

Efficacy of the Dawn Vesta Science Plan

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The Dawn Mission to the main belt asteroids (4)Vesta and (1)Ceres presents unique challenges for science planning and operations. The uncertainties of achieving orbit around a substantial body with an unknown gravity field limit the ability of the mission designers to predict in advance the timing of geometric events and orbit parameters. Therefore the science plan architecture had to be robust to a large range of planning uncertainties. However, the complexity of instrument interactions with each other and with the spacecraft required that the science plan and instrument sequences be developed a year in advance of Vesta arrival. Because the science sequence planning and execution timeline did not allow for significant adjustments of the sequences prior to execution, and because the operations time at the asteroids was quite limited, the science plan was designed to be functionally redundant. Functional redundancy was intended to provide multiple observations of the same surface under different conditions. Observing in this manner was intended to protect against potential data losses while providing complementary datasets in the event that all data are successfully acquired. The Dawn spacecraft was captured into orbit around Vesta in July 2011 and will complete Vesta science operations in the summer of 2012. During the approach and early science operations phases there were multiple, unrelated incidents resulting in instrument datasets that were partially lost or degraded. Careful accounting of the datasets returned to date clearly illustrates how the data losses were successfully offset by the redundancy in the observation plan. One specific success is the framing camera stereo imaging from the High Altitude Mapping Orbit, which is needed to generate the topography map. This paper describes the results of the execution of the science operations plan and how that compared to the assumptions that informed the development of the plan.

I. Introduction

THE Dawn spacecraft began its Vesta science phase on May 3, 2011 when it acquired its first optical navigation image of asteroid (4)Vesta. The spacecraft was captured into Vesta orbit on July 17, 2011 where it will remain until August 26, 2012 when it will escape from Vesta on its way to asteroid (1)Ceres. Dawn is a Discovery Mission managed by the Jet Propulsion Laboratory with the Principal Investigator and Science Operations Center located at the University of California, Los Angeles. The Dawn spacecraft payload consists of two redundant Framing Cameras (FC1 and FC2) developed and built under the leadership of the Max Planck Institute for Solar System

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Research, Katlenburg-Lindau, Germany, with significant contributions by DLR German Aerospace Center, Institute of Planetary Research, Berlin, and in coordination with the Institute of Computer and Communication Network Engineering, Braunschweig, a Visible and Infrared Mapping Spectrometer (VIR) contributed by the Agenzia Spaziale Italiana in Italy, and a Gamma Ray and Neutron Detector (GRaND) developed by the Los Alamos National Laboratory and currently operated by the Planetary Science Institute. Details of these instruments and their operations have been published previously.^{1,3,7}

Prior to arrival of the spacecraft at Vesta, the Dawn Science Plan was developed to establish architecture for acquiring the necessary datasets to satisfy the science objectives of the mission. The science observations in each of the three different science orbit altitudes were designed to take advantage of the unique characteristics of that orbit (Fig 1.). Additional observations were designed for the approach to and departure from Vesta. Table 1 lists the dates and durations of the science phases of the Vesta mission. The final two phases, HAMO-2 and Departure, have not yet executed so only the planning dates are listed. While all three instruments are operated during each science orbit phase, one instrument is designated as the primary observer, which means that the spacecraft attitude is designed specifically to meet the objectives of that instrument. The highest science orbit, Survey, provided the opportunity to observe multiple rotations of Vesta in a single orbit because the orbit period of 69 hours was much greater than the 5.3-hour rotation period of Vesta. The VIR instrument was the primary observer during this science phase and was able to take advantage of the orbit characteristics to obtain near-global coverage with a combination of pushbroom mapping and use of the scan mirror. After Survey, the spacecraft transferred down to the High Altitude Mapping Orbit (HAMO), which was the optimum science phase for acquiring global topography and color datasets with FC2. The spacecraft ground track of this approximately 12-hour orbit provided complete coverage of Vesta in 10 orbits allowing a self-contained mapping cycle in 5.5 days. The spacecraft will pass through the HAMO altitude twice, taking similar datasets at two different Vesta seasons. Six mapping cycles were included in the first HAMO imaging phase (HAMO-1). Two cycles were at a nadir attitude and color filter images were acquired in addition to clear filter data for the topography analysis. The remaining four cycles were imaged at different off-nadir attitudes to obtain clear imaging to support both stereo analysis as well as stereophotoclinometry⁵. Following another transfer period, the spacecraft arrived at the Low Altitude Mapping Orbit (LAMO). LAMO was dedicated to acquiring data to determine elemental composition with GRaND and obtain gravity science measurements using coherent Doppler tracking with both the high gain and low gain antennas. The spacecraft operated in LAMO for over 4.5 months orbiting Vesta nearly six times a day with communications to Earth only three times per week. Having recently completed the LAMO observations, Dawn is now transferring back to the HAMO altitude to obtain a complementary set of six topography cycles that includes an additional color imaging cycle (HAMO-2). Following HAMO-2, the remote sensing instruments are planning a few additional observations of Vesta during departure before starting on a cruise to Ceres.

Table 1. Vesta Science Phase dates.

Science Phase	Start Date	End Date	Duration (days)
Approach	May 3, 2011	Aug. 10, 2011	100
Survey	Aug. 11, 2011	Aug. 31, 2011	21
HAMO-1	Sep. 29, 2011	Nov. 1, 2011	34
LAMO	Dec. 12, 2011	April 30, 2012	141
HAMO-2	June 15, 2012	July 25, 2012	41
Departure	July 26, 2012	Aug. 26, 2012	32

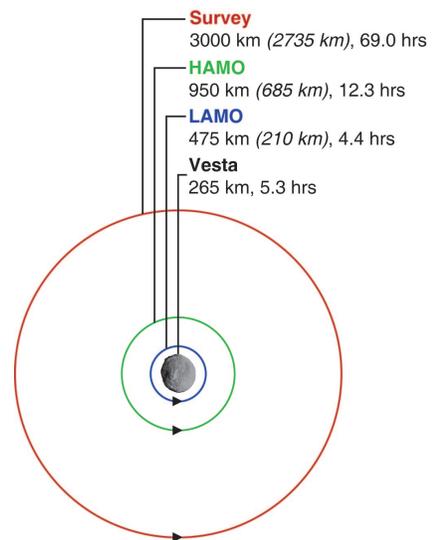


Figure 1. Vesta Science Orbits⁶.

II. Dawn Science Plan Concept

It is the job of the science operations team to provide a high quality dataset to the science team for their analysis. The observations needed to be planned, and the spacecraft and instrument sequences built, many months in advance of arrival at Vesta. As such the strategy had to be flexible enough to adjust to the final details of the orbits once they were defined, and robust against the inevitable losses of science data either during acquisition or transmission. Very

little was known about the surface of Vesta prior to arrival, so the observation strategy had to capture the interesting features regardless of what or where they were on the target body. The approach taken was to systematically map the surface of Vesta as the resolution increased with each lower science orbit, relying on global coverage to capture all interesting aspects of the body and minimizing reliance on observations targeted to specific features. The technique that evolved during the development of the Dawn Science Plan is referred to as functional redundancy. Functionally redundant datasets are not truly identical in nature but are designed to provide essentially the same data where either dataset would satisfy a given requirement in a unique way². The specific science planning constraints and uncertainties that led to the adoption of this approach are fully discussed in Ref. 2 and included knowledge of when the spacecraft would arrive at Vesta, the fixed length of time that the spacecraft could remain in orbit, Vesta season, Vesta pole orientation and spin rate, and the details of the science orbits such as period, inclination, and phasing. The science operations team developed a set of orbit requirements that would enable the observations, but those requirements had relatively large tolerances for error compared to the exact timing required for building spacecraft and instrument sequence products. The methods that were developed to obtain functional redundancy included repetition of particular observations over different longitude ranges, different off-nadir attitude, changing seasons, all with judicious deployment of margin. In general, a complete set of observations was packaged into intervals named cycles and cycles were repeated under varying conditions to acquire the functionally redundant datasets.

To illustrate some aspects of the science planning, examples of FC2 footprints on the surface of Vesta are shown in Fig. 2 for each science orbit. The views were generated using the Science Opportunity Analyzer (SOA) planning

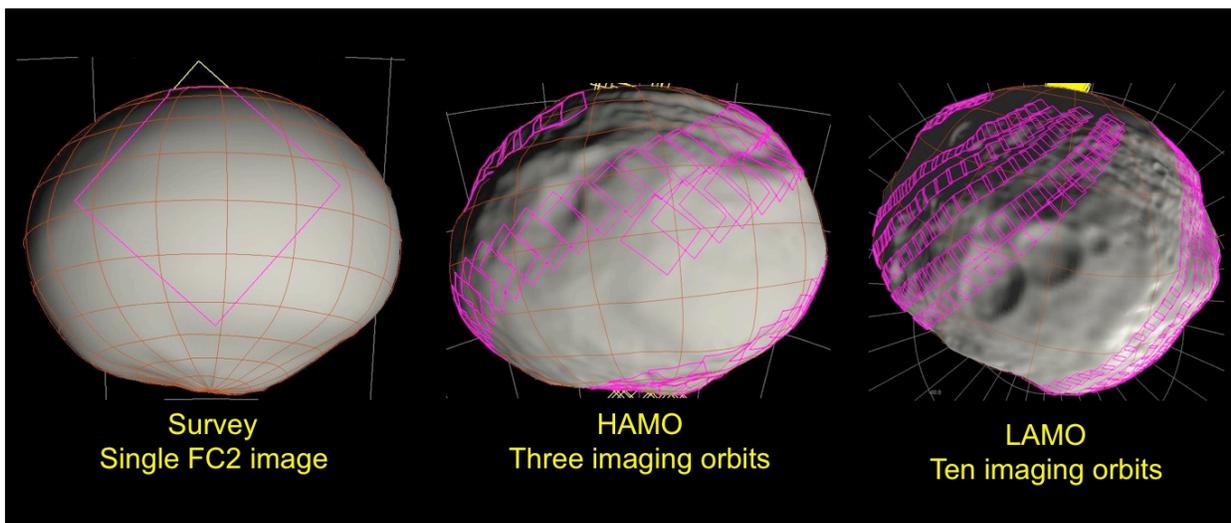


Figure 2. FC2 footprints on Vesta are shown for each science orbit. Vesta is represented by more mature versions of the shape model at each science orbit.

tool⁸, which was used by the science operations team to develop the Dawn Science Plan. The FC2 footprints are shown in magenta when they intersect the surface and yellow when displayed against the sky. Vesta is displayed using the best shape model available at the time that the observations were sequenced. Note that during the Survey orbit planning, no data was available to influence observation design. Instead eleven 1x3 mosaics were taken over a full Vesta rotation to provide global coverage. The mosaics were repeated four times (two from a southern viewing position and two from an equatorial position) for redundancy. In the HAMO example several orbits of footprints are displayed showing how the 10-orbit mapping cycle would provide global coverage. The footprints are displayed on the Vesta shape model derived from Survey and Approach data*. While features are now visible in the shape model (note the prominent set of 3 craters informally referred to as the Snowman), it is unnecessary to alter the previously determined mapping plan because all surfaces can be imaged. In LAMO there were many more nadir orbits than data volume available to return images so the camera could only acquire data from about one third of the orbits. The ten orbits shown are most of what could be accomplished by the camera in one week of LAMO. Since there were no requirements to obtain any imaging during LAMO, the plan to collect camera data using a fixed template of orbits

* Vesta shape models provided for planning by Robert Gaskell of the Planetary Science Institute.

between data playback passes was sufficient. The remainder of this paper will describe some of the as-flown results and explore the effectiveness of the Dawn Science Plan strategy.

III. Performance of the Science Plan

There are multiple ways to assess the efficacy of the Dawn Science Plan. The performance metrics used are specific to the individual datasets acquired. In this paper we will report on a subset of the science data that Dawn returned from Vesta including surface coverage for color imaging and topography, imaging of opportunity in LAMO, and the deployment of margin in LAMO to achieve the G RaND objectives. One of the most straightforward measurements to quantify is to compare the planned surface coverage in a given imaging campaign against the achieved coverage. The tool used by the Dawn science operations team to compute surface coverage is CKVIEW. CKVIEW is a tool that was developed at the Institute of Planetary Research at the DLR. Development started in 2000 with the start of planning for the Cassini Jupiter flyby. CKVIEW was later adopted for planning and image processing purposes for the Venus Express, Dawn, Rosetta, and MESSENGER missions. SOA was developed for Cassini after CKVIEW and incorporated the ability to output the SOA imaging observation plan in a format that could be directly ingested into CKVIEW for evaluation. CKVIEW was used in conjunction with SOA in the development of the Dawn Science Plan and it was also used during flight operations to monitor data gaps and gores. While CKVIEW can now ingest the Vesta shape model, this model was not available during the planning stages so the results will be presented using the triaxial-ellipsoid model of Vesta. Two different example FC2 datasets from HAMO-1 are described.

The first analysis is the performance of the FC2 color filter image acquisition. In Cycles 1 and 6 of HAMO-1, FC2 acquired global coverage of the illuminated surface in the clear filter plus the seven color filters. Two cycles were planned because it was known that there would be small gores between orbits at the HAMO-1 altitude. The expectation was that the images from Cycle 6 would fill the gores in Cycle 1 coverage. The planned coverage for the FC2 clear filter (F1) for Cycle 1 is shown in Fig. 3. Vesta is

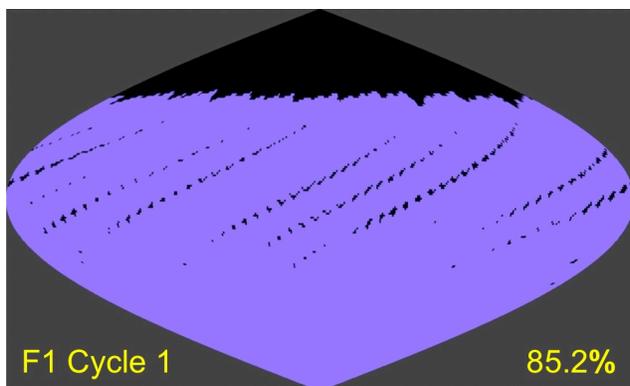


Figure 3. FC2 planned imaging coverage for HAMO-1, Cycle 1, clear filter.

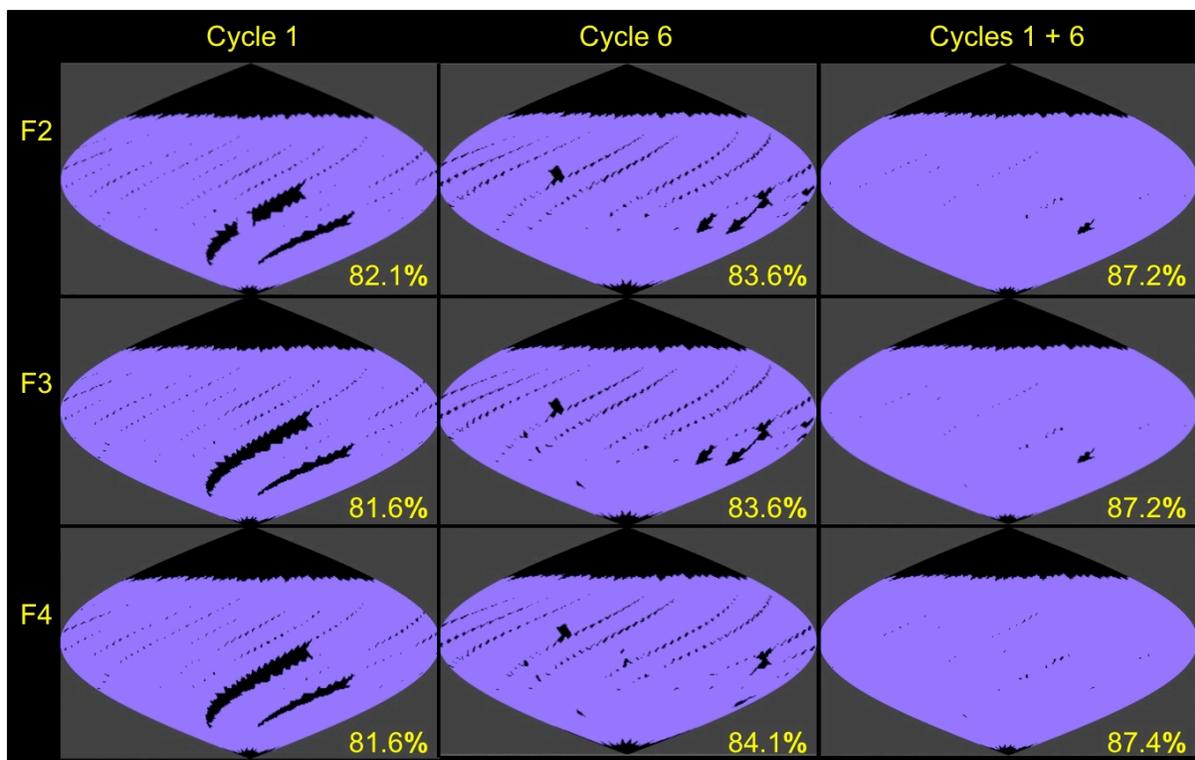


Figure 4. FC2 actual coverage for HAMO-1 three color filters in Cycles 1 and 6.

displayed with a sinusoidal projection with the purple area representing surface that was covered by one or more images with incidence angle less than 90 degrees. The northern hemisphere was in shadow above 50 degrees north latitude and could not be observed. The gores between ground tracks are black. During planning it was estimated that Cycle 1 and Cycle 6 would each provide coverage of 85% of the surface of Vesta for each filter.

Figure 4 shows a sample of the FC2 color coverage as-flown results for filters 2, 3 and 4. The data losses display a similar pattern for the all filters in a given cycle. This was not necessarily an expected result, but in the case of this dataset, the data losses were related to anomalies that impacted more than one image at a time. The gores between orbit ground tracks are clearly visible in all filters for the individual Cycle 1 and 6 coverage maps, but are significantly reduced in the combined coverage map. It was anticipated that the gores between orbits would disappear entirely, but deviations in the actual trajectory from what was planned resulted in minor residual gores. However, the prominent gores stemming from various unexpected data losses were almost completely eliminated in the combined dataset. In general, the FC2 color coverage imaging campaign in HAMO-1 was very successful covering 87% of the total surface of Vesta in at least three filters exceeding the goals for this dataset. An additional cycle of color imaging will be acquired in HAMO-2. While the primary goal of HAMO-2 is to obtain coverage in the newly illuminated northern latitudes, the planned color coverage shown in Fig. 5 will also extend to southern latitudes and provides yet another opportunity to fill gores from HAMO-1. In this view the footprints for the planned color imaging are yellow and the clear filter imaging is magenta.

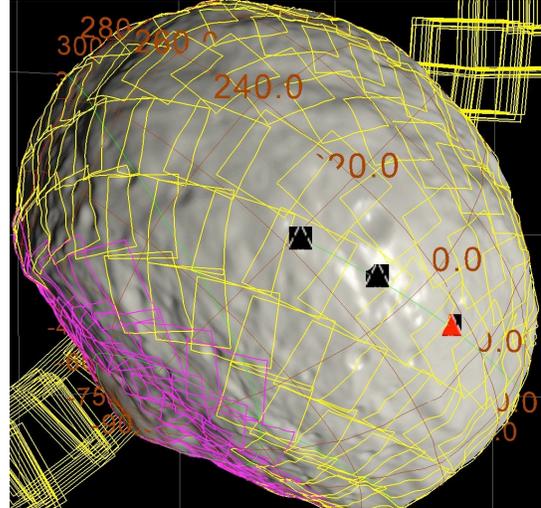


Figure 5. FC2 planned color imaging for HAMO-2.

The second objective of HAMO-1 was acquiring the optical topography dataset. This dataset consisted of the FC2 clear nadir images in Cycles 1 and 6 as well as clear off-nadir images in Cycles 2 through 5. Each topography cycle placed the spacecraft at a unique off-nadir attitude. This allowed the commanding for each orbit in the cycle to follow a similar template. Two off-nadir attitudes combined with one nadir view were required for stereo processing, so the additional two off-nadir cycles provided a functionally redundant dataset for margin. Images from

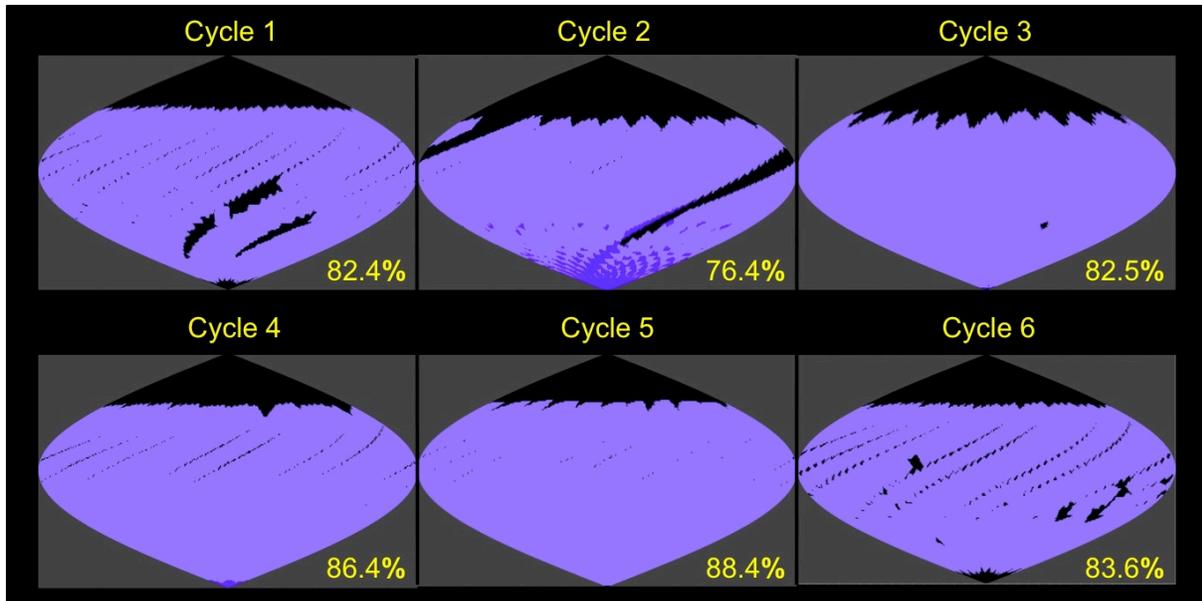


Figure 6. Actual FC2 coverage for HAMO-1 clear imaging in all six cycles.

any two of the four off-nadir attitudes could be used at each point on the surface to derive the topography, which allowed flexibility to accommodate minor data losses. Figure 6 shows the results of the clear imaging campaign for HAMO-1. The clear filter coverage in Cycles 1 and 6 display similar results to those described previously for the color filters. Aside from Cycle 2, which lost one full orbit of imaging, the off-nadir imaging cycles were essentially complete. The width of the gores between individual orbits varied with the off-nadir angle selected, but were generally reduced compared to the nadir cycles. No attempt was made to fill these gores because it was anticipated that different off-nadir images could be used in those areas. When combined, the usable stereo coverage is 76% of the body with resolution between 60 to 70 m/pixel. Figure 7 shows the six HAMO-1 cycles plotted in CKVIEW where the colors indicate how many views are available for each part of the surface that meet the criteria specified for stereo. In particular, the incidence angle for each image must fall between 5 to 75 degrees, and the stereo angle between images must be between 15 to 65 degrees. Any area that is green, blue or purple meets the stereo criteria. The only portions of the surface that do not meet that criteria are in the far northern latitudes where the illumination is poor, or at the south pole where the incidence angle criteria cannot be met even though those regions were imaged repeatedly in each cycle. The topography observation strategy proved robust to the incidental data losses. Even the worst case of the missing orbit in Cycle 2 did not result in any areas with less than three qualifying images. The topography campaign will be repeated again in HAMO-2 with slight variations to the off-nadir angle selections. The primary improvement in the topography model expected from HAMO-2 will be increased visibility into the northern hemisphere because the sub-solar point will have moved very close to the Vesta's equator.

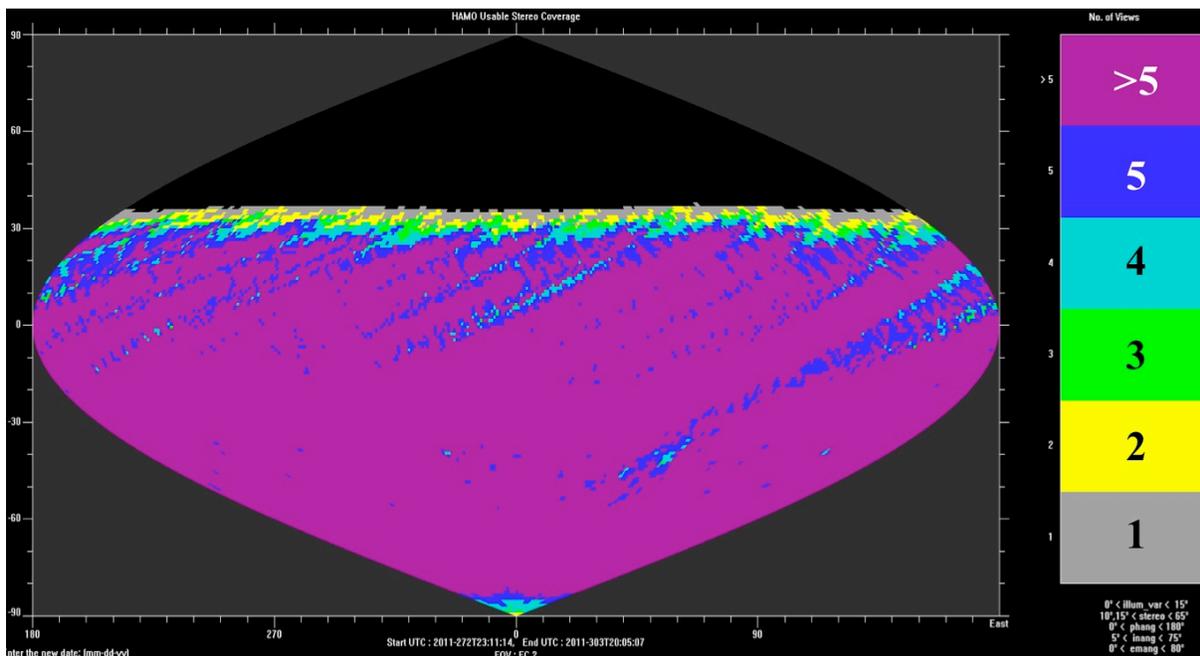


Figure 7. Actual FC2 usable stereo coverage for topography analysis. The incidence angle cutoff is <75 degrees. The colors display the number of available stereo views.

Accumulation of gamma ray and neutron data in the LAMO science orbit required a different strategy than used in the imaging campaigns. The GRaND instrument required a nadir attitude over a long period of time to collect enough data to detect the major rock-forming elements. The baseline operational requirement for the GRaND dataset was 70 days of observations at the LAMO altitude with the spacecraft within five degrees of nadir for 70% of the time. The remaining 30% of the time was spent at an attitude where the high gain antenna could communicate with the Earth so that gravity science could be obtained. This period was also used to return the GRaND science data accumulated while pointing nadir. The other two science orbits preferred a roughly 50/50 split between time at nadir and time returning data to Earth. The goal of the science plan was to put as much available time into the LAMO science orbit phase as possible to improve the GRaND results; however, the project also required that the science plan carry margin against unexpected anomalies that could impact any science orbit phase. The compromise was to carry 40 days of operations margin that could be used at any time to lengthen a science orbit phase to recover from a severe anomaly that was not already covered by functional redundancy. This time would not be sequenced

into the plan unless needed. Whatever margin was remaining at the start of LAMO would be used to delay the end of LAMO. With a nominal duration of 70 days there was sufficient planning time available to add the extra time to the end without a negative impact to the flight team schedules. Although there were three safe mode entries between the start of Approach and the start of LAMO, they all occurred during periods when the flight team was able to recover nominal operations without any loss of time to a science orbit phase. Therefore, the full 40 days of margin was added to the end of LAMO. Subsequently, the navigation team revised the time necessary to arrive at Ceres from Vesta departure allowing an additional 30 days to be added to LAMO. During LAMO there were two spacecraft safe mode entries at a cost of 15 days of GRaND data acquisition. In the end, the LAMO duration was 80% longer than the baseline plan resulting in a significant improvement to the GRaND dataset.

The extra time spent in the LAMO orbit provided a unique opportunity to deviate from the template-driven observation strategy to plan some rare FC2 targeted observations. However, the targets were image gaps, not Vesta features. This additional flexibility had been anticipated for periods near the end of the Vesta mission when the orbit behavior had been fully characterized. For 16 weeks, FC2 had acquired data on orbits dictated by the standard template. However, when the final 4-week mission extension was added, the available orbits for acquiring data were evaluated against the remaining gaps in coverage. While the trajectory would not provide opportunities to fill all remaining gores, careful selection of the remaining imaging orbits significantly improved the overall coverage. Using a conservative selection criteria of images with less than 70 degrees incidence, the CKVIEW plot in Fig. 8 shows 66% coverage of the surface at LAMO resolution of less than 30 m/pixel[†]. The actual image gores are visible as thin stripes. The other black areas in the illuminated region have been imaged, but are on slopes that do not meet the incidence angle criteria. This nearly global coverage is a spectacular result for “bonus” imaging that was not required at this science phase.

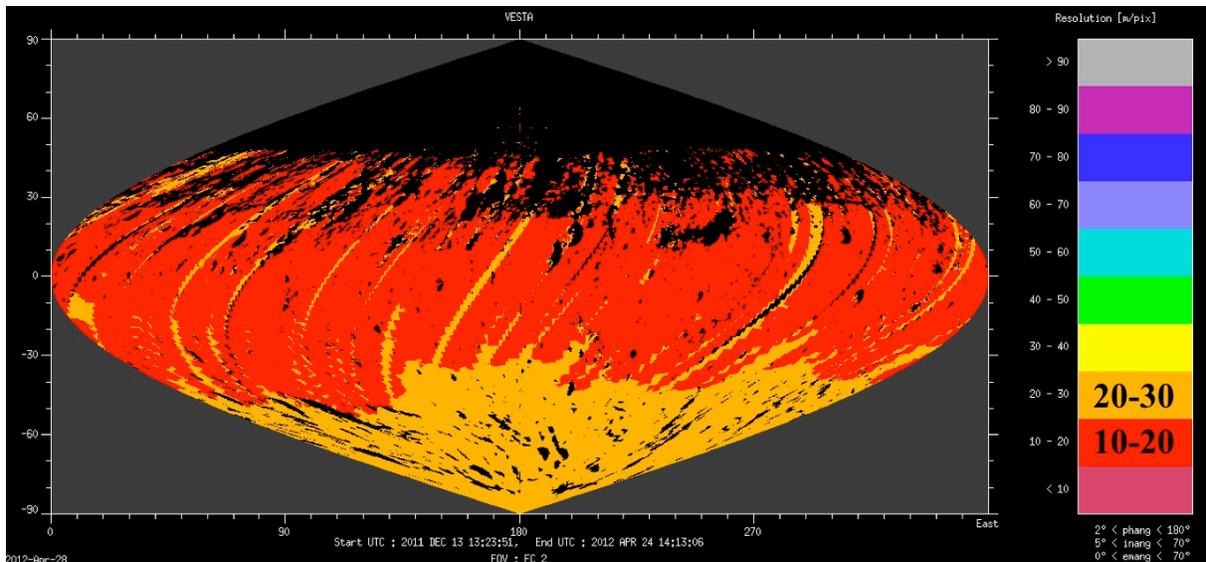


Figure 8. Actual FC2 coverage obtained during the LAMO phase. The most recent Vesta shape model is used to display the coverage for images with incidence angles less than 70 degrees. Resolution varies between 10-20 m/pixel and 20-30 m/pixel.

There was some flexibility built into the science plan architecture that was not exercised to the extent expected. Starting a year before arrival, the Vesta command sequences were all generated relative to geometric epochs related to Vesta. The most commonly used epoch was the time of the dark to lit terminator crossing for each orbit since the remote sensing instruments would typically observe only during the dayside portion of the orbit. All instrument activities were commanded relative to that single epoch. The Vesta arrival date had been uncertain by several weeks so command sequences built a year earlier were shifted to align with the final reference trajectory. Transfer times between science orbits were also unknown until shortly before each transfer started, therefore the sequence epochs were updated once at the start of each science phase. A mechanical process would update the epochs without requiring changes to the delivered instrument sequences. This process was executed without incident and all

[†] Plot and shape model coverage analysis provided by Thomas Roatsch, DLR, personal communication, 4/28/2012.

observations retained their required attributes as expected. However, there was also an expectation that the orbits would drift within a science phase or that the orbit periods would be substantially different from the original specifications requiring timing updates between observation cycles. For Survey and HAMO-1, the orbit delivery was extremely precise. The Survey orbit requirement was 3000 km radius with a range between 2800 km to 3200 km, and the orbit-phasing requirement was +/- 45 minutes change in the dark-to-lit terminator crossing time. The as-flown orbit results are reported in Ref. 4. The Survey orbit radius was 2997 km and generally varied by less than 4 km with the phasing error in the dark to lit terminator crossing never exceeding nine minutes. The HAMO-1 experience was similar. Following the epoch update to the initial sequence delivery, the deviation of the dark to lit terminator crossing was found to be significantly less than the 10-minute tolerance and the orbit radius variation between 934 km and 960 km was well within the allowed range of 925 km to 975 km. There was a change to the LAMO planned orbit radius, but it was identified well in advance. Prior to the delivery of the first set of LAMO sequences, the mean orbit radius was shifted higher by 10 km from 465 km to 475 km in order to improve orbit stability. This change was acceptable to the GRaND instrument team so no further sequence adjustments were required. While a sequence epoch update process was put in place to accommodate the expectation of mid-phase adjustments, the navigation performance exceeded expectations and the sequences were acceptable without additional intervention. The flight team was relieved of the work involved in updating the sequences, which simplified the overall uplink process.

IV. Conclusions

The Dawn mission has revealed Vesta and all of her mysteries to the world. Despite the challenges that are inevitable during the height of scientific discovery with an interplanetary spacecraft at an unknown body, a wealth of data has been returned to Earth achieving the goals that were set many years prior to launch. The principal of functional redundancy in science planning has proven to be effective and efficient for developing an observation strategy that was robust to the many varied sources of data losses experienced during a year of flight operations. Although real time commanding was often required to respond to instrument and spacecraft anomalies, real time intervention was not needed to change the observation plans when data were lost, because no given image or spectra was uniquely critical data. In the cases where the data return was complete, as expected, the variations in acquisition conditions allowed all data to contribute to the scientific analysis. Despite the many successes, there are still challenges ahead for Dawn. While the end of LAMO signals the completion of the successful GRaND data acquisition at Vesta, there is still a full phase of imaging and spectroscopy to come in HAMO-2. After departure from Vesta, the planning begins for the Ceres mission where the same principals will be exercised in developing the Dawn Ceres Science Plan. Many of the details of the Ceres mission will differ from Vesta, but the goals of redundancy and adaptability will be applied to the global mapping campaigns of the three Dawn instruments at their next asteroid rendezvous.

Appendix A Acronym List

FC	Framing Camera
GRaND	Gamma Ray and Neutron Detector
HAMO	High Altitude Mapping Orbit
LAMO	Low Altitude Mapping Orbit
SOA	Science Opportunity Analyzer
VIR	Visible and Infrared Mapping Spectrometer

Acknowledgments

The success of this endeavor depended greatly on the support of the Dawn flight operations team and their ability to respond to the many surprises and challenges during Vesta operations. Specific recognition is given to Thomas Roatsch, Klaus-Dieter Matz, and Ralf Jauman at DLR for development of the CKVIEW tool, which was critical to the evaluation of the observation plans as well as the as flown performance evaluation. The authors also thank the instrument operations leads, Pablo Gutierrez-Marques (FC, MPS), Tom Prettyman (GRaND, PSI) and Sergio Fonte (VIR, IFSI) and their teams for their support of operations and flexibility in responding to the challenges of the science phase of the mission. A portion of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

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