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

Part I. Onboard and Ground Navigation and Mission Design

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National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
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Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions

Part I. Onboard and Ground Navigation and Mission Design

Strategic Missions and Advanced Concepts Office
Solar System Exploration Directorate
Jet Propulsion Laboratory, California Institute of Technology
for
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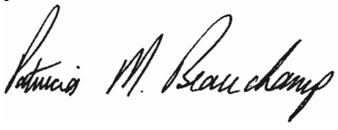
Foreword

Future planetary explorations envisioned by the National Research Council's (NRC's) *Vision and Voyages for Planetary Science in the Decade 2013–2022*,[1] developed at the request of NASA Science Mission Directorate (SMD) Planetary Science Division (PSD), seek to reach targets of broad scientific interest across the solar system. This goal can be achieved by missions with next-generation capabilities such as innovative interplanetary trajectory solutions, highly accurate landings, the ability to be in close proximity to targets of interest, advanced pointing precision, multiple spacecraft in collaboration, multi-target tours, and advanced robotic surface exploration. Advancements in guidance, navigation, and control (GN&C) and mission design—ranging from software and algorithm development to new sensors—will be necessary to enable these future missions.

Spacecraft GN&C technologies have been evolving since the launch of the first rocket. *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. *Guidance* is defined as the process of controlling the flight path of a vehicle so as to reach a desired target. *Control* is defined as the onboard manipulation of vehicle steering controls to track guidance commands while maintaining vehicle pointing with the required precision. As missions become more complex, technological advancements of GN&C systems must keep pace. Recognizing the significance of this research, the National Research Council of the National Academies listed many GN&C technologies as top priorities in the recently released *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*[2] (see Appendix A).

This document—Part I, Onboard and Ground Navigation and Mission Design—is the first in a series of three technology assessment reports 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. Part I covers 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 only loosely coupled (as is the case the majority of the time in a typical planetary mission). Part II, Onboard Guidance, Navigation, and Control,[3] will cover 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 is the case during certain critical phases, such as entry, descent, and landing, in some planetary missions). Part III, Surface Guidance, Navigation, and Control,[4] will examine GN&C for vehicles that are not in free flight, but that operate on or near the surface of a natural body of the solar system. Together, these documents provide the PSD with a roadmap for achieving science missions in the next decade.



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Other Reports in This Series

Power Technology

- Advanced Radioisotope Power Systems Report, Report No. JPL D-20757, March 2001.
- Solar Cell and Array Technology for Future Space Missions, Report No. JPL D-24454, Rev. A, December 2003.
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In Preparation

Guidance, Navigation and Control Technology

- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part II. Onboard Guidance, Navigation, and Control
- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part III. Surface Guidance, Navigation, and Control

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Executive Summary

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*.[1] Deep space navigation enables missions to precisely target distant solar system bodies, as well as particular sites on these bodies. This navigation not only takes place in real time for control and operation of the spacecraft, but also in many cases includes later, higher fidelity reconstruction of the trajectory for scientific and/or operational purposes. Existing technologies have been used in varying degrees since the early 1960s to navigate spacecraft with ever-increasing precision and accuracy, and NASA's expertise in deep space mission design and navigation has enabled many successful planetary missions. Future missions 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.

Progress in these technologies will allow missions—that were barely conceivable a few years ago—to be accomplished efficiently and effectively resulting in scientific insights and understanding far beyond what is currently in hand. For example, investment in new mission design techniques would

- Enable new planetary science missions by developing design techniques for new mission classes and reducing required resources on others
- 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.)
- Reduce design times by an order of magnitude, allowing more exploration of the design space and trade studies to increase science quality and quantity

This document—Part I, Onboard and Ground Navigation and Mission Design—is the first in a series of three technology assessment reports that evaluate the current status of guidance, navigation, and control (GN&C) and mission design capabilities, and provide a roadmap for technologies needed in the future. This report includes a number of findings and recommendations, which are summarized below.

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.

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.

Finding 2

Deep space navigation functions, traditionally performed on the ground, can be mission enabling or enhancing in certain situations when moved onboard 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 and specific, focused application developments 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.

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.

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. 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 PSD 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.

Finding 4

The Deep Space Atomic Clock (DSAC) can use 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 Office of the Chief Technologist (OCT)-funded DSAC Technology Demonstration Mission should move forward with strong support from the PSD.

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.

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.

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 on a more frequent basis.

1 Study Overview

1.1 Introduction

Deep space navigation enables missions to precisely target distant solar system bodies, as well as particular sites on these bodies. This navigation not only takes place in real time for control and operation of the spacecraft, but also in many cases includes later, higher fidelity reconstruction of the trajectory for scientific and/or operational purposes.

Existing technologies (i.e., Doppler, range, delta-differential one-way range [Delta-DOR], and onboard optical) have been used in varying degrees since the early 1960s to navigate spacecraft with ever-increasing precision and accuracy. Higher fidelity models of the solar system and its dynamics, as well as spacecraft trajectory dynamics, have evolved, imposing much higher computing demands both in terms of speed and precision. In addition, methods of designing more complex trajectories, associated with an expanded understanding of spacecraft dynamics, have called for more stringent requirements on spacecraft 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. Missions that use the complicated gravitational interaction of the sun and Earth to accomplish specific mission objectives and constraints, such as Genesis, have also succeeded.

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.).

- Missions consisting of multiple spacecraft will require coordinated navigation.
- Missions in the New Frontiers and Discovery classes will require development of low-thrust and low-energy mission design and navigation capabilities, and more extensive search capabilities for multiple flyby trajectories, to enable efficient and economical exploration. This is particularly important for sample-return missions and proposed outer planet flagship missions.
- Methods of efficiently exploring complex satellite tour designs, innovative science orbits, and efficient capture into these orbits will need to be developed. This requirement also applies to missions using any type of low-thrust propulsion—including solar electric, nuclear electric, solar sail, and plasma sail—for any mission segment.
- Future small-body sample return and interior characterization missions will require reduction of the uncertainties in navigation delivery to small bodies by an order of magnitude.
- Finally, missions that need very high navigation accuracy relative to the target body (i.e., planet, satellite, asteroid, or comet) to achieve science goals, reduce the mission costs for ground resources, and release ground resources for other applications will require the continued development and extension of the multimission, autonomous, onboard navigation system (AutoNav) to form a complete autonomous guidance, navigation, and control (AutoGNC) system.

Sections 1.2–1.4 discuss the technology challenges for deep space navigation and mission design.

1.2 Mission Design and Navigation Methods

Mission design encompasses the methods and techniques used to find the existence of, develop the specific details of, and outline the operational considerations and constraints for a specific concept necessary to accomplish a set of scientific objectives. This is usually done initially within the context of an "envelope" of potential designs generally meeting the overall desires.[5] Navigation methods include both the analysis of real-time data received during the actual operation of the mission and an analysis simulation in the design phases as part of the mission design. For both mission design and navigation, a large set of software tools and analysis techniques is necessary at a variety of precision and fidelity levels for different stages from early mission concept studies through flight operations. This set includes tools and techniques for propagating and optimizing trajectories; reducing observational quantities using mathematical filtering algorithms; and simulating spacecraft guidance, attitude control, and maneuvering capabilities.[6]

Extension of current methods for finding and navigating complex trajectories, involving multiple flybys, low-thrust trajectories (see Figure 1.2-1), low-energy trajectories, and trajectories involving lengthy three-body arcs, is necessary to meet the requirements of many future mission scenarios. In some cases, a single mission may involve a number of these aspects.

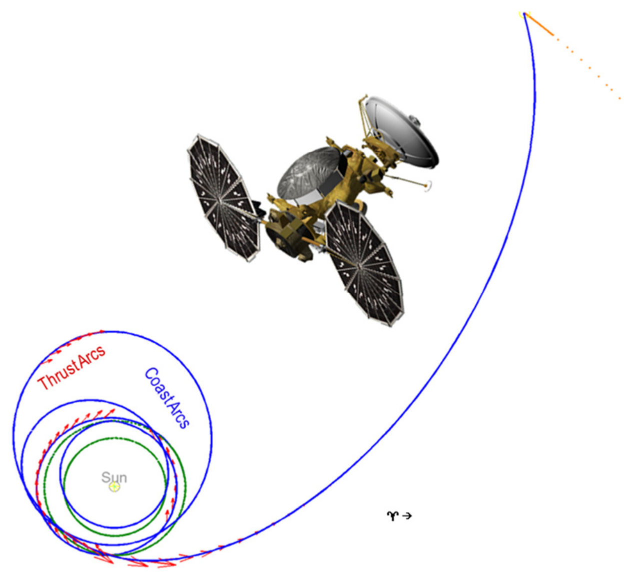

Figure 1.2-1. Interplanetary trajectory design can leverage electric propulsion to enable new missions and reduce project risk.

Algorithms are required that provide rapid and highly accurate thrust profiles for maintaining an orbit about a small body. In addition, advances are needed to decrease the time required to compute small-body landing trajectories in a highly complex gravity and topography field from several months to a few hours or less. Most missions to small bodies will arrive at their destination with no detailed knowledge of the gravitational and topographical characteristics of that body. The algorithms, both on board and on the ground, to characterize this unknown environment and appropriately control the spacecraft must be adaptable and flexible enough to ensure spacecraft safety and to accomplish the mission objectives.

1.3 Precision Tracking, Guidance, Navigation, and Control

Precision tracking, guidance, navigation, and control are required for delivery of landers to the surface of a planetary body (e.g., Mars Exploration Rover, Phoenix, and Mars Science Laboratory) to minimize the propellant necessary to insert an orbiter into the desired orbit and to maintain the knowledge and control of the orbit (e.g., Mars Reconnaissance Orbiter [MRO] at Mars and Cassini at Saturn). Flyby missions of gravitating bodies will also require high-precision tracking and guidance; even very small delivery errors at an intermediate body are greatly magnified (due to the spatial variations in the body's gravity field) and must be corrected after the flyby with potentially costly maneuvers.

Various navigational tracking measurements (currently done with the vehicle's X-band communications system) and involving observations of two-way Doppler shifts, two-way ranging, and interferometric observations of the angular offsets from extragalactic radio sources (Delta-DOR) are needed to accomplish the above navigational objectives.[7,8] Future frequency migration to Ka-band, arraying of ground-based antennas, spacecraft-to-spacecraft tracking, and optical communication will offer new challenges as well as opportunities for tracking measurement accuracy improvements.

Small-body missions will require the characterization of internal/subsurface physical attributes, leading to modeling of the complex gravity field of a nonspherical body as well as the characterization of spatial and temporal variations of surface composition. A near-term goal is to achieve navigation accuracy to 1 m in the vicinity of a small body, which will allow very close orbiting, hovering, "touch-and-go" sampling of, and safe landing on the surface.

Future spacecraft with advanced capabilities will allow landing on the surface of a planetary body with an atmosphere to within tens of meters rather than tens of kilometers. Hazard avoidance will be enabled by active trajectory and attitude control during the atmospheric portion of the flight and will require the development of analysis tools to design such trajectories. Precise and safe lunar landing will require similar technology advancement.

1.4 Onboard Autonomous Guidance, Navigation, and Control

Onboard autonomous guidance, navigation, and control requirements have been met in the past by the Deep Space 1, Stardust, Deep Impact, EPOXI, and Stardust New Exploration of Tempel 1 (NExT) missions, which together have captured all of NASA's close-up images of comets. For these missions, a system called AutoNav performed an autonomous navigation function, using images of the target body—a comet—and computing the spacecraft's position and correcting the camera-body pointing to keep the comet nucleus in view. In the case of Deep Space 1 and Deep Impact, AutoNav corrected the spacecraft trajectory as well; for Deep Impact, it was used to guide the impactor spacecraft to a collision with the nucleus.

The challenge for future missions is to provide systems that are capable of precise and safe autonomous landing, orbital rendezvous, sample capture, and sample return. This will require autonomous systems that interact with observation systems (optical sensors, altimeters, etc.), onboard planning, surface-relative measurements, and highly accurate onboard reference maps, which will include an extensive array of surface feature-recognition capabilities to provide accurate terrain-relative navigation. Autonomous system error detection and self-maintenance can be integrated with AutoGNC functions into pre-developed mission flight software to provide a high degree of robustness, intelligence, adaptability, "self-awareness," and fault recovery (see Figure 1.4-1).

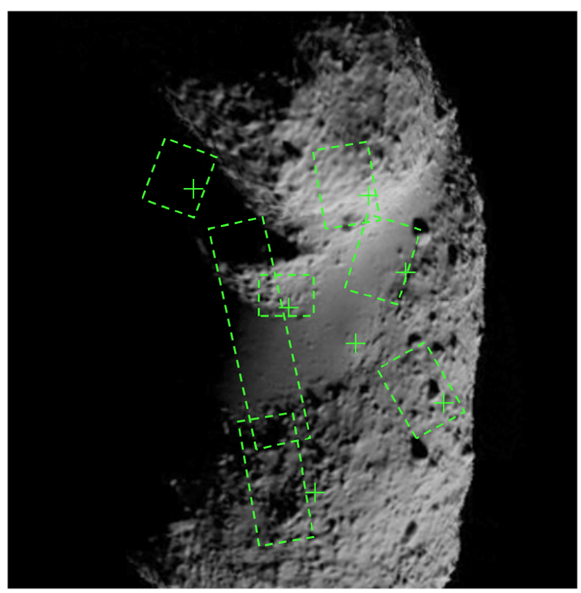
Figure 1.4-1. Example of AutoGNC system capable of touch-and-go operations.

1.5 Summary

NASA's mission design and GN&C technologies have enabled every deep space mission ever flown by NASA. The continued advancement of these technologies has facilitated the continued success of more complex missions. Further progress in this area will allow missions—that were barely conceivable a few years ago—to be accomplished efficiently and effectively resulting in scientific insights and understanding far beyond what is currently in hand.

1.6 Sources of More Detailed Background Information

Recent overview articles and books present more detailed discussions of the state-of-the-practice in deep space mission design and navigation.

- Ocampo and Byrnes[5] present an overview of mission design and trajectory optimization techniques (not limited to deep space applications).
- Russell,[9] Davis and Anderson,[10] and Scheeres[11] provide overviews or comprehensive treatments of more specialized mission design topics.
- Wood[6] presents an overview of deep space navigation.
- Thornton and Border,[7] Border, Lanyi, and Shin,[8] and Moyer[12] provide more detailed and comprehensive treatments of particular aspects of deep space tracking and navigation.
- Wood,[13] Owen, et al.,[14] and Wood[15] detail the historical development of deep space navigation techniques and the application of these techniques in many past missions.

2 Mission Design Technologies

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*:[1]

> *The identification of trajectories that enable planetary missions or significantly reduce their cost is an essential and highly cost-effective element in the community's tool kit.*
>
> *A sustained investment in the development of new trajectories and techniques for both chemical propulsion and low thrust propulsion mission designs would provide a rich set of options for future missions.*
>
> *Research and development in the fields of celestial mechanics, trajectory optimization, and mission design have paid substantial dividends in the recent past, identifying new and higher performance opportunities for planetary missions. A future sustained effort in this technology area is essential, both to exploit fully the expanding range of possible mission modes (electric propulsion, aerocapture, etc.), and to continue to develop the automated software tools for searching rapidly for the "best" mission opportunities.*

This section describes the general categories of mission design capabilities that need further development in support of future planetary science missions.

2.1 Need for Further Development of Mission Design Capabilities

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 continue 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.

- Enable new science missions (recent examples include Genesis, Dawn, and Mercury Surface, Space Environment, Geochemistry and Ranging [MESSENGER])
- Increase science and investment return even while in flight (for example, the extended mission for the Deep Impact spacecraft to image comet Hartley-2 or the Time History of Events and Macroscale Interactions during Substorms [THEMIS] mission extension [renamed Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS)] to send two in-flight spacecraft to orbit the moon)
- Reduce cost, velocity change (ΔV), mass, and risk (always critical to any mission)
- 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

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 of 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 (described in the following sections) would

- Enable new planetary science missions by developing design techniques for new mission classes and reducing required resources on others
- 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.)
- Reduce design times by an order of magnitude, allowing more exploration of the design space and trade studies to increase science quality and quantity

Sections 2.2–2.6 detail some important focus areas for future astrodynamics research.

2.2 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

MESSENGER (see Figure 2.2-1). 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

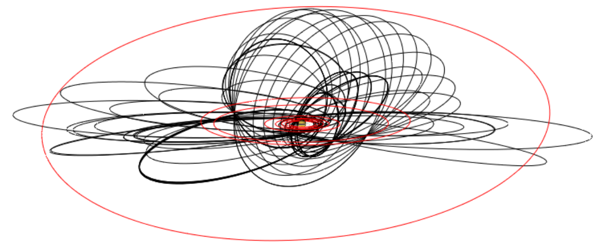

Figure 2.2-1. Exploration of multiple encounter tour designs.

- Trajectories to multiple small bodies such as comets or asteroids
- Satellite tours at outer planets, such as a Jupiter moons or a Uranus orbiter mission

2.3 Close-Proximity Trajectory Design for Small-Body Missions

The design of trajectories to/from and around small bodies such as asteroids (see Figure 2.3-1), 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.

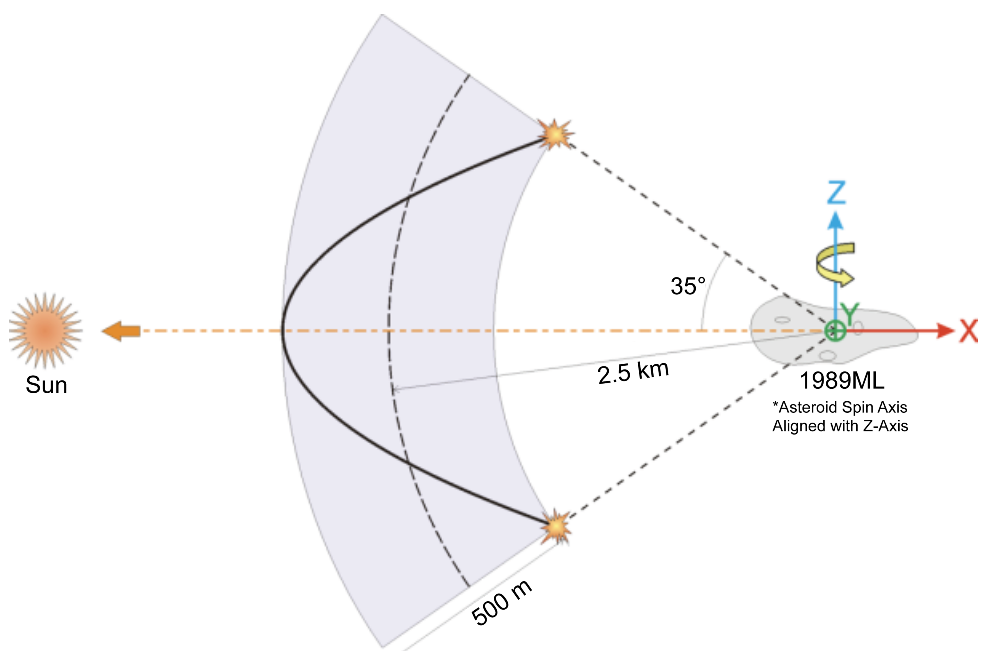

Figure 2.3-1. Close-proximity trajectory design for small-body missions.

- 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.

2.4 Low-Energy Trajectory Design and Optimization

Low-energy trajectory design (see Figure 2.4-1), 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 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

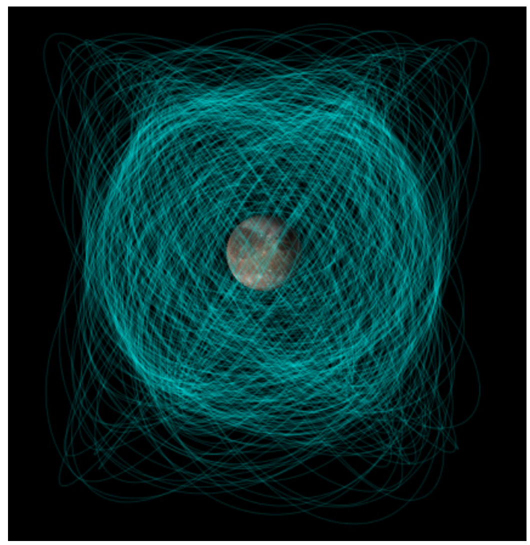

Figure 2.4-1. Innovative trajectory design enables efficient low-energy transfers, captures, and orbits.

- Ability to rapidly design and optimize trajectories that take advantage of multibody dynamics (also potentially useful in spacecraft autonomous operations)
- Design of efficient transfers and captures into desired science orbits, especially when combined with low-thrust capabilities
- 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
- 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

2.5 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 (see Figure 2.5-1), 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.

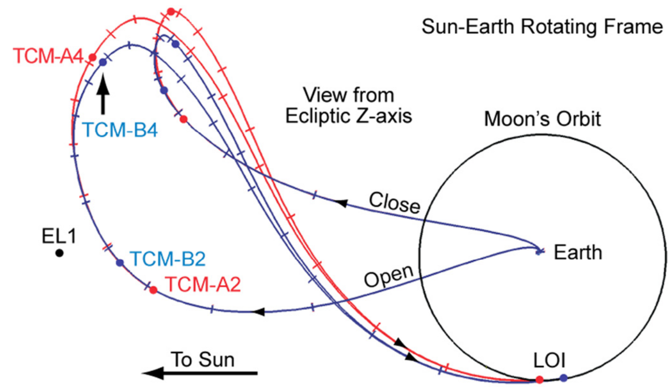

Figure 2.5-1. Trajectory design for the GRAIL mission, with multiple spacecraft elements.

2.6 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:

- Robustness to unplanned missed thrusting
- High-fidelity designs for trajectories with many revolutions
- Broader, more rapid search capabilities
- Low-thrust trajectories in a multibody environment
- Trajectory design capabilities for new types of propulsion systems
- 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.

2.7 Concluding Remarks

Research and innovation in mission design will continue to advance the state-of-the-art and lead to development of new revolutionary concepts and techniques. These developments will enable new mission concepts to advance scientific knowledge, but only if adequate funding is available to conduct the necessary astrodynamic research and development.

Tables 2.7-1 and 2.7-2 summarize the advanced mission design capabilities and list the planetary mission types that would benefit. Appendix B provides additional pertinent material, which has been excerpted from a white paper on astrodynamics written by Strange, et al.,[16] and strongly endorses astrodynamics as a NASA research and technology area.

Table 2.7-1. Key advances in mission design capabilities.

Mission Design Capabilities	Current Status	Desired Status	Benefits to Missions
Multiple encounter tour design	• Conic 2-body techniques and code are still being used • Does not take into account latest optimization and tour design techniques	• New, more rapid, and higher fidelity tour design techniques to allow more extensive analysis in order to increase science return • The ability to connect tours with science orbits in a cost-efficient manner	• Increased delivered mass (and hence, payload; hundreds of kg in some cases) and reduced cost • Reduced design cycle time and increased variety of science mission options
Close-proximity trajectory design for small-body missions	• Capabilities are slow, provide little to no optimization or automation, and offer no insight into an integrated systems approach to the mission architecture	• Small-body mission design techniques in high-fidelity dynamical system (comets, binary asteroids, etc.) • Dynamic/autonomous control laws • End-to-end hovering-to-landing-to-ascent design capabilities	• Thorough exploration of mission trade space • Ability to rapidly respond to new environment and opportunities
Low-energy trajectory design and optimization	• Trajectories designed through trial and are brittle to changes • Little or no optimization and limited insight into underlying dynamics	• The ability to rapidly design and optimize trajectories that take full advantage of multibody dynamics, possibly with low-thrust and/or multiple spacecraft	• Reduced design cycle time and increased variety of science mission options • Reduced cost and increased payloads
Multiple-spacecraft trajectory optimization	• Limited capability that is difficult to use	• The ability to rapidly optimize trajectories for missions with multiple spacecraft	• Enabling technology for science and the ability to rapidly design innovative solutions
Low-thrust trajectory design and optimization	• Current capabilities are adequate, but trajectory design is laborious and time-consuming, requiring expert skills to hand-craft solutions	• Improved optimization and search techniques for more complete trade space studies • Greater ability to perform statistical Monte Carlo studies to characterize performance and identify risks • Tighter integration with navigation processes and spacecraft constraints	• Broader understanding of design space to reduce development time as well as risk and cost for future missions • Increased automation in trajectory design to enable more complex missions

Table 2.7-2. Mission types benefiting from proposed advanced mission design capabilities.

Mission Type	Multiple Encounter Tour Design	Close-Proximity Trajectory Design for Small-Body Missions	Low-Energy Trajectory Design and Optimization	Multiple-Spacecraft Trajectory Optimization	Low-Thrust Trajectory Design & Optimization
Outer planet	✓				✓
Outer planet with satellite tour	✓		✓		✓
Outer planet with multiple mission elements (e.g., probes, orbiter/lander)	✓		✓	✓	✓
Venus with multiple mission elements			✓	✓	
Multiple asteroids	✓	✓ (if rendezvous)	✓	✓	✓
Asteroid sample return	✓	✓	✓		✓
Comet sample return	✓	✓	✓		✓
Comet rendezvous	✓	✓	✓		✓
Small body with multiple mission elements	✓	✓	✓	✓	✓
Lunar sample return			✓	✓	

3 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 a companion document.[3]

3.1 Improvements in Dynamical and Measurement Modeling

3.1.1 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 will 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 2×10^{-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 3.1-1) 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.

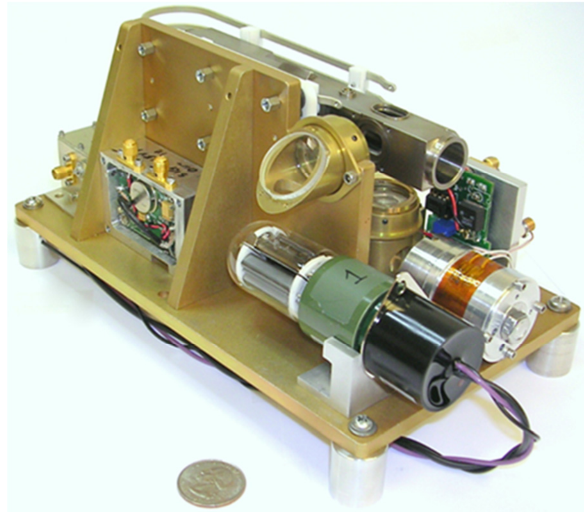
Figure 3.1-1. Laboratory brassboard version of DSAC in a low-mass and low-volume package; accurate to 1 ns in 10 days.

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). More specifically, a navigation infrastructure based on one-way radio metric tracking on the return link provides the following immediate benefit to NASA missions:

1. It capitalizes on DSN's ability to support multiple downlinks on a single antenna, called Multiple Spacecraft Per Aperture (MSPA), since no uplink is required for DSAC-enabled one-way radio metric tracking. For instance, at Mars, two spacecraft equipped with DSAC can be tracked simultaneously on the downlink by a single antenna. The current two-way tracking capability requires the two spacecraft to split the time on the uplink, resulting in a near *doubling* of the usable tracking for each spacecraft using DSAC. Preliminary studies have indicated that the additional tracking data volume can yield several times more accurate orbit and gravity field estimation.
2. Deep space missions using DSAC can take full advantage of station view periods for tracking, unlike in the case of two-way radio metric tracking where view periods are reduced by round-trip light time. For example, Cassini's northern hemisphere view periods at Goldstone and Madrid are currently on the order of 11 hrs, so that a round-trip light time in the 4–5 hr range yields an effective 6-hr two-way pass. On the other hand, a one-way pass using DSAC can employ the full view period of 11 hrs (a near doubling of the usable data) without needing to transition to a complicated three-way tracking operation across multiple ground stations.
3. Planetary atmospheric investigations using radio occultations can benefit from DSAC as well. Compared to today's radio occultations that rely on one-way tracking derived using ultrastable oscillators, DSAC-enabled measurements are upwards of 10 times more accurate on the time scales relevant to these experiments (that is, the several minutes during which a spacecraft radio signal to Earth passes through a planetary atmosphere, before being occulted by the planet).

4. For outer planet missions, solar corona plasma effects are a frequency-dependent error source that dominates other measurement errors and affects radio metric tracking across both short and long time scales. As seen with the Cassini mission, navigators de-weight their two-way measurement data by a factor of 3 over other measurement errors to account for this effect. Use of a Ka-only one-way downlink reduces these effects by 10 times relative to those on an X-up/Ka-down two-way link. Thus, in Cassini's case, these solar corona effects would be 3/10 the size of the other errors, rather than 3 times. Future outer planet missions, such as a Europa orbiter/flyby mission, can benefit from this use by potentially eliminating the need for a dual-frequency electronics system (which itself allows removal of the solar corona effect, but at the expense of a noisier measurement), resulting in an overall mass and power savings. Gravity science would particularly benefit as a result of both an increase in data quantity and an improvement in data quality.

These benefits can be achieved with little to no modification to the typical navigation paradigm of collecting and processing data on the ground.

DSAC also enables 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 enables 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.

As a specific example, delivery of a Mars lander to the top of the atmosphere (i.e., entry) using current ground-based navigation procedures typically yields a knowledge uncertainty of 2–3 km (3-sigma), which results from uploading a final trajectory solution 6 or more hours prior to entry. Using DSAC, one-way radio tracking on the uplink, and an onboard GN&C system, this knowledge uncertainty reduces to a *handful of meters* because the tracking and associated trajectory solution generation are available continuously and nearly instantaneously, including during entry. This, coupled with active guidance during the lander's hypersonic descent phase, can effectively eliminate residual top-of-the-atmosphere delivery error to return the lander to its nominal descent trajectory prior to parachute deployment. With this reduction in atmospheric delivery errors, the powered descent portion of a pin-point landing must only correct for wind drifts and map-tie error, thus reducing the overall delta-V required. The use of DSAC for entry is a key step toward achieving a resource-efficient pin-point landing.

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. During a one-year experiment scheduled to begin in early 2015, the payload (consisting of DSAC, an ultrastable oscillator, and a Global Positioning System [GPS] receiver/antenna) will be hosted on an Earth-orbiting spacecraft and collect pseudo-range and phase data to any and all in-view GPS satellites almost continuously. These data will be telemetered to the ground and processed to simultaneously determine precision orbits and DSAC performance relative to the International Global Navigation Satellite System Service (IGS) time scale (which is aligned to Universal Coordinated Time). Figure 3.1-2 illustrates DSAC's Earth-orbiting mission architecture. This TRL 7 demonstration will enable DSAC technology to be readily incorporated into multiple future missions.

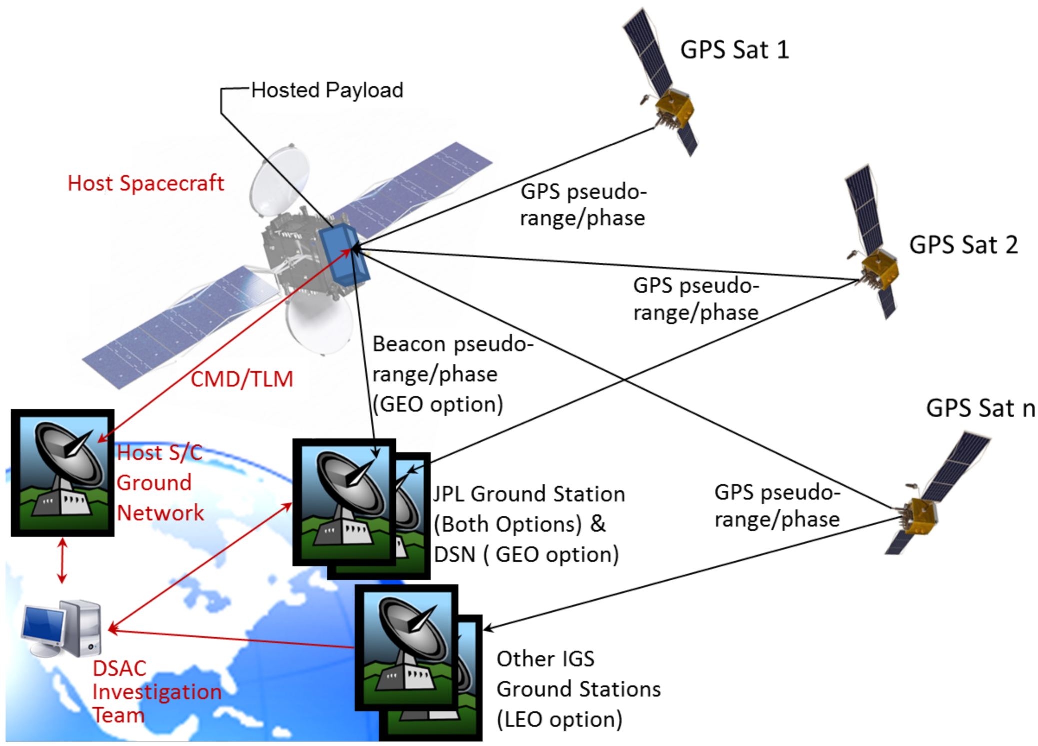

Figure 3.1-2. DSAC's Earth orbiting mission architecture.

3.1.2 *Other Necessary Improvements*

Various other improvements in observational and dynamic modeling are needed to most effectively navigate certain future planetary missions. Cometary nuclei and most asteroids have very irregular gravity fields due to their irregular shapes and possible variations in mass density. This gravity field uncertainty makes the orbital behavior of a nearby spacecraft difficult to predict. In addition, cometary nuclei expel volatile material near their perihelia, which makes the long-term motions of these bodies less predictable, and can also affect the relative orbital motion of a nearby spacecraft. The modeling of the shapes of small bodies, so as to derive accurate navigational information from spacecraft measurements of angles or distances to the bodies, represents another challenge.

Techniques for navigation and gravity field improvement developed for use at one solar system body (e.g., the GRACE mission in orbit about the Earth, with its use of a vehicle-to vehicle radio metric link) may be highly useful when applied to an analogous mission at a different body (e.g., the GRAIL mission in orbit about the moon).

3.2 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:

- 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
- Improvements to the onboard filtering capability (stochastic parameter estimation, filter smoothing, etc.)
- Addition of trajectory optimization
- Improvements in overall robustness/error checking and handling
- Improvements in interfaces to other spacecraft elements

These enhancements would enable a wide range of mission scenarios as described below.

3.2.1 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.

3.2.2 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

- Long (e.g., days) turnaround of navigation and maneuver designs and uplink product generation
- The number of possible gravity-assist flybys constrained by ground operation limitations
- Maximum orbit control frequency limited to one independently calculated maneuver per 10 days, which limits targeted flyby frequency
- 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 (see Figure 3.2-1) can substantially reduce light-time and other delays associated with the navigation process, and would result in

- Rapid turnaround between navigation data capture and orbit control, as well as post-flyby clean-up
- Rapid successive and safer lower-altitude satellite flybys to reduce mission Delta-V
- More efficient outer planet orbit insertion with closer (to event) targeting, rapid clean-up, and lower altitude
- Automation of routine navigation activities, such as turn and maneuver sequence generation
- Less propellant mass required to achieve orbit around or landing on an outer planet satellite, such as Europa or Titan

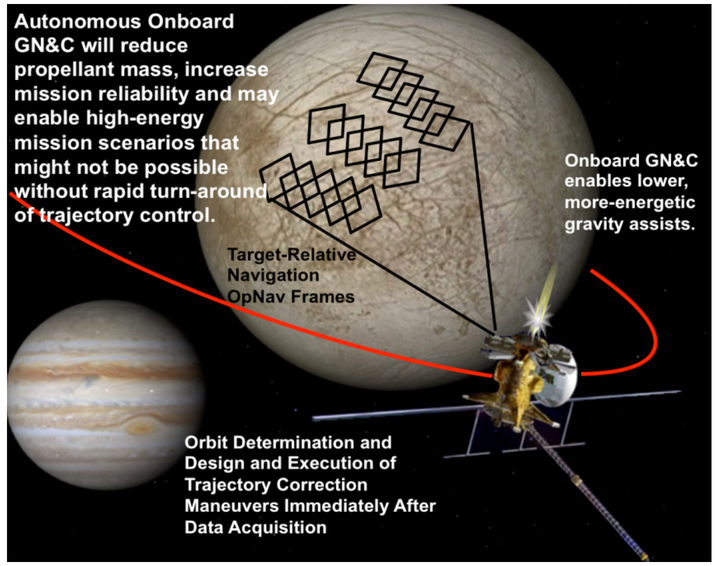

Figure 3.2-1. Autonomous onboard navigation for a Europa orbiter.

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

- Savings of hundreds of m/s of Delta-V
- Double or triple the frequency of satellite flybys, with an order of magnitude increase in science return
- Automation of routine navigation operations and operations planning, such as image capture and maneuver turns and execution, significantly reducing operation costs

3.2.3 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.[17]

3.3 Beyond the Current Deep Space Network

3.3.1 *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,[18] 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-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 satellite navigation 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.

3.3.2 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.

Many NASA studies have been done for, and significant technology development invested in, laser communications for future planetary missions. The laser communications capabilities offer potentially improved data transmission for a given amount of spacecraft power. A laser communications 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.[19,20] With improved timing circuits, which are already used in SLR stations, 1-cm accuracy is achievable.

Two-way laser range measurements with 1-cm accuracy are much better than the 1-m level accuracy achieved with current radio range measurements systems (and better than the 10-cm radio range capability planned as a science experiment on the BepiColombo mission of the European Space Agency, ESA). With current radio Doppler measurements, changes in range are measured with an accuracy of about 1% of the radio carrier wavelength of about 1 cm for Ka-band or 3 cm for X-band, which is much more accurate than with one or two laser range measurements. However, most deep space navigation applications are based on averaging measurements over several hours. Because of the way the media errors accumulate, a track several hours long of laser ranging measurements will give more information content than a pass of radio range and Doppler measurements.[21] Over long time scales (several hours), the laser range measurements give better performance because they are limited mainly by the fluctuations in the dry troposphere, while radio signals, which have much longer wavelengths, are limited by charged particles in the Earth's ionosphere and the solar wind, and are also disturbed by fluctuations in atmospheric water vapor levels. The laser range measurements therefore can provide information content comparable to the best radio Doppler measurements, with dual-band X/X and Ka/Ka radio carrier signals used to calibrate the charged particle effects and water vapor radiometers at the tracking stations used to calibrate the water vapor effects. Laser range measurements will thus allow navigation performance better than in most missions today, which use single-frequency radios, and better science products derived from orbit determination, such as planetary gravity field and tidal model estimates, which give strong constraints on planetary interior structures.[22,23] The range measurements give additional strength to the estimation of parameters of general relativity, and possibly the determination of the masses of asteroids that perturb planetary orbits.[24]

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.

In addition to line-of-sight Doppler and range measurements, most planetary missions now use angular position measurements from VLBI/delta-DOR, which measure the angular separation of the spacecraft from a radio quasar. There are two possible means of achieving similar angular accuracy with a laser communication package.

If the spacecraft includes capabilities for timing of uplink laser pulses, then two tracking stations within the footprint of the spacecraft's laser signal can uplink to the spacecraft simultaneously while also recording the downlink pulse times. By comparing the timing of pulses at both stations and on the spacecraft, the difference in time at the stations can be calibrated and the angular position of the spacecraft can be determined.[21]

Another approach is to image the spacecraft relative to a star. Currently, the positions of stars are not known as well as the positions of radio quasars. Star position accuracies are currently about 0.020 arcsecond (for the 118,000 stars in the Hipparcos Catalog), while radio quasar positions are known to about 0.0002 arcsecond. However, the ESA Gaia mission, planned for launch in 2013, is expected to produce star positions with accuracies better than the current radio quasar positions. Narrow-angle charge-coupled device (CCD) instruments have shown the ability to measure the angular separation of two stars with an accuracy of about 0.001 arcsecond, comparable with VLBI/delta-DOR radio measurements of spacecraft.[25] A spacecraft transmitting a laser signal can be detected and measured in the same way. There are several systematic effects that need to be investigated, such as color-dependent effects associated with differing laser signal (monochromatic) and starlight (broad-band) frequency distributions, and the effect of scattered light from target planets on the CCD instruments; but these effects are thought to be possible to calibrate. It should be noted, however, that for stars angularly close to the sun (within about 30 degrees) this astrometric approach may not be usable because of the brightness of the sky background.

3.3.3 X-Ray Pulsar Navigation

X-ray pulsar navigation is closely analogous to GPS navigation. The idea is to make use of the large number of extremely stable millisecond pulsars, with the regularity of the pulse arrival times allowing the determination of the position and time of a deep space probe relative to the solar system's barycenter (center of mass). It offers the possibility of accurate tracking to 1 km or better, with relatively weak dependence on the distance from the solar system's barycenter.[26] However, a number of challenges need to be addressed before this approach could become feasible in deep-space applications:

- Mass and volume issues: Large detector areas are needed for X-ray photon detection and arrival timing, which makes such detectors difficult to accommodate on a planetary spacecraft.
- Difficulty of use in environments with variable dynamics (e.g., orbit insertion, atmospheric flight, landing): Long integration times are needed for photon detection and arrival timing.
- Lack of optimal X-ray sources: X-ray sources need to be found that are sufficiently luminous, stable, and well-distributed over the sky. Although the recent success of the Fermi Gamma-Ray Space Telescope mission has doubled the number of suitable millisecond pulsars, accurate astrometric catalogs and ephemeris tables will need to be developed and maintained for these X-ray sources.

X-ray pulsar navigation determines the position of a spacecraft relative to the solar system's barycenter, not relative to some destination body, which may have an inaccurately determined orbit (or ephemeris). For example, the New Horizons mission to Pluto, arriving in 2015, must contend with a Pluto ephemeris error that is nominally about 2,700 km (1σ). With a ground-based observing campaign, this error may be reduced to about 1,600 km (1σ). The impressive absolute X-ray pulsar tracking accuracy, if currently available for mission use, would do little to improve the situation, because of the large planetary ephemeris error. However, a target-relative tracking method such as optical navigation can achieve the required flyby accuracy relative to Pluto of 100 km (1σ), perpendicular to the relative flight path. X-ray pulsar navigation would be more applicable to missions where no frame tie is needed, for example, a mission to the solar gravitational lens foci beyond 548 AU.

A dramatic reduction in DSN tracking time and consequent cost saving are sometimes claimed with X-ray navigation. However, DSN coverage is currently driven by telecommunication needs in almost all cases, so that Doppler data are available for navigational use at essentially no cost. (This cannot be guaranteed to be true into the indefinite future, however.)

3.4 Closing Remarks

The recently released document *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*[2] 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. Appendix A provides more detailed information about the pertinent top technical challenges and associated technologies described in Ref. 2.

4 Key Findings and Recommendations

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.

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 Ref. 3, 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.

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 PSD 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.

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.

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.

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.

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.

Appendix A: Pertinent GN&C Challenges and Technologies in the NASA Space Technology Roadmap

This appendix discusses pertinent top technical challenges and high-priority technologies that are documented in the recently released *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*,[2] henceforth referred to as the Roadmap.

A.1 Top Technical Challenges

The Roadmap lists a number of technical challenges pertinent to this technology assessment. Among them is a challenge identified by the review panel for technology area 05 (TA05) Communications and Navigation Systems, which reads:[*]

> **1. Autonomous and Accurate Navigation:** Meet the navigation needs of projected NASA missions by developing means for more autonomous and accurate absolute and relative navigation.
>
> NASA's future missions show a diverse set of navigational challenges that cannot be supported with current methods. Precision position knowledge, trajectory determination, cooperative flight, trajectory traverse, and rendezvous with small bodies are just some of the challenges that populate these concepts. In addition, NASA spacecraft will need to do these things farther from Earth and more autonomously. Proper technology investment can solve these challenges and even suggest new mission concepts.

A challenge identified by the review panel for TA04 Robotics, Tele-Robotics, and Autonomous Systems reads:

> **1. Rendezvous:** Develop the capability for highly reliable, autonomous rendezvous, proximity operations, and capture/attachment to (cooperative and non-cooperative) free-flying space objects.
>
> The ability to perform autonomous rendezvous and safe proximity operations and docking/grappling are central to the future of mission concepts for satellite servicing, Mars sample returns, active debris removal scenarios, and other cooperative space activities. Major challenges include improving the robustness of the rendezvous and capture process to ensure successful capture despite wide variations in lighting, target characteristics, and relative motion.

Two challenges identified by the review panel for TA09 Entry, Descent, and Landing read:

> **3. Precision Landing:** Increase the ability to land space vehicles more precisely.
>
> A precision landing capability allows a vehicle to land closer to a specific, predetermined position in order to assure that the vehicle lands safely (without damage to itself or other personnel that may already be on the surface), or in order to meet other operational or science objectives. The level of precision (e.g., 1000 m, 100 m, etc.) that is achievable at touchdown is a function of the design of the guidance, navigation, and control (GN&C) system, the control authority of the

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vehicle, and the entry environment. Precision landings require accurate GN&C performance throughout the entire descent and landing phases. This requires accurate control of vehicle position, velocity, attitude, and other vehicle states….

4. Surface Hazard Detection and Avoidance: Increase the robustness of landing systems to surface hazards.

The surface hazards associated with exploration destinations remain uncertain to some degree until the site has been visited. Relying on passive systems alone to characterize a landing site can be problematic, as was evident on during the Apollo Program, where each of the six landing missions faced potentially mission-ending hazards at the landing sites. Hazardous rocks, craters, and slopes were perilously close to each of the successfully landed missions and brought to light the incredible challenge each mission faced… Active hazard detection methods can quickly optimize safe sites and reduce fuel costs while directly characterizing a landing surface in real time, but technology development is needed to improve key capabilities in this area….

A.2 High-Priority Technologies

The Roadmap lists high-priority technologies that respond to the identified top technical challenges. In response to top challenge 1 for TA05, the document lists the following high-priority technologies:

5.4.3 Onboard Autonomous Navigation and Maneuvering Systems

Onboard autonomous navigation and maneuvering (OANM) techniques are critical for improving the capabilities and reducing the support requirements for many future space missions, and will reduce the dependence on routine position fixes from the Earth, freeing the communication network for other tasks. The onboard maneuver planning and execution monitoring will increase the vehicle agility, enabling new mission capabilities and reducing costs by eliminating the large work force required to support routine spacecraft operations. The alignment of this technology to NASA's needs is high because it will impact deep space exploration with crew, robotic science missions, planetary landers, and rovers.

5.4.1 Timekeeping and Time Distribution

Underlying NASA's communications and navigation infrastructure are atomic clocks and time transfer hardware and software. New, more precise atomic clocks operating in space, as well as new and more accurate means of time distribution and synchronization of time among such atomic clocks, will enable the infrastructure improvements and expansion NASA requires in the coming decades. Advances in timekeeping and distribution of several orders of magnitude were judged to provide major benefits, since increased precision of timekeeping and transfer leads to increased precision of relative and absolute position and velocity which in turn provides better starting solutions to enable autonomous rendezvous, docking, landing, and formation flying remote from Earth. Alignment with NASA's needs is considered high due to the substantial impact of the technologies to multiple missions in multiple mission areas including human and robotic spaceflight involving rendezvous, relative station keeping and landing missions.

In response to top challenge 1 for TA04, the document lists the following high-priority technology:

> ***4.6.2 Relative Guidance Algorithms***
>
> Relative guidance technologies encompass algorithms that determine the desired trajectories to be followed between vehicles performing rendezvous, proximity operations, and/or docking and capture. These algorithms must anticipate applicable environmental effects, the nature of the trajectory change/ attitude control effectors in use, and the inertial and relative navigation state data available to the guidance algorithms. The new Level-3 technologies of interest provide real-time, onboard algorithmic functionality that can calculate and manage spacecraft maneuvers to achieve specific trajectory change objectives. Relative guidance aligns well with NASA's needs because it impacts crewed deep-space exploration, sample return, servicing, and orbital debris mitigation.

In response to top challenges 3 and 4 (and others) for TA09, the document lists the following high-priority technologies:

> ***9.4.7 Guidance, Navigation, and Control (GN&C) Sensors and Systems (EDL)***
>
> The ability to accurately hit entry corridors, to control the vehicle during entry and descent, to navigate the vehicle during all phases of EDL, and to safely and precisely land a vehicle in hazardous terrain are examples of a high performing EDL GN&C system. The ability of the GN&C system to achieve its mission objectives is a function of GN&C sensor performance, vehicle actuator ability, and the designer's ability to craft them sensibly together onboard a capable, real time, computing platform. GN&C Sensors and Systems are common to all of the foreseen EDL generic reference missions and align extremely well with NASA's expertise, capabilities, and facilities. This technology is game-changing because it significantly enhances the ability to increase mass to the surface, the ability to land anywhere, and the ability to land at any time.
>
> ***9.4.5 EDL Modeling and Simulation***
>
> EDL Modeling and Simulation (M&S) technology provides the ability to conduct computational predictions necessary for robust and efficient design in all phases of EDL missions. This technology includes computational fluid dynamics analysis, finite element modeling, fluid-structural interaction analysis, aerothermodynamics modeling, coupled stability and 6DOF (degrees of freedom) trajectory analysis, multi-disciplinary analysis tools, and other high-fidelity analysis. This technology also includes development and application of experimental validation including flight tests. This technology is widely applicable to all EDL missions and to the successful development and implementation of the other high-priority technologies in this roadmap.

Recommendations

All five high-priority technologies listed here benefit PSD missions—Sections 3.1 and 3.2 of this technological assessment illuminate the benefits of the first two technologies to PSD; and Ref. 3

describes the benefits of the last three technologies to PSD. PSD should advocate that the OCT fund each technology.

In analyzing the 83 high-priority technologies selected by the panels reviewing the broad range of 14 technology areas TA01–TA14, the steering committee for the Roadmap determined that some of these technologies "were highly coupled or addressed the same technology pedigree." Consequently, "during the prioritization process, these highly coupled technologies were grouped together and considered as one unit." One instance of this grouping involved the aggregation of the separate high-priority technologies 4.6.2, 5.4.3, and 9.4.7, mentioned above, into the unified technology category, X.4 GN&C.

In the final prioritization of the broad range of high-priority technologies, this unified technology, GN&C (X.4) 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.

A.3 Omission of Mission Design from Roadmap

The structuring of NASA's space technologies into 14 technology areas, as done in the development of the Roadmap, can potentially result in a particular technical discipline's falling outside of the perceived domain of each individual technology area, despite having significant intrinsic importance. This occurred in the case of space mission design (or astrodynamics).

One can view the trajectory-related aspects of space mission design as the front end of GN&C. One can also view such work as an important part of modeling and simulation. However, the trajectory-related aspects of space mission design are not covered to a significant degree in TA05, TA11 (Modeling, Simulation, Information Technology, and Data Processing), or elsewhere, apart from being mentioned in an EDL-focused sense in TA09.

While not explicitly mentioned in the Roadmap, 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 Ref. 1.

Appendix B: Supporting Material from Astrodynamics White Paper

The following material has been excerpted from a white paper on astrodynamics written by Strange, et al.,[16] which strongly endorses astrodynamics as a NASA research and technology area:

> *Astrodynamics, the study and application of space travel, is at the core of all past, present and future space science and exploration missions. From the dawn of the space age to the present, each new mission beyond the Earth's atmosphere has relied on our engineering and scientific understanding of the design, navigation and control of space vehicle trajectories. However, just as all space missions depend on the field of astrodynamics, our ability to explore new worlds and carry out innovative scientific experiments is also limited by our current abilities in the field of astrodynamics. This dependence can be restated as a fundamental principle: New insights and advances in our understanding of motion in space will ultimately yield new prospects for carrying out innovative scientific measurements, increase the efficiency and extend the life of current missions, and create the ability to explore and reach new realms of the Solar System.*
>
> *Past research in astrodynamics has uncovered many mission-enabling techniques such as the gravity-assists used by the Voyagers, Galileo, and Cassini spacecraft; aerobraking used by Magellan, Mars Odyssey, MRO, and other spacecraft; Lissajous and N-body orbits used by missions such as Genesis, Spitzer, and ICE; and low thrust trajectory design techniques used for the Dawn and Hayabusa missions…*
>
> *Despite the demonstrated benefit of this research, there has been no funding source for academic research in this field, and there has not been an effort to coordinate research with planning for future scientific exploration. Rather, the development of these techniques is typically funded as part of existing projects, projects that are formulated with only the knowledge of astrodynamics techniques used in past missions. This current process drives astrodynamics research to only consider the improvement of existing mission concepts and severely limits the ability to develop revolutionary new techniques that would enable new types of missions. We believe that new astrodynamics techniques could be better leveraged into improving our capability for Solar System exploration and science if they were available at the time of mission formulation. Development of new techniques may also create new paradigms for carrying out missions that were not considered before.*
>
> *The project-focused model of funding astrodynamics research has also had deleterious effects on university astrodynamics research. The lack of a predictable funding source for research in astrodynamics for planetary and space-based missions has made it difficult to attract talented graduate students to the field, and has made it difficult to argue for the importance of the field within university engineering departments where other disciplines receive more funding from their respective industries. The lack of a coordinated funding effort from NASA has also limited NASA's ability to influence what work is done. A quick survey of the literature will find many papers on formation flying and other*

problems important to defense application, and no papers seeking to solve the problem of how to find feasible fast trajectory designs for Neptune orbiters (a type mission currently in need of enabling astrodynamics techniques).

The nature of advances in astrodynamics can be divided into two categories: incremental and fundamental. The first category is the incremental improvement of existing approaches and technologies. Such advances, such as improved trajectory optimization methods, more detailed and deeper understanding of existing phenomen[a], and improved measurement and modeling precision, can all yield incremental but enabling advances in our ability to explore the Solar System.

The design of the Cassini extended mission is an example of incremental improvement to existing techniques. The initial design[s] of the satellite tours for Galileo and of the Cassini prime mission were performed using the theory of patched conics. This approach enables the rapid generation of multiple candidate tours from which a final design can be chosen that finds the best balance in achieving a mission's science goals. For the Cassini extended mission design this approach was expanded to use trajectory arcs calculated in a higher order Saturn gravity field. This extension enabled more accurate targeting of encounters with Saturn's inner moons including Enceladus. As a result of this improvement, the extended mission design was better able to achieve diverse science goals … including doubling the rate of Enceladus encounters from the prime mission (which enabled more extensive follow up investigations of the Enceladus plumes discovered during the Cassini prime mission).

The second category is fundamental advances in our understanding. These are much less predictable, yet can have extremely important and enabling outcomes…. Such advances are difficult to predict as they result from new insight or the application of theory from one branch of science and mathematics to the field of spaceflight. A clear example is the application of celestial mechanics and dynamical systems theory to the rigorous understanding and automation of space mission design to the Earth-Sun and Earth-moon libration point regions of space. The roots of our current ability to design complex trajectories and missions in the Earth's neighborhood grew organically out of many different avenues. First and foremost were the initial applications of exotic orbits in the restricted 3-body problem for scientific purposes … and the use of the dynamics of the 4-body problem for capture into lunar orbit…, and the enabling design for Genesis.... Following these applications, the rigorous study of mathematicians and astrodynamicists…over the decades after the first halo missions made fundamental connections between the abstract theory of dynamical systems and practical and applied spaceflight. These connections have yielded an expansive growth in our ability to efficiently design transfers in the larger space about the Earth-Moon system. Future applications of these connections to planetary satellite orbiters (including Earth's Moon) and other applications are waiting development and are necessary for the reliable and robust design of spacecraft transfers to any highly dynamic environment.

Recent advances in computer hardware and software engineering techniques hold promise as another source for future breakthroughs in this category. In particular, the solutions of many computationally intensive combinatorial problems in astrodynamics (e.g. tour design) are becoming feasible to solve with the extraordinary new hardware and memory capabilities of modern computers. The infusion of astrodynamics research with new advanced software engineering techniques could lead to dramatic improvements in the feasible set of science missions.

A speculative example of a possible future topic of research that could have significant impact would be coupled navigation and mission design. Current approaches to designing trajectories decouple the process of navigation (i.e., actually "flying" the spacecraft while correcting for errors and uncertainties) and mission design (charting the course of the spacecraft). This decoupling is acceptable in relatively benign dynamical environments such as inter-planetary flight or planetary orbiters, but is no longer acceptable in highly dynamic environments such as low-altitude planetary satellite orbiters, such as the Europa Orbiter mission. Intensive gravitational tours, such as the Cassini trajectory at Saturn, are on the edge of this decoupled process, and require a large team of navigators and mission designers to constantly iterate new solutions due to small navigation dispersions. This approach entirely results from the classical and somewhat arbitrary academic separation of these two fields. There are many possible approaches to improving this problem, but all of them would require a deeper understanding of spacecraft trajectories as being "uncertainty distributions." Making such connections [is] feasible … and could enable a transformative understanding of how to design trajectories that simultaneously satisfy scientific goals and which are safely "navigable" in strongly dynamic systems. This understanding could be leveraged into either lowering the operations costs or to increase the science capability of future missions.

Acronyms

ΔV	velocity change
ACE	Advanced Composition Explorer
ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun
AutoGNC	autonomous guidance, navigation, and control
AutoNav	autonomous navigation
CCD	charge-coupled device
Delta-DOR	delta-differential one-way range
DOF	degrees of freedom
DSAC	Deep Space Atomic Clock
DSN	Deep Space Network
EDL	entry, descent, and landing
EPOXI	Extrasolar Planet Observations and Characterization (EPOCh)/Deep Impact Extended Investigation (DIXI)
ESA	European Space Agency
GN&C	guidance, navigation, and control
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRAIL	Gravity Recovery and Interior Laboratory
IGS	International GNSS [Global Navigation Satellite System] Service
IKAROS	Interplanetary Kite-craft Accelerated by Radiation of the Sun
ISEE-3/ICE	International Sun-Earth Explorer 3/International Cometary Explorer
JPL	Jet Propulsion Laboratory
LAGEOS	Laser Geodetic Satellite
M&S	modeling and simulation
MESSENGER	Mercury Surface, Space Environment, Geochemistry and Ranging
MRO	Mars Reconnaissance Orbiter
MSPA	Multiple Spacecraft Per Aperture
NASA	National Aeronautics and Space Administration
NEAR	Near Earth Asteroid Rendezvous
NExT	New Exploration of Tempel 1
OANM	onboard autonomous navigation and maneuvering
OCT	Office of the Chief Technologist
PSD	Planetary Science Division
ROSES-12	Research Opportunities in Space and Earth Sciences-12
SCaN	Space Communications and Navigation
SLR	satellite laser ranging
SMART-1	Small Missions for Advanced Research in Technology 1
SMD	Science Mission Directorate
SOHO	Solar & Heliospheric Observatory
TA	technology area
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TRL	technology readiness level
TRN	target-relative navigation
VLBI	very long baseline interferometry

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