AAS 08-057

THE NEXT 25 YEARS OF DEEP SPACE NAVIGATION

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This paper reviews the most probable set of NASA deep space missions that will be launched in the next twenty-five years, discusses the navigational challenges that will confront them, and outlines the most probable solutions to these challenges.

INTRODUCTION

A significant number of future NASA deep-space missions may require navigation capabilities and performance beyond that needed by past and current missions. Over the last fifty years NASA has sent probes to fly-by, orbit, and land on a number of solar system bodies, performing those missions that could be accomplished with the navigational means of the time. As navigational means have improved, the types of missions that could be executed have expanded, allowing for increased science and exploration returns. The same can be expected for the next twenty five years, with enhanced navigation capabilities enabling new types of missions that could not be executed otherwise.

FUTURE MISSION SET AND CHALLENGES

The set of future NASA deep-space missions changes sporadically, as mission roadmaps are updated and missions are added to or removed from the forecast. The set of missions in a five-year horizon is usually well known and fairly stable, but trying to forecast up to twenty-five years from now requires some educated guesswork. In a previous paper[1] we described the process used to update the forecast, and analyzed the set of missions planned at that time. Since then the forecast has not changed significantly and a very similar set can be used at the current time. Table 1 lists some of the most challenging current and future deep-space missions that NASA will or may carry out in the next twenty five years.

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Table 1
CURRENT AND FUTURE MISSION CHALLENGES

Mission	Characteristics and Challenges
Dawn (minor planet orbiter)	*Low-thrust, precise landmark tracking optical navigation*
Mars Science Laboratory (rover)	*Requirements to be able to (a) land at higher elevations, (b) perform Entry, Descent and Landing (EDL) with more a more massive landing vehicle, (c) perform closed-loop hazard avoidance prior to landing (on future variants of the 2009 MSL mission)*
Juno (Jupiter polar orbiter)	*Ka-band tracking*
Mars Scout – landers/rovers	*Increased reliance on in-situ navigation means, pinpoint landing, hazard avoidance*
Mars com/nav relay orbiter	*UHF, X-, Ka-band and/or optical links*
Mars Sample Return	*Pinpoint landing, Mars ascent, Mars-orbit detection and rendezvous*
Mars Scout – aero-rovers	*Atmospheric navigation at Mars*
Comet sampling mission	*Close-proximity operations in an unpredictable environment, flight path/attitude control interaction, pinpoint landing*
Outer-planet moon orbiter	*Three-body navigation, radiation environment, long round-trip light times, possible use of aerocapture*
Multiple-spacecraft telescopes	*Precision formation flying*
Venus in-situ explorers	*EDL and/or atmospheric navigation at Venus*
Mars human precursor missions	*Demonstration of highly reliable capabilities with human-in-the-loop capabilities*
Outer-planet moon lander	*Three-body navigation and EDL, radiation environment*

The main trends and challenges that can be derived from these missions are:

1. Increased need for autonomous navigation. Many missions will require fast-update closed-loop control that cannot be accomplished if the ground has to be in the loop.
2. Increased use of in-situ and optical navigation that take advantage of in-situ assets and enables autonomous navigation and close-proximity operations.
3. Increased use of low-thrust propulsion and low-energy transfers using three- or four-body dynamics, in order to deliver more instrument payload to the target.
4. Increased need for higher accuracy in guidance, navigation, and control, in order to perform pinpoint landing, and to take advantage of higher-resolution instruments.
5. Increased need for integration between flight path and attitude control, for aero-assist operations, low-thrust navigation, small-body proximity operations, and formation flying.

In addition there will always be the desire to decrease the cost and risk of high-performance navigation, by producing low-mass, low-cost, highly reliable navigation components. The availability of these components will enable missions that would not be possible or affordable otherwise.

ENABLING STRATEGIES

Many of the navigation capabilities required by future missions are currently available, but some future missions have requirements that cannot be fulfilled without improving existing capabilities or developing new technologies. NASA will pursue the following strategies in order to improve deep-space navigation capabilities.

Advance Radio-Metric Tracking Capabilities

NASA will leverage the improvements in communication capabilities in order to benefit its navigation users, including the migration to the Ka frequency band, and the cooperation with other deep-space antenna operators.

Ka-band tracking has the advantage that it is less sensitive to charged-particle effects and has a smaller measurement noise. Moreover, radio-frequency sources are more compact in Ka-band, and the 500 MHz of spectrum allocated to deep space Ka-band is ten times the 50 MHz allocated to X-band. However, in order to be able to use Ka-band tracking at its full potential it will be necessary to improve the accuracy and timeliness of neutral media and Earth orientation calibrations, and to obtain a more precise quasar catalogue for Ka-band sources. Missions such as Cassini and Juno used or will use Ka-band mostly for scientific applications, but as additional ground antennas are updated for Ka-band downlink and uplink, it should be possible to use it also for operational navigation.

In the future deep-space communications networks may have apertures much greater than those of the 70m antennas operated by the DSN. This most probably be accomplished not by building larger antennas, but by arraying a large number of smaller antennas. The increased sensitivity would allow us to use weaker, and consequently more and closer radio sources, thereby reducing the spatial interpolation errors due to the separation between the natural source and the spacecraft. If the antennas are small, the beamwitdth would be wider, and it may be possible to use the Same-Beam Interferometry technique to also eliminate temporal interpolation errors.

Interoperability through the sharing of antenna assets with other science and space agencies, will increase the availability of spacecraft tracking, especially for spacecraft Very Large Baseline Interferometry (VLBI). Using NASA's Deep Space Network (DSN) it is only possible to perform VLBI tracking of a given spacecraft twice a day in two somewhat narrow temporal windows when two DSN ground complexes have common visibility of the spacecraft. By using additional non-DSN antenna sites we can obtain improved observation geometry, extended common visibility by using distant antennas with the same approximate longitude, and in general have many additional VLBI tracking opportunities. The NRAO Very Long Baseline Array[2] has performed a number of spacecraft tracking experiments[3] using imaging techniques, showing that it can track at accuracy comparable to that of the Delta-DOR technique used by the DSN. ESA has used its 35m meter deep-space antennas at New Norcia and Cebreros to perform Delta-DOR tracking of ESA and NASA spacecraft, and experiments will also be performed using one ESA and one NASA ground antenna. An important contributor to increased interoperability will be the development and implementation of standardized tracking services and exchange formats, as is currently being done by the CCSDS[3] for navigation messages and Delta-DOR cross-support.

In the future the DSN, and possibly other networks, will be able to perform pseudo-noise ranging in order to make ranging simpler and more reliable[5]. Pseudo-noise ranging does not require precise coordination of uplink and downlink ranging operations, and allows for the adjustment of the integration time at the downlink side to compensate for the actual signal strength, thereby reliably providing the required range accuracy. This is especially useful when performing three-way ranging and for long round-trip light times, and can be combined with regenerative ranging to improve the range signal-to-noise ratio, by making it proportional to the inverse of the square of the distance instead of the inverse of the fourth power. The DSN could also improve the accuracy of range calibrations, by performing automated, multiple-frequency antenna delay calibrations. Increased DSN automation, required to efficiently and affordably operate multiple antennas, would also benefit navigation by allowing navigation users to reliably optimize the tracking parameters in order to accommodate changes in the communication link and the accuracy needs.

Expand the Use of Optical Navigation

Optical navigation (opnav) is the use of an onboard camera to image solar system bodies or other spacecraft against a star background in order to improve the knowledge of the spacecraft's angular position relative to that body. The solar system body can be a planet, planetary satellites, or minor planets such as asteroids or comets. This data type can be used on its own, or as is more common, combined with radiometric data types to compute a more robust navigation solution.

The data type is most useful when the trajectory of the spacecraft relative to the target body is not known to the desired accuracy. Thus, it has been extensively used for missions to the outer planets, either for flybys (Voyager at Jupiter, Saturn, Uranus and Neptune), of for satellite tours (Galileo and Cassini). For Voyager, opnav was used to image the large satellites in order to pinpoint the location of the spacecraft relative to the planet (a technique which can also be applied at Mars, as has been demonstrated by Viking and by the Mars Reconnaissance Orbiter during its approach to Mars). For Galileo and Cassini, opnav used images of the satellites in order to accurately target flybys of those bodies, as well as to help improve the overall ephemeris accuracies of the satellites.

Opnav is critical for missions to small bodies because their ground based ephemerides are only accurate to the tens to hundreds of km for asteroids, and up to thousands of km for comets. The Galileo encounters of Gaspra and Ida, NEAR, Deep Space 1 (DS1), Stardust, and Deep Impact (DI) missions all would not have been possible without it. In addition to the flybys of these bodies, opnav is necessary for characterizing the shape, orientation, and spin rate of these bodies, which is critical for close approaches or landings. Optical images are also used for planetary Entry Descent, and Landing (EDL), such as the DIMES system used on the Mars Exploration Rovers for reducing the lateral velocity before impact. Future requirements to perform pinpoint landings on any of these targets drive the continuing need for cameras.

Historically, opnav has been performed using cameras whose primary purpose is as a science instrument. The trend however, is to develop a dedicated opnav camera which is affordable both in terms of cost, mass, and power. Such a camera has been flown as a demo on MRO. This camera has a focal length of 500 mm, an aperture of 60 mm, uses 3-5 W of power, but weighs only 2.8 kg. With improvements in ground processing, the accuracy of this should rival that of Cassini's 25 kg camera. Further improvements in a dedicated camera would be to place it on gimbals, which reduces or eliminates the need to slew the entire spacecraft in order to take images. Improvements in onboard image processing methods to compress large images and extract relevant information without sending back the entire image also can optimize the amount of opnav data sent back, thus contributing to improved navigation results. A small camera will make opnav possible as a main or complementary navigation type for many missions, including small missions that need to navigate autonomously in the proximity of small bodies.

The landmark tracking technique to navigate NEAR around Eros has been improved and automated to reduce the time and effort needed to identify landmarks, define the shape and motion of the target and to navigate the spacecraft relative to the target[6]. The improved method has been demonstrated[7] during the Hayabusa encounter with Itokawa, and will be used by Dawn during its asteroid operations. The method can be used to navigate to or around any type of small body.

As a related but distinct topic, the DSN is also considering the use of optical frequencies for communications with deep space assets, and in that case there could also be the possibility of adding metric capabilities to the communication system in order to measure range very accurately. The big difference with respect to near-Earth laser ranging systems is that, due to the great distance, corner cube reflectors could not return enough signal, so a regenerative optical transponder would need to be used, with the difficulty of reliably calibrating transponder delays in order to be able to obtain high-precision measurements. It will also be possible to track the optical beacon using astrometry techniques, allowing for a straight forward plane-of-sky measurement.

Develop General-Purpose Autonomous Navigation Capabilities

Autonomous Navigation (Autonav) for spacecraft has the primary benefit of enhancing or enabling missions which would otherwise not be possible due to round-trip light time or other limitations. Autonav was first used on the DS1 mission as a technology demonstration. DS1 successfully used optical images of asteroids to perform orbit determination and then guide the spacecraft's trajectory by performing maneuvers, either with long term control of the ion engines or with impulsive delta-Vs using hydrazine thrusters. A subset of this software was then used to control camera pointing during the flyby of the comet Borrelly; this same software was also used for the Stardust flyby of comet Wild 2. A heritage DS1 Autonav system was used by DI impactor to control its trajectory to a high enough accuracy to hit a lit side of Tempel 1, as well as image the resultant crater from the flyby spacecraft. The Autonav system in the impactor not only updated the knowledge of the spacecraft trajectory relative to Tempel-1, but also autonomously identified a well-lit spot on the comet as the target, and computed and commanded trajectory correction maneuvers to impact that new target.

The above missions show examples of the mission-enhancing capabilities of Autonav. For example, in all the comet flybys, most or all of the frames have the target in them as compared to a non-autonomous flyby, such as the Galileo Gaspra or Ida flybys, where dozens of images were taken in order to capture the target in a handful of frames. For the DI impactor, Autonav was enabling in that the comet had to be resolved in order to hit a lit spot on the nucleus; this only occurred several hours before impact which precluded ground control due to the light time delay[8].

Up to now, Autonav use has been limited to small body flyby and impact missions. However, there are many new missions and mission phases of very high exploration and scientific value, such as ascent, pinpoint landing, deep-space or Mars-orbit rendezvous, and deep-space formation flying, that require more reliance on closed-loop integrated six-degrees-of-freedom control of attitude and trajectory, and that cannot be performed with the ground in the loop. Thus, in order to fully realize the benefits of Autonav, the current DS1/DI heritage system is being re-engineered to make it more general and applicable to a wider range of missions. For example, the current system only uses optical data, whereas future missions will need additional data types such as LIDAR, or in situ radiometric data. The integration of new hardware with the software, such as Draper Laboratory's Inertial Stellar Compass[9], which can provide attitude determination as well as translational information if combined with Autonav, is also being pursued. The experimental MRO opnav camera is another piece of hardware which can be folded into an Autonav system; this camera combined with a gimbal would be very attractive for lower-cost Discovery or Mars Scout missions, allowing them to autonomously and safely operate in close proximity to a small body, or to land or navigate at Mars.

Improve Frequency and Timing Systems

Highly-stable on-board frequency standards reduce the need for two-way data types and, because there is no need to close the communication link, free users from round-trip light time constraints. They also allow multiple users to be served by just one asset, decreasing the cost of supporting multiple spacecraft. Currently multiple Mars spacecraft can be tracked simultaneously using just one DSN antenna; but only one of them can be tracked in two-way mode. Only when the spacecraft tracked in one-way mode has an ultra-stable oscillator (USO), such as Mars Global Surveyor (MGS), is the one-way data suitable for trajectory determination. In the future we could have in-situ GPS-like systems at the Moon or Mars, with a few high-orbit spacecraft serving many low-orbit and landed assets, and USOs would be needed at least for the service provider spacecraft, in order for the users to be able to obtain real-time trajectory and timing solutions. Furthermore, the user spacecraft should also have USOs in order to reduce the number of required service-provider spacecraft and to enable the use of sparse data with dynamics-based orbit determination approaches.

In addition, many parts of the Frequency and Timing Subsystem (FTS) of the DSN are obsolescent. The systematic upgrading of the FTS on an element-by-element basis, which has been underway for several years, should be continued.

Develop In-situ Tracking Infrastructure

NASA already has multiple assets at Mars providing – Odyssey, MRO – and using – Mars Exploration Rovers, soon Phoenix – in-situ communications and navigation capabilities. In-situ radio-metric tracking was used by the MER mission in order to improve the position determination of the landed rovers, and to allow for the imaging of the rovers by MGS. MRO is hosting a proximity radio that can be used by other future missions. Phoenix and Mars Science Laboratory are planning to use in-situ radio-metrics for EDL reconstruction and landed position determination. In the future we may have high-orbit dedicated relay spacecraft that provide longer tracking passes for landed or low-orbit assets, and that can track spacecraft arriving at or departing Mars. The NASA Mars Program is developing radios and software that can exploit these in-situ capabilities, and can enable high-precision trajectory and position determination, even for real-time applications, such as during guided EDL for pinpoint landing.

These kinds of capabilities may also be available at other bodies of interest, starting with the Moon in order to allow for global communications and navigation capabilities in support of Lunar exploration; and eventually at other solar system bodies such as Europa or Titan, in order to allow for simpler landed assets, more precise navigation, and increased data rates.

Explore New Means of Deep Space Navigation

A number of new methods for deep space navigation are being currently investigated.

One is the use of X-ray pulsars as GPS-like sources for spacecraft navigation[10]. This method relies on the stability and predictability of certain pulsars to use the time of arrival of pulsed radiation from a number of pulsars to compute the clock offset and position of the spacecraft.

There are some questions that need to be resolved in order for this method to become a reliable and practical navigation alternative. One of them is how well we can predict the pulsar behavior. Glitches may alter the spin rates of the pulsar, and some pulsars have time-varying periods, so we may need a system similar to the GPS ground control that monitors and updates the expected intensity, period, and time of arrival at some reference point of usable sources, and provides these updates to spacecraft using X-ray navigation. Another question that needs to be answered is what antenna size and pointing would be needed to obtain precise tracking measurements. Getting range accuracies at the 10 meter level may require detector areas in the 5 m^2 size and integration times of minutes. If the detector needs to point to multiple sources, we will need either a gimbaled detector or for the spacecraft to slew to point at the sources, with both methods imposing significant constraints to the design and operation of the spacecraft.

Another promising technique is to use highly sensitive accelerometers to sense the non-gravitational forces acting on the spacecraft, so that these dynamical perturbations can be either accurately modeled or compensated for. That will reduce the trajectory prediction and reconstruction error by removing the non-gravitational dynamic model parameters from the navigation solution. One possibility would be to use cold-atom interferometers[11]. The main challenge for this technique would be to develop a compact, reliable space-qualified accelerometer with the sensitivity necessary for the desired application.

CONCLUSION

In the future NASA is going to develop and operate missions that require navigation capabilities that are beyond what is available today. We have identified the main challenges for these future missions, and outlined strategies to enable the successful operation of these missions.

The solutions to these navigation challenges involve new on-board hardware (improved and new sensors), improved coordination and efficiencies in ground tracking assets, and on-board autonomy. The ground-based solutions will have the greatest multi-mission benefit, but the on-board improvements will go furthest in enabling specific challenging new missions. All are needed in order to support NASA's future missions, and they should be implemented in a coordinated manner, but they do not need to be implemented simultaneously.

ACKNOWLEDGMENT

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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