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DAWN ORBIT DETERMINATION TEAM: TRAJECTORY MODELING AND RECONSTRUCTION PROCESSES AT VESTA

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The Dawn spacecraft spent over a year in orbit around Vesta from July 2011 through August 2012. In order to maintain the designated science reference orbits and enable the transfers between those orbits, precise and timely orbit determination was required. Challenges included low-thrust ion propulsion modeling, estimation of relatively unknown Vesta gravity and rotation models, tracking data limitations, incorporation of real-time telemetry into dynamics model updates, and rapid maneuver design cycles during transfers. This paper discusses the dynamics models, filter configuration, and data processing implemented to deliver a rapid orbit determination capability to the Dawn project.

INTRODUCTION

The NASA Dawn spacecraft was launched on September 27, 2007 on a mission to study the asteroid belt's two largest objects, (4) Vesta and (1) Ceres, to search for clues about the early formation of the Solar System. Dawn is equipped with instruments to capture visible, infrared, gamma ray, and neutron spectrometry, imagery, and gravimetry while in orbit about each target body[5]. It is the first spacecraft to orbit a main belt asteroid and will be the first to orbit two separate extraterrestrial bodies once its mission is complete[5]. The enabling technology for accomplishing this feat is solar-electric ion propulsion, which provides the high amount of delta-V necessary for capture, orbital transfer, and escape at two extraterrestrial bodies[6]. The Dawn ion propulsion system directs the spacecraft along a desired flight path by executing low-thrust maneuvers designed by the navigation team. The Dawn navigation team, consisting of orbit determination, mission design, and optical navigation, is tasked with designing and maintaining a safe flight profile that meets science goals. The flight path at Vesta included four planned science orbits for data collection and five transfer phases for transitions between the orbits. Orbit determination (OD) was a key component of the navigation process at Vesta, enabling the science mission by maintaining knowledge of the flight dynamics encountered by the Dawn spacecraft along its flight path. OD deliverables supported the maneuver design and execution process, instrument pointing updates, and science acquisition sequence updates.

The primary Dawn OD function at Vesta was reconstruction of the Dawn as-flown trajectory and projection of its future flight path via estimation of dynamics parameters related to spacecraft performance and the surrounding environment. The trajectory reconstructions were performed using ground-based radiometric observations in the form of 2-way Range and Doppler measurements and onboard optical observa-

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tions. Orbit determination responsibilities included maintaining the onboard ephemeris knowledge to meet science instrument pointing requirements, delivering state, gravity, and thrust performance estimates for the maneuver design process, and reviewing thrust sequence products uplinked to the spacecraft. These responsibilities required standard interfaces between the OD team and several other subsystem teams to ensure a well-oiled process. The Dawn OD paradigm was unique from most other deep space missions due to the challenges of operating a low-thrust, power-dependent propulsion system in orbit about a body with coarsely known physical characteristics. A tight maneuver design cadence was needed to maintain visibility and control of the spacecraft flight path during periods of frequent, long duration thrusting. This required an OD process with highly automated data processing and model configuration. While Kennedy[1] discusses the trajectory prediction performance of the OD products, this paper discusses the dynamics models, filter configuration, and data processing implemented to deliver a rapid orbit determination capability to the Dawn project.

VESTA

Vesta is the second largest body in the main asteroid belt, lying between the orbits of Mars and Jupiter. The body is highly oblate, with a polar radius of ~230km and an equatorial radius of ~290km. It has a GM of 17.28838 ± 0.00015 km^2/sec^3, orbits the Sun every 1,325.85 days, and rotates about its axis every 5.342 hours.

MISSION OVERVIEW

The Dawn mission at Vesta consisted of science collection from four distinct science orbits to achieve global coverage at desired spatial resolution and lighting conditions. The spacecraft carries the following scientific instruments aligned with the spacecraft +Z axis for the capture of visible, infrared, and gamma ray spectra emitted by Vesta:

- The visible light Framing Camera (FC).
- The Visible and Infrared Spectrometer (VIR).
- The Gamma Ray and Neutron Detector (GRaND).

In addition, gravimetry is recorded via the Doppler shift observed over the antenna transmission to Earth as Dawn orbits Vesta.

Table 1. Dawn Science Orbits and Instruments

Orbit	Dates	Target Radius	Primary Instrument	Resolution
Survey	Aug. 2011	3000 km	VIR	800 m/pixel
HAMO	Oct. 2011	950 km	FC	100 m/pixel
LAMO	Dec. 2011 – May 2012	475 km	GRaND / Gravimetry	270km/90km half wavelength
HAMO-2	Jun. 2012 – Jul. 2012	950 km	FC	100 m/pixel

The first science orbit, Survey Orbit, was positioned at an orbital radius of 3000 km about Vesta in order to obtain global VIR coverage at a resolution better than 800 meters per pixel. After six orbits in Survey, Dawn spiraled down to the High Altitude Mapping Orbit (HAMO) at 950 km orbital radius to obtain global coverage of the Framing Camera at a resolution better than 100 meters per pixel. Dawn then spiraled to its lowest orbit, the Low Altitude Mapping Orbit (LAMO), at an orbital radius of 475 km to obtain global coverage of GRaND at a 270km resolution and determine the gravity field at a half-wavelength better than 90 km. Following LAMO, Dawn returned to the HAMO altitude for High Altitude Mapping Orbit-2 (HAMO-2) to obtain Framing Camera data of the Vesta northern latitudes, which were not illuminated during HAMO. Table 1 lists the primary instrument and data resolution requirements for each science orbit.

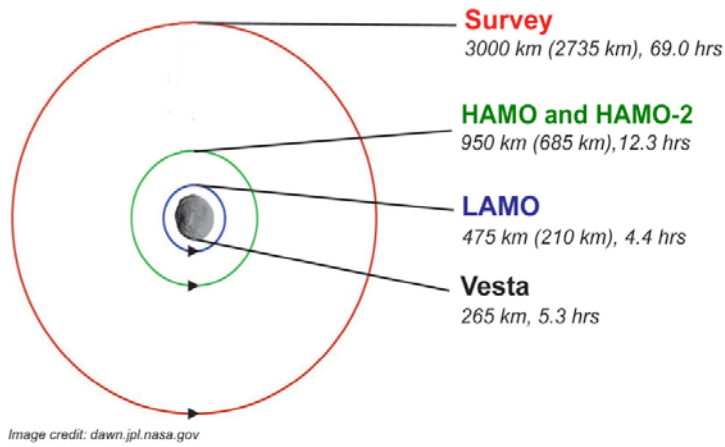

Figure 1. Dawn Science Orbits

OD supports the science mission in two ways. First, it supports the maneuver design, implementation, and execution process for navigating the spacecraft between each of the science orbits and maintaining the flight path while in the science orbits. The second function of orbit determination is ephemeris management. This entails maintaining an accurate prediction of the Dawn trajectory for ground planning processes and onboard pointing calculations. Kennedy[1] covers the ephemeris management process at Vesta in detail. Both OD roles required maintaining knowledge of the spacecraft as-flown path (trajectory reconstruction) and applying knowledge from that reconstruction to project a future flight path. The trajectory reconstruction was a key input to science data analysis for determining the altitude, latitude, and longitude of each science observation recorded. Likewise, the knowledge gained from each reconstruction was a key input for each maneuver design. The requirements levied on the Dawn orbit determination team specified an orbit determination reconstruction capability with the following accuracies:

- 200 m (1-σ) and 10 cm/sec (1-σ) @ 2000 km altitude (Survey)
- 70 m (1-σ) and 3 cm/sec (1-σ) @ 700 km altitude (HAMO-1, HAMO-2)
- 20 m (1-σ) and 0.5 cm/sec (1-σ) @ 200 km altitude (LAMO)

These requirements ensured that the trajectory knowledge was maintained at a level no greater than 1 pixel in the Framing Camera at each science orbit. They also ensured sufficient spacecraft state knowledge to enable stable maneuver designs during transfer phases.

DAWN SPACECRAFT

The Dawn spacecraft (Fig. 2) is a 740-kg dry mass payload built by Orbital Sciences Corporation of Dulles, Virginia. The spacecraft features 19.7 meters of Gallium Arsenide solar arrays aligned with the spacecraft Y-axis that power the spacecraft systems as deep as 3 AU from the Sun. For maneuvering capabilities, Dawn is equipped with three gimbaled NASA Solar-electric propulsion Technology Application Readiness (NSTAR) ion engines, known as the Ion Propulsion Subsystem (IPS). The IPS was flight-tested on NASA's Deep Space 1 mission and provides a total ΔV of nearly 11 km/s for the Dawn mission[6]. The primary thruster used during Vesta operations, IPS-3, is aligned with the –Z spacecraft axis. During operations, the IPS-3 gimbal was used to manage the torque incident on the spacecraft bus, while the spacecraft platform orientation was articulated to achieve the desire thrust vector. Since the propulsion system performance is dependent on available power, the thrust level must be throttled to manage a healthy power margin on the spacecraft. The IPS engine features discrete thrust throttle levels numbered from 0 to 111 in an onboard throttle table, corresponding to thrust levels from 18.8 mN to 91.0 mN (Reference 6). During Vesta operations, the ion engines were able to provide thrust magnitudes from 46mN (throttle level 45) to 76mN (throttle level 89) based on the available power from the solar arrays[1,4].

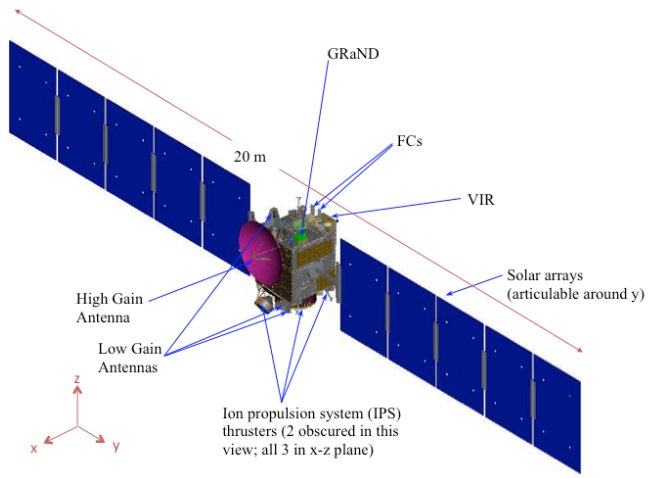

Figure 2. Dawn Spacecraft

For attitude articulation and determination, Dawn features an Attitude Control Subsystem (ACS). A set of four Reaction Wheel Assemblies (RWAs) provides three-axis stabilized pointing control of Dawn during all nominal phases of the Vesta mission. During IPS thrusting, RWAs are used to control attitude about the thrust vector, while the IPS gimbal provides control perpendicular to the thrust vector via thrust vector control (TVC). A partially coupled hydrazine Reaction Control System (RCS) is used to de-saturate the angular momentum built up ("desat" event) on the RWAs as well as provide attitude control as a backup to the RWAs. The RCS system consists of two independent strings of six 0.9-N thrusters with a hydrazine capacity of 45.4 kg[5]. RCS control about the Z-axis is balanced, but it is unbalanced for X-axis and Y-axis control, resulting in net delta-V along the X and Z axes when firing. ACS incorporates star trackers and gyroscope data to estimate the spacecraft attitude and rates and relays this information to the ground in telemetry.

Dawn communicates to the Earth using a 1.52-m diameter high-gain antenna (HGA), aligned with the spacecraft +X axis, and three low-gain antennas (LGAs), aligned with the –Z, +X, and +Z axes[9]. While the HGA requires a dedicated turn to Earth for communications, the LGAs are able to provide uniform communications coverage over various spacecraft orientations due to their higher beam width.

ORBIT DETERMINATION MODELS

Orbit determination for Dawn was performed using JPL's integrated navigation toolkit, called the Mission-analysis, Operations, and Navigation Toolkit Environment (MONTE), which provides a set of callable functions for the design, estimation, and control of spacecraft trajectories. MONTE was used to define orbit parameters, propagate trajectories, and filter measurements for determination of a final trajectory reconstruction.

Parameters were defined in MONTE by selecting an applicable model in the toolkit library and establishing *a priori* values for each parameter in the model set. For example, IPS thrusting was defined by a finite burn model with *a priori* values for force magnitude and direction. For trajectory propagation, the MONTE trajectory propagator was configured with initial conditions, defined as the epoch state, and a set of dynamics models to include in the propagation. At Vesta, these models included accelerations from IPS thrusting, RCS firings, Vesta gravity, solar pressure, and stochastic acceleration noise. Parameter estimation was performed with a batch sequential, UD-factorized Extended Kalman Filter in MONTE. The filter setup involved establishing data weights for the measurements and uncertainty values for each estimated parameter.

Error Source	Est?	A priori 1σ error	Correlation Time	Update Time	Comments
2-way Doppler	-	5.6 mHz	-	-	0.1 mm/s
Range	-	14 Range Units	-	-	2 m
Optical Centers	-	0.25 to 1.0 pixels	-	-	
Optical Landmarks	-	0.25 to 1.0 pixels	-	-	
Spacecraft State	Y	20 km, 1 m/s	-	-	
Vesta GM	Y	0.4 km^3/sec^2	-	-	
Vesta harmonics	Y	500% of Kaula power law[9]	-	-	
Vesta Pole	Y	5°, RA and Dec			
Vesta Rotation	Y	2.5° phase, 15°/day rotation			
IPS thrust	Y	0.25% of thrust	-	-	
IPS direction	Y	0.25°, RA and Dec			
Range Biases	Y	2 m per pass	-	pass	
RWA Desats	Y	5 mm/s (3 axis)	-	Per desat	
Stochastic Noise (Poly Accel)	Y	1e-11 km/s/s ballistic 1e-10 km/s/s while thrusting	-	1 hour	
Solar Pressure Scale	Y	5%	-	-	Three Plate Model
Station locations	C	2-5 cm per axis	-	-	W. Folkner, Oct 2003
Troposphere	C	1 cm	-	-	Wet and Dry Components
Ionosphere	C	5 cm day and 1 cm night	-	-	X-band values
Earth Orientation	C	10 cm per axis	-	-	X, Y pole position, TAI-UT1

Table 2. Filter Models

An OD solution was obtained iteratively by propagating a trajectory using current parameter estimates, computing predicted measurements, fitting the observed-computed residuals to new parameter estimates, and repeating with the new parameters until convergence. Convergence was typically defined as the point when the residuals computed from the trajectory propagation were zero mean with a standard deviation at or below measurement noise values. This indicated a match between the trajectory reconstruction and the observed measurements. The nominal Dawn parameters estimated at Vesta included the spacecraft epoch state, Vesta gravity field, Vesta pole and prime meridian, Vesta rotation rate, Vesta ephemeris, IPS thrust parameters, RCS thrust parameters, solar pressure, range measurement biases, and random accelerations. Additional consider parameters were added for measurement uncertainties that could not be estimated, including DSN station locations, troposphere and ionosphere effects, and Earth orientation uncertainty. Table 2 details the filter configuration used for OD at Vesta. These models will now be discussed in detail.

Measurements

Radiometric and optical measurements used at Vesta included 2-way Doppler measurements, 2-way Range measurements, optical center measurements inferred from the Vesta limb, and optical point measurements of Vesta landmarks. The radiometric measurements were recorded by the DSN and delivered prior to each OD session with a Doppler compression time of 60 seconds. Range and Doppler measurements provided line-of-sight slant range and range rate from the tracking station on Earth to the Dawn spacecraft antenna. The default weights in the OD setup for Doppler and Range were set to 2 meters and 0.1 mm/s, respectively. A stochastic range bias model was established in MONTE to estimate the range bias at each tracking pass with a 1-σ uncertainty of 2 meters. The optical measurements were recorded using the Framing Camera and delivered by the optical navigation team with weights between 0.25 and 1.0 pixels. These measurements provided angular information of the spacecraft relative to Vesta over time. Mastrodemos[7] discusses the optical navigation acquisition and weighting strategy in detail and Kennedy[11] discusses the merging of radio and optical data in a merged OD solution.

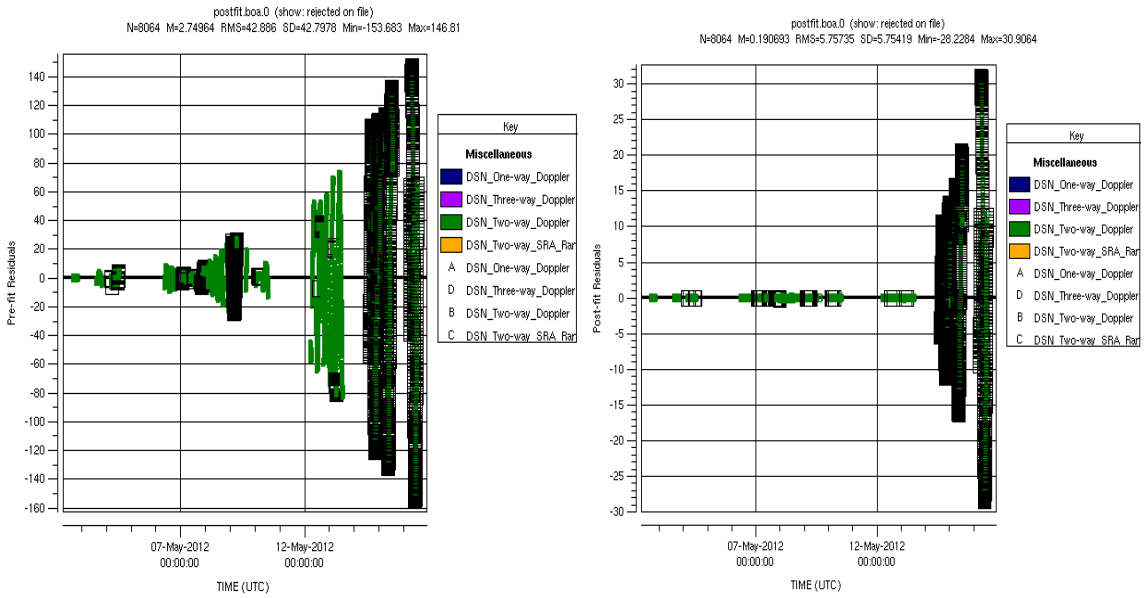

Figure 3. Pre-fit (left) and Post-fit (right) Doppler Residuals (Hz). Measurements marked by black boxes excluded from fit.

Figure 3 shows pre-fit and post-fit Doppler measurements from a LAMO to HAMO2 measurement arc. The gaps between each batch of measurements indicate IPS thrusting periods when tracking data was not available for OD. In the case illustrated here, measurement residuals were calculated as high as 150 Hz prior to the filter fit with strong nonlinear signatures due to the orbital motion about Vesta. In order to ensure linear filter convergence, the magnitude of the prefit residuals needed to be minimized as much as possible. OD approached this issue in two ways. One approach was to feed forward parameter estimates from a recent OD solution as the *a priori* values for the next OD solution. During Vesta operations, the latest estimates for epoch state, IPS thrust arcs, Vesta gravity field, and Vesta coordinate frame were fed forward between OD solutions by automated scripts. The second approach was to fit smaller segments of measurement data by using intermediate data cutoff points. In the fit illustrated here, an intermediate data cutoff was set prior to the last two batches of measurement data. By fitting the first segment of measurements, the residuals of the second segment were reduced to 30 Hz, closer to a linear region about the trajectory. As each intermediate data segment converged, the data cutoff was advanced to incorporate more of the measurement arc into the fit until all measurement data converged.

Attitude Model

Although OD only estimates the translational motion of the spacecraft, several force models in MONTE were dependent on a model of the spacecraft attitude motion. The ACS team was responsible with providing a detailed attitude profile representing the pointing of the spacecraft platform over time. Once imported into MONTE, the attitude profile defined the Dawn body-fixed coordinate frame model for the entire timespan provided. The primary uses of the attitude profile in the OD process were to model the solar pressure radiation incident on the spacecraft body and to model the orientation of the IPS for thrusting events.

IPS Thrust Model

The IPS engine thrusting events were time-varying, low thrust accelerations intended to modify the spacecraft orbit. They were modeled in MONTE as finite burn objects defined by a time varying thrust vector and mass flow rate. The time-varying thrust vector was parameterized as a force magnitude and a pointing direction. Since most of the time-varying thrust vectoring was defined by the attitude profile, the MONTE construct defined the thrust pointing as a fixed direction relative to the Dawn body-fixed frame, called the aim vector. The aim vector consisted of two angles, theta and phi, representing the right ascension and declination angles in the body-fixed frame, respectively. The motion of the IPS-3 gimbal during thrusting was typically a periodic motion of less than ±1° in each axis to balance the body torque, so a fixed

thrust direction approximation was appropriate.

The finite burn model included the burn start and stop times, the aim vector, and individual time series models for thrust magnitude and mass flow rate. The time series models were implemented as instantaneous parameter changes at defined epochs to represent discrete modes of the IPS system. At Vesta, the time series for a finite burn typically modeled a one-hour engine warmup at low thrust, a brief quiet interval of no thrust, and the nominal burn at the designated throttle level. Although the filter provided the capability to model each level with a polynomial function, only constant terms were used at Vesta due to the discrete thrust magnitude levels inherent in the IPS system.

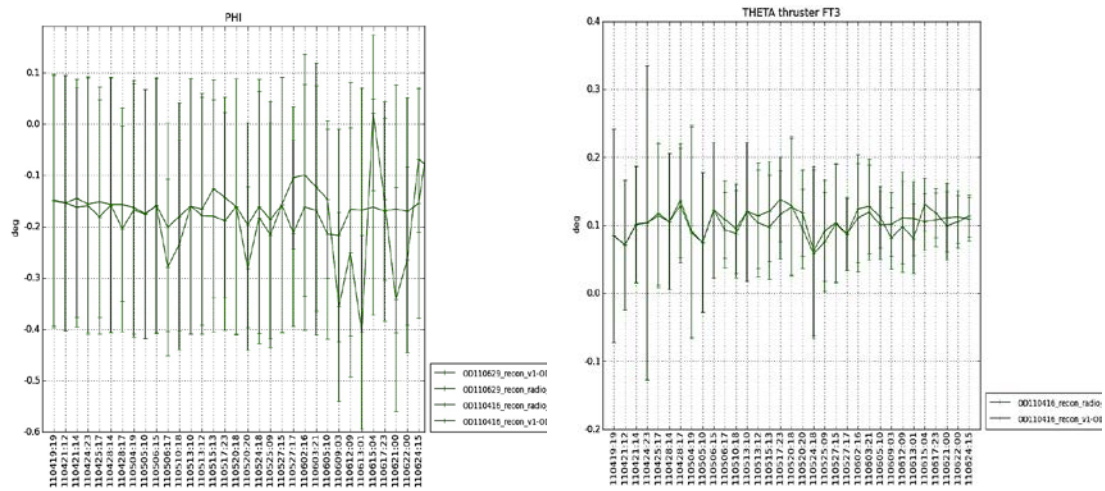

Figure 4. Aim Point Estimation For Individual Thrust Arcs During Approach Phase

The navigation filter was configured to estimate corrections to the constant terms for thrust magnitude and aim vector for each IPS maneuver. Corrections to the burn timing were not estimated in the filter. The *a priori* values and uncertainties for the aim point were determined based on estimates during early approach, as shown in Figure 4, since approach featured long thrust segments with little or no gimbal actuation. For most of the Vesta mission, phi was set to -0.15°, while theta varied between 0° and 0.1°, each with a 1-sigma uncertainty of 0.25°.

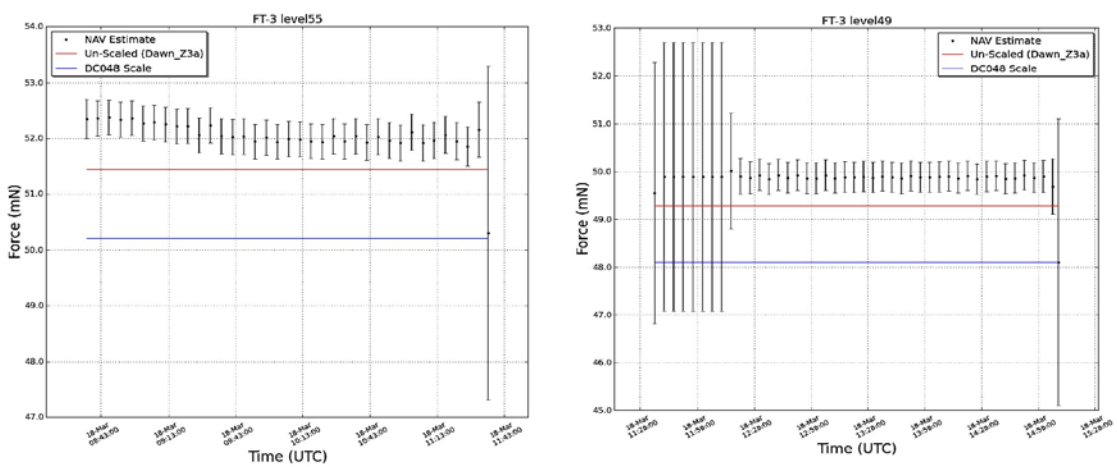

Figure 5. Thrust Calibrations for Throttle Levels 55 and 49

The *a priori* thrust magnitude was calculated from thrust values in the IPS throttle level lookup table and calibrated based on recent OD estimates of engine performance. The calibration values were main-

tained in a scale factor table as multiplicative scale factor adjustments for each IPS throttle level. The initial scale factor table was generated prior to Vesta approach by testing each family of IPS throttle levels in flight and calculating scale factors based on OD estimates of the thrust magnitude. Figure 5 shows the results of calibrations for throttle levels 55 and 49. Throttle level 55 was determined to have a scale factor of 1.01238 relative to the unscaled throttle lookup table, while throttle level 49 was found to have a scale factor of 1.01230. This calibration process was repeated for every seventh throttle level bounding a thrust family and the values within each family were derived by linear interpolation. The 1-sigma filter uncertainty was set to 0.25% of the *a priori* thrust magnitude, based on the uncertainties in the calibration estimates.

Vesta Gravity Model

The Vesta gravity field was modeled in MONTE by a spherical harmonics expansion in the Vesta body-fixed reference frame with a reference radius of 265 km (Reference 9). The gravity field parameterization in MONTE consisted of the Vesta gravitational constant, GM, and a set of normalized harmonic coefficients (J_n, C_{nm}, S_{nm}), where n and m represent the degree and order, respectively, of the spherical harmonics expansion. The degree of the spherical harmonics estimated was dependent on the signal strength observable in the Doppler data, which increased as the altitude was lowered. For example, at HAMO the accelerations due to gravity were expected to be on the order of 10^{-5} km/s^2, compared to 10^{-4} km/s^2 at LAMO[9]. At Vesta, a 4x4 gravity field was estimated during Survey, followed by an 8x8 gravity field at HAMO, and a 13x13 gravity field at LAMO.

Before reaching Vesta, the *a priori* gravity field was based on an 8x8 homogenous Hubble-derived shape model of Vesta[10]. The assumed GM was 17.8 km^3/sec^2 with a 1-σ uncertainty of 0.4 km^3/s^2. The uncertainties of the spherical harmonics coefficients were based on a Kaula power law[9] and scaled up by a factor of five to be conservative. At Survey and HAMO, a series of one-week independent data arcs were used to reassess the statistics of the gravity field estimates. The mean and standard deviation of these results were used to rescale the nominal values and uncertainties of the gravity parameters. Figure 6 provides an example of the independent data arc estimates in HAMO to determine a new mean of 17.28866 km^3/s^2 and sigma of 2.048 x 10^{-4} km^3/s^2 for the transfer to LAMO.

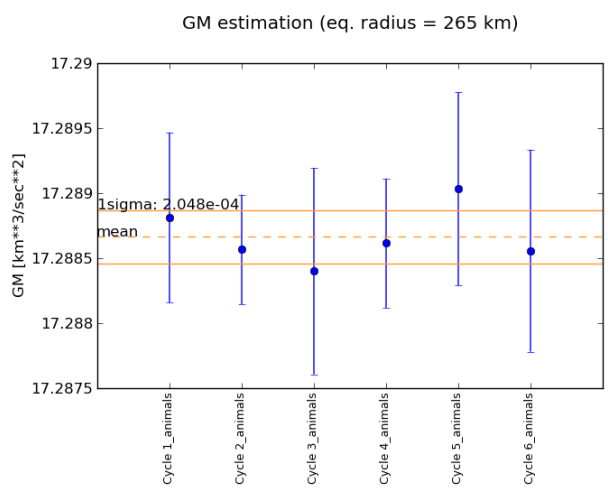

Figure 6. HAMO Independent GM Estimates

Vesta Body-Fixed Reference Frame

The Vesta body-fixed reference frame is modeled by a fixed pole location and a constant rotation rate about that pole. This was parameterized in MONTE as right ascension and declination angle to define the pole and a prime meridian phase angle and rotation rate to define the orientation about the pole. The initial values for the pole location were RA=305.8°, DEC=41.4°, as delivered by the Dawn Science team based on Hubble observations[7]. The initial value for the rotation phase was set to 292.0° at the J2000 epoch and 1617.332776°/day for the rotation rate, based on Hubble observations[10]. The estimates for these parameters

were refined during approach to Vesta using optical navigation data, as described by Mastrodemos[7]. Radiometric data can also be used to estimate these parameters by observation of the gravity signal periodicity on successive orbits. *A priori* filter uncertainties were set at 5° for the pole angles, 2.5° for the prime meridian, and 15°/day for the rotation rate. Similar to the Vesta gravity field, these uncertainties were reassessed based on one-week independent data arcs at each science orbit.

RCS Thrust Model

The RCS was fired on average every 1-3 days at Vesta to remove angular momentum from the RWAs, typically exerting velocity changes on the order of 1-3 cm/s. These desat events were modeled in MONTE as impulsive velocity (delta-V) and mass changes to the spacecraft state. The nominal delta-V pulses were exerted along the spacecraft +Z, +X, and –X axes, as shown for LAMO in Figure 7. MONTE was configured to estimate the executed delta-V via stochastic parameters representing velocity corrections along the body-fixed X, Y, and Z axes with batch boundaries defined between each desat event. The corrections were modeled as stochastic parameters in order to allow compatibility with desat designs, which listed each desat as one record, and desat telemetry reconstruction records, which often split each desat into 1-minute segments. The *a priori* uncertainty of each delta-V bias component was configured to 5 mm/s in the filter.

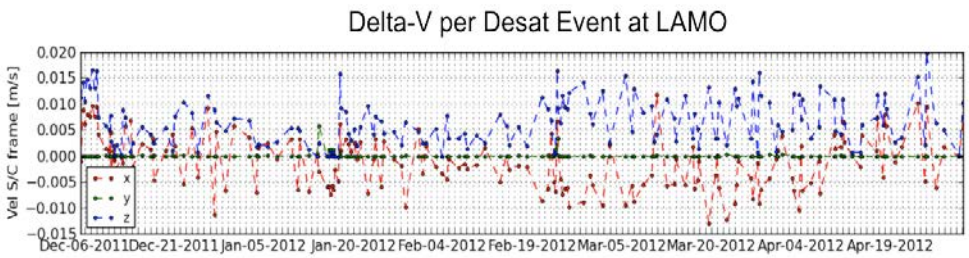

Figure 7. Delta-V Exerted in the Dawn Body-Fixed Frame per Desat at LAMO

Solar Pressure Model

The solar pressure model used a three-plate model to represent the spacecraft bus area along each body-fixed axis and an additional plate oriented in the Sun direction to represent the solar panels. A scale factor was estimated to scale the acceleration based on observations in the measurements with an uncertainty of 5%. The solar pressure was a second-order perturbation at Vesta, due to it exerting accelerations on the order of 10^{-11} km/s^2, compared to 10^{-4}-10^{-7} km/s^2 for gravity[9].

Stochastic Accelerations Model

A stochastic model was established to estimate random unmodeled acceleration noise incident on the spacecraft. The model estimated the random accelerations in the J2000 X, Y, and Z directions in one-hour stochastic batches. The *a priori* uncertainties for each batch interval were set to 1 x 10^{-11} km/s^2 during ballistic coasting and 1 x 10^{-10} km/s^2 during thrusting activities to soak up thruster noise, especially motion of the IPS gimbal. Figure 8 shows a typical periodic signature soaked up as stochastic accelerations during a LAMO to HAMO-2 thrusting arc.

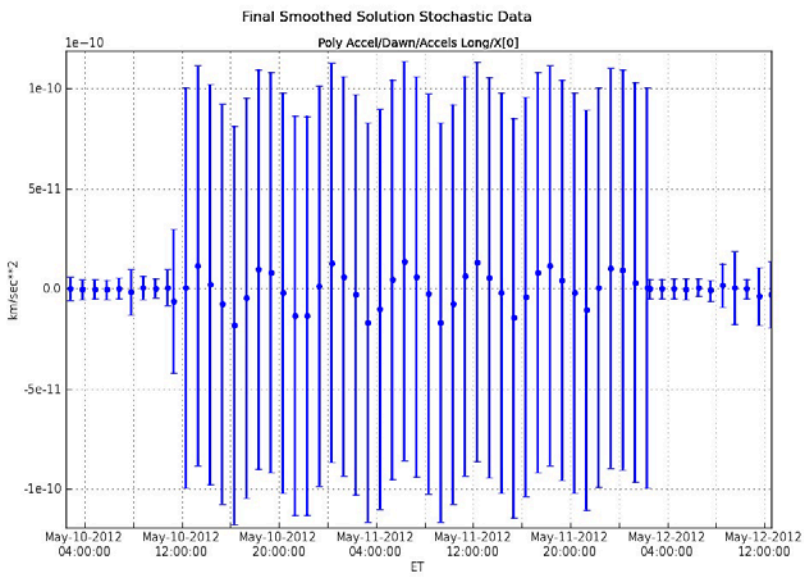

Figure 8. Sample Stochastics during a LAMO to HAMO-2 Thrust Arc

Arc Length and Tracking Data Management

Arc length refers to the span of measurement data fit in an OD solution. In nominal OD operations, three measurement arcs were maintained: a long arc, a medium arc, and a short arc. The long arc typically spanned 2-3 weeks, while the medium arc spanned 1-2 weeks, and the short arc spanned a duration that only contained the most recent maneuver cycle. At each new maneuver cycle, the previous long arc was retired, the medium and short arcs were promoted, and a new short arc was adopted by moving the epoch state forward to the tracking pass preceding the last executed maneuver cycle. The variations in arc length provided important insights into parameter aliasing and greater confidence in the delivered OD solution. Figure 9 illustrates an example of long, medium, and short arc GM estimates converging to similar solutions.

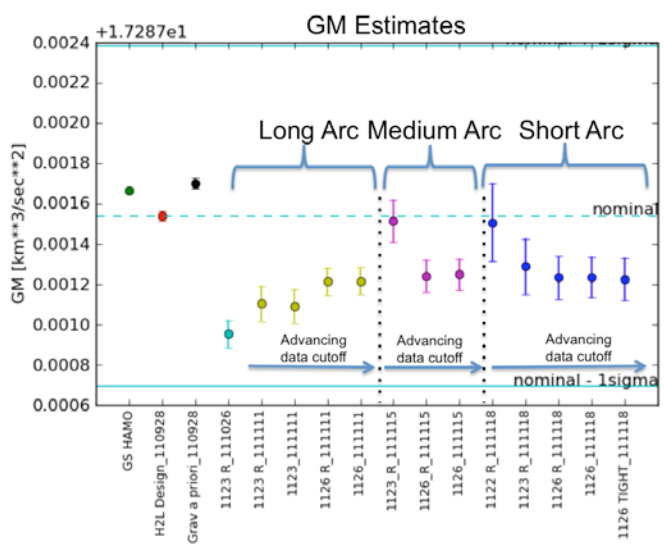

Figure 9. Illustration of arc length variations to ensure solution stability

The tracking data management strategy at Vesta utilized automated data editing to remove outliers and antenna motion from the measurements. An automated process was established to delete any outlier measurement points exceeding 5 standard deviations from the data mean. Additional data editing included edits for measurements acquired during antenna slews and desat events. The antenna slew edits were generated during each sequence build, while the desat event edits were built automatically upon receipt of RCS firing telemetry from the spacecraft. Figure 10 shows edited Doppler points marked by a square box during a 10-minute desat event during the HAMO to LAMO transfer.

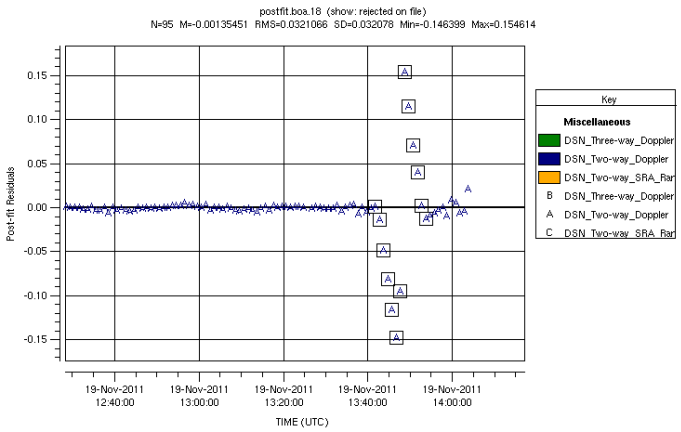

Figure 10. Example of data editing during a desat event

Lastly, automatic data weighting was used to aid filter convergence and ensure the maximum extraction of the signal from the tracking data. At each OD iteration, the measurement data was split into 1-hour segments and weighted at 3 times the standard deviation of the noise in each segment.

ORBIT DETERMINATION INTERFACES

The OD process described in the previous section was reliant on data inputs from other subsystems to produce the products needed for the maneuver design and ephemeris update processes. The MONTE modeling environment was the central repository for all information related to flight dynamics of the Dawn spacecraft. The OD team imported data from multiple spacecraft subsystem teams in order to seed several of the flight dynamics parameters described in the previous section with *a priori* values. In turn, the OD team delivered products to enable the design of thrust, attitude, and RCS firing profiles by subsystem teams. The primary end product generated by the OD process was a Vesta-centered Dawn trajectory containing both the trajectory reconstruction (epoch time to measurement data cutoff) and the trajectory prediction (measurement data cutoff to 15-30 days in the future). Figure 11 depicts the OD process receivables and deliverables.

The OD team relied on four primary receivables to generate its *a priori* models of the spacecraft dynamics: (1) spacecraft attitude profile, (2) IPS maneuvers, (3) RCS firings, and (4) an antenna schedule. The ACS team delivered a predicted spacecraft attitude profile as a NAIF* CK file of interpolated quaternions. This attitude profile represented a design to accommodate upcoming science observations (+Z nadir), thrust vectoring (+Z aligned with thrust profile), and antenna pointing (+X to Earth). This receivable established the Dawn body-fixed reference frame. The mission design (MD) team delivered the IPS maneuvers as a series of thrust vector magnitudes and directions over finite time intervals in a Thrust Vector File (TVF). The TVF receivable established the *a priori* finite burn acceleration models. The ACS team delivered the RCS event firings as time-tagged velocity impulses in a Small Forces File (SFF); this established the *a priori* RCS delta-V for the OD filter. The antenna history was built based on a Timed Sequence Of Events

* http://naif.jpl.nasa.gov/naif/index.html

(TSOE) file delivered by the spacecraft (SCT) team and describes the time intervals when each spacecraft antenna has a two-way link established with the Earth. This assigns an antenna model to each segment of radiometric measurements received.

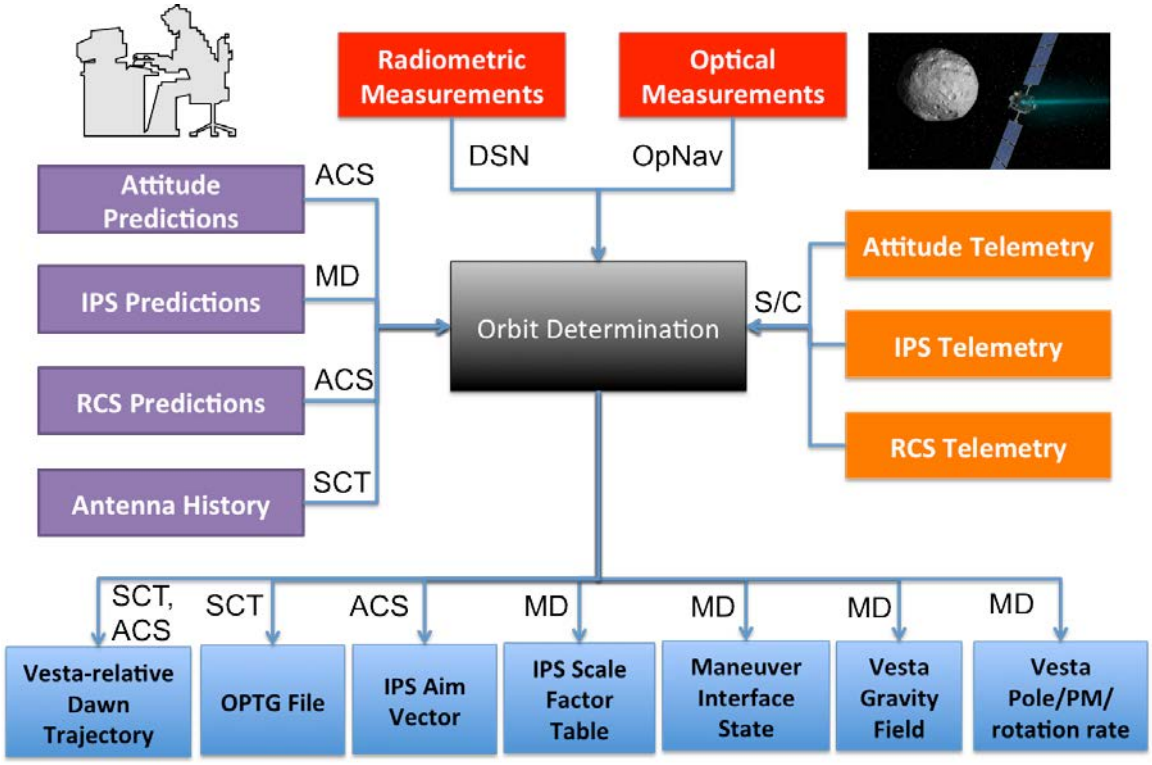

Figure 11. Orbit Determination Process Inputs and Outputs (DSN = Deep Space Network, OpNav = Optical Navigation Team, ACS = Attitude Control Subsystem Team, MD = Mission Design Team, SCT = Spacecraft Team, S/C = Spacecraft)

The initial CK, TVF, SFF, and TSOE inputs delivered to OD were generated based on a command sequence design for an upcoming flight segment. The items on the left side of Figure 11 represent these as-designed prediction models for subsystem performance. As the designed activities were executed on the spacecraft, the as-flown performance was transmitted to the ground in telemetry and the predictions were replaced by the telemetry data. The items on the right side of Figure 11 represent these telemetry models. Of the initial inputs, only the antenna schedule was not updated by telemetry, since the as-designed antenna schedule was typically static enough to not warrant a telemetry update. Once telemetry was received on the ground, automated scripts were notified of the new data and automatically converted the attitude, IPS, and RCS telemetry data into the standard MONTE format. By the time the OD analyst arrived for his/her shift, the latest model inputs were built and ready for inclusion in the OD solution for that day. In essence, this OD configuration maintained an advancing boundary between as-flown telemetry and as-designed prediction models with each playback transmission from the spacecraft. This ensured the best as-flown performance estimates for the trajectory reconstruction while maintaining the latest designs for trajectory prediction. Figure 12 shows an example of the SFF design compared against its telemetry playback during LAMO, with differences as much as 9 mm/s indicating the importance of telemetry inclusion in the OD process.

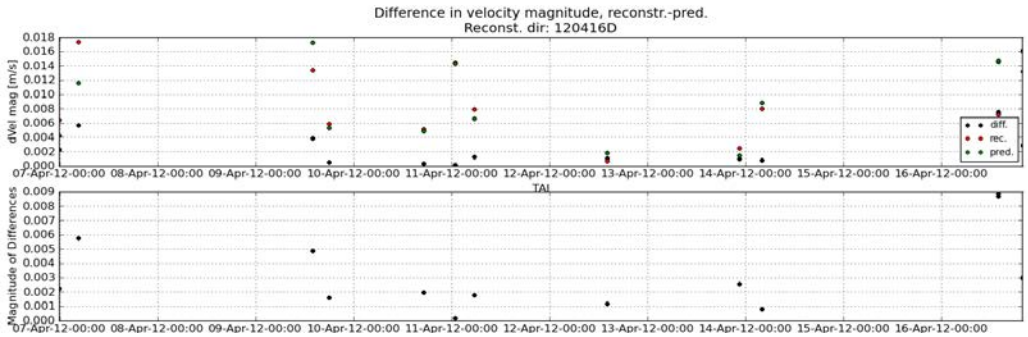

Figure 12. Comparison of SFF Design and SFF telemetry

The OD deliverables are enumerated at the bottom of Figure 11. Deliverables to the spacecraft and ACS teams included (1) the Dawn trajectory as a NAIF SPK kernel, (2) the expected IPS thrust aim vector in body-fixed coordinates, and (3) a list of Vesta's equator, terminator, and pole crossings of the Dawn trajectory in an Orbit Propagation and Timing Geometry (OPTG) file. Deliverables to the mission design team included (1) the IPS scale factor table, (2) the Dawn state at the maneuver design interface epoch, and (3) estimates of the Vesta physical parameters. These deliverables are required for two critical Dawn processes:

1. Onboard ephemeris updates during science phases
2. Maneuver design and implementation during transfer phases and LAMO

For the ephemeris update process, OD was tasked with delivery of a Vesta-relative Dawn trajectory containing all upcoming designed thrusting and desat events. The primary considerations for updating the onboard ephemeris were (1) to maintain spacecraft instrument pointing in the Vesta nadir direction and (2) to maintain accurate timing of sequenced science acquisition activities. An ephemeris update was deemed necessary at LAMO when either the pointing error was projected to be greater than 0.4° or the timing error was projected to be greater than 300 seconds due to the onboard stale ephemeris. In order to determine whether the thresholds would be crossed, the OD team generated a new ephemeris based on the latest tracking data twice per week and compared the projected pointing and timing against the last uplinked ephemeris. If the thresholds were exceeded, OD delivered an updated Dawn trajectory to the spacecraft team for uplink to the spacecraft. Kennedy[1] covers the effectiveness of this process at each mission phase at Vesta.

For the maneuver design process, the OD team was responsible for OD deliveries to the mission design team, thrust design verification and propagation, and thrust command sequence verification. This process will be described in detail in the next session.

MANEUVER DESIGN CYCLE ARCHITECTURE

The Dawn navigation strategy at Vesta called for the use of reference trajectories for targeting of the spacecraft flight path during operations[2]. Reference trajectories were built for each science orbit and transfer phase two to four weeks in advance of execution based on the best available knowledge of IPS scale factors, aim vectors, and the Vesta gravity field at the time. As navigation errors accrued during flight, TVF profiles were designed to return the spacecraft to the reference trajectory. This approach was implemented during each of the transfer phases, as well as during LAMO for Orbital Maintenance Maneuvers (OMMs)[12]. Since the OMM maneuver design process is essentially a more relaxed version of the transfer design process, it will not be described in detail here.

For the transfer phases, significant flight path control was required. Due to the low-thrust characteristics of the IPS, these phases typically spanned 30-40 days with approximately 50% of the total time reserved for IPS thrusting[8]. Since operation of the transponder during thrusting would require a drop in thrust on the order of 3mN due to the extra power consumption, tracking data was not recorded during thrusting activities at Vesta. The major challenge at Vesta was a scheduling one: to balance spacecraft control authority

via thrusting segments with navigation knowledge availability on the ground via tracking pass segments. Specifically, the tracking pass segments needed to be scheduled within the current thrust arc such that an updated OD solution could be delivered in time for the design of the next thrust arc.

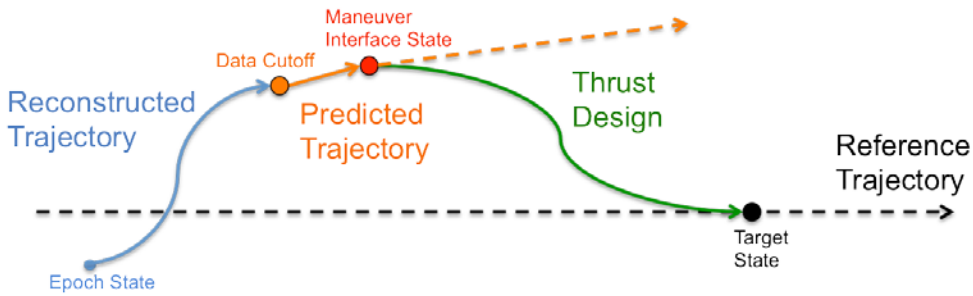

Figure 13. Illustration of the Dawn navigation strategy

In order to manage navigation error accrual during flight, the transfer phases were split into smaller segments called maneuver design cycles. Figure 13 illustrates the maneuver design approach. The OD team was responsible for determining the maneuver interface state based on a projection of the reconstructed trajectory, and the mission design team was responsible for designing a maneuver starting at this state and returning to the reference trajectory by the next interface epoch. The time between the data cutoff and the maneuver interface state was required for the design, verification, and uplink of the thrust sequence design. Typically, the maneuver cycle being designed on the ground was two cycles ahead of the maneuver executing on the spacecraft, requiring a quick design turnaround to prevent navigation error buildup. The maneuver design cycles were chosen with varying durations from 2 to 7 days by the mission design team to provide a high confidence of success based on statistical analyses of trajectory perturbations during the transfer.

In total, 43 maneuver design cycles were designed for the mission at Vesta: 5 on Approach, 4 from Survey to HAMO, 10 from HAMO to LAMO, 10 during LAMO, 11 from LAMO to HAMO-2, and 3 during Departure. Five of the maneuver cycles at LAMO were cancelled due to better-than-expected navigation errors, while one additional cycle was added during HAMO to LAMO due to a safe mode, leaving 38 maneuver cycles in total executed at Vesta.

Orbit Determination Team Roles in the Maneuver Design Cycle

The end goal of each maneuver design cycle was to generate a command sequence governing operation of the spacecraft during the next thrusting segment. The OD team had several prominent roles in the sequence build process process to determine and verify parameters related to IPS thrust execution. The OD team was responsible for four supporting activities during a maneuver design cycle:

1. Delivery of a preliminary OD solution
2. Delivery of a final OD solution
3. Integration, verification, and delivery of a trajectory implementing the thrust vector profile design
4. Verification of the thrust command sequence

Figure 14 depicts a typical 4-day maneuver design cycle with OD tasks highlighted in blue and delivery products highlighted in red. The overall design cycle involved (1) obtaining the latest trajectory knowledge from an OD solution, (2) designing the maneuver, (3) integrating the maneuver in a trajectory, (4) building the command sequence, and (5) verifying the command sequence. In a typical 4-day design cycle, the start of the OD process was timed to coincide with the end of a tracking pass to capture the latest available measurements of the spacecraft motion. As discussed in the last section, the OD team imported products from the previous cycle design and from telemetry to establish *a priori* parameter values.

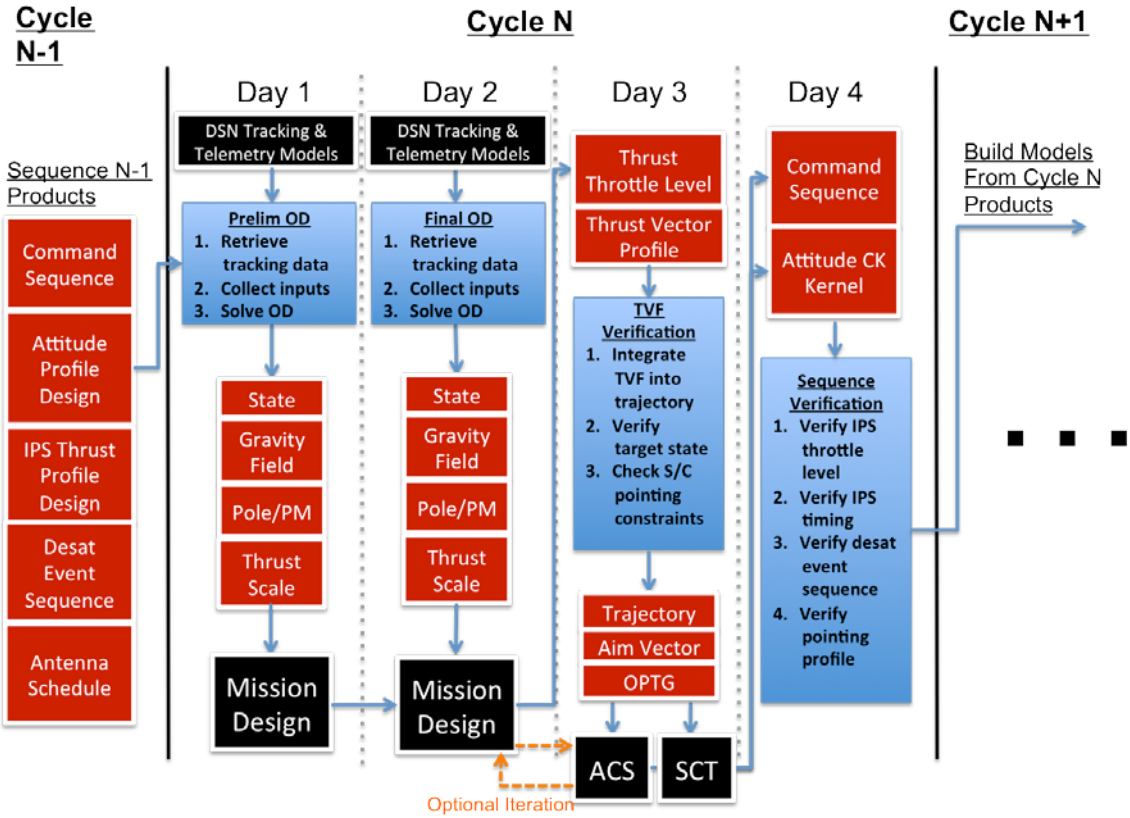

Figure 14. Example 4-day maneuver Design Cycle

Day 1 OD responsibilities included producing a preliminary OD solution and delivering select parameters to the mission design team. These deliverables included the following items:

1. Vesta-relative Dawn state vector in EME2000 (km, km/s) and mass (kg) at the maneuver interface epoch
2. Vesta GM (km^3/s^2) and spherical harmonics normalized coefficients
3. Vesta Pole Orientation (deg)
4. Vesta Prime Meridian Phase (deg at J2000 epoch) and Rotation Rate (deg/day)
5. Updated scale factor table for IPS throttle levels

Four hours were typically allocated for a preliminary OD delivery. The OD analysts were tasked with verifying availability and consistency of the latest telemetry-based models, investigating arc and model variations, iterating the OD solutions to convergence, selection of an acceptable OD solution, and inspection of the final products to be delivered to mission design. The purpose of the preliminary OD delivery was to offer an opportunity for the mission designers to explore the maneuver design space before the time-critical final maneuver design began.

On day 2 of the maneuver design cycle, OD produced an updated OD solution using new measurements and telemetry obtained since the first day and delivered a final OD solution to mission design. Six hours were allocated to the final OD delivery in order to close all open issues from the preliminary delivery and ensure an on-time delivery for the final maneuver design. A majority of the time during the final OD process was spent checking the stability of the final trajectory to variations in measurement arc length, *a priori* Vesta gravity and pole parameters, and selection of telemetry-based models. The mission design team iterated on the final thrust vector profile design for the remainder of day 2. A TVF file was delivered back to OD along with a chosen IPS throttle level for implementation and verification.

On day 3, the OD team incorporated the thrust vector profile into an integrated spacecraft trajectory

and verified that the states targeted by mission design were met and that no spacecraft pointing constraints were violated. Scripts automatically checked the thrust vectors for any flight rule violations. Once all checks were complete, the integrated trajectory product, IPS aim vector, and OPTG file were delivered to the ACS and SCT teams. The aim vector and trajectory were used by the ACS team to design an attitude profile and desat sequence, while the SCT team used the trajectory and OPTG file to define a command sequence. Since the new set of desats were designed after the TVF design, an optional iteration could be executed between mission design and ACS to compensate for the desat perturbations in the TVF design. In practice, this iteration was only executed a few times at Vesta when highly accurate trajectory deliveries were required, such as the start of the LAMO to HAMO-2 transfer.

On day 4, OD received an attitude profile in NAIF CK kernel format and a fully integrated command sequence for the maneuver cycle. A set of scripts were executed to splice the command sequence and check the following items: IPS start and stop times, IPS selected throttle level, desat mode and schedule, and a comparison between the attitude in the CK kernel and thrust vector pointing the TVF file. If all checks were successful, OD approved the sequence for uplink to the spacecraft. At that time, new IPS, RCS, attitude, and antenna *a priori* models were built and a new trajectory was propagated for use in the next maneuver cycle. Since the MD team did not typically model desats or an IPS initialization mode called Diode Mode in the TVF design, this propagated trajectory was typically dispersed from the targeted waypoint by a few tens of kilometers once the desats and Diode Mode were incorporated in MONTE.

ORBIT DETERMINATION PERFORMANCE

The OD performance at Vesta was measured by inspecting the effectiveness of OD products delivered for the maneuver design cycle.

Gravity Performance

The signal strength of the gravity field in the Doppler data increased significantly as the orbit altitude was lowered, resulting in higher fidelity OD gravity field estimates as Dawn approached LAMO. During the transfer from HAMO to LAMO, it was important for OD to deliver a consistent and stable gravity field to the MD team to minimize navigation dispersions from the reference trajectory. In order to measure the consistency of subsequent gravity field deliveries made during the HAMO to LAMO transfer, trajectories were propagated over LAMO using fixed initial conditions and a gravity field from each maneuver cycle delivery (DL011 through DL020).

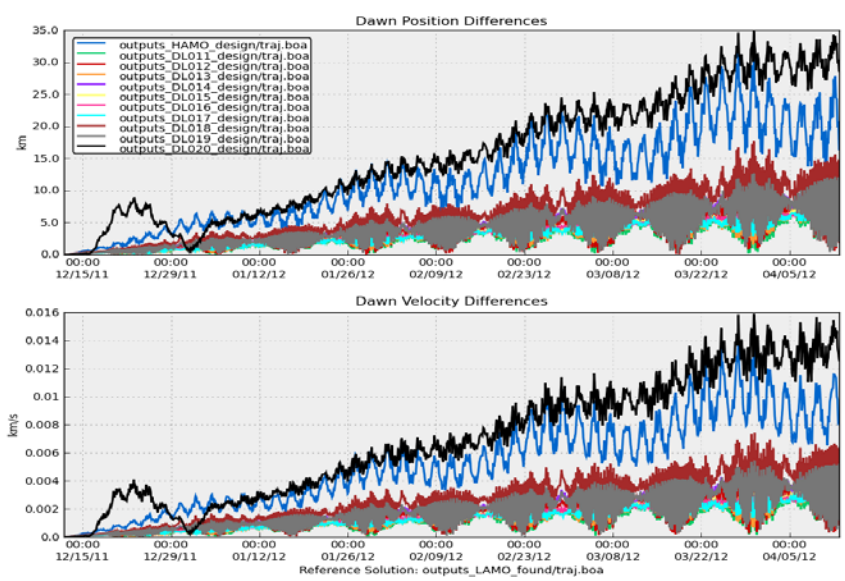

Figure 15. LAMO Trajectory Dispersions From Intermediate Gravity Fields Delivered During HAMO to LAMO

In **Figure 15**, the trajectory dispersions relative to the LAMO reconstructed trajectory are plotted. Results indicate highly consistent gravity field deliveries. The gravity field determined by the end of HAMO would have only caused a 25 km dispersion over the duration of LAMO and as the altitude was lowered (DL011 cycle onwards), the trajectory dispersions nest together nicely within a 10 km region. The one exception is DL020, which was the first delivery following a safe mode event. Due to the limited tracking data available post-safing, the DL020 gravity field was set identical to the DL019 gravity field up to the 9th order terms and only the 10th through 13th order terms were estimated. The DL020 delivered gravity field produced dispersions of 30 km over LAMO, slightly larger than even the HAMO gravity field.

IPS Performance

The effectiveness of IPS parameter deliveries was measured during the LAMO to HAMO-2 transfer once the gravity field was well determined. During this phase, the gravity model was fixed to a 13x13 field determined by one-week independent arcs at LAMO. Since the gravity was fixed, the primary trajectory perturbations at this phase were due to IPS and RCS execution errors, with the IPS having a dominant effect due to long periods of thrusting. Accurate prediction of the IPS thrusting levels was important for minimizing navigation dispersions due to maneuver execution errors during transfer.

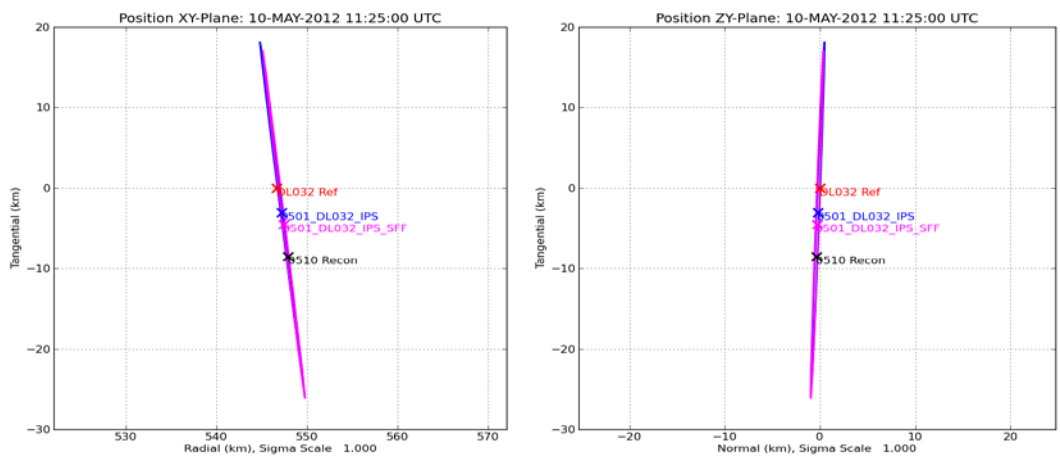

Figure 16. Position Dispersions at DL032 Waypoint

Navigation dispersions were assessed at intermediate waypoint epochs between each IPS thrust cycle. Figure 16 illustrates a typical interface plot used by the OD team to assess predicted and reconstructed trajectory states at each waypoint. These states and their formal uncertainties are plotted in the inertial X-Y and X-Z planes at the DL032 waypoint epoch, which immediately follows the DL032 thrust arc. The DL032_Ref state indicates the target state for the DL032 thrust design. Since Diode Mode and desat predictions were not modeled in the thrust design targeting DL032_Ref, the predicted trajectory was slightly dispersed from the target state. In the plot, the state appended with "IPS" represents the dispersed trajectory due to Diode Mode modeling and the state appended with "IPS_SFF" represents the same trajectory with desat model dispersions incorporated. Both of these trajectories are predictions built with models prior to DL032 thrusting, while the state appended with "Recon" is a reconstructed trajectory solved after DL032 thrusting. The difference between the target state and "IPS_SFF" state is defined as the modeling dispersion error. The difference between the "IPS_SFF" state and the "Recon" state is defined as the execution dispersion error. The total dispersion error is the sum of these two errors, or the dispersion of the reconstructed trajectory from the reference trajectory.

Table 3. LAMO to HAMO-2 Trajectory Dispersions

Thrust Design Cycle	Waypoint Epoch (11:25 UTC)	Throttle Level	IPS Scale Factor Adjustments	Total Dispersion from Reference (km)	Desat and Diode Mode Modeling Dispersions (km)	IPS/Desat Execution Dispersions (km)
DL031	04-MAY-2012	51	-0.2%	26.0 Downtrack	23.7 Downtrack	2.3 Downtrack
DL032	10-MAY-2012	51	0%	12.5 Downtrack	8.5 Downtrack	4.0 Downtrack
DL033	13-MAY-2012	51	0%	10.0 Downtrack	6.8 Downtrack	3.2 Downtrack
DL034	15-MAY-2012	50	0%	6.9 Downtrack	7.0 Downtrack	0.1 Uptrack
DL035	19-MAY-2012	50	-0.15%	8.8 Uptrack	5.8 Downtrack	14.6 Uptrack
DL036	23-MAY-2012	50	0%	37.6 Downtrack	33.9 Downtrack	3.7 Downtrack
DL037	27-MAY-2012	50	0%	65.2 Downtrack	36.2 Downtrack	29.0 Downtrack
DL038	31-MAY-2012	49	+0.2%	28.0 Downtrack	23.0 Downtrack	5.0 Downtrack
DL039	04-JUN-2012	49	0%	11.8 Uptrack	30.5 Downtrack	42.3 Uptrack
DL040	09-JUN-2012	49	-0.15%	17.5 Downtrack	14.3 Downtrack	3.2 Downtrack

Table 3 lists the breakdown of dispersions due to modeling and execution errors at maneuver cycle waypoints during LAMO to HAMO-2. One finding is that the execution dispersions were typically lower than the modeling dispersions. The two exceptions were DL035 and DL039, when overburns of the IPS dispersed the spacecraft uptrack of the waypoint state prediction. A second finding is that the slight adjustments to the IPS scale factors during DL031 and DL035 had little effect on the execution dispersions, while adjustments at DL038 and DL040 corrected for an underburn at DL037 and an overburn at DL039. This suggests that the throttle level calibrations performed during Approach were sufficient to characterize systematic biases in the throttle levels and adjustments during real-time operations were likely compensating for random thrust-to-thrust variations. Since the dispersions due to modeling and execution are on the same order of magnitude, it can be concluded that the IPS deliveries provided by OD provided adequate stability for the transfer phases at Vesta.

Pole estimation

The Vesta coordinate frame was also an OD deliverable requiring stability. The pole and rotation of Vesta were well determined by the gravity signal in the Doppler data by Survey orbit.

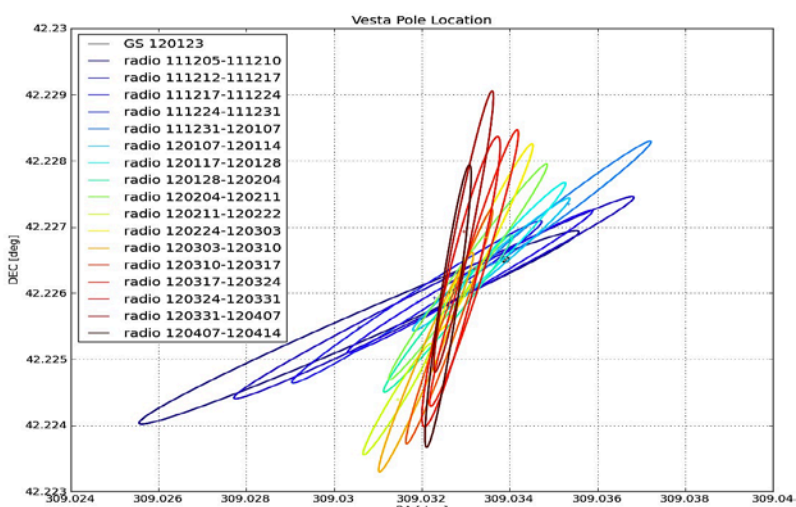

Figure 17. Vesta Pole Estimates in LAMO

Figure 17 depicts the stability of one-week independent Vesta pole estimates at LAMO. The maximum uncertainty was on the order of ±0.005° and the final determined value of RA=309.033°, DEC=42.226° was within 1 millidegree of an independent estimate solved by the Dawn gravity science team. Mastrodemos[7] and Kennedy[11] discuss discrepancies between radiometric-based and optical-based estimates of the Vesta pole and prime meridian.

Desat Performance

Although not delivered as an OD product, the desat estimates provided insight into any observed biases in the SFF telemetry records. During HAMO-2, the desats were the primary trajectory perturbation due to a stable gravity field and no IPS thrusting. Estimates of the Z-axis desat corrections indicated an underprediction of 0.02 to 0.03 mm/s in the SFF records delivered by telemetry. Since each desat consisted of 10-15 records, this indicated desat over performance of 0.2-0.5 mm/s. Given that the differences between the SFF design and SFF telemetry was on the order of 1-10 mm/s, this was a secondary source of error. Similarly, a Y-axis bias of -0.04 to -0.06 mm/s per record indicated an error of 0.4-1.0 mm/s per desat. This is particularly noteworthy since it may indicate an RCS thruster misalignment of a few degrees.

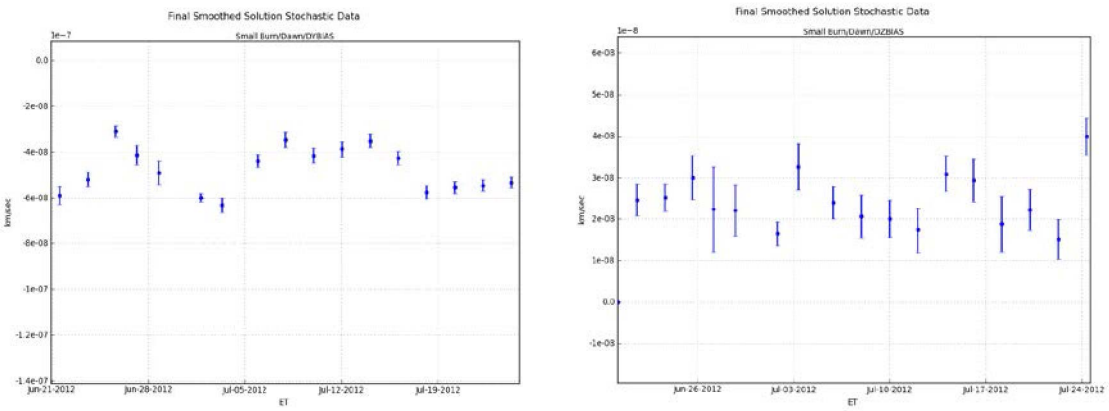

Figure 18. Observed Bias in HAMO-2 Y-axis and Z-axis Desat Reconstructions

Trajectory Reconstruction Performance

Lastly, the OD trajectory reconstructions were examined. The intermediate OD trajectory deliveries at LAMO were compared against a final trajectory reconstruction generated post-LAMO to assess OD knowledge performance during the mission.

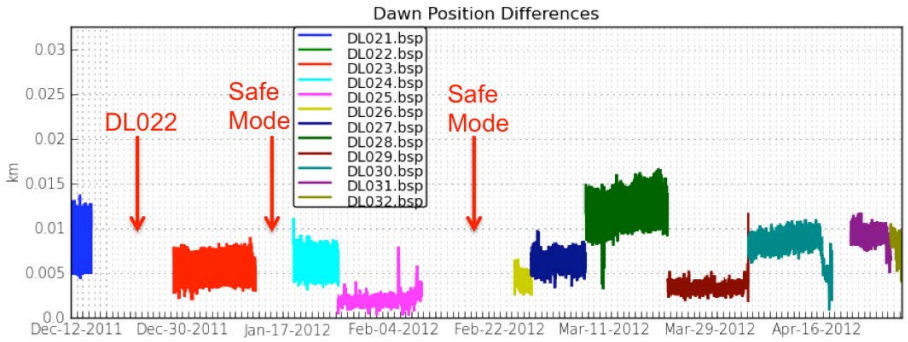

Figure 19. Dawn OD Intermediate Trajectory Solutions Compared to Final LAMO Reconstruction

Figure 19 plots the position differences between each intermediate OD delivery up to its data cutoff and the final LAMO trajectory reconstruction. Two gaps exist in the data span due to off-nominal safe mode

operations that occurred during LAMO. All intermediate trajectory deliveries show agreement to within 15 meters [except] for the DL022 delivery, which exhibits errors up to 150 meters. The DL022 trajectory appears to be an outlier because it was the only delivered solution at LAMO to incorporate both radiometric and optical measurements. Kennedy[11] discusses discrepancies between the optical and radiometric measurements observed at LAMO. The final OD trajectory reconstruction was compared to an independent trajectory solution generated by the gravity science team, showing peak disagreements of 2 meters and an RMS disagreement of only 0.6 meters, confirming the validity of the trajectory reconstruction.

CONCLUSION

This paper discussed the OD models and processing steps developed to implement a rapid orbit determination capability at Vesta. The OD team was an integral part of the overall maneuver design and sequence build process that ensured safe navigation of the Dawn spacecraft about Vesta. The OD process was able to successfully generate and deliver OD solutions within tight time constraints over all phases of the mission due to automated incorporation of model predictions and telemetry reconstructions. OD deliveries of the Vesta gravity field, IPS engine performance, and trajectory state provided sufficient accuracy and consistency to maintain the spacecraft within tens of kilometers of the reference trajectory during flight.

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REFERENCES

[1] Kennedy, B., *et. al.,* "Dawn Orbit Determination Team: Trajectory and Gravity Prediction Performance during Vesta Science Phases", 23rd AAS/AIAA Spaceflight Mechanics Meeting, Kauai, Hawaii, Feb. 10-14, 2013.

[2] Han, D., "Orbit Transfers for Dawn's Vesta Operations: Navigation and Mission Design Experience", 23rd International Symposium on Space Flight Dynamics (ISSFD), October 29-November 2, 2012, Pasadena, California.

[3] Parcher, D.W., and Whiffen, G.J., "Dawn Statistical Maneuver Design for Vesta Operations", AIAA/AAS Astrodynamics Specialist Conference, New Orleans, Louisiana, Feb. 13-17, 2011.

[4] Garner, C., Rayman, M., "Performance of the Dawn Ion Propulsion System Through Operations at Vesta", 23rd AAS/AIAA Spaceflight Mechanics Meeting, Kauai, Hawaii, Feb. 10-14, 2013.

[5] Rayman, M.D. *et al., "*Dawn: A mission in development for exploration of main belt asteroids Vesta and Ceres", *Acta Astronautica*, Vol. 58, Issue 11, June 2006, pp. 605-616.

[6] Brophy, J., "The Dawn Ion Propulsion System". Space Sci Rev, Vol 163, pp. 251-261, 2011

[7] Mastrodemos, N., Rush, B., Vaughn, A., Owen, W., "Optical Navigation For The Dawn Mission At Vesta", 23rd International Symposium on Space Flight Dynamics (ISSFD), October 29-November 2, 2012, Pasadena, California.

[8] Parcher, D., "Low-Thrust Orbit Transfer Design For Dawn Operations At Vesta", AAS Paper, 11-183, AAS/AIAA Space Flight Mechanics Meeting, New Orleans, Louisiana, Feb. 13-17, 2011.

[9] Konopliv, A.S. *et al.,* "The Dawn Gravity Investigation at Vesta and Ceres", Space Sci Rev, Vol 163, pp. 461-486, 2011

[10] Thomas P.C., Binzel R.P., Gaffey M.J., Zellner B.H., Storrs A.D., Wells E,. "Vesta: Spin pole, size and shape from HST images", Icarus 128, pp. 88-94, 1997

[11] Kennedy, B., *et. al.,* "Dawn Orbit Determination Team: Modeling and Fitting of Optical Data at Vesta", 23rd AAS/AIAA Spaceflight Mechanics Meeting, Kauai, Hawaii, Feb. 10-14, 2013.

[12] Parcher, D *et. al.,* "Dawn Maneuver Design Performance at Vesta", 23rd AAS/AIAA Spaceflight Mechanics Meeting, Kauai, Hawaii, Feb. 10-14, 2013.