AAS 20-447

THE EVOLUTION OF DEEP SPACE NAVIGATION: 2012-2014*

Lincoln J. Wood†

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 seventh in a chronological sequence dealing with the evolution of deep space navigation. The time interval covered extends from 2012 to 2014. 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 15 planetary missions.

INTRODUCTION

Six previous papers[1,2,3,4,5,6] have described the evolution of deep space navigation over the time interval 1962 to 2012. 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, fifth, and sixth 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, Dawn, Akatsuki, IKAROS, and Mars Science Laboratory missions that took place between 1999 and early 2012.

The current paper extends Ref. 6 by two and a fraction years. It covers the portions of the Cassini, 2001 Mars Odyssey, Mars Express, Rosetta, MESSENGER, EPOXI, Mars Reconnaissance Orbiter, Venus Express, New Horizons, Dawn, IKAROS, Juno, Mars Science Laboratory, Mars Orbiter, and MAVEN missions (listed chronologically by launch date) that took place between early 2012 and mid-to-late 2014. 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

2001 Mars Odyssey

The interplanetary, aerobraking, and early orbiting phases of the 2001 Mars Odyssey mission have been described in References 3 and 5 and references listed therein, as well as Reference 7. From time to time on

† Principal Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 301-121, 4800 Oak Grove Drive, Pasadena, California 91109, USA.

orbit it was necessary to modify the local mean solar time (LMST) at descending equator crossings and its drift rate, for science data acquisition and spacecraft health and safety. Such adjustments were made by executing orbit trim maneuvers (OTMs) perpendicular to the orbit plane at descending or ascending equator crossings, to change the orbit inclination. The first such OTM of 9.3 m/s was performed on 24 September 2003, changing the inclination by -0.16 deg. The next, 32.7 m/s in size, was performed on 30 September 2008, changing the inclination by -0.56 deg and, consequently, the LMST drift rate from 8 to -135 min/year. Later OTMs to modify the LMST drift rate were executed on 9 June 2009, 5 September 2012, and 11 February 2014, producing inclination changes of 0.52, 0.15, and 0.04 deg by means of transverse velocity changes (ΔVs) of 30.6, 8.7, and 2.5 m/s. The latter two OTMs were intended to produce a slow, multi-year nodal drift in LMST toward later times, based on engineering constraints and remote sensing science considerations.[8,9]

Sometimes it was necessary to adjust the orbit period, so as to pass by a targeted location at a particular time or compensate for unplanned velocity changes due to a safe mode entry (of which 12 were experienced between 2002 and 2014). Orbit period could be adjusted by executing an OTM parallel or antiparallel to the spacecraft's velocity. As noted in Reference 3, the first such OTM of 0.50 m/s was performed on 22 November 2003, changing the orbit period by 3.3 s. This was to maintain Odyssey's overflight of the Spirit rover on 4 January 2004, the timing of which had been disrupted by an Odyssey safe mode entry several weeks earlier. A close approach of the Odyssey spacecraft to the Mars Express spacecraft was predicted for 7 May 2005, and plans for an Odyssey collision avoidance maneuver were developed. However, the Mars Express spacecraft executed such a maneuver instead, eliminating the need for Odyssey to do so.[9]

In order to provide a relay link between the Mars Phoenix Lander and the Earth during Phoenix's entry, descent, and landing (EDL), it was necessary to make certain modifications to the Mars Odyssey orbit. Specifically, the orbit phasing at the time of Phoenix's EDL needed to be delayed by about 42 min. A plan was developed to make the desired change through routine reaction wheel assembly (RWA) angular momentum desaturations (AMDs), which were at this time occurring daily and typically producing ΔVs of 3-4 mm/s. A contingency OTM was also planned in the event of any unexpected events occurring prior to Odyssey's overflight of the Phoenix Lander during its EDL. No unexpected events occurred, and the OTM was not needed to meet the required timing accuracy of ±30 s. The achieved timing accuracy was 2 s.[9]

In order to provide a relay link between the Mars Science Laboratory (MSL) spacecraft and the Earth during MSL's EDL, it was again necessary to make certain modifications to the Mars Odyssey orbit. Odyssey's LMST of 3:56 PM at the descending node was satisfactory, so that no change in orbit plane was required. However, the orbit phasing at the time of MSL's EDL needed to be advanced by about 35 min. A plan was developed to make the desired change through routine RWA AMDs, thereby saving propellant. AMD events occurred more frequently than prior to the Phoenix EDL, until a solar array configuration change, after which the frequency dropped dramatically. This strategy of shifting orbit phasing with AMDs worked fine until a safe mode entry due to an RWA anomaly caused thrusting that produced unanticipated ΔVs. An OTM of 0.06 m/s was performed on 11 July 2012 to change the orbit period by 0.4 s, since AMDs alone could no longer produce the desired orbit phasing. A second safe mode entry thereafter required the execution of another OTM (of 0.38 m/s) on 24 July to compensate, changing the orbit period by -2.5 s.[9]

An OTM of 0.36 m/s was performed on 5 August 2014 to modify the orbit phasing so that the spacecraft would be on the opposite side of Mars at the time of maximum flux of incoming particles from long-period comet C/2013 A1 (Siding Spring) when it passed near Mars on 19 October. This OTM changed the orbit period by 2.3 s. Unexpected attitude rate damping and associated thrusting after the OTM added 0.1 s to the orbit period change; but this was within the allowable tolerance, with no further action necessary.[9]

Throughout the Mars-orbiting phases of the Odyssey mission, the navigation team computed predicted orbits 21 days into the future on a weekly basis, for uplinking spacecraft ephemerides, science image targeting and observation refinements, and Deep Space Network (DSN) signal acquisition, and 56-90 days into the future once a month, for sequence-of-event (SOE) file development and science and relay overflight planning for Mars rovers. The prediction accuracy of the timing of descending equatorial crossings up to 56 days in the future (based on a 28-day development cycle for an SOE file of 28-day duration) was required to be within 60 s. The ability to model the effects of future AMDs was important in meeting these requirements. Based on Doppler data analysis after the fact, the timing of equatorial crossings could generally be reconstructed to within 0.01 s.[9]

Mars Express

The interplanetary, nominal orbiting, and first mission extension phases of the European Space Agency's (ESA's) Mars Express mission have been described in References 4 and 5 and references listed therein. A second mission extension ran from November 2007 to the end of 2012 and was followed by a third extension. On 2 April 2012, a maneuver was performed at periapsis to reduce the orbital period by 15.5 s, to adjust the orbit phasing for relay support of the MSL spacecraft's entry, descent and landing.[10]

MESSENGER

The interplanetary and primary orbital phases of the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission have been described in References 4, 5, and 6 and references listed therein, as well as Reference 11. An extended MESSENGER mission began on 18 March 2012. Two orbit correction maneuvers (OCMs) were executed near periapsis in April to reduce the orbital period, in order to enhance the future science return and the orbit stability. The first was designed to be a final, efficient, bipropellant burn consuming the remaining oxidizer. It was executed on 16 April, imparted a ΔV of 53.3 m/s, and reduced the orbital period from 11.6 to 9.08 h, while having negligible effect on the periapsis altitude. Once the actual performance of this OCM was known, the second OCM was quickly redesigned and executed (in monopropellant mode) on 20 April, imparting a ΔV of 31.4 m/s and reducing the orbital period from 9.08 to 8.00 h, while depleting one of two main fuel tanks.[11,12,13,14]

During this first extended mission, solar gravity dominated orbit perturbations, more than doubling periapsis altitude to 450 km and increasing the sub-spacecraft periapsis latitude to 84.1 deg N on 6 March 2013. Throughout this extension, improving estimates of Mercury's gravity field and solar and planetary radiation pressure improved the accuracy of spacecraft orbit determination and prediction.[14]

A second extended mission began on 18 March 2013. Solar gravitational effects caused the periapsis altitude and sub-spacecraft latitude to decrease after 6 March, though OCMs to boost the periapsis altitude were not performed for more than a year. On 18 November 2013, comet 2P/Encke passed within 0.0249 AU of the spacecraft, which allowed the collection of imaging and other data related to the comet. On 19 November the hyperbolic comet C/2012 S1 (ISON) passed within 0.2420 AU of the spacecraft, providing a similar, though more distant, cometary observing opportunity.[14,15]

With the periapsis altitude dropping below 200 km in late April 2014 for the remainder of the mission, the accurate modeling of Mercury's gravity field and planetary radiation pressure became increasingly important. The 20x20 field used for navigation was periodically compared with the science team's independently derived 50x50 field. The radiation pressure parameters estimated by the orbit determination filter (62 in all) included specular and diffuse solar, planetary infrared, and planetary albedo coefficients for each of the ten plates in the spacecraft model, along with overall scale factors for the planetary infrared and visible-wavelength re-radiation models.[14,16]

An OCM of 5.0 m/s was executed on 17 June 2014 to raise the terrain-relative minimum altitude from 115 to 156 km, while drawing propellant from the auxiliary fuel tank. An OCM of 8.6 m/s was executed on 12 September to raise the minimum altitude from 24 to 94 km, while drawing propellant first from the second main fuel tank and then the auxiliary fuel tank, with reduced thrust produced by expelling helium pressurant before switching tanks. An OCM of 19.2 m/s was executed on 24 October to raise the minimum altitude from 26 to 185 km, while drawing propellant from the auxiliary fuel tank. Each of these OCMs was designed to boost the periapsis altitude sufficiently that it would drift downward and hold for a while near 25 km before the next OCM.[11,16,17,18,19]

Mars Reconnaissance Orbiter

The interplanetary, aerobraking, and primary science phases of the Mars Reconnaissance Orbiter (MRO) mission have been described in References 4 and 5 and references listed therein, as well as Reference 20. The prime mission came to an end in September 2010 (after being augmented to include relay and extended science phases); the first extended mission began in October 2010.[21]

Multimission Navigation Ground Data System. Beginning in 2003, a multimission Ground Data System (GDS) infrastructure was designed and developed within the Jet Propulsion Laboratory's (JPL's) Navigation and Mission Design Section, to allow the trajectory design and navigation of an increasing number of simultaneous missions to be performed with maximum efficiency. The MRO mission was one of several early users of this multimission navigation GDS, which consisted of client and server hardware, compute clusters, storage, network infrastructure, and software. Emphasis was placed on standardization, inheritance, scalability, robustness, and overall cost of the GDS, along with security, ease of maintenance, and performance. While the project-specific Galileo navigation GDS, for example, offered a computing capability of 2 gigaFLOPS (billion floating point operations per second) when that mission ended in 2003, the multimission navigation GDS compute clusters offered a dramatically larger 2 teraFLOPS by 2010.[22]

Multimission navigation GDS hardware was typically replaced on a five-year replenishment cycle, roughly 20% each year in the case of desktops, and independent of specific mission milestones. The newest, most capable hardware could then be used wherever it was most needed. As of 2012, desktop workstations were typically Intel-based hardware running Red Hat Enterprise Linux, with enough computing power to perform all but the most intensive navigation-related tasks. Servers, accessed over a network, were typically rack-mounted, Intel-based hardware running Red Hat Enterprise Linux, with multiple and faster CPUs, more RAM, and faster network interfaces than was cost-effective for the desktops.[22]

Network-attached storage was available to all clients over high-speed networks. Networks within the multimission navigation GDS employed InfiniBand and 1- and 10-Gigabit Ethernet technologies. The choice of a UNIX operating system dates back to the early 1990s, when it was selected for hardware performance reasons. The selection of Linux over other UNIX operating systems for the multimission navigation GDS was primarily due to the speed and value of Intel-based hardware relative to the alternatives available at GDS inception.[22]

Use as a Relay Satellite. As had been done for the Phoenix mission, the MRO spacecraft provided telecommunication relay support to the MSL mission through its Electra Proximity Link Payload. To do so required that the MRO spacecraft's orbit have the proper LMST and phasing at the time of MSL's EDL, to within certain tolerances. It was evident shortly after MSL's launch that MRO would have a satisfactory LMST around MSL's landing time, without the need to perform a sequence of (potentially expensive) inclination-changing maneuvers to depart from and ultimately return to a desired sun-synchronous orbit. In fact, an inclination-change maneuver had been needed only once, on 4 February 2009 (3.2 m/s), to maintain the ascending-node LMST within ±15 min of 3 PM, since the start of the primary science phase.[23,24]

It was also evident shortly after MSL's launch that a substantial orbit phasing error, initially estimated to be 75 min, would exist at the time of MSL's EDL and that MRO orbit synchronization maneuvers (OSMs) would be needed to reduce the phasing error to the specified tolerance of ±30 s. Accordingly, a first OSM of 0.15 m/s was executed on 1 February 2012 to remove the majority of the phasing error. The OSM was deliberately biased below the best estimate of that needed for full correction, given the uncertainties in what the timing error would be a bit over six months in the future.[23]

Uncertainties in downtrack timing for the MRO spacecraft are due to four effects: atmospheric drag, angular momentum desaturation (AMD) events, maneuver execution errors, and orbit determination errors. Atmospheric drag is the most significant of these effects and was modeled as a combination of orbit-to-orbit drag variations of 105% (3σ) and (more importantly) a drag bias of 30% (3σ), consistent with several years of observed atmospheric variations. AMD events, nominally balanced but with small residual velocity-change errors, were performed every 2-3 days to desaturate spacecraft reaction wheels. They were modeled as producing velocity changes of 0.7 mm/s per event (3σ).[23]

A second OSM scheduled for 20 June was cancelled, since the phasing error was then smaller than anticipated. A final OSM of 0.13 m/s was executed on 13 July, reducing the phasing error to 9 s. The groundtrack walk repeat error was nominally maintained between ±40 km at this time in the mission; however, it was allowed to drift out of this range for a couple of months around MSL's EDL. Overall, the changes in orbit phasing to support MSL's EDL had minimal impact on the primary science orbit configuration for MRO, with the frozen and sun-synchronous orbit conditions being preserved.[23,24]

Conjunction Assessments. Although the number of man-made and natural objects orbiting or arriving at Mars around the year 2012 was modest and the probability of a collision between any pair of them was quite low, mission-ending collisions were at least possible, however unlikely. Thus, conjunction assessment analyses were regularly performed to provide advance warning of potential collision scenarios involving the Mars Odyssey, Mars Express, MRO, and Mars Science Laboratory spacecraft.[25]

Venus Express

The interplanetary phase of ESA's Venus Express mission, the establishment of an operational orbit, and an Aerodynamic Drag Experiment have been described in References 4, 5, and 6 and references listed therein. With the spacecraft lifetime limited by the remaining propellant, an aerobraking campaign was carried out between 19 May and 24 July 2014, in which the orbital period was reduced from 24.0 to 22.4 h. The campaign began with the periapsis altitude already diminishing from about 190 km due to solar gravitational effects. During the campaign, maneuvers to adjust the periapsis altitude were executed on 24 May, 23 and 28 June, and 2 and 11 July, the first and last to raise periapsis and the rest to lower it. Dynamic pressures of 0.4 Pa were targeted in the first two maneuvers and 0.55 Pa or higher in the remainder, and the periapsis altitude dropped as low as 130-135 km for several weeks. The aerobraking campaign was terminated by maneuvers to raise periapsis altitude once again to 460 km.[26]

IKAROS

The nominal mission of JAXA's IKAROS solar-sailing spacecraft has been described in Reference 6 and references listed therein. The spacecraft continued to operate after flying by the general vicinity of Venus, until communication was lost on 24 December 2011. At this time, attitude control propellant had nearly run out, attitude could not be properly controlled, and solar power generation had become sufficiently low that the spacecraft entered a hibernation mode. By modeling the solar radiation pressure torque over time, the vehicle's subsequent attitude history was estimated, yielding an estimate of the solar radiation pressure force over time, from which the orbital history was estimated. This allowed ground antenna pointing to sufficient accuracy for the reestablishment of communications on 6 September 2012, once sufficient solar power had become available once again.[27]

Mars Science Laboratory

Late Cruise. The interplanetary flight of the MSL spacecraft through the second trajectory correction maneuver (TCM) has been described in Reference 6 and references listed therein. Subsequent calibrations of the descent stage inertial measurement units, needed for accurate EDL, produced turn ΔVs that were different from (and typically smaller than) those expected based on the prior attitude control subsystem (ACS)/navigation calibrations. Consequently, an overall turn ΔV scale factor was added to the orbit determination filter as a weekly stochastic parameter; and the turn ΔV uncertainty was doubled.[28,29]

In May 2012 the final planetary ephemeris update for the MSL mission was released, with a shift of about 25 m in the position of Mars. The predicted uncertainties in Earth-Mars position at the time of arrival were about 100, 150, and 10 m in right ascension, declination, and range. As entry drew closer, delta differential one-way range (ΔDOR) and range data for the Mars Odyssey and MRO orbiters were processed to confirm the accuracy of this latest Mars ephemeris.[28,30,31]

By comparing on-board estimates of spacecraft attitude with ground-derived Doppler spin signature information, it was possible to check the accuracy of the spacecraft timing system. The timing offset of 15 ms derived from this comparison was well within the accuracy needed for safe landing.[28,32]

Prior to launch, the entry flight path angle was required to be controlled to ±0.20 deg. In flight, the smaller threshold of ±0.05 deg was used as the criterion for late TCM decisions. The pre-launch requirement for entry state knowledge was 2.8 km for position and 2 m/s for velocity. Subsequently, smaller thresholds (300 m and 1 m/s) were used to evaluate entry state update opportunities.[28,30,33,34,35]

The successful execution and analysis of in-flight calibration and verification activities allowed the targeted landing error ellipse (99% probability) on Mars to be reduced in size from 20 by 25 (used for landing site selection) to 7 by 21 km. (Much of this contraction was due to a reduction in the assumed attitude estimation error at entry.) This allowed the targeted landing site to be moved closer to the area of highest scientific interest without decreasing the probability of a successful landing. Accordingly, a third TCM was executed on 26 June (in no-turn vector mode, with axial and lateral burns of 29 and 25 mm/s) targeting for entry conditions consistent with this revised landing site. Orbit determination data cutoff times were seven days before TCM execution for each of the first three TCMs.[28,29,33,36,37]

ΔDOR measurements played an important role in achieving highly accurate orbit determination in the MSL mission. Recent increases in communication bandwidth between DSN complexes and JPL had reduced the time from ΔDOR data acquisition to its delivery to the navigation team to potentially less than three hours. ΔDOR measurements involving the Mars Odyssey or MRO spacecraft were also acquired at times, which allowed the creation of doubly-differenced carrier phase measurements relating the plane-of-sky position of the MSL spacecraft to that of an orbiter in a well-known orbit about Mars and thus to Mars itself. 79 ΔDOR sessions were successfully executed during interplanetary flight, including 10 multi-spacecraft data collections. The delivery of transmission media and Earth orientation calibrations to the navigation team was accelerated to once per day two weeks before arrival at Mars.[28,29]

Final Approach to Mars. On 29 July a fourth TCM was executed. With the entry flight path angle and time becoming highly correlated, it became inefficient to try to correct both parameters simultaneously. Thus, the landing site was targeted instead, resulting most simply in a lateral maneuver of 10 mm/s. Such a maneuver could not fully correct entry flight path angle or time; but it was one third the size of a vector-mode TCM, did not target away from the landing site in the first portion of the TCM before targeting back, was presumed to be more accurate, and did not result in flight path angle or time errors large enough to be of concern. The orbit determination data cutoff time was 13 h before execution for this TCM.[28,29,35,36]

35 hours after the fourth TCM, an orbit determination solution was obtained that provided the basis for an entry state to be uploaded to the spacecraft, to provide initial conditions for the entry guidance algorithm that would seek to control the atmospheric flight path based on inertial measurement unit (IMU) information. Several days after the fourth TCM, a Doppler-based solution for spacecraft attitude was derived to confirm the accuracy of the on-board solution based on star scanner data.[28,29,32,35]

As the decision point for a possible fifth TCM (two days before arrival) drew close, it became apparent that the predicted entry conditions were well within the allowed tolerances. Consequently, the TCM was cancelled. Similarly, when opportunities arose to update the entry state stored on board at 33, 14, and 6 h before the 6 August entry, the changes in the predicted entry state were too small relative to their uncertainties to warrant making updates, based on the latest assessment of atmospheric conditions and taking into account the fact that no TCM execution or updating of parameters is totally without risk. Finally, a contingency TCM opportunity 9 h before entry, available in the event of a late discovery of non-survivable delivery errors, was determined to be unnecessary.[28,29,30,34,35,36,37,38,39,40]

The details of the orbit determination process varied somewhat from one mission phase to another. During late cruise and on final approach, spacecraft position and velocity at a reference time (or epoch), tracking station range biases, three solar radiation pressure Fourier series coefficients, ACS event ΔVs, charged-particle signal delays, and components of pertinent TCMs were estimated as constant parameters. Per-pass range biases, thermal radiation pressure acceleration, and ACS turn ΔV scale factor were estimated as stochastic parameters. Errors in tracking station locations, future ACS event ΔVs, quasar locations, Earth orientation parameters, ionospheric and tropospheric signal delays, Mars and Earth ephemerides, and the gravitational parameter of Mars were treated as considered parameters. As many as 40 variations of filtering strategies (involving data type and accuracy, force modeling, estimated and considered parameter, and data arc length assumptions) were routinely executed and the results compared. It was felt that the trajectory prediction accuracy was optimized by limiting the number of parameters being estimated and weighting the tracking measurements according to per-pass, post-fit, rms residuals.[28,29,30,34]

After processing all of the two-way (and ΔDOR) data before entry, it was estimated that the actual entry flight path angle was just 0.013 deg shallower than the desired -15.5 deg target and the entry position and velocity were about 200 m and 0.11 m/s away from the values stored on the spacecraft. The actual entry position was 700 m from that targeted by the fourth TCM. Due to accurate launch injection, interplanetary navigation, and spacecraft performance, 60% of the cruise propellant remained unused after the last ACS turn prior to EDL.[28,29,30,33,34,36,37]

Entry, Descent, and Landing. Cruise stage separation from the entry stage took place 10 min before entry (E). Subsequently, the aeroshell was despun and turned to its desired entry attitude (predicted trim angle of attack and sideslip angle and desired initial bank angle at atmospheric contact). The cruise balance masses were ejected after the vehicle was despun, resulting in a displacement of the center of mass from the vehicle's axis of symmetry. This would cause the capsule to trim aerodynamically at a non-zero angle of attack, producing lift (a hypersonic lift-to-drag ratio of 0.24), which was needed to maintain altitude in delivering a planetary rover of unprecedented size and mass. At entry, defined to occur at a Mars radius of 3522.2 km (125 km altitude), the aeroshell entry vehicle was traveling at 5.8 km/s relative to Mars.[41,42,43,44,45,46,47,48,49,50]

The MSL avionics computing system consisted of two RAD750 processors (designated prime and backup) with 256 MB of RAM each and various forms of non-volatile memory of several GB. The flight software was written in the ANSI C programming language and ran under the VxWorks real-time operating system. The software was partitioned into some 150 modules, four of which were specifically for EDL.[51]

Atmospheric guidance, involving bank angle modulation of the lift vector and derived from the Apollo command module final phase guidance algorithm, was used while traveling through the atmosphere prior to parachute deployment, to target for the desired down-range and cross-range targets. The landing error ellipse needed to be smaller than in previous missions by a substantial amount, necessitating the first use of closed-loop entry guidance in a Mars mission. The use of this guidance scheme gave the knowledge of the entry conditions increased importance relative to the control of these conditions, since any known errors could be compensated for, if not too large – the entry guidance could correct for errors in initial delivery state, atmospheric conditions, and vehicle aerodynamics. The initiation of atmospheric guidance was triggered when a drag acceleration of 0.2 Earth *g*s was sensed (which happened earlier and at a higher altitude than expected, due to the drag coefficient or atmospheric density being greater than expected). Estimates of vehicle position and velocity were derived from IMU data, and the estimated entry state and dynamical models stored on board. Nominal trajectory and associated bank angle information was stored on board. Corrections to the commanded bank angle history were derived from the deviations of the estimated trajectory from the nominal. Changes in attitude were implemented using the entry vehicle's propulsive reaction control system.[28,30,37,38,40,41,42,43,44,45,46,48,49,50,52]

The first regime of the guidance scheme was range control, in which the down-track drag acceleration was matched to that needed to place the vehicle in the proper location at the time of parachute deployment, while keeping the cross-range errors within certain bounds. The vehicle underwent three bank reversals during the lift vector modulation. Peak heating occurred at E+63 s, at an altitude of 39.1 km. Peak deceleration (12.6 *g*s) occurred at E+80 s, at an altitude of 23.0 km. The second regime of the guidance scheme, beginning at a speed of about 1100 m/s, was heading alignment, in which cross-track errors that had accumulated due to bank reversals and other disturbances were corrected, with no further efforts at range control. At the end of heading alignment, the capsule's attitude was reset for parachute deployment, and the entry balance masses were ejected to eliminate the asymmetry-induced lift.[37,38,41,42,43,44,45,46,47,48,49,50,52,53]

Parachute deployment was triggered when the entry vehicle had slowed to 406 m/s (at E+259 s and an altitude of 12.1 km). The disk-gap-band parachute used in the MSL mission was a larger version of that used in the Viking mission. At a speed of 146 m/s (20 s later and at an altitude of 10.0 km), the heatshield was jettisoned; and the terminal descent sensor (a Ka-band pulse-pair Doppler radar) acquired the ground at an altitude of 8.4 km. As has been typical with Mars soft landers such as Viking and Phoenix, MSL made use of an IMU to measure attitude rates and translational accelerations and a landing radar to measure three-axis ground-relative velocity and altitude. The terminal descent sensor (TDS) measured ground-relative velocity and slant range along the boresight of each of its six narrow beams. The antenna configuration included a nadir-pointing beam, three beams pointing 20 deg off of nadir, and two beams pointing 50 deg off. The backshell and parachute were jettisoned at an altitude of 1.7 km (at E+376 s and a speed of 79 m/s). A number of event triggers during EDL were based on the atmosphere-relative velocity, as computed by the on-board navigation filter. The timing of backshell separation, however, was based on altitude and vertical velocity.[28,33,37,41,43,44,45,46,48,50,52,53,54,55]

Powered descent began thereafter, with eight monopropellant hydrazine Mars landing engines (MLEs) derived from Viking heritage activated to avoid impacting the backshell (by moving laterally) and then bring the descent stage to vertical flight at a descent rate of 32 m/s. After a constant speed vertical flight segment of adjustable length (to allow for errors in prior estimates of altitude with the TDS pointing away from the eventual landing site), there was a constant deceleration segment with the vertical speed reduced to 0.75 m/s. Once the desired vertical speed had been reached, the MLEs were throttled back (with four effectively shut down) and transient attitude and velocity disturbances allowed to settle. At an altitude of 21.6 m, the Curiosity rover was separated and lowered on a bridle system about 7.5 m below the descent stage, as the constant-speed descent continued. The large size and mass of the rover had led to the creation of a new landing architecture, employing a sky crane to deposit the rover on the surface with its wheels deployed, with a low touchdown velocity needed to avoid damaging the wheels. (The lighter Mars Pathfinder and Mars Exploration Rover (MER) spacecraft had used solid-rocket motors in the backshell to reduce the terminal velocity and, in the case of MER, the lateral velocity component before impact, with airbags needed to cushion the landing.) Touchdown of the rover, sensed by monitoring the MLE throttle settings needed to suspend the various vehicle components, was detected at E+431 s. Then the bridle and electrical umbilical devices were cut, and the four MLEs still in use (selected to minimize the likelihood of plume impingement on the rover) were throttled up to cause the descent stage to ascend and then pitch away from vertical and fly 650 m from the rover (well beyond the required 150 m) before crashing onto the surface. The various EDL events all occurred within 7 s of their predicted times. The rover's vertical and horizontal touchdown speeds were 0.60 and 0.12 m/s, which were respectively a bit lower and a bit higher than predicted, likely due to the use of only two TDS beams at touchdown and the local gravity field assumptions that were needed as a result. In addition, the TDS produced sporadic velocity errors during the sky-crane phase that were likely caused by surface material set in motion by the MLE thruster plumes and range errors on one beam that were likely caused by surface reflectivity variations. Neither of these unexpected errors affected the landing accuracy significantly.[28,33,37,41,43,44,45,46,48,50,52,53,55,56,57]

About a minute before cruise stage separation, X-band communication was switched from the medium-gain antenna to a low-gain antenna. One-way X-band Doppler data and low-bandwidth tones were used to confirm various EDL events, but were lost at E+306 s as the spacecraft was approaching occultation by Mars. A UHF relay link with the Mars Odyssey spacecraft (operating in receive-only demodulation mode) was established around E+140 s, a minute later than expected due to a plasma black-out and an initial false lock on a sideband. Real-time telemetry relayed by this spacecraft in a bent-pipe configuration (to the Canberra and ESA's New Norcia stations at X-band) confirmed a successful landing, with the first images from the hazard detection cameras received minutes later. A UHF relay link with the MRO spacecraft was established around E-489 s; however, the telemetry was recorded open loop (to maximize the probability of signal recovery through ground processing in the event of unexpected, extreme signal dynamics) rather than made available in real time. In addition, open-loop recorded carrier data were available through a UHF relay link with the Mars Express spacecraft until the line of sight became obstructed about 1 min before landing. Low-gain UHF antennas on the backshell, descent stage, and rover were used in sequence to radiate signals generated by the prime Electra-Lite UHF transceiver on the rover. Phasing adjustments were made to the orbits of the Mars Odyssey, MRO, and Mars Express spacecraft before MSL's arrival at Mars to reduce the phasing errors to within the specified tolerances of ±60, ±30, and ±60 s. The UHF carrier signal was also received via direct transmission at the Parkes Observatory in Australia until the MSL spacecraft was occulted by Mars.[9,28,33,41,43,46,53,58,59]

The MSL spacecraft was imaged by the MRO spacecraft while descending on its parachute. MSL's Mars Descent Imager (MARDI) took pictures of the surface as it descended, allowing a prompt determination of the actual landing site, which was about 2.4 km east (downrange) of the target. The landing error was dominated by attitude initialization and atmospheric modeling errors, rather than interplanetary navigation errors. More specifically, the landing error was attributed primarily to the limited time available to correct the downrange drift from the final bank reversal and a suspected tailwind during heading alignment. The processing of two-way Doppler data, from the time of their initial availability after landing until the rover started moving, provided another means of determining the landing site, yielding a solution 76 m removed from the MARDI estimate.[28,30,33,37,40,44,45,46,47,48,52,53,60]

Mars Orbiter Mission

The Indian Space Research Organization (ISRO) launched the Mars Orbiter Mission spacecraft into an elliptical Earth orbit on 5 November 2013. After six burns near periapsis to increase orbital energy, a trans-Mars injection burn was performed on 30 November (and executed quite accurately). While ISRO had primary flight dynamics responsibility for the mission, JPL provided various forms of navigation support in development and operations. The DSN provided radiometric data and data conditioning, media calibrations, and network operations engineering and scheduling. Navigation solutions, maneuver designs, tracking data messages, and other data were exchanged through interface servers at JPL and ISRO.[61]

The primary source of tracking data (two-way Doppler, two-way range, and ΔDOR) was the DSN. From late June 2014 until shortly before Mars orbit insertion (MOI), 23 ΔDOR sessions were conducted using the Goldstone-Madrid baseline and 21 using the Goldstone-Canberra baseline. The Doppler and ΔDOR data were less accurate than in typical planetary missions of this era because telecommunications were at S-band, rather than the higher-frequency X-band (with diminished charged-particle effects on signal propagation). In addition, two-way data could not be obtained at the Madrid complex, because an S-band uplink was not available there (to avoid conflicts with mobile telecommunications). Recommended ΔDOR data weights varied from pass to pass for the Goldstone-Madrid baseline due to the low elevation angles of the spacecraft at both northern-hemispheric station complexes. Orbit solutions that included ΔDOR data were considerably more accurate than those without such data. In addition to DSN data, tracking data were collected using ISRO's 32-m tracking station near Bangalore, primarily for the purpose of performance assessment.[61]

With an unbalanced thruster alignment, AMDs were quite frequent – about 6-10 per day before a solar array attitude change on 2 June 2014 and 7-11 per day thereafter. Fortunately, the largest AMD ΔV component (in spacecraft body axes) was visible in line-of-sight Doppler data. Nevertheless, the AMDs had a significant effect on hyperbolic impact plane (or B-plane) orbit determination accuracies.[61]

A TCM of 7.7 m/s was performed on 11 December 2013. A second TCM of 1.6 m/s was performed on 11 June 2014. Each burn was executed to an accuracy of better than 0.8 percent. Unlike the near-Earth maneuvers, which had used the 440-N liquid apogee motor (LAM), these TCMs used the eight 22-N ACS thrusters. TCMs were designed by both ISRO and JPL and the results compared, with ISRO ultimately deciding which design to execute. A third TCM was scheduled for various times in August, before ultimately being cancelled. The scheduling and thruster selection for the fourth TCM also changed several times before its execution at MOI-41 h. This 4.0-s TCM reduced the periapsis altitude by about 200 km and made use of the LAM, as a test firing to increase confidence that MOI would execute successfully despite the failure of a pressure regulator. The execution of contingency TCMs planned for MOI-24 and MOI-6 h was not necessary, which was fortunate because of the limited design time that would have been available.[61]

The MOI burn of 1099 m/s was executed on 24 September, using both the LAM and the eight ACS thrusters. Only the first four min of the burn took place while the spacecraft was visible from Earth, with the remainder occurring in occultation. The burn was terminated based on accelerometer measurements. The achieved period for the highly elliptical orbit was 3.04 days, close to the targeted value of 3.06 days.[61]

MAVEN

The Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft was launched toward Mars on 18 November 2013, on a type-II trajectory (heliocentric transfer angle between 180 and 360 deg). The interplanetary trajectory was biased away from Mars sufficiently to ensure that the probability of the launch vehicle upper stage impacting Mars was less than 10^{-4}. A TCM was performed on 3 December to remove the launch aimpoint bias (and test the main thrusters), in two parts: a settling burn using the 22-N TCM thrusters and a main burn using the 170-N Mars orbit insertion thrusters. The burn, jointly optimized with a later TCM but subject to a lower bound on magnitude, totaled 4.8 m/s.[62,63]

Two-way coherent Doppler and range data were acquired continuously for the first 27 days after launch, by three 8-h station passes per week thereafter until 60 days before arrival at Mars, then by daily 8-h passes until 11 days before arrival, and continuously for the last 11 days. In addition, tracking was continuous for three days around scheduled TCMs. ΔDOR data were acquired weekly beginning at 90 days after launch and twice weekly for the last 60 days before arrival. A low-gain antenna was used for communication for the first 90 days of flight. A fixed-mounted high-gain antenna was used for the remainder of the interplanetary flight.[62]

The attitude of the three-axis stabilized MAVEN spacecraft is controlled with four reaction wheels. During the interplanetary flight, desaturation maneuvers due primarily to solar radiation pressure torques were performed about once per week. While the 1-N ACS thrusters were fired in nominally balanced pairs for this purpose, the thrusters were not perfectly aligned and equal in thrust, so that small translational ΔVs (averaging 0.5 mm/s) resulted, producing the largest trajectory perturbations during cruise.[62]

Quantities estimated in the orbit determination process included spacecraft position and velocity at a reference epoch, a solar radiation pressure scale factor, tracking station range biases, and desaturation maneuver ΔV components. During the first two weeks after launch, an exponentially decaying acceleration was estimated to model spacecraft outgassing. Tropospheric and ionospheric signal delays, tracking station location errors, Mars and Earth ephemerides, gravitational parameters of Mars, Earth, and moon, and quasar locations were treated as considered parameters during portions of the flight. Orbit determination solutions were typically delivered every 10 days, except during the weeks after launch and before arrival.[62]

Calibrations for the ACS thrusters and solar pressure modeling were performed on 6 and 8-20 January 2014, respectively, with estimates of specular and diffuse reflectivity coefficients improved from the latter. A second TCM of 0.7 m/s was performed on 26 February using the TCM thrusters, to target the desired Mars arrival conditions. Comparisons of Doppler and accelerometer data revealed spacecraft clock errors of several seconds at the time of each TCM.[62,63]

Orbit determination solutions were stable after the second TCM; and two later scheduled statistical TCMs (the first at 60 days before Mars arrival) were thus cancelled, reflecting the accuracy of the launch injection, maneuver execution, and navigation solutions. A pair of late contingency TCMs, to be executed only to avoid an unacceptably low periapsis altitude, were also cancelled.[62]

Requirements on the 22 September Mars orbit insertion (MOI) involved achieving an orbit with a period of 35 ± 5 h, an inclination of 75 ± 1.5 deg, and an altitude at first periapsis after MOI of 380 ± 50 km, with all uncertainties being 3σ. The burn of 1230 m/s was executed with the six main thrusters, with the TCM thrusters used for attitude control (after brief use in a settling burn to ensure subsequent propellant flow to the main thrusters). Because of its 33-min duration, MOI was executed with a constant-rate pitch-over about the orbit normal, to maintain the thrust near the anti-velocity direction. As in other maneuvers, the MOI command was designed to apply thrust until the accumulated ΔV measured by the accelerometer had reached the desired value. Minimum and maximum timer values and a restart capability were included to guard against an accelerometer or short-term engine malfunction during this critical event. An orbit period of 34.9 h, an inclination of 74.2 deg, and a periapsis altitude of 380 km were achieved.[62]

EXPLORATION OF THE OUTER PLANETS

Cassini

Enceladus-17, Enceladus-18, and Enceladus-19 Encounters. The interplanetary flight of the Cassini spacecraft and almost eight years in orbit about Saturn (through the Titan-82 encounter) have been described in References 2, 3, 4, 5, and 6 and references listed therein, as well as Reference 64. The inbound Enceladus-17, -18, and -19 encounters took place on 27 March, 14 April, and 2 May 2012 at nominal altitudes of 75 km. The "cleanup" OTM after the Titan-82 flyby was easily absorbed within a 3.6-m/s "trajectory-shaping" OTM near a subsequent periapsis, which was needed to change the orbit period by several hours and establish a 13:1 orbit resonance with Enceladus. As in the Enceladus-16 to Dione-3/Titan-79 transfer, special planning of a contingency OTM was needed, since the normal backup procedure would have resulted in excessive propellant consumption as the spacecraft moved away from the optimal, near-periapsis OTM location. Once again, the contingency OTM did not have to be used. As in two prior multi-revolution orbit transfers, an auxiliary OTM was designed to ensure that the approach OTM would be small enough to be executed with the monopropellant reaction control subsystem (RCS). In this case, execution of the auxiliary OTM was indeed necessary. The subsequent approach OTM, as first designed, was too small for execution. Shifting the time of arrival by 0.3 s made the OTM large enough to execute and avoided the downstream ΔV penalty that would have resulted from OTM cancellation.[65]

The optimal allocation of ΔV across the cleanup and shaping OTMs in the Enceladus-17 to -18 transfer resulted in the latter OTM being eliminated and avoided short turnaround times between successive OTMs. During the design of the Enceladus-18 approach OTM, it was discovered that a shift of a few km in B-plane targeting would save a small amount of ΔV. Since such a trajectory change was scientifically acceptable, it was implemented. In the Enceladus-18 to -19 transfer, the 0.24 m/s shaping OTM near apoapsis was executed with the bipropellant main engine assembly (MEA), in order to test the spacecraft's electrical system, thereby becoming the smallest OTM executed with the MEA.[65]

Titan-83 and Titan-84 Encounters. The outbound Titan-83 and -84 encounters took place on 22 May and 7 June 2012 at nominal altitudes of 955 and 959 km. The execution of an approach OTM before the Enceladus-19 encounter allowed the post-encounter cleanup OTM to be cancelled in favor of an 8.3 m/s trajectory-shaping OTM near apoapsis. This OTM was needed to avoid a collision with Titan and to set up the proper encounter conditions for ending the first equatorial phase of the solstice mission and entering the second inclined phase. Since this OTM was nearly perpendicular to the direction to Earth, it was more difficult than usual to reconstruct from telemetry and tracking data. Thus, the subsequent approach OTM was delayed until its backup opportunity to allow the processing of more data.[65]

The optimization of the cleanup and near-apoapsis shaping OTMs in the Titan-83 to -84 transfer resulted in the cancellation of the former, with the latter needed to avoid a collision with Titan and set up the desired encounter conditions. An approach OTM was needed to correct the incoming trajectory asymptote direction. Over the full Titan-77 to Titan-84 time period, 26 of the 38 scheduled OTMs were executed (eight with the MEA); and 12 were cancelled. Two of the maneuver executions occurred during backup, rather than primary, opportunities.[65]

Titan-85 Through Titan-89 Encounters. The outbound Titan-85, -86, -87, -88, and -89 encounters took place on 24 July, 26 September, 13 and 29 November 2012, and 17 February 2013 at nominal altitudes of 1012, 956, 973, 1014, and 1978 km and resulted in increases in orbit inclination to 32.2, 39.0, 46.3, 53.0, and 57.1 deg. The cleanup and shaping OTMs preceding the Titan-85 encounter were designed in an optimization chain along with downstream OTMs for the first time since May 2011. (It had been possible to nearly optimize the intervening OTMs with single-impulse maneuver strategies.) Commands related to the cleanup and approach OTMs were uplinked to the spacecraft earlier than usual to minimize the likelihood of having to execute relatively costly backup OTMs. (The same procedure continued to be used in the future when backup OTMs were calculated to be relatively large.) The near-apoapsis shaping OTM, at 10.1 m/s, was the largest OTM since May 2010.[66]

The cleanup OTM after the Titan-85 encounter was cancelled because there was no downstream cost associated with deriving the needed trajectory changes from the shaping OTM to follow. With the efficient use of propellant becoming increasingly important relative to other concerns that could cause OTMs to be cancelled, such as minimizing the number of maneuver cycles, this was to be the last OTM cancellation for more than seven months. The shaping and approach OTMs preceding the Titan-86 encounter were the first to be computed based on new and improved maneuver execution error models. The analysis of OTMs performed since January 2009 had allowed the improved identification of magnitude and pointing biases in maneuver execution, which were subsequently (for magnitude biases) largely removed through flight parameter changes or modifications to the maneuver design process.[66,67]

The cleanup and shaping OTMs preceding the Titan-87 encounter were designed in an optimization chain along with downstream OTMs, a trend that was commonly followed thereafter. It was possible to receive two-way Doppler data through closest approach in the Titan-87 flyby, allowing an estimation of the atmospheric density profile high above Titan. The 0.25-m/s cleanup OTM after the Titan-87 encounter was executed using the MEA, reflecting an increased desire to diminish usage of the RCS and preserve as much hydrazine as possible for attitude control, pointing the high-gain antenna at Earth for communication, and reaction wheel speed management over the remainder of the mission. Whereas OTMs smaller than 0.3 m/s had been executed with the RCS earlier in the mission, that threshold was now dropped to 0.25 m/s (and had been tested at a slightly lower level in the Enceladus-18 to -19 transfer). The approach OTM prior to the Titan-88 encounter was uplinked to the spacecraft earlier than usual because the backup OTM was considered nonviable due to a sequencing complexity.[64,66]

The cleanup OTM after the Titan-88 encounter was small relative to the shaping OTM to follow, with substantial variations in its optimal solution as successive orbit determination solutions were generated. The resulting variations in maneuver direction caused changes in the corresponding reaction wheel strategies, which were time consuming to address. Consequently, the decision was made to hold the OTM direction fixed at its first acceptable value in this case and any future situations of high solution sensitivity. The transfer to the Titan-89 encounter was to be the last consisting of as many as six revolutions about Saturn for several years.[66]

Rhea-4 and Titan-90 Encounters. The inbound Rhea-4 encounter took place on 9 March 2013 at a nominal altitude of 1000 km. The cleanup OTM after the Titan-89 encounter was executed seven days after the encounter, rather than the usual three. The 0.26-m/s shaping OTM prior to the Rhea-4 encounter was executed using the MEA, following the recent precedent of allowing smaller MEA burns. The approach OTM was cancelled due to the lack of a downstream cost or an impact on Rhea science observations – the first OTM cancellation in many months. Whereas a typical flyby of Titan at 1000 km and 5.5 km/s would produce a ΔV of about 840 m/s, this faster flyby of the less massive Rhea produced a modest ΔV of 19 m/s.[66]

The outbound Titan-90 encounter took place on 5 April at a nominal altitude of 1400 km and increased the orbit inclination to 61.7 deg. The cleanup OTM after the Rhea-4 encounter was cancelled because the downstream ΔV penalty was small and the insertion of additional RWA biases could be thereby avoided. Thus, any needed deterministic trajectory changes were accomplished by the shaping OTM prior to the Titan-90 encounter. The time of flight targeted by the approach OTM was shifted by 0.3 s in order to make the OTM large enough to be implemented.[66]

Titan-91 Through Titan-93 Encounters. The outbound Titan-91, -92, and -93 encounters took place on 23 May and 10 and 26 July 2013 at nominal altitudes of 970, 964, and 1400 km and resulted in decreases in orbit inclination to 59.4, 56.7, and 53.4 deg. As in the case of the cleanup OTM after the Titan-88 encounter, the cleanup OTM after the Titan-90 encounter was small and sensitive to orbit determination updates. Thus, its direction was held fixed at its first acceptable value as successive orbit solutions were obtained. The time of flight targeted by the Titan-91 approach OTM was shifted by 0.2 s in order to make the OTM large enough to be implemented.[66]

The cleanup OTM after the Titan-91 encounter was small compared to the shaping OTM to follow and was computed based on the first set of post-flyby tracking data. This simplified the reaction wheel speed management process, while introducing errors that were small compared to the likely execution errors in the shaping OTM. The cleanup OTM after the Titan-92 encounter was executed in its backup location to avoid a downstream ΔV cost and allow usage of the MEA to preserve hydrazine.[66]

Over the full Titan-84 to Titan-93 time period, 27 of the 30 scheduled OTMs were executed (thirteen with the MEA) and three were cancelled, reflecting the increased importance of following the reference trajectory and conserving propellant rather than minimizing maneuver cycles. One maneuver execution occurred during a backup, rather than a primary, opportunity. In two cases, the time of flight was biased to create an OTM large enough to be implemented.[66]

Titan-94 Through Titan-96 Encounters. The outbound Titan-94 and -95 and inbound Titan-96 encounters took place on 12 September, 14 October, and 1 December 2013 at nominal altitudes of 1400, 961, and 1400 km and resulted in orbit inclinations of 51.9, 49.7, and 51.3 deg. The transfer orbits to these encounters were resonant with Titan's orbital motion in the spacecraft-to-Titan orbit period ratios of 3:2, 2:1, and 3:1, respectively. The small target miss at the Titan-93 encounter allowed the subsequent cleanup OTM to be cancelled. The 3.6-m/s MEA apoapsis OTM that followed was the largest OTM in the fourth year of the solstice mission. The approach OTM for the Titan-94 encounter was executed with an aimpoint shifted by several km in the B-plane relative to the reference trajectory, in order to save 0.17 m/s of downstream ΔV.[68]

The execution of the standard three OTMs (and the chained optimization of the first two) was needed in the transfer to the Titan-95 encounter to avoid a downstream ΔV penalty. The cleanup OTM after the Titan-95 encounter was cancelled because it was too small to implement and there was no ΔV penalty associated with its cancellation. The initial design of the Titan-96 approach OTM was too small to implement, but the OTM was needed to avoid a downstream ΔV cost. Consequently, the targeted encounter time was shifted by a fraction of a second to produce a small OTM that could be executed.[68]

Titan-97 Through Titan-100 Encounters. The inbound Titan-97, -98, -99, and -100 encounters took place on 1 January, 2 February, 6 March, and 7 April 2014 at nominal altitudes of 1400, 1236, 1500, and 963 km and resulted in decreases in orbit inclination to 50.1, 48.1, 45.5, and 40.7 deg. The transfer orbits for all four encounters were in 2:1 resonances with Titan's orbital motion. The cleanup OTM after the Titan-96 encounter was cancelled because the ΔV penalty was small, some hydrazine could be saved, a maneuver cycle could be avoided, and the trajectory reconstruction would be more accurate. The cleanup OTM after the Titan-97 encounter targeted directly for the Titan-98 encounter, making the following apoapsis OTM unnecessary.[68]

The cleanup and apoapsis OTMs after the Titan-98 encounter were designed once again with a chained optimization approach, to conserve downstream ΔV. After an accurate Titan-99 flyby, the cleanup OTM was found to be unnecessary, with the cancellation allowing a small downstream ΔV savings. The commands for executing an apoapsis OTM were uplinked to the spacecraft early, as a precaution against an uplink failure, since the spacecraft was on a Titan-impacting trajectory.[68]

Titan-101 and Titan-102 Encounters. The outbound Titan-101 and -102 encounters took place on 17 May and 18 June 2014 at nominal altitudes of 2994 and 3659 km and resulted in increases in orbit inclination to 44.3 and 46.5 deg. The transfer orbit between the Titan-100 and -101 encounters was a special case of a non-resonant transfer, with the spacecraft orbit period an odd half-integer multiple (in this case 5/2) of Titan's orbital period. Thus, the orbital longitude of Titan shifted by pi radians between encounters, giving rise to the name "pi transfer" for such a scenario. The cleanup and apoapsis OTMs after the Titan-100 encounter were designed with a chained optimization approach, to conserve current and downstream ΔV. The approach OTM for the Titan-101 encounter was executed with the B-plane aimpoint shifted by several km, in order to create an OTM large enough to implement and save 0.12 m/s of downstream ΔV.[68]

The transfer orbit to the Titan-102 encounter was in a 2:1 resonance with Titan. The use of a chained optimization approach to compute cleanup and apoapsis OTMs after the Titan-101 flyby would have resulted in both being too small to implement. Thus, a stand-alone cleanup OTM was computed and executed; and the apoapsis OTM was cancelled at insignificant cost.[68]

Over the full Titan-93 to Titan-102 time period, 21 of the 27 scheduled OTMs were executed (five with the MEA); and six were cancelled. Target conditions were modified for three of the encounters. The reconstructed spacecraft position components for all nine encounters were well within 1 km and 0.1 s of their targeted values in B-plane components and time of flight. Over the first four years of the solstice mission, the navigation ΔV cost per encounter averaged 0.12 m/s, well below the corresponding figures for the prime and equinox missions (0.32 and 0.45 m/s).[64.68]

New Horizons

The early interplanetary flight of the New Horizons mission, including a 21.2-km/s flyby of Jupiter at a distance of 2,304,505 km, has been described in Reference 5 and references listed therein, as well as References 69, 70, 71, and 72. The Jupiter flyby increased the spacecraft's heliocentric speed by 3.8 km/s and was controlled to a Jupiter B-plane accuracy of 1174 km and a time-of-flight accuracy of 113 s, both within design tolerances. A 2.4-m/s TCM was executed on 25 September 2007 to correct Jupiter flyby errors and reduce aimpoint errors at Pluto from 500,000 km to about 50,000 km.[69,71,72,73]

Much of the eight years after the Jupiter flyby was spent in a spinning hibernation mode, with no thruster-induced disturbances present for months at a time. Most radiometric tracking data were acquired during annual checkouts (ACOs) about 50 days long. With the distance from the sun steadily increasing (causing solar radiation pressure to diminish) and little thruster activity, thermal radiation pressure due to the radioisotope thermoelectric generator (RTG) became relatively easy to isolate and measure as part of the orbit determination process, with the resulting acceleration found to be about 1.3×10^{-12} km/s^2 in 2008-09, dropping to about 1.2×10^{-12} km/s^2 by 2012-13, as the RTG temperature slowly decreased. This acceleration, acting over a number of years, would affect the eventual time of arrival at Pluto by several tens of minutes.

Thus, a small compensating TCM of 0.4 m/s was performed on 30 June 2010, once this effect had become reasonably well understood. Rehearsals of the 2015 flyby of the Pluto/Charon system were carried out during the ACOs of 2012 and 2013. Among the results was an improvement in the modeling of the ΔVs associated with ACS activity.[71,72,73,74,75,76,77]

Juno

The Juno spacecraft was launched on 5 August 2011. A TCM scheduled for 25 August to correct injection errors was cancelled because the launch was highly accurate. A TCM was executed on 1 February 2012 to target for the Cartesian coordinates of an upcoming deep space maneuver (DSM). The TCM, executed in vector mode using the monopropellant RCS, had axial and lateral components of 0.9 and 0.8 m/s.[78]

The DSM was performed in two segments on 30 August (344 m/s) and 14 September 2012 (388 m/s), to return the spacecraft to the general vicinity of the Earth on 9 October 2013. The DSM was split because the bipropellant main engine had not been qualified to operate for the duration needed to execute the DSM in a single maneuver. The second segment was delayed by ten days relative to the planned schedule to allow time to investigate high oxidizer line temperatures and pressures observed during the first segment. A TCM was executed on 3 October 2012 to correct any errors in the DSM. The TCM, executed in vector mode using the RCS, had axial and lateral components of 0.4 and 1.7 m/s. The DSM and the TCM that followed targeted a biased Earth-relative aimpoint, to reduce the Earth-impact probability below 10^{-4}.[78]

On 1 May 2013, a main engine flush maneuver of about 1.1 m/s was performed. This required maintenance activity performed in the cruise attitude was not intended to correct any known trajectory errors. On 7 August, a TCM was performed to remove the trajectory bias and target for the proper Earth flyby conditions. The TCM, executed in vector mode using the RCS, had axial and lateral components of 1.5 and 3.1 m/s. Another TCM was executed on 9 September to remove remaining trajectory errors. The TCM, executed in vector mode using the RCS, had axial and lateral components of 120 and 50 mm/s. A final approach TCM, scheduled for 29 September, was cancelled due to the accuracy of the flight path without it and the modest ΔV cost of correcting the remaining trajectory errors after the Earth flyby. Because of the low, but nonzero, risk of a collision with an active satellite or space debris when flying past the Earth, two axial collision avoidance maneuvers, changing the time of closest approach by ±1 s, were designed in advance, to be executed 12 h before the Earth flyby if needed. A conjunction assessment risk analysis did not reveal any catalogued object that posed a threat, so that no collision avoidance maneuver was executed. The 9 October gravity assist flyby provided a ΔV of 7.3 km/s and was controlled to an accuracy of 6 km in the B-plane and 0.17 s in time of closest approach. Relative to the orbit determination solution used as justification for cancelling the 29 September TCM, the corresponding errors were only 1 km and 0.05 s.[78]

Given the small, anomalous velocity changes that had been observed in a number of previous Earth flybys, there was a desire to obtain relatively complete tracking coverage during Juno’s Earth flyby. In this regard, DSN tracking was augmented with tracking from ESA’s stations at Malargüe, Argentina, and Perth, Australia. Unfortunately, the spacecraft entered a safe mode about 10 min after its 561-km altitude closest approach, which resulted in a small unbalanced turn toward the sun a few minutes later, while tracking was unavailable. At the time of the Earth flyby, the Juno spacecraft was spinning at roughly 2 rpm. The accurate processing of Doppler tracking data required the removal of the spin signature, which was done in the same fashion as in the MSL mission. The small attitude shift after safe mode entry caused unexpected changes in the Doppler spin signature and the solar radiation pressure acceleration and increased multi-path errors in the spacecraft’s radio signal. Nevertheless, it was possible to reconstruct the flyby trajectory to an accuracy of some number of meters; and no evidence was found of a velocity anomaly in the along-track direction.[79]

An Earth flyby cleanup TCM was executed on 13 November 2013. The TCM, executed in vector mode using the RCS, had axial and lateral components of 1.3 and 1.5 m/s. This TCM targeted the Cartesian state associated with a Jupiter approach TCM to be executed in 2016. Because of the accurate execution of this TCM and the preceding Earth flyby, a TCM scheduled for 9 April 2014 was calculated to be only 5 mm/s in size, was too small to be reliably executed, and thus was cancelled. A second main engine flush maneuver was executed on 28 May 2014.[78]

EXPLORATION OF COMETS AND ASTEROIDS

Rosetta

The interplanetary flight of ESA's Rosetta spacecraft, including flybys of Earth, Mars, Earth, the asteroid Steins, Earth, and the asteroid Lutetia, has been described in References 4, 5, and 6 and references listed therein. The Rosetta spacecraft was brought out of hibernation on 20 January 2014 and restored to its normal three-axis stabilized mode. Solar radiation pressure uncertainties, the largest error source causing trajectory deviations during the 31 months of hibernation, resulted in plane-of-sky position errors that were a very small fraction of the beam width of ground antennas; thus, proper antenna pointing for a resumption of communications was easily achieved. Initial detection of the destination body, comet 67P/Churyumov-Gerasimenko, was attempted with the scientific narrow angle camera (NAC), with its greater sensitivity for detecting dim objects than the navigation cameras. After a preliminary sighting of the comet on 20 March, the regular collection of optical navigation images began on 24 March (at visual magnitude 13.1). The comet's estimated position shifted by 2020 km, based on the processing of the first six images.[80,81,82]

Two-way coherent Doppler and range data, as well as optical navigation data, were used for orbit determination. Starting 28 April, the conventional radiometric data were augmented with ΔDOR data, collected primarily along ESA's Cebreros, Spain to New Norcia, Australia and Cebreros-Malargüe baselines and occasionally along the Goldstone-Canberra or New Norcia-Malargüe baselines. The Rosetta transponder did not generate DOR tones. Instead, harmonics of the telemetry subcarrier were used; and highly accurate knowledge of the subcarrier frequency was needed. Due to a reboot during hibernation, the clock driving the on-board timing system had switched to a slightly different rate, changing the subcarrier frequency and producing inaccurate ΔDOR data until the problem was diagnosed and corrected around 20 June.[81,83]

Cometary Approach Phase. The approach phase of the mission began on 8 May. During this phase, the nucleus grew in size from a point source to more than 500 picture elements (pixels). The comet became detectable (at visual magnitude 10.8) with the navigation camera on 8 May at a distance of 1,800,000 km. Five images were acquired per day with this camera, while five images were acquired twice per week with the NAC, as before, until NAC images were terminated (for navigation purposes) on 6 June. Until 3 July, when the comet reached visual magnitude 2 and subtended a full pixel, it was possible to detect enough stars in each image to accurately evaluate the camera attitude, thereby correcting for thermal effects and attitude control errors. Thereafter, the comet and stars were imaged separately to avoid overexposing the comet, until 24 July, at which point the star images were abandoned. Reliance was then placed on independent knowledge of the spacecraft attitude and nominal camera alignment for determination of the inertial direction to the comet's center. On 1 August, the optical navigation image acquisition rate was increased to one image per hour. Several hundred thousand imaging frames were acquired at 2.5-s intervals during much of the 13 July to 1 August time interval to construct an accurate light curve for the comet and deduce from this its rotational period of 12.43 h. In addition, preliminary work on deriving a photometric model for the comet was carried out during the approach phase.[80]

Propulsive burns were executed on 7 and 21 May, 4 and 18 June, 2, 9, 16, and 23 July, and 3 and 6 August in the amounts of 20, 291, 271, 89, 59, 26, 11, 4.8, 3.1, and 0.9 m/s to incrementally slow the spacecraft relative to the comet to less than 1 m/s, as the distance diminished from 1,800,000 to 120 km. These maneuvers caused the spacecraft to travel along a slightly curved path relative to the comet, to generate a small amount of parallax in the optical navigation images. Small spacecraft accelerations lingering after the larger maneuvers were concluded to be due to combustion products initially adhering to the spacecraft and later evaporating when exposed to sunlight after a spacecraft slew.[81,82]

EPOXI

The primary Deep Impact mission and three Earth gravity assist flybys and an encounter with comet 103P/Hartley 2 in the extended EPOXI mission have been described in References 4, 5, and 6 and references listed therein. With very limited propellant remaining after the Hartley 2 encounter, it was nevertheless thought possible to fly past a near-Earth asteroid. Accordingly, a TCM of 8.8 m/s was performed on 25 November 2011 to begin targeting the spacecraft for the object 2002 GT. However, this encounter never took place, due to a software bug (similar to the Year 2000 problem) that put the spacecraft computer into an infinite reboot loop in August 2013.[84]

Dawn

LAMO to HAMO-2 Transfer. The interplanetary flight of the Dawn mission and operations near the main-belt asteroid 4 Vesta through the low altitude mapping orbit (LAMO) have been described in References 5 and 6 and references listed therein. On 1 May 2012 the spacecraft began a transfer from LAMO to the second high altitude mapping orbit (HAMO-2), to be completed over 45 days and 139 revolutions about Vesta. The transfer design, striving at a high level to minimize propellant consumption while satisfying certain end conditions at a fixed final time, included 16.5 days of deterministic thrusting and 28.6 days of coasting, certain portions of which (totaling 11.0 days) could be allocated in operations to thrusting, should it turn out to be necessary. Criteria for a satisfactory reference trajectory design included the absence of eclipses for at least 25 days if the thrusting should unexpectedly stop at any point, powered-flight stability such that trajectory perturbations would take at least 4 to 5 days to grow to 400 km, and the avoidance of thrusting within 20 deg of the sun/anti-sun direction (to avoid unachievable ACS rates and corrections). Eleven maneuver design cycles were planned for the transfer, with sequence build timelines of either three days or (twice) 36 h. The first ten extended maneuvers each targeted for some intermediate waypoint on the reference transfer trajectory. This allowed each thrust sequence to be designed independently during operations. A reference trajectory design, including numerous iterations to meet the eclipse avoidance, powered-flight stability, and thrust direction criteria, required weeks of effort, so that full trajectory redesigns during the LAMO to HAMO-2 transfer were impractical. The largest trajectory deviation of more than 400 km occurred between waypoints 8 and 9 and was due to attitude control constraints forcing the spacecraft's trajectory away from the reference. With the gravity field of Vesta no longer a dominant error source, the LAMO to HAMO-2 transfer provided an opportunity to assess the impact of ion propulsion system (IPS) modeling and execution errors on trajectory dispersions.[85,86,87,88,89,90]

Near the 1:1 resonance with Vesta's rotation period, there was a designed quiet period in which no angular momentum desaturation maneuvers were to be performed, to allow accurate orbit determination. Resonant gravitational effects were potentially larger than the spacecraft's propulsive capabilities, making the passage through this resonance risky if not planned and executed carefully (with safe-mode entries avoided). Gravity gradient torques associated with angular pointing errors averaging 1.5 deg (due to the suspension of AMDs) caused an unexpected angular momentum buildup and the execution of an inaccurate AMD at the end of this period.[90,91]

HAMO-2. The final maneuver in the LAMO to HAMO-2 transfer, intended to be a relatively brief statistical TCM, was cancelled as unnecessary. Thus, the HAMO-2 orbit was effectively reached on 6 June, a number of days early. With the first few days in the 685-km altitude orbit devoted to engineering reconfiguration activities, the HAMO-2 science phase began on 15 June. The HAMO-2 orbit was generally similar to the earlier HAMO-1, with six cycles of repeating ground tracks and a 12.3-h orbit period. (A repeat cycle lasted 5.1 days and consisted of 23 Vesta rotations and 10 spacecraft orbits.) Changes in solar illumination since HAMO-1 allowed previously unavailable science observations and the incorporation of landmarks at northerly latitudes between 45 and 80 deg. The angle between the orbit plane and the Vesta-sun line was required to be 35-47 deg (with 37 deg targeted). The orbit inclination was targeted for 94 deg. Terminator crossing times were required to be controlled to ±10 min.[85,86,90,92,93]

Instrument pointing accuracy in HAMO-2 was required to be no worse than 0.5 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, with every such opportunity used. With an accurate gravity field available and no IPS thrusting, HAMO-2 provided an opportunity to assess the impact of AMD maneuvers on trajectory dispersions. With this effect better understood, it was possible to place AMDs so as to minimize changes in longitude crossings in successive mapping cycles. The improvements in knowledge of the Vesta gravity field, spin pole and rotation period, landmark positions, and ephemeris derived from the spacecraft's operations near Vesta are described in Reference 94.[89,91,93]

Departure from Vesta and Subsequent Interplanetary Cruise. The Dawn spacecraft began its spiraling departure from Vesta on 25 July. Three maneuver design cycles were used for the departure. Nine days of thrusting in August were missed due to problems with an RWA and the ensuing reconfiguration and replanning activities. A fourth rotation characterization was carried out for several days in late August from an altitude of about 5300 km, providing better views of Vesta's northerly latitudes. Escape from a bound orbit about Vesta occurred on 5 September, at an altitude of 16,000 km. While near Vesta, 350 m/s of ΔV were expended to achieve and maintain the desired science orbits. For the cruise to Ceres, IPS thrust arcs were increased in duration from seven days to 14-28 days to reduce hydrazine consumption.[85,88,89,92]

The RWA anomaly on departure from Vesta represented the second loss of an RWA, leaving just two functioning RWAs for the remainder of the mission and resulting in potentially more RCS thrusting for attitude control. To reduce hydrazine consumption during cruise, high-gain antenna downlinks were reduced in frequency from once per week to once every four weeks. However, thrust verification sessions were carried out twice per week using a low-gain antenna (with the IPS throttle setting reduced to allocate power to the radio downlink). In addition, the slew rate for turns between thrusting and Earth-pointing attitudes was reduced by 75%.[95,96]

Solar array calibrations were carried out in June and October 2013. For four weeks during November-December 2013, thrusting was non-optimal (as had been the case for a longer period in 2008-2009). Tests of a hybrid attitude control algorithm using the two healthy RWAs and RCS thrusters were carried out in November, to verify that accurate pointing could be achieved later in orbit about Ceres while minimizing the use of hydrazine. As of 1 June 2014, the Dawn spacecraft had been thrusting for 14,000 h (92% of the time) since escaping from Vesta and 39,000 h overall, producing a total propulsive ΔV of 9.8 km/s.[95,96]

CONCLUSION

Deep space navigation capabilities, which had evolved enormously from the 1960s through the early 2000s, continued to evolve thereafter, benefiting the 15 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. Unprecedented accuracies were achieved in delivering a spacecraft very accurately to the top of the Martian atmosphere and subsequently to the planet's surface. Accurately controlled gravity assist flybys of planets and planetary satellites allowed the execution of missions that would have been infeasible using chemical propulsion alone for trajectory modification. The challenge of accurately modeling spacecraft non-gravitational accelerations, particularly due to attitude control subsystem activity, was a recurring theme.

ACKNOWLEDGMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference to any specific commercial product, process, or service by trade name, trademark, manufacturer or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology. Funding for the writing of this paper was provided by the Deep Space Network and the Jet Propulsion Laboratory's Multimission Ground Systems & Services Program Office and Mission Systems & Operations Division.

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] L.J. Wood, "The Evolution of Deep Space Navigation: 2009–2012," *Advances in the Astronautical Sciences: Astrodynamics 2019*, Vol. 171, Pt. I, ed. K.R. Horneman, C. Scott, B.W. Hansen, and I.I. Hussein, Univelt, San Diego, 2020, pp. 227-248.

[7] D.A. Spencer and R. Tolson, "Aerobraking Cost and Risk Decisions," *Journal of Spacecraft and Rockets*, Vol. 44, Nov.-Dec. 2007, pp. 1285-1293.

[8] C.D. Edwards, Jr., P.R. Barela, R.E. Gladden, C.H. Lee, and R. De Paula, "Replenishing the Mars Relay Network," 2014 IEEE Aerospace Conference, Big Sky, MT, Mar. 2014.

[9] P. Esposito, D.C. Jefferson, and J. Lee, "Odyssey Mars Orbiter – Thirteen Years of On-Orbit Navigation," 25th International Symposium on Space Flight Dynamics, Munich, Germany, Oct. 2015.

[10] O. Reboud, M. Denis, and T. Ormston, "Mars Express and the NASA Landers and Rovers on Mars – Sustaining a Backup Relay in an Interplanetary Network," SpaceOps 2012 Conference, Stockholm, Sweden, June 2012.

[11] D.P. Moessner and J.V. McAdams, "Design, Implementation, and Outcome of MESSENGER's Trajectory from Launch to Mercury Impact," *Advances in the Astronautical Sciences: Astrodynamics 2015*, Vol. 156, Pt. III, ed. M. Majji, J.D. Turner, G.G. Wawrzyniak, and W.T. Cerven, Univelt, San Diego, 2016, pp. 3231-3250.

[12] 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.

[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] J.V. McAdams, C.G. Bryan, D.P. Moessner, B.R. Page, D.R. Stanbridge, and K.E. Williams, "Orbit Design and Navigation Through the End of MESSENGER's Extended Mission at Mercury," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2014*, Vol. 152, Pt. III, ed. R.S. Wilson, R. Zanetti, D.L. Mackison, and O. Abdelkhalik, Univelt, San Diego, 2014, pp. 2299-2318.

[15] D.P. Moessner and J.V. McAdams, "The Final Two Years: MESSENGER's Trajectory from the Third Year in Orbit through Mercury Impact," 24th International Symposium on Space Flight Dynamics, Laurel, MD, May 2014.

[16] B.R. Page, C.G. Bryan, K.E. Williams, A.H. Taylor, and B.G. Williams, "Tuning the MESSENGER State Estimation Filter for Controlled Descent to Mercury Impact," AIAA Paper 2014-4129, AIAA/AAS Astrodynamics Specialist Conference, San Diego, CA, Aug. 2014.

[17] S.H. Flanigan, M.N. Kirk, D.J. O'Shaughnessy, S.S. Bushman, and P.E. Rosendall, "The First Three Maneuvers During MESSENGER's Low-Altitude Science Campaign," *Advances in the Astronautical Sciences: Guidance, Navigation, and Control 2015*, Vol. 154, ed. I.J. Gravseth, Univelt, San Diego, 2015, pp. 969-980.

[18] J.V. McAdams, et al., "Engineering MESSENGER's Grand Finale at Mercury – The Low-Altitude Hover Campaign," *Advances in the Astronautical Sciences: Astrodynamics 2015*, Vol. 156, Pt. III, ed. M. Majji, J.D. Turner, G.G. Wawrzyniak, and W.T. Cerven, Univelt, San Diego, 2016, pp. 3251-3270.

[19] M.N. Kirk, S.H. Flanigan, D.J. O'Shaughnessy, S.S. Bushman, and P.E. Rosendall, "MESSENGER Maneuver Performance During the Low-Altitude Hover Campaign," *Advances in the Astronautical Sciences: Astrodynamics 2015*, Vol. 156, Pt. III, ed. M. Majji, J.D. Turner, G.G. Wawrzyniak, and W.T. Cerven, Univelt, San Diego, 2016, pp. 3291-3309.

[20] S.M. Long, et al., "Mars Reconnaissance Orbiter Aerobraking Navigation Operation," SpaceOps 2008 Conference, Heidelberg, Germany, May 2008.

[21] M.D. Johnston, D.E. Herman, R.W. Zurek, and C.D. Edwards, "Mars Reconnaissance Orbiter: Extended Dual-Purpose Mission," Paper No. 1278, 2011 IEEE Aerospace Conference, Big Sky, MT, Mar. 2011.

[22] D.V. Gerasimatos and A.A. Attiyah, "Engineering a Multimission Approach to Navigation Ground Data System Operations," SpaceOps 2012 Conference, Stockholm, Sweden, June 2012.

[23] J.L. Williams, P.R. Menon, and S.W. Demcak, "Mars Reconnaissance Orbiter Navigation Strategy for Mars Science Laboratory Entry, Descent and Landing Telecommunication Relay Support," AIAA Paper 2012-4747, AIAA/AAS Astrodynamics Specialist Conference, Minneapolis, MN, Aug. 2012.

[24] S.V. Wagner, P.R. Menon, M.-K.J. Chung, and J.L. Williams, "Mars Reconnaissance Orbiter Navigation Strategy for Dual Support of InSight and ExoMars Entry, Descent and Landing Demonstrator Module in 2016," *Advances in the Astronautical Sciences: Astrodynamics 2015*, Vol. 156, Pt. III, ed. M. Majji, J.D. Turner, G.G. Wawrzyniak, and W.T. Cerven, Univelt, San Diego, 2016, pp. 3197-3214.

[25] D.S. Berry, J.R. Guinn, Z.B. Tarzi, and S.W. Demcak, "Automated Spacecraft Conjunction Assessment at Mars and the Moon," SpaceOps 2012 Conference, Stockholm, Sweden, June 2012.

[26] S. Damiani, J.M. Garcia, R. Guilanyà, P. Muñoz, and M. Müller, "Flight Dynamics Operations for Venus Express Aerobraking Campaign: A Successful End of Life Experiment," 25th International Symposium on Space Flight Dynamics, Munich, Germany, Oct. 2015.

[27] Y. Mimasu, et al., "Long-Term Attitude and Orbit Prediction of Solar Sailing IKAROS While Being Lost in Space," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. IV, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 3161-3179.

[28] 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.

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

[30] T.J. Martin-Mur, G.L. Kruizinga, P.D. Burkhart, F. Abilleira, M.C. Wong, and J.A. Kangas "Mars Science Laboratory Interplanetary Navigation," *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1014-1028.

[31] G. Lanyi, D.S. Bagri, and J.S. Border, "Angular Position Determination of Spacecraft by Radio Interferometry," *Proceedings of the IEEE*, Vol. 95, Nov. 2007, pp. 2193-2201.

[32] 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.

[33] 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.

[34] 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.

[35] A. Chen, M. Greco, T. Martin-Mur, B. Portock, and A. Steltzner, "Approach and Entry, Descent, and Landing Operations for Mars Science Laboratory," *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1004-1013.

[36] 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.

[37] M. San Martin, G.F. Mendeck, P.B. Brugarolas, G. Singh, and F. Serricchio, "Reconstructed Flight Performance of the Mars Science Laboratory Guidance, Navigation, and Control System for Entry, Descent, and Landing," *Advances in the Astronautical Sciences: Guidance, Navigation, and Control 2014*, Vol. 151, ed. A.J. May, Univelt, San Diego, 2014, pp. 771-800.

[38] G.F. Mendeck and L.C. McGrew, "Entry Guidance Design and Postflight Performance for 2011 Mars Science Laboratory Mission," *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1094-1105.

[39] A.D. Cianciolo, et al., "Atmosphere Assessment for Mars Science Laboratory Entry, Descent and Landing Operations," *Advances in the Astronautical Sciences: Astrodynamics 2013*, Vol. 150, Pt. III, ed. S.B. Broschart, J.D. Turner, K.C. Howell, and F.R. Hoots, Univelt, San Diego, 2014, pp. 2525-2536.

[40] A. Chen, et al., “Reconstruction of Atmospheric Properties from Mars Science Laboratory Entry, Descent, and Landing,” *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1062-1075.

[41] P.D. Burkhart and J. Casoliva, “MSL DSENDS EDL Analysis and Operations,” 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[42] P.B. Brugarolas, A.M. San Martin, and E.C. Wong, “The Entry Controller for the Mars Science Laboratory,” *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. 505-519.

[43] A.D. Steltzner, A.M. San Martin, T.P. Rivellini, and A. Chen, “Mars Science Laboratory Entry, Descent, and Landing System Overview and Preliminary Flight Performance Results,” *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. 521-528.

[44] A.M. San Martin, S.W. Lee, and E.C. Wong, “The Development of the MSL Guidance, Navigation, and Control System for Entry, Descent, and 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. 529-546.

[45] D.W. Way, “Preliminary Assessment of the Mars Science Laboratory Entry, Descent, and Landing Simulation,” Paper No. 2755, 2013 IEEE Aerospace Conference, Big Sky, MT, Mar. 2013.

[46] D.W. Way, J.L. Davis, and J.D. Shidner, “Assessment of the Mars Science Laboratory Entry, Descent, and Landing Simulation,” *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. 563-581.

[47] M. Schoenenberger, J. Van Norman, C. Karlgaard, P. Kutty, and D. Way, “Assessment of the Reconstructed Aerodynamics of the Mars Science Laboratory Entry Vehicle,” *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1076-1093.

[48] C.D. Karlgaard, et al., “Mars Science Laboratory Entry Atmospheric Data System Trajectory and Atmosphere Reconstruction,” *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1029-1047.

[49] A. Chen, et al., “Entry System Design and Performance Summary for the Mars Science Laboratory Mission,” *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. 1687-1702.

[50] A.D. Steltzner, A.M. San Martin, T.P. Rivellini, A. Chen, and D. Kipp, “Mars Science Laboratory Entry, Descent, and Landing System Development Challenges,” *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 994-1003.

[51] K.P. Gostelow, “The Mars Science Laboratory Entry, Descent, and Landing Flight Software,” *Advances in the Astronautical Sciences: Spaceflight Mechanics 2013*, Vol. 148, Pt. IV, ed. S. Tanygin, R.S. Park, T.F. Starchville, Jr., and L.K. Newman, Univelt, San Diego, 2013, pp. 3425-3434.

[52] S. Dutta and R.D. Braun, “Statistical Entry, Descent, and Landing Performance Reconstruction of the Mars Science Laboratory,” *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1048-1061.

[53] F. Abilleira and J.D. Shidner, “Entry, Descent, and Landing Communications for the 2011 Mars Science Laboratory,” 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[54] J.R. Cruz, D.W. Way, J.D. Shidner, J.L. Davis, D.S. Adams, and D.M. Kipp, “Reconstruction of the Mars Science Laboratory Parachute Performance,” *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1185-1196.

[55] C.W. Chen and B.D. Pollard, “Radar Terminal Descent Sensor Performance During Mars Science Laboratory Landing,” *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1208-1216.

[56] S.W. Sell, J.L. Davis, A.M. San Martin, and F. Serricchio, “Powered Flight Design and Performance Summary for the Mars Science Laboratory Mission,” *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1197-1207.

[57] B. Açikmeşe, S.W. Sell, A.M. San Martin, and J.J. Biesiadecki, “Mars Science Laboratory Flyaway Guidance, Navigation, and Control System Design,” *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1227-1236.

[58] B.C. Schratz, M. Soriano, P. Ilott, J. Shidner, A. Chen, and K. Bruvold, “Telecommunications Performance During Entry, Descent, and Landing of the Mars Science Laboratory,” *Journal of Spacecraft and Rockets*, Vol. 51, July-Aug. 2014, pp. 1237-1250.

[59] C.D. Edwards, Jr., et al., "Relay Support for the Mars Science Laboratory Mission," 2013 IEEE Aerospace Conference, Big Sky, MT, Mar. 2013.

[60] J.L. Davis, J.D. Shidner, and D.W. Way, "Mars Science Laboratory Post-Landing Location Estimation Using POST2 Trajectory Simulation," *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. 1671-1685.

[61] C. Helfrich, et al., "A Journey with MOM," 25th International Symposium on Space Flight Dynamics, Munich, Germany, Oct. 2015.

[62] M. Jesick, et al., "Maven Navigation Overview," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2016*, Vol. 158, ed. R. Zanetti, R.P. Russell, M.T. Ozimek, and A.L. Bowes, Univelt, San Diego, 2016, pp. 1235-1254.

[63] D. Jones, T. Lam, N. Trawny, and C. Lee, "Using Onboard Telemetry for MAVEN Orbit Determination," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2015*, Vol. 155, Pt. III, ed. R. Furfaro, S. Cassotto, A. Trask, and S. Zimmer, Univelt, San Diego, 2015, pp. 2715-2729.

[64] J. Bellerose, et al., "Cassini Navigation: The Road to Consistent Sub-Kilometer Accuracy Satellite Encounters," *Advances in the Astronautical Sciences: Guidance, Navigation, and Control 2016*, Vol. 157, ed. D.A. Chart, Univelt, San Diego, 2016, pp. 971-984.

[65] 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.

[66] S.V. Wagner, J. Arrieta, Y. Hahn, P.W. Stumpf, P.N. Valerino, and M.C. Wong, "Cassini Solstice Mission Maneuver Experience: Year Three," *Advances in the Astronautical Sciences: Astrodynamics 2013*, Vol. 150, Pt. I, ed. S.B. Broschart, J.D. Turner, K.C. Howell, and F.R. Hoots, Univelt, San Diego, 2014, pp. 223-242.

[67] S. Wagner, "Maneuver Performance Assessment of the Cassini Spacecraft Through Execution-Error Modeling and Analysis," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2014*, Vol. 152, Pt. III, ed. R.S. Wilson, R. Zanetti, D.L. Mackison, and O. Abdelkhalik, Univelt, San Diego, 2014, pp. 2641-2660.

[68] M. Vaquero, Y. Hahn, P. Stumpf, P. Valerino, S. Wagner, and M. Wong, "Cassini Maneuver Experience for the Fourth Year of the Solstice Mission," AIAA Paper 2014-4348, AIAA/AAS Astrodynamics Specialist Conference, San Diego, CA, Aug. 2014.

[69] S.A. Stern, "The New Horizons Pluto Kuiper Belt Mission: An Overview with Historical Context," *Space Science Reviews*, Vol. 140, Oct. 2008, pp. 3-21.

[70] W.M. Owen, Jr., P.J. Dumont, and C.D. Jackman, "Optical Navigation Preparations for New Horizons Pluto Flyby," 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, Oct.-Nov. 2012.

[71] Y. Guo, B. Williams, F. Pelletier, J. McAdams, and W.-J. Shyong, "Trajectory Monitoring and Control of the New Horizons Pluto Flyby," 25th International Symposium on Space Flight Dynamics, Munich, Germany, Oct. 2015.

[72] D.R. Stanbridge, et al., "New Horizons Pluto Encounter Maneuver Planning and Analysis," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2016*, Vol. 158, Pt. II, ed. R. Zanetti, R.P. Russell, M.T. Ozimek, and A.L. Bowes, Univelt, San Diego, 2016, pp. 1331-1350.

[73] G.D. Rogers, S.H. Flanigan, and M. Kirk, "New Horizons Trajectory Correction Maneuver Flight Implementation and Performance," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2016*, Vol. 158, Pt. II, ed. R. Zanetti, R.P. Russell, M.T. Ozimek, and A.L. Bowes, Univelt, San Diego, 2016, pp. 1187-1204.

[74] Y. Guo and R.W. Farquhar, "New Horizons Mission Design," *Space Science Rev.*, Vol. 140, Oct. 2008, pp. 49-74.

[75] G.D. Rogers, S.H. Flanigan, and D. Stanbridge, "Effects of Radioisotope Thermoelectric Generator on Dynamics of the New Horizons Spacecraft," *Advances in the Astronautical Sciences: Guidance, Navigation, and Control 2014*, Vol. 151, ed. A.J. May, Univelt, San Diego, 2014, pp. 801-812.

[76] B. Williams, et al., "Navigation Strategy and Results for New Horizons' Approach and Flyby of the Pluto System," *Advances in the Astronautical Sciences: Astrodynamics 2015*, Vol. 156, Pt. III, ed. M. Majji, J.D. Turner, G.G. Wawrzyniak, and W.T. Cerven, Univelt, San Diego, 2016, pp. 3271-3290.

[77] G.D. Rogers and S.H. Flanigan, "New Horizons Encounter Rehearsal Planning and Execution," 24th International Symposium on Space Flight Dynamics, Laurel, MD, May 2014.

[78] T.A. Pavlak, R.B. Frauenholz, J.J. Bordi, J.A. Kangas, and C.E. Helfrich, "Maneuver Design for the Juno Mission: Inner Cruise," AIAA Paper 2014-4149, AIAA/AAS Astrodynamics Specialist Conference, San Diego, CA, Aug. 2014.

[79] P.F. Thompson, M. Abrahamson, S. Ardalan, and J. Bordi, "Reconstruction of Earth Flyby by the Juno Spacecraft," *Advances in the Astronautical Sciences: Spaceflight Mechanics 2014*, Vol. 152, Pt. IV, ed. R.S. Wilson, R. Zanetti, D.L. Mackison, and O. Abdelkhalik, Univelt, San Diego, 2014, pp. 3229-3242.

[80] F. Castellini, D. Antal-Wokes, R. Pardo de Santayana, and K. Vantournhout, "Far Approach Optical Navigation and Comet Photometry for the Rosetta Mission," 25th International Symposium on Space Flight Dynamics, Munich, Germany, Oct. 2015.

[81] T. Morley, F. Budnik, B. Godard, P. Muñoz, and V. Janarthanan, "Rosetta Navigation from Reactivation Until Arrival at Comet 67P/Churyumov-Gerasimenko," 25th International Symposium on Space Flight Dynamics, Munich, Germany, Oct. 2015.

[82] A. Accomazzo, et al., "Rosetta operations at the comet," *Acta Astronautica*, Vol. 115, Oct.-Nov. 2015, pp. 434-441.

[83] S. Bhaskaran, et al., "Rosetta Navigation at Comet Churyumov-Gerasimenko," *Advances in the Astronautical Sciences: Guidance, Navigation, and Control 2015*, Vol. 154, ed. I.J. Gravseth, Univelt, San Diego, 2015, pp. 787-801.

[84] D.J. Grebow, S. Bhaskaran, and S.R. Chesley, "Search & Selection for Future Flyby Targets for the DI/EPOXI Spacecraft," AIAA Paper 2012-5070, AIAA/AAS Astrodynamics Specialist Conference, Minneapolis, MN, Aug. 2012.

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

[86] 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.

[87] 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.

[88] 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.

[89] 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.

[90] J.C. Smith, D.W. Parcher, and G.J. Whiffen, "Spiraling Away from Vesta: Design of the Transfer from the Low to High Altitude Dawn Mapping Orbits," *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. 2317-2335.

[91] 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.

[92] 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.

[93] 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.

[94] A.S. Konopliv, et al., "The Vesta gravity field, spin pole and rotation period, landmark positions, and ephemeris from the Dawn tracking and optical data," *Icarus*, Vol. 240, Sep. 2014, pp. 103-117.

[95] B.A. Smith, R.S. Lim, and P.D. Fieseler, "Dawn Spacecraft Operations with Hybrid Control: In-Flight Performance and Ceres Applications," *Advances in the Astronautical Sciences: Guidance, Navigation, and Control 2014*, Vol. 151, ed. A.J. May, Univelt, San Diego, 2014, pp. 671-683.

[96] M.D. Rayman and R.A. Mase, "Dawn's operations in cruise from Vesta to Ceres," *Acta Astronautica*, Vol. 103, Oct.-Nov. 2014, pp. 113-118.