The Deep-space Positioning System Concept: Automating Complex Navigation Operations Beyond the Earth

Joseph R. Guinn*, Joseph E. Riedel*, Shyam Bhaskaran*, Ryan S. Park*, Andrew T. Vaughan*, William M. Owen*, Todd A. Ely*, Matthew Abrahamson*, Tomas J. Martin-Mur*

*Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA

There is no equivalent of GPS in "deep space," that is beyond the Earth Moon system (and use of GPS beyond LEO and MEO is already problematic.) NASA has been awarded a patent on the concept of the "Deep-space Positioning System" (DPS) which is a self-contained instrument concept that would use in-situ observations to provide an automated and autonomous means of determining its position in the Solar System, and at least as important, its position relative to a target, whether that target is a planet, asteroid, moon or comet. In addition, the DPS system computes trajectory change parameters, as necessary to keep a spacecraft on a planned trajectory. Implementation options include the use of a radio receiver to receive a frequency beacon from a non-in-situ source for additional navigation information over and above that which can be provided by the cameras that are the principal data source of DPS. This paper discusses the DPS instrument concept, and its potential use in deep space.

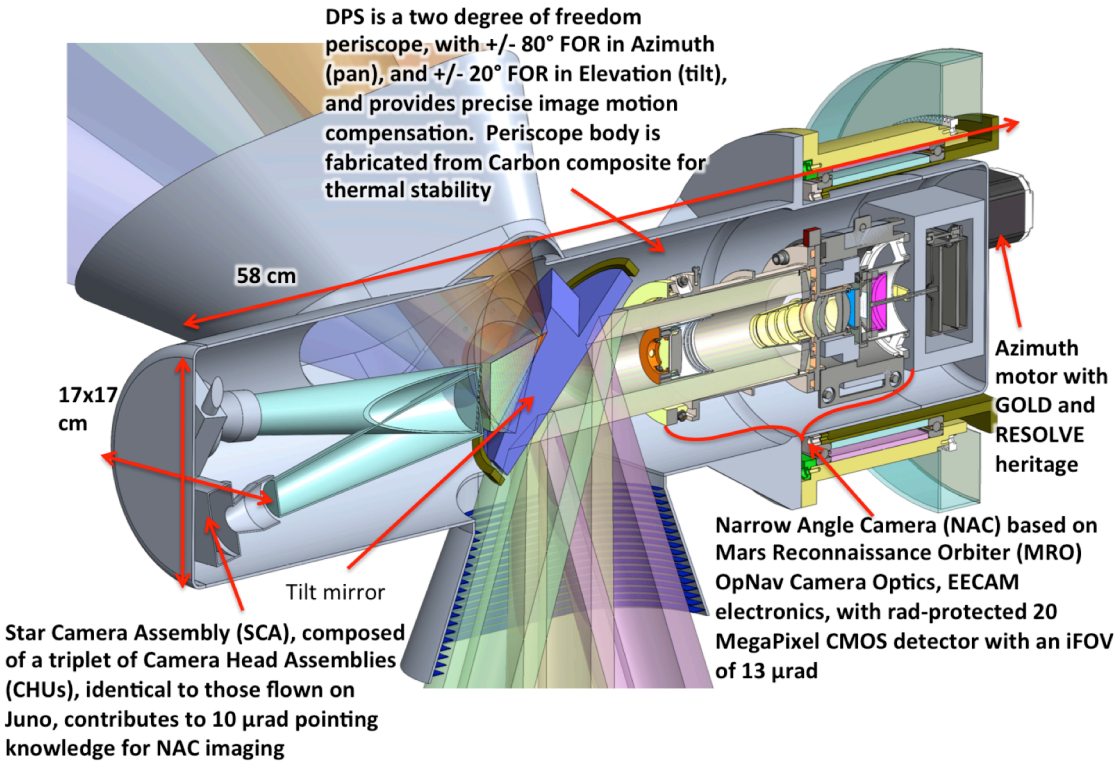


Figure 1: Preliminary Hardware Integration Design for DPS Instrument

I. Introduction

The Deep Space Positioning System (DPS) concept is a self-contained, automated and autonomous deep space navigation hardware and software system that can solve the problem of general navigation in the solar system. It is akin to the way the Global Positioning System (GPS) does around the Earth; but, without the need for the satellite infrastructure. Alternatively, DPS can be a source for Earth-independent navigation observables (processed optical data) for use by extant GN&C systems (such as Orion). The baseline design is small (40 cm by 15 by 15 cm) and light weight, under 15 kg. Most importantly, DPS gives absolute and relative position information, that is, relative to the center of the solar system, and relative to a local target (such as the Moon, Mars or an asteroid).

Navigation is required for every flight into deep space. Beyond Earth, something other than GPS is required. Although fully autonomous navigation systems have been flown utilizing GPS in LEO[1], and these systems satisfy some of the requirements of deep space autonomous navigation systems, they by no means satisfy them all. There has been only a single deep space autonomous navigation system flown, the same one on three different missions, and this system, "AutoNav," used optical data of the approach target[2,3,4,5]. Radiometric data provides excellent geo-centric navigation, but for any target other than Earth, Moon and Mars, *in situ* target-relative navigation will be required for precise targeting (such as landing). Short of planting radio beacons on the targets of interest, optical navigation must be used in such cases. To provide the ability to return a craft safely to Earth without a ground link (e.g., during periods of compromised telecommunications) optical data must be processed onboard autonomously, and trajectory change maneuvers computed onboard as well.

DPS uses self-pointing narrow and wide-angle cameras to take images of near-field objects (distant asteroids, or a planetary target) and background stars to determine the position of the camera (and therefore the host spacecraft). These processed data, reduced to precise inertial angle measurements, can be passed to a resident GN&C system, or processed within DPS itself, to provide prime or back-up position determination. The determination of spacecraft position and velocity is via a least squares estimate using dynamical models of the spacecraft motion through the solar system with all gravitational and non-gravitational perturbations accurately accounted for. With the estimate of the position and velocity in hand, trajectory correction maneuvers can be computed.

Optical Navigation (OpNav) is the only way to provide automated and autonomous navigation for NASA's exploration and science craft because any mission to a body other than the Moon or Mars that demands very precise positioning relative to the surface of that body (e.g. 10's of meters) will require *in situ* target relative navigation, due to uncertainty in the positions of those bodies. And in the case of a spacecraft returning to Earth, though the position of the Earth in heliocentric space is very well determined (to the meter level), without an Earth-radio-link it may be impossible to accurately determine the position of the Earth (e.g., to the level of a few km) due to the uncertainty of the position of the Earth's limb as seen through the atmosphere. For this, alternative means of relative navigation may be necessary, such as sighting of artificial satellites, or even the Moon itself via optical navigation, such as will be provided by DPS.

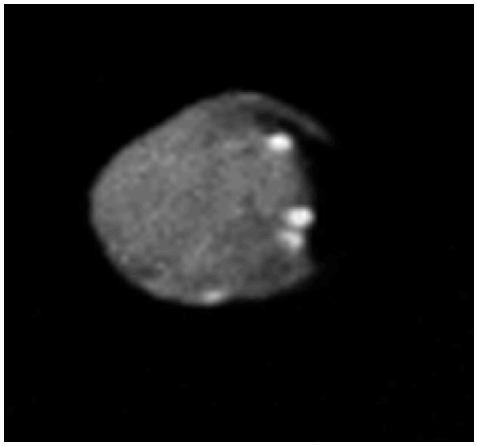


Figure 2: Voyager 1 image taken on 5 March 1979 of Jupiter's largest non-Galilean satellite, Amalthea; without approach optical navigation this image would not have been possible.

Though Optical Navigation (OpNav) is the core capability for *in situ* observations of the target, DPS will also feature an option to provide powerful 1-way Doppler radiometric measurements from a known-source beacon, which could be an Earth station (e.g. DSN), or another spacecraft. Software within the Iris radio[6] extracts these observables and provides them to the AutoNav orbit determination filter. Though not shown in the Fig 1, one concept for integrating the radiometric measurements into the system is to attach a patch antenna, such as the MER rover X-band patch antenna, to the actuation mechanism, to provide two-dimensional orientation of the antenna. For the highest accuracy radiometric data, a very good frequency reference is necessary, which can be provided by the Deep Space Atomic Clock (DSAC) that is being developed by STMD. The DSAC conditions the frequency reference being used to drive the transmitter within the Iris radio. In combination, the 1-way radiometric and optical data of the DPS provide a complete

navigation solution for virtually any deep space navigational challenge.

Exploration craft like Orion, require automated safe return; as did the Constellation program, the Orion project currently has a requirement to provide for automatic safe return of the crew and craft to Earth in an emergency, and especially in the event that the radio-link is compromised to the point of making Earth-based radiometric navigation impossible[7]. In this event, without a backup capability, loss of crew or loss of mission is highly possible if not probable. For this serious contingency, DPS can serve as a remediation, by providing navigation services to the resident GN&C system.

DPS integrates several flight-proven or flight-inheritance technologies: the miniature MRO OpNav telescope[8], the Iris radio (which will fly on the INSPIRE and MARCO cubesat missions) – to provide computational power and one-way radio reception for DPS, motor-actuators and rate control (as will fly on OCO-3 and has flown on GRAIL), the Mars2020 EECam CMOS 20Megapixel camera electronics and detectors, the Deep Impact AutoNav autonomous navigation system (with additional Stardust and Deep Space 1 flight heritage), the MER X-band patch antenna (for the 1-way radio link navigation), and a command and control s/w suite that has been the automated robotic control language used on over a dozen of NASA's missions, including the Spitzer space telescope and Mars Reconnaissance Orbiter.[9,10]

From these flight heritage or inheritance elements DPS creates a robust, "bolt-on" hardware and software system. This system will plan and take OpNav images and automatically perform the compute-intensive image-processing, making results available to other onboard GN&C systems. Optionally, solutions for spacecraft position and velocity anywhere in the Solar System can be provided as needed – which in general is a need for robotic spacecraft. It will also provide maneuver estimates for trajectory maintenance. The overall operation is very analogous to the manner of operation of a star tracker providing automated spacecraft attitude. Though planned as an instrument that can be replicated for multi-use on a variety of NASA's missions (as well as commercial missions), the system can be adapted to a number of configurations. Where self-pointing cameras cannot be accommodated, due to mass or other constraints, the AutoNav software aboard the IRIS software-defined-radio (SDR) can accommodate images from a small fixed camera, making the DPS system compatible even for use on a CubeSat. But for crewed and larger robotic missions the capabilities of the full DPS instrument shown in Fig. 1 provides the greatest cost to benefit ratio.

In addition, the instrument can serve as a powerful sensor to detect internal structure, strength and motion of dynamic and energetic bodies such as Europa, Io, and Enceladus.[11,12,13,14] The genesis of the DPS instrument is the Advanced Pointing and Imaging Camera (APIC) that is currently undergoing risk-reduction engineering work under SMD's Homesteader program. This instrument is designed to obtain very high-resolution images of planetary surfaces while simultaneously determining the pointing from the camera to that surface, and in so doing, extracting information with regard to motions and deformations in planetary surfaces. The requirements to obtain this very precise geometric information are exactly the same as those required for high-precision optical navigation, and so the DPS/APIC instrument can perform both functions. Recently, DPS was awarded a US patent for the various options and configurations in which DPS can be instantiated[15].

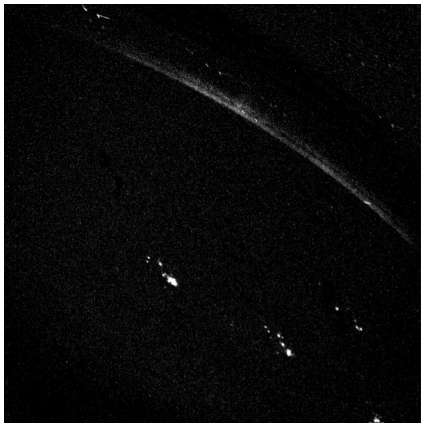


Figure 3: Jupiter imaged by Voyager 1, 5 March 1979 six hours after a very accurately targeted close-approach using target-relative navigation; the light along the limb is an aurora and the bright spots near the center and bottom of the frame are thought to be lightning.

II. The Deep Space Navigation Challenges

A. Target Knowledge

The principal challenge for autonomous and automated navigation for missions that "go somewhere" – i.e., to a target – is to know precisely where that target is, relative to the spacecraft, i.e., 'target-relative-navigation.' Starting with the Mariner missions to Mars, NASA's Jet Propulsion Laboratory embarked on an extensive effort to use ground-based (and occasionally space-based) astrometric observations to improve the ephemerides of the planetary bodies of the Solar System, to enable the many missions to explore them *in situ*. For the Moon, Mars, Mercury and Venus, the combination of this improved position

determination and the relatively high quality radio-metric measurements, that are part of the normal radio communications protocols, no target-relative navigation measurements (e.g., optical) were necessary. However, for the Voyager mission to Jupiter, then Saturn, Uranus and Neptune, the tight requirements necessary to achieve the "Grand Tour" of all the gas giants required substantially better navigation accuracy than could be achieved with radiometric data alone[16,17], even advanced methods like delta-differenced-one-way-range (DDOR), an interferometric comparison between the spacecraft signal and that of several quasars. As the Voyager craft ventured further out into the Solar System, the Earth-based ephemerides got progressively worse, up to several thousand kilometers in the case of Neptune.

Along with the uncertainties in the planets themselves were large uncertainties in the satellites that were the actual navigation targets used by Voyager (because the limbs of the gas giants could not be modelled with sufficient accuracy to serve as fiducial reference.) Figure 2 shows a Voyager 1 picture of Amalthea that was only possible to obtain by virtue of approach optical navigation, due to the gross uncertainty in the satellite's position. In turn, improvements made in Amalthea's orbit helped resolve a critical parameter of the flyby, the mass of Jupiter itself, by virtue of this small inner satellite's rapid 12 hour orbit. By the time Voyager took the backward looking image of Jupiter in Figure 3, six hours had passed since close-approach. Without approach target-relative navigation (OpNav), the gravitational amplification of the close-approach navigation errors would have been too large for the modest maneuvering capabilities of the Voyagers to compensate, and the subsequent planetary encounters would not have been possible. In the case of Neptune, several of the satellites used for navigation had to await discovery by Voyager 2 itself, the first of those being Puck, Fig. 4.[18] Optical Navigation was the means of performing this target-relative orbit determination of the spacecraft and the related orbit-determination of the satellites. But these navigation operations were performed on the ground, and the results uplinked to the spacecraft. With the first generation flight computers of the Voyagers, it would not have been possible to load the 100's of kilobytes of data necessary to hold this ephemeris information onboard, let alone the software necessary to process the images, but such requirements are easily met by current flight computers, even very small imbedded FPGA-based processors such as in the IRIS radio that DPS uses.

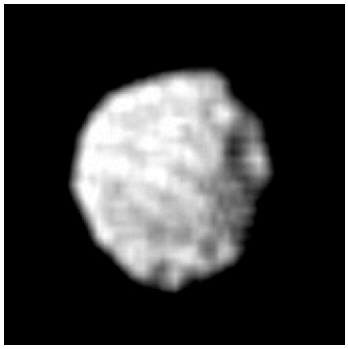


Figure 4: Puck, an inner satellite of Neptune, discovered by the Optical Navigation Team on approach by Voyager 2, and used as a navigation target post-discovery

Ephemeris challenges for target-relative navigation have not been limited to planets and their satellites, indeed the biggest challenges have been the small bodies of the solar system, asteroids and comets. The Galileo mission was the first to fly by an asteroid, Gaspra. Optical navigation was necessary in order to image the object, and imaging had to take place weeks in advance in order to tune the trajectory of the flyby, because uncertainty of several hundred kilometers had to be reduced prior to the encounter – and this with a severely reduced downlink capability due to the failed deployable antenna. Some unorthodox methods of imaging were used to maximize the data return, and the encounter was successful, and the process repeated for Ida. (Ref – Vaughn Galileo paper). The NEAR approach to EROS had a similar challenge[19].

Approaches of Deep Space 1 to Borrelly, Stardust to Wild 2, and Deep Impact to Tempel 1, had even greater challenges, as comets are friable and propulsive bodies, that have enormous orbital uncertainties, compounded by the fact that the nucleus is generally hidden in a cloud of dust and gas. For each of these encounters, initial ephemeris improvement was performed in the traditional way, with ground processing of images, but at close approach, the automated onboard navigation system[5,26] (AutoNav, the same for all three missions) performed autonomous target-relative optical navigation to target close approach imaging and in the case of Deep Impact also direct the path of the impactor spacecraft with the comet nucleus.

B. Needs for Autonomy

The Deep Impact Mission – imaging the crater-generating impact of a projectile with a comet nucleus – depended upon onboard automated navigation – specifically AutoNav to accomplish its prime mission objectives. In the early analysis of the mission, extensive simulations were run, and given the expected uncertainty of the position of the nucleus, it was determined that without onboard automation, the chance of success for the mission was only about 5%. There simply was not sufficient time – given the long round-trip light-times to perform conventional ground-

based optical navigation. Thus, the Deep Space 1 AutoNav system was adapted for use on the new mission. Figure 5 shows the numerous successes of the AutoNav system that is the core navigation software capability of DPS.

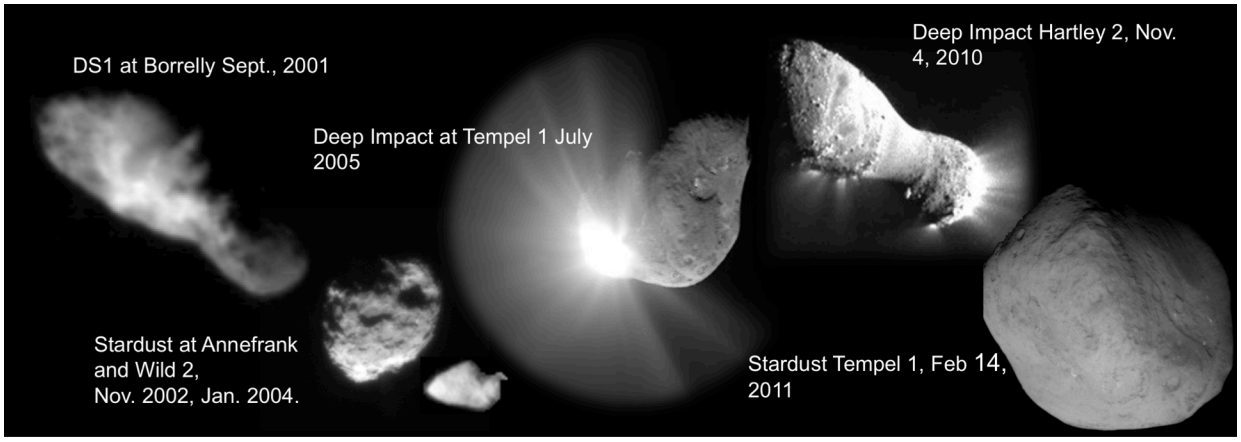
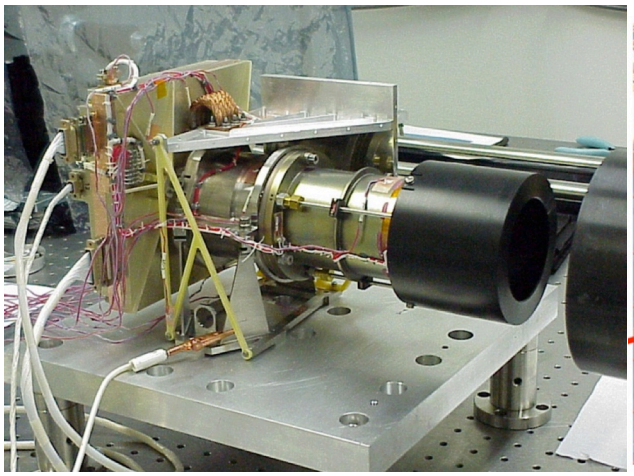


Figure 5: A gallery of images achieved by autonomous onboard optical navigation using the core DPS software element, "AutoNav"

In a similar way, OSIRIS-REx is implementing two independent means to autonomously descend to the surface of asteroid Bennu and obtain a sample. Though one system uses automated loop-closure on a LIDAR, the other, much like AutoNav, uses passive optical navigation, with images of landmarks on the surface. As with Deep Impact, this methodology was chosen because there is insufficient time or telecommunications link to send images of the surface back to Earth for processing and retuning directed commands for the contact and sampling sequence.

Close orbits around small bodies are often sufficiently unstable as to require onboard automation and autonomy. Solar pressure can be a dominant perturbing force that requires frequent repetitive maneuvering that would tax most ground teams. In the outer solar system, there are investigations that could require substantial navigation autonomy. These would include orbits around the enticing, possibly life-harboring world Enceladus, where low orbiting spacecraft would require frequent maneuvers to overcome third body perturbations by Saturn. The Europa mission may use autonomy in a similar way to reduce operations cost, and allow closer flybys of Europa to shorten the mission and enhance science.

Finally, the greatest imperative for onboard navigation autonomy is probably safety and mission assurance, especially in the case of crewed missions. The Constellation Program required that every crewed vehicle have the capability to returned the crew safely in the event of corruption of the Earth-link. It has been shown that periodic



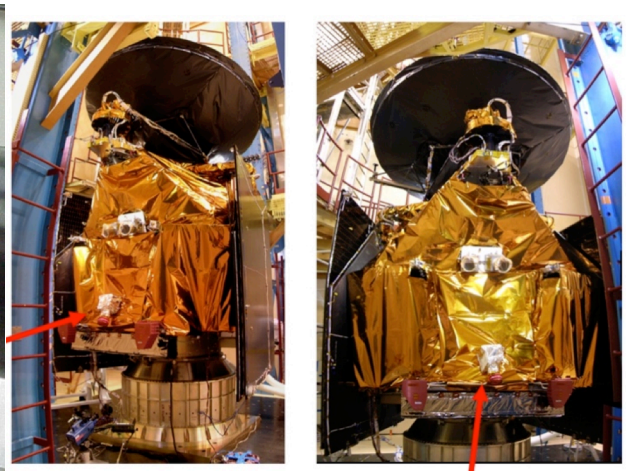


Figure 6 (left): The MRO ONC, on the optical bench being tested via collimator, in a similar manner as will be the DPS NAC. Figure 7 (right). ONC ready for flight, with red-tag lens covers (arrows).

coronal mass ejection events (CME's) can disrupt convention radiometric data to the extent that successfully targeting an Earth re-entry might become impossible[7]. Thus Constellation was planning on having automated and autonomous optical navigation systems onboard to provide the needed capability. Orion is planning something similar.

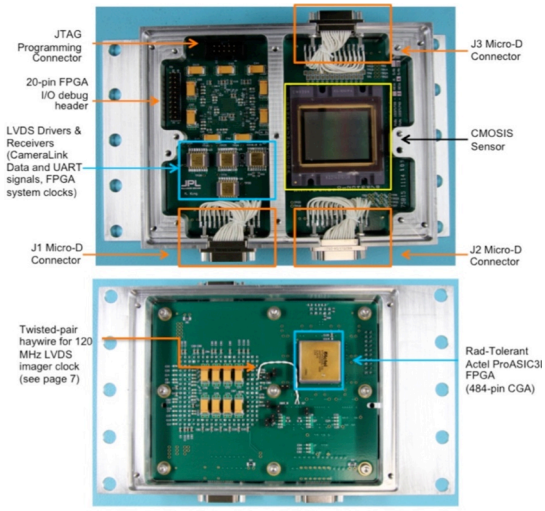


Figure 8: The Mars2020EECAM brassboard utilizing the CMV20000 CMOS Detector

C. Costs and Risks for Mission Point Designs

A very significant cost of mission development, especially for instruments and associated software is integration and test of those subsystems. For the three missions that utilized AutoNav, Deep Space 1, Stardust, and Deep Impact, all had substantial problems with the cameras that provided the data to the AutoNav system. Though these technical issues (ranging from serious stray light intrusion to incorrect focus) did not directly or ultimately threaten the science objectives, they played havoc with capabilities of the onboard navigation system. In the case of Deep Impact, a mystery of ill behavior of the attitude control system, upon which the AutoNav software was critically dependent (for knowledge of the pointing attitude of pictures, as seeing stars through the comet coma was problematical) was not resolved until 10 days before the close approach with Tempel 2, with the resolution being a frightening upload of new software into the star tracker. Again, in this instance, the curious behavior posed no risk to the spacecraft or mission in and of itself, but posed a very grave risk to AutoNav performance that did indeed risk the mission.

These are examples of hardware and software elements upon which AutoNav was dependent, but were developed and integrated independently from the navigation system. The DPS system will serve to prevent these incidents by providing cameras specifically intended for the navigation function, and integrating them with the navigation software prior to the flight. In addition to increased mission reliability, such pre-integration will save mission cost by reducing the amount and complexity of testing required by the mission. In addition, with multiple units built, the recurrent-cost of the flight units will be dramatically reduced over a single-copy custom instrument point-design for a specific mission.

III. Building the DPS Instrument

A. The flight-Heritage and/or Inheritance elements

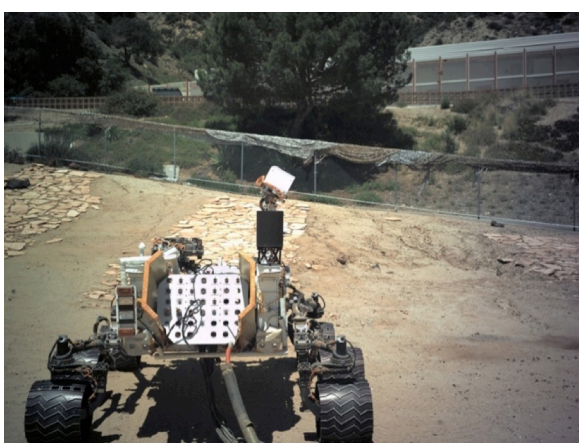


Figure 9: A sample frame from the DPS-Mars2020-EECAM 20 Megapixel camera breadboard.

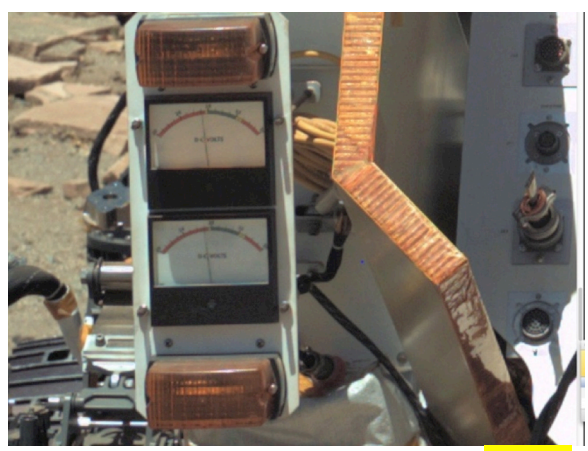


Figure 10: Vignette of detail (shown in Figure 5) from the sample DPS NAC frame demonstrating the exquisite detail obtainable with the EECAM.

1. The MRO ONC

The DPS NAC telescope, which is of a Cassegrain reflector design, will be a rebuild of the MRO Optical Navigation Camera (ONC), with minor lens prescription changes (to account for the 2× wider detector chip). This telescope retains the same aperture (6.25 cm actual, 5.9 cm effective area) as the ONC, a very powerful and efficient imager that was intended to see the 16 cm lofted Mars soil sample from up to 9,000 km range for the MSR mission. Figure 6 shows the ONC being tested in the lab prior to launch. Figure 7 shows the camera with red-tag lens-cover, on the launch pad.

2. Mars 2020 EECam

The NAC detector will be identical to the Mars2020 EECAM engineering camera. M2020 will fly several of these cameras for combined engineering and science functions. Currently configured to use the CMV20000 CMOS 20 Megapixel detector, development is proceeding for the DPS NAC based on the successful radiation TID-testing to 100 kRad. Additional testing of the radiation resilience of the detector at Brookhaven National Laboratory (high-energy electrons), and U.C. Davis Crocker Laboratory (high-energy Protons) to determine the ability of the detector to adequately image in a high-radiation environment. Specifically, to see if with modest shielding the imager would operate sufficiently well for navigation purposes at Europa and Io, and the answer was an unqualified 'yes.' Figure 8 shows the brassboard version of the EECam detector and processor plane. Figures 9 and 10 show a sample image of the MSL EM rover in JPL's Mars Yard, with a very small portion of the overall image magnified to show the very high detail obtainable with this high resolution detector.

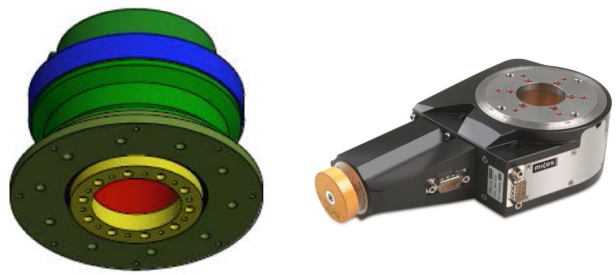


Figure 11: DPS Azimuth actuator developed by Honeybee Robotics (left) based on the OCO-3 gimbal, and the elevation actuator from Physik Instrumunte (right) which is a COTS product

3. Actuation subsystem

The azimuthal actuator is being built by HoneyBee Robotics, and is a modification of the OCO-3 azimuth actuator. It is planned to fly soon aboard the ISS, but for DPS use will be modified to be of higher precision to provide for the ability to track landmarks at close approach to a body, and provide image-motion compensation. The elevation action of the DPS instrument is being provided by PI (Physik Instrumente), a builder of very high-precision actuation devices for terrestrial scientific applications in high vacuum, and cryogenic conditions.. Both of these actuators provide very precise position and rate control. For purposes of demonstrating the APIC engineering model, terrestrial controller units have been used. Flight qualified FPGA units will replace these when applied to a flight project. Figure 11 shows these actuators.

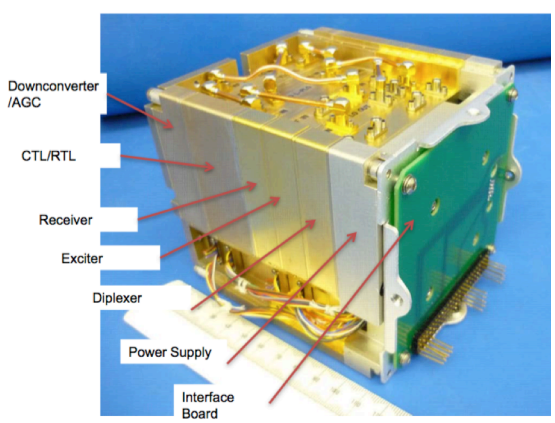


Figure 12: Iris Software Defined Radio as will be Flown on the INSPIRE mission

4. Iris Software Defined Radio

The Iris radio[6] is a cubesat compatible radio that is both the DPS CPU and the means of collecting and processing one-way radio metric observables. By the time DPS makes its first flight, Iris will have likely flown at least four times, on NEA Scout, Lunar Flashlight, INSPIRE, and MARCO – all of which are cubesat missions. Figure 12 shows the Iris radio as it was instantiated for INSPIRE, showing the discrete functional slices, including power, transmitter, receiver, and CPU. For a DPS that has no transmit function (in other words, where the Iris is not the full communications element for the spacecraft), the transmit slice can be omitted. For one way Doppler reception and reduction, the current version of IRIS needs to be updated to support one-way radio range and phase tracking, and a high precision frequency reference is required for accurate formulation of the observables. The local reference needs

to have sufficient stability and accuracy to support the navigation requirements of the using mission. This could be provided by an Ultra Stable Oscillator (USO); however, routine use of USO-only one-way radio navigation has been limited due to a USO's intrinsic drift, thermal sensitivity, and stability characteristics that includes a large frequency random walk on long time scales. The reliability of one-way radio navigation can be significantly enhanced with use of an atomic clock such as the Deep Space Atomic Clock (DSAC), which is significantly more stable and less sensitive to environmental variations than a USO. For less demanding cubesat-applications with significant resource limitations, a Chip Scale Atomic Clock (CSAC) may prove useful. A CSAC's long term stability and sensitivity falls between a USO and DSAC.

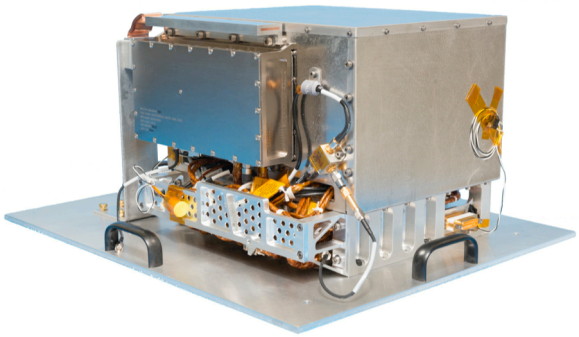


Figure 13: DSAC has demonstrated a stability of better than 3e-15 at one-day (on par with DSN ground atomic clocks) in ground testing, and is scheduled to demonstrate this and its utility for autonomous navigation in orbit beginning Sept 2017.

5. DSAC

The Deep Space Atomic Clock (DSAC)[20] Technology Demonstration Mission is building an advanced prototype of a small, low-mass atomic clock based on mercury-ion trap technology that will provide the stability needed for autonomous and automated deep space radio-metric-based navigation and radio science (Fig. 13). Ground based atomic clocks are the cornerstone of spacecraft navigation for most deep space missions because of their use in forming precision 2-Way coherent Doppler and range measurements. The DSAC provides an equivalent capability on-board a spacecraft for forming precision one-way radiometric tracking data (i.e., range, Doppler, and phase) using a properly configured radio such as IRIS or the Universal Space Transponder in development by JPL. By virtually eliminating spacecraft clock errors from this data, it is as precise as its two-way counterparts used today for ground-based navigation. With DSAC, operationally accurate and reliable one-way radiometric data sent from a radio beacon (i.e., a DSN antenna or other spacecraft) and collected using a spacecraft's radio receiver enables the development and use of autonomous radio navigation as envisioned by DPS. Autonomous navigation using only passive optical imaging provides strong angular information about a spacecraft's 'plane-of-sky' relationship to the object being imaged. Range (or 'line-of-sight') information, orthogonal to the plane-of-sky, is more difficult to determine from optical data due to parallax issues of observations taken from far distances. Range and Doppler

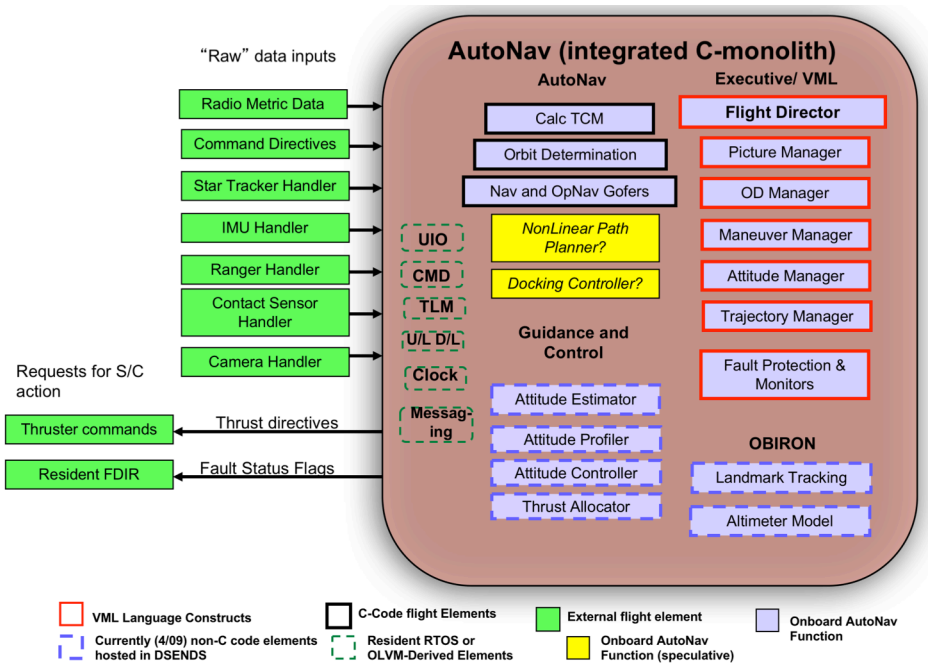


Figure 14: DPS Core FSW Architecture; This GN&C flight system architecture has been applied to small body proximity operations, landing, and to an Altair-like lunar landing scenario, the navigation elements of AutoNav have flown on three missions, and the VML command and control system on over a dozen.

data yield a more direct measure of line-of-sight. These measurements compliment the optical data such that, when combined with optical, yield a more complete, almost kinematic, ***robust solution*** for a spacecraft's absolute position in space. Indeed, the ***fusion*** of these two data types is central to a future DPS capability that would be needed for providing robust, fault tolerant trajectory solutions for a wide range of future missions (examples include autonomous landings on small or large bodies, human asteroid and Mars explorations, and efficient navigation for future orbiters and interplanetary craft) and all flight phases (including cruise, approach and orbit insertion, landing, or routine orbit operations).

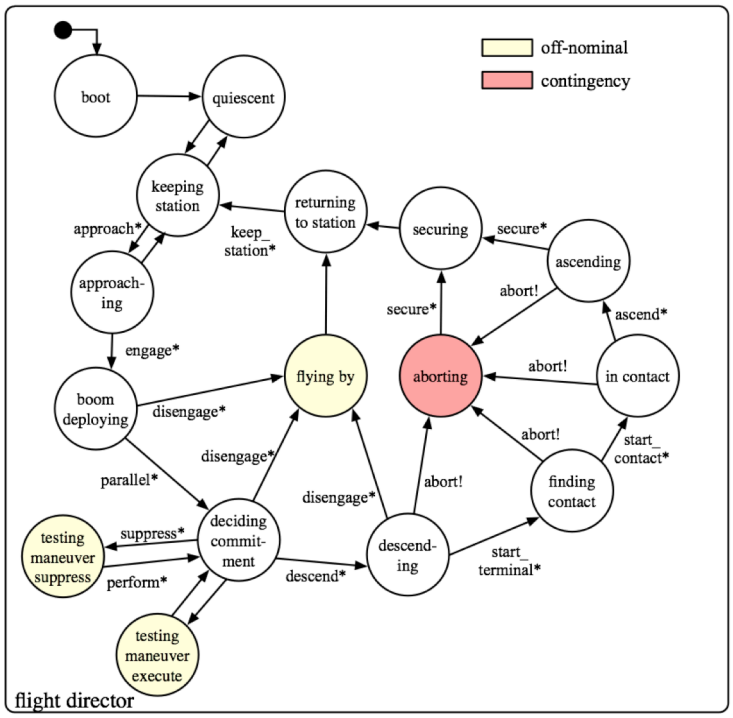


Figure 15: The AutoNav flight director state machine, as instantiated for a small body "Touch-and-Go" sampling.

NASA's DSAC project is building a demonstration unit and payload that will be hosted on the Orbital Test Bed spacecraft provided by Surrey Satellite Technologies US LLC, Englewood, Colorado. It will launch in 2017 into Earth orbit aboard the USAF Space Technology Program 2 rocket. NASA's DSAC Technology Demonstration Mission will operate for a year to demonstrate DSAC's functionality and utility for space navigation

6. DPS FSW

The DPS FSW is composed of three heritage elements: 1) The AutoNav autonomous and automated navigation system, developed for Deep Space 1, and flown additionally on Stardust and Deep Impact, 2) The Virtual Machine Language (VML 3) developed originally for the SIRTF/Spitzer space telescope, and 3) the Iris plug-in application layer that hosts the IRIS software defined radio application as well as AutoNav. Element 2 is a commercial elements provided by Blue Sun Enterprises (BSE), and Element 3 is provided by BSE as well, and is being developed under a NASA SBIR.

AutoNav is a software system that automatically plans, and processes optical navigation images, reduces that data in an orbit determination filter, and provides spacecraft state information to the host spacecraft. The system can also provide computed maneuver estimates to keep the spacecraft on a desired trajectory. The provided estimated spacecraft state can be used to keep the spacecraft pointed toward a desired target. Various combinations of these functions were used by the three missions that flew AutoNav, with the highest functionality utilized by Deep Impact, which included two instantiations of AutoNav, one on the flyby spacecraft that used it to point at the target comet nucleus, and one on the Impact spacecraft that used the system to guide the impactor to a collision with the nucleus.

The overall architecture of the AutoNav system is shown in Figure 14, where the heritage flight software elements common to DS1, Stardust, and Deep Impact are shown, namely the image processing, orbit determination and maneuver computation processes. For DPS, the architecture includes the VML-based memory management, command handling and I/O capabilities, which in total, create a flexible and control environment for the AutoNav elements as shown. The navigation computations are controlled by a series of linked state machines within the executive. The state machines are hierarchical, with the principal machine being the "Flight Director" (FD), as shown in Figure 15, as instantiated for a proposed Comet Sample Return mission[21,22,23]. Beneath the FD are multiple other state machines that are aware of state-transitions within the FD, and pend on the transition within the FD to

move to the next state. Thus, extremely complex behavior can be achieved through multiple level-use of this architecture, but with very simple software, as the state machine construct is native to VML3.

B. Build Configurations

A variety of cascading configurations of the Deep Space Positioning System present themselves as easy variations on the basic concept. When the system is considered as a set of hardware and software components, the following main "blocks" could be considered as build options: the core DPS flight software; an optical instrument (camera, telescope); a radio instrument (radio, antenna, clock); and a variety of other instruments (LIDAR, radar, etc.), Fig. 16.

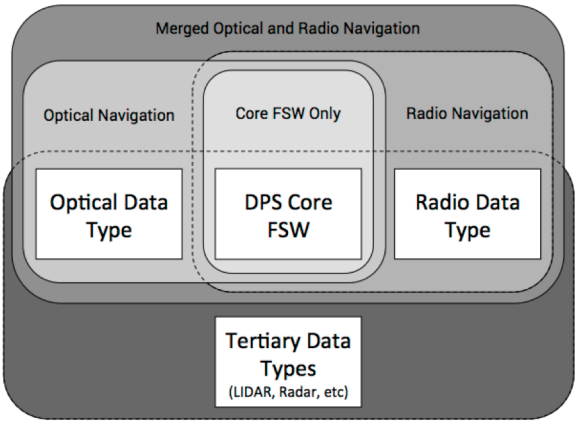


Figure 16: Possible DPS build configurations.

1. DPS S/W Only

The minimum delivery of a system that could rightfully be called DPS is the bare flight software. The software package could be deployed, for example, if the customer already had an astrometric quality optical instrument with a powerful CPU, and wanted to adapt this instrument into a stand-alone navigation unit. Some amount of configuration and calibration would obviously be required.

S/W + Optical

The most basic complete DPS instrument consists of an astrometric grade optical instrument (with CPU) that is pre-integrated with the core software elements. This would be a true off-the-shelf navigation solution for a particular mission: imagery from the built-in camera would directly result in a navigation solution that could be provided to the spacecraft over a very simple interface.

2. S/W + Optical + Radio

A more sophisticated version of DPS also includes radio observables, either from an Earth-based source such at the Deep Space Network, or another nearby spacecraft. This option requires the obvious additional hardware to create a one-way radio observable, and also sophisticated software integration. The navigation filter is required to properly merge the complimentary optical and radio data types, and some software element (be it the software defined radio itself or a post-processing function) must also be capable of properly managing a variety of radio sources, antenna and media calibrations, and other details of high fidelity radio communications.

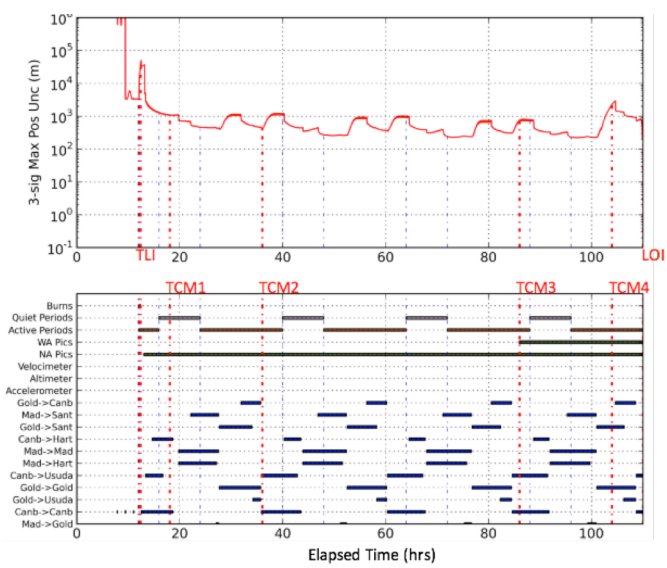


Figure 17: Nominal trans-lunar cruise current state navigation performance using both radio and optical tracking data for the period beginning at TLI – 12 hrs to LOI.

3. S/W + Radio

It would also be possible to remove the optical component from the fully merged solution above. A radio-only DPS would be less practical for relative navigation applications near distant bodies, but would provide highly reliable solutions for certain applications such as interplanetary cruise.

4. Additional external data types, e.g., laser ranging, LIDAR, Radar

Other instruments and data types are also considered practical for integration into the DPS instrument. In particular, local ranging/altimetry measurements, for example by laser or radar ranging, could be integrated into the filter and are very useful in the terminal approach phases of missions that involve landing on, or sampling from, small bodies.

IV. Potential DPS Use Cases

A. Mission to the Moon

Until its cancelation in 2010, NASA's Altair lunar lander required a robust navigation system that required a capable, fault-tolerant on-board navigation system that was suitable for safely navigating Altair in all mission phases in the event of loss of ground support. This involved a combination of radio and optical navigation capabilities. The concept envisioned at the time was a precursor to the DPS that is being discussed presently. It, too, consisted of a gimbaled narrow angle and wide angle camera system. The optical data types were augmented with radio-based trajectory solutions that were telemetered from Earth. This was prior to advent of DSAC, if envisioned today, radio tracking data would be collected onboard simultaneously with the optical data and optimally processed to produce real time trajectory solutions rather than an ad hoc combination of radio nav states with optical nav states that was considered previously. In this case, the role of the ground could be effectively relegated to monitoring the onboard solution. These prior navigation studies conducted for the Altair project examined the role of optical and radio navigation under the assumption that the ground-based radio-navigation used a combination of two-way and three-way radiometric data types. Since DSAC would enable replacement of these two-way/three-way data types with equivalent onboard one-way data types, these early studies are still a viable proxy for what would be possible using a fully configured DPS for onboard navigation. These results were documented by Ely[24] and will be highlighted here for cis-lunar, orbit, and landing navigation.

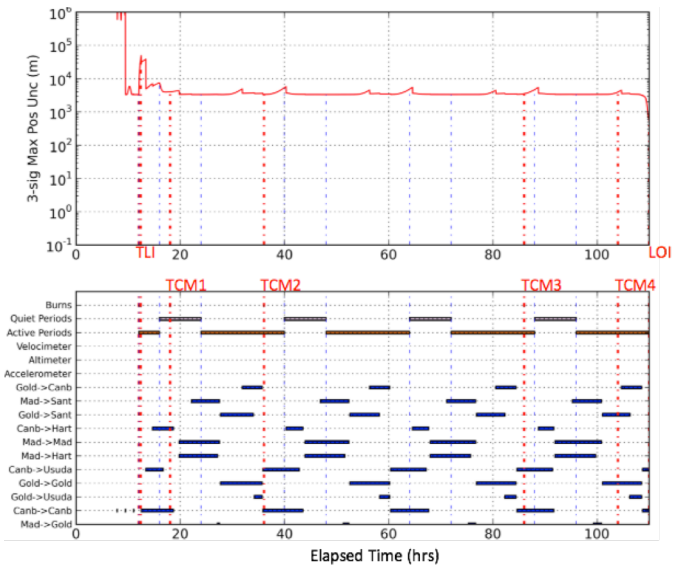


Figure 18: Trans-lunar cruise current state navigation performance with only radiometric tracking (no OpNav) for the period beginning at TLI – 12 hrs to LOI.

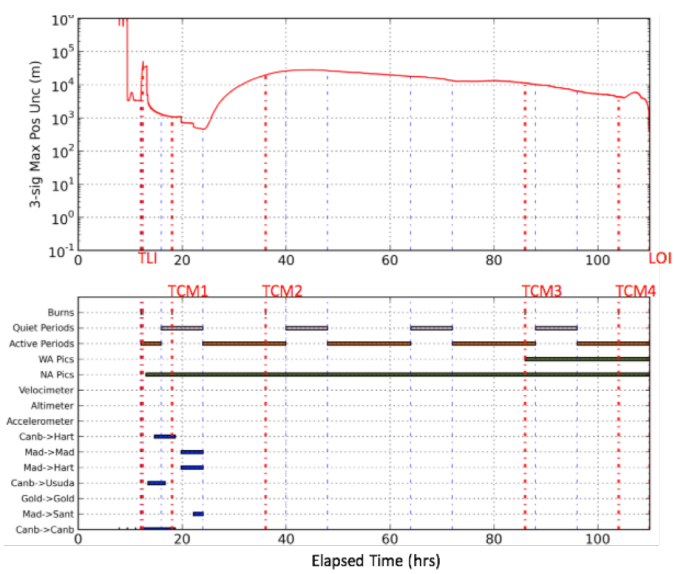


Figure 19: Trans-lunar cruise current state navigation performance with only optical lunar landmark tracking beginning 12 hrs after TLI.

A specific challenge for analyzing navigation of crewed vehicles is the presence of unusually significant non-gravitational disturbances (such as the environmental venting) that dominate a crewed vehicle's navigation errors seen during a transit to and orbit around the Moon. These accelerations cause trajectory dispersions and trajectory knowledge errors of such significance that they require more Earth tracking than is typical for robotic deep space missions. For instance, during the Apollo lunar orbit it was typical that these non-gravitational accelerations produced trajectory dispersions at a rate of 500 ft per hour. These acceleration disturbances are an order of magnitude larger than is typically seen with robotic missions. The combination two dissimilar data types (here radio and optical) is an effective, robust strategy to mitigate the effects of both determining an accurate trajectory in the presence of these errors, and controlling these disturbances.

In these prior results radio-based navigation, optical-based navigation, and the combination of the two were investigated for Altair trans-lunar navigation, orbit, and landing. The results are summarized as follows (Figs 17-19):

1. Translunar Cruise Phase: Radio-only trajectory knowledge uncertainty was on the order of 3 km (3-sigma), and the optical-only solutions ranged from 30 km (3-sigma) near Earth to 4 km (3-sigma) nearing the Moon. Impressively, the combined solutions were consistently less than 1 km (3-sigma) showing that not only was fault tolerance improved, but overall solution quality was as well. Delivery errors to lunar periapsis insertion were not markedly different with (12 km, 3-sigma) or without optical navigation (13 km, 3-sigma); however, in this critical mission phase, having the natural solution assessment provided by the two data types would be critical to ensuring a safe lunar orbit insertion.
2. Orbit Phase: Radio and optical trajectory knowledge uncertainty was on the order 100 m (3-sigma), which was more than sufficient to ensure delivery to powered descent on the order of 1 km or less. This was important towards minimizing delta-V expenditures needed to 'fly-out' descent trajectory injection errors.
3. For Altair, landing was executed with the optical data performing terrain relative navigation and a radar, and was shown to achieve sub-10 m (3-sigma) landing accuracies. Inertial only navigation yielded only kilometer level landing accuracies. Optical terrain relative on-board navigation using a DPS like instrument was enabling for a precision landing. Again, in the case of onboard radio tracking using one-way and DSAC, these data could be used to discipline the absolute navigation in areas where landmark tracking was episodic or obscured by shadows.

Extrapolating these results towards navigating crewed vehicles heading to Mars that possess Altair's characteristics (or Orion's as well) will prove to be a challenge. Use of DPS with optical and radio tracking will be an enabling capability to ensure safe, robust onboard navigation of these vehicles.

B. Mission to Mars

Mars missions have traditionally been navigated mostly using ground-based radiometric data from the DSN and other similar networks, with the orbit determination task performed by the operations team on the ground. The one exception to this approach was the Optical Navigation Camera (ONC) Technology Demonstration that was performed during Mars approach for MRO[8]. This demonstration showed the performance of a small visible-light camera imaging the moons of Mars against the star background and how those images could be used to determine the position of the spacecraft with respect to Mars as the spacecraft approached the planet. For this demonstration the images were transmitted to Earth and the data processing was done on the ground. Images were taken between 28 and 3.3 days before arrival to Mars, with the goal of being able to predict the trajectory during the final approach with an accuracy better that 1 km. A total of 480 images were taken and processed, containing observations of either Deimos or Phobos, and sometimes of both satellites. The optical data was combined with ground-based Doppler and range data and was compared with the operational solutions that used Doppler, range, and Double Differenced One-way Range (DDOR) data. The final position estimates were indeed better than one kilometer, showing the potential of optical navigation. The optical data needed to be combined with the Doppler and range data because optical images have a poor observability of the distance and rate between the camera and the target, but the experiment showed that optical could replace DDOR to assist with the determination of the plane-of-sky position of the spacecraft, which is poorly observed using line-of-sight measurements such as range and Doppler.

While the ONC demonstration was focused on Mars approach navigation, other phases of a Mars mission could also be navigated using an on-board optical navigation system. During Earth departure and return, imaging of artificial satellites could be used to determine the position the spacecraft relative to the Earth and the rest of the solar system; during mid-cruise asteroids could be imaged to triangulate the trajectory of the spacecraft; during approach the system could image both asteroids and the moons of Mars for a three-dimensional position determination; when in orbit the system could take pictures of the Mars limb and surface to determine its location with respect to the planet. The optical images could also be combined with Doppler and/or range measurements if the navigation requirements cannot be fulfilled just using optical measurements. If on-board orbit determination is necessary, the system can be augmented with a precise clock in order to allow for ground-to-space one-way radiometric measurements. A candidate for this is the Deep Space Atomic Clock (DSAC)[20], but a smaller clock could be used for less demanding applications.

A DPS could be used to navigate a Mars spacecraft during all mission phases. The navigation performance in some cases would be dependent on the dynamical cleanliness of the spacecraft, as it is for ground-based orbit determination, but a DPS could provide very similar performance to that obtainable using current methods. The combination of optical and one-way radiometrics would allow for different levels of accuracy that would be useful during operations. An optical-only solution should be possible even in the absence of a priori knowledge, by

searching in succession for planets, moons, asteroids and, when applicable, limbs and surface features, and this optical-only solution can then be used to reduce the search space, in orientation and frequency, for ground-transmitted navigation signals, allowing for an autonomous high-performance navigation capability even after a cold restart.

C. Visiting a small body with DPS

The heritage of DPS flight software development at JPL includes the capability for navigation near a small body, including cruise, approach, proximity operations, and even a surface sample[27]. Additional work presented by Riedel, Vaughan, et al [21] provides analysis and performance characteristics for such a mission.

1. Cruise and Target Detection

After launch from Earth, DPS can be immediately engaged to provide navigation and guidance solutions for the spacecraft. In the vicinity of the Earth, navigation targets such as the Moon and known geostationary or semi-geostationary satellites can be used for navigation. In interplanetary cruise, DPS can use planets and asteroids as 'beacons' for an optical-only solution, or a radio-equipped version of the technology would perform as described in Section A above. The core navigation element of the DPS flight software system, the AutoNav code of Deep Impact (DI) and Deep Space 1 (DS1) heritage, was tested in interplanetary cruise during the DS1 mission and found to provide an OD solution between 150km accuracy (best case) and 10,000 km accuracy (worst case)[4,28,29].

Target detection as the spacecraft approaches the small body is performed using the optical instrument. Well in advance of the terminal approach, DPS will be provided with the best-available Earth-based ephemeris for the target, and this information combined with the instrument's estimate of the spacecraft state allow it to predict the target location in the field of view. This capability was validated during the Deep Impact mission's encounter with comet Tempel-1. Kubitschek, Mastrodemos, et al detail the "Trials of Targeting the Unknown[5]", but note that even at the relative velocity of ~10km/s, the integrated DN brightness of the comet in the camera frame was 400 DN at 140 hours before impact and over 1000 DN at 80 hours out. At 90 minutes from encounter, the target was 10 pixels across, and the autonomous flight system had no trouble tracking the target. A small body rendezvous would be significantly slower and there would be few issues identifying the target in the image frame.

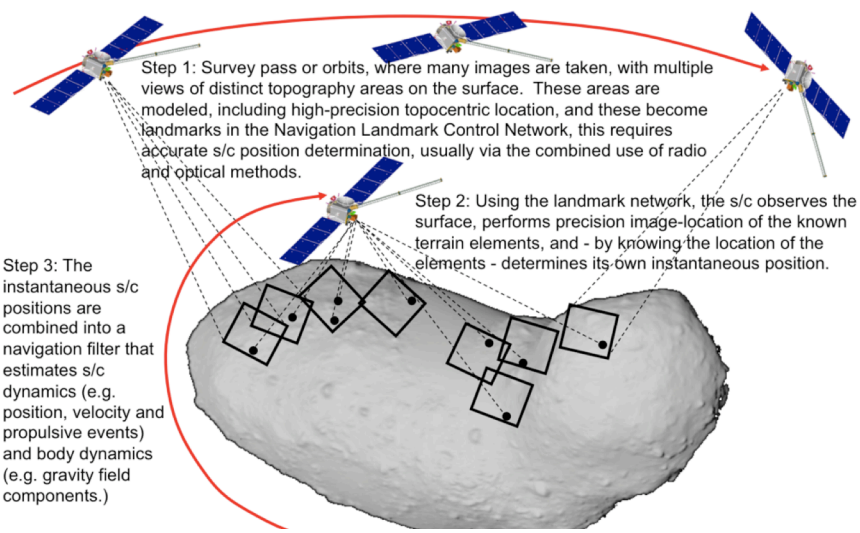


Figure 20: . Survey orbit around a small body.

2. Approach, rendezvous, and survey

With DPS performing frequent navigation solutions based on optical observations of the target, the instrument would compute rendezvous maneuvers for implementation by the spacecraft. Typically, these maneuvers would take the form of pre-computed deterministic capture burns and a series of corrective maneuvers that the autonomous system can be update based on the current OD. Once in proximity to the target (gravitationally bound or not), the spacecraft would maintain a large "survey orbit" for the purpose of gathering surface imagery of most of the body at different view angles and illuminations, as shown in the cartoon in Figure 20. Reconnaissance images are typically transmitted to Earth, where ground-based modeling software is used to construct a shape model of the body. The model is uplinked back to DPS, and this data can be used to navigate the spacecraft at significantly lower altitudes.

3. Proximity Operations, Descent, and Sampling

Figure 21 shows a candidate timeline for proximity operations, descent, and sampling, as studied by Riedel et al.[21]. The descent trajectory is defined by a series of deterministic maneuvers, along with a set of nominally zero corrective maneuvers, all of which can be updated by the instrument in response to the optical OD.

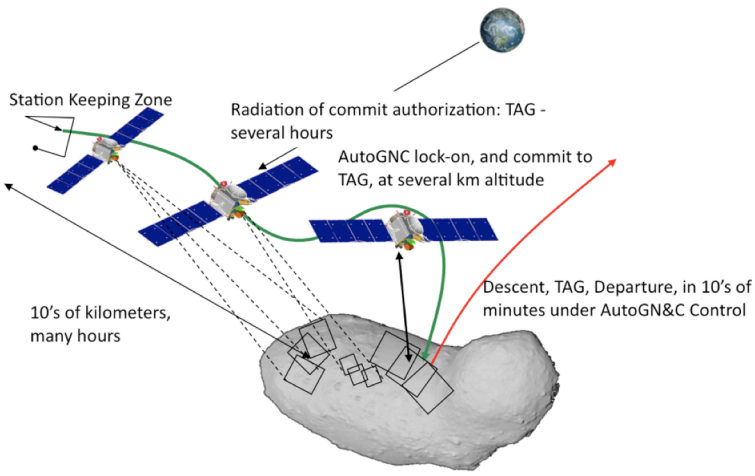


Figure 21: Touch-and-go proximity operation timeline.

Figure 22 shows the nominal descent trajectory for the touch-and-go. The trajectory is represented in the landing-site-frame, with the Z-direction "up," such that the red line is approximately altitude. Several deterministic maneuvers shape the trajectory in response to mission needs (e.g. avoiding surface contamination[5]). This particular mission targets a touchdown with a vertical velocity of 20 cm/s and a horizontal velocity of 0 cm/s, +/- 2 cm/s. The sampling arm is designed to provide the nominal contact force required by the sampling instrument over a period of 5 seconds, after which the spacecraft executes an escape burn.

Figure 23 shows the performance of the navigation system for this particular mission. The analysis was carried out using a high-fidelity simulation that included landmark tracking against a realistic model, full attitude control, thruster control modeled to individual thruster pulses on properly pointed thrusters (in response to merged force and torque requests), and multi-body dynamic simulation of the spacecraft including the sampling mechanism and solar arrays. The navigation

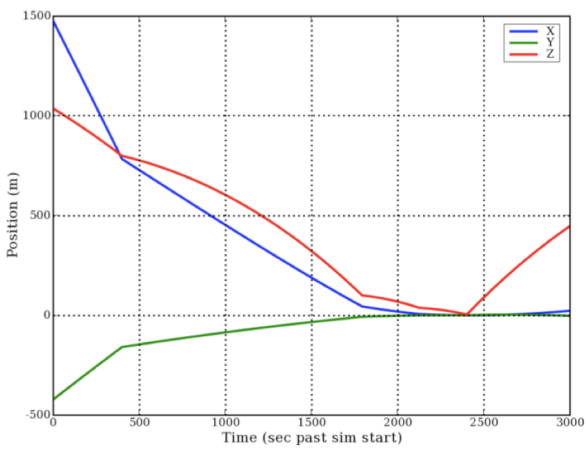


Figure 22: Nominal trajectory profile in the landing site fixed frame (Z up).

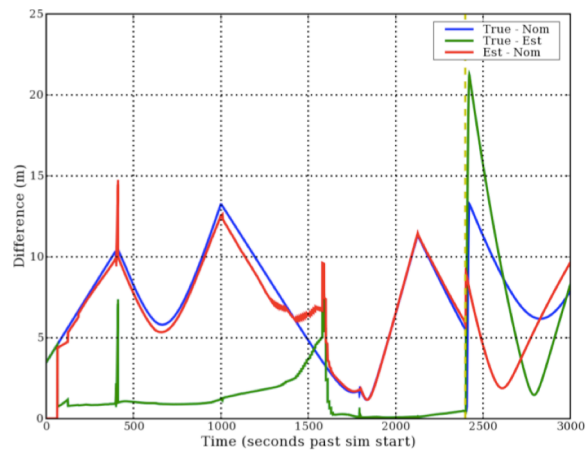


Figure 23: Simulated flight system performance using landmark tracking.

performance (as represented by the green line: the difference between the true position and the instrument's knowledge) is quite good, shown to be better than 5m through all phases of the mission, except immediately following large burns and contact with the surface. Once the spacecraft has escaped the immediate surface of the body, it is free to return to station-keeping where it can continue to follow the mission profile. This could include subsequent sampling operations, or escape from the small body and return to Earth. Return to Earth orbit is easily accomplished by the same techniques as the interplanetary cruise in the first half of the mission.

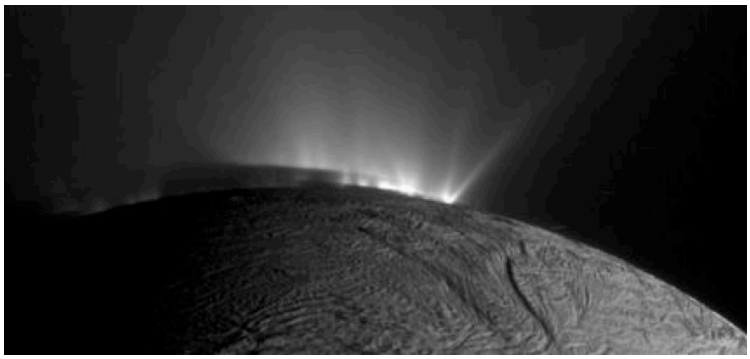


Figure 24: Water vapor plumes on Enceladus, an important science goal for NASA

D. Visiting Enceladus with DPS

When the Voyagers approached the Saturnian system, extensive use of optical navigation allowed update of the orbital elements of the major satellites sufficient to use the positions of those satellites as navigation targets. When Cassini subsequently approached that system, additional (though much smaller) updates were made, and continued partway through the mission until the positions were sufficiently resolved that ground-based radio navigation could achieve the necessary in-orbit accuracy without much additional in situ observation.

Cassini has observed continuous pluming of water vapor from Enceladus (Fig. 24), almost guaranteeing the presence of a mass of liquid water beneath the icy crust. Some as yet unidentified energy source is keeping this small satellite highly active, and so NASA has prioritized a mission to study this moon, and take samples of the water (and more important, potential signs of life or pre-life in that water). Figure 25 shows one concept for a mission to study Titan and Enceladus accommodating a complex gravity interaction with Saturn and then these two moons. Such missions can entail very high operations costs, due to the need to carefully plan, implement and subsequently correct maneuvers and flybys associated with the repeated gravity assists. Often, such high-cadence operations require multiple shifts of the navigation and other teams to handle the high operational burden. In addition, if depending on ground-based radiometric and optical navigation for these operations, substantial additional downlink time would likely be required prior to key navigation events to obtain these data.

DPS has the potential to substantially reduce the operations costs of such highly intensive large-outer planet tours. The reason has not only to do with navigation team size (which could certainly be reduced) but by virtue of the fact that with the navigation and maneuver design taking place onboard, the full implementation of these events can then take place onboard as well, including design of the turn sequences and operation of the engines. The precursor of the DPS flight software, Deep Space 1 AutoNav, actually accomplished such fully automated and autonomous activities in 1999 and 2000 during the technology validation phase of that mission. (Subsequent use of these capabilities during the extended DS1 science mission was precluded by the loss of the single star tracker)[4].

Mission safety and planetary protection are also important potential contributions that DPS can make to a moon-system tour. As with other planetary bodies, the prohibition against accidental contact with the surface (or sub-surface) of Enceladus will result in complicated target biasing requirements (less than $1e^{-5}$ likelihood). DPS can also provide mission safety, in that anomalous trajectory states (e.g., resulting from maneuver or orbit determination errors) can be quickly remedied onboard. Thus, preventing extreme deviations from the nominal trajectory, and potential "loss of mission" requiring long-duration corrective trajectory re-planning and re-acquisition (assuming recovery is possible at all). With such quick, reactive onboard response, it is possible to engineer the flybys at lower altitudes to increase the gravity deflections and to increase the potential science. In particular, for Enceladus, careful targeting of specific plumes may be desired, and particularly low altitude flybys for sampling of heavier molecules.

DPS offers still an additional benefit to a mission. Using the version of the gimbaled camera as shown in Figure 1, the cameras can take images with sufficient accuracy (several cm) that can measure the physical tides of the ice shell that are – in one form or another – providing the heat source to keep the oceans of Enceladus liquid. By measuring the deflection of the body under tidal deflection, DPS (augmented with internal star trackers as shown in the figure) can make important determinations regarding internal structure of Enceladus, including thickness of the ice shell, depth of the ocean and presence and size of a rocky core[11].

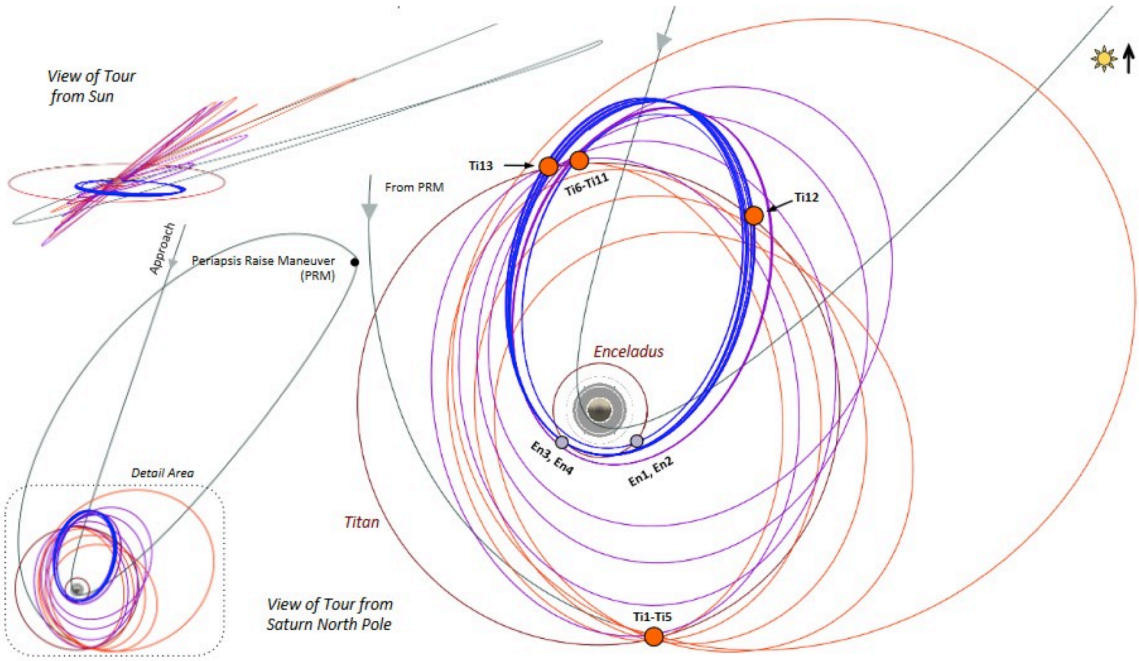


Figure 25: Concept mission trajectory study for an Enceladus Titan tour, that would have multiple close gravitational flybys that could be enhanced or even enabled with onboard autonomous and automated navigation as could be provided by DPS

V. Conclusions

Deep space missions in the future are going to be more aggressive, requiring ever more complex navigation and mission design strategies[25]. At the same time, cost constraints on these missions are likely to become more severe, as the missions become smaller and they undertake more aggressive science investigations for less cost. This compounding of demands on navigation and mission design will require more onboard autonomy. DPS will serve these needs, and additionally reduce the risks entailed in these more elaborate mission scenarios by allowing the development and pre-integration of hardware and software elements into a "bolt-on" capability that can be used on a wide diversity of different spacecraft for very different missions. There is precedent for the DPS concept. For more than 40 years, automated star trackers have provided a no-worry "bolt-on" solution to the s/c attitude estimation problem: "how am I oriented?" We will soon be entering a new era where spacecraft can similarly ask an onboard instrument "where am I?" DPS will answer that question, and further answer the question "How do I get to where I want to go?", and in the case of crewed missions, ask the very important question: "how do I get safely home?"

Acknowledgment

The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. © 2016 California Institute of Technology. Government sponsorship acknowledged.

References

[1] Guinn, J.R., "Autonomous Navigation Flight Demonstration Results for the New Millennium Program EO-1 Mission," presented at the AIAA/AAS Astrodynamics Specialist Conference, Monterey, CA, 5-8 August 2002.

[2] Riedel, J.E., Bhaskaran, S., Synnott, S.P., Desai, S.D., Bollman, W.E., Dumont, P.J., Halsell, C.A., Han, D., Kennedy, B.M., Null, G.W., Owen Jr., W.M., Werner, R.A., and Williams, B.G. "Navigation for the New Millenium: Autonomous Navigation for Deep Space-1," Proceedings of the 12th International Symposium on Flight Dynamics, Darmstadt, Germany, Jun. 1997.

[3] Bhaskaran, S., J. E. Riedel, B. Kennedy, T. C. Wang, "Navigation of the Deep Space 1 Spacecraft at Borrelly," AIAA paper 2002-4815, AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Monterey, CA, August5-8, 2002.

[4] Riedel, J.E., Bhaskaran, S., Desai, S.D., Han, D., Kennedy, B., McElrath, T., Null, G.W., Ryne, M., Synnott, S.P., Wang, T.C., Werner, R.A., "Using Autonomous Navigation for Interplanetary Missions: The Validation of Deep Space 1 AutoNav," IAA Paper L-0807, Fourth IAA International Conference on Low-Cost Planetary Missions, Laurel, Maryland, May 2000.

[5] Kubitschek, D., Mastrodemos, N., Werner, R., Kennedy, B., Synnott, S., Null, G, Bhaskaran, S., Riedel, J. , Vaughan, A., "Deep Impact Autonomous Navigation: The Trials of Targeting the Unknown," AAS 06-081, 29th Annual AAS Guidance and Control Conference, Breckenridge, Co., Feb. 4-8, 2006

[6] Duncan, C.B., et al., "Iris Transponder – Communications and Navigation for Deep Space", SSC14-IX-3, 28th Annual AIAA/USU Conference on Small Satellites

[7] Morabito, D. D., O. P. Verkhoglyadova, D. Han, and J. E. Riedel (2011), The effects of earthward directed interplanetary coronal mass ejections on near-Earth S band signal links, Radio Sci., 46, RS6001, doi:10.1029/2011RS004718

[8] Synnott, S.P., "Optical Navigation Technology Demonstration on MRO", Internal Jet Propulsion Laboratory Document, JPL D-37674.

[9] Grasso, C. A., Lock, P. D., "VML Sequencing: Growing Capabilities over Multiple Missions", AIAA Space Operations Conference Proceedings, April 2008.

[10] Grasso, C. A., "The Fully Programmable Spacecraft: Procedural Sequencing for JPL Deep Space Missions Using VML (Virtual Machine Language)", IEEE Aerospace Applications Conference Proceedings, March 2002.

[11] R.S. Park, B. Bills, B.B. Buffington, W.M. Folkner, A.S. Konopliv, T.J. Marti-Mur, N. Mastrodemos, T.P. McElrath, J.E. Riedel, and M.M. Watkins, "Improved detection of tides at Europa with radiometric and optical tracking during flybys," Planetary and Space Science, In Press, 2015.

[12] R.S. Park, S.W. Asmar, E.G. Fahnestock, A.S. Konopliv, W. Lu, and M.M. Watkins, "Gravity Recovery and Interior Laboratory Simulations of Static and Temporal Gravity Field," Journal of Spacecraft and Rockets, 49(2), 390-400, 2012.

[13] R.S. Park, S.W. Asmar, B.B. Buffington, B. Bills, S. Campagnola, P.W. Chodas, W.M. Folkner, A.S. Konopliv, A.E. Petropoulos, "Detecting Tides and Gravity at Europa from Multiple Close Flybys," Geophysical Research Letters, 38, L24202, 2011.

[14] R.S. Park, et al., "A partially differentiated interior for (1) Ceres deduced from its gravity field and shape", *Nature* (2016), doi:10.1038/nature18955

[15] Vaughan, A., and Riedel, J., National Aeronautics and Space Administration, Washington, DC, US Patent for a "Deep Space Positioning System," Application No. US14470438, filed 27 Aug. 2014, US Patent No. 9382020 B1, published 05 Jul. 2016.

[16] J. K. Campbell, **S.** P. Synnott. J. E. Riedel, **S.** Mandel, L. A. Morabito. and G. C. Rinker. "Voyager 1 and Voyager2 Jupiter encounter orbit determination." presented at the AIAA 18th Aerospace Sci. Meet., Pasadena, CA. Jan. 14- 16. 1980, paper AIAA 80 0241.

[17] J. K. Campbell, **S.** P. Synnott., Bierman, G. J., "Voyager orbit determination at Jupiter", IEEE Transactions on Automatic Control; AC-28; Mar. 1983,

[18] Riedel, J. E., W. Owen, J. Steve, S. Synnott, "Optical Navigation During the Voyager Neptune Encounter", AIAA paper 90-2877-CP, AIAA/AAS Astrodynamics Conference, Portland Oregon, August 1990.

[19] Owen, W. M., T. Wang, A. Harch, M. Bell, and C. Peterson2002. NEAR optical navigation at Eros. In Astrodynamics 2001D. B. Spencer, C. C. Seybold, A. K. Misra, and R. J. Lisowski, Eds., Advances in the Astronautical Sciences, Vol. 109, paper 376, pp. 1075–1087. Univelt, San Diego, 2002.

[20] https://www.technology.org/2015/04/27/the-deep-space-atomic-clock/

[21] Joseph E. Riedel, Todd Ely, Allan Y. Lee, Robert A. Werner, Tseng-Chan Wang, Andrew T. Vaughan, Simon Nolet, David M. Myers, Nickolaos Mastrodemos, Christopher Grasso, and David Bayard, "Optical Navigation Plan and Strategy for the Lunar Lander Altair.", AIAA 2010-7719, Toronto, 2010

[22] Riedel, R., Bhaskaran, S., Eldred, D., Gaskell, R., Grasso, C., Kennedy, B., Kubitschek, D., Mastrodemos, N., Synnott, S., Vaughan, A., Werner, R., "AutoNav Mark3: Engineering the Next Generation of Autonomous Onboard Navigation and Guidance," AIAA Paper AIAA 2006-6708, AIAA GN&C Conference, 21-24 August 2006, Keystone, CO.

[23] Riedel, J. E., et. al, "Configuring the Deep Impact AutoNav System for Lunar, Comet and Mars Landing", AIAA-2008-6940; AIAA/AAS Astrodynamics Specialist Conference; Honolulu, HI, 18-21 August 2008.

[24] T. A. Ely, M. Heyne, and J. E. Riedel, "Altair Navigation During Trans-Lunar Cruise, Lunar Orbit, Descent and Landing," J. Spacecr. Rockets, vol. 49, no. 2, pp. 295–317, 2012.

[25] Marco B. Quadrelli, Lincoln J. Wood, Joseph E. Riedel, Michael C. McHenry, MiMi Aung, Laureano A. Cangahuala, Richard A. Volpe, Patricia M. Beauchamp, and James A. Cutts. "Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions", Journal of Guidance, Control, and Dynamics, Vol. 38, No. 7 (2015), pp. 1165-1186.

[26] Bhaskaran, S., Riedel, J. E., and Synnott, S. P., "Autonomous Target Tracking of Small Bodies During Flybys", Paper AAS-04-236, *AAS/AIAA Astrodynamics Specialist Conference*, Maui, Hawaii, February 2004.

[27] Bhaskaran, S., Nandi, S., Broschart, S., Wallace, M., Cangahuala, L., Olson, C., "Small Body Landings Using Autonomous Onboard Optical Navigation", *Journal of the Astronautical Sciences*, Vol. 58, No. 3, pp. 409-427, July-August 2011.

[28] Bhaskaran, S., Desai, S. D., Dumont, P. J., Kennedy, B. M., Null, G. W., Owen, W. M., Riedel, J. E., Synnott, S. P., Werner, R. A., "Orbit Determination Performance Evaluation of the Deep Space 1 Autonomous Navigation System", Paper AAS 98-193, *AAS/AIAA Spaceflight Mechanics Meeting*, Monterey, CA, February 1998.

[29] Bhaskaran, S., Riedel, J. E., Synnott, S. P., Wang, T. C., "The Deep Space 1 Autonomous Navigation System: A Post-flight Analysis", Paper AIAA 2000-3935, *AIAA/AAS Astrodynamics Specialist Conference*, Denver, CO, August 2000.