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THE EVOLUTION OF DEEP SPACE NAVIGATION: 2009-2012*

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The exploration of the planets of the solar system using robotic vehicles has been underway since the early 1960s. During this time the navigational capabilities employed have increased greatly in accuracy, as required by the scientific objectives of the missions and as enabled by improvements in technology. This paper is the sixth in a chronological sequence dealing with the evolution of deep space navigation. The time interval covered extends from 2009 to 2012. The paper focuses on the observational techniques that have been used to obtain navigational information, propellant-efficient means for modifying spacecraft trajectories, and the computational methods that have been employed, tracing their evolution through 11 planetary missions.

INTRODUCTION

Five previous papers[1,2,3,4,5] have described the evolution of deep space navigation over the time interval 1962 to 2009. The missions covered in the first of these ranged from the early Mariner missions to the inner planets to the Voyager mission to the outer planets. The second paper extended the previous paper by one decade. It covered the entirety of the Magellan, Mars Observer, Mars Pathfinder, Mars Climate Orbiter, and Mars Polar Lander missions, as well as the portions of the Pioneer Venus Orbiter, Galileo, Ulysses, Near Earth Asteroid Rendezvous, Mars Global Surveyor, Cassini, and Deep Space 1 missions that took place between 1989 and 1999. The third, fourth, and fifth papers covered the portions of the Galileo, Near Earth Asteroid Rendezvous, Mars Global Surveyor, Cassini, Deep Space 1, Stardust, 2001 Mars Odyssey, Hayabusa, Mars Express, Mars Exploration Rover, Rosetta, MESSENGER, Deep Impact/EPOXI, Mars Reconnaissance Orbiter, Venus Express, New Horizons, Phoenix, and Dawn missions that took place between 1999 and 2009.

The current paper extends Ref. 5 by almost three years. It covers the portions of the Cassini, Stardust-NExT, Hayabusa, Rosetta, MESSENGER, EPOXI, Venus Express, Dawn, Akatsuki, IKAROS, and Mars Science Laboratory missions that took place between mid-2009 and early 2012. As in the previous papers, attention is limited to those missions that involved travel well in excess of 1,500,000 km from the Earth and that were targeted to fly close to one or more distant natural bodies.

EXPLORATION OF THE TERRESTRIAL PLANETS

MESSENGER

Mercury Orbit Insertion. The Earth, Venus, and Mercury flyby portions of the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission have been described in References 4 and 5 and references listed therein, as well as References 6 and 7. No trajectory-correction maneuvers

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(TCMs) were performed in preparation for Mercury orbit insertion subsequent to the deep space maneuver executed 478 days earlier. Instead, any needed trajectory modifications (and reaction wheel angular momentum management) were carried out by varying sunshade orientation and solar panel tilt angles to modulate solar radiation pressure forces and torques on the spacecraft. While this had been done for the Mercury gravity-assist flybys, additional complications came into play on approach to orbit insertion, such as the now-fixed nature of the arrival time and inconsistencies among orbit determination solutions associated with different arc lengths of radiometric tracking data. Improved orbit solutions were obtained too late to make useful final adjustments to solar radiation pressure forces, but shifting the start of the orbit insertion maneuver 5 s earlier allowed a reasonable compromise in the elements of the targeted post-burn orbit.[7,8,9]

The spacecraft arrived near Mercury displaced 8.0 km from its hyperbolic impact plane (or B-plane) aimpoint, primarily in the radial direction. The spacecraft was inserted into orbit about Mercury on 18 March 2011, by means of an 885-s burn executed primarily with the bipropellant, large velocity adjust thruster, with the thrust direction slowly rotating to track the Mercury-relative velocity vector for efficient propellant usage. The velocity change, integrated along the flight path, was 862 m/s. The burn was placed asymmetrically relative to periapsis, in order to obtain the needed rotation of the line of apsides. The achieved orbit semimajor axis was 10,175 km (corresponding to a 12.07-h orbit period), 40 km greater than planned. The achieved orbit eccentricity was 0.7399 (corresponding to a 207-km periapsis altitude), 0.0004 greater than planned. The achieved orbit inclination, right ascension of the ascending node, and argument of periapsis were 82.52, 350.17, and 119.16 deg (each accurate to within 0.04 deg of its desired value), which translate to a sub-spacecraft periapsis latitude of 59.98 deg N. The various trajectory errors were all well within allowable tolerances, and no cleanup maneuver was needed after orbit insertion.[7,8,9,10,11,12,13]

Primary Science Orbit. Perturbing effects such as solar gravity, Mercury's gravity field, and solar radiation pressure caused the spacecraft's orbital elements to drift from their desired values. During the primary science mission, the most important consequences of these perturbations were increases in periapsis altitude and latitude. In addition, propulsive angular momentum adjustments took place roughly weekly, producing small velocity changes (ΔVs). An orbit-correction maneuver (OCM) of 27.9 m/s was executed on 15 June 2011 near apoapsis to restore the periapsis altitude, which had grown to 505 km, to 200 km. Although most of the ΔV was produced with the large velocity adjust thruster, the full burn sequence included fuel-settling, auxiliary fuel tank refilling, main bipropellant thrusting, trim, and attitude-stabilizing segments, involving the use of a variety of thrusters. (A similar burn sequence had been used for the Mercury orbit insertion.)[10,11,12,13]

With this first OCM having unavoidably reduced the orbit period to 11.80 h, a second OCM of 4.1 m/s was executed on 26 July near periapsis to restore the period to 12.00 h. This smaller OCM was executed in a monopropellant mode using medium and small thrusters. A third OCM of 25.0 m/s was executed in bipropellant mode on 7 September near apoapsis to restore the periapsis altitude, which had again grown to 470 km, to 200 km. A fourth OCM of 4.2 m/s was executed on 24 October near periapsis to restore the period, which had dropped to 11.76 h, to 12.00 h. A fifth OCM of 22.2 m/s was executed on 5 December near apoapsis to restore the periapsis altitude, which had grown to 441 km, to 200 km. This OCM was executed in monopropellant mode because the limited amount of oxidizer remaining posed the risk of erratic thrusting in bipropellant mode. A sixth OCM was executed near apoapsis on 3 March 2012 in monopropellant mode to lower periapsis altitude to 200 km.[11,12,13,14]

Spacecraft orbit determination solutions were obtained by processing two- and three-way Doppler and two-way range data, typically available about 10 h per day. Orbit solutions were typically delivered for project use once per week, based on nine days of tracking data. The orbit predictions ran 30-35 days into the future after the weekly data cut-off, to allow the planning of observations and instrument pointing by the science team. Estimated parameters included spacecraft position and velocity, reflectivity coefficients associated with direct solar radiation and Mercury's reflected light and infrared thermal radiation pressures, commanded angular momentum dump ΔVs, OCM ΔVs, Mercury's ephemeris, and Mercury gravity field parameters. Parameters that were "considered," rather than estimated, included tracking station locations, tropospheric and ionospheric model parameters, Earth orientation parameters, and Earth's ephemeris. Initially, the estimates of the radiation pressure parameters would sometimes take on non-physical, negative values. Reducing their a priori uncertainties would resolve the situation for some parameters, but simultaneously cause other parameter estimates to become negative. As more tracking data were collected and processed, an improved 20x20 planetary gravity field was derived; the planetary radiation pressure model was refined; and the orbit determination results became more realistic and accurate, with improved tracking data residuals.[2,13,15]

Predictions of the spacecraft trajectory were limited in accuracy by the unknown nature of the unbalanced thrusting from future angular momentum dumps. Ephemeris time-tag biases were generated by identifying trends in a family of recent orbit solutions. When applied to the on-board ephemeris in the current command load, the biases resulted in more accurate trajectory prediction and thus instrument pointing.[13]

Venus Express

The interplanetary phase of the European Space Agency's Venus Express mission and the establishment of an initial operational orbit have been described in References 4 and 5 and references listed therein. From August 2008 to September 2012, nine Aerodynamic Drag Experiment campaigns were conducted, aimed at providing estimates of atmospheric density at altitudes of 165 to 200 km. The periapsis altitude was dropped as low as 165 km for this purpose, at times when third-body gravitational perturbations due to the sun had minimal impact on periapsis altitude, to ensure spacecraft safety.[16,17,18]

Akatsuki

The Japan Aerospace Exploration Agency (JAXA) launched the Akatsuki (Venus Climate Orbiter) spacecraft on 21 May 2010. Two-way X-band Doppler and range tracking data were provided by JAXA's tracking stations at Usuda and Uchinoura, as well as NASA's Deep Space Network (DSN). In addition, delta differential one-way range (ΔDOR) data were collected; but the accuracy was limited because telemetry sidebands were used, in the absence of DOR tones (with a higher spanned bandwidth). Orbit determination solutions were generated by JAXA and the Jet Propulsion Laboratory (JPL), with the latter solutions used for independent comparisons with the former. Solar radiation pressure provided the largest nongravitational force on the spacecraft, and models of increasing sophistication were developed during the flight to Venus. The unloading of reaction wheel angular momentum by thrusters took place once or twice per week, contributing only modestly to trajectory errors.[19,20,21]

The first TCM of 2.9 m/s was performed on 8 November. Subsequent TCMs of 0.26 and 0.04 m/s were executed on 22 November and 1 December, on approach to Venus. The JAXA and JPL orbit determination solutions were in approximate agreement throughout the interplanetary transit and consistent to within a few km late in the interplanetary flight. The approach trajectory had an estimated periapsis altitude of 547 km, 3 km below that targeted.[19,20,21]

The design of the Venus orbit insertion maneuver on 7 December was such that only the very beginning was visible from the Earth. Communication with the spacecraft was expected to resume after a 22-min Venus occultation, but did not. After more than an hour, a low data-rate signal was recovered at Usuda, with the spacecraft spinning in a safe mode. Reestablishing high-rate contact was challenging because of the uncertainty as to what had happened while the spacecraft was in occultation and what orbit had resulted. Rough estimates of the fractional completion of the orbit insertion burn, based on the limited available data, allowed DSN 70-m stations to make contact and return the spacecraft to a normal operating mode. It was subsequently determined that the burn had terminated when only 18 percent complete, due to a loss of attitude control, itself caused by a clogged propulsion subsystem valve. The spacecraft was thus traveling in a 203-day heliocentric orbit, rather than in orbit about Venus.[19,20,22]

The heliocentric orbit after passing by Venus was such that a follow-on encounter with Venus was possible several years in the future. Small test maneuvers with the bipropellant orbit maneuver engine in September 2011 revealed a thrust level that was too low to perform the maneuvers that would be needed to reach Venus and be captured into orbit. Consequently, the remaining oxidizer was released in a favorable direction (producing a ΔV of 26 m/s); and attention shifted to using the nominally lower thrust/specific-impulse monopropellant reaction control system (RCS) for performing these maneuvers. On 1, 10, and 21 November 2011, near-perihelion maneuvers of 89, 91, and 64 m/s were performed with RCS thrusters to place the spacecraft in an 8:9 orbit-period resonance with Venus.[21,22,23,24]

IKAROS

The Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS) spacecraft was launched on 21 May 2010 along with the Akatsuki spacecraft, as one of five piggy-back payloads. On 9 June the deployment of a rectangular solar sail with a length and width of 14 m and a thickness of 7.5 μm was completed. The spinning motion of the spacecraft provided attitude stabilization and maintained the shape of the sail, which was not deployed or supported by rigid structural members.[25,26]

Though targeted directly for Venus by the launch vehicle, the spacecraft's flight path was shifted away from the planet by selecting a sail attitude profile to generate the desired solar radiation pressure forces (up to 1-2 mN at the heliocentric distances of interest). The spin rate and spin-axis orientation were controlled with RCS thrusters. Electrically-operated reflectance control devices were also used to control spin-axis orientation, without the use of propellant. Use of the solar sail allowed the flight path of the spacecraft to be shifted by many tens of thousands of km relative to Venus in the B-plane (through a ΔV accumulation of 100 m/s) and controlled to an accuracy of several thousand km. The trajectory control accuracy was limited by uncertainties in sail reflectivity (due in part to wrinkling of the thin membrane) and sail area (since the membrane was a flexible structure). Thermal radiation pressure forces were calculated to be about 1% as large as solar radiation pressure forces and did not need to be taken into account, since the latter were uncertain by as much as 4%. The nominal mission ended in December 2010 after the spacecraft had passed by Venus at a distance of 80,800 km.[25,26,27,28]

Mars Science Laboratory

The Mars Science Laboratory (MSL) spacecraft was launched toward Mars on 26 November 2011, on a type-I trajectory (heliocentric transfer angle less than 180 deg) with a 6 August 2012 arrival date. Four launch periods had been considered, each with advantages and disadvantages. The one selected did not require changes in local mean solar time by the Mars-orbiting relay satellites and offered the convenience of a fixed arrival date regardless of the actual launch date, at the cost of somewhat degraded direct-to-Earth communication during entry, descent, and landing (EDL). The primary navigation challenges during the interplanetary flight were to deliver the spacecraft to an atmospheric entry interface point and estimate those entry conditions with sufficient accuracy that the vehicle's atmospheric guidance system could achieve touchdown within a landing ellipse that had been determined to be safe and compatible with the mission's scientific objectives (with coverage in this paper ending several months before EDL).[29,30,31,32]

The design of the MSL flight system was, in many respects, an extrapolation (to larger dimensions) of the Mars Pathfinder and Mars Exploration Rover (MER) spacecraft designs. During interplanetary flight, the flight system was spin stabilized at a spin rate of 2 rpm. The MSL flight system consisted of four major components: a cruise stage, an aeroshell (heatshield and backshell), a descent stage, and a rover. Direct-to-Earth communications were carried out at X-band, using small deep space transponders and amplifying electronics located on the descent stage or (as a backup) the rover. During the interplanetary flight, low- and medium-gain antennas located on the backshell and cruise stage, respectively, were used for transmitting and receiving signals.[29,31,33]

Based on pre-launch navigation analyses, DSN tracking was planned as continuous during the first 30 days after launch and the last 45 days before entry. Five tracks per week were planned at other times. The actual number of tracking passes acquired through mid-cruise exceeded these numbers, due to operational considerations involving spacecraft checkout activities and software uploads. Two-way Doppler and range data were collected during the tracking passes. In addition, ΔDOR measurements were scheduled once per week between launch plus 30 days and entry minus 67 days, twice per week between entry minus 67 days and entry minus 28 days, and twice per day between entry minus 28 days and entry. Since the radio signals transmitted by the spacecraft were circularly polarized, the spinning motion introduced a bias in the Doppler data. In addition, the displacement of the antenna's phase center from the spin axis introduced a periodic signature at the spin rate. Both of these effects were modeled and removed from the Doppler and range data with a new spin signature removal software tool, a slightly different approach than had been taken in the Mars Observer and MER missions. A side benefit of this modeling effort was that an independent estimate of spacecraft attitude could be derived, when needed.[29,30,33]

The launch vehicle's injection of the spacecraft onto its trans-Mars trajectory was quite accurate, so that the first planned TCM could be delayed for a month while some issues with the spacecraft's computer were being investigated. This investigation required that the star scanner be shut off, during which time spacecraft attitude determination relied on Doppler spin signature and sun sensor information. Spacecraft accelerations due to outgassing were evident during the first few weeks of cruise, and small stochastic accelerations had to be estimated to obtain good fits to the tracking data. Fortunately, these accelerations became negligible within a few weeks. A lateral calibration maneuver (optimized jointly with later TCMs) was performed on 22 December to assess the health of the monopropellant hydrazine cruise propulsion system, with the planned and actual maneuver magnitude and direction matching quite well.[29,30,31,33,34,35]

On 11 January 2012 the first TCM, consisting of axial (along the spin axis) and nine-segment lateral (approximately orthogonal to the spin axis) burns of 1.65 and 5.73 m/s, was executed. This TCM was performed in a no-turn vector mode, which was less propellant-efficient than rotating the spacecraft and thrusting in the desired direction, but was operationally simpler, introduced fewer trajectory perturbations, and allowed the spacecraft attitude to easily remain compliant with thermal and telecommunication constraints. The accurate launch injection had ensured that the required 99% probability of being able to target to the desired atmospheric entry point with the available propellant could be met with relative ease. The purpose of this TCM (jointly optimized with two subsequent TCMs) was to remove a large portion of the targeting bias included in the launch trajectory to ensure that the probability of the launch vehicle impacting Mars was less than 10^{-4}, as well as to correct injection errors. Thus, the B-plane miss distance was reduced from 47,513 to 4,956 km; and the error in the time of closest approach (selected before launch to minimize the highest cost of retargeting to any of several landing sites) was reduced from 14 h 50 min to 34 min.[29,30,31]

On 25 January an attitude control subsystem (ACS)/navigation calibration, using specially designed turns, was carried out to assess the residual translational ΔV resulting from nominally balanced spacecraft turns. The translational ΔV was found to be small – less than 0.03 mm/s per degree of turn. An increase in solar activity in late January produced noticeable effects on the range and Doppler data residuals. As a result, the orbit determination filter was modified to estimate signal transmission delays due to charged particles. On 28 February the spacecraft was commanded to switch from using the low-gain to the medium-gain antenna, with reduced tracking data noise resulting.[29,30,35]

Solar radiation pressure forces were modeled through a few terms in Fourier series expansions (in the angle between the sun line and the spin axis), rather than attempting to explicitly model each spacecraft surface. As the distance to the sun and the sun angle changed significantly, it became apparent that the combined modeling of solar and thermal radiation pressure effects (with different dependencies on heliocentric distance) was somewhat inaccurate, due to the presence of a radioisotope thermoelectric generator (RTG) on the rover. Consequently, the modeling was changed to include just three Fourier series coefficients for solar effects, one per axis, and a weekly stochastic acceleration along the spin axis to represent RTG thermal radiation.[29,30,32,35]

Even with a requirement that the probability of a non-nominal impact with Mars due to a failure in cruise or on approach be less than 10^{-2}, it was possible to target the second TCM, on 26 March, directly for the Mars atmospheric entry interface point consistent with landing within Gale Crater (4.6 deg S latitude and 137.4 deg E longitude), rather than performing a chained optimization as for the first TCM. The second TCM was performed in a no-turn vector mode and consisted of axial and lateral burns of 0.20 and 0.73 m/s. It shifted the B-plane position by 5002 km and the time of closest approach by 21 min 30 s.[29,30,31,34]

EXPLORATION OF THE OUTER PLANETS

Cassini

The interplanetary flight of the Cassini spacecraft and the first five years in orbit about Saturn have been described in References 2, 3, 4, and 5 and references listed therein, as well as References 36 and 37. The creation of a secure, high-reliability/high-availability computational environment to support Cassini navigation data processing is described in Reference 38.

Titan-59 Through Titan-62 Encounters. The Titan-59, -60, -61, and -62 encounters took place on 24 July, 9 and 25 August, and 12 October 2009 at altitudes of 955, 970, 962, and 1300 km. These encounters, all occurring inbound toward Saturn periapsis, gradually decreased the spacecraft's orbital inclination to allow ring viewing around the time of Saturn's equinox. As described in Reference 4, three Orbit Trim Maneuvers (OTMs) were nominally scheduled between successive encounters, but not all were actually executed. Maneuver cancellation was sometimes desirable to avoid OTMs that were too small (9 mm/s or less) to be performed accurately, reduce propulsion system usage, and reduce the workload for flight operations personnel. However, cancellation would only be approved if subsequent trajectory deviations and ΔV penalties were evaluated as being sufficiently small. One OTM (between the Titan-60 and -61 encounters) was executed with a biased aimpoint (shifted almost 15 km from the nominal target), in order to save ΔV.[39]

Enceladus-7, Enceladus-8, Titan-63, and Titan-64 Encounters. The Enceladus-7, Enceladus-8, Titan-63, and Titan-64 encounters took place on 2 and 21 November and 12 and 28 December 2009 at altitudes of 100, 1604, 4850, and 955 km. The Enceladus-8 encounter was inbound; the others were outbound. These and numerous subsequent orbits were equatorial and often involved non-resonant transfers. Early in the satellite tour, optical navigation images had been critical in determining the orbital motions of the satellites. Well into the tour, these images were no longer critical, but were still processed from time to time to maintain knowledge of the satellite ephemerides. Despite improvements in the ephemeris of Enceladus resulting from the Enceladus-4 to -6 encounters of August and October 2008, the ephemeris uncertainty had grown to 2 km by the time of the Enceladus-7 encounter. Consequently, 22 optical navigation images were processed between the Enceladus-6 and -7 encounters. In comparison, Titan's ephemeris uncertainty was stable at less than 300 m around this time, due to the large number of prior encounters.[37,39]

Between the Titan-63 and -64 encounters was the opportunity for an end-to-end ring occultation. The cleanup OTM after the Titan-63 encounter was used to target the nominal position of the subsequent near-apoapsis OTM (so-called XYZ targeting). The latter then targeted for the Titan-64 encounter, achieving the occultation geometry a few days before the encounter by following the reference trajectory closely.[39]

Titan-65, Titan-66, Rhea-2, Titan-67, and Dione-2 Encounters. The Titan-65, Titan-66, Rhea-2, Titan-67, and Dione-2 encounters took place on 12 and 28 January, 2 March, and 5 and 7 April 2010 at altitudes of 1073, 7490, 100, 7438, and 500 km. The first two encounters were outbound; the remainder were inbound. Between the Titan-65 and -66 encounters was another opportunity for an end-to-end ring occultation, 2 h after an Enceladus plume occultation. The cleanup OTM after the Titan-65 encounter used XYZ targeting to target the nominal position of the subsequent near-apoapsis OTM. The latter OTM then targeted for the Titan-66 encounter, achieving the two occultation geometries two days before the encounter by following the reference trajectory closely. The Rhea-2 flyby was less accurate than anticipated, due to a larger than expected error in the satellite ephemeris. Consequently, it was practical to target only one satellite in the upcoming Titan-67/Dione-2 double flyby accurately. Dione was chosen, because certain science objectives required accuracy in executing its moderately low flyby, while the Titan flyby was relatively distant. About 46 optical navigation images were processed in preparation for the Dione-2 encounter.[37,39]

Enceladus-9, Enceladus-10, Titan-68, and Titan-69 Encounters. The Enceladus-9, Enceladus-10, Titan-68, and Titan-69 encounters took place on 28 April, 18 and 20 May, and 5 June 2010 at altitudes of 100, 439, 1400, and 2044 km. The Enceladus-10 encounter was inbound; the others were outbound. The Enceladus-10/Titan-68 double flyby, like the Titan-67/Dione-2 double flyby, called for careful analysis of several trajectory control options. The selected option was to use the cleanup OTM after the Enceladus-9 encounter to target the nominal position of the next OTM, which then targeted for the Titan-68 encounter. Even without explicitly targeting for Enceladus, the flight path was accurate enough to allow a plume occultation. Other options considered resulted in either excessive trajectory errors at Enceladus or ΔV consumption.[39]

Titan-70, Titan-71, Enceladus-11, and Titan-72 Encounters. The Titan-70, Titan-71, Enceladus-11, and Titan-72 encounters took place on 21 June, 7 July, 13 August, and 24 September 2010 at altitudes of 880, 1005, 2552, and 8175 km. The Titan encounters were outbound; the Enceladus encounter was inbound. During this time the orbit inclination was reduced from 19 deg to 3 deg, using resonant Titan-to-Titan transfers. The Titan-70 flyby altitude was the lowest of the satellite tour. Because of the ΔV cost of a backup maneuver during the Enceladus to Titan transfer, the nominal maneuver strategy over this more-than-single-revolution transfer included four OTMs, rather than the usual three (though not all were actually executed). Over the full Titan-69 to Titan-72 time period, nine of the 13 scheduled OTMs were executed, and four were cancelled.[40]

On 15 August a test of the ability to obtain precise Doppler measurements using a low-gain antenna was conducted. This was of interest because low-gain communication with the Earth was feasible at times when ongoing science investigations precluded pointing the high-gain antenna at the Earth. It was found that the low-gain antenna could produce Doppler data useful for gravity-field determination if the Earth was less than 55 deg from the antenna's boresight, spacecraft attitude telemetry was available, and the position of the antenna phase center in the spacecraft body frame was estimated.[41]

Transition from Equinox Mission to Solstice Mission. On 26 September, the Cassini Equinox Mission came to an end; and on 27 September, the Cassini Solstice Mission began. Of 58 OTMs planned for the time between the Titan-58 and Titan-72 encounters (the portion of the Equinox Mission covered here), 40 were actually performed, 27 using the main engine assembly (MEA) and 13 using the reaction control subsystem, with the remaining 18 (mostly statistical approach OTMs) cancelled. Time-of-flight biasing, to avoid performing excessively small maneuvers, was considered for a number of approach OTMs, but not actually used during this time interval. As noted above, one OTM was executed with a biased aimpoint. The navigation ΔV cost (the reconstructed ΔV minus the deterministic ΔV for the reference trajectory) per flyby averaged 0.43 m/s over the 38 satellite flybys of the Equinox Mission.[39,40]

Titan-73, Enceladus-12, Enceladus-13, and Rhea-3 Encounters. The Titan-73, Enceladus-12, Enceladus-13, and Rhea-3 encounters took place on 11 and 30 November and 21 December 2010 and 11 January 2011 at altitudes of 7923, 50, 50, and 69 km. All encounters were outbound. Prior to the Titan encounter, the spacecraft entered a safe mode, which produced a small ΔV due to thruster activity and shifted the trajectory away from the desired aimpoint. The next scheduled OTM, executed under RCS (rather than the usual small-OTM reaction wheel) control, compensated for this error and also shifted the aimpoint away from that of the reference trajectory by a few km, in order to save a small amount of ΔV downstream.[40]

With the spacecraft in a nearly equatorial orbit about Saturn, three close icy satellite flybys took place. The cleanup OTM after the Enceladus-12 encounter was executed in its backup (rather than its prime) location, to allow a second pass of tracking data and avoid low-speed operation of a reaction wheel over an extended period of time. The apoapsis OTM that followed was designed to produce a small shift in arrival time for the Enceladus-12 encounter, in order to generate an OTM of sufficient size for execution. The aimpoint for the Rhea approach OTM was shifted by several km from the reference trajectory to reduce ΔV cost and provide an improved science return during the (now closer) encounter. About 34 optical navigation images were processed in preparation for the Rhea-3 encounter. Over the full Titan-72 to Rhea-3 time period, eight of the 12 scheduled OTMs were executed (one with the MEA), and four were cancelled.[37,40]

Titan-74 Through Titan-77 Encounters. The Titan-74, -75, -76, and -77 encounters took place on 18 February, 19 April, 8 May, and 20 June 2011 at altitudes of 3651, 10053, 1873, and 1359 km. The encounters were alternately inbound and outbound. The aimpoint for the apoapsis OTM before the Titan-75 encounter was shifted by several km from the reference trajectory to reduce ΔV cost, with no impact on science return. The approach OTM that followed would have been cancelled, based on the criteria used earlier in the mission. However, with long-term conservation of propellant being assigned increasing significance relative to minimizing the number of maneuver cycles, the OTM was executed in order to save several dozen grams of hydrazine downstream. The Titan-76 encounter could be targeted accurately using only a single orbit-shaping OTM of the two nominally planned. Thus, the first was executed; and the second (near apoapsis) was cancelled. The approach OTM that followed incorporated a small change in encounter time, in order to be of sufficient size for execution. The OTM on approach to the Titan-77 encounter similarly incorporated a small change in encounter time. Earlier in the tour, this OTM would simply have been cancelled; but a saving of downstream ΔV motivated its execution. Over the full Rhea-3 to Titan-77 time period, nine of the 12 scheduled OTMs were executed (one with the MEA), and three were cancelled.[40]

Titan-78, Enceladus-14, Enceladus-15, and Enceladus-16 Encounters. The inbound Titan-78, Enceladus-14, Enceladus-15, and Enceladus-16 encounters took place on 12 September, 1 and 19 October, and 6 November 2011 at nominal altitudes of 5821, 100, 1236, and 500 km. The Titan-78 encounter completed a sequence of four non-resonant Titan-to-Titan transfers, which rotated the orbital line of nodes in order to accomplish several scientific objectives. With the Titan-77 to -78 transfer taking place over several revolutions about Saturn, four OTMs were planned, rather than the usual three, to ensure that the last of these would be small enough to be executed with the RCS. It turned out, however, that neither the approach

OTM nor the auxiliary OTM planned for a week earlier were necessary, given the trajectory accuracy achieved by the first two OTMs. The Titan-78 encounter reduced the spacecraft's orbital period to 17.8 days, a 13:1 resonance with the motion of Enceladus, to set up the next three inbound encounters.[37,42]

No cleanup OTM was needed after the Titan-78 encounter, with any necessary trajectory corrections made by a near-apoapsis trajectory-shaping OTM of 5.1 m/s, which rotated the line of nodes sufficiently to enable three successive Enceladus encounters. A small OTM was needed on approach to the Enceladus-14 encounter to correct position errors on the order of 10 km. Even with the mass of Enceladus being much less than that of Titan, this close approach provided a gravity assist ΔV of 6 m/s. Only one deterministic OTM was scheduled between the Enceladus-14 and -15 encounters. After its execution, a statistical OTM scheduled for near apoapsis was below the implementation threshold. Rather than bias the time of closest approach to increase the maneuver size, this OTM was simply cancelled. Of the three OTMs scheduled between the Enceladus-15 and -16 encounters, only the second, near apoapsis, was actually needed.[42]

Dione-3 and Titan-79 Encounters. The outbound Dione-3 and Titan-79 encounters took place on 12 and 13 December at nominal altitudes of 100 and 3586 km. As in the Titan-77 to -78 transfer, the Enceladus-16 to Dione-3/Titan-79 transfer included four OTMs, to ensure that the last of these would be small enough to be executed with the RCS. The first two of these OTMs, with significant deterministic components, were 2.1 and 3.0 m/s in size. Special planning of an accelerated, contingency OTM was needed for the second of these, since the normal backup scheduling would have resulted in excessive propellant consumption as the spacecraft moved away from the optimal, near-periapsis OTM location. As it turned out, a contingency or backup OTM, seldom executed in this mission in general, was not needed on this particular occasion.[42]

The last two planned OTMs prior to the Dione-3/Titan-79 double encounter were executed, but were statistical in nature and much smaller than the first two OTMs. Since Dione and Titan could not be targeted independently, with the encounters 1.4 days apart, a decision had to be made as to which to target explicitly. Ultimately, Titan was selected, due largely to a smaller downstream ΔV penalty. A 3σ miss in the Dione encounter, due to ephemeris errors, caused a miss of about 10 km in the Titan encounter, which was among the largest encounter trajectory errors in the Cassini mission to date (though not problematical).[37,42]

Titan-80, Titan-81, and Titan-82 Encounters. The Titan-80, -81, and -82 encounters took place on 2 and 30 January and 19 February 2012 at nominal altitudes of 29,415, 31,131, and 3803 km. The encounters were alternately inbound and outbound. After the Dione-3/Titan-79 double flyby, it was determined that 0.6 m/s of ΔV could be saved by shifting the Titan-80 B-plane target by 107 km, thereby reducing errors in upcoming encounter approach asymptotes. Only two OTMs were planned and executed between the Titan-79 and -80 encounters. Only one OTM was planned and executed between the Titan-80 and -81 encounters. The standard three-OTM pattern was used to design OTMs for the Titan-81 to -82 transfer. An optimal design for the first OTM effectively eliminated any need for the second. The third OTM was deliberately executed during the backup, rather than the primary, opportunity. This avoided a shift in time of arrival associated with the primary opportunity (due to OTM size) and strains on the reaction wheel assembly (RWA) subsystem, saved ΔV, and brought the actual trajectory closer to the reference trajectory.[42]

EXPLORATION OF COMETS AND ASTEROIDS

Stardust-NExT

Cruise and Approach Phases. The primary Stardust mission and the early portion of the extended Stardust-NExT mission have been described in References 3, 4, and 5 and references listed therein, as well as Reference 43. The objective of the extended mission was to fly past comet 9P/Tempel 1, the earlier destination body of the Deep Impact mission, on 14 February 2011 for a post-impact examination. In February 2010, a TCM was executed for the purpose of delaying the spacecraft's arrival at the comet by 8 h, to synchronize the arrival with the desired rotational phase of the cometary nucleus, based on the best available predictions of the comet's rotational state. After this flight path modification, the propellant remaining to execute TCMs and control attitude through the time of encounter was estimated to be quite small.[44,45]

The fact that attitude control was performed using unbalanced thrusters (and no reaction wheels) meant that the spacecraft experienced frequent velocity changes while its attitude was being maintained within certain deadbands or when changes in attitude were sought. Modifications to the mission plan that added or deleted attitude changes caused changes in the predicted flight path. Unplanned events (such as safe mode entries) that caused thruster firings had similar effects. As a consequence of these spacecraft characteristics and the need to conserve propellant, a decision was made to maintain Earth pointing relatively loosely (to ±2 deg) until encounter (E) minus 40 days (and ultimately much later), to avoid the higher propellant consumption associated with the tighter pointing deadbands needed for science imaging. A TCM was executed at E-87 days, later than planned, due to the need to factor these considerations into its design.[44]

A TCM had been planned for E-32 days, on the assumption that optical navigation frames containing the comet would have been obtained by that time. In actuality, Tempel 1 was first detected in optical navigation images at E-26 days, about a month later than originally expected. This detection required the superposition of eight optical navigation frames, to obtain an adequate signal-to-noise ratio. The comet appeared to be dimmer than anticipated due to some inaccurate assumptions made in trying to translate prior optical navigation experiences to the current scenario. Due to spacecraft attitude motion, there was some smearing of star images in optical navigation frames. By reducing exposure times, this image smearing could be reduced, at the expense of reduced signal-to-noise ratio. Some optical navigation images contained significant background noise due to the scattering of sunlight off of the spacecraft structure. Rotations of the spacecraft and the navigation camera's scan mirror were used to mitigate this effect. Radiation damage to certain pixels and residual scattered-light effects produced a fixed-pattern noise in images. This effect could be reduced by power-cycling the camera, though each such cycling introduced a small risk of failure of the camera's power supply. Background and fixed-pattern noise could also be greatly reduced by calibration and subtraction of mean pixel values over sets of images taken around the same time.[44,46,47]

The charge-coupled device (CCD) photodetector of the Stardust-NExT navigation camera consisted of a 1024x1024 array of picture elements (pixels). To minimize data transmission requirements, 201x201 "windows" surrounding the comet and three reference stars were initially downlinked from each picture. However, between E-7 days and E-42 h, a single 351x351 comet window was used. The camera's optical surfaces were subject to contamination at times, which could be mitigated by turning on the CCD heater and placing the camera radiator in direct sunlight until the surface coatings evaporated. Optical surface contamination did not build up appreciably during the last two weeks of approach, and 9th- and 10th-magnitude astrometric reference stars within 150 pixels of the comet could be detected.[44,46]

The TCM scheduled for E-32 days was actually performed at E-14 days, and a TCM scheduled for E-10 days was delayed until E-7 days. These delays in TCM execution, largely due to the lack of optical navigation data on which to base the maneuver calculations, adversely affected propellant usage. As a result, the beginning of science imaging and the associated tightening of the attitude control deadband to ±0.25 deg (to allow higher data transmission rates to Earth) were delayed until E-7 days.[44,46]

Sets of eight optical navigation images were taken nearly daily from E-25 to E-9 days and as frequently as once every two hours thereafter (with interruptions for a final "camera bake" and TCM execution). The comet became visible in individual optical navigation frames at E-7 days. Estimated optical data accuracies improved steadily as encounter was approached. The last ground-commanded optical navigation imaging frames were acquired at E-42 h. A total of 552 usable images were processed, compared to an original plan for 192 such images. (Another 86 images were not usable due to image smearing, pattern noise, stray light contamination, or other problems.)[44,46]

The final TCM was executed at E-48 h, with the most recent optical navigation images, thought to be finally detecting the nucleus rather than the rotationally-varying brightest part of the coma, given extra weight. The execution of a contingency TCM was possible at E-18 h if the estimated flyby location lay outside of a certain sector of the B-plane, determined by science requirements and the angular rate limit of the camera's scanning mirror. The standard 30-h time slot allocated to the design and execution of a maneuver dictated that any TCM performed this late be chosen from a menu of three maneuvers calculated and analyzed in advance. As it turned out, the estimated flyby point was well within the desired region; and the contingency TCM was not needed.[44]

Autonomous Navigation. With the spacecraft delivery accuracies at encounter predicted to be 30 km (1σ) in crosstrack directions and 90 s (1σ) along track using ground-based navigation, autonomous navigation was needed near closest approach to enable the reliable return of cometary images. The same autonomous navigation code was used as for the earlier Annefrank and Wild 2 encounters. Differences in flyby speeds and distances necessitated changes in certain parameter settings. Autonomous navigation began at E-24 min, with the best available ground-based orbit solution as a starting point. At 30-s intervals, images of the cometary nucleus were captured and processed. At E-10 min, the accumulated images were used to perform a first least-squares solution for the spacecraft position and velocity relative to the comet. Subsequent solution updates were generated after each image was acquired and processed. These orbit solutions were used by the ACS to compute the correct attitude for aligning the scan mirror plane and the mirror controller to point the mirror at the comet. At E-5 min, the spacecraft executed a roll maneuver to place the nucleus in the scan mirror plane. The encounter science imaging sequence began at E-4 min, with images taken every 6-8 s and every second or third such image processed for autonomous navigation. Autonomous navigation terminated at E+90 s.[43,44]

The flyby took place at a radial distance of 181 km and a speed of 10.9 km/s, a combination that was at the limit of the scan mirror's rotation rate capability. The comet was successfully tracked through closest approach, with the nucleus in the camera field of view in all 72 planned images. The final computed spacecraft state correction amounted to about 13 km in crosstrack directions (almost all radial) and 16 s in encounter time. (A timing error of 2 min or more would have resulted in a loss of high-rate imaging data.) The predictions of comet rotational phase were also confirmed as accurate, so that the Deep Impact mission's impact site was visible in images. The Stardust-NExT optical navigation experience underscored the desirability of having reaction wheels for attitude control in missions of this type, which would have resulted in less image smearing, a better cometary signal-to-noise ratio, and less telemetry contention between optical navigation and attitude control jet firing information. The small amount of remaining propellant was consumed and the spacecraft decommissioned on 24 March 2011.[43,44,45,46]

Hayabusa

The interplanetary flight and near-asteroid operations of JAXA's Hayabusa mission have been described in References 4 and 5 and references listed therein, as well as Reference 48. Powered flight using an ion engine continued until 27 March 2010 for the purpose of returning the spacecraft to the vicinity of Earth. Subsequently, a series of TCMs was performed using the ion engine to accurately target the spacecraft for conditions at Earth entry consistent with an accurate delivery of the sample return capsule (SRC) to Australia's Woomera Prohibited Area (WPA). The TCMs were calculated by targeting for specific values of orbit periapsis radius and time of periapsis, taking into account the attitude constraints that the solar array panel be properly illuminated and the ion engine nozzle interior not be illuminated. (The chemical propulsion system would have allowed less constrained TCM execution but was not available because of a propellant leak several years earlier.) Radiometric tracking data for orbit determination were provided by the tracking facilities of JAXA and the DSN. While JAXA had primary responsibility for spacecraft navigation, JPL personnel provided support in the areas of orbit determination, maneuver verification and observation, and entry, descent, and landing verification.[48,49,50]

The first TCM took place from 4 to 6 April, provided a ΔV of 2.1 m/s, and was less accurate than expected in execution. The second and third TCMs took place from 1 to 4 and 22 to 26 May, provided ΔVs of 3.4 and 5.1 m/s, and were more accurately executed. These first three TCMs all targeted for a close flyby of the Earth, rather than atmospheric entry, and took place over several days due to the low thrust level. The fourth TCM took place from 3 to 5 June, provided a ΔV of 2.8 m/s, and targeted for WPA for the first time. The fifth TCM took place on 9 June and provided a ΔV of 0.1 m/s. These TCMs were substantially limited to the downtrack direction due to spacecraft attitude constraints mentioned above. The TCMs were sometimes redesigned while being executed. The orbit determination accuracy over the last 100 days of flight was better than expected, due to smaller than anticipated nongravitational forces and the availability of more radiometric tracking data than planned. In spite of this uncertainty reduction, the five TCMs were considerably larger than anticipated (though still feasible to implement), due to the need to work around various spacecraft component failures and the resulting constraints.[48,49,50]

The SRC separated from the main spacecraft three hours before atmospheric entry on 13 June, achieving an entry flight path angle of -12.31 deg at the entry radius of 6573.7 km. The unprotected main spacecraft was destroyed upon entry. The SRC jettisoned its forebody and aftbody heatshields at an altitude of several km. A parachute was deployed a fixed number of seconds after a sensed deceleration of 5 *g*s. A timer-based backup parachute deployment trigger was available also, but not needed. The remaining portion of the SRC, its instrument module (IM), began transmitting a beacon signal 8 s after parachute deployment. Four radio direction finding sites deployed at WPA then tracked this beacon signal. The IM was located on the ground by a beacon receiver-equipped helicopter less than 30 min after it had landed.[49,50]

With no TCMs performed during the last four days of flight, the instrument module landed twenty-some km from the intended landing point (well within the allowable range), but only 500 m from the landing point estimated on 12 June based on the most current wind predictions. Although the sampling process at the asteroid years earlier had not worked as intended, the instrument module was nevertheless found to contain small particles of asteroidal material.[48,49]

Rosetta

Third Earth Flyby. The early interplanetary flight of the European Space Agency's Rosetta spacecraft, including flybys of Earth, Mars, Earth, and the asteroid Steins, has been described in References 4 and 5 and references listed therein, as well as Reference 51. A third Earth flyby was targeted by a 7-m/s maneuver on 19 March 2009. The 13 November flyby was at an altitude of 2480 km. In addition to providing an essential gravity assist (increasing the heliocentric speed by 3.6 km/s), this flyby offered the opportunity to track the Earth and moon as extended targets in preparation for the subsequent asteroid flyby.[52,53]

Lutetia Flyby. Tracking to support a flyby of the roughly 121x101x75-km, main-belt asteroid 21 Lutetia began on 4 February 2010. Two-way coherent Doppler and range data were collected, primarily from ESA's 35-m antenna at New Norcia, Australia. From 25 May to the July flyby, there were 35 tracking passes involving DSN stations (at Goldstone and Madrid). Determination of the ephemeris of Lutetia initially relied on astrometric data from 31 observatories – 1630 right ascension and declination measurements recorded between 1866 and 2010, with the post-1990 measurements weighted more heavily.[54,55]

Beginning 31 May, optical data were acquired from three on-board cameras, with imaging sessions initially twice per week and then daily beginning 28 June. The incorporation of these optical data allowed the position and velocity components of the spacecraft and the asteroid to be determined simultaneously, rather than through two separate processes. As in the earlier Steins flyby, solution inconsistencies became apparent, with the ground-based astrometric observations containing systematic errors due to biases in the star catalogs used for data reduction. As a result, increased data weighting was subsequently applied to those observatory data that had been reduced with either the USNO CCD Astrograph Catalog-2 (UCAC-2) or the Tycho-2 Catalogue, both quite accurate.[54]

An approach TCM of 27.5 cm/s was executed on 18 June. The 15.0-km/s flyby took place on 10 July 2010 at a closest-approach distance of about 3170 km. An hour before the closest approach, the spacecraft switched into an asteroid flyby mode, in which the asteroid was tracked by a navigation camera and the spacecraft attitude adjusted to maintain science instrument pointing. In the Steins flyby of 2008, the pointing performance had been degraded, due to the presence of warm pixels and certain attributes of the target body and the navigation camera software. For the Lutetia flyby, the warm pixels were characterized in advance; and adjustments were made to the camera's integration time and detection threshold. As a result of these changes, the asteroid was tracked with sufficient accuracy to allow the acquisition of high-resolution images with the science narrow-angle camera.[53,54]

From the flyby tracking data, the gravitational parameter of Lutetia was estimated to be 0.108 km^3/s^2 ± 1.7% (1σ). In preparation for operations near comet 67P/Churyumov-Gerasimenko in 2014, 1788 landmark observations were generated from science camera images acquired around the closest approach to Lutetia; and a coarse shape model was computed. After the encounter, an improved landmark mapping technique based on stereo-photoclinometry and stereo-photogrammetry was applied to 5926 landmark observations in 90 images from various distances. The automated landmark observations obtained in this fashion were found to be more accurate than the previous manually generated observations, resulting in more accurate orbit and asteroid dynamics estimation for the encounter, successfully testing techniques intended for operational use later in the mission.[53,54,56]

Between 17 and 24 January 2011, preliminary rendezvous maneuvers (six in all, due to thruster performance issues) were executed to allow an eventual comet rendezvous. A trim maneuver was executed on 17

February, bringing the maneuver set ΔV up to 788 m/s. On 8 June, the spacecraft was spun up and put into a state of hibernation, to last until early 2014, to decrease power consumption while farthest from the sun.[57]

EPOXI

The primary Deep Impact mission and two subsequent Earth gravity assist flybys in the extended EPOXI mission have been described in References 4 and 5 and references listed therein, as well as References 43 and 58. As in the primary Deep Impact mission, X-band Doppler, range, and ΔDOR data were collected and processed throughout the extended mission for radiometric orbit determination.[59]

Earth Gravity Assist-3. A TCM of 0.1 m/s was executed on 28 May 2010 to set up a third Earth gravity assist flyby on 27 June. The ephemeris of the eventual target body, periodic comet 103P/Hartley 2, was updated before this TCM using all available ground-based observations as of April, with the comet's predicted position at encounter shifting by about 2200 km as a result. The Earth flyby took place at a radial distance of 36,875 km. A TCM of 0.8 m/s was executed on 19 July, subsequent to the Earth flyby. Whereas small unexplained increases in Earth-relative velocity had been observed in Earth gravity assists in the Galileo, Near Earth Asteroid Rendezvous, and Rosetta missions, none were observed in the three EPOXI Earth flybys (which took place at considerably greater distances). The B-plane delivery accuracies for the three flybys varied from 700 m to 16 km.[59,60,61,62]

Cruise and Cometary Approach Phases. Optical navigation imaging began 60 days before encounter with Hartley 2. As in the primary Deep Impact mission, the Medium Resolution Imager was used for optical navigation, due to focus problems with the High Resolution Imager. "Snip boxes" (each 250 by 250 pixels in size), rather than full imaging frames, were transmitted to the ground for the comet and up to five stars. Picture registration for initializing precision centroiding routines was performed at first manually and later in an automated fashion. Once optical navigation had begun, it became apparent that the ground-based ephemeris for Hartley 2 contained large errors, which were due to the volatile nature of the comet's outgassing and the difficulty in modeling this behavior. With optical navigation data used to improve the cometary ephemeris, a TCM of 1.5 m/s was executed on 29 September, to shift the spacecraft location at encounter by almost 4000 km. A subsequent TCM of 1.6 m/s was executed on 27 October to shift the target location by several hundred km, based on additional data and a further refinement of the cometary ephemeris. A final TCM of 1.4 m/s was executed on 2 November to improve the accuracy of the Hartley 2 encounter on 4 November 2010, based on an updated model of cometary outgassing.[47,59,60,63,64]

During the ground-based optical navigation process, a number of comet centroiding algorithms were tried, with a Gaussian fit to a 5 by 5 array of pixels, centered on the brightest pixel and with an adjustable background value, found to work best. For the simpler centroiding of stellar images, a similar fitting procedure was used, but on an 11 by 11 array of pixels. Post-fit comet position residuals were about 0.1-0.2 pixels. 692 usable optical navigation pictures were obtained between E-60 days and E-26 h, at rates varying from one picture every six hours to hourly (with no pictures taken during certain blocks of time). Science images taken after E-26 h were also processed as optical navigation images (with some modifications needed as the cometary nucleus became fully resolved) and were useful in reconstructing the spacecraft trajectory near encounter. Whereas the spacecraft was designed such that the high-gain antenna could point at Earth while the imaging systems were pointed at comet 9P/Tempel 1 on approach in 2005, differences in geometry made this impossible on approach to Hartley 2. Thus, large slews away from comet pointing were needed to downlink data.[63,64]

Autonomous Navigation. With the flyby spacecraft having successfully navigated the encounter with Tempel 1 and there being no longer an impactor spacecraft, performing autonomous navigation during the Hartley 2 encounter seemed at first blush to be relatively simple. Only parameter updates, rather than code modifications, were needed. However, autonomous navigation was not engaged during the closest approach to Tempel 1, since the spacecraft turned to a shielded attitude during the flyby. There was no need to seek this degree of protection when passing roughly 700 km from Hartley 2; and imaging data around this time, dependent upon the use of autonomous navigation for accurate pointing, were of high interest. In addition, possible ACS/autonomous navigation velocity estimate interactions, such as had occurred with the impactor spacecraft, needed to be taken into account.[43]

Autonomous navigation began at E-50 min – later for the smaller and more elongated Hartley than for Tempel 1 – with the best available ground-based orbit information used for initialization. Advance calculations indicated that the comet might exit the Medium Resolution Imager's field of view at E-10 min without the use of autonomous navigation. Optical navigation images were processed roughly every 15 s, with the first on-board orbit solution generated at E-42 min. Subsequent solution updates were generated every minute, as had been done during the encounter with Tempel 1. The most recent eight min of data were processed to generate orbit solutions, with older data discarded. Observations from E-7 to E+2 min were deweighted relative to measurements made at other times and were based on locating the centroid of all pixels above a brightness threshold in a defined image subframe, rather than seeking the largest "blob" above a threshold. Attitude estimation errors accumulated during the period of rapid spacecraft slewing near closest approach and were absorbed as position errors in the autonomous navigation calculations. Once the star trackers reacquired lock after closest approach, these attitude estimation errors were reduced; and the accuracy of the orbit solutions improved. With the information in the imaging data becoming weaker, the final on-board orbit determination solution was calculated at E+30 min. The autonomous navigation process was terminated at E+50 min, and ground-based orbit determination resumed.[59,65]

The on-board calculations were accurate enough that all 307 images taken included the comet in the field of view, which would not have been achievable with ground-based navigation given the downtrack position uncertainty. The spacecraft flew past the comet at a radial distance of 694 km and a relative speed of 12.3 km/s. The flyby location was about 6 km from the desired B-plane location, and the closest approach time was accurate to better than 1 s.[59]

Requirements on knowledge of the spacecraft's comet-relative trajectory were more stringent than those on trajectory control. Comet-relative trajectory knowledge of ±3.5 km (3σ) was needed to maintain the comet within the Medium Resolution Imager's 10-mrad field of view at closest approach, which translated to a time-of-flight knowledge of ±0.3 s (3σ). In contrast, the final ground-based trajectory uplinked to the spacecraft 24 h prior to the flyby was uncertain in time of flight to ±3.1 s (3σ). Hartley 2 was successfully tracked through the encounter; however, it was systematically displaced from the center of the imaging frames. It turned out that the commanded off-center displacement needed for imaging the impactor landing site on the sunlit portion of Tempel 1 had never been cleared from the spacecraft's memory.[43,65]

Dawn

Interplanetary Cruise. The early interplanetary flight of the Dawn mission, including a Mars flyby, has been described in Reference 5 and references listed therein, as well as Reference 66. Cruise operations during interplanetary flight consisted primarily of thrusting with the Ion Propulsion System (IPS), employing three gridded electrostatic ion thrusters, with only one used at a time. When thrusting was optimal, it was applied about 95% of the time, interrupted by weekly communication with the DSN for data downlink, commanding, and radiometric navigation. The flight team followed a repeated pattern of designing and sequencing five weeks of thrusting, uplinking those commands to the spacecraft, and then developing the subsequent thrusting plan.[66,67]

Various tests and calibrations of the two 19-mm aperture, visible-light framing cameras, used for both science imaging and optical navigation, were performed during cruise. These included photometric calibrations (using standard stars), point-spread function measurements, and geometric calibrations (using an open star cluster) for measuring the focal length, alignment, and distortion parameters. In addition, IPS thruster calibrations were performed in the input power regimes that would be of interest near the destination body, the main-belt asteroid 4 Vesta.[67,68,69]

Approach to Vesta. The Vesta approach mission phase began on 3 May 2011 with the acquisition of the first optical navigation image of Vesta (already an extended body subtending about 5 pixels) from a distance of about 1,200,000 km. Limb scans were used as an optical navigation data type up to late approach (with Vesta subtending as many as 500 pixels); and landmarks were used from mid-approach (with Vesta subtending 60 or more pixels) until the eventual departure from Vesta. The limb scan method was used to deduce the center of figure of the extended body and was typically accurate to 1-2% of body radius for a body subtending 100 or more pixels. A landmark was defined to be a vector from the body's center to the center of a small digital terrain and albedo model or landmark map extending over a fraction of the body's surface. It did not need to correspond to a specific surface feature – only a modest distinguishing contrast in surface brightness was necessary.[47,67,69,70]

Optical navigation observations were star-relative as long as Vesta subtended less than the full field of view (and did not saturate image areas that included stars). Because of the large brightness ratio between Vesta and background stars and the limited dynamic range of the photodetector, the optical navigation imaging alternated between long star exposures and short Vesta exposures. Based on ACS accuracy characteristics, the correlation accuracy of Vesta and star images was thought to be about 0.2 pixels (1σ).[69]

During the approach phase, 24 optical navigation sessions were scheduled (with 23 actually executed). Four of these sessions were rotation characterizations, which lasted for full rotations of Vesta. The first rotation characterization was performed at a distance of 120,000 km. Dawn was the first mission to orbit a massive solar system object that had not been visited previously by a flyby spacecraft. Consequently, there were large uncertainties in such physical properties as its rotational pole and gravity field. At the start of the approach phase, knowledge of Vesta's rotational pole and gravity field were derived from Hubble Space Telescope imagery and shape models deduced from that imagery, with the pole orientation known only to about ±8 deg. Optical navigation data, during rotation characterization imaging events in particular, allowed a substantial improvement in pole knowledge. The construction of landmarks and a shape model began with the first rotation characterization session.[67,69,71,72]

A baseline thrust profile was developed before approach and then updated with the latest knowledge of the orbit and physical parameters before implementation. On 27 June the IPS unexpectedly stopped thrusting. The problem was resolved by power cycling the controller electronics. The thrust profile was redesigned to compensate for the thrust outage by thrusting through a planned coast period (and removing a planned optical navigation session as a result).[66,67]

A second rotation characterization was performed on 9-10 July from a distance of 37,000 km. It included a search for moons orbiting Vesta, with none detected. Capture into a bound orbit around Vesta occurred on 16 July, at an altitude of about 16,000 km. A third rotation characterization began on 22 July at an altitude of about 5200 km, lasted for several days, and allowed a preliminary reconnaissance of Vesta and an improved determination of the orientation of its pole, based upon both radiometric and optical data, particularly the latter. This improved pole orientation estimate was needed before completing the final designs of the various upcoming science orbits and orbit transfers.[67,69,73]

Additional optical navigation sessions allowed accuracy improvements in the landmarks and the shape model. Some of the early landmark images were eventually deleted from the data set as higher-resolution images became available. Ultimately, 61,602 observations of 816 landmarks, derived from 255 images and with post-fit root mean square (RMS) residuals of 554 m, were available at the end of the approach phase. By the end of this phase, the best estimate of the Vesta ephemeris had shifted by 20 to 40 km relative to that determined solely from ground-based observations.[67,69,70]

During the approach phase, spacecraft trajectory predictions needed to be sufficiently accurate that the slit of the visible and infrared spectrometer could be pointed at the desired region of Vesta's surface, taking into account the time delays between acquiring the tracking data to be used for orbit determination and observing Vesta with the spectrometer. (There were also less stringent pointing requirements associated with framing camera imaging.) The worst pointing error at the time of any of the eight spectrometer observations turned out to be 9 mrad, and all observations were successful.[72]

Thrust sequences (five in total) on the 100-day approach to Vesta were built over time intervals of four weeks or one week, since trajectory control accuracies were not yet critical and time remained for correcting errors by subsequent thrusting, as the radial distance of the spacecraft from Vesta dropped from 1,200,000 to 3,000 km.[71]

Spacecraft thrusting terminated upon achieving the survey orbit on 2 August. This culminated a journey to Vesta in which the spacecraft had been thrusting for nearly 70% of the time since launch, while achieving a post-launch propulsive ΔV of 6.7 km/s (augmented by a Mars gravity assist ΔV of 2.6 km/s).[67,73]

Survey Orbit. The Dawn spacecraft was inserted, in sequence, into four major science orbits about Vesta (the first three of which are covered in this paper), with the first being the 2735-km altitude survey orbit.

(Altitudes stated here are referenced to an idealized body with a mean radius of 265 km, although Vesta is more accurately represented as a triaxial ellipsoid with semiaxes of 285, 277, and 226 km.) With the first few days in this orbit devoted to refining orbit estimates and updating command sequences, the survey science phase began on 11 August.[67,71]

The survey orbit science phase consisted of seven full orbits (of 69-h period) about Vesta – six for data collection and a seventh to allow the Navigation Team to prepare for the transfer to the first high altitude mapping orbit (HAMO-1). The survey orbit and subsequent science orbits were near polar, with inclinations targeted to be between 85 and 95 deg, to allow eventual observation of all of Vesta. The survey orbit inclination, targeted for 90 deg, wound up being 88.9 deg, reflecting the uncertainty in the pole orientation at the time of the final orbit design. The angle between the orbit plane and the Vesta-sun line was required to be $\leq$ 15 deg in the survey orbit, to allow good illumination while avoiding eclipses. Terminator crossing times were required to be controlled to $\pm$45 min, to ensure the downloading of science data. Six optical navigation sessions were carried out (one per orbit). In addition, several image mosaics were acquired. Older images of inferior resolution were discarded, and landmarks were added or rebuilt at higher accuracy. Once in the survey orbit, no maneuvers were needed to satisfactorily maintain the orbit.[67,69,70,71,73]

Orbit determination in the Dawn mission was performed using a batch-sequential, unit upper triangular-diagonal (U-D) factorized Extended Kalman Filter in the Jet Propulsion Laboratory's MONTE software (which was used for other missions as well). The parameters estimated for operations near Vesta included the spacecraft position and velocity at a reference time (or epoch); Vesta's gravity field (with degree and order varying with mission phase), pole, prime meridian, rotation rate, and ephemeris; IPS thrust parameters; RWA AMDs (unbalanced about two axes and occurring every 1 to 3 days); solar radiation pressure; random nongravitational accelerations; and per-pass range measurement biases. Tracking station locations, tropospheric and ionospheric signal delays, and Earth orientation parameters were considered as error sources, rather than estimated. The orbit determination process needed as inputs various subsystem performance predictions related to spacecraft attitude, IPS maneuvers, RCS firings, and antenna schedule. As the planned activities were executed, the as-flown performance was transmitted to the ground in telemetry; and the predictions were replaced by the telemetry data.[5,74]

Instrument pointing requirements in the survey orbit were relatively loose at 2 deg. Only one update to the on-board spacecraft ephemeris was needed, after which pointing errors never exceeded 0.2 deg. Orbit reconstruction accuracy requirements (1σ) were 200 m in position and 10 cm/s in velocity. Vesta's pole orientation was determined to about 0.04 deg.[70,72,74]

Transfers Between Science Orbits. Transferring from one orbit around Vesta to another required the use of time-varying thrust directions, since the durations of IPS thrust segments were long compared to the orbital period about Vesta. Changing spacecraft orientation while thrusting imposed dynamic constraints, in addition to geometric pointing constraints, on the thrusting profile, which increased the coupling between the trajectory design and attitude control processes relative to traditional interplanetary missions, in which propulsive burns could be approximated as impulsive. The IPS engines were gimballed to maintain spacecraft attitude about the two directions orthogonal to the thrust vector. Attitude about the thrust vector was maintained through hydrazine thrusters or reaction wheels. Due to the low level of thrust, the IPS engine had limited control authority in angular rate and acceleration. In addition, gyroscopic torques had to be overcome as the spacecraft rotated. For relatively low orbits, gravity gradient torques became significant, given that the solar arrays extended to a total length of 20 m. These various considerations made it difficult to match the actual thrust vector to that desired (while maximizing the sunlight incident on the solar arrays) and mandated that checks be made of the accuracy with which the thrust profile could be achieved before transmitting commands for its implementation. Traditional low-thrust trajectory optimization criteria, such as minimizing ΔV or transfer time, sometimes resulted in thrust direction time evolutions that could not be accomplished with Dawn's ACS. Unachievably high angular rates would be commanded when the desired thrust direction was near the sun or anti-sun direction. Instead, optimal control objectives penalizing undesired thrust directions were developed and put into use. In addition, thrust vector profiles needed to be computed relatively quickly, so as to be based on reasonably current (and hence accurate) orbit information, and then implemented promptly.[66,74,75,76]

Each orbit transfer required a robust plan accounting for uncertainties in maneuver execution, orbit determination, and physical characteristics of Vesta. Such a plan had to satisfy the requirements of the target science orbit and spacecraft safety, while including margin to accommodate unforeseen anomalies and being compatible with spacecraft capabilities and supportable by a small operations team. The transfer orbits consisted of both powered flight and coasting periods for obtaining tracking data for orbit determination, downloading spacecraft engineering data, and uploading command sequences to the spacecraft, posing a scheduling challenge to balance the transfer time between these competing, essential activities. Few optical navigation sessions were scheduled, given the limited time available for acquiring tracking data or images. The placement of coasting periods had to be decided well in advance in order to schedule DSN tracking and the work of the flight team. Similarly, any image acquisition opportunities had to be scheduled well before the illumination conditions for the actual trajectory were known.[69,71,74]

Because the Dawn spacecraft was bound for a second target (1 Ceres) after exploring Vesta, the total time that could be spent near Vesta was limited. Thus, the transfers between the various orbits around Vesta needed to be reasonably fast, so as to allow as much time as possible in the various science orbits, while being safe even in the event of a loss of spacecraft control for several weeks. With the transfer orbits being sensitive to the gravity field of Vesta, which was not well known initially, the transfer orbits went through several design cycles, as knowledge of the gravity field improved. A fourth-degree gravity field deduced from survey orbit data allowed the design of a transfer orbit to HAMO-1, while meeting a stringent ground-track requirement for HAMO-1.[71,72]

Beginning with the transfer from the survey orbit to HAMO-1, a three-day build timeline was typically used for constructing thrust sequences. Four such sequences (each seven days in length) were used for this particular transfer. Since the timing of thrusting and coasting during the transfer phases was not known until after DSN tracking schedules had been established (a month or more in advance), the Dawn project reserved continuous coverage throughout the Vesta operational period, releasing tracks as subsequent analysis revealed them to be unnecessary.[71]

Due to the low level of thrust provided by the IPS (46-76 mN near Vesta's heliocentric distance), thrusting took place much of the time during orbit transfers. The spacecraft could not be tracked while thrusting because the on-board transmitter had to be turned off to maximize the power available to the IPS. Coast periods were typically eight hours long, with six or fewer hours available for Doppler and range data and the remaining time allocated to turning between IPS thrusting and high-gain antenna Earth-pointing attitudes. Thus, IPS thrusting activities were not observed directly through tracking data. Instead, thrusting behavior was inferred through engineering telemetry data recorded and then downlinked during the coast periods. IPS thrusting periods were estimated as finite burns with time-varying thrust levels (piecewise constant, since there were 112 discrete thrust throttle levels, selectable according to the solar array power available) and 1σ a priori uncertainties in thrust magnitude and direction of 0.25% and 0.25 deg.[71,74]

Dawn's trajectories were designed with a software toolset called Mystic, which was built to compute, analyze, and visualize optimal high-fidelity, low-thrust trajectories. A new Monte-Carlo low-thrust trajectory statistical analysis tool, called Veil, was built to work with Mystic, since no existing statistical maneuver analysis tools relying on the linear mapping of a state transition matrix were adequate for studying Dawn's highly nonlinear and complex sequences of maneuvers for orbit transfers. Veil was used to reoptimize trajectories to the science orbit targets while simulating errors in orbit determination, low-thrust maneuver execution, attitude control thrusting, and Vesta's physical parameters.[71,73,77]

Thrusting to depart from the survey orbit began on 31 August and continued over numerous spiraling revolutions until arrival at HAMO-1 on 28 September. The four thrusting segments were each designed to return the spacecraft to some "waypoint" on the reference trajectory – a different approach than had been used to achieve the survey orbit, where the trajectory was reoptimized after each thrusting segment to achieve the desired end state and no intermediate waypoints were specified. The four thrusting segments accomplished ΔVs of 25.8, 26.7, 12.7, and 0.2 m/s, with the last maneuver being purely statistical and thus quite small. The last maneuver had been scheduled to execute four days earlier, but failed to execute at that time. During the transfer to HAMO-1, additional, higher-resolution optical navigation images became available, resulting in a set of 14,828 landmarks, with post-fit RMS residuals of 62 m, derived from more than 1.2 million observations.[67,69,73]

HAMO-1. With the first few days in the 685-km altitude HAMO-1 orbit devoted to engineering reconfiguration and checkout activities as well as resolving an entry into safe mode, the HAMO-1 science phase began on 1 October. This mission phase was divided into six cycles of 10 orbits, each cycle fully mapping Vesta's illuminated surface. The orbit period was 12.3 h, and equatorial crossings were roughly evenly spaced. The angle between the orbit plane and the Vesta-sun line was required to be 25-35 deg. Terminator crossing times were required to be controlled to ±10 min to ensure the downloading of science data. However, once in HAMO-1, no maneuvers were needed to satisfactorily maintain the orbit.[67,69,71,73]

Instrument pointing accuracy in HAMO-1 was required to be no worse than 1 deg, primarily to control the overlap in framing camera images. Provisions were made for uploading a new spacecraft ephemeris at the start of each orbit cycle, but the achieved pointing accuracy was such that only half of these opportunities were used. The gravity field of Vesta determined from survey orbit tracking data was sufficiently accurate to produce a 30-day error accumulation of only 0.5 km in spacecraft position while in HAMO-1. Orbit reconstruction accuracy requirements (1σ) were 70 m in position and 3 cm/s in velocity.[72,74]

During HAMO-1 there was no dedicated optical navigation imaging, but all of the science clear filter images acquired for topography were used for optical navigation as well. The addition of 2533 such images resulted in about 69,250 landmarks, with post-fit RMS residuals of 28 m, being available for processing in subsequent orbits. One discovery early in HAMO-1 was that the center of the coordinate system of the landmarks was shifted by about 700 m (in the polar direction) relative to Vesta's center of mass, as established by the radiometric data. This was most likely due to the lack of optical landmarks above 45 deg north latitude, due to the solar illumination conditions.[69,70]

Once adequate gravity field knowledge (an eighth-degree field) had been obtained while in HAMO-1, over 200,000 different low altitude mapping orbit (LAMO) designs were analyzed for long-duration orbit stability and compliance with ground-track requirements. The implementation (coupled with final design updates) of a six-week transfer to this lower orbit began on 1 November. In order to reach LAMO, the spacecraft had to pass safely through a 1:1 orbit-period resonance with Vesta's rotation period of 5.34 h, near which the spacecraft was subject to significant orbit perturbations. Ten maneuver design cycles were planned for the HAMO-1 to LAMO transfer. In two cases, with precise flight path control and spacecraft safety overriding considerations, the sequence build timeline was shortened to 36 h. The maneuver targeting waypoint 8 (of 10) terminated prematurely, resulting in an inaccurate delivery to waypoint 8 and the cancellation of the already computed, but no longer suitable, maneuver targeting waypoint 9. Nevertheless, LAMO was achieved by executing a relatively small (2.4 m/s) final maneuver. Based on experience gained during the survey orbit to HAMO-1 transfer, the HAMO-1 to LAMO transfer was carefully designed to avoid thrusting near the sun/anti-sun line. Thus, aside from the waypoint 8-9 issue, trajectory excursions away from the reference trajectory were generally smaller during the latter transfer, with attitude-rate constraints anticipated well enough to avoid forcing significant trajectory deviations.[66,67,71,73]

LAMO. On 12 December the LAMO science phase began, with the mean altitude being 210 km and the orbit period 4.3 h. Equatorial crossings were to be separated by no more than 6 deg. The angle between the orbit plane and the Vesta-sun line was required to be $\leq$ 60 deg. Terminator crossing times were required to be controlled to ±10 min. This planned 70-day mission phase was augmented with the operational schedule margin of 40 days, which had been allocated to accommodate any anomalies that might have arisen but had not actually been used. An updated power analysis indicated that the spacecraft could remain for an additional 40 days at Vesta and still arrive at Ceres on schedule. Thus, the total time in LAMO was extended to 141 days. Five pairs of orbital maintenance maneuvers were executed with the IPS to control the trajectory sufficiently to maintain the science observation plan, avoid eclipses, and preserve the desired orbital stability characteristics. Ten such maneuver pairs had been originally planned, but a few were cancelled because the trajectory errors were small. In addition, the spacecraft was unable to execute the maneuvers targeting waypoints 3 and 6. Recovery maneuvers successfully targeted the following waypoints in each case. All of the orbit maintenance maneuvers were relatively small (averaging 0.34 m/s per weekly-separated pair) and in inertially-fixed directions (which made it simpler to accommodate ACS constraints).[67,69,71,73]

The on-board ephemeris during LAMO was required to be accurate to 0.4 deg in phase to avoid problematical gravity gradient torques associated with inadvertently pointing the spacecraft away from the center of Vesta, which would cause unanticipated accumulations of angular momentum in the RWAs. Consequently, ephemeris updates were scheduled twice per week. On seven occasions, pointing errors greater than 0.4 deg resulted – four times due to large AMDs, twice due to procedural conflicts or errors, and once due to a safing event. Orbit reconstruction accuracy requirements (1σ) were 20 m in position and 0.5 cm/s in velocity.[72,74]

During LAMO, there was no dedicated optical navigation imaging; but all of the science clear-filter images were used for optical navigation as well. Inconsistencies arose in trying to register LAMO surface images relative to the landmark set as of the end of HAMO-1. This led to a small updating of Vesta's rotation rate relative to the prior value determined from ground observations. Throughout LAMO, orbit prediction and trajectory control accuracies improved due to refinements in the knowledge of Vesta's gravity field and the understanding and prediction of AMDs. A 13x13 gravity field was estimated in LAMO. Even without the improvements in the gravity field derived from LAMO data, the end-of-HAMO-1 gravity field would have produced only a 25-km trajectory dispersion over the duration of LAMO. By the end of LAMO, the landmark database had grown to 70,496 landmarks.[69,70,73,74]

CONCLUSION

Deep space navigation capabilities, which had evolved enormously from the 1960s through the mid-2000s, continued to evolve thereafter, benefiting the 11 planetary missions that have been described. Increases in computing power allowed more accurate orbit determination by permitting more detailed dynamical and measurement modeling and allowing large numbers of scenarios to be investigated. Accurately controlled gravity assist flybys of planets and planetary satellites allowed the execution of missions that would have been infeasible using chemical propulsion alone. A spacecraft was accurately inserted into various orbits around the second-largest main-belt asteroid using an ion propulsion system. The challenge of accurately modeling spacecraft nongravitational accelerations, particularly due to attitude control subsystem activity, was a recurring theme.

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REFERENCES

[1] L.J. Wood, "The Evolution of Deep Space Navigation: 1962–1989," *Advances in the Astronautical Sciences: Guidance and Control 2008*, Vol. 131, ed. M.E. Drews and R.D. Culp, Univelt, San Diego, 2008, pp. 285-308.

[2] L.J. Wood, "The Evolution of Deep Space Navigation: 1989–1999," *Advances in the Astronautical Sciences: The F. Landis Markley Astronautics Symposium*, Vol. 132, ed. J.L. Crassidis, et al., Univelt, San Diego, 2008, pp. 877-898.

[3] L.J. Wood, "The Evolution of Deep Space Navigation: 1999–2004," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2014*, Vol. 152, Pt. I, ed. R.S. Wilson, R. Zanetti, D.L. Mackison, and O. Abdelkhalik, Univelt, San Diego, 2014, pp. 827-847.

[4] L.J. Wood, "The Evolution of Deep Space Navigation: 2004–2006," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2017*, Vol. 160, Pt. IV, ed. J.W. McMahon, Y. Guo, F.A. Leve, and J.A. Sims, Univelt, San Diego, 2017, pp. 3271-3292.

[5] L.J. Wood, "The Evolution of Deep Space Navigation: 2006–2009," *Advances in the Astronautical Sciences: Astrodynamics 2018*, Vol. 167, Pt. IV, ed. P. Singla, R.M. Weisman, B.G. Marchand, and B.A. Jones, Univelt, San Diego, 2019, pp. 2985-3006.

[6] McNutt, R.L., Jr., et al., "The MESSENGER mission: Results from the first two Mercury flybys," *Acta Astronautica*, Vol. 67, Oct.-Nov. 2010, pp. 681-687.

[7] D.J. O'Shaughnessy, J.V. McAdams, P.D. Bedini, A.B. Calloway, K.E. Williams, and B.R. Page, "MESSENGER's use of solar sailing for cost and risk reduction," *Acta Astronautica*, Vol. 93, Jan. 2014, pp. 483-489.

[8] J.V. McAdams, D.P. Moessner, K.E. Williams, A.H. Taylor, B.R. Page, and D.J. O'Shaughnessy, "MESSENGER – Six Primary Maneuvers, Six Planetary Flybys, and 6.6 Years to Mercury Orbit," *Advances in the Astronautical Sciences: Astrodynamics 2011*, Vol. 142, Pt. III, ed. H. Schaub, B.C. Gunter, R.P. Russell, and W.T. Cerven, Univelt, San Diego, 2012, pp. 2191-2209.

[9] B.R. Page, et al., "Applying Experience from Mercury Encounters to MESSENGER's Mercury Orbital Mission," *Advances in the Astronautical Sciences: Astrodynamics 2011*, Vol. 142, Pt. III, ed. H. Schaub, B.C. Gunter, R.P. Russell, and W.T. Cerven, Univelt, San Diego, 2012, pp. 2251-2270.

[10] D.P. Moessner and J.V. McAdams, "The MESSENGER Spacecraft's Orbit-Phase Trajectory," *Advances in the Astronautical Sciences: Astrodynamics 2011*, Vol. 142, Pt. III, ed. H. Schaub, B.C. Gunter, R.P. Russell, and W.T. Cerven, Univelt, San Diego, 2012, pp. 2211-2230.

[11] S.H. Flanigan, D.J. O'Shaughnessy, and E.J. Finnigan, "Guidance and Control Challenges to the MESSENGER Spacecraft in Achieving and Operating from Orbit at Mercury," *Advances in the Astronautical Sciences: Guidance and Control 2012*, Vol. 144, ed. M.L. Osborne, Univelt, San Diego, 2012, pp. 735-752.

[12] P.D. Bedini, et al., "MESSENGER at Mercury: A mid-term report," *Acta Astronautica*, Vol. 81, Dec. 2012, pp. 369-379.

[13] B.R. Page, et al., "MESSENGER Navigation Operations During the Mercury Orbital Mission Phase," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. III, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 2825-2844.

[14] S.H. Flanigan, D.J. O'Shaughnessy, M.N. Wilson, and T.A. Hill, "MESSENGER's Maneuvers to Reduce Orbital Period During the Extended Mission: Ensuring Maximum Use of the Bi-Propellant Propulsion System," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. III, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 2811-2824.

[15] D.R. Stanbridge, et al., "Achievable Force Model Accuracies for MESSENGER in Mercury Orbit," *Advances in the Astronautical Sciences: Astrodynamics 2011*, Vol. 142, Pt. III, ed. H. Schaub, B.C. Gunter, R.P. Russell, and W.T. Cerven, Univelt, San Diego, 2012, pp. 2231-2249.

[16] L. Arona, M. Müller, G. Huguet, I. Tanco, and N. Keil, "Venus Express Solar Arrays Rotation Experiments to Measure Atmospheric Density," 22nd International Symposium on Space Flight Dynamics, São José dos Campos, Brazil, Feb.-Mar. 2011.

[17] P. Rosenblatt, S.L. Bruinsma, I.C.F. Müller-Wodarg, B. Häusler, H. Svedhem, and J.C. Marty, "First ever *in situ* observations of Venus' polar upper atmosphere density using the tracking data of the Venus Express Atmospheric Drag Experiment (VExADE)," *Icarus*, Vol. 217, Feb. 2012, pp. 831-838.

[18] S. Damiani, M. Lauer, and M. Müller, "Monitoring of Aerodynamic Pressures for Venus Express in the Upper Atmosphere During Drag Experiments Based on Telemetry," 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[19] T. Ichikawa, et al., "Orbit Determination Results of Akatsuki, (Planet-C) Mission – Venus Climate Orbiter," *Advances in the Astronautical Sciences: Astrodynamics 2011*, Vol. 142, Pt. II, ed. H. Schaub, B.C. Gunter, R.P. Russell, and W.T. Cerven, Univelt, San Diego, 2012, pp. 1571-1582.

[20] M.S. Ryne, et al., "Navigation Support at JPL for the JAXA Akatsuki (Planet-C) Venus Orbiter Mission," *Advances in the Astronautical Sciences: Astrodynamics 2011*, Vol. 142, Pt. II, ed. H. Schaub, B.C. Gunter, R.P. Russell, and W.T. Cerven, Univelt, San Diego, 2012, pp. 1799-1818.

[21] T. Ichikawa, et al., "Orbit Determination Demonstration for Akatsuki (Planet-C) Mission," 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[22] C. Hirose, N. Ishii, Y. Kawakatsu, C. Ukai, and H. Terada, "The Trajectory Control Strategies for Akatsuki Re-Insertion into the Venus Orbit," 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[23] Y. Kawakatsu, S. Campagnola, C. Hirose, and N. Ishii, "An Orbit Plan Toward Akatsuki Venus Reencounter and Orbit Injection," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2012*, Vol. 143, Pt. II, ed. J.V. McAdams, D.P. McKinley, M.M. Berry, and K.L. Jenkins, Univelt, San Diego, 2012, pp. 1535-1547.

[24] C. Hirose, N. Ishii, Y. Kawakatsu, C. Ukai, and H. Terada, "The Trajectory Control Strategies of Akatsuki for Venus Orbit Reinsertion," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. III, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 2909-2918.

[25] Y. Tsuda, et al., "Flight status of IKAROS deep space solar sail demonstrator," *Acta Astronautica*, Vol. 69, Nov.-Dec. 2011, pp. 833-840.

[26] Y. Tsuda, et al., "Achievement of IKAROS – Japanese deep space solar sail demonstration mission," *Acta Astronautica*, Vol. 82, Feb. 2013, pp. 183-188.

[27] M. Nakamiya, Y. Tsuda, and Y. Kawakatsu, "A Study of the Guidance Method for the Small Solar Power Sail Demonstrator, IKAROS," 22nd International Symposium on Space Flight Dynamics, São José dos Campos, Brazil, Feb.-Mar. 2011.

[28] J. Van der Ha, Y. Mimasu, Y. Tsuda, and O. Mori, "Solar and Thermal Radiation Pressure Models and Flight Evaluation for IKAROS Solar Sail," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2014*, Vol. 152, Pt. I, ed. R.S. Wilson, R. Zanetti, D.L. Mackison, and O. Abdelkhalik, Univelt, San Diego, 2014, pp. 789-806.

[29] T.J. Martin-Mur, G.L. Kruizinga, P.D. Burkhart, M.C. Wong, and F. Abilleira, "Mars Science Laboratory Navigation Results," 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[30] G.L. Kruizinga, et al., "Mars Science Laboratory Orbit Determination," 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[31] M.C. Wong, J.A. Kangas, C.G. Ballard, E.D. Gustafson, and T.J. Martin-Mur, "Mars Science Laboratory Propulsive Maneuver Design and Execution," 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[32] T.J. Martin-Mur, G. Kruizinga, and M. Wong, "Mars Science Laboratory Interplanetary Navigation Performance," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. I, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 473-485.

[33] E.D. Gustafson, G.L. Kruizinga, and T.J. Martin-Mur, "Mars Science Laboratory Orbit Determination Data Pre-Processing," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. II, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 1145-1158.

[34] F. Abilleira, "2011 Mars Science Laboratory Trajectory Reconstruction and Performance from Launch through Landing," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. I, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 487-503.

[35] P.F. Thompson, E.D. Gustafson, G.L. Kruizinga, and T.J. Martin-Mur, "Filter Strategies for Mars Science Laboratory Orbit Determination," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. II, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 1159-1176.

[36] S.W. Asmar, "Communicating by Doppler: Detecting Spacecraft Dynamics During Critical Maneuvers," SpaceOps 2012 Conference, Stockholm, Sweden, June 2012.

[37] F.J. Pelletier, et al., "Cassini Orbit Determination Performance (July 2008 – December 2011)," SpaceOps 2012 Conference, Stockholm, Sweden, June 2012.

[38] R.M. Beswick and D.C. Roth, "A Gilded Cage: Cassini/Huygens Navigation Ground Data System Engineering for Security," SpaceOps 2012 Conference, Stockholm, Sweden, June 2012.

[39] C.G. Ballard, J. Arrieta, Y. Hahn, and P.W. Stumpf, "Cassini Maneuver Experience: Ending the Equinox Mission," AIAA Paper 2010-8257, AIAA/AAS Astrodynamics Specialist Conference, Toronto, Canada, Aug. 2010.

[40] S.V. Wagner, J. Arrieta, C.G. Ballard, Y. Hahn, P.W. Stumpf, and P.N. Valerino, "Cassini Solstice Mission Maneuver Experience: Year One," *Advances in the Astronautical Sciences: Astrodynamics 2011*, Vol. 142, Pt. II, ed. H. Schaub, B.C. Gunter, R.P. Russell, and W.T. Cerven, Univelt, San Diego, 2012, pp. 1899-1917.

[41] F. Barbaglio, J.W. Armstrong, and L. Iess, “Precise Doppler Measurements for Navigation and Planetary Geodesy Using Low Gain Antennas: Test Results from Cassini,” 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[42] J. Arrieta, C.G. Ballard, Y. Hahn, P.W. Stumpf, P.N. Valerino, and S.V. Wagner, “Cassini Solstice Mission Maneuver Experience: Year Two,” AIAA Paper 2012-4433, AIAA/AAS Astrodynamics Specialist Conference, Minneapolis, MN, Aug. 2012.

[43] S. Bhaskaran, “Autonomous Navigation for Deep Space Missions,” SpaceOps 2012 Conference, Stockholm, Sweden, June 2012.

[44] A.A. Wolf, et al., “Stardust-NExT: Lessons Learned from a Comet Flyby Mission,” *Advances in the Astronautical Sciences: Guidance and Control 2012*, Vol. 144, ed. M.L. Osborne, Univelt, San Diego, 2012, pp. 771-785.

[45] T.W. Larson, “Lessons Learned in the Decommissioning of the Stardust Spacecraft,” SpaceOps 2012 Conference, Stockholm, Sweden, June 2012.

[46] S.D. Gillam, et al., “Ground Optical Navigation for the Stardust-NExT Mission to Comet 9P/Tempel 1,” *Advances in the Astronautical Sciences: Astrodynamics 2011*, Vol. 142, Pt. II, ed. H. Schaub, B.C. Gunter, R.P. Russell, and W.T. Cerven, Univelt, San Diego, 2012, pp. 1227-1246.

[47] W.M. Owen, Jr., “Methods of Optical Navigation,” *Advances in the Astronautical Sciences: Spaceflight Mechanics 2011*, Vol. 140, Pt. II, ed. M.K. Jah, Y. Guo, A.L. Bowes, and P.C. Lai, Univelt, San Diego, 2011, pp. 1635-1653.

[48] J. Kawaguchi, “Hayabusa – Asteroid Sample Return Through Hardships During its Seven Years Round-Trip Voyage,” *Advances in the Astronautical Sciences: Guidance, Navigation, and Control 2014*, Vol. 151, ed. A.J. May, Univelt, San Diego, 2014, pp. 457-468.

[49] J. Kawaguchi, H. Kuninaka, and M. Yoshikawa, “Return of Hayabusa Spacecraft and Reentry of Its Capsule,” *Advances in the Astronautical Sciences: Guidance and Control 2011*, Vol. 141, ed. K.B. Miller, Univelt, San Diego, 2011, pp. 403-414.

[50] R.J. Haw, et al., “Hayabusa: Navigation Challenges for Earth Return,” *Advances in the Astronautical Sciences: Astrodynamics 2011*, Vol. 142, Pt. II, ed. H. Schaub, B.C. Gunter, R.P. Russell, and W.T. Cerven, Univelt, San Diego, 2012, pp. 1247-1261.

[51] A. Accomazzo, P. Ferri, S. Lodiot, A. Hubault, R. Porta, and J.-L. Pellon-Bailon, “The first Rosetta asteroid flyby,” *Acta Astronautica*, Vol. 66, Feb.-Mar. 2010, pp. 382-390.

[52] P. Ferri, A. Accomazzo, S. Lodiot, A. Hubault, R. Porta, and J.-L. Pellon-Bailon, “Preparing the Rosetta deep-space operations,” *Acta Astronautica*, Vol. 67, Nov.-Dec. 2010, pp. 1272-1279.

[53] M. Lauer, S. Kielbassa, and R. Pardo, “Optical Measurements for Attitude Control and Shape Reconstruction at the Rosetta Flyby of Asteroid Lutetia,” 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[54] T. Morley, F. Budnik, M. Croon, and B. Godard, “Rosetta Navigation for the Fly-by of Asteroid (21) Lutetia,” 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[55] H. Sierks, et al., “Images of Asteroid 21 Lutetia: A Remnant Planetesimal from the Early Solar System,” *Science*, Vol. 334, 28 October 2011, pp. 487-490.

[56] R. Pardo de Santayana, M. Lauer, P. Muñoz, and F. Castellini, “Surface Characterization and Optical Navigation at the Rosetta Flyby of Asteroid Lutetia,” 24th International Symposium on Space Flight Dynamics, Laurel, MD, May 2014.

[57] P. Ferri, A. Accomazzo, A. Hubault, S. Lodiot, J.-L. Pellon-Bailon, and R. Porta, “Rosetta enters hibernation,” *Acta Astronautica*, Vol. 79, Oct.-Nov. 2012, pp. 124-130.

[58] D.G. Kubitschek, et al., “The Challenges of Deep Impact Autonomous Navigation,” *Journal of Field Robotics*, Vol. 24, Apr. 2007, pp. 339-354.

[59] S. Bhaskaran, et al., “Navigation of the EPOXI Spacecraft to Comet Hartley 2,” *Advances in the Astronautical Sciences: Astrodynamics 2011*, Vol. 142, Pt. II, ed. H. Schaub, B.C. Gunter, R.P. Russell, and W.T. Cerven, Univelt, San Diego, 2012, pp. 1283-1299.

[60] M.-K.J. Chung, et al., "EPOXI Trajectory and Maneuver Analyses," *Advances in the Astronautical Sciences: Astrodynamics 2011*, Vol. 142, Pt. II, ed. H. Schaub, B.C. Gunter, R.P. Russell, and W.T. Cerven, Univelt, San Diego, 2012, pp. 1213-1226.

[61] J.D. Anderson, J.K. Campbell, J.E. Ekelund, J. Ellis, and J.F. Jordan, "Anomalous Orbital-Energy Changes Observed during Spacecraft Flybys of Earth," *Physical Review Letters*, Vol. 100, 7 March 2008, 091102.

[62] S.G. Turyshev and V.T. Toth, "The Puzzle of the Flyby Anomaly," *Space Science Reviews*, Vol. 148, Dec. 2009, pp. 169-174.

[63] B.P. Rush, W.M. Owen, Jr., S. Bhaskaran, and S.P. Synnott, "Optical Navigation for the EPOXI Mission," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2011*, Vol. 140, Pt. II, ed. M.K. Jah, Y. Guo, A.L. Bowes, and P.C. Lai, Univelt, San Diego, 2011, pp. 1669-1676.

[64] R.R. Rieber and G.R. LaBorde, "New Mission, Old Spacecraft: EPOXI's Approach to the Comet Hartley-2," SpaceOps 2012 Conference, Stockholm, Sweden, June 2012.

[65] M.J. Abrahamson, B.A. Kennedy, and S. Bhaskaran, "Autonomous Navigation Performance During the Hartley 2 Comet Flyby," SpaceOps 2012 Conference, Stockholm, Sweden, June 2012.

[66] C.E. Garner, M.M. Rayman, G.J. Whiffen, J.R. Brophy, and S.C. Mikes, "Ion Propulsion: An Enabling Technology for the Dawn Mission," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. III, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L K. Newman, Univelt, San Diego, 2013, pp. 2195-2213.

[67] M.D. Rayman and R.A. Mase, "Dawn's exploration of Vesta," *Acta Astronautica*, Vol. 94, Jan.-Feb. 2014, pp. 159-167.

[68] N. Mastrodemos, B. Rush, D. Vaughan, and B. Owen, "Optical Navigation for Dawn at Vesta," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2011*, Vol. 140, Pt. II, ed. M.K. Jah, Y. Guo, A.L. Bowes, and P.C. Lai, Univelt, San Diego, 2011, pp. 1739-1754.

[69] N. Mastrodemos, B. Rush, A. Vaughan, and W. Owen, Jr., "Optical Navigation for the Dawn Mission at Vesta," 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[70] B. Kennedy, et al., "Dawn Orbit Determination Team: Modeling and Fitting of Optical Data at Vesta," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. III, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 2291-2310.

[71] D. Han, "Orbit Transfers for Dawn's Vesta Operations: Navigation and Mission Design Experience," 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[72] B. Kennedy, et al., "Dawn Orbit Determination Team: Trajectory and Gravity Prediction Performance During Vesta Science Phases," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. III, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 2251-2270.

[73] D.W. Parcher, et al., "Dawn Maneuver Design Performance at Vesta," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. III, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 2231-2250.

[74] M.J. Abrahamson, et al., "Dawn Orbit Determination Team: Trajectory Modeling and Reconstruction Processes at Vesta," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. III, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 2271-2290.

[75] B.A. Smith, C.A. Vanelli, and A.Y. Lee, "Understanding Spacecraft Agility for Orbit Transfers on the Dawn Low-Thrust Mission," *Advances in the Astronautical Sciences: Guidance and Control 2012*, Vol. 144, ed. M.L. Osborne, Univelt, San Diego, 2012, pp. 753-770.

[76] G.J. Whiffen, "Thrust Direction Optimization: Satisfying Dawn's Attitude Agility Constraints," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. III, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L K. Newman, Univelt, San Diego, 2013, pp. 2215-2230.

[77] G.J. Whiffen, "Mystic: Implementation of the Static Dynamic Optimal Control Algorithm for High-Fidelity, Low-Thrust Trajectory Design," AIAA Paper 2006-6741, AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Keystone, CO, Aug. 2006.