AAS 13-345

DAWN ORBIT DETERMINATION TEAM: TRAJECTORY AND GRAVITY PREDICTION PERFORMANCE DURING VESTA SCIENCE PHASES

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The Dawn spacecraft was launched on September 27th, 2007. Its mission is to consecutively rendezvous with and observe the two largest bodies in the asteroid belt, Vesta and Ceres. It has already completed over a year's worth of direct observations of Vesta (spanning from early 2011 through late 2012) and is currently on a cruise trajectory to Ceres, where it will begin scientific observations in mid-2015. Achieving this data collection required careful planning and execution from all spacecraft teams. Dawn's Orbit Determination (OD) team was tasked with accurately predicting the trajectory of the Dawn spacecraft during the Vesta science phases, and also determining the parameters of Vesta to support future science orbit design. The future orbits included the upcoming science phase orbits as well as the transfer orbits between science phases. In all, five science phases were executed at Vesta, and this paper will describe some of the OD team contributions to the planning and execution of those phases.

INTRODUCTION

The Dawn spacecraft was launched on September 27th, 2007 as the ninth mission of NASA's Discovery Program. The primary mission is to consecutively rendezvous with and observe the two largest bodies in the asteroid belt, Vesta and Ceres, in hopes that they will yield insights into the formation of planetoids during the early eras of our solar system. The rendezvous with Vesta began in July, 2011, and ended in September, 2012. The rendezvous with Ceres will occur in early-2015 (see Figure 1).

SCIENCE OVERVIEW

The science plan involved the acquisition and transmission of these types of scientific data:

- Visible imagery
- Infrared spectroscopy
- Gamma ray and emitted neutron counts
- Gravity science observations

The mission was divided into several phases, listed in Table 1.

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Table 1. Vesta Science Phases.

Phase	Distance from Vesta	Orbit period	Dates of phase
Approach (see Figure 2)	1,800,000 km – 3000 km	N/A	April, 2011 – August 2nd, 2011
Rotational Characterizations (see Figures 2 and 3)	6000 km – 4000 km	N/A	Late July, 2011
Survey (see Figure 3)	3000 km	2.5 days	August, 2011
High Altitude Mapping Orbit (HAMO) (see Figure 3)	950 km	12 hours	October, 2011
Low Altitude Mapping Orbit (LAMO) (see Figure 3)	47 5km	4 hours	December 2011 –May, 2012
High Altitude Mapping Orbit-2 (HAMO-2) (see Figure 3)	950 km	12 hours	June, 2012 – July, 2012

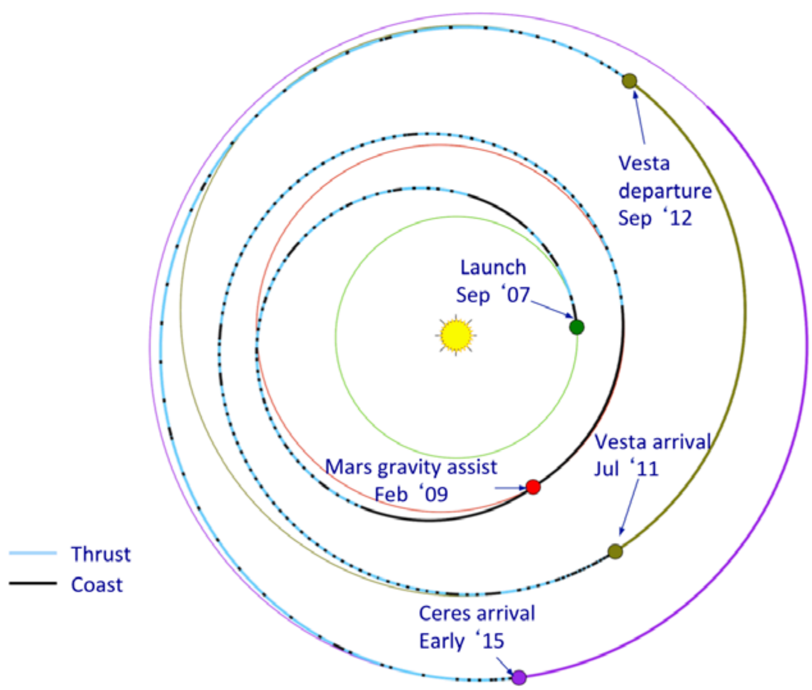

Figure 1. Heliocentric view of Dawn mission interplanetary trajectories spanning 2007 to 2015.

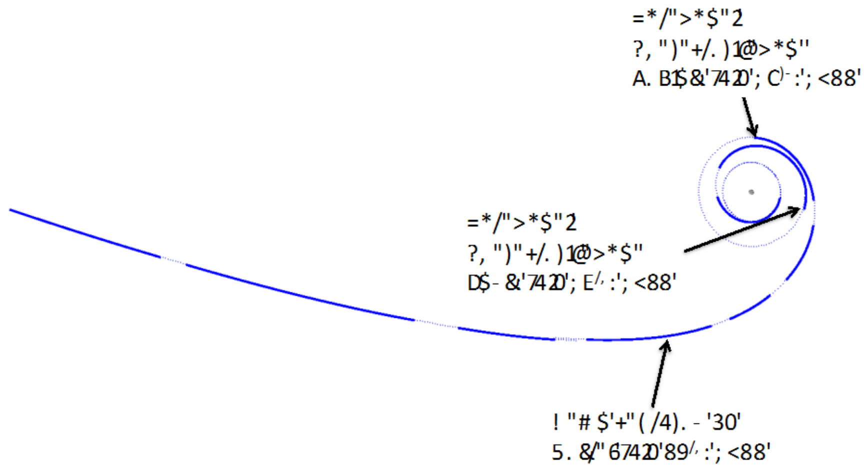

Figure 2. Dawn's approach and entry into polar orbits around Vesta (solid blue arcs denote low thrust periods, dashed lines indicate coasting). Viewer is near 0º declination to Vesta body fixed frame.

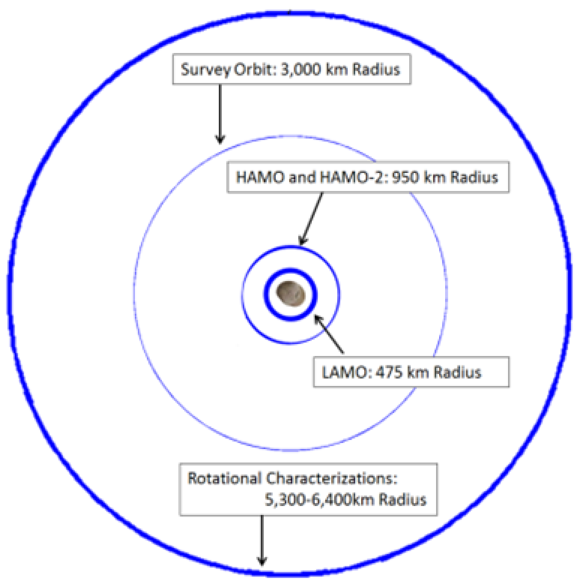

Figure 3. Vesta science orbits

VESTA OVERVIEW

The asteroid Vesta is a massive, asymmetrical, highly oblate asteroid, located in the main asteroid belt. It orbits the Sun once every 3.63 years, has a rotational rate of 5.342 hours and has an estimated GM of 17.28838 km^3/sec^2 (Reference 1). For this GM and the above orbit radii, the Dawn science orbit periods were of order 2.5 days, 12 hours and 4 hours for Survey, HAMO and LAMO, respectively. The period for LAMO (see Figure 3.) places it inside the Vesta 1:1 orbit period/rotation resonance.

SPACECRAFT OVERVIEW

A Dawn spacecraft image is shown in Figure 4, in alignment with the spacecraft body coordinate frame. The spacecraft science suite contains three instruments, all of which are aligned along the spacecraft +Z axis.

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

The spacecraft's Attitude Control Subsystem (ACS) provided three-axis stabilized control of Dawn during all nominal phases of the Vesta mission. Reaction Wheel Assemblies (RWAs) were used nominally for attitude actuation, and a partially coupled hydrazine-fueled Reaction Control System (RCS) was used to desaturate the angular momentum buildup in the RWAs.

Propulsion was provided by one of three Ion Propulsion Subsystem thrusters, each capable of producing 91mN of thrust when 2.5 kW of excess power is available from the solar panels.[2] However, at near-Vesta distances the available excess power was in the range of 1 to 1.5 kW, which only enabled thrust magnitudes of order 40-60 mN.

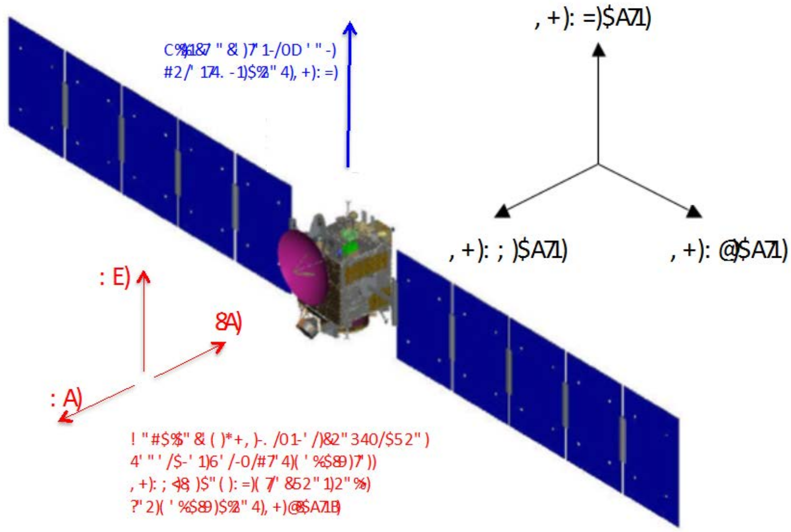

Figure 4. Dawn spacecraft schematic. All boresights for science instruments are aligned along the "Dawn Spacecraft" +Z-axis. RCS causes perturbations along SC –X, +X and +Z axes.

SUPPORTS PROVIDED BY THE OD TEAM

The OD team directly supports the engineering of the science data acquisition in two ways: the prediction of the trajectory and the estimation of Vesta parameters (GM, gravity harmonics and pole orientation)

The typical metric on OD team performance for a deep space mission is the accuracy of the predicted trajectories delivered to the spacecraft team (SCT). For Dawn, the OD team had the additional task of providing the Dawn Mission Design (MD) team with estimates of the Vesta gravitational and orientation parameters. For this paper, we will focus on the gravitational parameters. Vesta frame orientation parameters are discussed in Reference 7.

In this paper we will describe the levels to which the OD team met the requirements levied on the trajectory predictions. We will also describe the work to generate the gravity field confidence, the operational timeline for each orbit design, how accurately each field was determined and how well the as-flown trajectory compared to the designed reference trajectory. Finally, this paper will briefly discuss any lessons learned at Vesta and how they might change the planning and execution of the Dawn science mission at Ceres, in 2015.

TRAJECTORY PREDICTION

During the operations at Vesta, these forces, among others, notably impacted the orbit of the Dawn spacecraft:

- low thrust from the IPS during orbit transfers
- solar radiation pressure
- Delta-V from the RCS during RWA momentum desaturation (desats)
- gravitational pull from Sun (GM only) and major planets (GM only)
- gravitational pull of Vesta (GM and harmonics)

For this paper, only the effects of the IPS thrusting, RCS desats and Vesta gravity will be directly addressed.

Regarding trajectory prediction, the OD team was required to predict the trajectory well enough for the spacecraft to accurately point the science instruments during data acquisition while in orbit around Vesta. The predictions also needed to be accurate enough to minimize the build-up in angular momentum at low altitudes. The spacecraft team took the predicted trajectories from the OD team, converted them into a format appropriate for use as an onboard ephemeris and uploaded them to the spacecraft to implement the pointing. Two other trajectory requirements exist, but will not be discussed in the scope of this paper. One, the OD team's predictions were also used to determine timing of the commands in the onboard sequences that are relative to orbit geometry. Two, the OD team's predictions are used by JPL's Deep Space Network (DSN) for antenna pointing. Both of these latter requirements were easily met by the OD team operational capabilities and, again, will not be discussed further in this paper.

The science pointing requirements are intended to make sure desired regions of the Vesta surface are within the FC camera field of view (FOV) and/or the VIR slit scan width during data acquisition. Of particular interest are the VIR scans performed during approach. Although there were full-framed FC image planned, the pointing allowances were much more lenient. During HAMO and HAMO-2 the tight mosaic of the overlapped FC images yielded the driving ephemeris requirement for those phases. During LAMO, the driving requirement for pointing performance was levied by the ACS team, which was concerned about the secondary effects of gravity gradient torque.

In the case of each requirement, the OD team performed covariance studies to determine the OD system capabilities. In this paper, the assumptions for these covariance studies will only be discussed where relevant to the main thrust for this paper, which is to discuss the performance of the system with respect to the pointing requirements.

APPROACH PHASE

During the Approach phase, the IPS was in use for almost 2500 hours. At that time, the delivered thrust was of order 70-75 mN. When pushing a nearly one metric ton spacecraft, the resulting acceleration was on the order of 6 m/s for each day of low thrust. Errors in thrusting were assumed 0.50% in magnitude, 1-sigma, and 0.50º in direction, 1-sigma. This level of error in the thrust could result in positional error of a thousand kilometers in a month of thrusting. In practice, the thrusting performed better than these assumptions, with those results being discussed by Abrahamson.[1]

In order to maximize the amount of Vesta signal, only a limited number of VIR slit captures would be taken during a VIR scan. Since the width of the VIR slit was 0.014º, several to tens of slit captures were needed for each Vesta observation. The successful pointing of these VIR observations was subject to delivery errors caused by weeklong arcs of IPS thrust needed to get Dawn into orbit around Vesta. A too narrow scan would result in some, most, or even all, of Vesta being left out of the scan. In order to accommodate the trajectory delivery errors, the OD team performed a covariance analysis on the expected pointing errors due to any hypothetical trajectory errors. The covariance analysis was performed by simulating the expected Doppler, range, and optical data that would be acquired during Approach, and filtering it using the nominal filtering scheme.[1]

To complicate things for the OD team, the nominal schedule for communications with the spacecraft was to occur after observations are taken, so they can be immediately downlinked. Also, since the process for collecting data, estimating the orbit and creating a new spacecraft ephemeris took several hours, the ephemeris could not be updated in a timely fashion. In Approach, this would often result in several days of pointing error accumulating in the ephemeris before its first use by the ACS to point the instrument boresights at Vesta (see Figure 5).

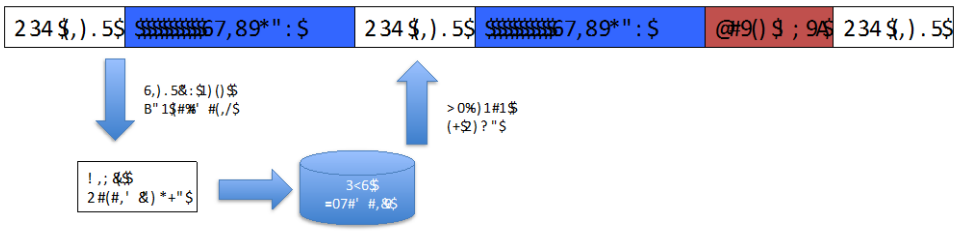

Figure 5. During the Approach phase, the operational schedule placed Vesta imaging sessions just before the communication pass. At best, any uploaded ephemeris contained two thrust arcs worth of error before it was used for asteroid pointing. Some of the thrust arcs were up to one week long.

During approach, the SCT implemented eight VIR observations Vesta. The times and Vesta distances are shown in Table 2, along with the pointing errors derived from the nominal and best-case OD knowledge capability, and the actual pointing performance. The nominal capability assumed that the on board ephemeris used is the one uploaded on board along with the design of the next set of sequenced thrust commands. Since these thrust sequences are weeks long, this ephemeris would often be ineffective for keeping the VIR scans on Vesta. As Dawn neared Vesta in the Approach spiral (see Figure 2), the Dawn-Vesta relative direction changed at faster rate, so the pointing errors typically became larger as Dawn flew later into Approach. The numbers in Table 2 represent one-sigma capability. The capability from the best case pointing capability was used to set the width of each VIR scan. This OD capability then became the *de facto* OD requirement. Because the error models were acknowledged to be conservative, the project accepted 2-sigma tolerance for pointing error instead of 3-sigma. As shown in Table 2, all of the actual pointing errors were within 2-sigma of the expected capabilities, and the VIR scans for each Vesta observation were successful. Figure 6 shows, graphically, the pointing performance throughout Approach. The pointing only exceeded 1 degree in one period, and almost reached 7 degrees before being updated.

SURVEY PHASE

The Survey phase spanned August 4th, 2011 to September 2nd, 2011. During this time, Dawn orbited Vesta seven times, taking imagery with the VIR and the FC whenever Dawn was in the lit-side of its polar orbit around Vesta. The pointing requirements during Survey were lenient at 2º. Only one update was made to the on-board ephemeris during this phase. The performance of the on-board ephemeris during Survey is shown graphically in Figure 7. After the update was made, the pointing never exceeded 0.2º during the remainder of Survey. At the 3000 km orbit radius of Survey, a 0.2º error in pointing is caused by a 10-kilometer error in the orbit.

Table 2. Pointing errors due to expected ephemeris error for various VIR observations in Approach. One milliradian is approximately ten FC pixels. 2-sigma pointing capability from the best case pointing was used as the VIR scan width.

Date of VIR observation	Distance to Vesta (km)	Predicted pointing using ephemeris from thrust sequence design (mrad, 1-□)	Predicted pointing using ephemeris from late-as-possible update (mrad, 1-□)	Date of DCO for late update	Actual pointing error (mrad)
5/10/2011	1,018,000	1.46	0.29	4/27/2011	0.39
6/8/2011	363,000	2.38	0.84	6/1/2011	0.33
6/30/2011	102,000	2.59	2.59	6/24/2011	0.56
7/9/2011	42,000	14.22	4.61	6/30/2011	3.44
7/18/2011	12,400	8.34	8.34	7/13/2011	9.35
7/23/2011	5,600	77.03	18.70	7/19/2011	1.02
7/31/2011	4,400	187.70	6.34	7/24/2011	2.58
8/4/2011	3,000	335.59	39.8	7/28/2011	7.89

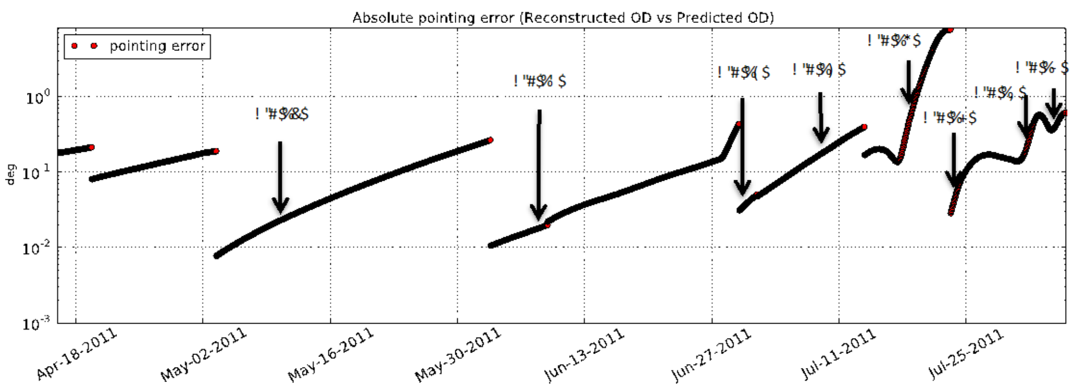

Figure 6. Absolute pointing accuracy, based on reconstructed Dawn trajectory during Approach phase.

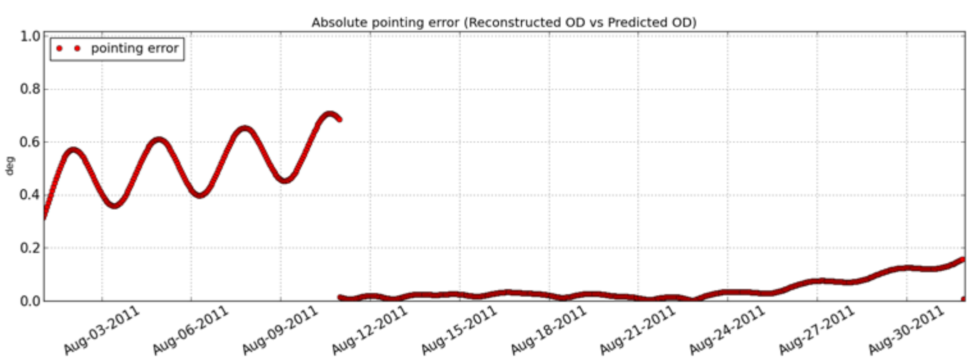

Figure 7. Absolute pointing accuracy, based on reconstructed trajectory during Survey phase.

HAMO AND HAMO-2 PHASES

The goal of HAMO and HAMO-2 was to produce full coverage maps of the surface of Vesta from an altitude of 800 km. Six full coverage maps were collected in each of these phases. This coverage was achieved by using a 10-orbit cycle with a repeat ground track, an example of which is shown in Figure 8. In both HAMO and HAMO-2, the primary driver for pointing accuracy was the need to control the overlap of the images from the FC. Figure 8 also shows an image with the FC footprint from consecutive images taken during neighboring orbits. Based on inspection of this overlap, the science team levied a 1º requirement on the on-board ephemeris in HAMO. This was tightened to a 0.5º requirement for HAMO-2. In practice, this pointing requirement means that if the orbit phase error between the on-board ephemeris and the latest available OD solution was ever predicted to exceed 1º before the following opportunity to update the ephemeris, then the ephemeris would be updated at the current opportunity. An opportunity was made in the Dawn operations schedule to upload a new ephemeris at the start of each orbit cycle. Since each cycle is 10 orbits long and the orbit period is 12 hours these opportunities were five days apart, with some uploads scheduled earlier to avoid work on the weekends.

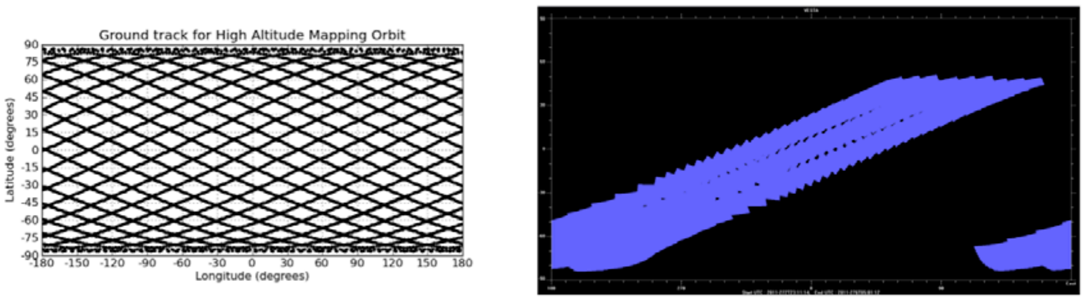

Figure 8. HAMO and HAMO-2 10-orbit, 5-day repeat groundtrack is on the left, juxtaposed with the framing camera image footprints for three adjacent orbits on the right.

The performance of the pointing during HAMO can be seen in Figure 9. In that phase, only half of the update opportunities were used. Over the course of the phase, the prediction errors can also be seen to decrease over time as the gravity field became better known with more data being collected at the HAMO altitude.

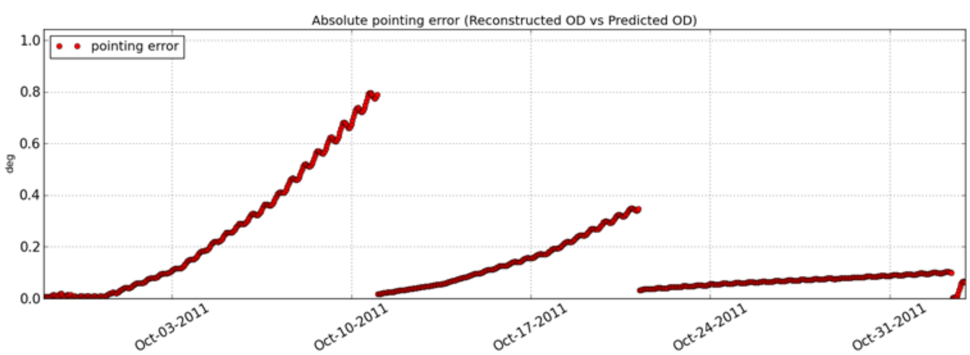

Figure 9. Pointing performance of the onboard ephemeris during the first HAMO phase. Predicted pointing was required to be less then 1º during this phase.

Pointing performance during the HAMO-2 phase is visually depicted in Figure 10. In order to achieve the tighter 0.5º pointing requirement, every ephemeris update opportunity was used.

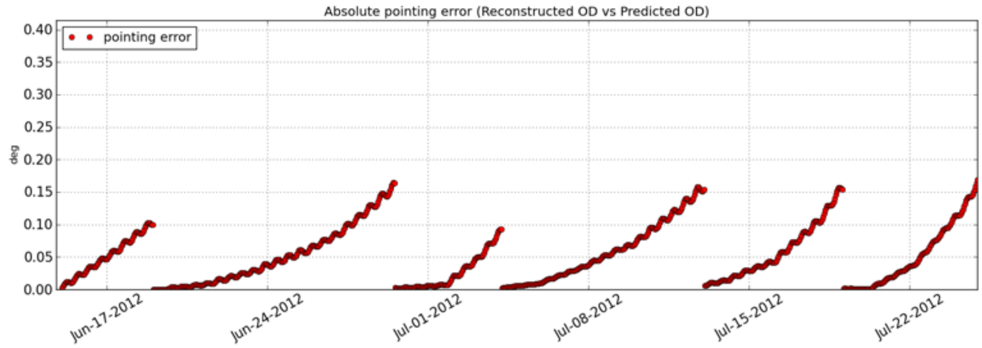

Figure 10. Pointing performance of the onboard ephemeris during the HAMO-2 phase. Predicted pointing was required to be less than 0.5º during this phase.

LAMO PHASE

During the five months of LAMO, the science goals were different from HAMO. Specifically, mapping with the FC was not the main science objective at LAMO. Therefore, tight control of the FC image footprint was not required. The main science requirement was the pointing of the GRaND instrument, which was a relatively lenient 5º. The driving operational requirement on the ephemeris in LAMO came, instead, from ACS. After analyzing the effects of gravity gradient torque (Figure 11) in the presence of ephemeris knowledge errors, the ACS team levied a conservative 0.4º requirement on the onboard ephemeris. Much like the HAMO pointing requirement, in practice this meant that if the on-board ephemeris was predicted to be more than 0.4º in phase away from the current OD prediction by the time of the following ephemeris update opportunity, then the ephemeris must be updated at the current opportunity.

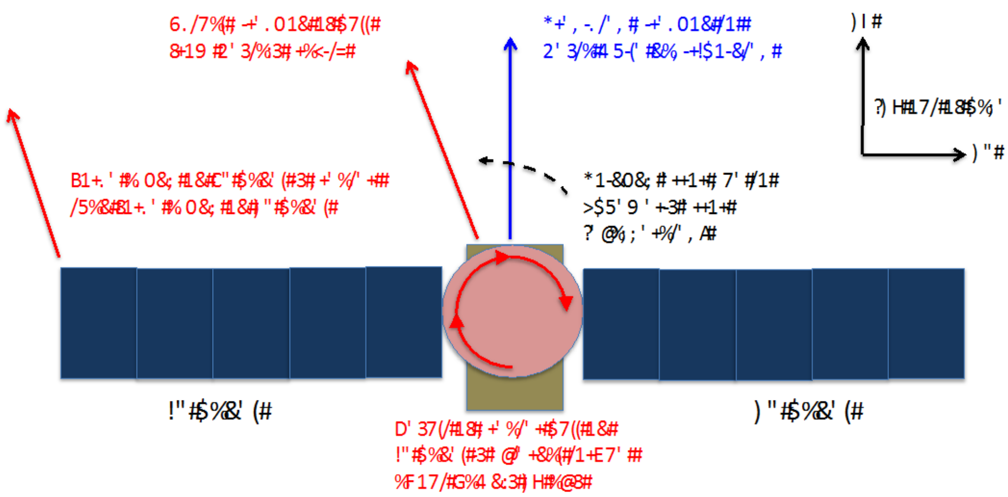

Figure 11. How gravity gradients due to ephemeris error can cause external torques.

Gravity gradient torque is noteworthy because Dawn is deep in Vesta's gravity well at the LAMO altitude. The RWAs on Dawn automatically compensate or gravity gradient torque, like any other external torque, by increasing the angular momentum. This angular momentum build-up is due to unpredicted gradient torques during the LAMO science orbit. This is unpredicted because, during the majority of time at LAMO, the +Z axis of the spacecraft is oriented towards the center of Vesta for the collection of science data. When in that attitude, the ACS team predictive models assume that external spacecraft torques due to gravity gradients along the spacecraft +Y axis are symmetrical, and therefore provide a net zero gradient torque.[3] The spacecraft's ability to point toward the center of Vesta is based on the onboard ephemeris, so errors between the onboard ephemeris and the actual spacecraft position result in unpredicted gravity gradient torques. If the onboard ephemeris errors become too large, unpredicted momentum build-up that may result in an autonomous des-saturation response, or possibly entry into spacecraft safehold. Trajectory errors were tightly coupled with the gravity gradient torque errors and desat errors in a feedback loop, described in Figure 12.

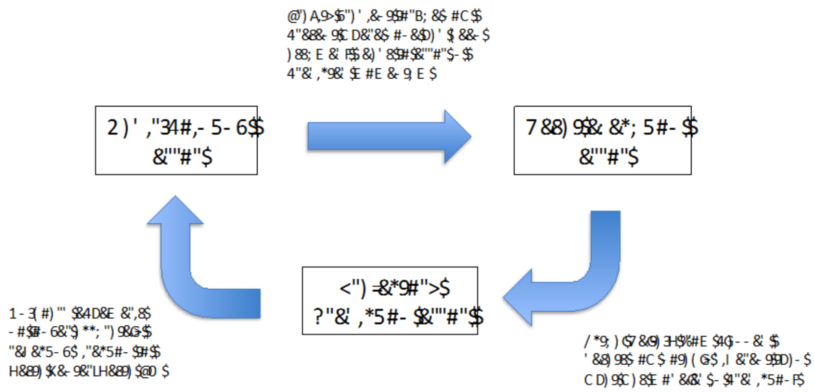

Figure 12. Error feedback loop in LAMO

Before getting to Vesta, the OD team and ACS team performed a joint study of the effects of gravity gradient torque on the LAMO orbit predictions. As previously noted, small errors in the ephemeris would result in one of the solar panels being closer to Vesta than the other panel. The OD team created a nominal trajectory, and two off-nominal trajectories. The ACS team created a desat delta-V prediction where RWA desaturations (desats) were assumed to occur once every 24 hours. After creating this nominal desat plan, a momentum profiler was applied in which one of the off-nominal trajectories was flown, but the nominal trajectory was used to simulate the onboard ephemeris. The resulting desat magnitudes from this test were given to the OD team. Using the angular difference between the off-nominal and nominal trajectory over time, the OD team generated Figure 13, which shows the correlations between desat duration and average angular prediction error before each desat. Not shown, but with a nearly identical signature, is the correlation between desat DV magnitude and the same average angular error before each desat. This study showed large angular errors could result in long duration desats as well as larger prediction errors.

Two operational constraints were also considered in LAMO: that desats should not run for longer than 1800 seconds, and that the desats might be as much as three days apart. From these two constraints and the results of the desat study, the ACS team realized that keeping the ephemeris pointing errors small (certainly smaller than one degree) was required for LAMO. So, the conservative 0.4º criterion was adopted for ephemeris updates in operations.

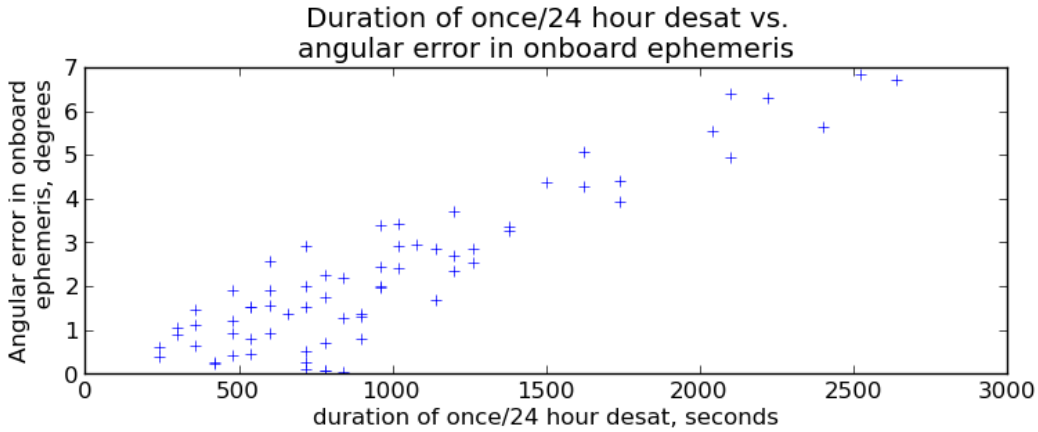

Figure 13. Correlations exist between the duration of a desat and the preceding average angular error in the onboard ephemeris.

The study also showed that there is a striking correlation between desat magnitude prediction error and the average angular error in the ephemeris, shown in Figure 14. This extension of the study shows the risk of the prediction error feedback caused by desat execution error. A single desat error of 1.0 cm/s can be expected from an average angular error of 2.0º (Figure 14). This single desat error can, in turn, cause a trajectory prediction error of 7 km in five days (see Figure 15). At the average LAMO radius of 470 km, this level of error in the ephemeris is equivalent to a pointing error of 0.85º. This highlights the OD team concerns of what appears to be meta-stability of the trajectory predictions in LAMO.

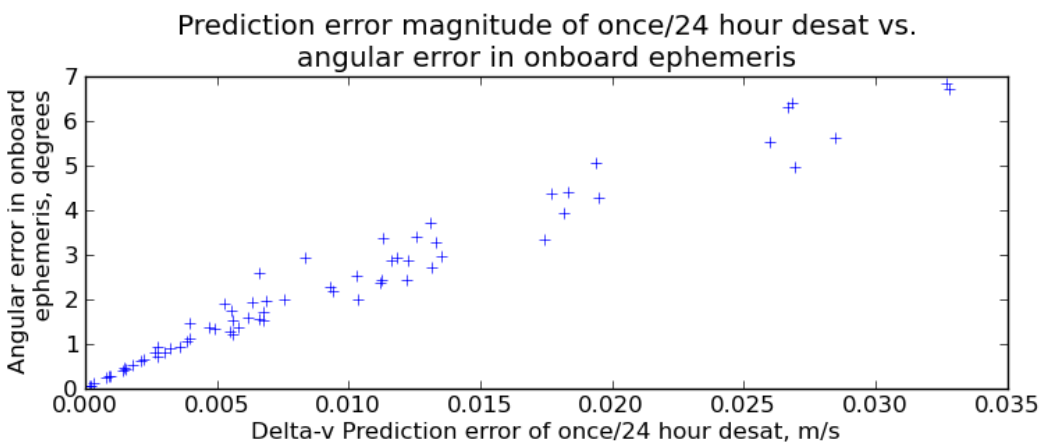

Figure 14. Strong correlations exist between the magnitude of the prediction error in the desat DV and the preceding angular error in the onboard ephemeris.

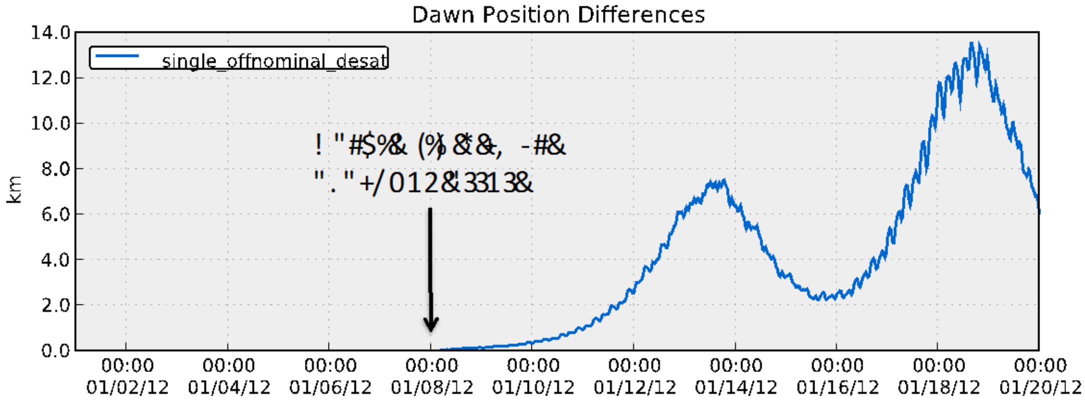

Figure 15. Deterministic effect of a 1.0 cm/s prediction error in a single desat, modeled here at 00:00 on January 8th.

There was one other concern that could also complicate the predictability of the trajectory in LAMO. This had to do with the oblateness of Vesta. Because Dawn was so close to Vesta, the apparent pull of gravity due to the complete Vesta gravity field was not always from the Vesta center. Figure 16 shows, for a given location over the surface, the difference in angle between the direction to the predicted center of Vesta, and the apparent pull of Vesta's full gravity field. From Figure 16, there are areas of Vesta over which this angle is as over 2º. Fortunately, this difference does not result in a persistent angular projection into the spacecraft's Y-axis. Figure 17 shows the angular projection along the Y-axis over an example two-day portion of the LAMO trajectory. The time varying angular bias is clearly present, but only shows an average bias of less than one tenth of a degree over that time span, hardly enough for a 1 mm/s desat error on its own. So, for Vesta (and even more so for Ceres), the impact of oblateness-induced gradient torque is not itself a practical concern.

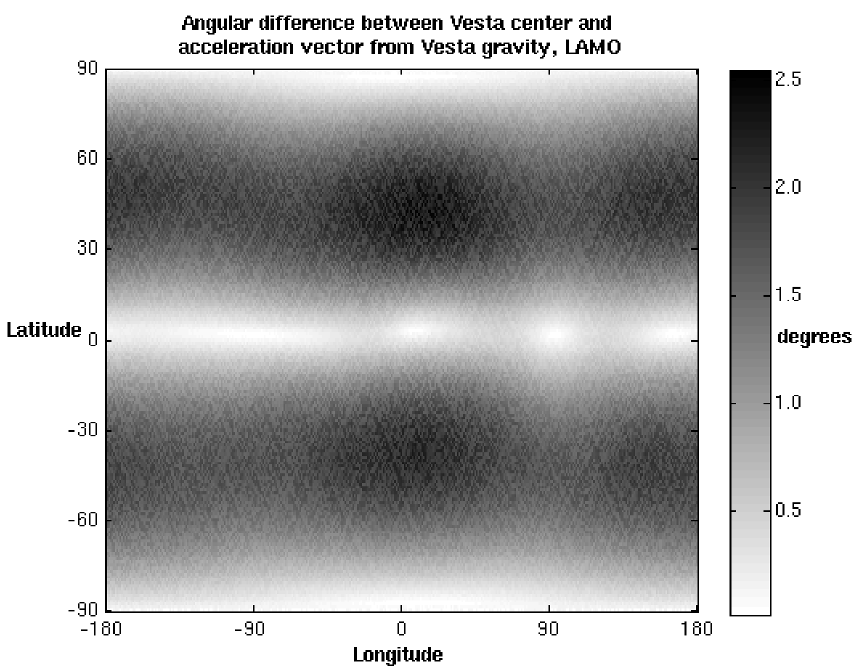

Figure 16. Angle between the Dawn-> Vesta vector and the pull of Vesta gravity from the combination of the Vesta GM and the Vesta oblateness.

Based on these concerns about LAMO perturbations due to poorly predicted angular momentum desaturations, the operations plan was to provide windows for two ephemeris update opportunities each week. An additional ephemeris update was scheduled once every two weeks as part of the routine Orbit Maintenance Maneuver (OMM) schedule, described further by Parcher.[5] The OMMs were also a cause for prediction perturbation, and the two updates per week were scheduled to best manage OMM delivery errors. Figure 18 depicts the performance of the on-board ephemeris over the five months of LAMO. Table 3 shows seven instances where the ephemeris notably exceeded the 0.4º criterion. Figure 19 shows the magnitudes of desats executed during LAMO, and during the latter half of LAMO it can be seen that the desat frequencies had to be slightly increased. This was done to deal with levels of solar torque that increased over the course of LAMO. The average desat magnitude was the same during both halves of LAMO, so it became slightly more difficult to stay on top of the ephemeris errors in March and April. Based on these results, scheduling three updates per week in LAMO rather than two might have been prudent, although this would have added staffing stress by scheduling weekend work on each weekend for five months.

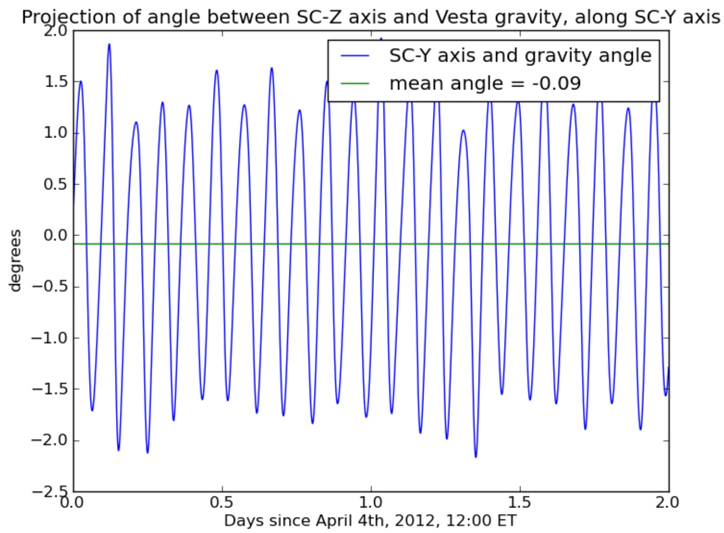

Figure 17. In the spacecraft body frame, the projection of angle between the Vesta gravitational pull and the nominal Vesta center. The projection into the SC-Y axis is a proxy for the addition/removal of angular momentum.

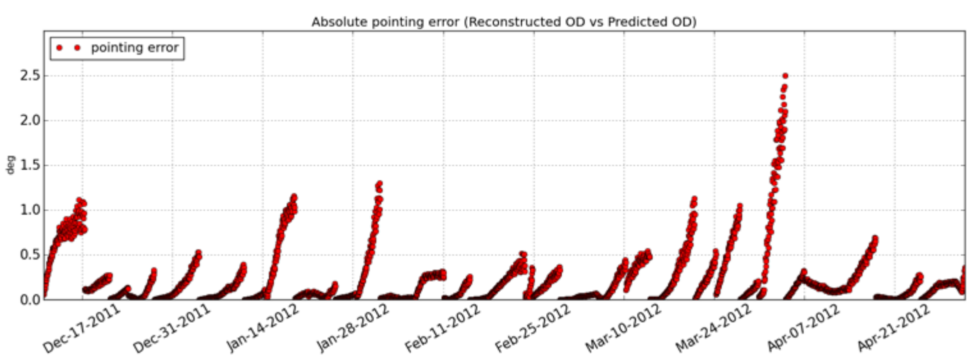

Figure 18. Absolute pointing error during LAMO phase, based on reconstruction of trajectory in LAMO. Excessive pointing errors are highlighted in Table 3.

Table 3. Times in LAMO when 0.4º pointing error was notably exceeded.

Date	Reason that pointing error exceeded 0.4º
12/17/2011	Team still finishing transition from HAMO-to-LAMO transfer and had not yet settled into LAMO operations schedule
1/19/2012	Safing event on January 14th
1/31/2012	Large desat occurred on January 28th, along with execution error from IPS OMM
3/21/2012	Large desat on March 17th
3/29/2012	Large desat on March 24th
4/5/2012	On-board ephemeris lacked appropriate attitude model during OMM due to OD team procedural error (identified and corrected)
4/19/2012	Large desat on April 14th

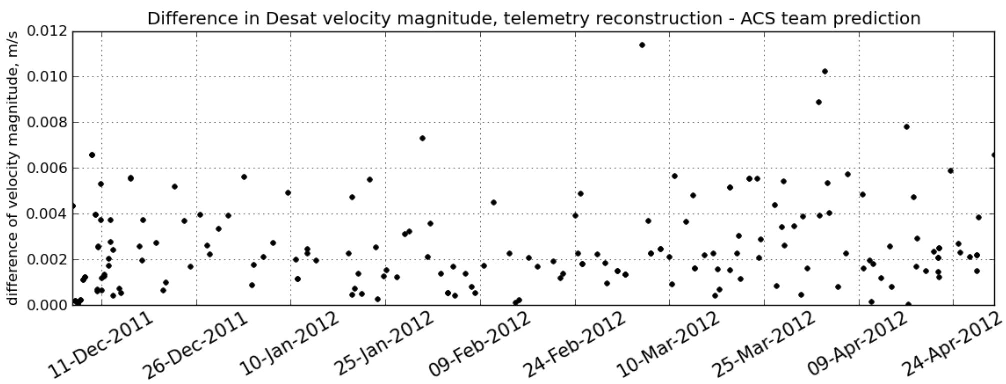

Figure 19. The magnitude of the errors in desat prediction during LAMO.

In LAMO, concerns about gravity gradient torque effects on trajectory prediction errors, desat execution errors and desat durations were well founded. However, the only real "close call" caused by gradient torque occurred during the transfer from the LAMO phase to the HAMO-2 phase, in early May of 2012. During this transfer, there was a designed "quiet period" in which Dawn was sitting in the 1:1 rotation/period resonance. At this time, the maneuver team wanted no desats to occur in order to allow for a clean OD solution and clean OD prediction for the design of the thrust sequence to get Dawn out of the resonance. Therefore, there were three days between the desat at the start of the quiet period (May 7th, 0500 UTC) and the end of the period (May 10th, 0500). Due to IPS delivery errors leading into the resonance, the average angular pointing error during this time was of order 1.5º, resulting in a May 10th desat with a 1.7 cm/s error (see Figure 20). If we refer back to Figure 14, we see that a 1.5º error for a 24-hour desat might yield 0.6 cm/s error, so seeing an error yield of 1.7 cm/s for a 72-hour desat is expected. To make this event even more sobering, the May 10th desat did not occur until after a turn to Earth point. During this turn, the unpredicted wheel speeds of the RWAs reached 98% of the level that would have tripped a safing response from the fault protection system on board. In operations, the OD team noted issue with the poor quality of the prediction leading to the quiet period on May 6th, but the impacts on wheel speeds were not considered serious enough to warrant commanding an unscheduled desat or an *ad hoc* update of the ephemeris. The larger context of the LAMO to HAMO-2 transfer is discussed by Smith.[6]

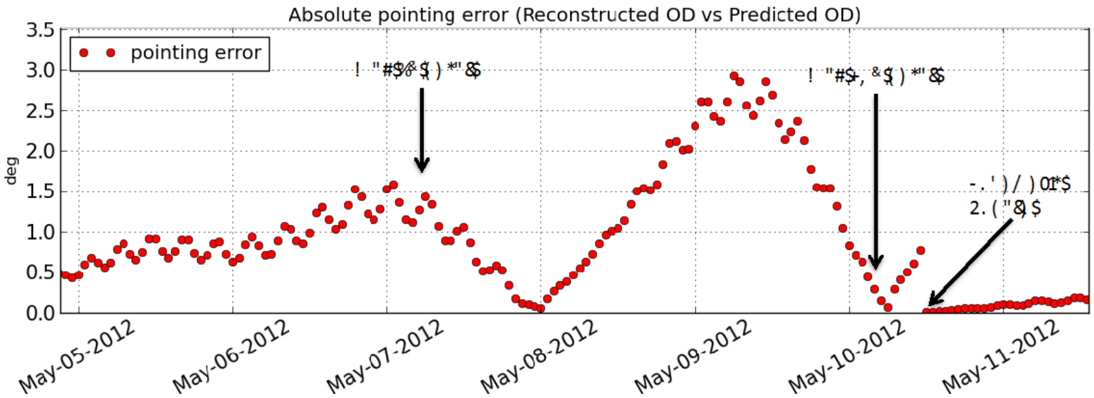

Figure 20. Following LAMO, there was a prediction pointing error during the transfer up to HAMO-2, during which there was an excessive build-up in angular momentum due to gravity gradient torque. The three-day build-up between the May 7th desat and May 10th desat resulting in nearly a 2 cm/s execution error in the May 10th desat.

VESTA GRAVITY PARAMETER PREDICTION

For the Vesta parameter estimation, the OD team needed to predict the effects that Vesta will have on Dawn's orbit once the next science phase is reached. The process by which Dawn transfers between science phases is not described in this paper, but is described by others.[1,4,5,8] Once in a science orbit, gravity perturbations due to Vesta's oblate, asymmetrical shape will alter the Dawn trajectory. Monte Carlo work [4,5,8] was performed to make sure that the orbits we would place Dawn in would not violate requirements on altitude, coverage and orbit angular rate, among others.

As with the trajectory requirements, numerous covariance studies were performed to study the OD system capabilities and determine the expected confidence of the gravity field parameters that were to be used to design the next science orbit. However, rather than being an end in themselves, these studies provides inputs into the Mission Design team's Monte Carlo runs. As part of each Monte Carlo sample, these studied parameter uncertainties were sampled to provide a perturbed gravity field that was flown through to generate each sample's true trajectory. The suite of sampled orbits were assessed for any orbit requirement violations, and any necessary adjustments were made to operational scheduling of the data cutoffs used for the field estimation to avoid designing a field with insufficient data. There were two types of covariances made with each delivery. The first covariance was used to define the boundaries of the true gravity that should be assumed for the start of each sample. The second type of the covariance was used to sample how well the OD team could be expected to know the true gravity field during the design for each thrust segment of the transfer. There were 5 segments for the Approach phase, 4 for the transfer from the Survey phase to the HAMO phase, and 10 for the transfer from HAMO to LAMO. For this paper, only the first type of covariance will be considered, since this reflects the performance of the OD team in estimating the field well enough to design the orbit (Survey, HAMO or LAMO) that Dawn will be transferring to. Also, only the gravity parameters will be discussed in this paper, while success in estimating the orientation parameters is described by Kennedy.[7]

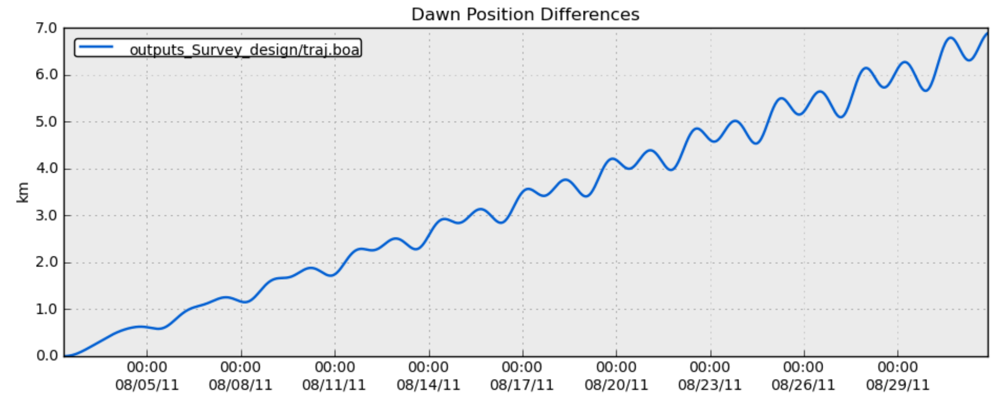

Figure 21. Propagation of Dawn trajectory using the "Survey design" gravity field, vs. a propagation using the best estimate of the gravity field from LAMO. At Survey altitude, gravity prediction errors contribute only 7 km of error to the achieved orbit.

For the Vesta Survey orbit, the maneuver team started designing the final orbit on July 21st, 2011. This was 13 days before the start of Survey. While relatively close to Vesta, the actual gravity field was not yet seen in the tracking data. Only the GM of Vesta could be estimated by the OD team. The other parameters of the field were based on an assumed Vesta shape seen in early Hubble data. Figure 21 shows how well this preliminary field and estimate GM behaved when propagated against the GM and highest fidelity gravity field that were estimated at the LAMO altitude. Over the month of Survey, the design of the Survey orbit would only be in error by 7 km by gravity modeling. The GM estimated in Approach was off from the GM estimated in LAMO by only 9.4e-4 km^3/s^2, which was within 0.05 sigma of the Approach GM confidence.

The HAMO orbit design began on August 7th, 2011, using one week of data from the Survey altitude. This design was started just over three weeks before thrusting to HAMO would begin. Figure 22 shows how effective the Survey data was in estimating the gravity field that would perturb Dawn at the HAMO altitude. At that HAMO altitude, the gravity was predicted well enough with Survey tracking data to create a deterministic error of only half a kilometer after the thirty days in HAMO.

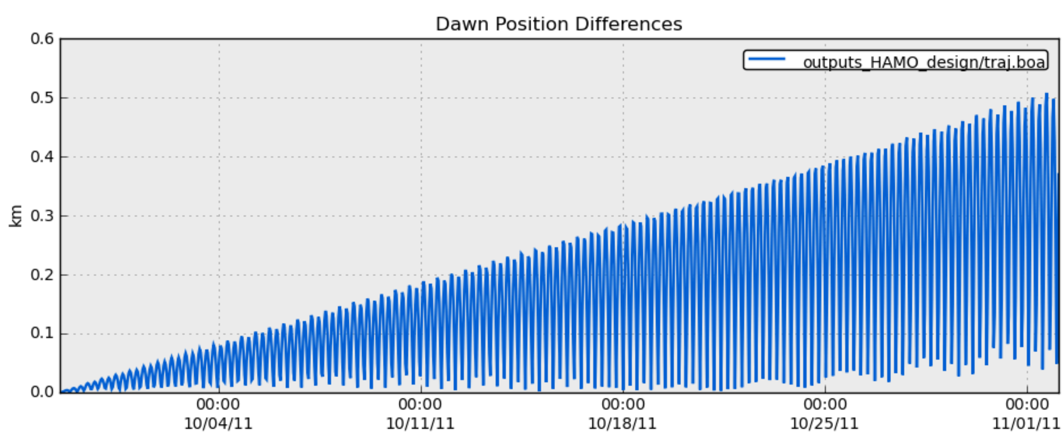

Figure 22. Propagation of the HAMO trajectory using the "HAMO design" gravity field, vs. a propagation of the HAMO orbit using the best estimate of the gravity field while at LAMO. At HAMO altitude, gravity prediction errors only contributed 0.6 km of error to the achieved orbit.

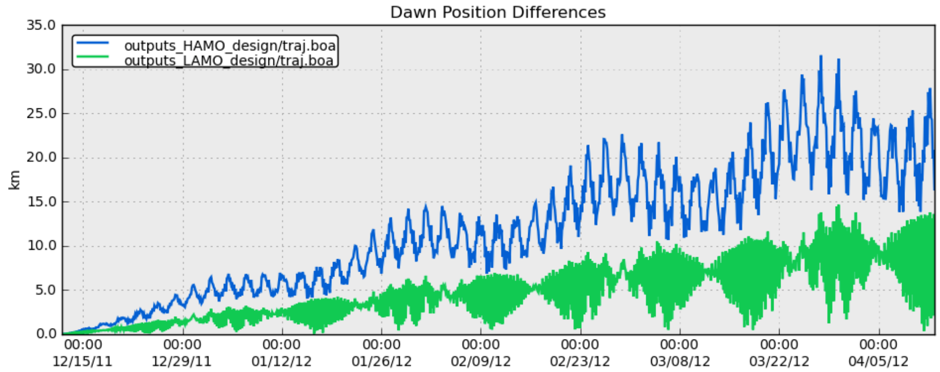

Figure 23. Propagation of the LAMO trajectory using the "HAMO design" (blue) and "LAMO design" (green) fields, vs. a propagation of the LAMO orbit using the best estimate of the gravity field while at LAMO. At LAMO altitude, gravity prediction errors only contributed ~10 km of error to the achieved orbit.

The LAMO orbit design began on October 17th, 2011, which was two weeks before the start of the transfer thrusting to that orbit. Figure 23 shows how effective this HAMO-estimated gravity field is at emulating the perturbations of the gravity field at LAMO altitudes. The inclination only changes by 1.1º and the ascending node changes by 2.7º over the entire LAMO trajectory. Both of these drifts were correctable and controllable by the LAMO Orbital Maintenance Maneuvers (OMMs) performed at Vesta.[5,8] Figure 23 also shows that the gravity estimated at the Survey altitude is, surprisingly, only twice as inaccurate at modeling the field at LAMO altitudes as the HAMO-estimated field is. For this Survey-estimated gravity propagation, the angular drift performance was even slightly better, with an inclination change of 1.0º and an ascending node change of 2.5º over the LAMO trajectory. Figure 24 contains an additional comparison, in which the preliminary field (used to design the Survey orbit) is shown with the fields estimated at the Survey altitude (used to design the HAMO orbit) and HAMO altitude (used to design the LAMO orbit). In this comparison, the obviously poor performance of the preliminary field at modeling LAMO-altitude gravitational perturbations is clear, with drifts of 90º and 180º in inclination and ascending node, respectively.

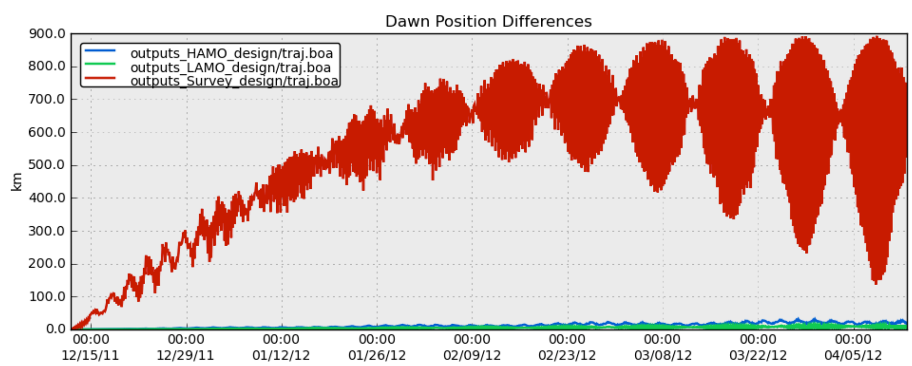

Figure 24. This is an extension of Figure 22, in which a trajectory is also propagated using the "Survey design" (red) field, which based almost entirely on a preliminary Hubble shape model. This orbit quickly diverges from the fields estimated with *in situ* tracking data. The HAMO and LAMO design fields (blue and green, respectively) from Figure 22 are retained for context.

As shown in Figure 23, the performance of the HAMO-estimated field in designing the LAMO orbit is more than adequate for engineering the mission. However, we should explore how statistically consistent the LAMO-estimated field is with the HAMO-estimated field. Figure 25 shows a per-parameter breakdown of this comparison, in which four parameters show a multi-sigma shift between the HAMO-estimated field and the LAMO-estimated field: GM, J[3] S[2][2] and C[3][3]. This is partly due to the presence of optical data in the solution and is still under investigation.[7]

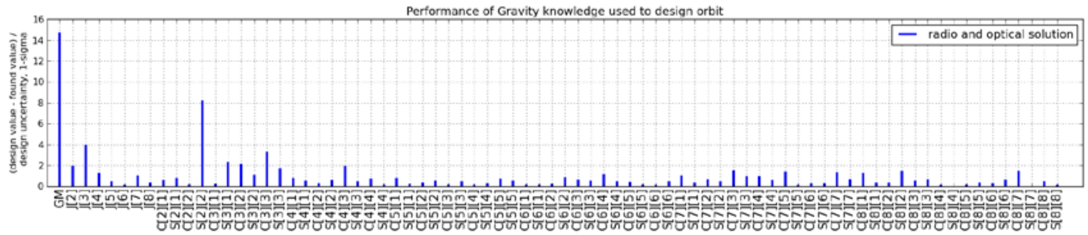

Figure 25. This is a study of the statistical agreement between the "LAMO design" field and the best estimate of the Vesta field, found at the LAMO altitude. The parametric differences are divided by the formal knowledge of that parameter per the HAMO solution. Some significant differences in GM and S[2][2] are noted.

Early in Vesta operations the OD team noticed that OD solutions with a merge of optical data and radio data did give field parameters that differed from solutions made using only radio data. The HAMO-altitude solution from which the LAMO design field was used was made with both optical and radio data. As a counterpart to Figure 25, Figure 26 was made to show a side-by-side comparison of the statistical performance of the radio-only HAMO case with the merged radio-optical case. In this Figure 26 we can see the multi-sigma shifts are not in the radio case, which indicates consistency in the radiometric data solution. However, when looking at the formal uncertainties of the respective solutions, the uncertainty for the radio-only GM was 2.3e-4 km^3/s^2, while the uncertainty for the optical/radio GM was 2.6e-5 km^3/s^2. The nearly order of magnitude improvement in GM knowledge is the main explanation for the 11-sigma shift in GM observed in Figure 25. The Dawn OD team does not credibly believe this level of GM confidence from the optical solution, and this seeming artifact of fitting optical data is discussed more in other document.[7] Like GM, the formal uncertainty for S[2][2] in the merged radio and optical case (3.2e-7) is also overly optimistic, at one-fifth the uncertainty of S[2][2] for the radio case (1.5e-6). Efforts were made by the OD team to study the statistical consistency of the field parameters using arcs with independent data.[1] Formal uncertainties aside, the two solved-for fields were practically equivalent when applied to a LAMO-altitude trajectory, as shown in Figure 27.

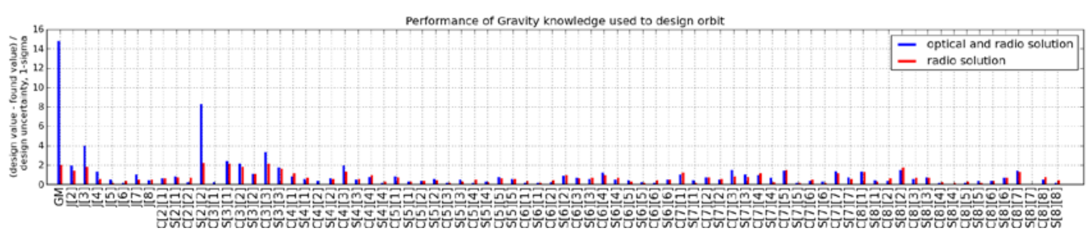

Figure 26. A side by side comparison of the statistical agreement of a radio-only HAMO solution and a radio/optical HAMO solution, against a solved-for field at the HAMO altitude and the best estimate of the field at the LAMO altitude.

One final assessment of the gravitational knowledge performance is presented in Figure 28, which shows some of the breadth of the performance of gravity field samples at LAMO altitude from the Mission Design team's final HAMO-to-LAMO Monte Carlo studies. This Figure 28 reflects only 1% (randomly chosen) of the samples made for that study, but there is still some insight to be gained here. It would appear that the envelope of delivery errors from this subset of samples is more than an order of magnitude greater than the performance of the OD team's field estimate at the HAMO altitude. It is also similarly greater than the OD team gravity field estimate *from the Survey altitude*, both of which are shown against the LAMO-estimated field back in Figure 23. When comparing Figures 28 and 23, note that the X-axis time spans are different; Figure 28 shows hundreds of km of deflection over just one month, while Figure 23 shows 20-30 km of deflection over four months. A full distillation of all 1,050 samples will be undertaken, but our initial impression is that the assumed uncertainties for the field parameters were quite conservative. These will certainly need to be tightened up when we prepare for Ceres.

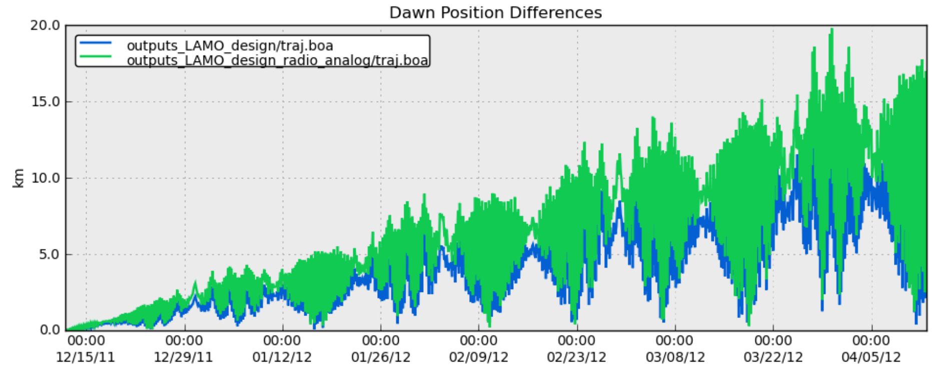

Figure 27. When the fields from the merged HAMO solution used for the LAMO design (blue), and the radio-only HAMO solution (green) are propagated against the best estimate LAMO field, the two HAMO-estimated fields are seen to be practically identical.

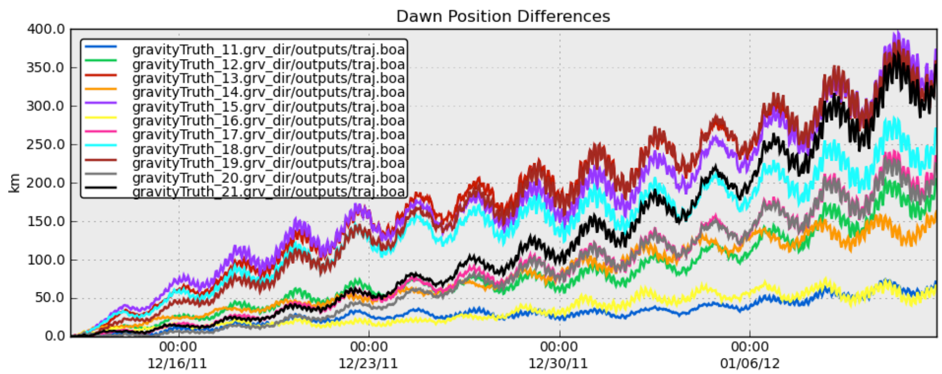

Figure 28. This plot shows the spread of trajectories propagated through a small (1%) set of sampled truth gravity fields for the final Monte Carlo used to validate the HAMO to LAMO transfer. When compared against the small delivery errors of the Survey- and HAMO-estimated fields in Figure 22, the spread implies that the injection covariance used to simulate the truth field for each sample is too conservative.

CONCLUSIONS AND IMPLICATIONS FOR CERES MISSION DEVELOPMENT

It should be noted that much of the science data acquisition at Ceres will be performed using only two RWAs, since the second of four RWAs failed after departing Vesta. The first of the four RWAs failed en route to Vesta. The difference in the perturbing effects of 2-RWA vs. 3-RWA operations will need to be considered when applying any lessons learned from Vesta.

At Vesta, the pointing performance was successful in all mission phases. It was a routine during the HAMO and HAMO-2 phases, so it is likely that, at Ceres, we can carry a less stressful update schedule for those Ceres phases that are analogous to the Vesta HAMO phases. The Approach pointing was likewise well met, but since some deliveries were more than one-sigma off, we should carry the same uncertainty models and 2-sigma confidence tolerance when designing the Ceres Approach VIR observations.

The effects of gradient torque were seen throughout LAMO, and the twice/week schedule of ephemeris updates might need to be increased to three times/week during LAMO-analogous Ceres phases. Also, the gradient torque effects will also need to be considered during transfers into a Ceres LAMO, with appropriate changes made to desat and ephemeris update schedules. Fortunately, at Ceres, the gradient torque effects at a Ceres LAMO should be reduced since that phase will be at a higher orbit altitude and gravity gradient torque changes with the cube of the orbit radius.

The OD team's gravity field solutions proved more than sufficient to engineer the science phases. In almost all cases, the effects of desat error created greater perturbation than gravity modeling. Gravity fields that cause perturbations at low altitudes can be estimated at higher altitudes well enough, but this capability might not permit us the confidence in transitioning from a Survey-like altitude to a LAMO-like altitude at Ceres without stopping to estimated gravity at an intermediate HAMO-like altitude. Also, the assumed uncertainties for the gravity field might have been much too conservative, and this conservatism might have needlessly stressed the Monte Carlo studies used to confirm Dawn's transfer capabilities. If this conservatism can be confidently relaxed, our team might be able to justify implementation of Ceres transfer plans with a less aggressive workload.

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