AAS 13-347

DAWN ORBIT DETERMINATION TEAM: MODELING AND FITTING OF OPTICAL DATA AT VESTA

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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 main 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 Dawn operations teams. Dawn's Orbit Determination (OD) team was tasked with reconstruction of the as-flown trajectory as well as determination of the Vesta rotational rate, pole orientation and ephemeris, among other Vesta parameters. Improved knowledge of the Vesta pole orientation, specifically, was needed to target the final maneuvers that inserted Dawn into the first science orbit at Vesta. To solve for these parameters, the OD team used radiometric data from the Deep Space Network (DSN) along with optical data reduced from Dawn's Framing Camera (FC) images. This paper will describe the initial determination of the Vesta ephemeris and pole using a combination of radiometric and optical data, and also the progress the OD team has made since then to further refine the knowledge of Vesta's body frame orientation and rate with these data.

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 mid-2011, and ended in mid- to late-2012. The rendezvous with Ceres will occur in mid-2015 (see Figure 1).

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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.

Table 1: Vesta Science Phases.

Phase	Distance fromVesta Center	Orbit period	Dates of phase
Approach (see Figure 2)	1,800,000 km down to 3000 km	N/A	April, 2011 to August 2nd, 2011
Rotational Characterizations (RCs) (see Figures 2 and 3)	6000 km down to 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)	475 km	4 hours	December ,2011 through May, 2012
High Altitude Mapping Orbit-2 (HAMO-2) (see Figure 3)	950 km	12 hours	June/July, 2012

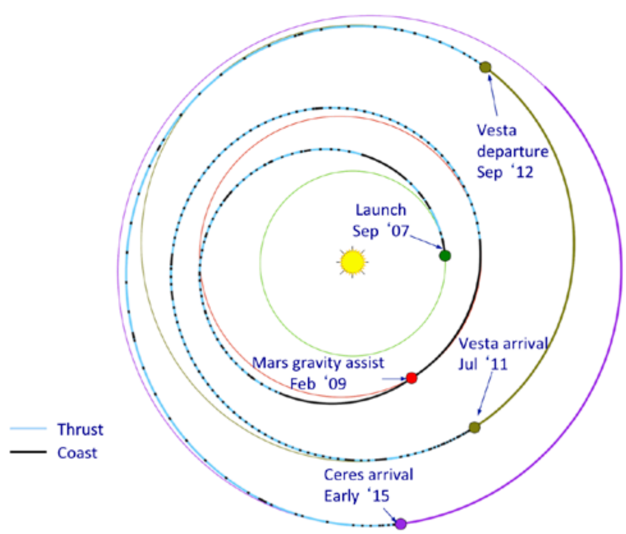

Figure 1: Heliocentric view of Dawn mission interplanetary trajectories spanning 2007 to 2015.

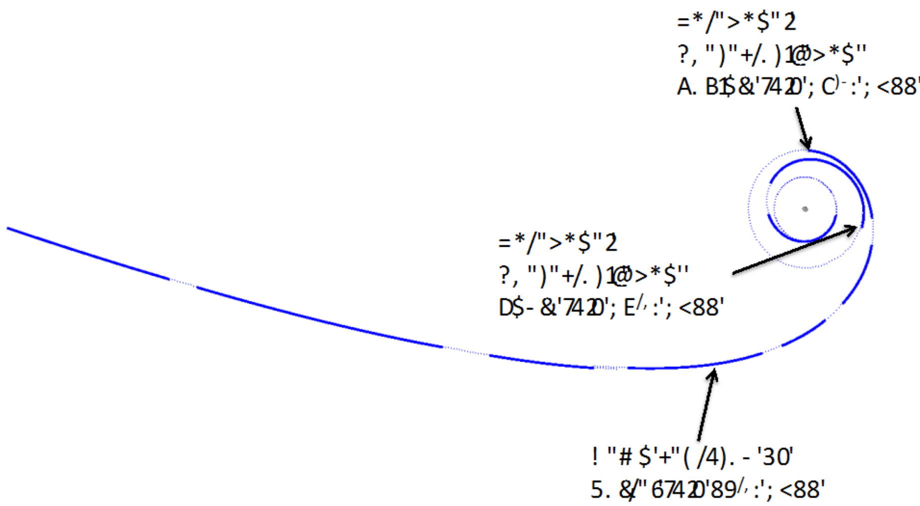

Figure 2: Dawn's approach and entry into polar orbits around Vesta. Solid blue arcs denote low thrust period with the Ion Propulsion System, dashed lines indicate coasting. Viewer is near 0° declination to Vesta body fixed frame.

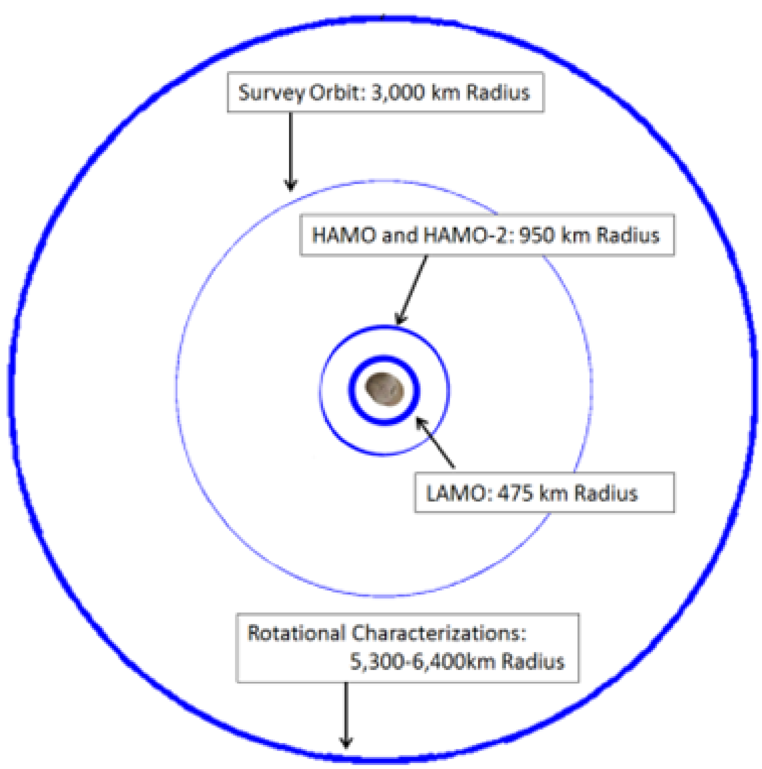

Figure 3: Vesta science orbits

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 period of 5.342 hours and has an estimated GM of 17.28838 +/- 0.00015 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.

- Two visible light Framing Cameras (FC1 and FC2), each with a 1-megapixel sensor and a 5º field of view.
- 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 Reaction Control System (RCS) was used to de-saturate 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.[7] 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.

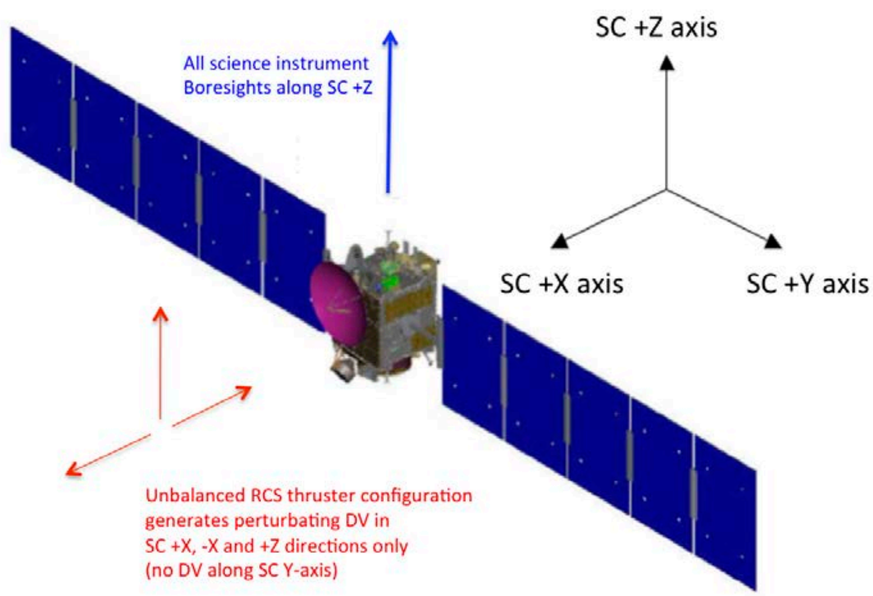

Figure 4: Dawn spacecraft schematic. The FC boresight, along with boresights for the other science instruments, is aligned along the +Z-axis. RCS causes perturbations along the -X, +X and +Z axes.

Navigation Overview

During the Vesta mission, the Dawn Navigation team provided the following high-level support to the Dawn spacecraft team and Dawn science team:

- Reference trajectory designs.[3,4,5]
- Tactical timelines.[2,3,4,5]
- Targeted science orbits.[4,5]
- Low-thrust maneuver profiles.[4,5]
- Predicted trajectory products (Vesta-relative).[2,6]
- Reconstructed trajectory products (Vesta-relative).[2]

Internal to Navigation, the Orbit Determination Team provided the following products to the Mission and Maneuver design team to support development of the above low-thrust maneuver profiles:

- Predicted spacecraft state at next thrust start.[2,6]
- Gravity field reconstruction.[2,6]
- Vesta frame orientation and rate.[2,6]

For the Dawn Navigation team, the two FCs served as sources of navigation data. They each contain a 1-megapixel sensor and have a field of view of just over 5º. The processing of the images to extract navigation information by the Optical Navigation team is described by Mastrodemos.[8] Two outputs were provided by Opnav: a landmark vector database and a Picture Sequence File (PSF). The landmark vector database was a text file containing dozens to tens of thousands of landmark locations. Each landmark was registered with a Cartesian vector in the Vesta body fixed frame. The PSF, for each image in the data arc, contained the picture timestamp, a nominal attitude for the camera at that time, and pixel locations for each landmark observed in the picture. During Approach, the PSF also contained the pixel location of the nominal center of Vesta, which was used when Vesta was too distant to resolve surface features into landmarks.

Observations of Vesta with the FCs began on May 7th, 2011, and continued for more than a year. Figure 5 shows one of the early images of Vesta, taken on May 22nd, 2011. In this image, the range to Vesta is approximately 700,000 km and each pixel is almost 70 kilometers across. Later in the mission the resolution of Vesta would improve dramatically, all the way down to 20 meters per pixel in LAMO. Figure 6 shows this progression of resolution through the science phases described back in Table 1 and Figure 3.

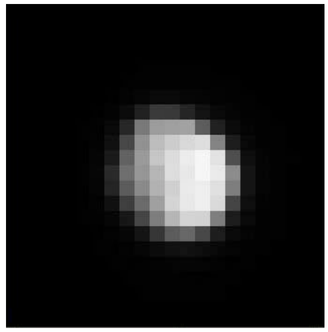

Figure 5: An early image of Vesta, taken with the Dawn FC during Optical Navigation session #4, on May 22nd, 2011.

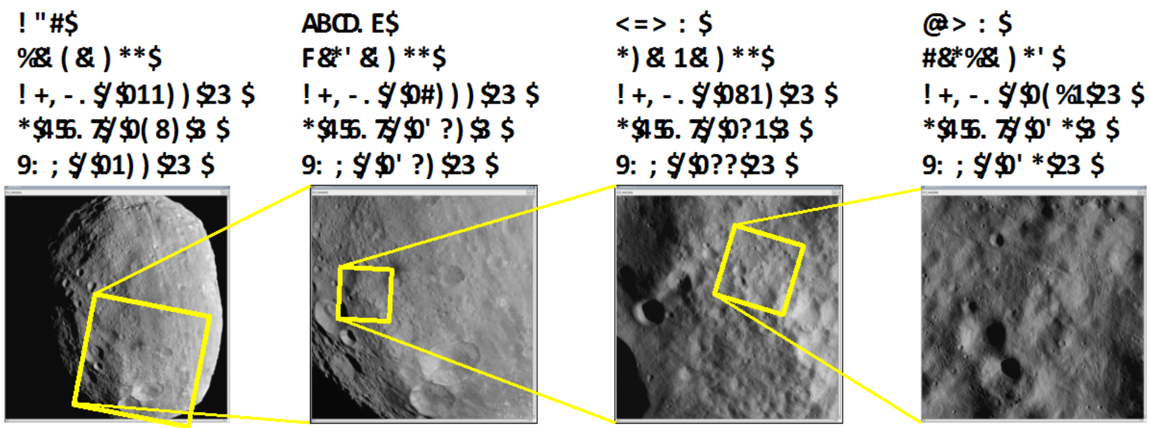

Figure 6: Dawn FC2 Images of Vesta from each of the main science phases.

During Approach, the OD team was responsible for the initial determination of the Vesta ephemeris, and to recover lingering delivery errors from the low-thrust maneuvers that brought Dawn to Vesta during the cruise phase of the mission. The team also used these observations to provide an initial estimate of the Vesta orientation, which was used by the Maneuver Design team to target a Survey orbit with a 90º inclination relative to Vesta's equator.

During the Survey, HAMO, LAMO and HAMO-2 phases of the mission, the spacecraft acquired imaging data from the FC that helped to meet (or exceed, in some cases) the level-1 science requirements. These images were reduced by the Optical Navigation team to produce a wealth of optical landmark data for the OD team to process. In the course of fitting this data, the OD team discovered many statistically significant differences in the resulting orientation solutions, the Vesta rate and also changes in the location of the Vesta body center with respect to the gravitational center. Further detail on the above tasks will be provided.

APPROACH PHASE

During the approach phase to Vesta, the Dawn Opnav team reduced the FC images into observations of the Vesta center[1,8] and observations of Vesta surface landmarks.[1,8] The first observations of the Vesta center were made on May 3rd, 2011, using images similar (at least initially) to Figure 5, and continued up until July 13th, 2011. Optical data during this phase was combined with radiometric data to correct the *a* priori ephemeris of Vesta. Figure 7 shows the corrections to the ephemeris using data from the end of the Approach phase, as Dawn was inserted into the

Survey orbit. The final corrections to the Vesta ephemeris were relatively small, at the level of 20 to 40 kilometers from the Vesta ephemeris generated by ground-based observations.

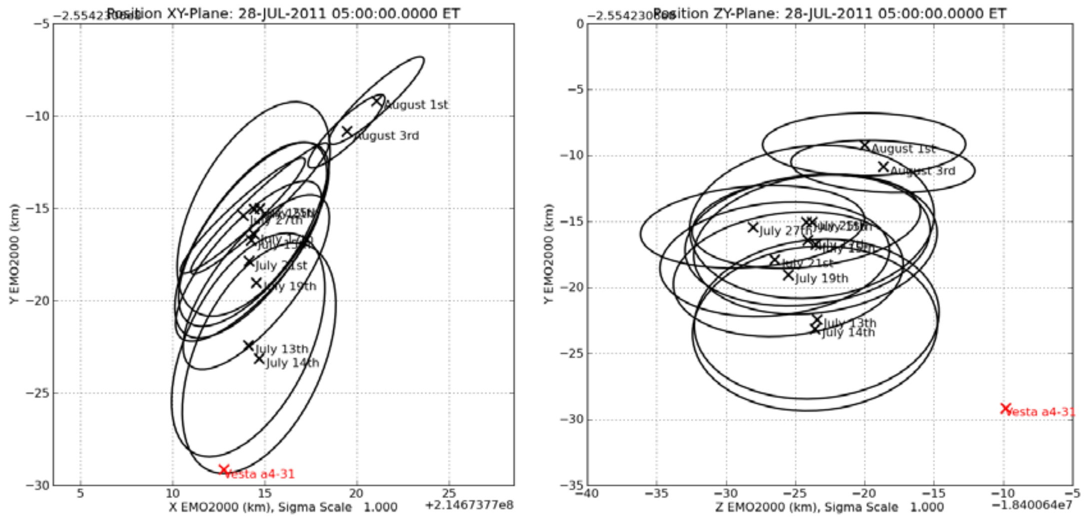

Figure 7: Progression of corrections to the Vesta Ephemeris, mapped near the end of Approach on July 28th.

The landmark observations began on June 30th, 2011, and continued past the end of the Approach phrase. The expected performance of these data in recovering the Vesta pole and GM is shown in Figure 8. The improvement in pole knowledge is expected. The GM knowledge is improved by the attitude fix for each landmark-laden image in the solution, which provides orthogonal geometry that further defines the orbit parameters. By the end of Approach, there were 295 landmarks constructed from the image data. These landmarks were not tied to specific features, but were instead assigned based on a lat/lon grid in order to uniformly cover the surface. (see Figure 9). The methodology for deciding the surface coverage that each landmark is described in Mastrodemos.[1,8]

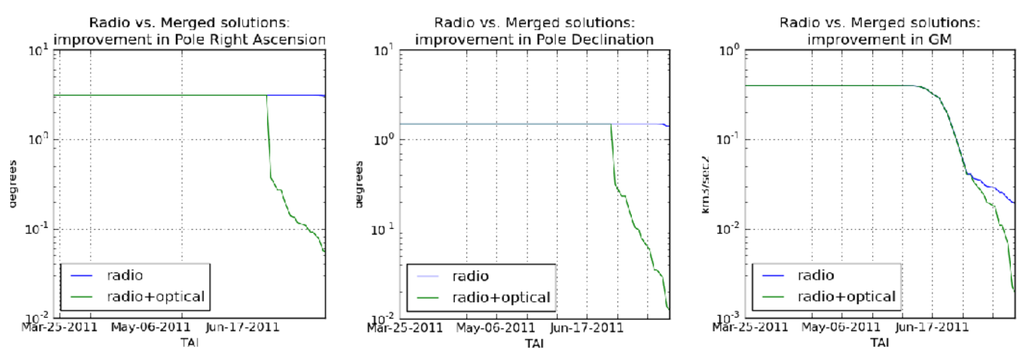

Figure 8: Covariance study showing improvement in Vesta pole and GM knowledge following the addition of optical landmarks data to the OD team solution. In this study, landmark data processing began on Jun 27th, 2011.

The actual performance in determination of the pole is shown in Figure 10. The initial pole estimates were well over one degree away from what would later be considered the best estimate of the pole. It is suspected that the causes for the large shifts in pole leading up to Survey are two: optimistic error modeling of the landmark locations as well as systematic process errors caused by sub-optimal lighting conditions at the various viewing geometries during the Approach phase. Landmark error modeling is given treatment later in this paper, and is a subject of further refinement. The improvements in image data processing are discussed further in Mastrodemos.[8]

The primary requirement on the orientation of the pole was 5º, which was driven by the science requirement that the Survey inclination be 90º, +/- 5º. Even with statistically significant shifting in the solutions, this formal requirement was easily met. The Survey orbit was targeted in late July using the July 21st OD solution. In Figure 10, this was 1.4º away from the best estimate of the pole orientation, with much of this error mapped into a crosstrack delivery error to the start of the Survey orbit. As achieved, the Survey orbit had an inclination of 88.9º after targeting a 90º inclination. Given the statistically significant shifts in pole solutions, the processing of the optical data during Approach will be re-visited in the near future since it does have bearing on how the OD team will perform in 2015, at Ceres.

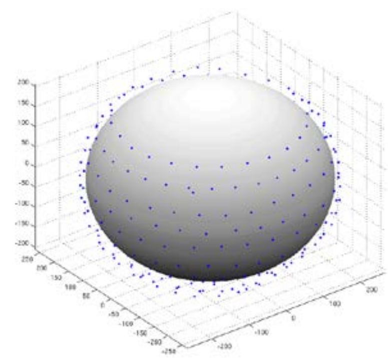

Figure 9: Vesta landmark locations from the final landmark vector database that was constructed from the Approach images. Vesta's winter kept high northern latitudes from being imaged.

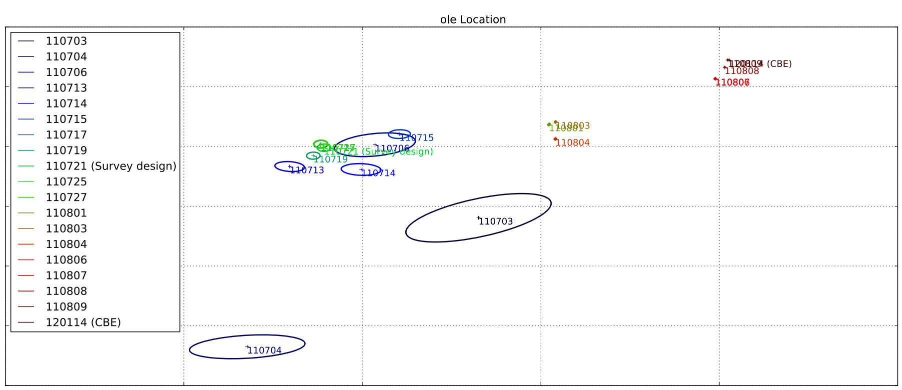

Figure 10: Progression of OD team's Vesta pole solutions, from July 3rd through August 9th.

SURVEY PHASE

The Survey phase of the mission spanned August 2nd, 2011 to August 31st, 2011. Including the pre-Survey "quiet period"[3], Dawn orbited Vesta 10 times while at the Survey altitude. Following the reducing of the Survey imagery into a database with 17,648 landmarks (see Figure 11), the OD team performed two trajectory reconstructions; one using radio data and the other using both radio and optical data. The pole orientation and GM results are shown in Table 2. For each solution, these quantities are in agreement at the 1-sigma level.

Figure 12 shows the differences in the estimated trajectory reconstructions. There, one can see a consistent ~35 meter bias in the radial difference, which is consistent with the difference in estimated GM values. One can also see a peak crosstrack oscillation of 600 meters, which is expected, given the nearly 0.04º difference in estimated pole orientations. These pole and trajectory results are on the borderline of not meeting the Survey reconstruction requirement of 300 meters, 1-sigma, and will be revisited in future studies.

Table 2: Pole and GM values for Survey solutions. Ground-based values are shown for context.

Solution	Pole R.A. (º)	Pole Dec. (º)	GM (km^3/s^2)
Ground-based	301.0 +/- 3.1	41.0 +/- 1.5	17.8 +/- 0.4
Survey Optical/Radio	309.03616 +/- 0.00024	42.24816 +/- 0.00027	17.289225 +/- 0.000022
Survey Radio	309.003 +/- 0.059	42.229 +/- 0.016	17.28864 +/- 0.00068

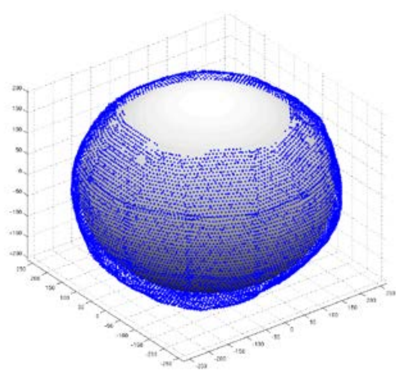

Figure 11: Vesta landmark locations from the final landmark vector database that was constructed from the Survey images. Vesta's winter kept high northern latitudes from being imaged.

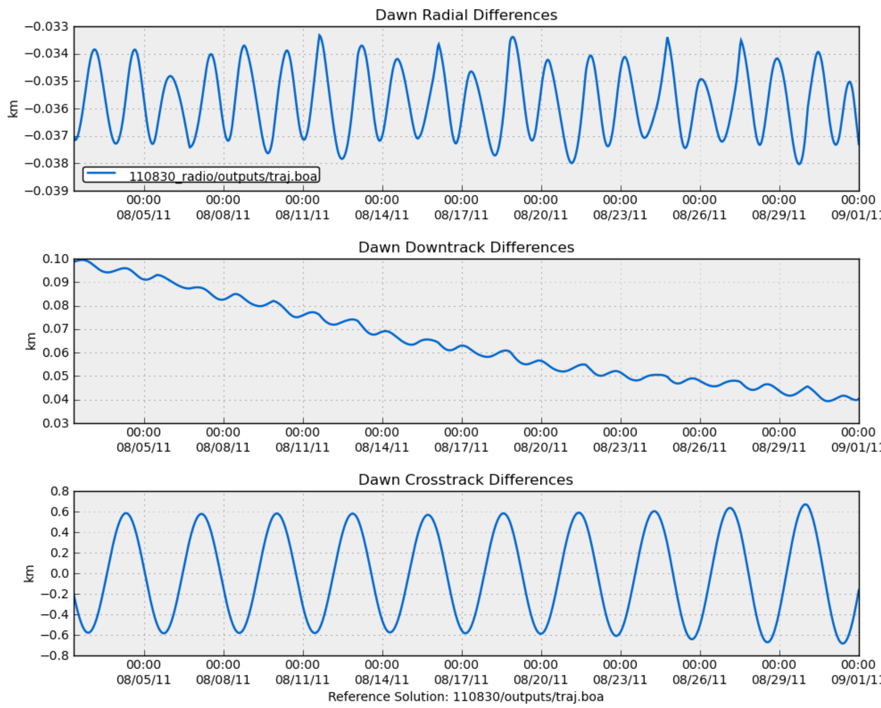

Figure 12: Differences between reconstructed solutions using only Survey radiometric data and a merge of both radio and optical data.

HAMO PHASE

The HAMO phase of the mission spanned September 28th, 2011 to November 2nd, 2011. During this time, Dawn recovered Vesta image data from 60 orbits, in six 10-orbit cycles. The data from each cycle was intended to collect stereo imagery of the Vesta surface, so that two cycles looked down for imaging, two looked left and two looked right. The stereo imagery allowed for a more accurate determination of the local surface altitude.[1]

These images were reduced by the Opnav Team, and the resulting database had 69,259 landmarks (Figure 13). The OD team processed these data to generate two trajectory reconstructions, one with only radio data and one with both radio data and optical data. The results for the estimation of the pole orientation and the GM are in Table 3. The GM, pole right ascension and pole declination agree tolerably well, out to two-sigma. The trajectory comparison in Figure 14 shows the similar, persistent radial bias due to differences in GM estimation. The crosstrack difference is still present, but it is much more agreeable than the Survey reconstruction, with a peak oscillation of 40 meters that is in line with the differences in the respective pole orientation solutions. This difference in trajectories satisfies the 90-meter reconstruction requirement for HAMO.

Table 3: Pole and GM values for HAMO solutions. Ground-based and Survey values are shown for context.

Solution	Pole R.A. (º)	Pole Dec. (º)	GM (km^3/s^2)
Ground-based	301.0 +/- 3.1	41.0 +/- 1.5	17.8 +/- 0.4
Survey Optical/Radio	309.03616 +/- 0.00024	42.24816 +/- 0.00027	17.289225 +/- 0.000022
Survey Radio	309.003 +/- 0.059	42.229 +/- 0.016	17.28864 +/- 0.00068
HAMO Optical/Radio	309.03418 +/- 0.00022	42.226924 +/- 0.000080	17.288582 +/- 0.000013
HAMO Radio	309.0348 +/- 0.0026	42.22659 +/- 0.00017	17.28879 +/- 0.00013

This study was also used to examine the estimation of the Vesta body rotation rate. Initially, each solution differed in rate by 0.4 millidegrees/day, which was four times the formal uncertainty of 0.1 millidegrees/day. After many test cases in which suspect data were scrubbed without impacting the results, a solution leaving out the data from cycle 2 resulted in a body rate agreement of 0.15 millidegrees/day. It is not clear why this is the case, but signatures in the per-picture pointing corrections (Figure 15) indicate that cycle 2 had large angular errors about the camera boresight (known as twist errors) compared to the other cycles. This was noted by the Opnav and OD teams for further investigation.

When processing the HAMO data, it was apparent that the origin of the landmark vector database could no longer be assumed to coincide with the Vesta center of mass. This offset between the center-of-figure and the center-of-mass (CFCM) was estimated in an iterative fashion, in which the OD team estimated the offset, the Opnav team applied the offset to the database, the OD team re-estimated the offset, and so on. The CFCM offset was found to be almost 750 meters, almost entirely on the –Z direction of the Vesta body fixed frame.

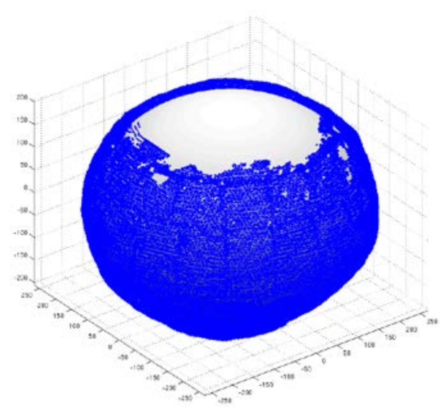

Figure 13: Vesta landmark locations from the database that was constructed from the HAMO images. Vesta's winter kept high northern latitudes in shadow.

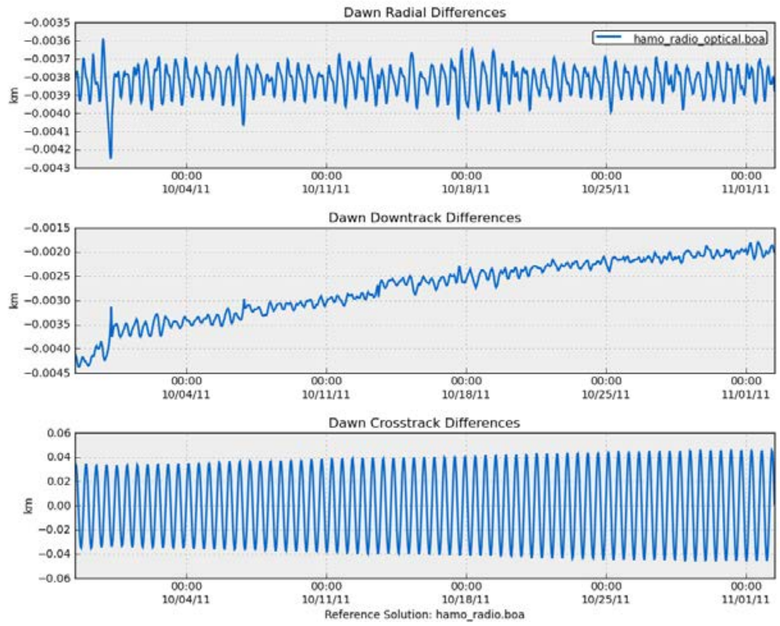

Figure 14: Differences between reconstructed solutions using only Survey radiometric data and a merge of both radio and optical data

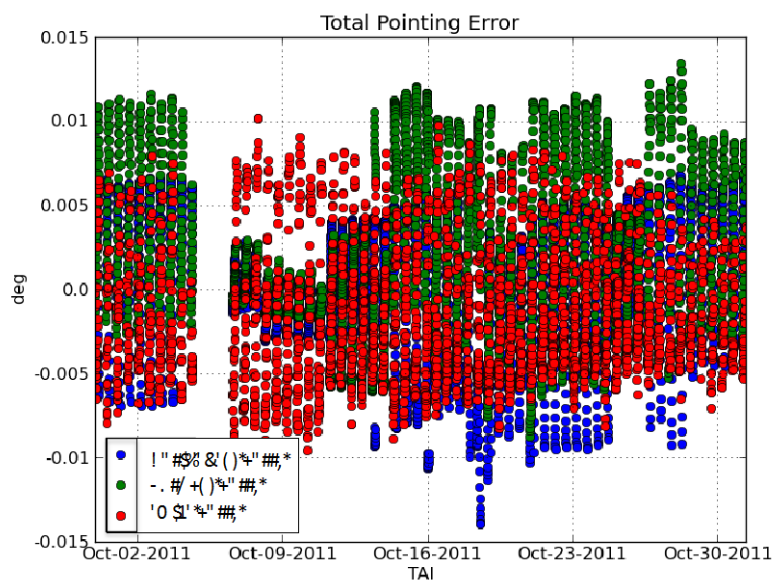

Figure 15: Pointing correction to each HAMO image, solved for to account for time-varying process noise. Cycle 2 (of six cycles) is the five day period centered on October 9th. 0.005° is ~one pixel.

LAMO PHASE

The LAMO phase of the mission began on December 11th, 2011 and lasted until May 1st, 2012. During this time, Dawn orbited Vesta over 700 times. Numerous images of Vesta were received at LAMO, with pixel resolutions of about 20 meters per pixel.

The Dawn Opnav team reduced the images as they came in. Following processing, the landmark database grew slightly more than what was in the HAMO database (see Figure 13), to 70,496 landmarks.[8] The OD team processed these data to generate two trajectory reconstructions, one with only radio data and one with both radio data and optical data. The results for the estimation of the pole orientation and the GM are in Table 4. The GM, pole right ascension and pole declination were found to disagree at ~20-sigma,which is a statistically significant difference. Figure 16 graphically shows the level of disagreement just in the pole solutions. Figure 16 also contains a montage of short (one-week) radio solutions. These independent radio solutions have a consistent pole solution, with the center of the ellipses aligning quite well with the solution from the longer radio arc. This indicates that the radio solutions are well modeled. This LAMO comparison showed that the data strength at LAMO uncovers obvious modeling errors that were suspected when processing data at the higher science altitudes. Image timestamp errors were considered, investigated and found not to be an issue. Attitude registration errors were also considered, but not found to be plausible. Two optical reconstructions were performed, one using the ACS-telemetered camera attitude for each image, and the other using the Opnav team's attitude solution for each image. The signatures in the per-picture pointing correction for each solution were indistinguishable. Deweighting of the optical data was also investigated. The nominal weight for each landmark is one pixel, so weights of 5, 25 and 125 pixels were applied. With each deweighting solution, the estimated pole shifted closer to the pole estimated by the radio solution (See Figure 17). Deweighting the landmark data, not surprisingly, produced consistent results with radio, but this level of deweighting might not be, in itself, a practical approach to understanding the causes of the modeling errors.

Table 4: Pole and GM values for LAMO solutions. Ground-based, Survey and HAMO values are shown for context.

Solution	Pole R.A. (º)	Pole Dec. (º)	GM (km^3/s^2)
Ground-based	301.0 +/- 3.1	41.0 +/- 1.5	17.8 +/- 0.4
Survey Optical/Radio	309.03616 +/- 0.00024	42.24816 +/- 0.00027	17.289225 +/- 0.000022
Survey Radio	309.003 +/- 0.059	42.229 +/- 0.016	17.28864 +/- 0.00068
HAMO Optical/Radio	309.03418 +/- 0.00022	42.226924 +/- 0.000080	17.288582 +/- 0.000013
HAMO Radio	309.0348 +/- 0.0026	42.22659 +/- 0.00017	17.28879 +/- 0.00013
LAMO Optical/Radio	309.02773 +/- 0.00014	42.223219 +/- 0.000066	17.286586 +/- 0.000073
LAMO Radio	309.03349 +/- 0.00018	42.226367 +/- 0.000085	17.288380 +/- 0.000095

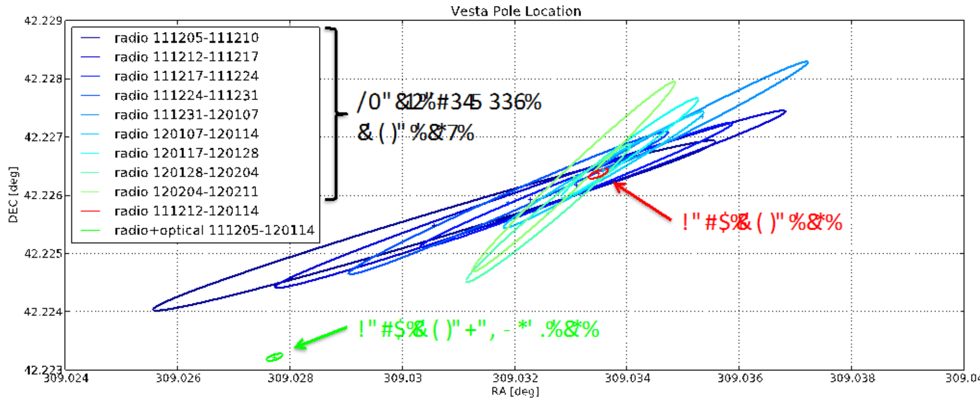

Figure 16: Pole orientation estimations in LAMO. A six-week long radio solution is statistically consistent with several one-week long radio solutions (each with independent data). The 6-week long solution using optical data is significantly different.

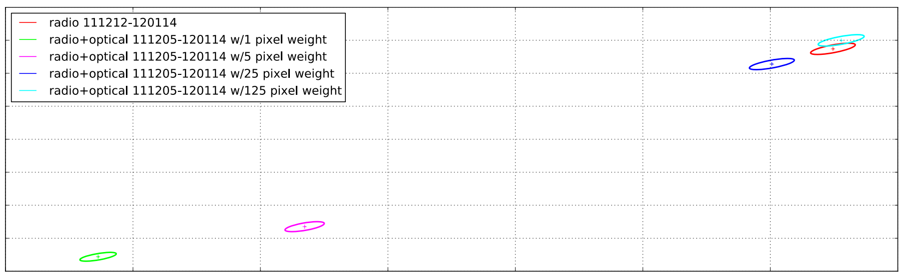

Figure 17: Effects of deweighting LAMO optical data.

Possible errors in construction of the landmark database were considered, and the OD team started a landmark location estimation study. With over 70,000 landmarks and a multitude of images being reduced for the OD solutions, the number of landmark observations in a long LAMO arc was quite large. This number of landmarks could be iterated in a nominal solution in a few hours, but this assumed that the landmark locations were perfect. Landmark estimation involved adding three parameters to the filter for each landmark being modeled, since the Vesta body fixed Cartesian locations of each landmark would be estimated independently. Estimating several thousands of landmarks posed problems with the availability of both computational and temporal resources. By necessity, a short LAMO arc was studied, in which only 990 landmarks were observed and estimated. These observations were taken over eleven consecutive orbits, and corrections to the landmark locations were estimated. Figure 18 shows a 3-D view of the shifts in the landmarks, with an exaggerated quiver plot. A pole view of the shifted landmarks is shown in Figure 19, which shows that much of the motion in landmarks is away from the south pole. The shifts seen at the limb of the pole view do not show any strong indications of a lingering body rate error. Figure 20 shows a breakdown of the magnitudes of the landmarks shifts by latitude. Many landmarks were shifted by less than twenty meters (~one pixel), with peak shifts of almost 60 meters (~three pixels). In the Z-axis plot (lower right of Figure 20), the average shift along the Vesta body fixed Z-axis is near zero, indicating that there is not a lingering CFCM offset to consider. However, there is a definite signature in which the southern latitude landmarks are shifted up, while the northern latitudes are shifted down. The X- and Y-axis shifts (upper right and lower left of Figure 20, respectively) show some bias and noise in the polar latitudes, but the lower latitudes, from 0º to -40º latitude, showed relatively benign shifts. The Z-axis shifts for those latitudes was also relatively small. With this in mind, a new study was performed in which a six-week LAMO arc was fit using only radio data and observations of landmarks that lay between 0º and -40º latitude. The resulting pole solution is shown in Figure 21, which is shifted towards the radio solution, but not in any way that is significant. It is possible that using only consistently located landmarks is helping, but part of the shift might simply be due to using 45% of the original landmark data with 100% of the original radio data. It is also possible that the X and Y shifts were small simply due to a relatively smaller number of images used to construct the models for those particular landmarks. This area is still open for further study.

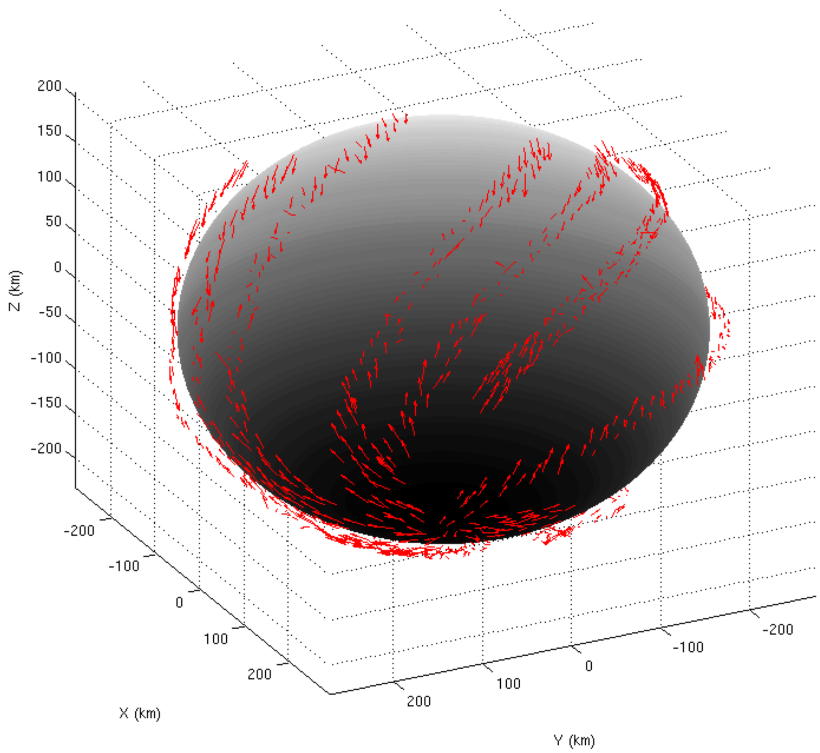

Figure 18: Vesta southern hemisphere, shown with estimated shifts of landmark locations (exaggerated).

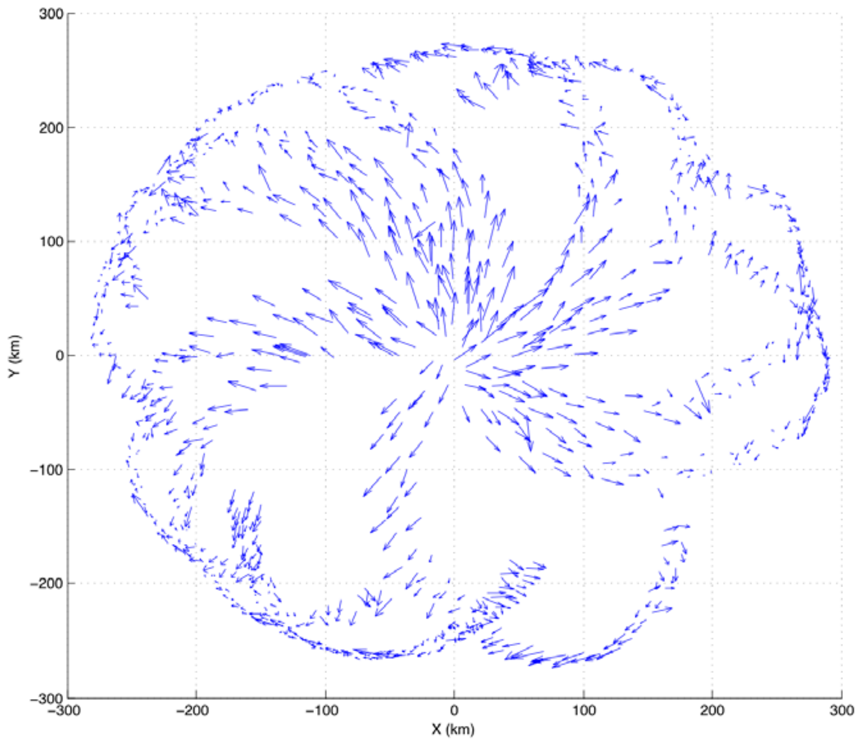

Figure 19: Looking directly along the Vesta pole, artifacts of the shift in the estimated landmark locations are seen.

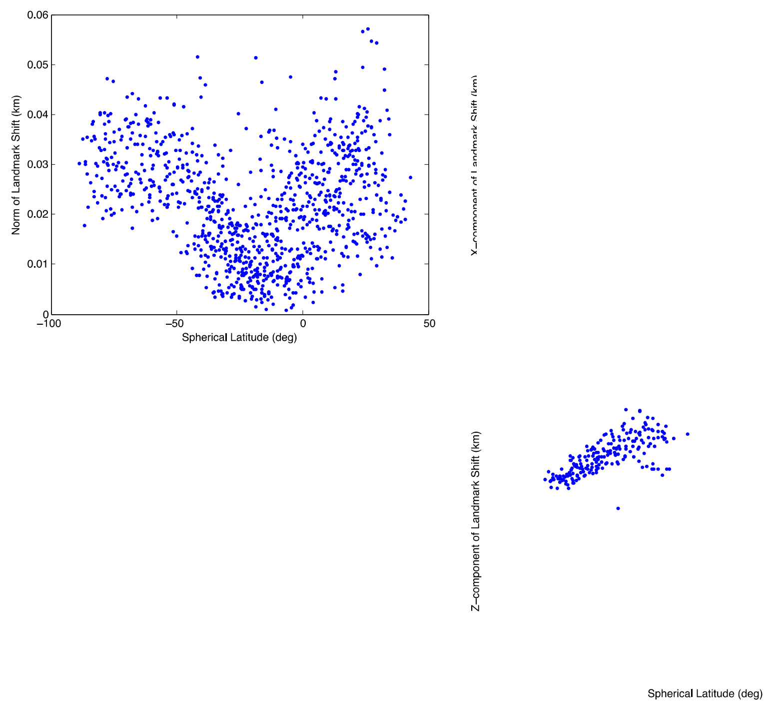

Figure 20: Magnitude of shifts in estimated landmark locations. Clockwise, from upper left: Total magnitude, X-direction, Z-direction and Y-direction (Vesta body fixed frame).

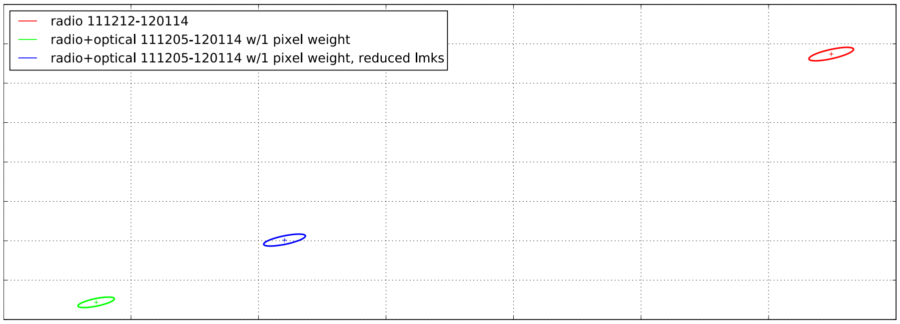

Figure 21: Shift in pole orientation estimation from optical solution when only well-known landmarks are fit.

HAMO-2 PHASE

The HAMO-2 phase of the mission began on June 11th, 2012 and ended on July 24th, 2012. Like HAMO, this phase had a repeating ten-orbit groundtrack, where each set of ten orbits recovered a complete cycle of mapping imagery (see Figure 22). Six complete cycles of data were recovered. Also, like HAMO, the camera was pointed directly at the Vesta center for two cycles, off-pointed to the right for two cycles and off-pointed to the left two cycles. Specifically, cycles 1 and 6 were nadir-pointed, cycles 2 and 5 were pointed to the right, and cycles 3 and 4 were pointed to the left. Unlike HAMO, the science, ACS and OD teams had a better awareness of the effects of RCS perturbations from RWA desaturations (desats) on the ground track. During the HAMO-2 sequence design, desats were placed specifically to minimize changes to the longitude crossings in each successive cycle. In this, they were mostly successful. The respective equatorial longitude crossings for cycles 1 through 5 were at most a few degrees apart, with only the last cycle, cycle 6, being off in longitude by ten degrees. This presents the OD team with a unique laboratory in which to conduct future landmark estimation cases. Because the longitude crossings were consistent, several images of each landmark existed, with images being spaced days apart from each other. Having multiple observations of the same landmark should, hypothetically, give the OD team landmarks shifts with fewer image-dependent artifacts.

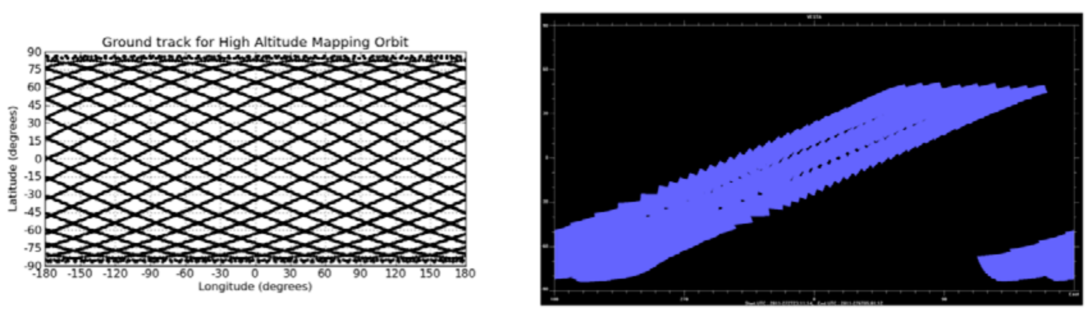

Figure 22: Left: HAMO-2 repeat groundtrack. Right: layout of the HAMO-2 images for neighboring orbit tracks.

The HAMO-2 landmark database was almost as big as the HAMO database, at 69,157 landmarks. For the next OD study, this database was randomly subsampled down to 866 landmarks. Figure 23 shows a side-by-side comparison of the depth of each database. The images from

HAMO-2 were reprocessed against this smaller database, and collected into 10 independent groups. Each group coincided with one of the ten nominal longitude crossings in the HAMO-2 ground track. For example, group 1 made use of orbits with a longitude crossing near -74º, which includes orbit 1 from cycles 1 and 6, orbit 8 from cycles 2 and 5, and orbit 4 from cycles 3 and 4. At the other end of the grouping, group 10 made use of orbit with a longitude crossing near 34º, which includes orbit 10 from cycles 1 and 6, orbit 7 from cycles 2 and 5, and orbit 3 from cycles 3 and 4.

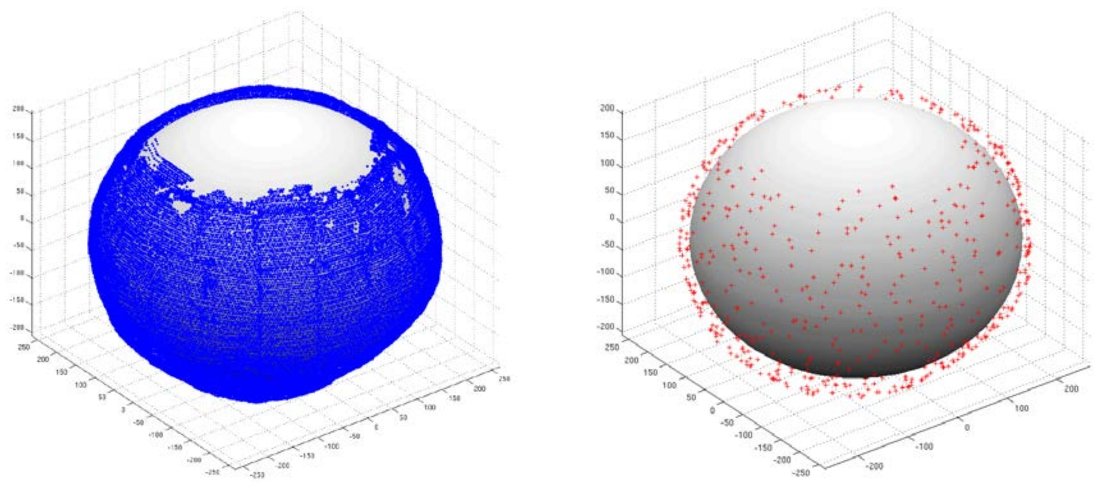

Figure 23: Left: full set of landmark locations used for HAMO-2 image processing. Right: random subset of just over 1% of the total set of available landmarks.

The study of these groups is still a work in progress, but there have already been some interesting results. The observations from data group 1 were fit into several optical-only solutions, in which, along with a tightly constrained epoch state, only the Vesta pole and the landmark locations are estimated. The underlying trajectory used to support the optical fit came from the best radio-only estimate. In Figure 24, the interesting (but again, possibly not useful) effects of data deweighting are shown. In Figure 25, the results of a consider analysis are shown. In the Opnav process, the typical landmark location uncertainties are estimated to be 10 meters. When these are considered, the effects on pole uncertainty grow to tenths of millidegrees. Larger landmark uncertainties may be needed to allow the uncertainty to account for the differences between the radio and radio and optical pole orientation solutions (see Table 4). As with deweighting, several pixels worth of position uncertainty (where 1 pixel is equivalent to 20 meters) does not seem physically justifiable.

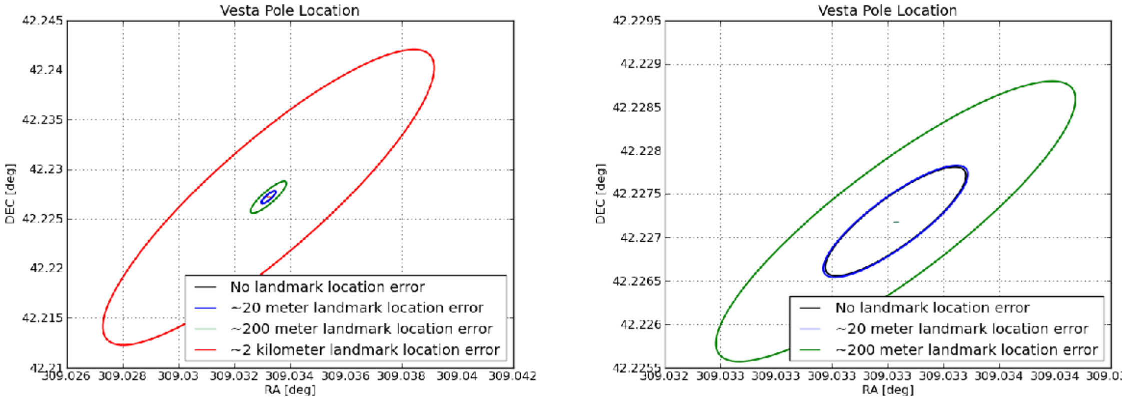

Figure 24: Changes in pole orientation uncertainty for different data weights.

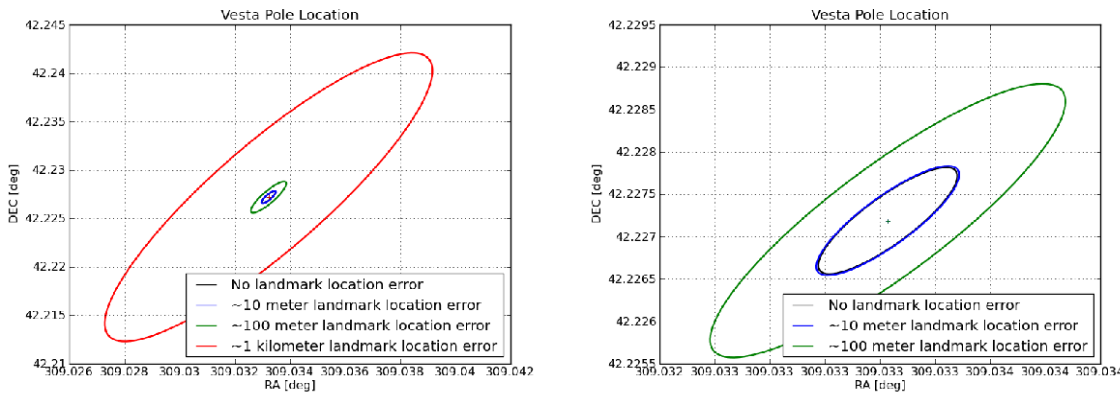

Figure 25: Changes in pole orientation uncertainty when landmark location errors are considered, but not estimated. 10 meters is equivalent to half a pixel.

Many studies are planned for the ten groups of imaging data. Once fit, the resulting set of solutions will be combined to generate a new pole and a new database of landmarks. The Opnav team will use these to again reduce the image data. In this way, we hope to iterate to a merged pole that has better agreement with the radio-only pole.

CONCLUSIONS

Performing Dawn OD at Vesta using optical data has been very challenging, both from a schedule and a technical standpoint. We successfully engineered the mission, and used our remaining available resources to perform in-depth studies of optical navigation capabilities. Before we get to Ceres, we are using the awareness of the overly optimistic pole solutions to apply more realistic uncertainties to the covariance studies used to validate the Ceres Approach plan. Over the next two years of cruise, we will continue to explore the rich Vesta imaging data set in the directions laid down in this paper. We will especially revisit the Vesta Approach data and Approach processes to understand what happened to cause large shifts in subsequent pole orientations solutions. If the HAMO-2 studies prove to be useful, we will use a similar solution combination approach to reprocess LAMO orbits with the same equatorial crossings in order to further refine the LAMO pole solutions.

ACKNOWLEDGEMENTS

The authors appreciate the efforts put forth from our fellow members of the Dawn Spacecraft Team, the Dawn Science Team and the Dawn Project Management. We also appreciate the tireless effort from the operators of the DSN facilities in Barstow, California; Madrid, Spain; and Canberra, Australia.

The work to be described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Copyright 2013 California Institute of Technology. Government sponsorship acknowledged.

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