Spect., mini camera	Tech. demo
2001			19P/Borrelly	Flyby (2200 km)	Spect., mini camera	Tech. demo
2002	Stardust	NASA	5535 Annefrank	Flyby (3300 km)	dust analyzer, monitor	Opportunity
2004			81P/Wild 2	Flyby, SR	dust analyzer, monitor	Return samples
2005	Deep Impact	NASA	9P/Tempel 1	Flyby, impact	Impactor, camera	Impact surface
2005	Hayabusa	JAXA	25143 Itokawa	RV, SR	LRF, LIDAR, NIR, X-ray	Return sample
2005	Mars Express	ESA	Phobos, Deimos	Flyby	Panoramic camera	Opportunity
2009			Phobos, Deimos	Flyby	Panoramic camera	Opportunity
2005	MER	NASA	Phobos	from Mars	Panoramic camera	Opportunity
			Deimos	from Mars	Panoramic camera	Opportunity
2008	MRO	NASA	Phobos	Flyby	HiRISE	Opportunity
			Deimos	Flyby	HiRISE	Opportunity
2010	WISE	NASA	NEOs, MBOs	Space-based scan	MIR	All-sky survey
2010	Astro-F	JAXA	NEAs	Space-based scan	IR cameras, filters	All-sky survey
2011	Dawn	NASA	4 Vesta	RV	Magneto., GRNS, MIR, LRF	Formation solar system
2015			1 Ceres	RV	Magneto., GRNS, MIR, LRF	Formation solar system
2011	Stardust-NExT	NASA	9P/Tempel 1	Flyby (200 km)	same as Stardust	Tempel 1 images
2011	EPOXI	NASA	103P/Hartley 2	Flyby	same as Deep Impact	Map comet
2008	Rosetta	ESA	2867 Steins	Flyby (800 km)	IR cameras	Opportunity
2010			21 Lutetia	Flyby	IR cameras	Opportunity

Year	Missions	Agency	Targets	Encounter	Instruments	Objectives
2014			67P/Churyukov-Gerasimenko	RV, landing	IR, dust analyzer, radar, and 10+ others	Nucleus, coma
2015	OSIRIS-REx	NASA	1999 RQ36	RV, SR	Cameras, LRF Vis/IR/Xray spectrometer	Return samples

4.1 Existing Data and Derived Products

Table 3 provides a comprehensive list of data and derived products available [18] for each of the small planetary bodies mentioned in Table 2. The table describes data made available by several missions to the same small planetary body and currently available data products (models and maps) in the PDS.

Table 3: Small body data and derived products, from ground-based g and space-based s observations [56, 57]. Other references are included in the table.

Small Bodies	Data	Derived Products
21P/Giacobini-Zinner	g: color/IR images/spectra, color/spectrophotometry, polarimetry radio occultation [17]	
1P/Halley	g: color/IR images/spectra, color/IR/spectrophotometry, polarimetry, radio occultation [17] s: color images, IR spectra solar wind/energy/dust/ion spectra, magnetism, radiowave, radio science	
26P/Grigg-Skejellerup	g: color/IR images/spectra long-wavelengths redundant s: color images, radio science [17]	
951 Gaspra	g: lightcurve, color spectra, spin s: color images, NIR spectra, solar wind/dust spectra	taxonomy mosaic, maps shape models [62, 69]
243 Ida	g: lightcurve, color spectra, spin s: color images, NIR spectra	taxonomy, binary state mosaic, maps, shape models [65]
1620 Geographos	g: lightcurve, color/NIR spectra polarimetry, spin, radar	taxonomy radar shape model [75]
253 Mathilde	g: lightcurve, NIR photometry radar, 3-micron, color spectra s: color/NIR images/spectra radio science	taxonomy mosaic, shape models [68]
433 Eros	g: lightcurve, photometry, color spectra radar, spin, polarimetry, 3-micron s: color/NIR images/spectra altimetry, radio science X/Gamma-ray spectra, magnetism	taxonomy mosaic, maps shape models [61, 76] Bouguer maps gravity model [43, 71]
2685 Masursky	g: color/NIR spectra s: color/NIR/UV spectra	taxonomy
9969 Braille	g: lightcurve, spin s: plasma/ions voltage/charge	
19P/Borrelly	g: lightcurve, images, photometry long-wavelength s: color images, SWIR/UV spectra plasma/ions charge, radio science	production rates elevation maps
5535 Annefrank	g: lightcurve, NIR photometry s: color/NIR images	
81P/Wild 2	g: color images s: color/NIR images,	maps, shape models [87]
9P/Tempel 1	g: lightcurve, color/NIR images	

Small Bodies	Data	Derived Products
	color/NIR spectra *s*: color/NIR images, microwave/UV/IR spectra, dust flux	 temperature maps/model [58] shape models [88]
25143 Itokawa	*g*: lightcurve, polarimetry, radar, spin, thermal IR images, NIR spectra *s*: color/NIR images/spectra, X-ray spectra, altimetry, radio science	 spectral maps [50, 52] shape models [38, 55, 61, 72] potential/slope maps [3, 23, 81]
4 Vesta	*g*: color/NIR spectra, photometry spin, lightcurve, polarimetry, radar, 3-micron *s*: color images, color/IR spectra Gamma-Ray/neutron data, radio science	taxonomy surface maps shape models [67]
1 Ceres	*g*: albedo, color/NIR spectra, lightcurve, spectra, polarimetry, photometry, radar, spin, 3-micron *s*: color images	taxonomy shape models albedo maps [40, 66]
103P/Hartley 2	*g*: color/spectrophotometry, short/long-wavelength, color spectra *s*: IR spectra, color/NIR images	production rates not yet available
2867 Steins	*g*: lightcurve, polarimetry, magnitude-phase relations[91] *s*: color/IR images/spectra, microwave, color/IR hyperspectra	 shape models [79] thermal hyperspectral images [11]
21 Lutetia	*g*: lightcurve, color/IR photometry, NIR spectra, radar, spin, 3-micron polarimetry, magnitude-phase relations *s*: color/IR images/spectra, microwave, color/IR hyperspectra	taxonomy shape models thermal hyperspectral images [11]
67P/Churyukov-Gerasimenko	*g*: photometry, long-wavelength *s*: Rosetta to reach 67P in 2014	
1999 RQ36	*g*: lightcurve, radar *s*: OSIRIS-REx to reach 67P in 2017	
Phobos	*g*: 3 micron, *s*: color/IR images/thermal fluxes stereo/color images, color/IR spectra subsurface radar[4], radio science magnetism data, particle data	 mosaic, maps [63] orthophoto, DTM maps shape models [61, 90]
Deimos	*g*: 3 micron, *s*: stereo/color images, color/IR spectra, subsurface MARSIS radar, radio science magnetism data, particle data	 mosaic, maps orthophoto, DTM maps shape models [64]
Irregular satellites	*s*: images	shape models [28]

Most data sets made available from past small body encounters include:

- Gaspra (Galileo, 1991): The Galileo spacecraft carried out the first encounter with an asteroid, 951 Gaspra [39], making a single flyby with a closest approach distance of 1600 km. It captured 57 images with its Solid State Imager (SSI) with the best resolution being 54 m/pixel, and it also captured observations with its Near Infrared Mapping Spectrometer (NIMS). Solar wind and dust measurements were taken during the flyby.

- Ida (Galileo, 1993): A few years after encountering Gaspra, Galileo also flew by 243 Ida on its way to Jupiter. Again, Galileo used its imager, spectrometer, and other instruments to gather data. It captured 96 images with the best resolution being 25 m/pixel [78].

- Mathilde (NEAR-Shoemaker, 1997): The NEAR-Shoemaker spacecraft performed a flyby of the asteroid 253 Mathilde. The Multi-Spectral Imager (MSI) and the Radio Science experiment are stored in PDS archives.

- Eros (NEAR-Shoemaker, 1998 & 2000): The primary target of the NEAR-Shoemaker mission was asteroid 433 Eros, where it performed a flyby (1998) and then entered into orbit (2000), and operated for approximately one year. There are over 40 data archives available in the PDS from NEAR-Shoemaker, including data from its MSI, the NIMS, and the X-ray Gamma-Ray Spectrometer (XGRS). Figure 5 shows a map of the distribution of the 2000 nm band strength measured with the NIMS, whereas Figure 6 shows the gamma-ray spectrum.

- Annefrank (Stardust, 2002): The Stardust spacecraft performed a flyby of 5535 Annefrank on its way to comet Wild 2, and collected several images with its navcam instrument.

- Wild 2 (Stardust, 2004): The comet 81P/Wild (also known as Wild 2), was approached by the Stardust spacecraft so that it could sample the coma. Data from the navcam and its suite of particle detection instruments is available in PDS.

- Itokawa (Hayabusa, 2005): The asteroid 25143 Itokawa was visited by the Hayabusa (formerly Muses-C) spacecraft which made distant observations, as well as a sample return touch-down. Hayabusa carried the Asteroid Multiband Imaging Camera (AMICA), the Near-Infrared Spectrometer (NIRS), and X-Ray fluorescence Spectrometer (XRS) instruments, of which there are AMICA, and NIRS data in the PDS.

- Tempel 1 (Deep Impact, 2005 and Stardust-NExT, 2011): The Deep Impact spacecraft performed a flyby past the periodic comet 9P/Tempel (also known as Tempel 1), and released an impactor. The Deep Impact spacecraft had the High Resolution Instrument Infrared Spectrometer (HRI-IR), the High Resolution Instrument Visible CCD (HRI-VIS), and the Medium Resolution Instrument

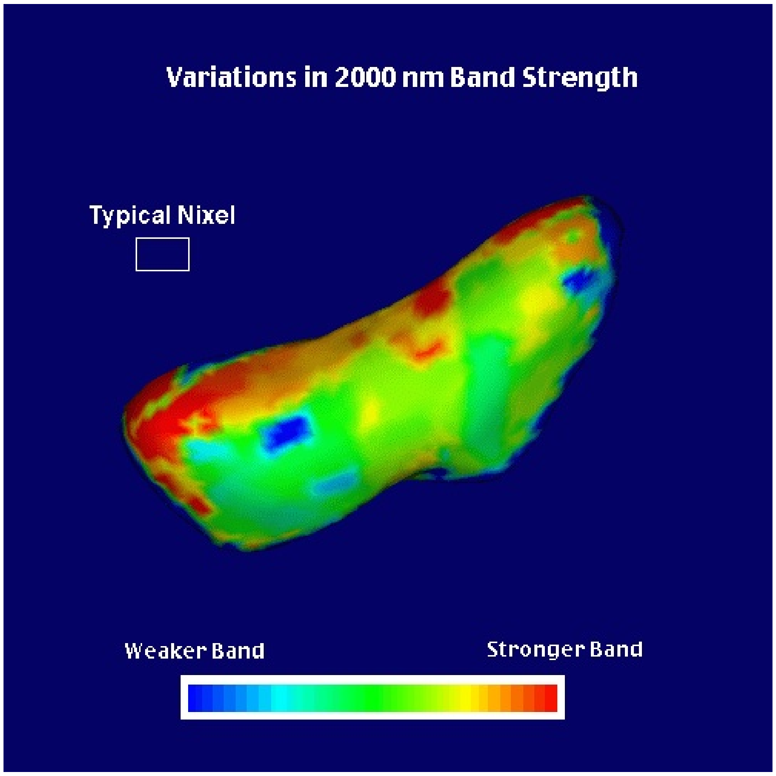

Figure 5. Distribution of the 2000 nm band strength measured with the NIMS onboard NEAR-Shoemaker.

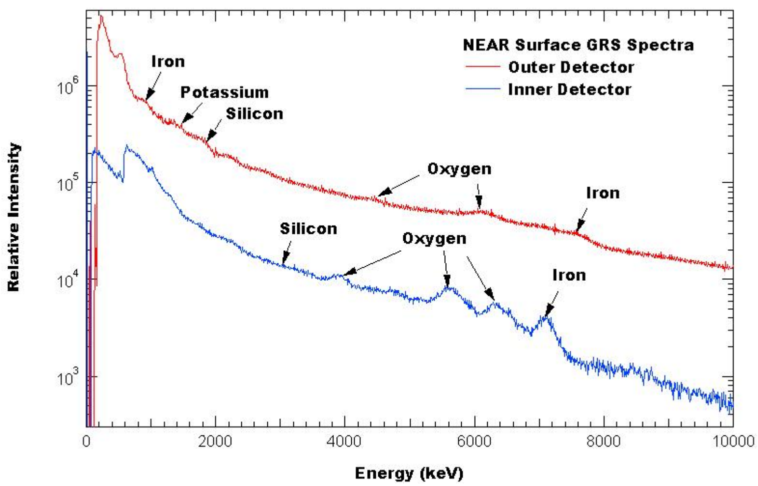

Figure 6. Elemental composition on Eros from the Gamma Ray spectrometer.

Visible CCD (MRI-VIS). The impactor had the Impactor Targeting Sensor Visible CCD (ITS-VIS). There are numerous archive volumes of both raw data and calibrations in the PDS.

Tempel 1 was subsequently visited by the Stardust spacecraft under the Stardust-NExT mission, which used its navigation camera (navcam) and dust flux monitor to observe the comet nucleus well after the Deep Impact encounter.

- Vesta (Dawn, 2011): The Dawn spacecraft completed its mission at asteroid 4 Vesta. It has been operating in proximity to the asteroid since summer 2011. Its instruments are the Framing Camera (FC), the Visible and Infrared Mapping Spectrometer (VIR), the Gamma Ray and Neutron Detector (GRaND), and the Radio Science Subsystem (RSS) package. These data will become available in PDS in 2013.

- Ceres (HST, 2003 and Dawn, 2015): The Dawn spacecraft will also visit the asteroid 1 Ceres in 2015. To date there is a set of imaging data collected by the Hubble Space Telescope (HST) and available in PDS.

4.2 Existing Data Processing Tools

There are several image processing, mapping, and cartography software packages developed within NASA and other government and academic institutions that provide a solid platform for generating large scale mapping and modeling solutions for small planetary bodies. This section describes the features of existing tools and how they relate to the requirements of small body exploration.

The NASA Vision Workbench (VW) [33] is a general purpose C++ image processing and computer vision library developed by the Intelligent Robotics Group at NASA Ames Research Center (ARC) and released as open source. This library is capable of supporting various planetary image formats, large scale satellite data and perform basic image processing operations in a memory efficient, highly parallel framework. The NEO Geography Toolkit (NGT) developed at NASA ARC incorporates a set of packages that build upon VW and support topography models, albedo and image mosaics and image alignment. The open source NASA Ames Stereo Pipeline (ASP) [34] is a component of NGT and consists in a suite of automated geodesy and stereogrammetry tools designed for processing planetary imagery captured from orbiting and landed robotic missions on other planets. It was designed to process stereo imagery captured by NASA spacecraft and produce cartographic products including Digital Elevation Model (DEM)s [7], ortho-projected imagery, and albedo maps[8]. VW and ASP were used to generate Lunar terrain in the Apollo zone (18% of the Lunar surface), and to create image and albedo mosaics at 40m/pixel using Apollo era imagery.

The Astrogeology Science Center develops and maintains the image processing software suite Integrated Software for Imagers and Spectrometers (ISIS) [89] [41]. This system allows for scientific analysis and cartographic manipulation of planetary images. ISIS provides sophisticated tools for the derivation of topographic information from planetary image data, thus enabling the detailed 2- and 3-D characterization of planetary terrains at the scale of the input images. ISIS uses SOCET SET Digital Terrain Model (DTM) creation for high resolution landing site mapping from stereo imagery. ISIS currently supports the following missions and instruments, although more are being added every year: Voyager 1 and 2, Viking 1 and 2, Mariner 9 and 10, Lunar Orbiter 3, 4, and 5, Apollo 15, 16,and 17 Metric and Panoramic cameras, Clementine UVVIS, NIR, HIRES and LWIR, Galileo SSI and NIMS, Cassini ISS, RADAR, and VISM, Mars Global Surveyor NA and WA, Mars Odyssey THEMIS IR and VIS, Mars Reconnaissance Orbiter (MRO) HiRISE, CTX, and MARCI, Mars Express HRSC, Messenger MDIS NAC and WAC, Lunar Reconnaissance Orbiter (LRO) NAC, WAC, and Mini-RF.

Recently the Jet Propulsion Lab has developed software capabilities to build shape models for small planetary bodies (Eros [76] and Itokawa).

4.3 Existing Visualization and Simulation Tools

Several visualization and simulation tools have been developed at NASA during the last two decades to support mission operations to low Earth orbit, planets and more recently small planetary bodies. This section describes several of these tools and performs a gap analysis based on the requirements for small planetary body exploration described in Section 3.

4.3.1 Visualization and Simulation Tools for Small Body Exploration.

These tools are specifically designed for future small planetary body missions and answer several but not all of the requirements in Sections 3.

- Small Body Mapping Tool (SBMT) [30] is a graphical application that allows the user to visualize small bodies in 3D, like Google Earth for asteroids. It supports non-ellipsoidal shapes like Eros and Itokawa by using a cartesian coordinate system and a triangular mesh derived from the shape models. The SBMT also allows for searching through the NEAR PDS data set in a more natural way via graphical regional constraints and text input boxes, and then displaying those results on the 3 dimensional (3D) model in the visualizer.

- Surface Exploration Analysis and Simulation (SEAS) tool [31] uses physics-based simulations to explore potential surface and near-surface mission operations at NEOs and other planetary bodies. Developed at Jet Propulsion Lab, the simulator can be used to provide detailed analysis of a variety of surface and near-surface NEO robotic and human exploration concepts. SEAS incorporates high-fidelity models of the NEO environment including its irregular geometry, the gravity field, and the effect of perturbing forces such as other body gravity fields and solar pressure.

4.3.2 Visualization Tools for Rover Operations on Mars.

These tools for robotic missions to Mars implement several capabilities relevant to small body exploration, but lack support for the representation of irregularly shaped small bodies and highly dynamic, low gravity environments.

The following tools developed by NASA ARC focus on the conceptual planning of rover operations, with an emphasis on developing science operations goals:

- MarsMap [12], developed for the Mars Pathfinder mission is an interactive 3D environment for offline planning of remote planetary exploration operations

- Viz developed at NASA ARC to support the Mars Polar Lander (MPL) mission, enhances MarsMap capabilities, and it is engineered to be extensible and adaptable to different missions and applications.

- Mars Exploration Rover (MER) Viz, developed at NASA ARC for the MER mission enhances MPL Viz, by supporting multi-site operations and by providing additional simulation and site understanding tools.

- Phoenix Viz, developed for Phoenix Mars Lander (MPL) mission extends the capabilities of MER Viz with geo-referenced terrain model support, and provides simulated trenching, and additional adaptations for the MPL mission.

- Antares, developed for the Mars Science Laboratory (MSL) mission, extends Phoenix Viz capabilities with science camera command sequence generation, and scalable representation techniques supporting ground-level microscopic models, large-scale terrain models from orbital imaging and ground level to orbital terrain alignment.

Jet Propulsion Lab (JPL) also has developed a number of visualization and simulation tools for Mars exploration focused on engineering rather than science operations. These tools include:

- Rover Control Workstation (RCW) [85], Developed for the Mars Pathfinder (MPF) mission. Provided a 3D environment for rover traverse planning, robotic arm operation, and rover command sequence generation.

- Web Interface for Telescience (WITS). Originally developed for MPF, WITS implemented a networked, collaborative tool for distributed robotic science operations and planning. WITS provided 2D and 3D visualization capabilities, the ability to define targets, waypoints, and activities associated with targets.

- Rover Sequencing and Visualization Program (RSVP). Successor to the RCW, developed for the MER mission. Provides improved rover and robotic arm simulation capabilities, including inverse kinematics, as well as command sequence timeline visualization.

- Science Activity Planner (SAP), also called "Maestro" as a publicly available version is a successor to WITS, developed for the MER mission. Originally an evolution and adaptation of SAP to the MSL mission, but developed into an essentially new tool. There is less emphasis on supporting distributed operations, but additional rover resource modeling, automated activity planning, and enhanced image analysis capabilities.

- MSL InterfaCE (MSLICE) [83] represents an evolution and adaptation of SAP to the MSL mission. MSLICE adds ability to plan operations in a global context with MRO High Resolution Imaging Science Experiment (HiRISE) base maps.

4.3.3 Research Tools for Rover Manipulation

These set of tools are developed to support various robotic field tests at NASA ARC and are designed to be used for future planetary rover exploration missions.

- Next Generation Ground Data Systems (xGDS) xGDS provides visual displays for robotic tele-operation planning, and real-time displays of robot telemetry. This tool utilizes Google Earth for visual planning of robot trajectories and traverses and uses a set of open source software, open standards, and off the shelf software to develop visual Ground Data Systems (GDS) tools for mission operations planning [54].

- Mercator [84] is a general purpose interactive visualization tool with a GIS focus. It was used by Phoenix Viz package.

- VERVE is an interactive 3D visual interface for tele-robotic control and display of the robotic state and environment.

4.3.4 Visualization and Simulation Tools for Low Orbit Operations of the Space Shuttle and Space Station.

While these tools developed by Integrated Graphics Operations and Analysis Laboratory (IGOAL) [5] at NASA Johnson Space Center (JSC) do not provide immediate applicability to small bodies, they contain aspects that are usable in the design requirements of the small body exploration tools including docking, rendezvous and robot manipulation.

- Advanced Graphics for Engineering Applications (AGEA) supports rendezvous operations, mission planning and pointing, station robotics operations and dexterous robotics.

- Multi-Mission Space Exploration Vehicle (MMSV) Human-In-The-Loop (HITL) software supports MMSV, NASA's exploration concept vehicles. The MMSV HITL Simulation is 6 degree-of-freedom fully dynamic simulation with flight controls and displays. The MMSV HITL Simulation is providing valuable information on the MMSV performance, propellant usage, mission concept and operations planning.

- The Systems Engineering Simulator (SES) is a real-time, crew-in-the-loop engineering simulator for the International Space Station (ISS), Orion, multi purpose crew vehicles, and advanced concepts. It provides the ability to test changes to existing space vehicles and flight software, test the interaction of a new vehicle system with existing systems, develop models of new vehicles for engineering analysis, and control concepts.

5 Recommendations

In this section, we recommend mapping products built upon available data sets, and complementing current data products. These mapping products reflect the requirements and constraints needed to support future missions. We also identify deficiencies with exiting processing data gaps.

5.1 Recommended Standards and Models

5.1.1 Standards development.

The recommendations from the IAU Working Group on Cartographic Coordinates and Rotational Elements [1], [2] cover the fundamental issues of how to set up and maintain coordinate systems for all bodies in the solar system, including small bodies such as dwarf planets, asteroids, and comets. Specific recommendations are given for bodies that have already been mapped (i.e. where there is a cartographic need) at reasonable resolution, e.g. from close flyby or orbiting mission, or from Earth based imaging of sufficient resolution, usually from e.g. the HST or Keck telescopes.

Usually a coordinate system is defined using the pole of rotation to define latitude and a surface feature to define longitude. For planets and their satellites, mostly for historical reasons, both planetographic and planetocentric systems are in use. For small bodies, the use of a (planetocentric) right-handed system has been specifically recommended. For instance, Figure 7 illustrates the Eros reference system, which uses latitudes and longitudes. The prime meridian passes though a large crater (indicated by an arrow in the lower left sub figures [48]). By convention, "west longitude" is used where it increases west from the prime meridian. Although not yet used for any body, recommendations

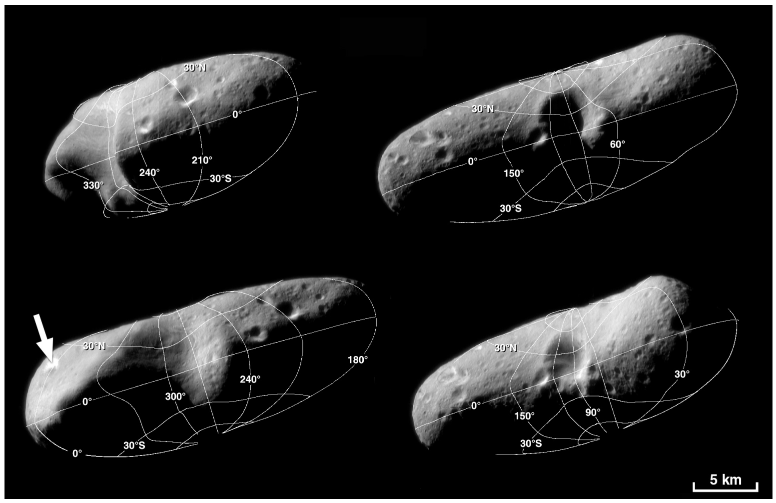

Figure 7. Eros surface reference system.

are also given to use a second surface feature to define a coordinate system should the rotation be chaotic or at least if the pole is moving significantly within the body, as may be the case with small near Earth asteroids.

More detailed specifications, such as the format of maps and data sets, are not specified by the Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE) and currently are left to individual researchers, missions, and space agencies. In the case of Mars and the Moon, NASA has set up Working Groups to facilitate such choices. These have been the Mars Geodesy and Cartography Working Group (MGCWG) [82], and the Lunar Geodesy and Cartography Working Group (LGCWG) [1]. These Working Groups have provided coordination among multiple missions and although NASA sponsored even space agencies.

Although operating on minimal or no funding, and due to limited resources going through periods of activity and inactivity, these Working Groups have still greatly facilitated the use of standardized coordinate systems (at a minimum, according to the recommendations of the WGCCRE) and some standardization of product formats, or at least examples of such formats that have been used in the development and creation of new products. For example the LGCWG has created a document [70] that describes again following WGCCRE recommendations as much as possible the fundamental lunar coordinate system and coordinate frame information to be used by the LRO and other international lunar missions. It has also created a (draft) set of detailed recommendations for mapping, beyond what is covered by the WGCCRE [49] as well as additional (draft) recommendations for evaluating and comparing lunar DEMs [74].

We recommend that a similar Small Bodies Geodesy and Cartography Working Group (SBGCWG) be established to coordinate between the various NASA and international missions, current and future, the development of similar detailed standards. Such a working group, would need to coordinate as much as possible with international missions and space agencies as well. An additional part of the work of such a WG would be one of facilitating discussion and education among all and particularly new missions, so that WGCCRE recommendations can either be followed or formal requests be formulated and made to them for changes in their recommendations, and for the development of more detailed standards and recommendations along the lines of what the Mars and Lunar working groups have done.

It is also important that missions and instrument teams have participants that understand and provide education to their missions or teams regarding existing recommendations and standards. Some coordinate system and mapping issues and recommendations to address them have been pointed out in a white paper prepared for the recent Decadal Survey [46] and at least mentioned in the Decadal Survey itself [59]. For example the latter says: "R&A programs like planetary cartography are also critical for mission planning by ensuring that (for instance) cartographic and geodetic reference systems are consistent across missions to enable proper analysis of returned data", that the "development of appropriate cartographic coordinate systems standards for geodetic and cartographic coordinate systems should be encouraged", and that separate support should be provided for development of high-level data products in cases where such support cannot be provided by mission funding (page 10-6).

5.1.2 True 3D Projection Support.

For larger bodies, and those with sufficient convexity, a longitude-latitude system can be used. However, as the objects get smaller, their 3D shapes become more interesting and can be more concave, such that a simple longitude-latitude system derived from spherical coordinates cannot uniquely 'address' an arbitrary location on the surface. On these more complex bodies, pure Cartesian systems have been used [30].

Beyond what coordinate system is used to find your way around a surface, new techniques and standards will need to be developed to support data projection onto these surfaces. For example, a naive approach might assume that since Eros (Figure 7) uses a longitude-latitude system, that imagery and other data could be placed into a map projection (such that different data sets could be co-registered and co-analyzed) by existing map-projection techniques. However, those techniques and algorithms either assume a basic ellipsoidal shape to project on to, or a detailed terrain model with 2.5 dimensions. To support truly arbitrary NEO shapes, we recommend developing a standard for representing coordinates on their surfaces, and also a standard for defining their shape and terrain models that can be incorporated into mapping and data analysis software algorithms to support map projection.

5.1.3 Small Body Dynamic Model.

The spin period, axis of orientation, and overall shape contribute to a small body dynamical model. This model is critical for proximity and surface activity planning and is needed by the NUT recommendations (Table 1). One can obtain sufficient information from ground-based observations if the small body makes a close enough approach to Earth. For instance, in 1994, the asteroid 1620 Geographos, came within 0.0333 AU, providing an excellent opportunity to use the Goldstone Solar System Radar in California [75] to image the asteroid [37, Figure 8]. However, accurate enough models for in situ operation can only be generated from in-situ observations. Small body flybys provide some opportunities to obtain a partial shape model due to the high speed encounter, whereas the most accurate dynamical models to date are the ones obtained by the NEAR-Shoemaker and Hayabusa spacecraft.

Since the small body environment is among the most gravitationally perturbed environments, trajectories in the vicinity of a small body may rapidly get unstable, leading to escape or impact. External forces such as solar radiation pressure, third body perturbations, and the presence of debris and satellites need to be included for accurate simulations. There have been a number of studies investigating the effects of external forces on small body dynamics, from orbital to surface dynamics [e.g. 9, 19, 21, 23, 24, 42, 60]. Any model needs to include external forces on a distributed mass for simulating and planning operations, and to predict surface behaviors.

5.1.4 Shape Models.

Shape models can be obtained from orbit and fly-by data. A bootstrapping solution for the mapping process iteratively adds images and develops a control-network-based 3D shape model from the fly-by low resolution imagery. This process may require minimal manual intervention in the early stages followed by a fully automatic data registration and shape model estimation. This entire process can benefit from existing low resolution shape models where available (e.g. shape from sil-

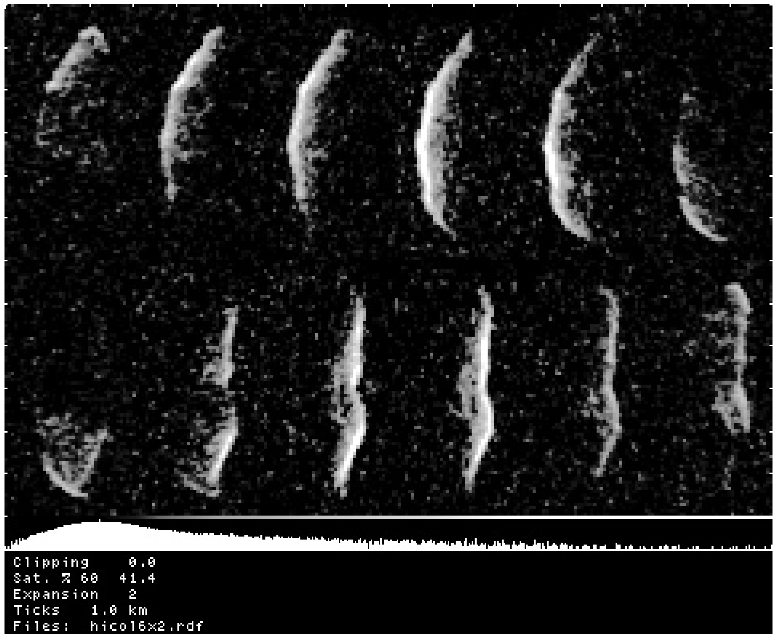

Figure 8. Ground radar observation of asteroid Geographos.

houette), photometric corrections, and robust image feature extraction and matching. Shape models can be used to roughly estimate the gravitational field (a needed product by NUT in Table 1) and provide an initial low resolution product that is used in determining the small body topography (highly recommended by NUT in Table 1).

Existing high resolution shape models are ones from Eros and Itokawa. Figure 9 shows the Eros shape model [76]. Two thousand landmarks were determined from more than 12,000 stereo measurements to generate this grid. The shape model is a mathematical representation of the surface passing through all those points. Surface gravity and steepness of slopes can be derived from this model. Increasing the speed of the estimation process is needed to support the rapid pace of operating near a small body, and estimate key properties.

In 2004, Earth-based radar observations of 1999 KW4 resulted in the first medium resolution shape model of a binary asteroid, which lead to research on binary formation and applications [22, 80]. Figure 10 shows the gravitational slopes on the binary primary body, named Alpha.

In the small body database, a number of binary and ternary systems' shape models have been obtained from radar [47]; a shape model like the one of KW4 is usually derived from the radar Doppler data. Single asteroid shape models are far more numerous, obtained from ground or space-based observations. For instance Geographos and Toutatis models were obtained from ground data, while Ida, Gaspra, Stein, Lutetia, and numerous outer planet irregular satellites models were obtained from spacecraft flybys [28, 65, 69, 79].

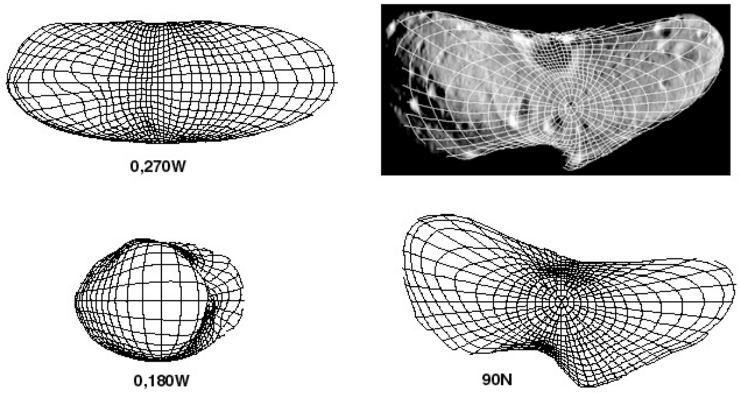

Figure 9. Eros shape model[76].

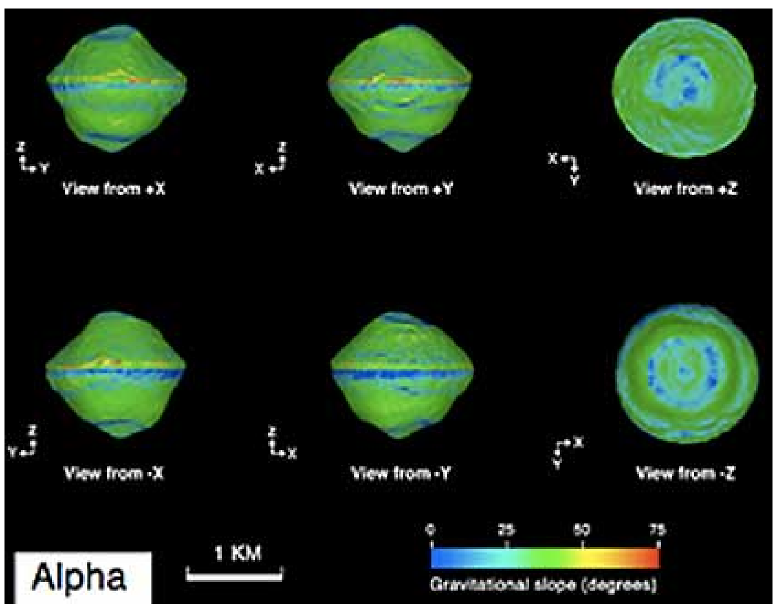

Figure 10. Mapping of the surface slope on the primary body of the Binary system 1999 KW4, Alpha[22, 80].

5.2 Recommended Mapping Products

5.2.1 Topography.

Topographic maps provide scientists and mission planners information vital to the decision making process. These products are highly recommended by NUT(Table 1).

- Global DTMs provide global elevation models derived from stereo (overlapping) images and corresponding photometric corrections.

- Local DTMs provide limited area higher-resolution topographic data, such as that needed for landing site analysis, these can be derived using stereogrammetry, photoclinometry, or multi-view techniques. Such local DTMs will enhance the accuracy and resolution of the global stereo DTM by using all or the best images taken over a specific site and their corresponding sun and camera positions.

- DTM accuracy, precision and confidence maps provide detailed error and uncertainty metrics for DTMs by taking into consideration computational modeling and data acquisition errors. The precision maps describe the relative elevation errors between computed terrain models using different methods or instruments. The accuracy maps describe the errors between computed terrain models and data that can be considered ground truth (lidar or high resolution terrain models). The confidence maps represent quantized version of the precision maps that can provide scientists in an intuitive way with global information about the quality of the derived terrain models. These products provide scientists and mission planners with vital confidence information in the decision making process.

- Lidar maps are to support landing and obstacle avoidance. Lidar technologies including single beam, multibeam, and flash/imaging Lidar, could be used to improve the accuracy of the terrain mapping products by providing sparse but more accurate elevation than image-based terrain reconstruction methods. Lidar mapping involves co-registration of overlapping lidar tracks and matching with other derived terrain products (DTM). Merging lidar and stereo-derived topography is an important research direction for obtaining highly accurate large coverage terrain models. NEAR-Shoemaker and Hayabusa carried a laser ranger and lidar. The Hayabusa spacecraft obtained local altitude and topographic measurements during descent rehearsals and touchdowns [77]. NEAR-Shoemaker obtained near-global topography. Figure 11 shows an example of the measured topography using the NEAR-Shoemaker laser rangefinder instrument. The Hayabusa mission also had a lidar. The instrument was used to better determine altitude distances and volumetric estimates, although no digital terrain models have been published. A particularly important aspect is the image to lidar coregistration that can potentially solve for improved camera positioning and improve the albedo mapping quality.

- Slopes and surface roughness information are derived from lidar data or DTMs to provide critical data for landing, navigation and small body illumination conditions.

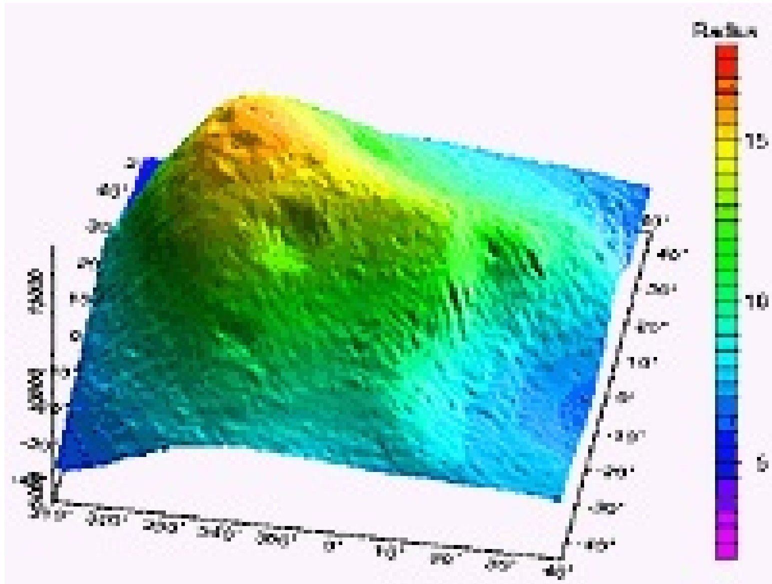

Figure 11. Topography map on Eros.

5.2.2 Image and albedo mosaic.

The image and albedo maps are produced using processing techniques that compensate for shadow regions, variations in illuminations, exposure time and surface reflectance. A key benefit of albedo reconstruction is that it will enable mission planners to create images of landing sites under arbitrary conditions. To date, albedo data exist for a variety of objects, although no derived maps have been obtained for small bodies visited so far. An albedo map has recently been constructed for the dwarf planet 1 Ceres using images taken by the HST [40].

5.2.3 Radio Science Products

The mass and gravity field of a small body can be estimated from the spacecraft trajectory deflection, range and Doppler data which is recorded through spacecraft tracking. These methods involve fitting a least-square curve to the residual frequency observations, and using the camera imaging and local ranging data, accounting for all Doppler contributions not related to the small body itself. Radio science products include gravitational fields and density and porosity estimates.

- The gravitational field is a highly recommended product by NUT (Table 1), desired to design close proximity operations, anchoring techniques, and other surface working tools. Using both radio tracking and the body shape, a Bouguer gravity anomaly map (Figure 12) can be obtained, which indicates the difference between the measured and shape derived gravity accelerations at all points on the surface.

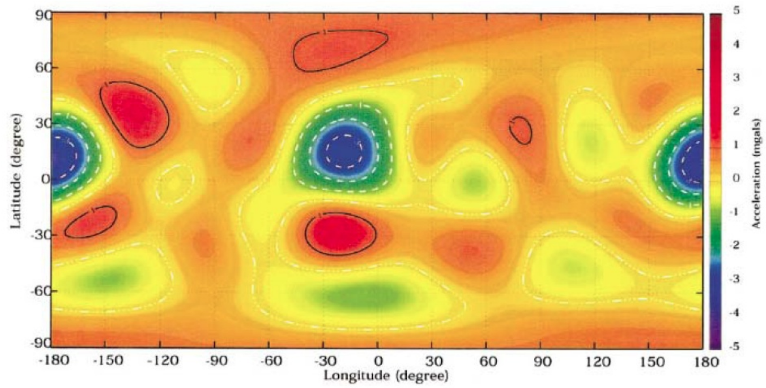

Figure 12. Eros Bouguer gravity anomaly map.

- The density model is obtained from combining mass and volumetric estimates.

- The porosity parameters are estimated from reflectance spectra and other composition measurements, combined with volumetric and density measurements.

To date we have mass estimations for about 25 asteroids, from combined ground-based and space-based campaigns and techniques including spacecraft tracking [23, 25, 26, 44, 53]. Knowledge of the bulk mass is necessary for gravity field, density and porosity estimation. Eros, Itokawa, and some of the larger bodies have gravity harmonic coefficients to higher order calculated. Eros's Bouguer anomaly map is the only one obtained from in-situ high accuracy mass. No density models or porosity parameters exist. The mass estimations are further used in the derivation of density and porosity, and to augment the small body dynamical model. These products are critical for refining close operations, tools development, and surface activity planning.

5.2.4 Subsurface Radar Maps.

This product can be obtained from radar, where the depth of measurement depends on the radar frequency. Synthetic Aperture Radar (SAR) can return information on the first centimeter to meter layers while ground penetrating radar can be used to probe the deep interior structure. The Mars Express mission recently obtained radar measurements of Phobos, although no interior maps have been generated [4]. Most current radar data are of subsurface layers of Earth, Moon, Venus, Titan, and Enceladus.

5.2.5 Mineralogical and Multispectral (UV to infrared) maps.

The mineralogical and multispectral maps (highly recommended by NUT (Table 1) are used to determine the location of material on the surface: metals, silicates, olivines, etc. Infrared measurements can reveal different mineral compositions from their spectral properties, or reveal hidden features due to the topography or low albedo. UV spectra can be used to detect debris fields in the close vicinity of the body. The determination of surface composition will give insights into the evolution of the body while assisting exploration goals.

5.2.6 Surface Mechanical-electrical Properties Maps.

A number of surface maps can be constructed to assist robotic and crewed surface interaction. Surface properties maps and DTMs can be obtained from navigation cameras, multispectral band cameras and spectrometers, and other element composition instruments. The surface roughness and stability can be first inferred from remote observations and crater counts, features orientation, and the distribution of regolith, although in-situ measurements are needed for better accuracy. The compaction, compressibility, shear, friction, and restitution properties are necessary for gathering samples, and are function of a number of parameters that can only be measured in-situ. Electrical properties can be a function of illumination and regolith size, but have never been recorded other than in a comet coma through electromagnetic sensors, some distance away from the surface. These products will assist in all simulations and operations in the vicinity or on the surface of the small body.

Besides remote sensing and mineralogy data from which bulk surface parameters can be inferred, no surface parameter maps exist. NEAR-Shoemaker carried a Magnetometer (MAG), which returned data from close orbits and flybys. The Hayabusa spacecraft obtained local surface friction and restitution from the spacecraft touchdown ([32]).

5.2.7 Thermal Inertia Maps.

Thermal properties can indicate the presence of rocks under the surface, hidden to visible imagery, and thus improve the accuracy of shape models, DTMs, and elevation maps. Bulk thermal inertia can be inferred from ground-based observations through measurements of albedos. The data necessary to build thermal inertia maps come from near-IR (NIR) and mid-IR (MIR) instrumentations in-situ, such as the one carried on NEAR-Shoemaker, Hayabusa and Dawn spacecraft. Models exist for calculating and mapping the body inertia [10]. However, there is only limited thermal data and products in the PDS: surface maps from the Deep Impact mission, and thermal hyperspectral images returned by the Rosetta mission during its flybys of Steins and Lutetia are the only thermal data and products available to date [11, 58]. .

The thermal maps are also used to refine modeling of the solar radiation forces such as the Yarkovsky-OKeefe-Radzievskii-Paddack (YORP) and Yarkovsky effects which cause changes in body spin state and momentum, respectively[27, 95]. These effects are important input parameters in modeling the body dynamical state, and in predicting small bodies' location and evolution. Detailed studies of these solar radiation effects have shown that YORP can contribute to the formation of multiple asteroid systems and the existence of fast rotator asteroids [20]. The Yarkovsky effect was demonstrated to be an important input into the transport of material from the main belt asteroid population [16].

Bulk thermal inertia can be inferred from ground-based observations. The data necessary to build thermal inertia maps come from NIR, and MIR instruments, such as those carried by NEAR-Shoemaker, Hayabusa, and Dawn. Although models exist for calculating and mapping the thermal inertia [10], no accurate data is available.

5.3 Recommended Data Matching Products.

Development of a large-scale, high-accuracy *data catalog* that establishes matches between salient features in images captured over the same terrain are particularly important in developing shape models, topography, image and albedo maps. The same image feature matching paradigm is also used to determine visual similarities between images taken over different areas. This enables capabilities for searching mission data for small/irregular bodies and appropriate tools to convert such data to useful formats. Such a content-based data mining tool enables users to identify and study visual similarities between datasets from different missions. Figure 13 illustrates the Content-based Data Mining (CBM) Tool [6, 51] developed at NASA ARC. This tool matches PDS images or image regions based on their visual similarity and in its current implementation deals with Lunar and Martian images captured by various NASA missions. Future developments of this product could incorporate small body data and include collaborations with the Open Geospatial Consortium (OGC) to assess and adapt existing mapping standards to small body needs.

5.4 Recommended Visualization and Simulation Tools

As planetary exploration concepts advance in complexity and ambition, the ability of ground control operators, astronauts, engineers, and scientists to quickly synthesize an understanding of mission state and the planetary surface environment will become increasingly important. The enhanced situational awareness and site understanding provided by mapping product visualizations and surface condition simulations will be enabling factors in achieving future mission productivity goals. In particular, a highly interactive, visual, 3D exploration tool leveraging high-

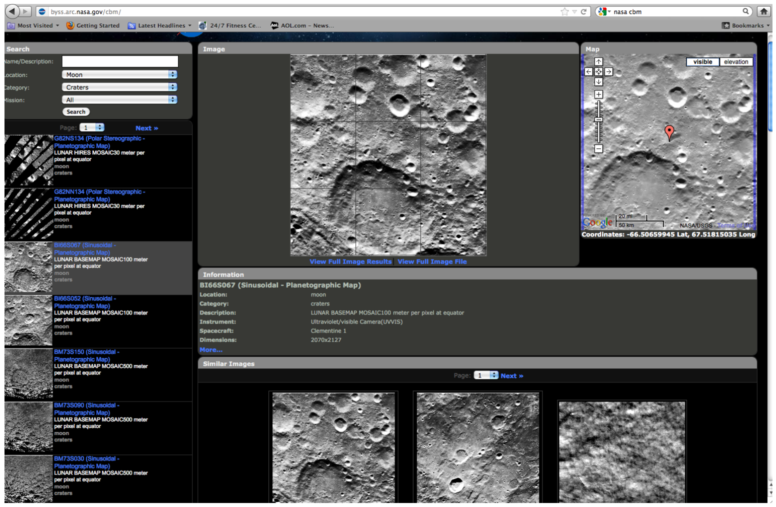

Figure 13. Content-based Data Mining developed at NASA ARC. The top center panel shows an example query image selected by the user from the left panel images. The top right panel shows the query image on the planetary map. The bottom panel shows the set of images matching the query image in descending order of the matching score. The left panel shows a subset of images obtained using text search criteria.

resolution mapping products will provide real-time tactical operations capabilities (e.g., ensuring communication continuity) that will mitigate risk and enhance mission productivity. Defining capabilities of such a 3D exploration tool include:

- simulation of a traverse mission to a NEO including:
  - prediction and update of the Sun visibility to allow astronauts to predict and continue exploration in direct Sun light.
  - support for simulation of direct communication of crew on the surface with Earth and spacecraft.
- simulation of surface conditions and interactions including
  - debris field stability following drilling operations or traverse operations and natural disturbances such as landslides
  - non-uniform gravitational fields.
- integrated real-time visualization and simulation for ground controllers and astronauts in the spacecraft andor on the surface.
- support for a variety of maps, models, and representations including:

- irregular small body shapes including full 3D rather than 2.5D data formats and map projections.
- dynamic model of the small planetary bodies (rotation rate, spinning, tumbling, etc).
- mapping products including topography, albedo, image, gravity, density, porosity, mineralogy, lidar maps and automatic or semi-automatic alignment of these products. The alignment of surface maps allows for navigation, exploration, sample collection or surface drilling.

- content-based image search interface for scientists and mission planers to determine image and terrain similarities, and define areas of interest for docking or anchoring.

In addition to operational scenarios, mission planning would be facilitated by advanced search and automated classification capabilities allowing mission planners and scientists to quickly access data based on data content as well as spatial and temporal properties. In the following, we review current visualization and simulation tools for space exploration, and note areas where current state of the art does not address the above-identified capabilities.

6 Gaps

6.1 Data Processing Gaps

The combined capabilities of the tools described in Section 4.2 cover several aspects of the processing requirements for small planetary body exploration. However many aspects remain open issues to be developed by dedicated processing tools. The following list describes the most important data processing gaps:

- Fully automatic geodetical control of the entire data available from the small body mission by creating a data catalog that is to be used for data registration, comparison between datasets, and assessment of the registration accuracy.

- Generation of standard coordinate systems and coordinate frames for small bodies.

- Improved accuracy solutions for stereo photoclinometry by combining stereo and shape from shading techniques and using well determined photometric models.

- Multi-view 3D Terrain Reconstruction to improve the quality and resolution of current stereo terrain reconstruction methods.

- Lidar and image coregistration to accurately register images and estimate camera positions.
- Real-time, fully automatic rover and crew localization within orbital maps.
- High resolution albedo maps to provide illumination independent surface characterization and to simulate the landing site visual appearance at landing time.
- High-accuracy (i.e. tenth-pixel level) DTMs are needed in order to properly project and photometrically correct (with proper slope information) multi-spectral data so that mineralogical information can be derived from it at sufficient accuracy.
- Tools to determine in simultaneous solutions the spacecraft position and pointing, and body size, shape, mass, and gravity field.

The creation of coordinate systems, coordinate frames, and controlled mapping products is strongly supported via a number of advisory groups in a variety of contexts. This includes: 1) an ad-hoc group including the NASA Planetary Cartography and Geologic Mapping Working Group (PCGMWG) [46] which notes the need to plan for the creation of controlled cartographic products; 2) the NASA Advisory Council [14] has recommended to NASA that all cartographic products for the Moon (the only body considered in the specific context, but the implication is for all bodies) be geodetically controlled; 3) the Committee on the Planetary Science Decadal Survey [59] notes that R&A programs like planetary cartography are also critical for mission planning by ensuring that (for instance) cartographic and geodetic reference systems are consistent across missions to enable proper analysis of returned data, that the development of appropriate cartographic coordinate systems standards for geodetic and cartographic coordinate systems should be encouraged, and that separate support should be provided for development of high-level data products in cases where such support cannot be provided by mission funding; and 4) the IAU Working Group on Cartographic Coordinates and Rotational Elements [1] has noted in their recommendation no. 1 the importance of geodetically controlled cartographic products and that Although a flood of new planetary datasets is currently arriving, it appears that the production of such products is often not planned for or funded. We strongly recommend that this trend be reversed and that such products be planned for and made as part of the normal mission operations and data analysis process.

6.2 Visualization and Simulation Gaps

This section identifies capability gaps specific to small body exploration visualization and simulation requirements. These are features, standards, and technologies that enhance mission safety and productivity and are only partially developed or non-existent in current simulation and visualization tools for planetary exploration. These gaps include lack of:

- Projection and coordinate system standards for mapping highly irregular planetary body shapes. While an exhaustive set of projections are available for spherical or almost spherical shaped planetary bodies, projection standards for irregularly shaped bodies have yet to be defined.

- Real-time integrated multi-view visualization support or ground control and astronauts in spacecraft or on the surface.

- Real-time processing, visualization and registration of new mapping products from a heterogeneous mix of mission instruments (e.g., visible and infrared cameras, lidar, spectrometers, and radar).

- Support for dynamic illumination condition simulation. While interactive illumination simulation capabilities do exist in current tools, none fully support the highly dynamic environments of small planetary bodies.

- Comprehensive debris field simulation modeling non-uniform and low gravity conditions, debris porosity and density, and the effects of proximity to other planetary bodies. Such simulations would inform operations and planning of the potential for terrain landslides or unstable debris that could affect the safety of the manned or robotic mission.

- Line-of-sight communication planning and prediction tools for highly dynamic small body mission scenarios. Effective communication simulation and prediction requires accurate shape and terrain maps as well as a dynamic model of the small planetary body.

While visualization and simulation tools for exploration cover some of the identified gaps, there is a lack of an integrated visualization and simulation solution that supports the specific set of needs of small body exploration. Some of the identified capability requirements are dependent on the existence of particular mapping products, and fully effective utilization of such an integrated tool will necessitate consideration of such dependencies early in the mission planning process.

7 Conclusions

This paper develops requirements for mapping products and visualization/simulation tools to support the operational and science goals of near-term and future NASA missions to small planetary bodies (asteroids, dwarf planets, comets, and irregular satellites such as the moons of Mars). The mapping product and the identified requirements are based on the analysis of current mission scenarios (rendezvous, docking, surface operations and sample return) and recommendations made by the Near Earth Asteroid User Team (NUT) in the framework of human exploration.

Data processing tools and techniques are surveyed and a gap analysis of the state of the art in planetary mapping and the requirements for missions to a small planetary bodies is performed. The main result of this analysis points to a need for generation, incremental refinement and registration of mapping products from large-scale, low resolution remotely sensed data to small-scale, high-resolution surface operations data. The highly dynamic environments of small planetary bodies also motivate requirements for real time spatial data processing tools that will produce and update mapping products in a tactically relevant time frame. In addition, the lack of coordinate system standards for the highly irregular shapes of small planetary bodies suggests a need for a NASA led international working group or committee to develop recommendations for new standards to address this gap.

Complementing the mapping product and data processing recommendations, this paper develops requirements for visualization of mapping products and the simulation of operational conditions including soil interactions, dynamics, and communications coverage. Such capabilities will also serve an important role in planetary scientific discovery and public outreach. A capability gap analysis is performed between state of the art visualization tools used in current NASA missions and the requirements of small body planetary exploration. The main outcome of this analysis is a recommendation for integrated visualization and simulation tools specifically targeted at small planetary body exploration.

Building robust, usable data sets and targeted visualization/simulation tools is the best way for NEA mission designers and planners to make good decisions for future missions. In the near term, it is the most useful way to begin building capabilities for small body exploration without needing to commit to specific mission architectures.

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8 Acronyms

AGEA Advanced Graphics for Engineering Applications

AMICA Asteroid Multiband Imaging Camera

APXS Alpha Particle X-ray Spectrometer

ARC Ames Research Center

ASP Ames Stereo Pipeline

RADAR	Cassini radar
CBM	Content-based Data Mining
CTX	Context Camera
DEM	Digital Elevation Model
DSN	Deep Space Network
DTM	Digital Terrain Model
DV	Delta-V
EPOXI	Extrasolar Planet Observation and Deep Impact Extended Investigation
ESA	European Space Agency
EVA	Extra-Vehicular Activity
FC	Framing Camera
FTIR	Fourier Transform Infrared Spectrometer
GDS	Ground Data Systems
GRaND	Gamma Ray and Neutron Detector
HIRES	High Resolution camera
HiRISE	High Resolution Imaging Science Experiment
HITL	Human-In-The-Loop
HRI-IR	High Resolution Instrument Infrared Spectrometer
HRI-VIS	High Resolution Instrument Visible CCD
HRSC	High Resolution Stereo Camera
HST	Hubble Space Telescope
ICE	International Cometary Explorer
IGOAL	Integrated Graphics Operations and Analysis Laboratory
IR	infrared
ISEE3	International Sun-Earth Explorer
ISIS	Integrated Software for Imagers and Spectrometers
ISS	Imaging Science Subsystem

ISS	International Space Station
ITS-VIS	Impactor Targeting Sensor Visible CCD
JAXA	Japan Aerospace Exploration Agency
JSC	Johnson Space Center
JPL	Jet Propulsion Lab
LEAG	Lunar Exploration Analysis Group
LIBS	Laser-Induced Breakdown Spectroscopy
LGCWG	Lunar Geodesy and Cartography Working Group
LRF	Laser RangerFinder
LRO	Lunar Reconnaissance Orbiter
LWIR	Long-Wave Infrared
MAG	Magnetometer
MARCI	Mars Color Imager
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding
MBO	Main-Belt Object
MDIS	Mercury Dual Imaging System
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rover
MGCWG	Mars Geodesy and Cartography Working Group
Mini-RF	Miniature Radio-Frequency instrument
MIR	mid-IR
MMSV	Multi-Mission Space Exploration Vehicle
MPF	Mars Pathfinder
MPL	Mars Polar Lander
MRI-VIS	Medium Resolution Instrument Visible CCD
MRO	Mars Reconnaissance Orbiter
MSI	Multi-Spectral Imager

MSL	Mars Science Laboratory
MSLICE	MSL InterfaCE
NA	Narrow Angle
NAC	Narrow Angle Camera
NASA	National Aeronautics and Space Administration
navcam	navigation camera
NEA	Near-Earth Asteroid
NEAWG	NEA Working Group
NEO	Near-Earth Object
NGT	NEO Geography Toolkit
NIMS	Near Infrared Mapping Spectrometer
NIRS	Near-Infrared Spectrometer
NIR	near-IR
NUT	Near Earth Asteroid User Team
OCC	Orbit Condition Code
OGC	Open Geospatial Consortium
OSIRIS-REx	Origins Spectral Interpretation Resource Identification Security Regolith Explorer
PCGMWG	Planetary Cartography and Geologic Mapping Working Group
PDS	Planetary Data System
MPL	Phoenix Mars Lander
RCW	Rover Control Workstation
RSS	Radio Science Subsystem
RSVP	Rover Sequencing and Visualization Program
RV	Rendezvous
SAP	Science Activity Planner
SAR	Synthetic Aperture Radar
SBGCWG	Small Bodies Geodesy and Cartography Working Group

SBAG	Small Bodies Assessment Group
SBMT	Small Body Mapping Tool
SEAS	Surface Exploration Analysis and Simulation
SES	Systems Engineering Simulator
SKG	Strategic Knowledge Gap
SR	Sample Return
SSI	Solid State Imager
Stardust-NExT	Stardust New Exploration of Comet Tempel 1
SWIR	Short Wave Infrared
3D	3 dimensional
THEMIS	Thermal Emission Imaging System
USSR	Union of Soviet Socialist Republics
UV	ultraviolet
UVVIS	Ultraviolet/Visible camera
VISM	Visual and Infrared Mapping Spectrometer
VIR	Visible and Infrared Mapping Spectrometer
Vis	visible
VIS	visible
VW	Vision Workbench
WA	Wide Angle
WAC	Wide Angle Camera
WGCCRE	Working Group on Cartographic Coordinates and Rotational Elements
WISE	Wide-Field Infrared Survey Explorer
WITS	Web Interface for Telescience
YORP	Yarkovsky-OKeefe-Radzievskii-Paddack
xGDS	Next Generation Ground Data Systems
XGRS	X-ray Gamma-Ray Spectrometer
XRS	X-Ray fluorescence Spectrometer

Appendix A

An appendix

Some appendix material.

A.1 Appendix sub

Are subsections numbered within the appendix?

Appendix B

Next

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14. ABSTRACT
This study investigates the requirements, performs a gap analysis and makes a set of recommendations for mapping products and exploration tools required to support operations and scientific discovery for near-term and future NASA missions to small bodies.
The mapping products and their requirements are based on the analysis of current mission scenarios (rendezvous, docking, and sample return) and recommendations made by the NEA Users Team (NUT) in the framework of human exploration. The mapping products that satisfy operational, scientific, and public outreach goals include topography, images, albedo, gravity, mass, density, subsurface radar, mineralogical and thermal maps. The gap analysis points to a need for incremental generation of mapping products from low (flyby) to high-resolution data needed for anchoring and docking, real-time spatial data processing for hazard avoidance and astronaut or robot localization in low gravity, high dynamic environments, and motivates a standard for coordinate reference systems capable of describing irregular body shapes.
Another aspect investigated in this study is the set of requirements and the gap analysis for exploration tools that support visualization and simulation of operational conditions including soil interactions, environment dynamics, and communications coverage. Building robust, usable data sets and visualisation/simulation tools is the best way for mission designers and simulators to make correct decisions for future missions. In the near-term, it is the most useful way to begin building capabilities for small body exploration without needing to commit to specific mission architectures.

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