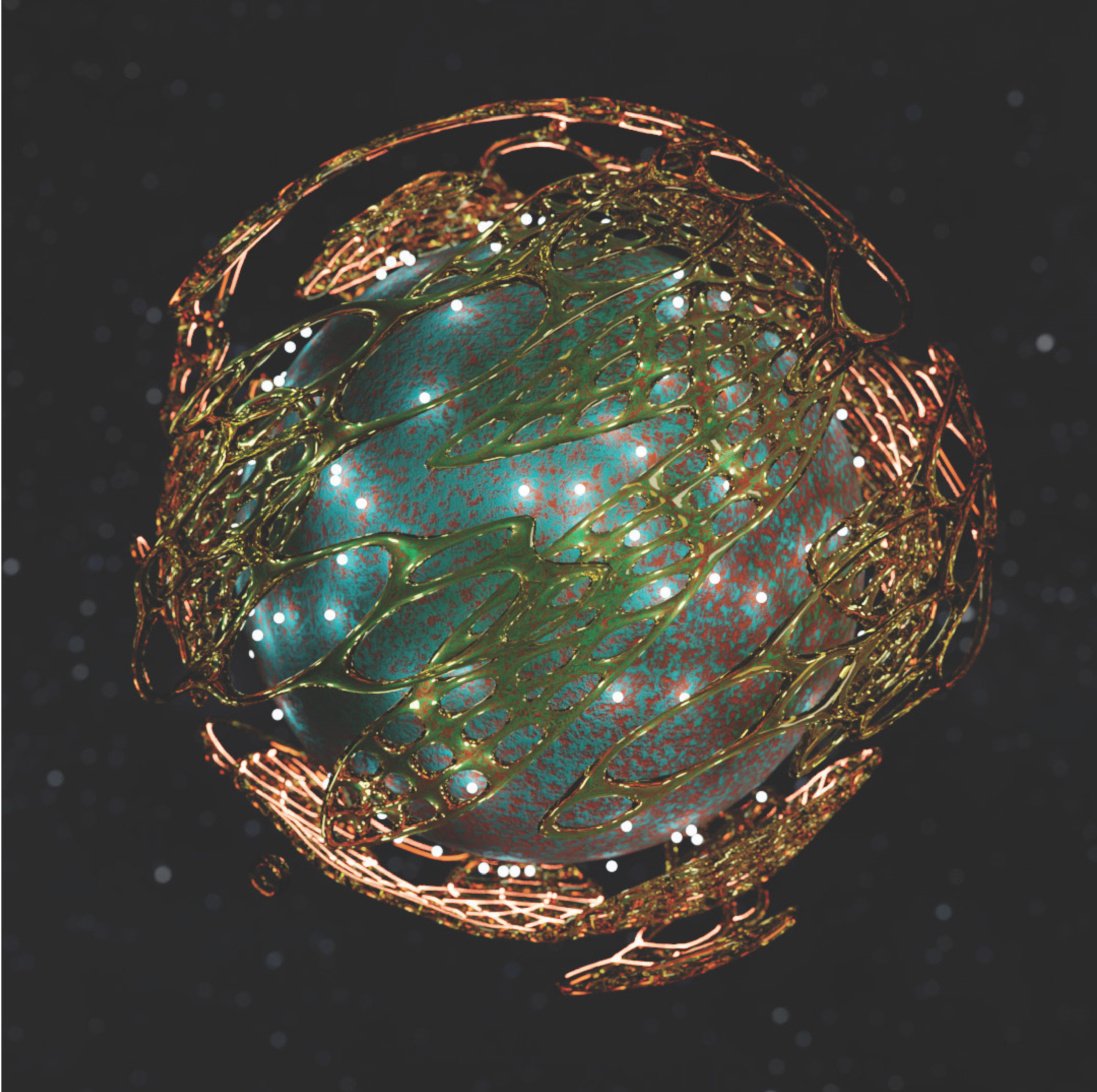

Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions

Part I.
Onboard and Ground Navigation and Mission Design

February 28, 2023

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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

Part I. Onboard and Ground Navigation and Mission Design

Engineering and Science Directorate
Jet Propulsion Laboratory
for
Planetary Science Division
Science Mission Directorate
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Foreword

Future planetary explorations envisioned by the National Research Council's (NRC's) *Origins, Worlds and Life 2023–2032*, 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, and the last decade has shown a lot of progress.

Part I, *Onboard and Ground Navigation and Mission Design*, is one of a series of four 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*, covers 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 and Sub-Surface Guidance, Navigation, and Control*, examines GN&C for vehicles that are not in free flight, but that operate on and below the surface of a natural body of the solar system. Part IV, *Aerial Guidance, Navigation, and Control*, examines GN&C for heavier-than-air and lighter-than-air vehicles in buoyant or sustained free flight in the atmospheric environment 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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These and other relevant reports can be found on https://solarsystem.nasa.gov/technology-reports/technology-assessment-reports/

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Executive Summary

The importance of research and development in the fields of celestial mechanics, trajectory optimization, and mission design was 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] and the Technology section of *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*.[2]

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 launch opportunities and operational considerations, and more.

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 other missions
- Allow better mission designs with 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, allowing computationally intensive risk-mitigation trades to increase likelihood of mission success or extend mission lifetime
- Enable comprehensive end-to-end mission simulations by integrating performance errors (from respective subsystems) that influence system design

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 ingenuity and creativity of scientists and engineers ensure 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 could 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. On the other hand, recent innovations in artificial intelligence, reinforcement learning, four-body dynamics and Hamiltonian techniques, combinatorics, and mathematical applications in general, all advanced in the last 10–20 years, are having some positive impact. Some development of new mission design capabilities occurs naturally as a result of flight project activities and pre-project studies, generally specific to a particular mission. More research is needed, particularly investments for general capabilities that are tailorable to specific missions, rather than the other way around.

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 when moved aboard 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. Flight-path predictions for onboard use can be efficiently provided in a timely manner and reduce latency of commanding, enabling adaptivity and responsiveness in highly variable environments. The onboard navigation software can be a compact, tailored version of the ground software, with unneeded capabilities deleted. Both continued onboard GN&C system-level work, as described in Ref. 23, 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. Fault detection and recovery capabilities are required to permit the autonomy. Both absolute and relative estimation will be needed for multi-spacecraft distributed systems.

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 mission design, navigation, and closed-loop control software applications on a variety of spacecraft built by various companies and laboratories.

Finding 3

The Deep Space Network 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. To broaden autonomous navigation to include radiometric information, signal conditions and an uplink "message" that enable onboard pseudo-range and Doppler observations, and potentially high-accuracy time transfer, need to be defined.

Recommendation: NASA should explore opportunities for improving radiometric tracking data by enhancing the capabilities of the DSN for radio tracking. This can be accomplished without changing the basic operating mode of the DSN.

Finding 4

Clocks are fundamental to space navigation. Highly accurate and stable onboard clocks, such as DSAC, are enabling for autonomous radio navigation, will generate new possibilities for radio science, and will allow use of the DSN in new and more efficient ways. This would include relying much more on one-way communication links, as allowed by improved clock performance over both long and short time scales, coupled with reductions in clock size, weight, and power attributes to permit their inclusion on planetary spacecraft. Investments in advancing clock and time dissemination/synchronization technologies is key to not only navigation, but also to in-situ science observations and coordination of distributed missions.

Recommendation: Clock 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. With the first Deep Space Atomic Clock Technology Demonstration Mission now completed, an STMD-funded DSAC-2 TDO, considered for flight on the VERITAS mission, would ideally be moving forward with strong support from the SMD. Unfortunately, the TDO has recently been cancelled due to near-term STMD funding issues. SMD should strongly endorse a DSAC-2 TDO as future opportunities may arise and should look for ways to include and utilize advanced onboard clocks in its planning for future missions.

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 (potentially enabling substantially improved data and time-transfer accuracy) 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. The SCaN Optical Capability roadmap identifies optimetrics in every future development.

Recommendation: Further studies and flight demonstrations (beyond the Laser Communications Relay Demonstration and the Deep Space Optical Communications experiment scheduled to fly on the Psyche mission) should be conducted to fully investigate how optical communication links can be used to provide metric tracking data for use in spacecraft navigation. Key considerations include ensuring that optical receivers have clock recovery capability and adequate resolution in the mixers. Implementation options should be codified, identifying the typical sticking points, to make this a pervasive capability in all optical communication implementations be they ground-based or space-based. PSD should push SCaN toward incorporating this capability and incentivize missions to demonstrate at different data rates and ranges and to use operationally.

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. Adaptive estimation techniques should be developed and incorporated to support in-situ navigation and science observations. The latter observations, in turn, can be used as data sets for the refinement of natural body ephemerides.

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 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 extent of models. In addition, methods of designing more complex trajectories, associated with an expanded understanding of spacecraft dynamics and perhaps needed for the fulfillment of mission objectives, 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, Neptune, Pluto, and a Kuiper Belt object; and missions to comets and asteroids, including sample returns to Earth.[3,4,5,6,7,8,9,10,11] Missions that use the intricate gravitational interactions of the sun, Earth, and moon to accomplish specific mission objectives and constraints, such as ISEE-3/ICE, Wind, Genesis, GRAIL, and the James Webb Space Telescope, have also succeeded. The Lucy mission will have analogous interactions involving Jupiter's Trojan asteroids.

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, as demonstrated in the Magnetospheric Multiscale mission, where four spacecraft must maintain a tetrahedral formation in a highly elliptical orbit.
- Missions in the Flagship, New Frontiers, Discovery, and SIMPLEx classes will all 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 and outer planet exploration missions.
- Methods of efficiently exploring complex satellite tour designs, innovative science orbits, landing, 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.
- Lastly, the potential for mission scenarios that require very rapid navigation and control sequences may lead to requirements for onboard navigation in certain circumstances. Highly dynamic mission scenarios, long round-trip light times, and occulted views of Earth would all make onboard navigation and closed-loop flight-path control desirable or mandatory. Operations cost savings and risk mitigation during long-

duration missions are additional possible benefits, with continued development and extension of the multi-mission, multi-spacecraft, autonomous, onboard navigation system to form a complete autonomous guidance, navigation, and control system providing such benefits and enabling transformative and responsive science. With autonomous operations comes the need for robust fault detection and recovery/correction.

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 implement a planetary mission to accomplish a set of scientific objectives for the mission. This is usually done initially within the context of an "envelope" of potential designs generally meeting the overall desires.[12] 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.[13,14,15,16]

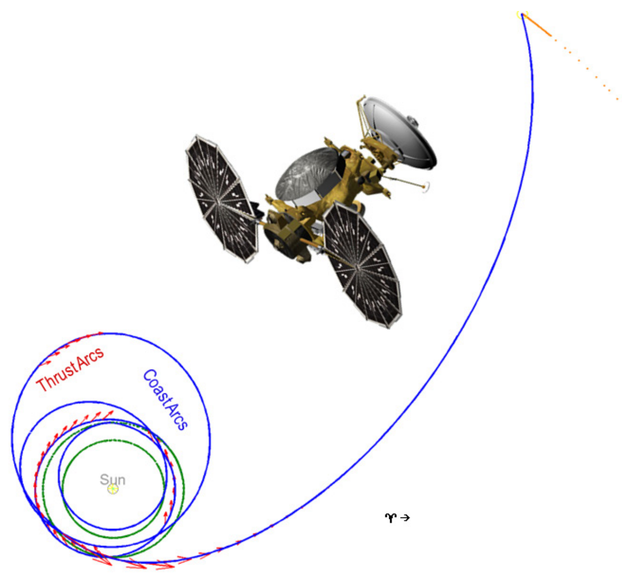

Figure 1.2-1. Interplanetary trajectory design can leverage electric propulsion to enable new missions and reduce project risk.

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.

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 (and medium-sized) body landing trajectories in a high-order gravity and topography field. Most missions to small bodies will arrive at their destination with no detailed knowledge of the gravitational and topographical characteristics of that body. The systems (GN&C and associated command, control and autonomy), both onboard 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 to deliver landers to the surface of a planetary body (e.g., Mars Exploration Rover, Phoenix, Mars Science Laboratory, InSight, Mars 2020, and Mars Sample Return), 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], Europa Clipper, Uranus Orbiter and Probe, Enceladus Orbilander, and VERITAS). Flyby missions of gravitating bodies 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. In addition, if the flyby object is Earth, then the large number of objects in the near-Earth volume requires small delivery errors to avoid possible collisions.

Various navigational tracking measurements (currently done primarily 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.[14,16,17,18,19] The frequency migration to Ka-band (already entering operational use), arraying of ground-based antennas, spacecraft-to-spacecraft tracking, and optical communication will offer additional tracking techniques and flexibility as well as potential tracking measurement accuracy improvements.

Missions to small bodies, the moon, and other planetary satellites require the characterization of internal/subsurface physical attributes, leading to modeling of the high-order gravity field as well as the characterization of spatial and temporal variations of surface composition. Achieving a navigation accuracy of 1 m in the vicinity of a small body will allow very close orbiting, hovering, "touch-and-go" sampling of, and safe landing on the surface (much of which has been recently demonstrated in the Hayabusa2 and OSIRIS-REx missions[20,21]). For such missions there is always a balance and trade between the accuracy of the modeling required for precise navigation-based control and fuel expenditure to "control-to-path" regardless of errors and unknowns in the models. Developing the means to accurately model the bodies (preferably without transmitting large amounts of data to Earth, followed by extensive ground processing) will allow the missions to intelligently trade between improved navigation modeling operations and propellant use.

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. Certain LiDAR systems can perform rapid sensing to inform the trajectory changes needed for hazard avoidance. Precise and safe landing on the moon and other bodies lacking atmospheres 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. More recent examples include the use of Natural Feature Tracking (NFT), the system built by Lockheed Martin that was used on the OSIRIS-REx mission to perform the sample retrieval, achieving a "touch-and-go" accuracy of less than a meter on the surface of asteroid Bennu. The Japanese Hayabusa 2 mission used onboard autonomy to also achieve a roughly meter-level accuracy in their sample retrieval from the asteroid Ryugu; this approach used a different paradigm, relying on homing in on an artificial target marker placed on the asteroid's surface to control the lateral spacecraft position and using radar altimetry to control the altitude. Finally, the Demonstration of Autonomous Rendezvous Technology (DART) mission, launched in November 2021, is slated to use an onboard guidance system called "SMARTNAV" to hit the secondary moon of the binary asteroid system Didymos in late September 2022 as a demonstration of a planetary defense capability. Unlike AutoNav, which used target relative orbit determination coupled with discrete maneuvers to hit Tempel-1, SMARTNAV uses an algorithm closer to missile guidance technology by continually firing thrusters in a feedback loop while maintaining the target in the center of the imaging camera's field of view.

The challenge for future missions is to expand the current uses of onboard navigation, in which the autonomy was mostly used for fairly limited time spans, to encompass broader mission goals, time spans, and scenarios. For example, this could include cislunar and lunar proximity operations, planetary approaches, and outer planetary satellite tours. This will require autonomous systems that interact with multiple observation systems (optical sensors, altimeters, one-way radiometrics, accelerometers/inertial measurement units, etc.), onboard planning, surface-relative measurements, highly accurate onboard reference maps, and high-accuracy clocks. Autonomous system error detection and self-maintenance can be integrated with navigation and control functions, as well as the executive that oversees the planning and scheduling, 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). Finally, nascent techniques such as pulsar-based navigation could be used to achieve reliable inertial navigation and universal time knowledge where radiometric and optical data types are less accurate, such as in the outer Solar System or even interstellar space.

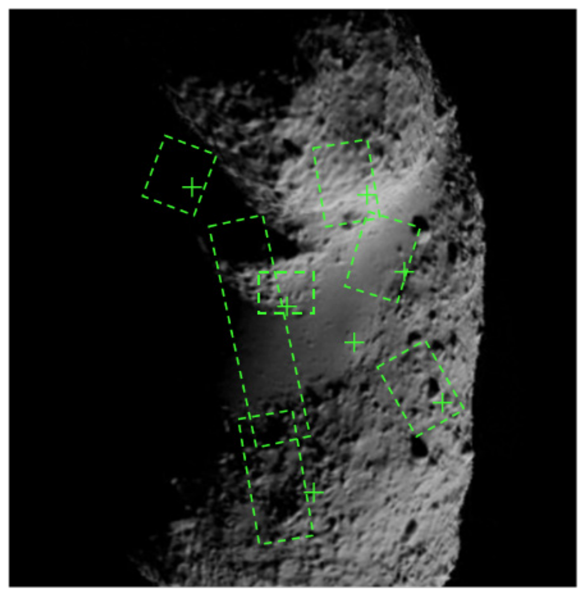

Figure 1.4-1. Example of AutoGNC system capable of touch-and-go operations.

1.5 Summary

NASA's mission design and GN&C capabilities and technologies have been essential to the success of 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 well beyond what is currently in hand, as well as reducing the overall mission cost.

A three-part guidance, navigation, and control technology assessment for future planetary science missions was produced in 2012–2013.[22,23,24] Subsequently, a slightly condensed version of Reference 22 was presented as a conference paper.[25] More highly condensed versions of References 22, 23, and 24, merged together, were prepared as a conference paper[26] and a journal article.[27] The present document is a revision of the first of these three parts. Whereas the technology assessments of 2012–2013 accounted for the most current Planetary Science Decadal Survey of the time,[1] the current document reflects the more recent decadal survey released in April 2022.[2]

1.6 Sources of More Detailed Background Information

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

- Ocampo and Byrnes[12] present an overview of mission design and trajectory optimization techniques (not limited to deep space applications).
- Russell,[28] Davis and Anderson,[29] Scheeres,[30] and Parker and Anderson[31] provide overviews or comprehensive treatments of more specialized mission design topics.
- References 14, 15, and 32 present overviews of deep space navigation.
- References 13, 15, 17, 18, and 19 provide more detailed and comprehensive treatments of particular aspects of deep space tracking and navigation.
- References 3, 4, 5, 6, 7, 8, 9, 10, 11, and 33 detail the historical development of deep space navigation techniques and the application of these techniques in many past missions, with the first nine of these citing almost 600 references containing more detailed information about planetary missions in flight from 1962 to 2018.

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 Dawn, SunRISE, Psyche, Europa Clipper, and Dragonfly)
- Increase science and investment return even while in flight (for example, the extended mission for the Deep Impact spacecraft to image comet Hartley 2; 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 transfer two spacecraft in Earth elliptical orbits into Earth-moon L1 & L2 quasi-halo orbits and then lunar orbits; and the earlier ISEE-3/ICE mission where ISEE-3 was redirected from sun-Earth L1 to explore a comet via several lunar gravity assists)
- Reduce cost, velocity change (ΔV), mass, and risk (always critical to any mission)
- Provide rapid updates to mitigate spacecraft anomalies that require a modified operational trajectory to attain mission goals
- 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
- Enable rapid design methodologies to adapt to changing mission objectives in highly nonlinear environments (e.g., Europa Lander mission concept)

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 ingenuity and creativity of scientists and engineers guarantee 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 could be lost. The Lucy mission is a recent example, where the alignment of the Trojan asteroids and careful and creative trajectory planning, including phasing via Earth gravity assists, led to a rapidly planned planetary launch opportunity. 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. At the same time, some improvements have been made based on dynamical system theory, use of artificial intelligence, and improved optimization techniques (sparse coding or basin-hopping and other combinatorics, etc.). 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 or more, 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 50 years, starting with Mariner 10, Pioneer 10 and 11, and Voyager and extending through Galileo, Cassini, MESSENGER, New Horizons, Parker Solar Probe, and Lucy (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 groundbreaking scientific discoveries from the inner solar system to the outer planets and beyond. However, next-generation tour designs will require innovative techniques with much higher fidelity and much more interaction between fast broad searches, intermediate models using 3- or 4-body effects, and high-fidelity models. 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

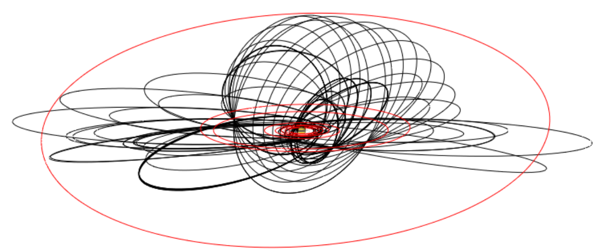

Figure 2.2-1. Exploration of multiple encounter tour designs.

- Trajectories to multiple small bodies such as comets or asteroids
- Satellite tours at the outer planets Jupiter, Saturn, Uranus, or Neptune
- Sample return trajectories, such as for an Io plume sample return

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 successes including Near Earth Asteroid Rendezvous (NEAR), Stardust, Deep Impact, Hayabusa 1 and 2, Dawn, and OSIRIS-REx. Much work has been done to understand the dynamics around small bodies; however, the techniques and analyses for designing small-body missions have not yet reached full maturity. 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 designs with low-thrust propulsion systems. This is critical since the trajectories around small bodies cannot be properly modeled with simple conic analysis.

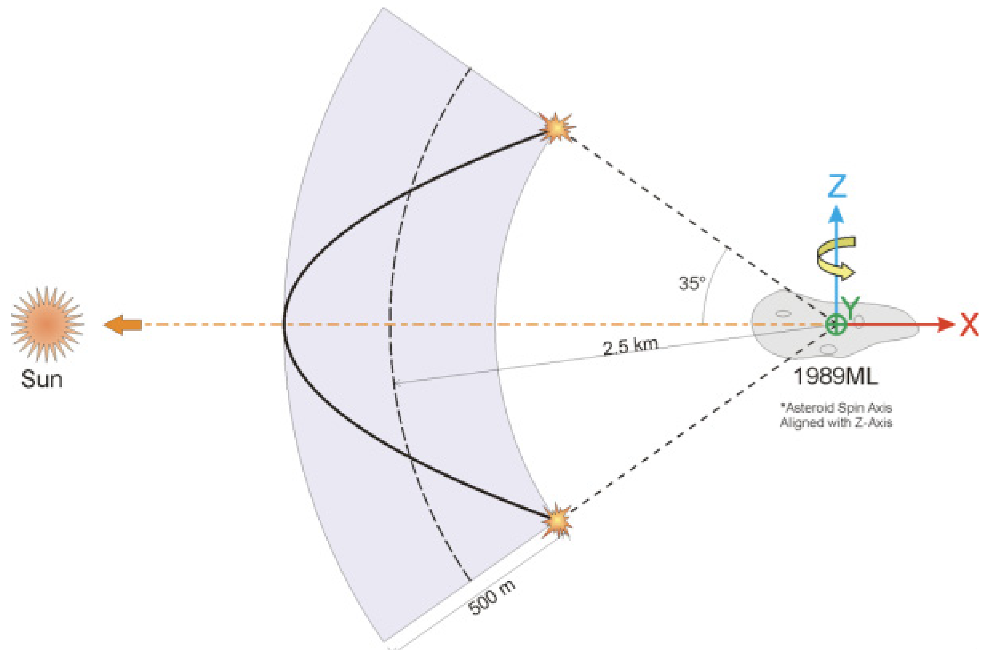

Figure 2.3-1. Close-proximity trajectory design for small-body missions.

- 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. In addition, solar radiation pressure, gravity, and low thrust may produce approximately the same level of acceleration.
- 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 (and there may be periods of Earth occultation precluding traditional navigation updates).
- 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 or involving multiple coordinated spacecraft around a small body.

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), Hiten, Geotail, Wind, Solar & Heliospheric Observatory (SOHO), Advanced Composition Explorer (ACE), Genesis, and the James Webb Space Telescope (JWST). 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 was also used with great success in the design of the Gravity Recovery and Interior Laboratory (GRAIL) and THEMIS/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

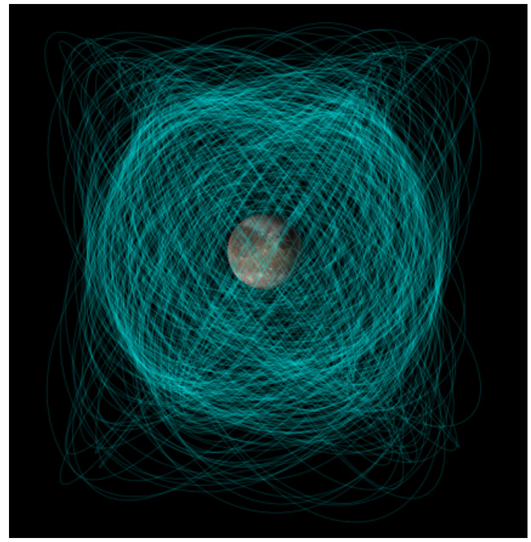

Figure 2.4-1. Innovative trajectory design enables efficient low-energy transfers, captures, and orbits.

- Ability to rapidly design and optimize trajectories that take advantage of multibody dynamics (also potentially useful in spacecraft autonomous navigation and 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 and Earth 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 successes of the Gravity Recovery and Climate Experiment (GRACE), GRAIL (see Figure 2.5-1), GRACE Follow-On, THEMIS/ARTEMIS, and MMS 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.

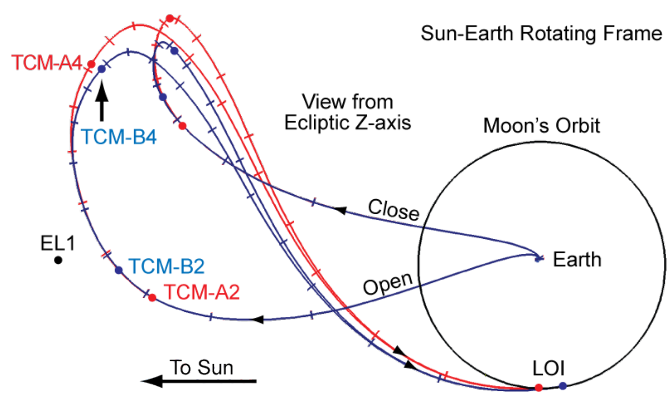

Figure 2.5-1. Trajectory design for the GRAIL mission, with multiple spacecraft elements.

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 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), Hayabusa, and Hayabusa2, and used on the science mission Dawn. Solar sailing, though less flexible due to thrust direction constraints, has been demonstrated on the Japanese mission Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS), with further use planned for the upcoming NASA NEA Scout mission. 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 (and navigate) missions using low-thrust propulsion.

Significant progress has been made in developing low-thrust trajectory design capabilities, particularly for the Dawn and Psyche missions; 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, including chemical/electric hybrids
- 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 (and further study of the benefits and complexity of solar sail trajectories more generally)

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

2.7 Machine Learning, GPUs, and Robust Trajectory Optimization

Machine learning methods may be used to enable and speed up the search for optimal trajectories, especially in multi-body and highly nonlinear systems. The large range of trajectory options required for the study of new, increasingly challenging missions often makes it difficult to rely on a trajectory designer's intuition or previously developed solutions for particular mission scenarios. Machine learning methods rely on GPUs (Graphics Processing Units) directly for their computations, and they are able to sift through large ranges of scenarios to find solutions that might otherwise be missed. These approaches rely on the computation of large datasets of trajectories, which are also made possible through the use of GPUs. The incorporation of mission design parameters that might not necessarily be directly related to the dynamics may also be achieved through the use of various related algorithms such as clustering. This type of approach has been successfully implemented for some initial studies including trajectory design around small bodies. More recently, significant progress has been made in the computation of optimal low-thrust trajectories transferring between Lagrange point orbits with no required initial guesses from trajectory designers. This marks a significant step forward, and lays the foundation for the further development of these techniques in even more challenging environments.[34]

The use of GPUs alone enables significant improvements in the ability to perform large trade space studies of different trajectory design scenarios. The use of GPUs for these types of applications has already been shown to enable trajectory design for applications such as moon approaches and trajectory design around small bodies. In general, these studies have shown improvements in the analysis and design time of several orders of magnitude for icy moons applications.

In summary, the application of GPUs and machine learning techniques to planetary mission design offers the potential for:

- Parallel processing on a cluster (or a cloud)
- High-fidelity, multiple-encounter broad search capabilities
- Rapid trajectory design in challenging dynamic environments—massive speed-up in trajectory generation
- Rapid and robust trajectory optimization
- Efficient computation of optimal low-thrust, gravity-perturbed orbit transfers
- Minimization of the need for initial heuristic guesses of trajectories

2.8 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 2.8-1 and 2.8-2 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.,[35] and strongly endorses astrodynamics as a NASA research and technology area.

Table 2.8-1. 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

Mission Design Capabilities	Current Status	Desired Status	Benefits to Missions
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 2.8-2. 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, Mars and Mercury 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, estimation algorithms, 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 were examined in Reference 23 and will be similarly covered in a revision thereof.

3.1 Improvements in Dynamical and Measurement Modeling

3.1.1 Precise One-Way Radiometric Tracking

NASA's Deep Space Atomic Clock (DSAC) Technology Demonstration Mission (TDM) was a low-Earth orbiting payload (see Figure 3.1-1) that launched on June 19, 2019 and began mission operations on August 18, 2019. The DSAC TDM's primary objective was to characterize the space-based performance of an advanced prototype mercury ion ($^{199}Hg^{+}$) atomic clock and to validate its utility for future deep space navigation and radio science. The more-than-two-year mission completed operations on September 18, 2021.

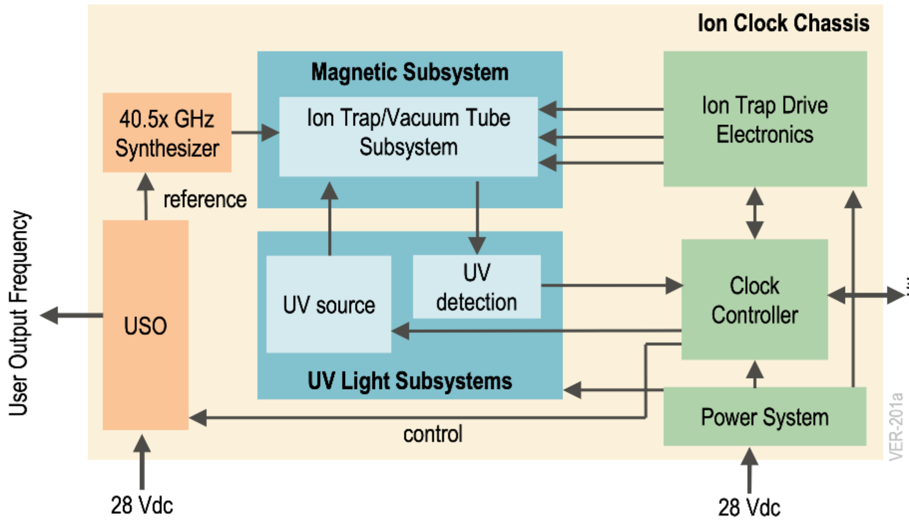

Figure 3.1-1. DSAC-2 block diagram with key clock subsystems and DSAC-2's inherently simple external interfaces.

Current deep space navigation depends primarily on ground-based atomic clocks for the formation of accurate two-way coherent radiometric measurements. Until the advent of DSAC, space-based clocks have lacked the stability necessary for most deep space navigation needs based solely on one-way radiometric signals. Navigating with typical space clocks (such as an Ultra Stable Oscillator or USO) using one-way tracking data has had limited use because of the correlation between long-term frequency drift and orbital parameters. That is, solving for large clock bias and drift terms following long periods with no tracking significantly degrades the orbit solution quality. DSAC (and subsequent clocks with improved performance and reduced size, weight, and power attributes) have the potential to bridge the gap between ground and space clocks, beginning with the recent mission's validation of its on-orbit performance and demonstrating that its long-term stability is in family with that of the Deep Space Network (DSN). The Allan deviation (AD) of DSAC was required to be less than 2×10^{-14} at one day. As recently reported by Burt, et al.,[36] DSAC successfully showed the technology's viability for sustained, reliable operations and for providing the most stable frequency ever demonstrated in space ($\sim3\times10^{-15}$ at one day and a drift of $<3\times10^{-16}$/day). Such low spacecraft clock errors are enabling for one-way radiometric tracking data with precision equivalent to and, in some cases better than, current two-way tracking data. (It should be noted that further advances in short-term relative clock stability and time transfer/synchronization may be needed in multi-spacecraft missions.)

Hosting DSAC aboard a spacecraft coupled with its frequency stability across integration times relevant to navigation and radio science enables precision one-way radiometric tracking that opens up an array of benefits. Notable examples include:

1. Flexible navigation operations with potential to support any user in a single DSN antenna beam with DSAC and a properly configured radio that can make radiometric

measurements, which will be fundamental to future satellite positioning systems beyond Earth. See Ely, et al.,[37,38] for examples and details.

2. Autonomous radio navigation needed for extended "lights out" operations. Autonomous navigation is critical to future human exploration of the solar system and could reduce risks to extended aerobraking operations, enable future satellite tours of the outer solar system, and/or improve the accuracy of planetary flyby/entry navigation. See Ely, et al.,[39] for a detailed case study of how this could work for navigating to Mars.
3. Radio science with 10–100 times more accurate data that could be used for gravity recovery, radio occultations of planetary atmospheres, tests of relativity,[40] and the potential for even more exotic tests such as very-low-frequency gravity wave detection.[41]

DSAC's success has warranted development of a next generation DSAC, called DSAC-2, that is planned to be hosted on NASA's VERITAS mission to Venus as a Technology Demonstration Opportunity (TDO) and supported by NASA's Space Technology Mission and Science Mission Directorates. (The availability of funds for this TDO has recently come into question due to broader budgetary issues.) The DSAC-2 design is intended to use less power, be smaller, and be longer-lived than DSAC-1, while maintaining excellent performance. DSAC-1 lessons learned will be applied to the design and development of DSAC-2 to facilitate achieving DSAC-2's desired design improvements and making it ready for future NASA, DoD, and commercial applications.

While DSAC-1 was a foundational advance that met its program requirements and proved the technology's space operability, it could not demonstrate DSAC's beneficial impact to deep space navigation and radio science. Nor was DSAC-1 designed for the long-lived operation needed for a typical NASA mission. The DSAC-2 TDO intends to rectify this. With DSAC-2 operating as an external reference to the VERITAS transponder, the IDST, it would become possible to collect X-band, Ka-band, and combined X/Ka one-way Doppler to characterize data quality and show equivalent (sometimes superior) accuracy to its ground-based, two-way Doppler counterparts. Via collection of this high-precision one-way radiometric tracking, key demonstration objectives of the DSAC-2 TDO include:

1. Perform one-way Doppler-based navigation and compare it to traditional two-way Doppler navigation in various flight phases including cruise, aerobraking, and orbiting.
2. Demonstrate the *potential* of onboard orbit determination to significantly ease the burden and risk of complex, time-critical operations such as aerobraking. In a ground-based experiment, the TDO will generate orbit solutions using the one-way data collected during orbit and, potentially, aerobraking to assess their viability for onboard navigation, thus providing critical information for use of DSAC-2 derived radio data as part of a future autonomous orbit navigation solution.
3. Perform tests to validate DSAC-2 derived radio data is suitable for radio science. Some examples include performing tests of general relativity to new levels of precision, radio occultations of the Venus atmosphere that would complement existing VERITAS experiments, supporting gravity science at Venus when two-way tracking is not available, and solar plasma characterization to improve modeling for navigation.

An important aspect of the DSAC-2 project is to advance the trapped ion clock technology beyond DSAC-1 to include: 1) superior stability, 2) increased lifetime, 3) reduced size, weight, and power (SWaP), and 4) improved fabrication yield percentage and robustness. A functional block diagram of the DSAC-2 clock with external interfaces is shown in Figure 3.1-1. . The DSAC-

2 design concept reduces the DSAC-1 design from multiple boxes to a single box into a footprint that is compatible with GPS atomic frequency standards. DSAC-2 will have a stability of $2\text{x}10^{-13}/\sqrt{\tau}$ in the short term and 1×10^{-15} at one day—similar to DSAC-1 stability achieved on the ground. The DSAC-1 instrument lifetime is limited by its DUV light source at 3–5 years. While DSAC-2 would only have a 2-year lifetime requirement, it is very desirable to improve this aspect of the technology for future applications. DSAC-2 would meet this goal by using an enhanced light source fabricated with different materials and a calibrated process that is likely to have a life span well beyond two years. To address the DSAC-2 SWaP requirements of < 13 L, < 13 kg, and < 42 W (current best estimates are 10 L, 10 kg, and 33 W), DSAC-2 would simplify the ion trap and frequency chain architectures used in DSAC-1, thereby reducing components and size as well as power, with current design estimates falling well below these requirements. Figure 3.1-2 shows a scale comparison of DSAC-1 and DSAC-2. In addition to design simplification, use of COTS parts and removal of high tolerances where possible will increase instrument manufacturability and reliability.

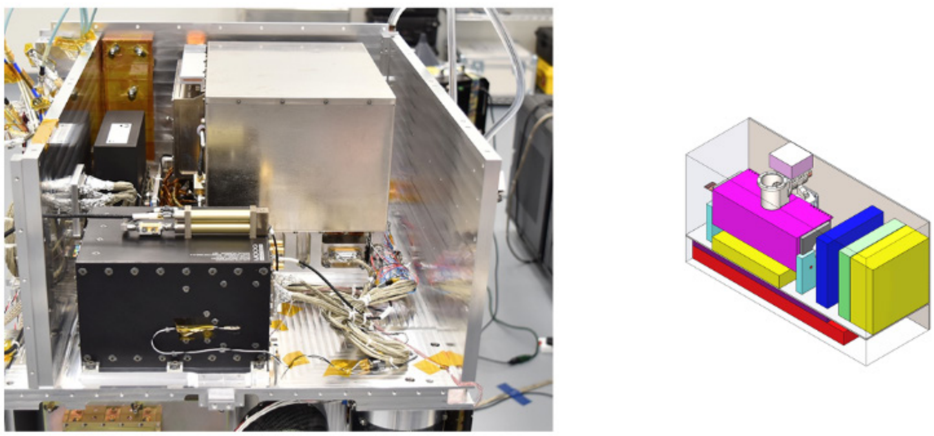

Figure 3.1-2. On the left is a photo of the DSAC-1 instrument (silver box) during space craft integration (a GPS receiver, shown in the foreground, will not be part of DSAC-2). On the right is shown to scale the DSAC-2 system concept.

DSAC-2 has the potential to be a true, multi-mission atomic clock with a design that is ready to support an array of NASA applications (and DoD and commercial telecom applications as well) with smaller SWaP and longer life than DSAC-1.

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 radiometric link) can be highly useful when applied to an analogous mission at a different body (e.g., the GRAIL mission in orbit about the moon).

Other areas meriting attention include sensor fusion; estimation algorithms; improved solar radiation pressure modeling; improved size, weight, power, and sensitivity of sensors such as accelerometers, gravimeters, and optical sensors such as navigation cameras and star trackers. These are areas where navigation improvements are needed for either observability, processing efficiency, processing effectivity, or full-state knowledge accuracy.

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, NFT, and SMARTNAV systems (with simpler code than the ground system) are initialized with the best available information from the ground and then allowed to operate on their own for some length of time to achieve the desired flyby, impact, or soft-landing conditions.

Several enhancements to the current onboard navigation systems would greatly increase their capabilities and usefulness to a wide variety of missions:

- Addition of data types (landmark tracking, lidar/radar altimetry, radiometric tracking [such as the DSAC], spacecraft-to-spacecraft radiometric tracking and time transfer/synchronization), and high-precision astrometry; in the case of radiometrics, the signal has to be structured properly for improved accuracy (a fixed frequency or a message with the ramp and time for Doppler plus pseudo-range from frames or the modulated main carrier or subcarrier)—such techniques are critical to future autonomous navigation to take advantage of uplink command time and reduce the reliance on Earth-based processing
- Advanced processing to handle onboard image processing and rapid updates
- Improvements to the onboard filtering capability (stochastic parameter estimation, filter smoothing, etc.)
- Addition of trajectory optimization, allowing greater coordination between mission design and guidance, navigation, and control functions
- 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 aboard 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, as has been demonstrated in the MAVEN mission with orbit determination improvements made by using onboard accelerometer and periapsis timing estimation data.

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 (as in 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 typically, which limits targeted flyby frequency
- Sufficient time between flybys to limit the ability to take advantage of complex satellite dynamics to minimize the 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, the identification of orbit insertion errors as they happen, as well as a post-flyby clean-up maneuver (possibly updated onboard in closed-loop fashion for a near-real-time correction)
- 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

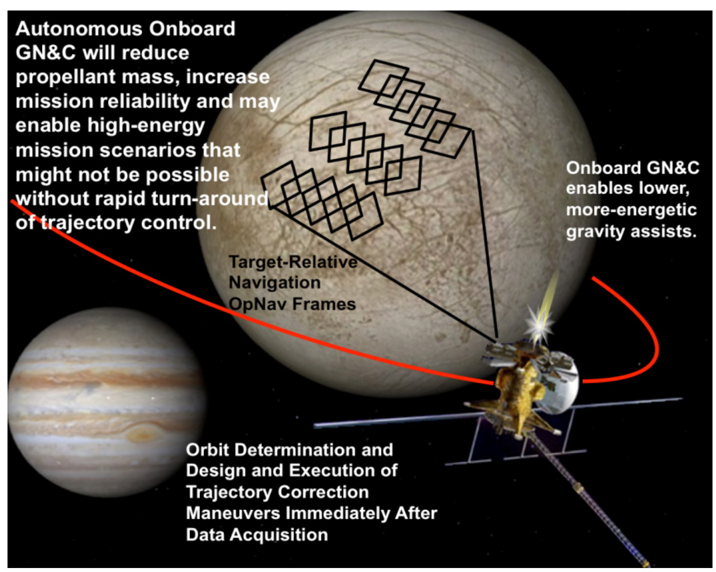

Figure 3.2-1. Autonomous onboard navigation for a Europa orbiter.

- Less propellant mass required to achieve orbit around or landing on an outer planet satellite, such as Europa, Titan, or Enceladus, with orbit insertion possibly occurring during Earth occultation

Achieving these performance improvements requires advancing current systems 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 radiometric data; and to extend the AutoNav executive functions to include comprehensive advanced fault tolerance. Improved accelerometer sensitivities and bias estimation/calibration, dynamic filter updates, and use of sensor fusion techniques would also be helpful.

The potential 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
- Inclusion of navigation metrics/outputs into the trajectory design process to understand whether particular trajectories that may be computed are practical for flying with navigation constraints, accounting for occultations, eclipses, feed-forward accuracy of optimized trajectories, etc.

3.2.3 Approach Navigation for Aerocapture at Outer Planets

The use of aerocapture to allow high-speed orbit insertion at Uranus or Neptune has the potential to substantially reduce the transit time from the Earth to either of these bodies. However, the anticipated approach navigation, atmospheric, and vehicle aerodynamic uncertainties have led to the conclusion that a mid-lift-to-drag ratio of 0.6–0.8 would be needed. A ratio in this range would be problematical since experience to date in planetary entry missions has made use of low-lift-to-drag ratios below 0.4, with their reduced control authority. Achieving a higher ratio would require the development and testing of a new entry vehicle design, with the associated significant time and investment, as well as dealing with the vehicle packaging issues associated with higher ratios.[42]

A recent study in the specific context of Neptune aerocapture has shown, however, that improved approach navigation and a new atmospheric guidance algorithm with onboard density estimation could allow the various uncertainties to be accommodated using a more familiar blunt-body aeroshell with a lift-to-drag ratio of 0.3–0.4.[42]

3.2.4 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 will 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 will 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.[43] Forms of autonomous navigation have recently been used to achieve such accuracies in the Hayabusa2 and OSIRIS-REx missions.

Simulations for precision landings on the moon also show that landings to within 20 m are possible, with landing at the lunar south pole from a near-rectilinear halo orbit being an example of interest. Optical navigation would be useful or essential for both lunar landers and low lunar orbiters, as would be true for lidars in unlit conditions.

3.3 Beyond the Current Deep Space Network

3.3.1 Evolutionary Improvements in DSN Radiometric 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 radiometric 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 radiometric data accuracies.

Radio science experiments have shown that Doppler data accuracy using Ka-band can result in improvements by at least an order of magnitude. The Cassini gravity wave experiment made use of a more elaborate radio system than is typically used,[44] 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, assuming that occasional losses of Ka-band data due to weather conditions can be satisfactorily addressed. Beyond the specialized usage of Ka-band radiometric data in the Cassini mission, Ka-band data have been used operationally in the Parker Solar Probe mission during science data downlink periods when the Earth is in view of the spacecraft's high-gain antenna.

There are several limiting error sources in radiometric measurements made for the purpose of navigation. Thermal noise is rarely a limiting factor, since longer integration times and wider bandwidths 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 provides this full improvement for Delta-DOR data. Tropospheric scintillations can be reduced by a factor of 2 to 10 through the use of accurate 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. (Such links could be useful for uplink one-way radiometrics based on frame ranging and Doppler.)

Systematic errors in tropospheric and ionospheric calibrations can limit accuracy for Delta-DOR data and for Doppler data at longer time scales. 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 Delta-DOR and for Doppler data at longer time scales. One 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 aboard, 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, lower thermal noise errors due to increased bandwidth, and phase dispersion corrections, 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 communication capabilities offer potentially improved data transmission for a given amount of spacecraft power. A laser communication package also offers some potential improvements for navigation, as well as some challenges, particularly if the laser communication package provides the sole downlink to Earth.

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

The narrow pulse widths are similar to those used for satellite laser ranging (SLR) in near-Earth applications. SLR achieves range measurement accuracy of about 1 cm by transmitting pulsed laser signals to spacecraft with corner-cube reflectors (e.g., Laser Geodetic Satellite [LAGEOS]) and measuring the time between transmission and reception of the reflected pulse. The SLR range measurement accuracy is limited by variation in the atmospheric refraction effects between transmission and reception. Laser ranging to a corner reflector on a planetary spacecraft is impractical since the signal losses scale as the inverse fourth power of the distance. With a laser communication package capable of measurement of the time between an uplink pulse and a downlink pulse, range measurements to planetary spacecraft with accuracy comparable to SLR measurement accuracy should be possible. Demonstrations of two-way laser ranging to planetary spacecraft have been done with altimeters on MESSENGER and Lunar Reconnaissance Orbiter, with resulting accuracies of a few meters limited by the altimeter timing measurement capabilities.[45,46] 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.[47] 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.[48,49] 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.[50]

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.[47]

Another approach is to image the spacecraft relative to a star. Currently, the ESA Gaia mission produces star positions with accuracies on the order of 0.0002 arcsecond, comparable to or 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.[51] 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

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.[52,53,54]

Onboard radio pulsar measurements are problematic, due to the large antenna size needed and the dispersion processing required to correct for interstellar medium (ISM) effects. However, the pulsar timing ephemeris is independent of frequency; and X-rays are not impacted by the ISM. In addition, the estimated X-ray detector size requirements (while still large) are smaller by approximately an order of magnitude.

The SEXTANT experiment on the International Space Station demonstrated the viability of the basic techniques for pulsar-based navigation. However, a number of challenges need to be addressed before this approach could become feasible in deep-space applications:

- Mass and volume issues: Large (~1 m by 1 m) silicon detector areas are needed for X-ray photon detection and arrival timing, which makes such detectors difficult to accommodate on a planetary spacecraft.
- Lack of multiple uses (e.g., scientific in addition to engineering, as for an imaging system) for an X-ray detector flying 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, information about which will need to be updated in flight.

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, which arrived at Pluto in 2015, contended with a Pluto ephemeris error that was about 1500 km after a detailed ground-observing campaign. The impressive absolute X-ray pulsar tracking accuracy could have done little to improve the situation because of the large planetary ephemeris error. Thus, a target-relative tracking method such as optical navigation was needed to 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 (though observations of high-parallax stars with a camera might serve the same purpose).

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

References 1 and 2 list a number of technical challenges and associated technologies pertinent to this document. In the first of these, 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 of Reference 22 provides more detailed information about the pertinent top technical challenges and associated technologies described in Ref. 1.

Appendix B of Reference 22 contains several pages of material excerpted from a white paper on astrodynamics written by Strange, et al.,[35] which strongly endorses astrodynamics as a NASA research and technology area.

4 Key Findings and Recommendations

Finding 1

The ingenuity and creativity of scientists and engineers ensure 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 could 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. On the other hand, recent innovations in artificial intelligence, reinforcement learning, four-body dynamics and Hamiltonian techniques, combinatorics, and mathematical applications in general, all advanced in the last 10–20 years, are having some positive impact. Some development of new mission design capabilities occurs naturally as a result of flight project activities and pre-project studies, generally specific to a particular mission. More research is needed, particularly investments for general capabilities that are tailorable to specific missions, rather than the other way around.

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 when moved aboard 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. Flight-path predictions for onboard use can be efficiently provided in a timely manner and reduce latency of commanding, enabling adaptivity and responsiveness in highly variable environments. The onboard navigation software can be a compact, tailored version of the ground software, with unneeded capabilities deleted. Both continued onboard GN&C system-level work, as described in Ref. 23, 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. Fault detection and recovery capabilities are required to permit the autonomy. Both absolute and relative estimation will be needed for multi-spacecraft distributed systems.

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 mission design, navigation, and closed-loop control software applications on a variety of spacecraft built by various companies and laboratories.

Finding 3

The Deep Space Network 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. To broaden autonomous navigation to include radiometric information, signal conditions and an uplink “message” that enable onboard pseudo-range and Doppler observations, and potentially high-accuracy time transfer, need to be defined.

Recommendation: NASA should explore opportunities for improving radiometric tracking data by enhancing the capabilities of the DSN for radio tracking. This can be accomplished without changing the basic operating mode of the DSN

Finding 4

Clocks are fundamental to space navigation. Highly accurate and stable onboard clocks, such as DSAC, are enabling for autonomous radio navigation, will generate new possibilities for radio science, and will allow use of the DSN in new and more efficient ways. This would include relying much more on one-way communication links, as allowed by improved clock performance over both long and short time scales, coupled with reductions in clock size, weight, and power attributes to permit their inclusion on planetary spacecraft. Investments in advancing clock and time dissemination/synchronization technologies is key to not only navigation, but also to in-situ science observations and coordination of distributed missions.

Recommendation: Clock 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. With the first Deep Space Atomic Clock Technology Demonstration Mission now completed, an STMD-funded DSAC-2 TDO, considered for flight on the VERITAS mission, would ideally be moving forward with strong support from the SMD. Unfortunately, the TDO has recently been cancelled due to near-term STMD funding issues. SMD should strongly endorse a DSAC-2 TDO as future opportunities may arise and should look for ways to include and utilize advanced onboard clocks in its planning for future missions.

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 (potentially enabling substantially improved data and time-transfer accuracy) 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. The SCaN Optical Capability roadmap identifies optimetrics in every future development.

Recommendation: Further studies and flight demonstrations (beyond the Laser Communications Relay Demonstration and the Deep Space Optical Communications experiment scheduled to fly on the Psyche mission) should be conducted to fully investigate how optical communication links can be used to provide metric tracking data for use in spacecraft navigation. Key considerations include ensuring that optical receivers have clock recovery capability and adequate resolution in the mixers. Implementation options should be codified, identifying the typical sticking points, to make this a pervasive capability in all optical communication implementations be they ground-based or space-based. PSD should push SCaN toward incorporating this capability and should incentivize missions to demonstrate at different data rates and ranges and to use such optical links operationally.

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. Adaptive estimation techniques should be developed and incorporated to support in-situ navigation and science observations. The latter observations, in turn, can be used as data sets for the refinement of natural body ephemerides.

Discussion

The findings and recommendations presented here are qualitatively similar to, but more detailed than, their earlier counterparts included in Reference 22. In a number of areas, modest progress has been made over the intervening years as modest funding has become available. In other areas, progress has been more substantial, due to the successful Deep Space Atomic Clock Technology Demonstration Mission (recommendation 4) and touch-and-go asteroid samplings in the OSIRIS-REx and Hayabusa2 missions (recommendations 2 and 6). However, further work remains to be done in all areas.

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
DART	Demonstration of Autonomous Rendezvous Technology
Delta-DOR	delta-differential one-way range
DSAC	Deep Space Atomic Clock
DSN	Deep Space Network
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
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
JWST	James Webb Space Telescope
L1, L2	colinear libration points
LAGEOS	Laser Geodetic Satellite
MESSENGER	Mercury Surface, Space Environment, Geochemistry and Ranging
MMS	Magnetospheric Multiscale mission
MRO	Mars Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration
NEAR	Near Earth Asteroid Rendezvous
NExT	New Exploration of Tempel 1
NFT	Natural Feature Tracking
OSIRIS-REx	Origins Spectral Interpretation Resource Identification Security-Regolith Explorer
PSD	Planetary Science Division
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
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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