Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions

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Future planetary explorations envisioned by the National Research Council's (NRC's) report titled *Vision and Voyages for Planetary Science in the Decade 2013–2022*, developed for NASA Science Mission Directorate (SMD) Planetary Science Division (PSD), seek to reach targets of broad scientific interest across the solar system. This goal requires new capabilities such as innovative interplanetary trajectories, precision landing, operation in close proximity to targets, precision pointing, multiple collaborating spacecraft, multiple target tours, and advanced robotic surface exploration. Advancements in Guidance, Navigation, and Control (GN&C) and Mission Design in the areas of software, algorithm development and sensors will be necessary to accomplish these future missions. This paper summarizes the key GN&C and mission design capabilities and technologies needed for future missions pursuing SMD PSD's scientific goals.

I. Introduction

Spacecraft Guidance, Navigation and Control (GN&C) and Mission Design capabilities and technologies have been evolving since the launch of the first rocket. Guidance is defined to be the determination (often onboard) of the desired path of travel from the vehicle's current location to a designated target. Navigation is defined as the science behind transporting ships, aircraft, or spacecraft from place to place; particularly, the method of determining position, course, and distance traveled as well as the determination of a time reference. Control is defined as the onboard manipulation of vehicle steering controls to track guidance commands while maintaining vehicle pointing with the required precision. Mission Design is defined to encompass celestial mechanics, trajectory optimization, and trajectory design.

In 2011, National Research Council's (NRC's) decadal study report titled Vision and Voyages for Planetary Science in the Decade 2013–2022[1] captured future missions envisioned to pursue NASA Science Mission Directorate (SMD) Planetary Science Division's (PSD's) scientific goals. Increasingly autonomous missions with increasing complex, technological demands on GN&C and mission design are envisioned. Corresponding capability and technology advancements are required. In 2012, Planetary Science Division commissioned a technology assessment evaluating the capabilities and technologies needed for the future missions identified in the PSD decadal study. The assessment was performed in three parts. Part I titled "Onboard and Ground Navigation and Mission Design"[3] covered planetary mission design in general, as well as the estimation and control of vehicle flight paths when flight path and attitude dynamics may be treated as decoupled or loosely coupled (as occurs the majority of the

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time in a typical planetary mission). Part II titled "Onboard Guidance, Navigation, and Control (GN&C)"[4] covered attitude estimation and control in general, as well as the estimation and control of vehicle flight paths when flight path and attitude dynamics are strongly coupled (as occurs during certain critical phases, such as entry, descent, and landing). Part III titled "Surface Guidance, Navigation, and Control"[5] examined GN&C for vehicles that are not in free flight, but that operate on or near the surface of a natural body. Together, these three parts provide the SMD PSD with a technology roadmap for achieving the science missions in the next decade. This paper presents an overview of the results and findings of this technology assessment activity. The paper presents the key future missions and an assessment of the associated advanced capabilities and technologies needed for these mission. In addition, the overall findings are summarized. Our readers are encouraged to read the full technology assessment captured in the three reports, available online at http://solarsystem.nasa.gov/scitech/reports.cfm , where the exciting future missions can be appreciated in further detail.

Table 1. Final prioritization of the top technologies, categorized by objective.[1]

Technology Objective A Extend and sustain human activities beyond low Earth orbit	**Technology Objective B** Explore the evolution of the solar system and the potential for life elsewhere (in situ measurements)	**Technology Objective C** Expand understanding of the Earth and the universe (remote measurements)
Radiation mitigation for human spaceflight	GN&C	(Instruments and sensor) optical systems
Long-duration (crew) health	Solar-power generation (photovoltaic and thermal)	High-contrast imaging and spectroscopy technologies
Environmental control and life support systems (ECLSS)	Electric propulsion	Detectors and focal planes
Guidance, navigation, and control (GN&C)	Fission (power)	Lightweight and multifunctional materials and structures
Thermal propulsion	EDL TPS	Active thermal control of cryogenic systems
Lightweight and multifunctional materials and structures	*In situ* instruments and sensors	Electric propulsion
Fission (power)	Lightweight and multifunctional materials and structures	Solar-power generation (photovoltaic and thermal)
Entry, descent, and landing (EDL) thermal protection systems (TPS)	Extreme terrain mobility	

Note: [1]Table 3.8 from *NASA Space Technologies and Roadmaps and Priorities—Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*. Reprinted with permission from the National Academies Press, Copyright 2012, National Academy of Sciences. Red circles added by author for emphasis—the solid circle highlights technology discussed in this document, having particular relevance to the missions of the Planetary Science Division; the dotted circle pertains mostly to the Human Exploration and Operation Mission Directorate (HEOMD), and so is not as strongly applicable to this document, but still somewhat relevant.

As an additional reference, it should be noted that in 2010, the National Research Council released the *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*.[2] It lists a number of technical challenges and associated technologies pertinent to this document. The GN&C technology area emerged as the number one technology priority for overall Technology Objective B: Explore the evolution of the solar system and the potential for life elsewhere (in-situ measurements). It also emerged as the number four technology priority for overall Technology Objective A: Extend and sustain human activities beyond low Earth orbit. More detailed information about the pertinent top technical challenges and associated technologies are described in Table 1 and in Ref. 2.

II. Onboard and Ground Navigation and Mission Design

NASA's expertise in deep space mission design and navigation has enabled many successful planetary missions—flyby and orbiter missions to Mars, Venus, and Mercury; lander missions to Mars; flyby, atmospheric probe, and orbiter missions to the Jupiter and Saturn systems; flyby missions to Uranus and Neptune; and missions to comets and asteroids, including sample returns to Earth. Future missions will need to build on these successes in order to meet tightening performance requirements and growing demands for the autonomous response of spacecraft to new environments (i.e., atmospheric winds, comet outgassing jets, high radiation, etc.).

A. Mission Design

The importance of research and development in the fields of celestial mechanics, trajectory optimization, and mission design is clearly stated in the Instrumentation and Infrastructure and Recommended Technology Investments sections of *Vision and Voyages for Planetary Science in the Decade 2013–2022*.

Mission design trade studies and analyses are used in all mission phases, from early concept studies through operations. Central to mission design capabilities is the ability to rapidly design efficient and innovative trajectories, as well as to perform wide-ranging parametric studies. This is most critical in the early design phases and can have far reaching implications throughout the rest of the project from science return, to spacecraft design, to operational considerations, and more.

As the set of mission concepts and challenges continues to grow more complex, the need to ensure that mission design tools and analyses are constantly maturing and evolving must be paramount. The following high-level goals provide key challenges for future mission design tools: 1) enable new science missions; 2) increase science and investment return even while in flight; 3) reduce cost, velocity change (ΔV), mass, and risk; and 4) enable development of mission designs that ensure the safety of spacecraft trajectories within unstable and highly dynamic environments, such as in close proximity to asteroids or comets.

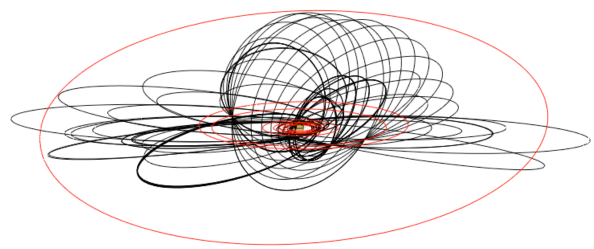

Figure 1. Exploration of Multiple Encounter Tour Designs.

A more complete understanding of the dynamically complex design space for a given mission will lead to better designs and a more efficient design process. Additionally, robust optimization and automation techniques are essential to meeting these high-level goals. The creativity, effort, and time it takes to develop more advanced mission designs can be much greater than that for traditional interplanetary missions. This additional burden can put design and development activities at risk or even eliminate certain possibilities from consideration. To increase the effectiveness of mission design in the future, increasingly more complex dynamical models must be used to perform preliminary designs.

The exceptional ingenuity and creativity of scientists and engineers guarantees that new mission concepts appear continually. In order to meet these creative challenges, mission designers must be able to rapidly design efficient and innovative trajectories; otherwise, opportunities for new missions will be lost. Much of the current mission design capability is based on techniques developed decades ago to meet more simplistic mission goals and often cannot support new concepts. Investment in new mission design techniques would: 1) enable new planetary science missions by developing design techniques for new mission classes and reducing required resources on others; 2) allow increased science return by increasing science payload mass capability (reduced propellant or higher delivered mass) and expanding the range of science opportunities (more targets accessible, more time at target, better geometry, etc.); and 3) reduce design times by an order of magnitude, allowing more exploration of the design space and trade studies to increase science quality and quantity.

The next five sub-subsections detail some important focus areas for future astrodynamics research.

1. Multiple-Encounter Tour Design

Tour design has been an integral part of mission design for the past 40 years, starting with Mariner 10, Pioneer 10 and 11, and Voyager and extending through Galileo, Cassini, and Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) (see Figure 1). The judicious use of gravitational interactions to eliminate the expenditure of large quantities of propellant was one of the first "enabling" mission design technologies. Such techniques allowed incredible scientific discoveries at the outer planets and beyond.

However, next-generation tour designs will require innovative techniques with much higher fidelity. Technology developments in aerodynamic gravity assists and aerocapture at atmosphere-bearing bodies will also benefit certain mission scenarios. These advancements will lead to lower ΔV requirements and allow more rapid design for a broader and enhanced range of science opportunities. Some potential example applications include: 1) trajectories to multiple small bodies such as comets or asteroids; and 2) satellite tours at outer planets, such as a Jupiter moons or a Uranus orbiter mission.

2. Close-Proximity Trajectory Design for Small-Body Missions

The design of trajectories to/from and around small bodies such as asteroids, comets, or small moons presents a new and exciting set of mission opportunities for scientific discovery. There have been a number of recent successes including Near Earth Asteroid Rendezvous (NEAR), Stardust, Hayabusa, Deep Impact, and Dawn. Much work has recently been done to understand the dynamics around small bodies; however, the techniques and analyses for designing small-body missions are still in their infancy. Further technological advances are necessary to support future small-body missions such as

- Automation and optimization of small-body mission designs in a high-fidelity dynamical system, possibly including low-thrust, such as for Dawn. This is critical since the trajectories around small bodies cannot be properly modeled with simple conic analysis.
- Dynamic environment characterization, mission scenarios, trajectory design, control, and station-keeping. This dynamic characterization and control is fundamental to the science goals and requirements of any small-body mission, especially since typically very little *a priori* knowledge is available about any given target. Characterization of the gravity field of an irregular small body by some means other than a spherical harmonic expansion becomes important near the surface, where such an expansion may diverge.
- Applicability to small-body rendezvous missions (involving asteroids, comets, or small moons) with a further goal of sample return. This applicability also includes autonomous operations around small bodies, since the round-trip light time to many destinations prohibits real-time ground interaction.
- Inclusion of significant third-body gravitational effects, as well as other small forces such as solar radiation pressure, etc., which would be critical for missions to Phobos/Deimos or Enceladus, for example.

3. Low-Energy Trajectory Design and Optimization

Low-energy trajectory design, incorporating the dynamical effects of two or more gravitating bodies, has been employed for many decades with missions such as International Sun-Earth Explorer 3/International Cometary Explorer (ISEE-3/ICE), Solar & Heliospheric Observatory (SOHO), Advanced Composition Explorer (ACE), Hiten, and Genesis. The state-of-the-art in low-energy trajectory design has evolved from tedious trial-and-error numerical analysis to a better understanding through the application of Dynamical Systems Theory to the n-body problem (the problem of solving for the motions of n bodies that interact gravitationally). This insight was instrumental in development of the Genesis trajectory that enabled sample return from the sun-Earth collinear libration points. This insight has also been used recently with great success in the design of the Gravity Recovery and Interior Laboratory (GRAIL) and Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) missions to the moon. The field of low-energy trajectory design is still developing, and there is much yet to discover and analyze. Some future areas of development that will yield significant improvements to missions include: 1) ability to rapidly design and optimize trajectories that take advantage of multibody dynamics (also potentially useful in spacecraft autonomous operations); 2) design of efficient transfers and captures into desired science orbits, especially when combined with low-thrust capabilities; 3) extension of applicability to a wide variety of mission concepts, including missions to Mars, Europa, Enceladus, Phobos, or other small bodies, as well as in the sun-Earth-moon system; and 4) use of lunar gravity assists and solar perturbations in the sun-Earth-moon system to reduce the cost of interplanetary missions and increase delivered payload.

4. Multiple-Spacecraft Trajectory Optimization

The use of multiple spacecraft in a formation or constellation enables science that cannot otherwise be achieved with a single spacecraft. The recent successes of the Gravity Recovery and Climate Experiment (GRACE), GRAIL, and ARTEMIS missions demonstrate the critical importance of missions involving two or more spacecraft flying in a coordinated manner to achieve science goals. Technological advances in multiple trajectory design may enable such missions and others in the future through the ability to simultaneously and rapidly optimize trajectories of multiple spacecraft. Some example applications include 1) missions with an orbiter and a lander/probe, or an ascent vehicle and an orbiter; and 2) a multiple-asteroid mission from a single launch.

5. Low-Thrust Trajectory Design and Optimization

Highly efficient propulsion systems, such as electric propulsion and solar sails, can be used to enable many types of extremely flexible and robust missions. Electric propulsion for missions to the moon and beyond has been demonstrated on Deep Space 1, Small Missions for Advanced Research in Technology 1 (SMART-1), and

Hayabusa and used on the science mission Dawn; and solar sailing has been demonstrated on the Japanese mission Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS). While being highly efficient, these propulsion systems typically produce only a relatively small amount of thrust. As a result, the engines operate during a significant fraction of the flight and at differing thrust levels dependent upon power availability, making it much more difficult to design trajectories for missions using low-thrust propulsion.

Significant progress has been made in developing low-thrust trajectory design capabilities, particularly for the Dawn mission; however, significant areas remain to be explored and developed further: 1) robustness to unplanned missed thrusting; 2) high-fidelity designs for trajectories with many revolutions; 3) broader, more rapid search capabilities; 4) low-thrust trajectories in a multibody environment; 5) trajectory design capabilities for new types of propulsion systems; and 6) pre-flight prediction and in-flight calibration of low-thrust propulsion systems, such as solar sails, to enable the ability to robustly meet mission goals.

To take advantage of the tremendous potential of low-thrust propulsion capabilities, the ability to design and navigate the corresponding trajectories needs to be developed.

B. Navigation Technologies

Key navigation technologies for future planetary science missions depend on improvements in measurement and dynamical modeling and autonomy. The applications of autonomy documented in this section focus on scenarios in which flight path estimation and control are relatively easy to separate from attitude estimation and control. Applications of autonomy to situations in which flight path and attitude dynamics, estimation, and control are tightly coupled are examined in Section III.

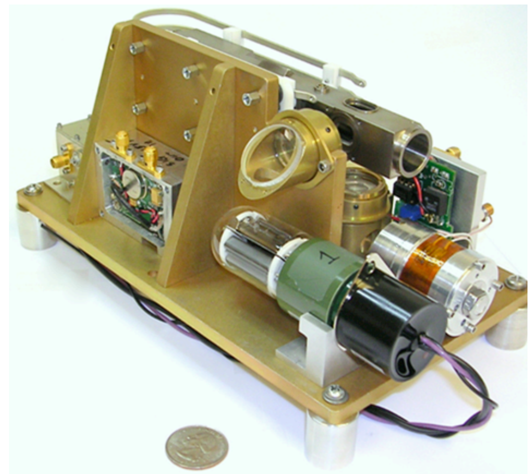

Figure 2. Laboratory Brassboard Version of DSAC in a Low-Mass and Low-Volume Package; Accurate to 1 ns in 10 Days.

6. Precise One-Way Radio Metric Tracking

Ground-based atomic clocks are the cornerstone of spacecraft navigation for most deep space missions because of their use in forming precise two-way coherent Doppler and range measurements. Until recently, it has not been possible to produce onboard time and frequency references in interplanetary applications that are comparable in accuracy and stability to those available at Deep Space Network (DSN) tracking facilities.

The developmental Deep Space Atomic Clock (DSAC) is a small, low-mass atomic clock based on mercury-ion trap technology that can provide the unprecedented time and frequency accuracy needed for next-generation deep space navigation and radio science. DSAC would provide a capability on board a spacecraft for forming precise one-way radio metric tracking data (i.e., range, Doppler, and phase), comparable in accuracy to ground-generated two-way data. With an Allan deviation (a measure of frequency stability in clocks, oscillators, and amplifiers due to noise processes) of better than $2{\times}10^{-14}$ at 1 day, DSAC will have long-term accuracy and stability equivalent to the existing DSN time and frequency references. Indeed, an early laboratory version of DSAC (shown in Figure 2) has demonstrated an Allan deviation $<10^{-15}$ at 1 day. By virtually eliminating spacecraft clock errors from radio metric tracking data, DSAC enables a shift to a more efficient, flexible, and extensible one-way navigation architecture.

In comparison to two-way navigation, one-way navigation delivers more data (doubling/tripling the amount to a user), is more accurate (by up to 10 times), and enables future autonomous radio navigation (improving performance, robustness, and safety of time-critical events such as probe landings or flybys). Many of these benefits can be achieved with little to no modification to the typical navigation paradigm of collecting and processing data on the ground.

DSAC would also enable a shift toward autonomous radio navigation where the tracking data are collected (from the DSN uplink) and processed on board. In the current ground-processing paradigm, the timeliest trajectory solutions available on board are stale by several hours as a result of light-time delays and ground navigation processing time. DSAC's onboard one-way radio tracking would enable more timely trajectory solutions and an autonomous GN&C capability. This capability can significantly enhance real-time GN&C events, such as entry, descent, and landing, orbit insertion, flyby, or aerobraking, by providing the improved trajectory knowledge needed to execute these events robustly, efficiently, and more accurately.

The NASA DSAC Technology Demonstration Mission is currently advancing DSAC technology to technology readiness level (TRL) 7 to demonstrate and validate the technology in an Earth orbit space environment. This TRL 7 demonstration should enable DSAC technology to be readily incorporated into multiple future missions.

7. Autonomous Navigation

Several planetary missions have made use of autonomous onboard navigation. This approach has been used when round-trip light-time delay makes it impossible to achieve the desired navigational accuracy with ground processing of data. The AutoNav system (with simpler code than the ground system) is initialized with the best available information from the ground and is then allowed to operate on its own for some length of time to achieve the desired flyby, impact, or soft-landing conditions.

Several enhancements to the current AutoNav system would greatly increase its capability and usefulness to a wide variety of missions: 1) addition of data types (landmark tracking, lidar/radar altimetry, radio metric tracking [such as the DSAC], spacecraft-to-spacecraft radio metric tracking), and high-precision astrometry; 2) improvements to the onboard filtering capability (stochastic parameter estimation, filter smoothing, etc.); 3) addition of trajectory optimization; 4) improvements in overall robustness/error checking and handling; and 5) improvements in interfaces to other spacecraft elements. These enhancements would enable a wide range of mission scenarios as described below.

Autonomous Aerobraking. A number of missions involving the orbiting of Mars or Venus have used the force of aerodynamic drag, high in the planet's atmosphere, to deplete energy from the spacecraft's orbit and thereby reduce the orbit's size and period. Over a number of months, a mission uses many atmospheric passes to accomplish this reduction in spacecraft orbit period.

Each atmospheric pass needs to occur in an altitude range such that aerodynamic effects do not result in excessive forces or heating rates, but still produce a sufficient aerodynamic effect such that the overall orbit modification process can be completed in a timely fashion. Thus, each atmospheric pass must occur within a certain atmospheric corridor, which is more properly a function of atmospheric density than altitude. (Density, the determinant of aerodynamic effects, varies with time and location in both predictable and unpredictable ways.)

Given the orbit accuracy requirements at each periapsis and the duration associated with the aerobraking process, developing a means to automate the functions of orbit determination and periapsis altitude control on board an orbiting spacecraft would allow the required accuracy to be achieved while minimizing the navigation operations workforce. The use of spacecraft accelerometer data would play a major role in enabling these capabilities.

Outer Planet Tour. Onboard autonomous navigation for a Europa orbiter–class mission would reduce turnaround times for navigation operations, allowing for exploitation of complex trajectories that minimize fuel and enhance science return. Conventional ground navigation and associated sequencing and operations processes (i.e., Galileo/Cassini) result in: 1) long (e.g., days) turnaround of navigation and maneuver designs and uplink product generation; 2) the number of possible gravity-assist flybys constrained by ground operation limitations; 3) maximum orbit control frequency limited to one independently calculated maneuver per 10 days, which limits targeted flyby frequency; 4) sufficient time between flybys to limit the ability to take advantage of complex satellite dynamics to minimize fuel required.

Integrating navigation, maneuver, and turn computation, design, and execution functions into a Europa Orbiter–class outer planet mission can substantially reduce light-time and other delays associated with the navigation process, and would result in: 1) rapid turnaround between navigation data capture and orbit control, as well as post-flyby clean-up; 2) rapid successive and safer lower-altitude satellite flybys to reduce mission Delta-V; 3) more efficient outer planet orbit insertion with closer (to event) targeting, rapid clean-up, and lower altitude; 4) automation of routine navigation activities, such as turn and maneuver sequence generation; and 5) less propellant mass required to achieve orbit around or landing on an outer planet satellite, such as Europa or Titan.

Achieving these performance improvements requires advancing the Deep Impact–based AutoNav system to TRL 6 to include the complex orbital dynamics for a satellite tour, target-relative-navigation (TRN) image processing, and additional data types, such as altimetry and one-way radio metric data; and to extend the AutoNav executive function to include comprehensive advanced fault tolerance.

The quantitative impact of these advancements would be: 1) savings of hundreds of m/s of Delta-V; 2) double or triple the frequency of satellite flybys, with an order of magnitude increase in science return; and 3) automation of routine navigation operations and operations planning, such as image capture and maneuver turns and execution, significantly reducing operations costs.

Primitive Body/Lunar Proximity Operations and Pinpoint Landing. The NEAR and Hayabusa asteroid landings demonstrated that such missions are feasible using ground-in-the-loop navigation at tens of meters of accuracy. For future landings on asteroids or comets, it may be necessary to achieve accuracies of less than 5 m, either because of the lack of safe landing spots at larger scales, or to target very specific regions for science. Furthermore, it may also be necessary to tightly control the velocity at touchdown for spacecraft safety. This combination of requirements makes it very difficult, if not impossible, to execute the landing with ground-based control due to light time and other lags that occur between navigation knowledge update and maneuver execution. AutoNav is ideally suited for this type of mission, achieving position control to within 3 m and horizontal velocity control better than 2 cm/s, as demonstrated by Monte Carlo simulations. Simulations for precision landings on the moon also show that landings to within 20 m are possible.

8. Evolutionary Improvements in DSN Radio Metric Data Accuracy

The evolution of deep space telecommunication frequencies from S-band (2.1 GHz uplink and 2.3 GHz downlink) to X-band (7.2 GHz uplink and 8.4 GHz downlink) has resulted in a considerable improvement in radio metric data accuracies. Certain error sources are directly related to the telecommunication frequency and diminish with increasing frequency. Other error sources diminish with increasing signal bandwidth, which can be made larger as the carrier frequency increases. A continued upward migration in telecommunication frequencies from X-band to Ka-band will further improve radio metric data accuracies.

Radio science experiments have shown that Doppler data accuracy can be improved by at least an order of magnitude. The Cassini gravity wave experiment made use of a more elaborate radio system than is typically used, in which signals were uplinked at both X-band and Ka-band. The spacecraft transponded the X-band uplink at both X-band and Ka-band, and the Ka-band uplink was separately transponded at Ka-band. The use of these multiple frequency links enabled complete cancellation of errors due to solar plasma and ionosphere. In addition, a water vapor radiometer was used at the ground station to calibrate line-of-sight delay change due to water vapor fluctuations. Doppler accuracies better than 0.001 mm/s were achieved for a 1000-s interval. This type of data, if routinely available, would result in scientific benefits, including improved navigation and gravity field mapping.

There are several limiting error sources in radio metric measurements made for the purpose of navigation. Thermal noise is rarely a limiting factor, since longer integration times can effectively reduce this error term. Accuracy at short time scales is usually limited by media fluctuations. Errors due to solar plasma and Earth's ionosphere can be reduced by a factor of 15 by making use of Ka-band radio links instead of X-band. To realize this improvement for Doppler and range data, both uplink and downlink would need to be at Ka-band. Ka-band for downlink only would provide this improvement for delta-differential one-way range (Delta-DOR) data. Tropospheric scintillations can be reduced by a factor of 2 to 10 through the use of water vapor radiometers at the tracking stations to provide calibrations. If Ka-band uplinks come into use for telecommunication purposes, some improvements in navigational accuracy (as well as radio science benefits) would result as a byproduct, as noted above. However, a decision to move to Ka-band uplinks primarily for navigational purposes would require a careful cost/benefit analysis, since spacecraft navigation accuracy in most deep space applications depends on a number of factors besides tracking data accuracy.

Systematic errors in tropospheric and ionospheric calibrations can limit accuracy for Doppler data at longer time scales and for Delta-DOR data. Observations of GPS satellites from receivers located near the tracking stations are the primary source of data for these calibrations. The relative sparseness of the GPS constellation makes it difficult to map media delay measurements to the spacecraft line of sight. However, the development of a similar European navigation satellite constellation, combined with satellites of other countries, provides denser coverage in the sky. An improvement of a factor of 2 or more in global calibration accuracy could be achieved by taking advantage of these signals.

Errors in real-time predictions of the rotation of Earth about its axis can limit accuracy for Doppler data at longer time scales and for Delta-DOR data. The difficulty at present is latency in the processing of very long baseline interferometry (VLBI) measurements made for the purpose of Earth orientation determination. However, data transfer capabilities over the internet have already been demonstrated to have a sufficient rate to enable much faster processing. Hence, accuracy improvements of a factor of at least 3 are readily possible.

Range data are strongly affected by the uncertainty in the calibration of path delay through tracking station electronics. This has proved a difficult problem to overcome, primarily due to the limited bandwidth of the ranging codes currently in use. However, wider bandwidth pseudonoise ranging codes are anticipated for future use. The wider bandwidth will provide more precision and is expected to enable much better calibration of station delay. Also, spacecraft will regenerate the ranging code on board; and errors due to thermal noise will be greatly reduced. Reduced thermal noise will enable ranging to be done in the far outer solar system or to spacecraft with only low-gain antennas. Furthermore, better ranging data will enable scientific studies of planetary dynamics and more sensitive tests of gravitational theories.

A significant improvement in Delta-DOR measurement accuracy is probably not possible at X-band frequencies. The spectrum allocation available for deep space research is limited, restricting the allowed bandwidth for the group delay measurements. More importantly, the measurement accuracy is already approaching the uncertainty level in the quasar coordinates caused by source structure. However, both of these problems could be reduced by using Ka-band frequencies. The spectrum allocation is 10 times wider at Ka-band, and research indicates that radio sources are more compact at the higher frequencies. With a better quasar catalog, and lower thermal noise errors due to increased bandwidth, an overall improvement of a factor of 5 is possible for Delta-DOR measurements.

9. Derivation of Metric Tracking Data from Optical Communication Links

Planetary spacecraft navigation has generally relied on the capabilities of the radio system used to communicate with the spacecraft, with several specific augmentations made to enhance navigation measurements (e.g., range measurement side tones and DOR tones). In the future, deep space telecommunication at much higher optical frequencies may come into use.

The laser communication capabilities offer potentially improved data transmission for a given amount of spacecraft power. A laser communication package also offers some potential improvements for navigation, as well as some challenges, particularly if the laser communication package provides the sole downlink to Earth.

The basic navigation measurement over the years has been the Doppler shift of the radio carrier frequency, as transponded by the spacecraft. Laser communication will most likely not be modulated on a carrier, since atmospheric turbulence causes significant fluctuations in frequency for patches in the atmosphere that are small (e.g., 10 cm) compared with the large collecting apertures needed to gather sufficient light from a planetary spacecraft. Instead, most planetary laser communication is envisioned to be based on pulsed transmissions, with pulse widths of a few nanoseconds. By adjusting the time at which the laser fires, data can be encoded based on the relative time between pulses (pulse position modulation), enabling multiple bits of data to be collected for a single received photon.

The narrow pulse widths are similar to those used for satellite laser ranging (SLR) in near-Earth applications. SLR achieves range measurement accuracy of about 1 cm by transmitting pulsed laser signals to spacecraft with corner-cube reflectors (e.g., Laser Geodetic Satellite [LAGEOS]) and measuring the time between transmission and reception of the reflected pulse. The SLR range measurement accuracy is limited by variation in the atmospheric refraction effects between transmission and reception. Laser ranging to a corner reflector on a planetary spacecraft is impractical since the signal losses scale as the inverse fourth power of the distance. With a laser communication package capable of measurement of the time between an uplink pulse and a downlink pulse, range measurements to planetary spacecraft with accuracy comparable to SLR measurement accuracy should be possible. Demonstrations of two-way laser ranging to planetary spacecraft have been done with altimeters on MESSENGER and Lunar Reconnaissance Orbiter, with resulting accuracies of a few meters limited by the altimeter timing measurement capabilities. With improved timing circuits, which are already used in SLR stations, 1-cm accuracy is achievable.

The laser range measurement accuracy discussed above is based on a two-way system with accurate timing circuits on the spacecraft. Much of the Doppler-like measurement capability could be achieved with a downlink-only system, if an accurate onboard time standard were used, such as the DSAC.

C. Key Findings and Recommendations

NASA's mission design and GN&C technologies have enabled every deep space mission flown by NASA. The continued advancement of these technologies has facilitated the continued success of more complex missions. Based on the work done in producing the report from which section II of this paper has been derived, a number of findings and recommendations have been conveyed to NASA's Planetary Science Division. These are listed below.

1. Finding 1

The exceptional ingenuity and creativity of scientists and engineers ensures that new mission concepts appear continually. In order to meet these creative challenges, mission designers must be able to rapidly design efficient and innovative trajectories; otherwise, opportunities for new missions will be lost. Much of the current mission design capability is based on techniques developed decades ago and is frequently unable to support these new concepts. Some development of new mission design capabilities occurs naturally as a result of flight project activities and pre-project studies, but more research is needed. The recent "ROSES-12 Amendment 6: New Opportunity in ROSES-12 via Appendix C.21, In-Space Propulsion Technology Program: Astrodynamics Research Grants" is a good starting point.

Recommendation: Significantly more resources should be made available to mission design technology development, a long-neglected area of research. A stable, long-term commitment to fund research and innovation should be made, separate from the funding of specific planetary missions. Mission design needs should be explicitly included in future NASA technology roadmaps.

2. Finding 2

Deep space navigation functions, traditionally performed on the ground, can be mission enabling or enhancing in certain situations when moved on board a spacecraft. Round-trip light-time delay can be eliminated, as can the need for a constantly available two-way spacecraft-ground communication link at critical times. The onboard navigation software can be a compact, simplified version of the ground software. Both continued onboard GN&C system-level work, as described in section III below, and specific, focused application developments, as discussed here, are important.

Standards for interfaces are also needed in order to allow modular autonomous navigation software applications to work on a variety of spacecraft built by various companies and laboratories. The need for autonomous navigation was so compelling in the case of missions such as Deep Impact that it was implemented without the development of such standards.

Recommendation: Both continued onboard GN&C system-level work and specific, focused application developments should be pursued. Moreover, the development of standards for interfaces would facilitate the use of modular autonomous navigation software applications on a variety of spacecraft built by various companies and laboratories.

3. Finding 3

The Deep Space Network (DSN) has been a cornerstone of deep space navigation for many years and will remain so for years to come. Some improvements in capabilities will take place in an evolutionary fashion, without affecting the basic use of the DSN for navigational purposes. These improvements will be driven by the use of higher transmission frequencies, driven largely by telecommunication considerations, and by improvements in electronics and computing capabilities, along with reductions in transmission times between the sites at which data are collected and the sites at which they are processed (sometimes on a different continent). The net effect here will be a steady improvement in the accuracy of metric data, without changing the basic operating mode of the DSN. It is important for the tracking capabilities of the DSN to improve with time, as technological advances allow, rather than to remain static or regress.

Recommendation: The Planetary Science Division should advocate that NASA's Space Communications and Navigation (SCaN) program provide for future funding of the DSN to enable continued improvement of radio metric tracking data accuracy.

4. Finding 4

DSAC will allow use of the DSN in new and more efficient ways; for example, relying much more on one-way communication links.

Recommendation: Innovations such as DSAC, which offer improvements in tracking data accuracy and efficiency, need to be brought to flight readiness and put into use in a variety of applications. The OCT-funded DSAC Technology Demonstration Mission should move forward with strong support from the PSD.

5. Finding 5

The use of optical communication links could produce metric information analogous to that produced by the DSN, but at transmission frequencies that are several orders of magnitude higher and involve the use of very different ground and onboard communication equipment. As optical links are developed for use in deep space communication, the use of these links for navigational purposes should be well understood and carefully planned from the beginning, rather than being an afterthought.

Recommendation: A study should be conducted to fully investigate how optical communication links can be used to provide metric tracking data for use in spacecraft navigation.

6. Finding 6

Various improvements in observational and dynamic modeling are needed to most effectively navigate certain future planetary missions. The complex dynamical environment in the vicinity of a small body and the construction of accurate, body-relative, navigational measurements comprise one such example. The close orbiting of terrestrial bodies with imprecisely known gravity fields is another example.

Recommendation: More sophisticated dynamical and measurement models should be developed and incorporated into NASA's deep space navigation software.

7. Finding 7

It can be challenging to develop a full and clear comprehension of the work that PSD funds in mission design and GN&C technologies across various NASA centers, universities, and industry. The facilitated distribution of pertinent information would enhance the development and execution of NASA's investment strategy in these areas and maximize the effective use of limited resources.

Recommendation: PSD should ensure that information regarding accomplishments and future plans be disseminated among the various organizations working in mission design and GN&C technology areas. A technology assessment group should meet on at least an annual basis, and pertinent material should be posted on a NASA website (such as that of the NASA Engineering Network, for example) on a more frequent basis.

III. Onboard Guidance, Navigation, and Control (GN&C)

A. Introduction to Onboard GN&C

Spacecraft onboard Guidance Navigation and Control is defined to be the attitude path planning, sensing, and control of the spacecraft to achieve desired spacecraft maneuvers and pointing. Navigation is defined to be determination of the vehicle's position and velocity and calculations associated with the adjustment of that position and velocity to achieve a desired course. Guidance and Control (G&C) is defined to be the onboard manipulation of vehicle steering controls to maintain vehicle pointing with the required precision, and simultaneously—when necessary—track navigation computations while maintaining vehicle pointing. Sensing and estimation are integral parts of onboard GN&C for in situ inertial, celestial, and target- or terrain-relative measurements and estimation of the spacecraft state.

GN&C has progressed in the 60 years of space flight but not enough to perform upcoming missions. Technology investments need to be made in on-board GN&C in order to accomplish the missions proposed for the next decade. To reach and explore the new scientific targets of SMD PSD interest, advances in GN&C capabilities are needed for the following mission scenarios, which will be described in the next section:

- Surface landers
  - Surface lander on targets with high gravity and atmosphere
  - Surface lander on targets with significant gravity and no atmosphere
  - Surface lander on low-gravity, small-body targets
- Proximity operation about low-gravity, small-body targets
- Sample-return missions
- Ascent, autonomous rendezvous and docking (AR&D)
- Sample return
- Multiple-target planetary tours
- Planetary orbiters
- Formation flying and spacecraft swarms

Very significantly advanced GN&C performance is needed to overcome the following natural challenges:

- Long round-trip light time
- Time-urgent in situ operations
- Unknown and dynamic environment
- Flight and mission system fault conditions
- Mission longevity

These challenges that apply variously to some or all of the above scenarios will drive the development of GN&C technology across the full span of functions, as will be discussed in the following sections. GN&C functions largely occur on board spacecraft, but there are many design simulations, support, and test functionalities that occur only as part of research and ground operations. GN&C functions divide coarsely into 1) algorithms and software, 2) flight instruments, 3) non-sensing flight hardware, and 4) ground test facilities.

GN&C algorithms and software can be divided into inertial onboard guidance and control, and target-relative estimation. Inertial onboard GN&C includes such functions as position and attitude estimation and path control, spacecraft path planning, autonomy systems, and low-thrust guidance. *GN&C flight instruments* can be divided into target-relative and inertial sensors. Target-relative sensors include landmark-relative position estimation, aeroguidance, LIDARs, hazard detection and avoidance, and precision pointing control. Inertial sensors include star-trackers, gyros, and accelerometers, as well as precision time determination. *Non-sensing GN&C flight hardware* includes microspacecraft GN&C subsystems, radiation-tolerant GN&C elements, aeroguidance and solar-sail control mechanisms, and advanced flight computers. Finally, *GN&C ground test facilities* include testbeds such as free-flying simulators, air-bearing facilities, crewed and uncrewed aerial vehicle (e.g., helicopters and UAVs) simulators, and atmospheric entry test platforms.

These technologies help meet a host of challenges to future aggressive and rewarding PSD missions, including operations in time-urgent, highly dynamic environments in the face of long round-trip light-times, long-lived missions, budgetary challenges, distributed spacecraft and spacecraft systems, autonomy requirements, complex fault responses, and stringent pointing requirements. Further, these challenges are met in a wide variety of mission scenarios, including surface landing in high or low gravity, in high or low density atmospheres, encountering primitive bodies, working in extreme physical environments, on airborne planetary platforms, during multibody planetary tours, in proximity operations around small bodies, and during touch-and-go contact with low-gravity objects, among others.

The use of these technologies, facing these challenges in these scenarios, was analyzed for the missions recommended in the Planetary Science Decadal Survey, and presented in Ref. 4. The missions considered are Mars sample return (MSR), comet surface sample return, lunar south-pole Aitken Basin sample return, Saturn probe, Trojan tour, Venus *in situ* explorer, Io observer, Lunar geophysical network, Titan Saturn system mission, Jupiter Europa orbiter, Uranus orbiter and probe, Europa orbiter, Neptune orbiter and probe, Ganymede orbiter, Europa lander, near-Earth object (NEO) surveyor or explorer, and Mars geophysical network. Potential Discovery-class missions are also considered.

Table 2 shows the results of these analyses, prioritizing technology development based on likely frequency of use ("raw prioritization"), and then qualified by estimated cost of development ("cost-moderated prioritization"), considering current technology readiness level (TRL). Fortunately, the ratings remained very similar under both rating criteria.

Raw Prioritization / Cost-Moderated Prioritization	Highest Priority	High Priority
Highest Priority	6-DOF G&C, nonlinear path planning, integrated GN&C software systems, target-relative position and attitude estimation, nano-g accelerometers, advanced onboard computation	Low-thrust guidance, terrain sensors
High Priority	Aerial platform GN&C emulators	Microspacecraft GN&C technology, precision planetary pointing systems, altimetry and velocimetry, hazard-detection sensors, free-flying propulsive platforms, laboratory 6-DOF emulators

Table 2 Results of technology assessment for missions recommended in the 2011 Planetary Science Decadal Survey (prioritization by frequency of potential use, and by frequency amplified by cost and technical maturity).

B. Survey of Onboard GN&C aplications to missions forecast in the Planetary Science Decadal Survey

1. *Surface Landing Missions*

a. *Landing on Mars*

Relevant future missions: Mars Sample Return (MSR), Mars NetLander, and future Mars rovers

Landing on Mars requires fully autonomous GN&C with linked attitude and trajectory guidance running on very-high-frequency, closed-loop control due to a highly dynamic environment, high gravitational forces, and atmospheric perturbations (Fig. 3) These systems will be increasingly linked to sensors and actuators, including IMUs, terrain-relative navigation sensors, hazard-detection sensors, altimeters, velocimeters, engine throttles, and other control mechanisms as the accuracy demands intensify for every new Mars landing.

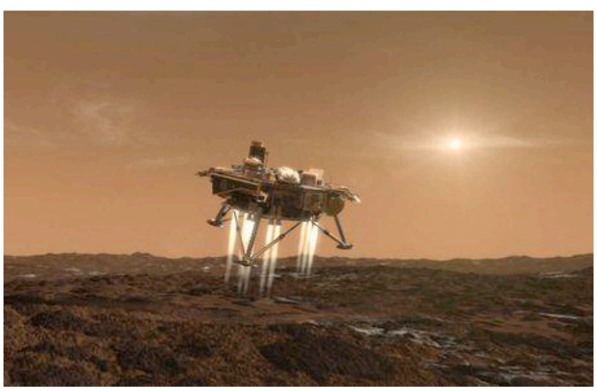

Figure 3. Phoenix-derived Mars Sample Return (MSR) concept shown performing precision landing on Mars in an artist's concept

Improved initial attitude knowledge at atmospheric entry, advanced atmospheric entry G&C technologies, advanced vehicle deceleration technologies, and new parachute deployment trigger and G&C strategies are new capabilities in the atmospheric entry phase that will directly facilitate improvements in landing accuracy and delivered mass of next-generation missions. The combination of improved pre-entry navigation and intelligent use of nano-g accelerometers can lead to dramatic targeting improvements at landing. Alternatively, in the powered descent and landing phase starting after parachute deployment, landmark-based navigation, with target-relative navigation (TRN), determining the offset to the target, followed by a large trajectory deflection to fly out vehicle offset from target, will enable very precise landing. With current technology, the divergence from the desired landing site at the end of the atmosphere entry phase is relatively large (e.g., 4–8 km at Mars) due to atmospheric perturbations. This large offset is one reason that missions require such large safe landing areas, within which they must subsequently "rove" to sites of scientific interest.

When pre-landing surveys are inadequate to guarantee terrain safety, hazard detection and avoidance (HDA) will be increasingly necessary for autonomous safe landing. Thus, some combination of improved pre-entry navigation, accelerometry, onboard landmark-based autonomous navigation with TRN, fuel-optimal large trajectory deflection guidance (path planning), and HDA will be needed for landing accuracy improvements. Using these methods, almost arbitrary landing accuracy will be possible enabling the positioning of a landed asset directly in a region of high science interest. These advanced systems will depend upon a high degree of interplay across the sensors, actuators, algorithms, and software, necessitating comprehensive iterative testing and demonstration at the system level in testbeds; Earth-based, free-flying, closed-loop demonstrations; and other realistic simulated environments.

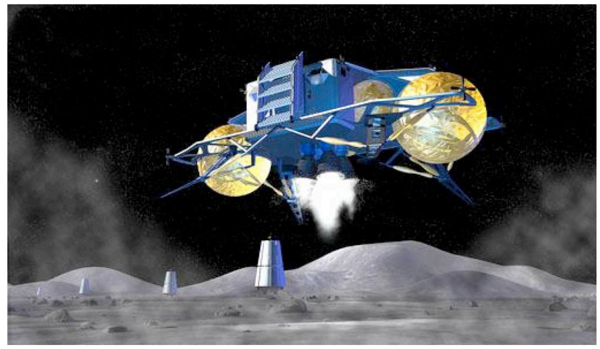

Figure 4: A concept heavy cargo-carrying lunar lander, shown re-supplying bases on the Moon**.**

Once landed, rovers will use a number of methods for surface navigation; these topics are covered in section IV below.

b. Landing on Bodies with Significant Gravity and No Atmosphere

Relevant future missions: Lunar south pole–Aitken Basin sample return, Lunar geophysical network, Europa lander, NEO surveyor or explorer

Robotic landing on large surfaces without atmosphere (e.g., the Moon) is less challenging than landing on Mars. Atmospheric uncertainties are not present and the target site is visible starting from very high altitudes with no entry "plasma phase" to block the view. Landmark-based autonomous navigation, with TRN and HDA are still necessary to reach critical landing sites of high scientific interest but surrounded by terrain hazards (Fig. 4).

c. Surface Landing on Low-Gravity, Small-Body Targets

Relevant future missions: Comet surface sample return, NEO reconnaissance, planetary defense, martian moon exploration

Low-gravity landing differs fundamentally from high-gravity in the time-scales and requirement for high thrust, as well as the need for closely operating trajectory and attitude-control loops (Fig. 5). Many missions to low-gravity targets will make multiple landings, and so will require landing and ascent capability. By definition, an atmosphere is not an issue at these targets, and with all "airless" landings, visibility of landmarks on the surface is continuous (if lighting is appropriate). Though much simpler than high-gravity EDL, low-gravity EDL can still require complex and time-critical combined trajectory and attitude control to gather a sample without making damaging contact with the surface, particularly if the spacecraft needs to remain fully functional for repeated descent, landing, and ascent cycles.

Figure 5. A small body explorer preparing to make contact on a small asteroid.

An important characteristic of these missions is the lack of *a priori* information about the body. In particular, detailed maps will be required to undertake the landmark-based navigation (TRN) as well as detailed gravity models. In general, this requires an extensive ground campaign to develop these maps in a process that can be highly labor intensive. This key element of navigation technology is discussed in Part I of this series, "Onboard and Ground Navigation and Mission Design."

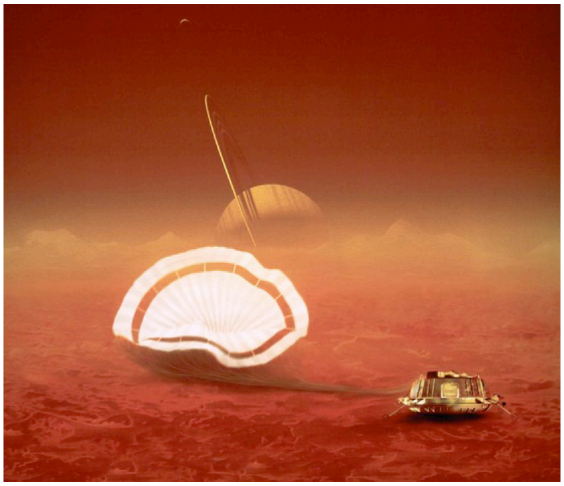

Figure 6: Artist rendering of a Titan probe.

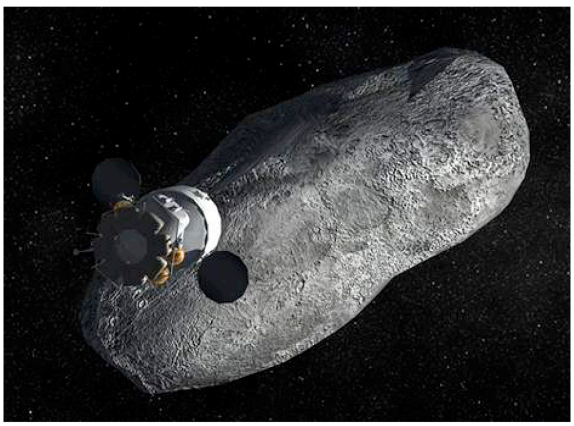

Figure 7. Conceptual mission performing proximity operations at a small body.

d. Landing on Titan and Venus

These two bodies, though dramatically different in size and surface acceleration, share a similar ratio of atmospheric density (proportional to entry drag) to gravitational potential. Thus entry trajectories, after deceleration to subsonic speeds, are very slow, with simple parachutes providing descent paths of many tens of minutes' duration. If precision guidance is necessary during this phase, there is generally ample time to accomplish it through control mechanisms on the parachute or balloon. The navigation of such descent trajectories is done with imaging (TRN) or radiometrics, using one-way data from Earth and a precision clock-reference on the vehicle, or to an orbiting relay craft (Fig. 6)

2. Proximity Operation about Low-Gravity, Small-Body Targets

Relevant future missions: Comet surface sample return, Trojan asteroid tour and rendezvous, Mars moon exploration

Key characteristics of small-body targets are lower gravity and lack of atmosphere. The low gravity allows for 1) longer timelines for surveillance and characterization of the target site, 2) gradual descent to the target, 3) multiple landings or contacts and ascent, and 4) aborting and restarting during critical activities. The lack of atmosphere removes uncertainties due to atmospheric and wind effects, and provides a clear scene for landmark-based autonomous navigation with TRN and closed-loop GN&C, except in the case of comets, which produce an outgassing atmosphere that at times can be substantially obscuring. Controlling the spacecraft to avoid contact with the surface during proximity operations is one of the critical requirements for this mission type. Additional challenges may arise from forces due to ejected material and gas. Unknown and complex gravity models and dynamics of the target body are effective perturbing forces that must be countered, while still maintaining landing accuracy and safety. Science requirements to avoid disturbing or contaminating the surface with propellant often add severe GN&C constraints that must also be overcome (Fig. 7).

A key dynamic attribute of such missions is "terramechanics," that is, interaction with surface material that can vary in strength and density by orders of magnitude between asteroids and comets. These factors of surface compliance, which affect extension and support mechanisms as well as immediate contact devices, are treated in part IV of this paper, "Surface Guidance, Navigation, and Control."

All of these missions require complex approach, rendezvous, and survey phases, entailing inertial navigation and terrain model development, which is covered in Part II of this Paper Similarly, Part II describes the technologies required for the orbital phase of the mission design.

Multiple forms of proximity operations and surface

Figure 8: Concept for a Mars Ascent Vehicle (MAV) launch for a possible MSR mission.

approaches are under examination, including touch-and-go (TAG); open-loop close flyby; and harpoons, darts, and others. These share, in various combinations, phases of operation including approach, descent, hovering, ascent, pursuit, and capture.

Figure 9: Notional capture and return ship in the rendezvous phase of a possible MSR mission.

These missions also present important autonomy challenges, especially for fault detection, isolation and recovery (FDIR) functions. For scenarios where the spacecraft is close to the surface of the body, a few moments of faulty attitude maintenance can end the mission, driving a solar array into the regolith or breaking an appendage. Therefore, more effective and reliable FDIR logic must be incorporated into the executive functions to provide varying levels of fallback, regroup, recovery, or simple escape from the region of danger. Such logic may also, in the case of active comets, need to assess the danger associated with the active body itself.

3. Sample-Return Missions

Sample-return missions from the different targets in our Solar System may take one of several forms, all requiring advanced GN&C skills. As currently envisioned, MSR will loft a sample into orbit from a surface rover, requiring the capturing craft to perform AR&D operations. A primitive-body sample return might require a TAG operation that is in some ways a very soft landing, with an immediate ascent, featuring the challenges of a low-gravity lander, plus other challenges associated with a brief grazing contact. This is the approach to be taken by the currently developing Osiris ReX mission. Other sample return missions may be MSR-like, with direct-to-Earth return, requiring onboard navigation ability to achieve a highly fuel-constrained return trajectory. Still others may use dart-like projectiles to mechanically take a sample and eject it back toward the waiting spacecraft, requiring an MSR-like AR&D operation. Some have proposed micro-sample-return missions to NEOs or other asteroids, or even to martian moons, where MiniSat or CubeSat-class vehicles would return samples to the Earth or Moon via micro-electric propulsion. Such missions would likely require highly reliable interplanetary autonomous navigation, for communication with the spacecraft in deep space would be impracticable (Fig. 8).

a. Ascent, Autonomous Rendezvous and Docking (AR&D), and Sample Return

Relevant future missions: MSR, comet surface sample return

AR&D requires tightly integrated suites of GN&C capabilities, including vehicle-landmark-based navigation, imagers, proximity/range sensors (e.g., LIDAR and RADAR), and generic GN&C autonomy. Ascent is included with AR&D in this subsection because planetary missions requiring an ascent phase are typically ascending to rendezvous with another craft (e.g., the Apollo missions). The ascent phase becomes the first phase of an AR&D operation and is actually not a distinct operation. Sample return is included here because some sample-return scenarios (e.g., MSR) include an AR&D component. Though the autonomous GN&C systems applied to AR&D are tuned specifically for an AR&D operation, they do share much, if not all, of the nature of a generic autonomous GN&C capability, including image/range processing, orbit determination and maneuver calculation. In addition, the generic autonomy of sequence and control is

Figure 10: Concept "Europa Clipper" mission in synchronous orbit around Jupiter enabling multiple close flybys of Europa.

required, as is FDIR. However, the tuning for AR&D, and requirements for AR&D operations testing and simulation, are fairly specific. It is also important to note that AR&D functions divide into two importantly different classes, rendezvous with cooperative targets vs. rendezvous with uncooperative targets. Apollo and MSR are examples of the former whereas docking with orbital debris or automated satellite rescue are examples of the latter (Fig. 9).

4. Multiple-Target Planetary Tours

Relevant future missions: Titan, Enceladus, and Saturn system mission, Europa orbiter/lander

A multi-target solar-system tour (e.g., of asteroids) is likely to be a low-thrust mission, and require some onboard ability to cope economically with the intense activity of electric propulsion over long cruise times. If the tour is of a multi-moon system of one of the gas giants, autonomous path planning and targeting will be necessary to accurately target mission-critical keyholes that are typically low-altitude points above the moons. To achieve the necessary accuracy, landmark-based autonomous navigation with TRN will be required. To increase data return and at the same time reduce downlink requirements, autonomous systems to plan, schedule, implement, and reduce science data linked to onboard GN&C, will be advantageous (Fig. 10).

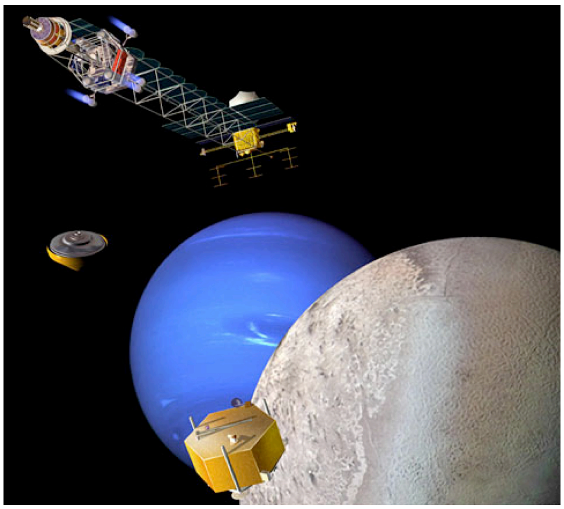

Figure 11: Notional concept for a nuclear-electric Neptune orbiter.

5. Planetary Orbiter

Relevant future missions: Jupiter Europa orbiter, Uranus orbiter and probe, Io observer

Though planetary orbiters have been successful without extensive autonomous onboard GN&C, future missions with more demanding requirements will feature such systems. With landmark- and TRN-based autonomous onboard GN&C, orbiters can maintain their own orbits. At Mars, autonomous aerobraking will save considerable operations costs. Autonomous aerobraking systems are closely related, if not identical, to autonomous onboard GN&C systems. Autonomous navigation, combined with automated event planning and sequencing, will greatly aid the mapping of bodies, or the high-resolution targeting of specific locations, or even the identification and targeting of newly arising features of interest. A concept Neptune orbiter is shown in Figure 11.

For orbiting or flybys of planetary targets with high radiation (e.g., Europa), innovative GN&C sensor/actuator technologies and shielding approaches should be augmented with algorithms that can maintain healthy GN&C solutions in the presence of radiation-induced hardware anomalies. System-level trades of individual hardware performance, integrated algorithmic and system design solutions, and traditional shielding options will lead to optimized flight system and mission-level design for these very challenging missions.

Figure 12: The GRAIL mission is a recent example of the utility of formation flying concepts to planetary science.

6. Formation Flying and Spacecraft Swarms

Relevant future missions: Magnetosphere and gravity missions, and fields/particles samplers

Holding multiple spacecraft in relative formation and maintaining a "swarm-pattern" are two distinct path-patterns of swarm operations. These flight configurations require precision methods of inter-vehicle metrology, from micrometer-class to meter-class. The former can be achieved with radio or infrared links, whereas the latter can be done passively with imagers. With distributed operations among the formation or swarm, independent position and attitude estimation may be required in addition to relative position estimation. Depending on the number of spacecraft and patterns to be flown, the guidance algorithms and control systems could require sophisticated use of generic autonomy and FDIR capabilities.

Though applications for formation flying and swarms technology have limited immediate application to *in situ* planetary exploration, such architectures will likely find a home in PSD in the future, and advantages of simultaneous multisite investigation (e.g., of magnetospheres and atmospheres) as well as remote interferometric observations will likely be seen in the future. Figure 12 shows the GRAIL spacecraft, which returned important lunar gravity science via formation-flying.

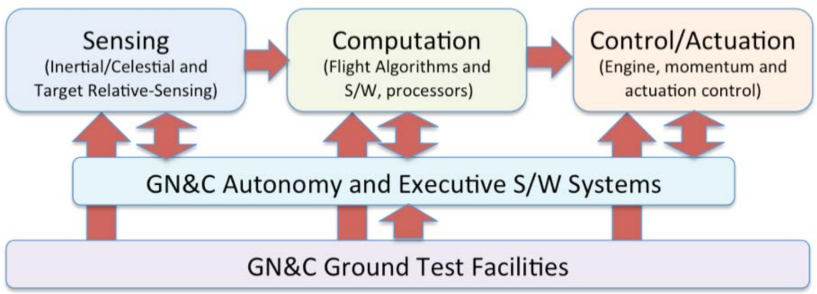

Figure 13: High-level interaction of GN&C technology categories

C. Onboard GN&C Technology Categories, Descriptions, and Status

GN&C onboard technology can be divided into four broad categories: 1) GN&C flight algorithms and software, 2) GN&C flight instruments, 3) other GN&C flight equipment, and 4) GN&C ground test facilities. The first two can be, in turn, subdivided into inertial-based subsystems (e.g., those using inertial coordinates, computations, or sensing) and target-relative-based subsystems (e.g., those making or making use of target-body [either natural or artificial] landmark measurements, coordinates, and computations). Figures 13 and 14 show the interaction and command and data flow between these GN&C technology elements. Following are brief descriptions of these technology areas.

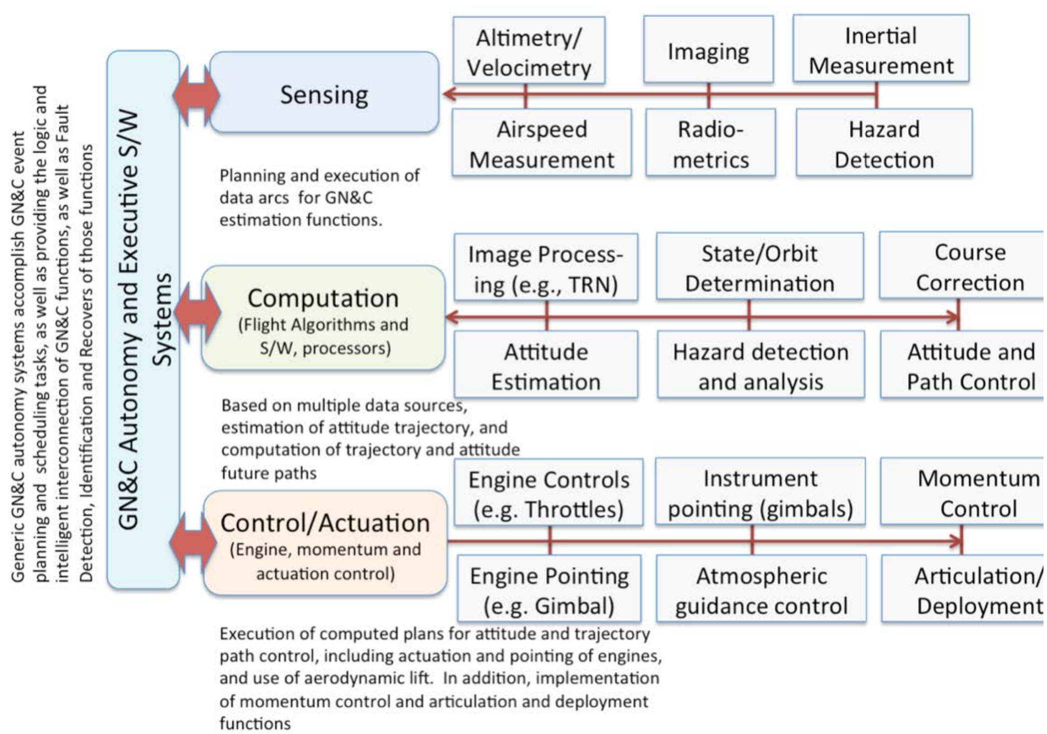

Table 3 is a distillation of the analysis performed in Ref. 4. Across the horizontal axis are listed the planetary missions of the decadal survey, and on the vertical axis the numerous forms of advanced GN&C technology that were assessed in the study. At each locus in the table a relevance factor was assigned in the form of color code representing high, medium or low relevance (red, yellow, green), allowing rapid survey of onboard GN&C capabilities needed for each type of mission. After assigning constant numerical values to each of the qualitative relevance “colors”, and summing across missions, as well as technologies, the priorities in Table II.1 were derived purely from numerical score.

D. Onboard GN&C Technology Assessment Findings and Recommendations

1. Finding

Autonomous onboard GN&C: Advancement in spacecraft autonomous GN&C capability, i.e., the ability to manipulate spacecraft trajectory and attitude autonomously on board in reaction to the *in situ* unknown and/or dynamic environment, is required for next-generation SMD PSD missions aimed to reach and explore scientific targets with unprecedented accuracies and proximities (Section 4.1.1).

Recommendation: Invest in autonomous GN&C capability, with parallel investments in innovative architectures, innovative and optimized algorithms, advanced sensors and actuators, and system-level demonstrations with relevant physical dynamics and environment conditions.

2. Finding

New and advanced GN&C sensors: Innovation and advancement of onboard sensing capabilities are critical, taking advantage of the most recent breakthroughs in component technologies such as LIDARs and spaceflight-qualifiable computing elements for enhanced on-instrument analysis ability (Section 4.2).

Recommendation: Invest in advanced GN&C sensors with direct relevance to future mission needs. Make advancement in individual sensors as well as in integrated sensor systems. With significant advanced computational capability and smaller, less power-hungry sensor components, integration of a few components can serve multiple purposes. For example, a camera, a LIDAR, an inertial measurement unit (IMU), and a computer can constitute an integrated sensor system that provides altimetry, velocimetry, target-relative navigation, and hazard detection—one sensor system replacing four sensor systems.

3. Finding

New and advanced GN&C algorithms: algorithms in guidance, estimation, and control are needed in parallel with advancements in hardware, software, and architecture (Section 4.1).

Recommendation: Invest in algorithms for innovative solutions to GN&C challenges, e.g., fuel-optimal, real-time GN&C solutions, new techniques and approaches that enable much greater landing accuracy, and fusion of data from multiple sensor sources for superior estimation of spacecraft states. Algorithms must be developed in parallel with new architectures, hardware, and software.

4. Finding

Onboard GN&C is performed by systems and not just components. As more complex systems with stringent performance requirements are pursued, the interplay across components, flight dynamics, and physical environment increases. System-level physical test and demonstration systems are necessary (Sections 4.1.1.4, 4.2.4).

Recommendation: Invest in system-level demonstration systems, such as ground based end-to-end GN&C system testbeds, aerial field tests, sounding rockets tests, and free-flying-vehicle-based, closed-loop GN&C system tests.

5. Finding

Testing capabilities are critical and need to be improved. End-to-end system-level modeling, testing, and simulation are required to flight-qualify newly developed system-level capabilities achieved through incorporation of new technology elements (Section 4.2.4).

Recommendation: Continue to advance integrated modeling and simulation at the mission capability level, with increasing fidelity matching advancements in component technologies.

6. Finding

There is substantial commonality in GN&C technology needs across missions. GN&C components and *systems* can be developed and deployed across multiple mission types more effectively and economically than point-design solutions engineered for individual mission scenarios.

Recommendation: Attention should be paid to GN&C *systems*, not just the individual algorithms, hardware, and software subsystems, because this will allow for reasoned cross-cutting trades across functions and missions. SMD provide incentives in the structure of announcements of opportunity such that feed-forward of developments for one project to the next can be maximized.

7. Finding

General onboard autonomy: Onboard autonomous GN&C is a significant part of overall spacecraft autonomy. It is closely related to advancement in areas of onboard planning, re-planning, and fault detection, identification, and recovery (Section 4.1.1.3).

Recommendation: GN&C technologists need to stay current with advancements being made in the related fields of general onboard autonomy, and onboard planning, re-planning, and fault detection, identification, and recovery. This would be best achieved through regular workshops where NASA GN&C technologists would invite leading technologists in other fields to explore technology-transfer opportunities.

8. Finding

GN&C commonality across NASA: There is much to be learned within the human spaceflight program from GN&C experience in SMD. Though the scales are vastly different, the methods and technologies are the same. For this reason, there should be substantial opportunities for SMD and the Human Exploration and Operations Mission Directorate (HEOMD) to cooperate on mutually beneficial GN&C technology and subsystem development.

Recommendation: Assign a task to the NASA Engineering and Safety Center GN&C Working Group/Community of Practice to identify cross-cutting GN&C technologies across the human and robotic exploration programs, and propose strategies for common development. Such a catalog and strategy should inform future technology plans for both the human and robotic programs and will be of substantial benefit to NASA.

IV. Surface Guidance, Navigation, and Control

Planetary surface missions cover a tremendously wide range of component and system GN&C technologies, and that breadth presents a particular challenge to the study undertaken here. Figure 1-1 depicts an artist's conception of planetary robots: the Mars Science Laboratory (MSL); lunar exploration with robots and humans; a picture of a possible undersea robot that would explore Europa's oceans for life; and a Venus altitude-cycling balloon based on phase-change buoyancy fluids. A greater emphasis is placed on mobility-based missions because the post-EDL GN&C challenges of purely lander-based missions are modest and are largely a subset of those associated with free-flying spacecraft. Of course, the space of mobility-based GN&C challenges is itself extremely diverse, encompassing the use of wheeled rovers, aerial platforms, small-body hoppers, and others. We have tried to emphasize technical areas with applicability across a spectrum of mobility types while still identifying challenges unique to particular forms of mobility.

While we have had recent successes with the Mars Exploration Rovers (MERs) and the Phoenix lander, significant improvements are possible to enable more ambitious missions. The current state of in situ planetary exploration is comparable to that of remote sensing in the 1970s. The complexity of the environment, be it poorly understood wind patterns or the behavior of heterogeneous soils and the resulting interactions with the vehicle, present critical challenges. Findings presented in this document represent a spectrum of needs both in cross-cutting technologies as well as systems engineering and prototype development targeted to specific mission types.

A. Definition of Surface GN&C

Surface GN&C is defined to be the motion planning, sensing, and control of the vehicle to achieve desired maneuvers in order to accomplish a specific goal. Some of the terminology associated with surface mobility systems can differ from that adopted for general spacecraft. In this document, determination of the vehicle's position, attitude, and velocity is referred to as "localization." Determination of a desired path of travel is referred to as "path planning" or "motion planning," while the broader problem of selecting and executing a path towards a specified goal position is referred to as "navigation."

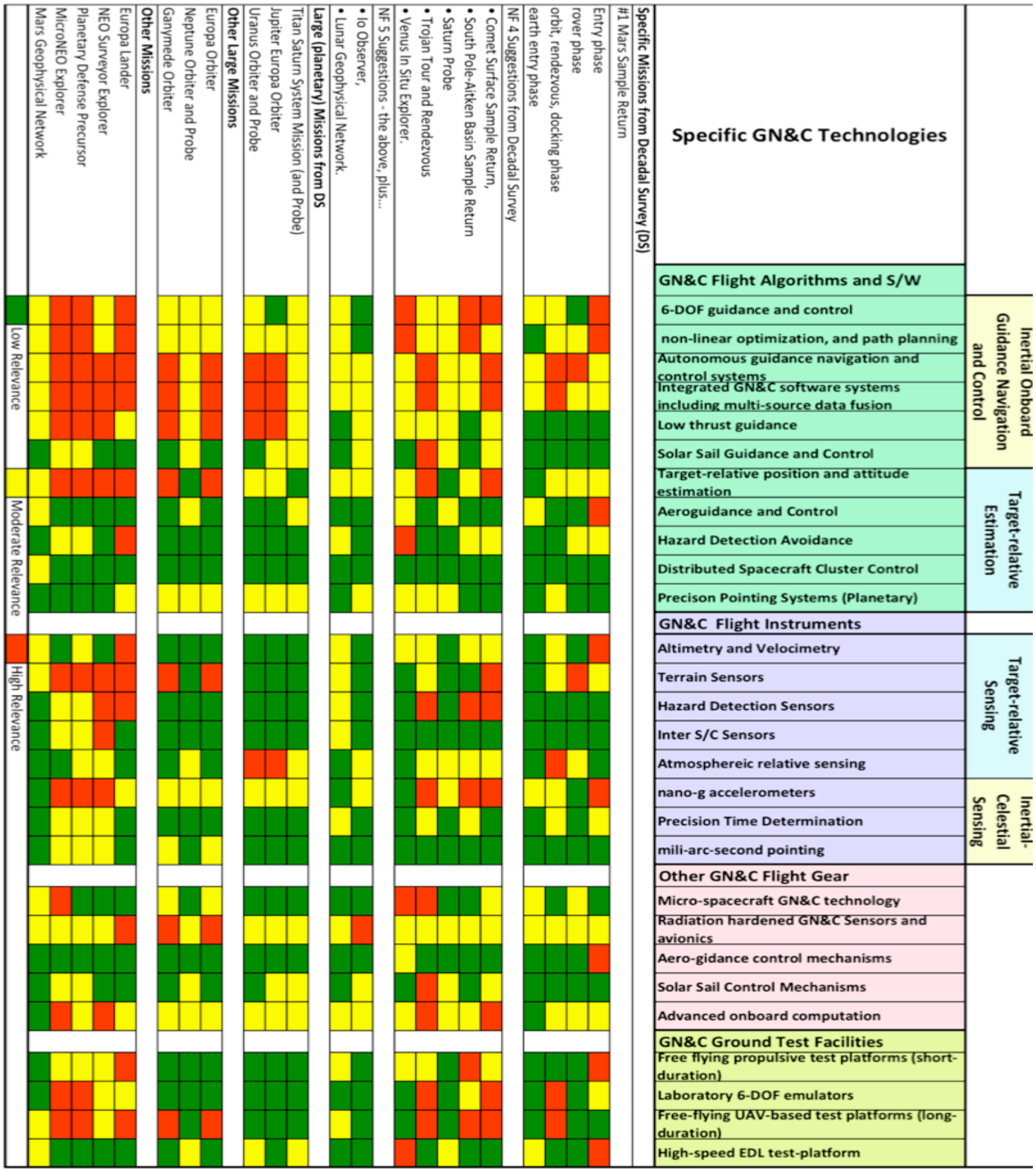

Table 3: Summary of application relevance of onboard GN&C technologies to missions from the Decadal Survey

B. Missions from 2011 Decadal Survey Requiring New Surface GN&C Capabilities

This section contains descriptions of the missions identified in the 2011 Decadal Survey followed by a description of specific surface GN&C technology needs for each.

Table 4 maps each identified capability (rows) to the mission types (columns) discussed above. The capabilities will be discussed in detail in the next section.

1. Mars Sample Return

Both the roving/sample gathering and caching segment, as well as the cache retrieval/Mars Ascent Vehicle (MAV) launch segments of a potential Mars Sample Return (MSR) mission, would contain substantial requirements for new surface GN&C technology. The need to collect samples from a rich and diverse set of well-characterized sites within a limited mission duration requires faster and more energy-efficient rover navigation. Better prediction of vehicle mobility via improved terrain sensing will improve mission safety and enable operation on more extreme terrains. When combined with methods to plan under uncertainty, quantitative measures of the uncertainty associated with terrain sensing and predicted vehicle mobility will enable more efficient operations, improve mission safety, and potentially enable access to more challenging terrain. Improvements in global localization will enable greater leveraging of orbital data in traverse planning, thereby enabling more efficient long traverses. Sampling acquisition and handling methods need to be matured and updated based on more demanding mechanical designs and constraints.

Table 4. Mission types benefiting from proposed surface GN&C capabilities.

	Mars Sample Return	Comet/ Small-Body Sample Return	Lunar Sample Return	Venus Climate Orbiter	Venus In Situ Explorer	Titan Missions	Europa Lander	NEO Missions
More Capable Rovers	√		√					
Extreme Terrain Mobility	√					√		√
Aerial Mobility				√		√		
Small Body Mobility		√						√
Sampling and Sample Handling	√	√	√			√	√	√
Efficient Operations	√	√	√		√	√	√	√
GN&C Modeling and Simulation	√	√	√		√	√	√	√

2. Comet Surface Sample Return (CSSR)

The New Frontiers Comet Surface Sample Return (CSSR) mission is one of several potential missions to small primitive bodies. There have been prior cometary missions beginning with the European Space Agency (ESA) Giotto (fast flyby) and continuing with Stardust, Deep Impact, and ESA's Rosetta mission, which will rendezvous with a comet and place a lander on it in 2015, and. Many of these new missions will require technologies such as Touch and Go (TAG), a type of autonomous rendezvous and docking GN&C system that can make close, controlled approaches and gentle contact with the rotating surface of the body, or different types of penetration systems such as harpoons, darts, or drilling end-effectors. Since ground testing of systems operating in microgravity is extremely costly, innovative approaches for integrated modeling and simulation of proximity operations will be needed to test system performance. Similar to the MSR mission, CSSR will require advances in the areas of sampling and sample handling, efficient operation methodologies, precise global localization, and advanced options for surface mobility in the cometary microgravity environments.

3. Lunar Sample Return (LSR)

The Lunar South Pole-Aitken Basin Sample Return is another potential New Frontiers mission. A soft landing on the Moon, probably in rugged terrain to ensure a sampling of material from the mantle, will require several novel surface GN&C elements. These include vision-based Target Relative Navigation (landmark modeling and tracking), fast and energy-efficient roving capability, precise global localization, efficient operations, advanced sample collection and sample handling capabilities, and automated path planning and optimization.

4. Venus

A variety of Venus missions have been proposed with very distinct science objectives, mobility systems, and GN&C requirements. The 2011 Decadal Survey includes an atmospheric-focused Venus Climate Orbiter (VCO) Mission based on an uncontrolled wind-driven balloon with global localization needs. In addition to the balloon, there is a mini-probe and two drop sondes. The surface-centric Venus In Situ Explorer (VISE) mission would place a lander on the surface capable of sample acquisition and analysis with extended mission duration. The New

Frontiers Surface and Atmosphere Geochemical Explorer (SAGE) mission would require an autonomous surface excavation system in an extreme environment (450°C, 92 bars) and in situ instrumentation for geochemical analysis.

Table 5. Surface GN&C characteristics of different aerial mobility systems.

	Venus Balloon	Titan Balloon	Airship	Airplane	Rotorcraft
Precise Global Localization	√	√	√	√	√
Altitude Control (ascent control)	√	√			
Autonomous Flight Control (6 dof)			√	√	√
Efficient Operations			√	√	√
Planning with Uncertainty	√	√	√	√	√
Long-term Wind-assisted Navigation	√	√			
Hazard Detection and Avoidance (Ground and Atmospheric)			√	√	√
Modeling and Simulation	√	√	√	√	√
Pointing and Stabilization of Antenna for Communication		√	√	√	√
Aerial Vehicle Deployment in the Atmosphere	√	√	√	√	√

5. Titan

There are two potential missions to explore Titan via different mobility systems: 1) based on a wind-driven Montgolfière, and 2) based on a lake lander. The Titan Saturn System Mission (TSSM), in which a wind-driven Montgolfière is used to survey the moon, and a lake lander is used to explore the methane and ethane lakes, require unique localization capabilities, assisted by efficient operations, and a sophisticated set of technologies in the areas of aerial mobility (for the balloon) and surface mobility (for the lake lander). All these capabilities will also need to rely on high-performance computing hardware and software, particularly in the path planning and management and correlation of science data collected by heterogeneous sensors. On the other hand, alternative mission concepts using passive elements such as floaters will not likely require precise localization. In general, all balloons require localization, but balloons operating near the surface require even higher levels of precision to avoid collisions and acquire surface samples from small terrain features. There is a range of possible Titan balloon missions going from uncontrolled, all-passive, helium, super-pressure balloons to sophisticated motorized blimps. There is a corresponding range of GN&C requirements associated with this aerial mobility. Besides a lander and an orbiter, the TSSM includes a hot air balloon (Montgolfière) that might require a vertical ascent/descent control system and accurate localization ability. More advanced versions of this balloon are possible in which the balloon changes altitude to catch favorable winds and go to desired locations above the ground. This wind-assisted navigation was not part of the original TSSM, but is a logical extension. Also, it is an example of the impact of GN&C technology on a mission on a planetary scale, since innovative mission planning strategies for long-duration flights might have to be developed while keeping in mind the limited lifetime of vehicle resources. Finally, challenges common to virtually all planetary science missions beyond the orbit of Mars include limited bandwidth and high-latency communications, which preclude real-time teleoperation, thus requiring a high degree of autonomy and reliability. Table 5 lists surface GN&C characteristics of different aerial mobility systems.

6. Europa Lander

Studies of a Europa lander were conducted by JPL as part of a Europa option study completed earlier in 2012. The lander option was ruled out as too costly in the current environment. However, it was recognized that a future Europa lander is important and that more information about the surface will be needed to design the lander. Accordingly, the Europa Clipper mission, consisting of multiple fly-bys, will be equipped to perform landing site characterization. This future lander mission will require advanced capabilities in the areas of efficient operations, sampling, and potentially deep drilling, all using rad-hard technology.

Table 6. Surface GN&C characteristics of different surface sampling mechanisms.

	Close Proximity Sampling				Projectile-Based Sampling	
	Brushed Wheel Sampler	Sticky Pad	Drill	Corer	Tethered Harpoon	Dart and Pellet Gun
Force-torque Sensing	√	√	√	√		
Efficient Operations	√		√	√	√	√
Planning with Uncertainty					√	√
Terramechanics	√	√	√	√	√	√
Modeling and Simulation	√	√	√	√	√	√
Anchoring			√	√		
Onboard Sampling Control	√		√	√		

7. Near Earth Objects (NEOs)

This is a class of missions that would investigate NEOs for general planetary science purposes, for planetary defense purposes, for pre-mission surveys, and reconnaissance for human exploration and retrieval. These missions will share characteristics of other small body missions, including the need for autonomous surface GN&C, precise global localization, small body mobility, and sample collection and handling. If surface contact is going to be made, precision sample collection and handling subsystems will be required (TAG, darts, harpoons, and others), which will also require interaction with the surface regolith. Initial planetary defense missions such as Planetary Defense Precursors (PDPs) will explore alternative defense strategies. These may be small investigatory surveyors to assess physical characteristics of the small body and leave precision-clock-based radio beacons for precise global localization and/or mitigation technology demonstrations incorporating one or more deflection methods such as electric propulsion (EP) systems or gravity tractors. Such missions will share all of the surface GN&C new technology needs of the sample return missions. Many future small body missions are likely to be micro-spacecraft missions. Aside from the already discussed technology requirements associated with small body missions in general, micro-missions will require specialized micro-spacecraft subsystems. Because of the small, compact, and inexpensive nature of micro-missions, these spacecraft will likely need more extensive autonomous capability than simple TAG functions, including better ways to manage operations, and to handle samples collected from different locations. Table 6 shows the Surface GN&C characteristics of different surface sampling mechanisms.

C. Surface GN&C Challenges

The list of missions outlined above demonstrates the multitude of challenges presented by future surface missions. Challenges general to virtually all of the surface missions include:

- Limited bandwidth and high-latency communications preclude real-time teleoperation (except to the Moon); thus, requiring a high degree of autonomy and reliability.
- Harsh environments lead to rapid degradation of components/systems and significant aging during longer missions. Achieving the required robustness and fault-tolerance in a cost-effective manner is a challenge of growing importance.
- The limited capability of available radiation-tolerant, flight-qualified processors constrains onboard processing even while avionic and software systems continue to grow in complexity. Currently, the performance gap between standard commercial processors, where the trend is toward greater parallelism, and flight processors remains large. Obtaining the levels of robustness and reliability required for space applications in the face of increasing cost constraints remains an open problem.
- Perhaps the single greatest determining feature of surface missions is the need to operate in a complex and only partially understood environment. We should point out that natural environments on planets are not always analogous to Earth. For example, comet surfaces, cryo-lakes, thermal extremes in shadows, etc., can require novel system designs and autonomy algorithms tailored for these new environments. Many of the future missions detailed above involve levels of interaction with the environment (terrain and soil, atmosphere, and lakes) far beyond those previously demonstrated. There is a need for improved environmental models as well as for planning and control algorithms that are robust to significant uncertainties to better address the challenges of steep slopes, operations in low gravity, or for aerial vehicles operating in changing and poorly understood winds.
- Closely related to the challenge of environmental uncertainties is the unique nature of operations for mobility-based missions. Mobility-based missions involve a rapid and continuous evolution of the understanding of the

environment, system performance, communication windows, and science objectives, all of which are reflected in a rapid turnaround operational pace. Table 7 lists the Surface GN&C technologies (rows) that impact surface GN&C capabilities (columns).

Table 7. Technologies (rows) that impact surface GN&C capabilities (columns).

		Fast and Energy-efficient Rovers	Extreme Terrain Mobility	Aerial Mobility	Small Body Mobility	Sampling and Sample Handling	Efficient Operations	GN&C Modeling and Simulation
Modeling and Simulation	Integrated system modeling and simulation	√	√	√	√	√	√	√
	Terramechanics	√	√		√	√		√
Planning and Control	Planning under uncertainty	√	√	√				√
	High-speed autonomous navigation	√	√	√				
	Ground operations tools			√			√	
	Model-based control	√	√	√	√	√	√	√
Sensing and Perception	Range sensing	√	√	√	√			
	Global localization	√	√	√	√	√	√	√
Mobility Systems	Extreme terrain		√					√
	Small body		√		√			√
	Aerial			√				
Sample Acquisition and Transfer	Sample acquisition and transfer		√	√	√	√		√

D. Surface GN&C Findings and Recommendations

This section provides an assessment of guidance, navigation, and control (GN&C) technologies for future planetary surface missions and concludes with a set of recommendations for improving the state of the practice. ***It should be noted that this is the first time that such an assessment and recommendations have been provided for surface GN&C technology.*** The organization of the third report closely follows the process used to arrive at the findings and recommendations. Specifically, the third report is organized into four sections: 1) a review of potential future missions involving significant surface components; 2) an outline of capabilities required for successful implementation of those missions; 3) a review and assessment of key technology areas addressing those capabilities; and 4) a set of findings and recommendations for future GN&C technology investments.

Even though we have successfully placed four rovers on Mars, GN&C development for planetary surface missions is still in its infancy. Surface GN&C must also address multiple conflicting demands. First, high levels of system robustness are required despite time delays that necessitate high levels of autonomy. Secondly, the operational environments are both very complex and yet only partially known. Finally, the variability of technology needs across the expanse of prospective surface missions is immense; yet technology development funding is extremely limited. Note that the scope of this document includes, in addition to ground systems, platforms operating in atmospheres, oceans, and lakes.

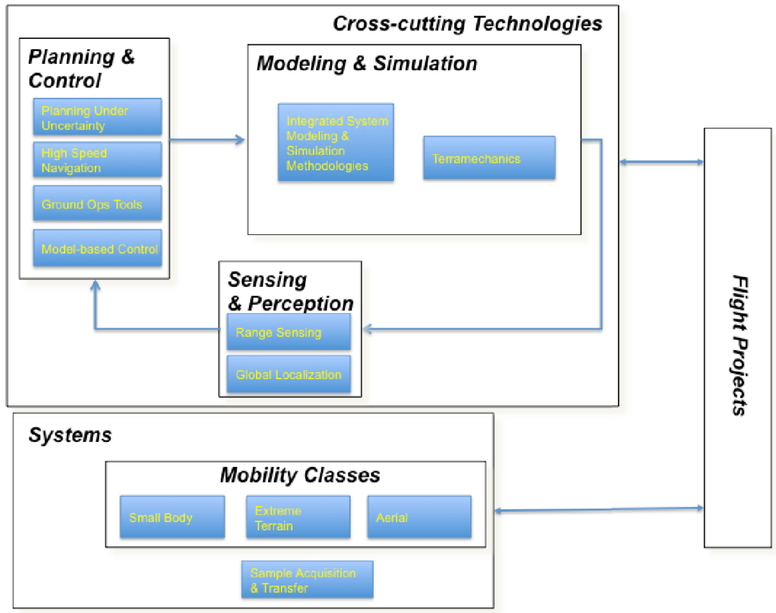

Figure 15. Relationship between findings in the Surface GN&C area. Cross-cutting technologies apply to all four systems in the lower box.

This technology assessment together with the findings and recommendations are an attempt to address the above mutually conflicting demands although not in a one-to-one fashion. The need for robust autonomy is addressed by a range of specific cross-cutting technology areas, all of which would leverage ongoing improvements in the computational power of radiation-hardened flight computing. Future surface missions will demand much more precise interaction with the terrain soil; examples include Mars sample caching, mobility systems operating on extreme slopes, or sampling systems collecting soil in micro-gravity. And since our ability to predict the results of those surface interactions will always be limited, guiding principles for evaluating the uncertainty and risk are required (both onboard and as part of ground operations). Lastly, the diversity of GN&C needs across the full range of surface missions makes cost-effective technology development a particular challenge. Greater reliance on system modeling and simulation will reduce costs through the full mission life cycle starting with pre-mission technology investment decisions all the way through flight operations. Figure 15 depicts the relationship between findings in the Surface GN&C area. Cross-cutting technologies apply to all four systems in the lower box. While not strictly technology related, some general recommendations can be made for any future surface GN&C technology development program. ***One overarching recommendation is that flight missions treat the surface phase with as much rigor as cruise and entry, descent, and landing (EDL). Similarly, surface phase (particularly GN&C) requirements and flow down need to occur early in the project with dedicated surface GN&C system engineers fully integrated with the initial design team. Surface GN&C technology development should be a sustained effort with a portfolio that includes both low Technology Readiness Level (TRL) efforts as well as infusion-focused efforts. Furthermore, planetary exploration programs must be closely coordinated with each other, with related efforts focused on human exploration, and of course, with early stage mission design efforts. Finally, flight projects should treat surface GN&C as a distinct discipline from traditional GN&C.***

The 12 technology findings and recommendations discussed in this report are given below:

Finding 1: Integrated System Modeling and Simulation Methodologies

In order to optimize system designs and reduce development cost/risk, there is a need for more comprehensive system-level modeling throughout life cycle (technology investment & development, mission development and implementation, Verification and Validation [V&V], and training).

Recommendation 1: Conduct a workshop and systems study exploring the use of fully functional system simulation to aid early-stage component and system design.

Recommendation 2: Based on the results of the above, conduct two pilot studies—one focused on pre-phase A design needs for a particular mission type (e.g., aerial mobility with surface sampling capability) and another focused on mid-mission V&V.

Recommendation 3: Conduct a workshop to explore state-of-the-art, high-performance computing methods (serial, parallel) to handle large-scale, multiple sampling rate, hardware-in-the-loop, and model-order reduction techniques that can enable real-time performance assessments for planetary missions.

Finding 2: Terramechanics

More sophisticated models of soil interaction for both sampling and mobility are required to better understand surface missions.

Recommendation 1: Hold a series of workshops engaging scientists, terramechanics experts, and the GN&C experts to identify the needed simulation capabilities and relevant surface material properties to address a variety of bodies and mission types.

Recommendation 2: Develop and validate a range of terra-mechanic models and/or simulations capable of supporting analysis of wheel-soil interaction in both low- and high-gravity environments, and sampling and mobility in micro-gravity.

Finding 3: Model-Based Control

In order to address increasing complexity of the spacecraft systems and the interaction with the environment we need to leverage new control techniques that model dynamically evolving systems.

Recommendation 1: Conduct a systems study to identify candidate operational scenarios where model-predictive control could provide significantly improved performance and conduct evaluation studies.

Finding 4: Planning Under Uncertainty

New methods for quantifying the uncertainty and risk are required to address future missions involving more uncertain environments (e.g., asteroids).

Recommendation 1: Hold a workshop, outlining a plan and ideas, engaging experts from diverse disciplines (control theory, mechanical engineering, systems engineering). The purpose of the workshop is to explore successful techniques for robust planning and control under different types of uncertainty.

Recommendation 2: Fund a multi-year, university-focused research program addressing planning under uncertainty while ensuring that a broad range of mobility systems are addressed, including aerial mobility, micro-gravity mobility, horizontal mobility in challenging terrain, and vertical mobility of a tethered system.

Finding 5: High-Speed Autonomous Navigation

Currently, autonomous navigation entails significant reductions in average drive speed. This in turn reduces energy efficiency and limits the areas reachable within a fixed mission duration. Ongoing advances in high-speed computing will eliminate the performance penalties associated with autonomous driving.

Recommendation 1: Undertake a systems study of the benefits of high-speed computing on planetary rovers. Pending the results, a follow-up effort to develop a prototype of a high-speed, low-mass rover should be considered.

Recommendation 2: Demonstrate at TRL 6 or 7, high-speed navigation of a prototype planetary rover running on prototype flight avionics.

Finding 6: Ground Operations Tools

The planning and visualization tools required for surface operations for missions other than rover missions have not yet been developed.

Recommendation 1: Conduct a small study to evaluate the cost and benefits of the development of a simulated operations system capable of supporting one or more future missions such as a Mars Sample Return (MSR), small body operations, or a Titan aerial platform.

Recommendation 2: Fund a study to evaluate and communicate the uncertainty and risks associated with prospective uplink sequences for an aerial platform or a rover operating in extreme terrain.

Recommendation 3: Establish and fund a multi-center team to coordinate development of three-dimensional (3-D) immersive visualization environments for surface operations.

Finding 7: Range Sensing

Industry is rapidly maturing alternative active range sensing devices (Light Detection and Ranging [LIDAR] and flash LIDAR), patterned light techniques and headlights, which require redesign for flight.

Recommendation 1: Conduct a study to estimate development/maturation trajectories of alternative range sensors, model their expected performance (including size, weight, and power [SWAP]), and quantitatively evaluate the benefits to multiple applications including mobility.

Recommendation 2: Undertake development of reusable, high-performance, flight-qualified implementations of multiple ranging techniques and sensors.

Recommendation 3: Fund the development of a new generation of engineering cameras suitable for a range of applications including deep space navigation as well as lunar and martian surface missions.

Finding 8: Global Localization

Small body mobility systems, as well as Venus and Titan aerial vehicles, need the ability to determine real-time surface references for science targeting and navigation. On Mars, rovers need to use real-time localization together with orbital localization data to more efficiently traverse long distances.

Recommendation 1: Develop a program to demonstrate vision-based global localization.

Recommendation 2: Develop techniques to enable low-gravity small body exploration.

Finding 9: Extreme Terrain Mobility Systems

Extreme terrains, such as steep slopes, present mobility challenges that are substantially different from those of existing planetary rovers.

Recommendation 1: Develop system models of a range of systems suitable for supporting early mission concept studies and gap analyses for access to extreme terrains on Mars, the Moon, Europa, Venus, or Titan.

Recommendation 2: Develop early stage prototypes targeted towards the highest priority mission concepts.

Finding 10: Small Body Mobility Systems

The challenges of evaluating small body mobility systems using Earth or orbital testbeds are prohibitive, and can only be addressed by simulation. Engineers need more insight into potential science objectives, while the science community needs increased awareness of mobility system capabilities and system trade-offs.

Recommendation 1: Conduct system studies initiated by a workshop, bringing together engineers and scientists with the objective of reaching a consensus regarding:

The targets for which mobility provides significant science value

A set of science-derived mobility requirements for each target/target type (e.g., motion accuracy, instrument pointing, and surface mechanical coupling in micro-gravity)

The mobility strategies (e.g., random hopping vs. controlled mobility) appropriate to each body.

Recommendation 2: Develop and disseminate a physics-based simulation to serve as a virtual testbed for the evaluation and maturation of prototype mobility system designs.

Finding 11: Aerial Mobility Systems

Higher fidelity simulation tools and prototype field testing are needed to design robust systems.

Recommendation 1: Extend existing modeling and simulation tools for planetary environments and robotic ground vehicles to make them suitable for exploration of aerial vehicle designs and early performance assessments.

Recommendation 2: Fund the development of prototypes (based on the systems study) and evaluate performance of vehicle deployment, localization, surface sampling, onboard autonomous science, and aerial vehicle mission operations interfaces.

Finding 12: Sample Acquisition and Transfer

The wide variety of missions requires development of a range of sample acquisition and transfer technologies because few currently exist.

Recommendation 1: Mature technology for coring and sampling of bodies with gravity (e.g., Mars and lunar) to TRL 7.

Recommendation 2: Fund a spectrum of low TRL prototype sampling systems appropriate for bodies with extreme temperatures (Venus and Titan), for bodies with low gravity (e.g., asteroids and comets), and for heterogeneous bodies (e.g., comets).

Recommendation 3: Conduct studies of *integrated* mobility and sampling systems, merging the sampling mechanism functions with the system-level functions; for example, small body sampling that relies on active compliance between the spacecraft and the surface.

Recommendation 4: Develop a flight qualified, general-purpose force torque sensor.

Recommendation 5: Endorse the Astrobiology Science and Technology for Instrument Development (ASTID) workshop in 2013, and ensure that there is sufficient and adequate GN&C participation.

The findings and recommendations presented in this section represent a spectrum of investments both in cross-cutting technologies as well as systems engineering and prototype development targeted to specific mission types. Architecture and systems engineering processes leading to a successful surface system design are still evolving but based on recent experience we note the following: a) Surface GN&C is still in its infancy; b) Surface GN&C is a distinct area from traditional spacecraft GN&C; c) Flight missions need to treat the surface phase with as much concern as cruise and EDL; d) Integrated modeling and simulation is not yet used to its potential; e) Sustained system-level analyses and design in surface GN&C needs to take place well before mission definition.

V. Conclusion

This paper summarizes the content of the three reports in a series of technology assessments evaluating the capabilities and technologies needed for future missions pursuing SMD PSD's scientific goals. These reports cover the status of technologies and provide findings and recommendations to NASA PSD for future needs in GN&C and mission design technologies.

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References

[1] Committee on the Planetary Science Decadal Survey, National Research Council of the National Academies, Vision and Voyages for Planetary Science in the Decade 2013–2022, National Academies Press, Washington, DC, 2011.

[2] Steering Committee for NASA Technology Roadmaps, National Research Council of the National Academies, NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space, National Academies Press, Washington, DC, 2012.

[3] Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part I. Onboard and Ground Navigation and Mission Design, Report No. JPL D-75394, October 2012.

[4] Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part II. Onboard Guidance, Navigation, and Control (GN&C), Report No. D-75431, January 2013.

[5] Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part III. Surface Guidance, Navigation, and Control (GN&C), Report No. D-78106, April 2013.