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SPIRALING AWAY FROM VESTA: DESIGN OF THE TRANSFER FROM THE LOW TO HIGH ALTITUDE DAWN MAPPING ORBITS

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Dawn has successfully completed its orbital mission at Vesta and is currently en route to an orbital rendezvous with Ceres in 2015. The longest duration and most complex portion of the Vesta departure trajectory was the transfer from the low to high altitude science orbit. This paper describes the design of this low-thrust trajectory optimized assuming a minimum-propellant mass objective. The transfer utilized solar-electric ion propulsion applied over 139 spacecraft revolutions about Vesta. Science drivers, operational constraints, and robustness to statistical uncertainties are addressed. The 45-day transfer trajectory was successfully implemented in early 2012.

INTRODUCTION

In September of 2012, the NASA Discovery mission Dawn successfully concluded its orbital mission about Vesta, the second-most massive main-belt asteroid. Dawn is currently en route to an orbital rendezvous with the dwarf planet Ceres in 2015 and will become the first mission to orbit two extraterrestrial bodies. Observations of these two strikingly different bodies are designed to provide an understanding of the conditions and processes present during the formation of the solar system[1,2,3]. The scientific instrumentation consists of panchromatic and multi-spectral imaging, visible, infrared, gamma ray, and neutron spectrometry, and gravimetry[1,2].

Science observations of Vesta were predominantly obtained from four near-polar, near-circular science orbits (Figure 1). In chronological order, the science orbits are referred to as Survey (3,000 km orbital radius), the High Altitude Mapping Orbit known as HAMO (950 km orbital radius), the Low Altitude Mapping Orbit known as LAMO (475 km orbital radius), and a return to the High Altitude Mapping Orbit known as HAMO-2 (950 km orbital radius). The second HAMO science orbit, HAMO-2, enabled illuminated observations of Vesta's northern hemisphere not available previously in the mission due to seasonal considerations. Brief but valuable science observations were made in two additional, higher altitude science orbits (5300-6400 km orbital radius) before and after the four major science orbits. The majority of the science observations were obtained at the HAMO and LAMO orbital radii. HAMO was optimized for global visual and topographic mapping, and LAMO was optimized for high-resolution spectral analysis and gravity field determination.

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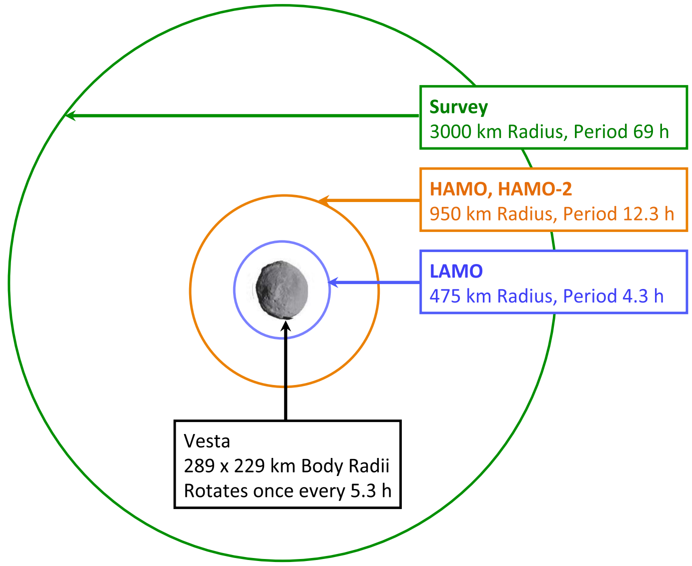

Figure 1. Vesta Science Orbits.

Transfer between each science orbit was accomplished via a series of low-thrust designs utilizing solar-electric ion propulsion applied over many spacecraft revolutions about Vesta. Each transfer had its own unique design considerations and challenges[4]. The most challenging transfers were the HAMO to LAMO and LAMO to HAMO-2 transfers[4,5] since these transfers penetrated deepest into Vesta's highly non-spherical gravity field and passed through the unstable[6] 1:1 spacecraft orbital period to Vesta rotational period resonance. This paper details the design of the 45-day LAMO to HAMO-2 transfer "reference" trajectory, which served as the baseline trajectory for operational implementation in mid 2012. A comparison of the reconstructed trajectory as compared to the design is forthcoming[7,8].

ION PROPULSION SYSTEM

Dawn is solar-powered and its large solar arrays (spanning ~20 m) are designed to provide 11.0 kW at 1 AU and 1.3 kW at their end of life at 3 AU. During the LAMO to HAMO-2 transfer, heliocentric distance ranged decreased from 2.489 to 2.520 AU. For reliability, the spacecraft has three ion thrusters, although only one thruster is operated at a time. Each thruster is mounted to a two-axis gimbal and has thrust vector control to maintain attitude about the two axes perpendicular to the thrust vector. The low thrust engine can produce thrust magnitudes from 19 to 91 mN depending on available power[9]. The specific impulse ranges from 1900 to 3200 sec. During operations, thrust and mass flow rates are selected from 112 discrete "mission levels". In general, the mission level providing the greatest thrust possible (dictated by the power available) was selected.

The Attitude Control System (ACS) is comprised of: four reaction wheel assemblies (RWAs), twelve 0.9 N hydrazine thrusters, and three gimbaled ion propulsion system (IPS) thrusters. RWAs were the primary actuator for attitude control when not using the IPS. The hydrazine thruster system consists of two redundant sets of six thrusters that can be used for attitude control, or to adjust the momentum of the RWAs. Momentum wheel desaturation ΔVs were not modeled in the transfer trajectory and usually were not modeled during operational implementation; these perturbations were one of the sources of error in achieving the desired trajectory targets.

While thrusting with the IPS, the specified thrust direction dictates the spacecraft attitude via an ACS algorithm known as "power steering". The ground can command a pointing vector (such as instrument boresight to nadir) and the always-active power steering algorithm determines the attitude steering commands to maximize solar illumination. Unfortunately, if the specified thrust vector passes through or near the Sun or anti-Sun direction, power steering will flip the spacecraft attitude by executing a nearly 180˚ rotation. This "power steering flip" can exceed the spacecraft ACS capabilities if the thrust vectors are within 15-20˚ of the Sun line and, as a result, constraints were added to the trajectory design process to ensure compliance with ACS requirements[10].

REQUIREMENTS AND CONSTRAINTS

The design of the HAMO-2 science orbit was driven by requirements placed by the Framing Camera (FC) and Visual and Infrared (VIR) Mapping Spectrometer instruments[1,2]. Key constraints were also levied by the Spacecraft Team to avoid entry into shadow and by the ACS to avoid excessive body rates and accelerations that could occur for certain thrust vector directions.

HAMO-2 Science Orbit Requirements

The objective of the HAMO-2 science orbit was to obtain global coverage at nadir and three off-nadir angles using the FC instrument and also obtain as much coverage as possible using the VIR mapping spectrometer[11]. The objectives were nearly identical to those of the first HAMO but permitted illuminated observations of the northern hemisphere not available in HAMO. The maximum sub-solar latitude during HAMO-2 was -3˚ as compared to a maximum value in HAMO of -26˚, which provided substantial improvement for north polar imaging observations.

HAMO-2 requirements are summarized in Table 1[11]. The general implementation strategy was to obtain six cycles of global coverage via a 10-rev repeating ground track pattern. Each 5.1 day repeat cycle consisted of 23 Vesta rotations and 10 spacecraft orbits. The required HAMO-2 orbit period was ~12.3 hours. The target radius was driven by the required FC spatial resolution. Only one exact repeat ground track pattern with 36˚ longitude spacing was available in the required 925-975 km range and lies at a radius near 951 km. Beta angle is the angle between the orbit plane and the Vesta to Sun direction. Low to moderate beta angles provide the illumination required by the FC and VIR instruments. Beta angle must be high enough, however, to avoid eclipsing the spacecraft, which is a violation of flight rules.

Table 1. HAMO-2 Science Orbit Requirements.

Parameter	Science Requirement	Purpose
10-rev repeat ground track pattern	Ideal ground track longitudinal spacing of 36˚, spacing up to 42˚ acceptable	Cyclic global coverage at nadir and three off-nadir angles using the FC instrument and obtain as much coverage as possible using the VIR mapping spectrometer
Radius wrt Vesta	925-975 km	Provide 60-65 m FC spatial resolution and achieve ground track spacing. Refine to achieve 10-rev repeat orbit.
Orbit period	>=12 h	Permit sufficient time for data downlink. Refine to achieve 10-rev repeat orbit.
Beta angle	Ideally <=45˚, acceptable range 35-47˚	Illumination enabling FC and VIR observations
Inclination	85˚-95˚	Global coverage (measured wrt Vesta Equator)

Eclipse Avoidance

The Dawn spacecraft was never qualified to enter eclipse in order to reduce spacecraft development costs. As a result, a flight rule barring passage of the spacecraft into the Sun's shadow at any time has been strictly applied to all Vesta mission phases. The transfers must remain free of eclipse for at least 25 days should thrusting be terminated at any time during the transfer. The most likely cause of an unplanned termination in thrusting would be safe mode entry. The 25 day period enables recovery of the spacecraft and development of a recovery sequence. This eclipse constraint was a significant driver in the design of the LAMO to HAMO-2 reference trajectory.

Attitude Control System Agility

Dawn's ACS has dynamic constraints on attitude rate, angular acceleration, and thruster gimbal rates[10]. While thrusting with the IPS, the designed thrust direction dictates the spacecraft attitude via the power steering algorithm. The Maneuver Team must design thrust profiles that avoid these dynamic constraints. These constraints are addressed primarily during implementation not during the design of the reference trajectory[12]. However, if the reference trajectory thrust vector passes within ~15-20° the Sun or anti-Sun direction, the always-active power steering may flip the spacecraft attitude by rotating it nearly 180°. The closer the thrust direction passes to the Sun/anti-Sun line, the faster the flip. To reduce the likelihood and severity of these "power steering flips", a consideration in the selection of the reference trajectory was the distance between the thrust vectors and the Sun/anti-Sun line - the greater the angular difference, the better.

Transfer Architecture

The design of maneuvers to transfer the spacecraft from one science orbit to another is a multi-stage process. The deterministic reference trajectory is created for the entire transfer just prior to the start of the transfer using the latest Orbit Determination (OD) Team estimation of the spacecraft state and Vesta physical parameters. The transfer "architecture" ensures there is sufficient flexibility available during the design of the reference trajectory to overcome OD and maneuver execution errors, as well as other sources of uncertainty[5]. This flexibility is manifest by the inclusion of coasting (thrust off) periods in the reference trajectory, referred to as Mission Expansion Periods (MEPs), which can be converted to thrusting during operations. For the reference trajectory design, the primary impact of the architecture is the specification of time periods when thrusting may occur and when thrusting must be turned off (Figure 2).

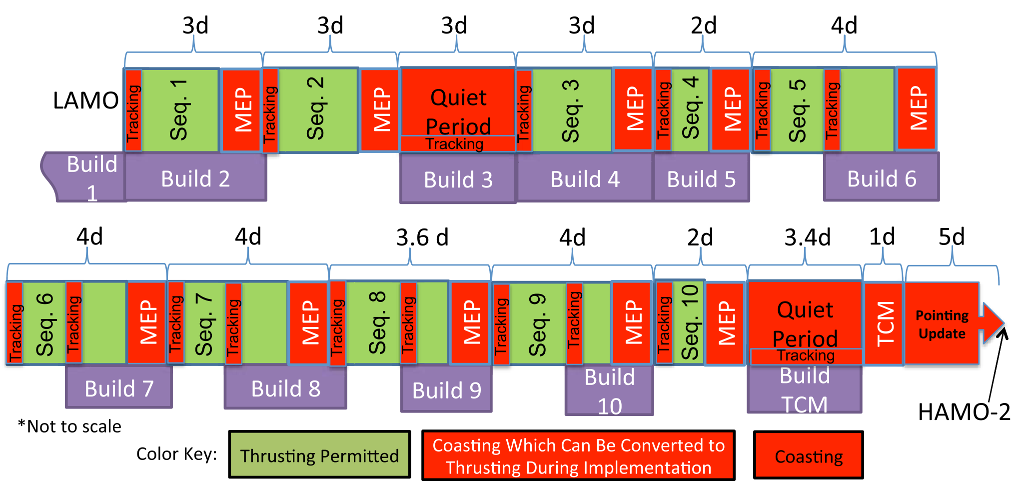

Figure 2. LAMO to HAMO-2 Transfer Architecture.

The transfer architecture was finalized months before the start of the transfer[5] in order to secure needed tracking periods from the Deep Space Network (DSN) antennae. During operational implementation, the reference trajectory is divided into 10 "thrust sequences" and a Trajectory Correction Maneuver (TCM) each from 1 to 4 days in duration (Figure 2). A thrust sequence is the set of commands to be executed onboard the spacecraft and governs all spacecraft activities. Each thrust sequence is produced using a ground build process that follows either a 2 or 3 day duration template (Figure 2). The thrust sequence build duration is governed by how fast the ground team can perform all the needed tasks to generate full set of commands comprising the thrust sequence. One to two DSN tracking and playback passes of ~10.4 hours duration were included in each thrust sequence. The last track prior to a build process served as the data cutoff for design of the next thrust sequence.

Thrusting is implemented open loop. Each thrust sequence is designed to deliver the spacecraft to the reference trajectory position and velocity "waypoint" at the end of the thrust sequence. The trajectory never exactly returns to this reference trajectory waypoint due to uncertainties in 1) the spacecraft initial state, 2) modeling of Vesta physical parameters such as pole orientation and gravity field, 3) maneuver execution error, and 4) propulsion modeling errors[13]. Also small momentum wheel desaturation ΔVs, which are typically not modeled by the Maneuver Team, perturb the trajectory. The flown trajectory is permitted to deviate from the reference trajectory up until the end of the sequence and these deviations can be significant[7]. Targeting each thrust sequence to achieve these reference trajectory "waypoints" enabled thrust sequences to be designed independently during operations, each design aiming to restore the reference trajectory characteristics for the remainder of the transfer. Since reference trajectory design requires weeks of effort, redesigning the remaining portion of the reference trajectory during the operational implementation of each thrust sequence was not practical.

The transfer architecture provided a total of 16.5 days for deterministic thrusting and required 28.6 days of coasting, including allocations for statistical thrusting. To accommodate uncertainties, each thrust sequence in the reference trajectory included a day-long MEP coast which could be converted to thrusting only during the operational implementation of each thrust sequence to correct for any errors accumulated during the previous thrust sequences. The TCM is similarly a day-long coast in the reference design that may be devoted entirely to statistical thrusting during implementation to clean up any errors and more accurately achieve the HAMO-2 science orbit. In Figure 2, these coasts are color coded differently than the permanent coasting blocks. Two 3 day "quiet periods" were included to provide ground time during implementation for thrust sequence design without accumulating maneuver execution errors. The quiet periods enabled a more accurate estimation the initial state to be used in the design of the next thrust sequence. A final 5 day pointing update coast was provided to enable the OD Team to precisely determine whether the required orbit had been achieved and to update the on-board spacecraft ephemeris for precision science pointing.

The architecture in Figure 2 was created prior to entering Vesta orbit and validated using trajectories designed with a primitive shape-based Vesta gravity field and a pole orientation based on distant observations. Architecture development was a time-consuming iterative process[5]. The feasibility of the architecture, i.e., the likelihood of being able to maneuver the spacecraft to the reference trajectory waypoints, was evaluated using a complex Monte Carlo method that sampled all modeled sources of uncertainty[5]. The architecture does not constrain thrust directions or require that the spacecraft thrust whenever it is permitted so. These traits enabled a wide diversity of candidate reference trajectory designs to be created.

REFERENCE TRAJECTORY SELECTION CRITERIA

Each of this paper's authors developed LAMO to HAMO-2 reference trajectories independent of one another in attempt to increase the diversity of solutions and improve the operational safety and ease of implementation of the final reference trajectory flown. Reference trajectory selection criteria are listed in Table 2. These are not the only selection criteria but became the key discriminators between candidates. Safety from spacecraft eclipse for at least 25 days should thrusting terminate was paramount at all times during the trajectory. The margin with respect to entering shadow was also a consideration.

Table 2. LAMO to HAMO-2 Reference Trajectory Selection Criteria.

Criteria	Description
Safety From Eclipse	Trajectory must be free of eclipse for at least 25 days should thrusting stop at any point during the trajectory
Stability	Powered flight stability should be maximized since it is a strong predictor of robustness to uncertainties. Stability is measured in terms of the time required for a group of perturbed states to grow apart 400 km from the reference under powered flight. Monte Carlo analysis had shown that stability of 4-5 days resulted in highly feasible designs.
Direction of Thrust Vectors	The number of times any thrust vector comes within ~20˚ of the Sun/anti-Sun line should be minimized. Thrust vectors which pass near Sun line can result in unachievable ACS rates and corrections during implementation complicate operations.
Resonance Exit Timing	The 1:1 Vesta rotation period to spacecraft orbital period resonance is more powerful than the spacecraft propulsive capabilities and can cause significant and rapid perturbations to the trajectory. The earlier this resonance is traversed, the lower the risk of unanticipated perturbations should the spacecraft experience operational problems such as safing.

Monte Carlo based analysis of each candidate's robustness to sources of uncertainty was not practical due to time limitations so a strong indicator of robustness, powered flight stability[6], was applied instead. In general, an unstable powered trajectory is one that rapidly diverges from its designed reference when subject to perturbations in position and/or velocity. For Dawn, stability was defined by the time required for the distance between the unperturbed trajectory and any of a dozen perturbed cases to reach 400 km. Approximately every 30 minutes the unperturbed trajectory position and velocity 6-state was sampled. This 6-state was then perturbed in 12 different ways. Each of these 12 states and the unperturbed state were then propagated modeling the unperturbed trajectory thrust profile. The 400 km distance was arbitrary since stability was used as a relative means of comparing trajectory candidates. Past experience had shown that stabilities greater than 4-5 days would likely result in highly robust designs.

As stated previously, thrust vector directions near the Sun/anti-Sun direction increase spacecraft rates and can require sudden changes in attitude that are unachievable by the ACS. When this occurs, the spacecraft fault protection system may trigger safe mode entry. The thrust direction can be modified during thrust sequence implementation[12*] but this additional operational complexity could not be adequately assessed at the time of the reference trajectory design. Therefore, the fewer close excursions of the thrust vectors to the Sun/anti-Sun directions, the better.

During the second or third thrust arc of the transfer, the spacecraft passes through the "keyhole" region, which is defined as close proximity to the 1:1 Vesta rotation period to spacecraft orbit period resonance. This resonance occurs when the spacecraft's period is equal to Vesta's rotational period of 5.3 hours. The 1:1 resonance repeatedly exposes the spacecraft to the same portion of Vesta's highly non-spherical gravity field[8,13], which can cause significant and rapid perturbations to the trajectory. Near the keyhole, gravitational perturbations can overwhelm the thrust capabilities of the spacecraft. Satisfying ACS agility constraints is the most difficult at lower orbit altitudes due to higher spacecraft angular rates. Spacecraft operational problems resulting in a loss of thrusting (such as safe mode entry) was therefore considered more perilous at or below the keyhole so there was a strong desire to pass above the 1:1 resonance as soon as possible. All candidate trajectories passed through this resonance in the second or third thrust sequence; earlier resonance passage was preferred.

REFERENCE TRAJECTORY DESIGN

The final development of candidate transfers began in the spring of 2012 about six weeks before the start of the transfer in conjunction with ongoing LAMO operations tasks. The trajectory had to be delivered a week in advance of the start of thrusting to permit processing and sequencing by other Dawn Teams. A wide range of transfer trajectories can achieve the same HAMO-2 orbit. Each author independently developed candidate reference trajectories in an attempt to maximize the diversity of solutions in the hopes of best optimizing the selection criteria. The design methodology employed by each author were slightly different but generally followed a process similar to that described below. The non-linear transfer trajectory design and optimization problem was solved as a fixed-time trajectory with a minimum-propellant mass optimization objective using the Static/Dynamic Optimal Control Algorithm embodied in a software toolset called Mystic[14,15,16]. Mystic was used to design both the interplanetary trajectory to Vesta and all Vesta mission orbital transfers[4].

Initial Design

The initial spacecraft state was at the end of the LAMO science orbit phase (Table 3) and was based on data supplied by the OD Team using the latest available tracking and optical navigation data. A high fidelity 13x13 Vesta gravity field, pole orientation, and ion engine thrust magnitude scale factors were supplied by the OD team[8,13]. The scale factors were estimated as part of the OD process to improve predicted engine thrust magnitudes.

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[*] Thrust direction optimization was often employed during operational implementation; when Sun avoidance was satisfied, direction optimization could be used to minimize the number of on/off engine cycles and/or attitude rates.

Table 3. Transfer Trajectory Initial Conditions.

Epoch (ET) (earliest transfer thrust)	1-May-2012 10:26
Semi-major Axis	473.5 km
Period	4.3 h
Eccentricity	0.051
Inclination (wrt Vesta Equator)	90.16°
Beta Angle	45.4°

The Mystic software requires an initial guess of the transfer trajectory before optimization can be performed. This was usually accomplished by assuming a simple spiral-out control law (thrust direction parallel to the spacecraft velocity direction) during entire thrust sequences. For an initial trajectory design, rather than try to guess when it would be optimal to thrust or coast, thrusting using the spiral-out control law was applied to entire thrust sequences using a thrust magnitude lower than the maximum possible thrust achievable. During optimization, thrust is applied at or near the maximum thrust achievable and is placed at the most efficient location in the orbit. Time periods when the spacecraft is permitted to thrust but is optimal to coast instead are referred to as "optimal coasts".

In Mystic, specifying the power available to the thruster controls thrust magnitude. By scaling the magnitude of the thrust, the user can vary the number of spacecraft orbits in a given time period. The number of revs in the initial guess is usually preserved in the final optimized design and can significantly alter the characteristics of the trajectory. This methodology was sufficient for creating initial thrust sequences but trajectory optimization using Mystic was required to achieve the required HAMO-2 science orbit. In an optimized trajectory, the spacecraft does not thrust at every possible opportunity available in the transfer architecture since the architecture contains thrusting time margin in order to accommodate sources of uncertainty. Optimal coasting is a form of thrust margin and was considered advantageous. However, it was not considered as a selection criteria since each thrust sequence contains a one day mission expansion period which could be converted to thrusting during the implementation thereby already providing significant thrust time margin.

By thrusting nearly the entire time during the first two thrust sequences near maximum achievable thrust, it was possible to pass above the 1:1 resonance region. By reducing thrust magnitude, resonance passage could be delayed to the third thrust sequence. The transfer architecture was designed assuming resonance exit in the third sequence since at the time of its design, power and thruster models were more conservative precluding resonance exit any earlier. The data cutoff for OD estimation of the initial state for the design of the first two thrust sequences was at the end of LAMO prior to the start of thrusting. Therefore, uncertainty in the trajectory prediction by OD would be much greater in the second thrust sequence than the third. The architecture included a "quiet period" coast between the second and third thrust sequences (Figure 2) to improve OD accuracy of the initial state used to design the third thrust sequence. Monte Carlo analysis had shown this accuracy was important for robustness against uncertainties[5]. However, the Navigation Team had confidence, based on the transfers already executed, that the initial state estimation for the design of the second thrust arc would be adequate since there would be eight more thrust sequences to correct any errors due to initial state error and considered the risk of lingering near the keyhole to be greater than passing through the region with a higher state uncertainty. Therefore, many more transfer candidates that passed through the 1:1 resonance in the second thrust sequence were developed than passed through in the third.

Trajectory Optimization and Selection

During the LAMO orbit phase, Navigation worked with the Dawn Science Team to further refine science orbit requirements. To achieve the HAMO-2 science orbit, trajectories had to be optimized using Mystic. Mystic state targets are listed in Table 4. Targeting the spacecraft angular momentum vector rather than several orbital parameters independently resulted in much faster and well-behaved convergence during optimization. The target inclination of 93.95˚ provided a negative beta angle rate of -0.18˚/d resulting in the lowest beta angle profile possible during the HAMO-2 orbit while still maintaining margin against the spacecraft entering eclipse. Low beta angles provide better illumination and were preferred by the Dawn imaging instruments. Two distinct orbit planes can satisfy the inclination, beta angle, and beta angle rate. The further constraint of a "+AM" orbit[4], defines a unique orbit plane by requiring the spacecraft ground track to pass through a Vesta local solar time between 6 AM and 12 PM.

The last two parameters in Table 4 ensure that the target orbit is near circular without explicitly targeting eccentricity. Targeting eccentricity is more problematic since the osculating value can vary significantly over an orbit. The driving science requirement (Table 2) was that altitude variation during HAMO-2 be less than +/-30 km.

Table 4. Mystic HAMO-2 Science Orbit Targets.

Target Parameter	Value	Description
Epoch (ET)	5-Jun-2012 03:01	End of deterministic thrusting (end 10^{th} thrust sequence)
Spacecraft Orbit Unit Angular Momentum Vector: Right Ascension, Declination (EMO2000)	-98.1095˚, -17.3533˚	Target equivalent to orbit inclination=93.95˚, beta angle=37˚, +AM orbit orientation. Inclination provides desired beta angle rate of -0.18˚/d.
Spacecraft Orbit Period	12.3475 hours	Results in 10 rev repeat ground track at radius 951 km
Circular Orbit Velocity	0.1348 km/s	Circular orbit velocity at radius 951 km. Used in conjunction with constraint below to target low eccentricity orbit without explicitly targeting eccentricity. HAMO-2 altitude variation constrained to be <=+/-30 km
Angle Between Spacecraft Radius and Velocity Vector (wrt Vesta)	90˚	Used in combination with above circular orbit velocity target low eccentricity orbit

Using Mystic, an initial guess of the trajectory is created using an interactive GUI in a Matlab environment. The Mystic optimizer runs non-interactively. Run times varied from several hours to often overnight to produce a converged solution. Initial trajectories only had target constraints specified at the end of thrusting. However, such transfers optimized without any intermediate constraints failed to meet the 25 day eclipse avoidance constraint and also resulted in very poor powered flight stability indicating a lack of robustness to sources of uncertainty. Oftentimes, trajectories would have thrust directions too close to the Sun/anti-Sun line, which would likely make them quite difficult to implement by the ACS. Improving one selection criteria often degraded another. To address these problems, intermediate constraints, i.e., constraints at epochs between the start and end of thrusting, on such quantities as beta angle, orbital period, inclination, eccentricity, and 6-state (position and velocity) were placed at various epochs along the trajectory. In addition, by varying the initial guess thrust magnitude, the effect of varying the number of orbits about Vesta during the transfer was examined. Over 100 distinct trajectory candidates were created, optimized, and then evaluated according to the selection criteria listed in Table 2. Choice and placement of intermediate constraints was based on intuition built up mostly by trial and error. The most common variation between candidates was the number of revs about Vesta during the transfer.

Due to the myriad designs investigated, a detailed description is only provided for the final reference trajectory selected. An initial trajectory guess was constructed by applying a spiral out control law at all times when thrusting was possible but with reduced thrust magnitudes with respect to the maximum thrust achievable: 79% of maximum thrust magnitude for the first three thrust sequences and then 68% of maximum over the remaining thrust sequences. An intermediate constraint forcing beta angle to be 45˚ at the epoch just prior to the start of the third thrust sequence (10-May-2012) kept beta angle from decreasing drastically during the long coast between the second and third thrust sequences which enabled the trajectory to meet the 25 days eclipse avoidance requirement. This trajectory was optimized to hit the HAMO-2 targets listed in Table 4 and its stability was exceptionally good during the first week of the transfer, which was of paramount importance due to the proximity to the resonance region. However, stability dipped to unattractive levels 8 days into the transfer so the trajectory as a whole was not desirable. A new trajectory was created that attempted to retain the early stability of this previous case while improving downstream stability. To retain early stability, the intermediate beta angle constraint was replaced by a 6-state (position and velocity) constraint equal to the state at that epoch from the previous high stability case. The thrust vectors from the first 2 thrust sequences were left unmodified but the remaining thrust sequences were reinitialized using the spiral-out control law and a thrust magnitude 68% of the maximum achievable value.

This hybrid case was optimized to hit the HAMO-2 targets. Even though downstream position differences were less than 40 km from the prior case, downstream stability significantly improved while retaining the superior stability during the first week of the transfer (Figure 3). The red bars along the horizontal axis in the figure indicate required coasting periods during the reference trajectory – thrusting is permitted at all other epochs. Stability was not computed beyond 30 d, since by that time, the spacecraft altitude was high enough that stability was inherently high for all trajectories. The stability of ~4 days early in the trajectory near the resonance region was comparatively excellent since many candidates had stabilities between 1 and 3 days in this region. Recall for stability, it's the relative comparison of values that matters – not the stability value itself. Most of the candidates that passed through the 1:1 resonance region in the second thrust sequence had minimum stabilities well below 3 days in the critical early portion of the trajectory. Eventually, after applying a complex chain of intermediate constraints on inclination, beta angle, and eccentricity, one author was able to develop candidates that had comparable stability. However, thrust directions were about 10-15˚ closer to the Sun/anti-Sun line and were approaching the proximity at which ACS constraints might be difficult to satisfy during operational implementation. Therefore, even though resonance passage was preferred in the second thrust sequence over the third, the best case with passage in the third thrust sequence was selected as the reference trajectory since the better thrust directions increased robustness to ACS agility constraints, which was considered to be more valuable. As mentioned, the transfer architecture was also designed assuming the resonance passage would occur in the third thrust sequence. If a candidate that exited the keyhole region in the second sequence had been selected, the transfer architecture would likely have to have been revalidated.

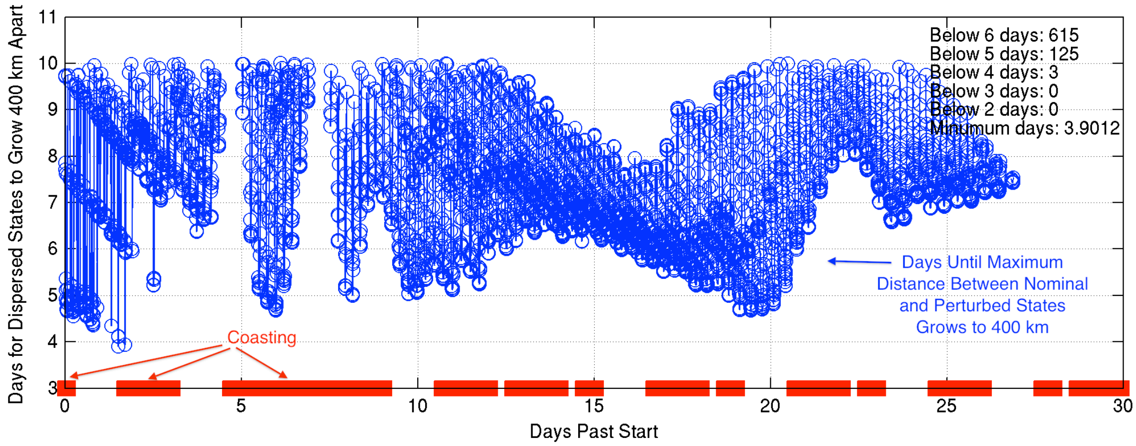

Figure 3. Reference Trajectory Powered Flight Stability.

Satisfaction of the eclipse constraint for the reference trajectory is demonstrated in Figure 4. The "hair plot", as it is referred to on the Dawn Project, was created by sampling states from the entire reference trajectory at small, constant time increments. Each 6-state sample was then ballistically propagated 25 days past the sample's epoch. No further thrusting was assumed simulating the scenario in which a spacecraft anomaly results in termination of thrusting for an extended period. The beta angle histories for each of these 25 day propagations are plotted in Figure 4 in blue if the spacecraft is free from eclipse and red if eclipse is encountered. No eclipses occurred.

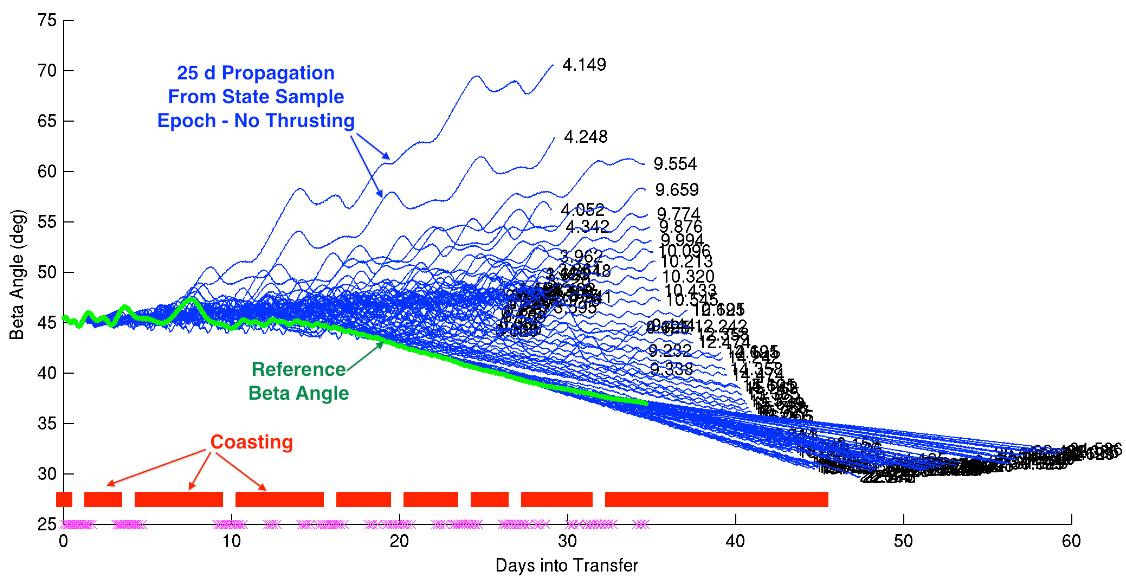

Figure 4. Reference Trajectory Eclipse Constraint.

The thrust directions with respect to the Sun line were excellent for the selected reference trajectory (Figure 5). Figure 5 displays the minimum angle between any thrust vector and the Sun/anti-Sun direction for each spacecraft rev about Vesta. Operational experience from prior transfers had shown that if this angle were greater than ~20˚, satisfying ACS agility constraints would be greatly simplified during operational implementation of the transfer.

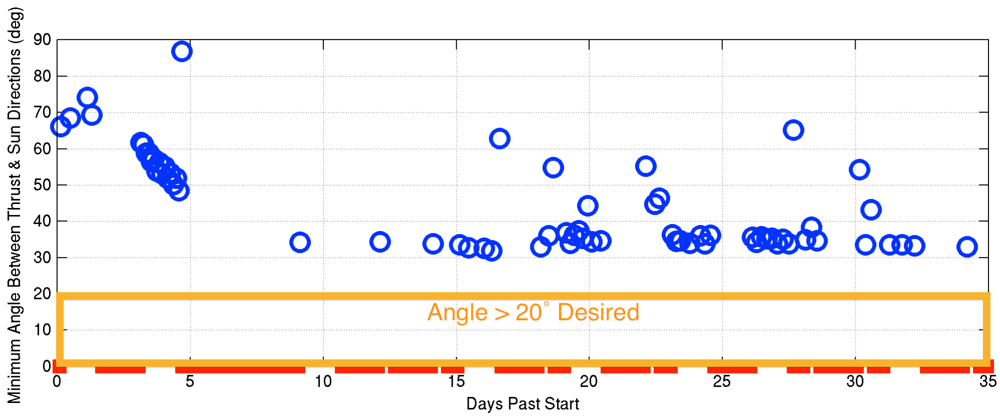

Figure 5. Reference Trajectory Thrust Direction With Respect To Sun/Anti-Sun Line.

REFERENCE TRAJECTORY CHARACTERISTICS

The 45.1-day reference LAMO to HAMO-2 transfer reference trajectory spanned from 1-May-2012 10:26 ET (start epoch in all figures unless otherwise noted) to 15-Jun-2012 13:26 ET. End of thrusting for the reference trajectory was 5-Jun-2012 03:01 ET (34.7 days past start). The transfer consisted of 12.3 days of thrusting, 28.6 days of required coasting, and 4.2 days of optimal coasting. The required coasting consisted of 10.0 days for ten MEPs, 6.0 days for two quiet periods, 1 day for the TCM, 6.6 days for multiple radiometric tracking and data playback passes via the DSN, and 5.0 days for a pointing update prior to entering HAMO-2 (Figure 2).

The trajectory is depicted in Figures 6 and 7. Thrust directions are included in Figure 7 to illustrate that considerable out-of-plane thrusting occurs during the transfer. Figure 8 depicts both radius and beta angle during the transfer. Thrusting periods are indicated in blue shading, coasting in red. Note the 6-state (position and velocity) constraint on the trajectory prior to the third thrust sequence preserved the excellent stability early on and constrained beta angle to 45˚ since that was the original form of the constraint. The spacecraft orbital period profile is depicted in Figure 9.

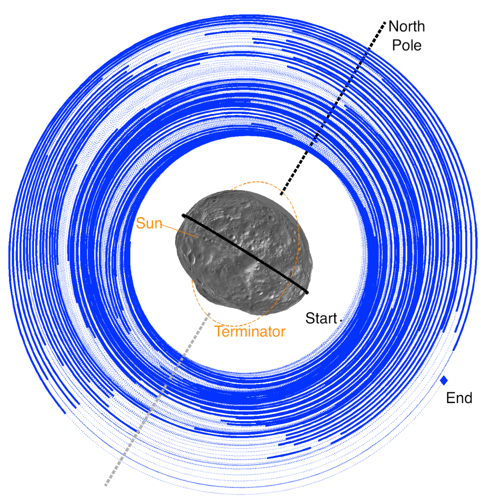

Figure 6. Trajectory View Face On (bold lines indicate thrusting, dotted lines coasting).

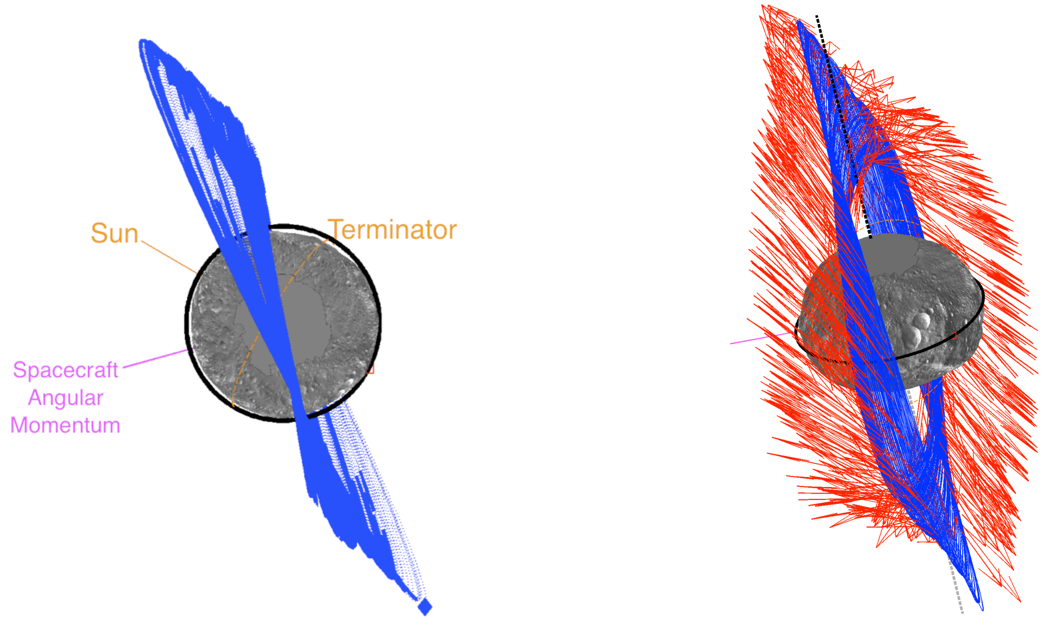

Figure 7. Trajectory View From Vesta North Pole (Left: bold lines indicate thrusting, dotted lines coasting) and Oblique (Right: red arrows indicate thrust direction).

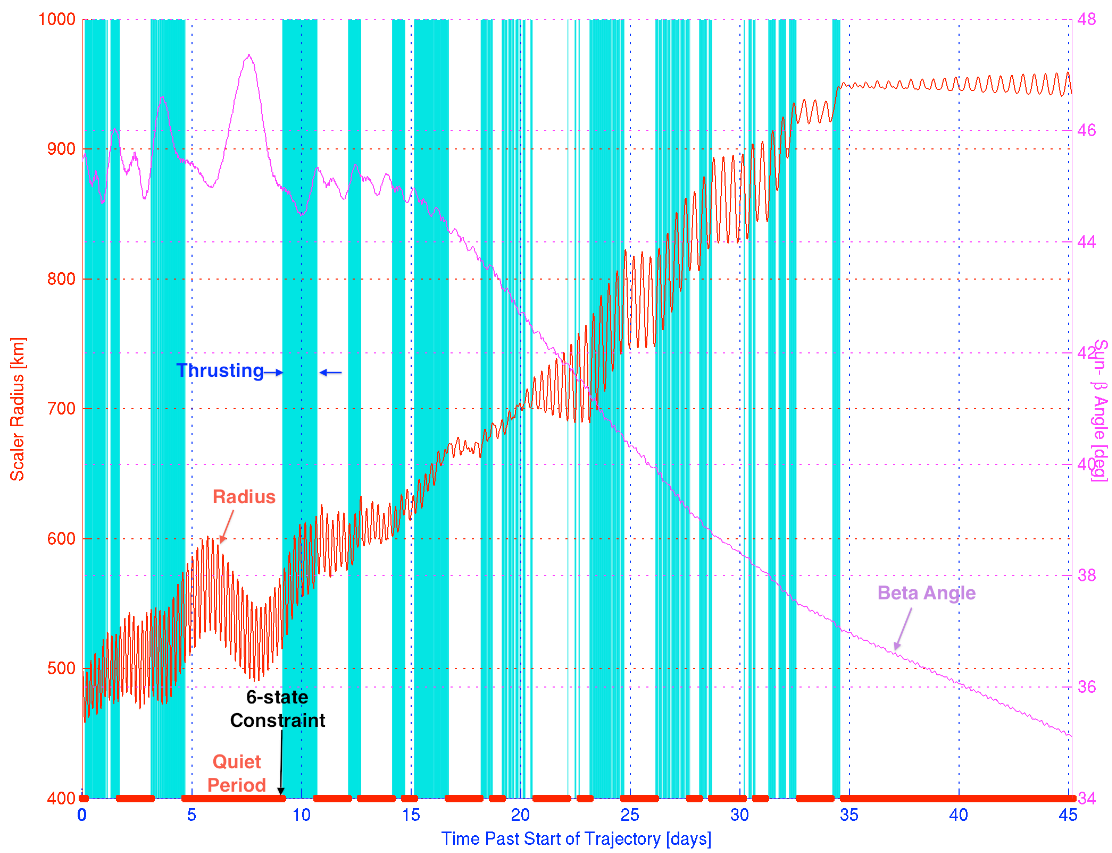

Figure 8. Radius and Beta Angle Profile.

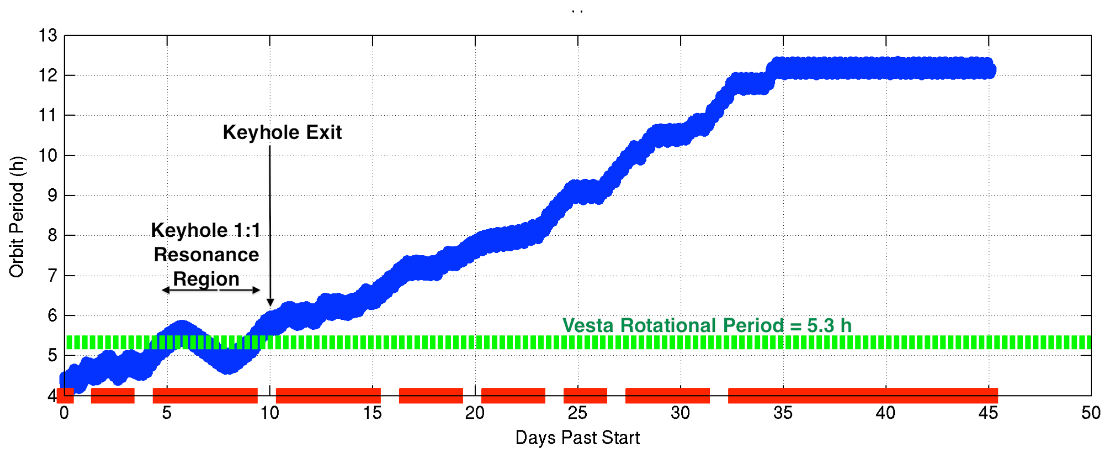

Figure 9. Orbit Period Profile.

Note that during the quiet period between the second and third thrust sequences, the radius and period (Figures 8 and 9) oscillate above and below Vesta's rotational period of 5.34 hours. During this time the spacecraft is in the keyhole 1:1 resonance region (dashed green line in Figure 9). These parameters would oscillate indefinitely if thrusting had not commenced in the third thrust sequence causing the spacecraft to exit the resonance. Past experience had shown attaining this sharp oscillation near the resonance resulted in stable trajectories with improved robustness to sources of uncertainty. Previous studies[4,5] had shown that such jagged, repeating "V-shaped" oscillations often provided powered flight stability near the keyhole and that the optimal strategy was to exit the resonance on the up (period increasing) portion of the oscillation. Figure 10 depicts the portion of the trajectory near the 1:1 resonance region. Stable trajectories have been found over different ranges of longitude so the ground track alone is not responsible for the excellent stability.

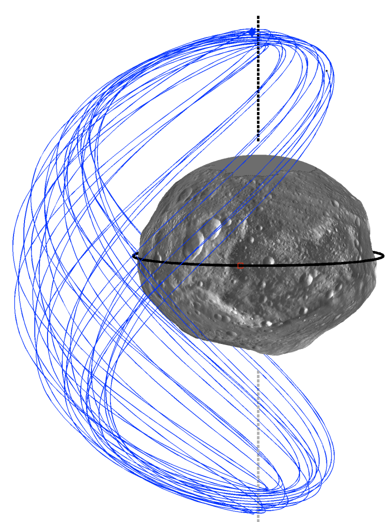

Figure 10. Vesta Body-Fixed Trajectory for Portion of Trajectory Near 1:1 Resonance.

Spacecraft inclination with respect to Vesta's equatorial plane is depicted in Figure 11. Note inclination also oscillates considerably near the resonance region. The spacecraft completes 139 revs about Vesta during the transfer (Figure 12). The ion engine used from 1.31 to 1.36 kW of power to produce thrust magnitudes from 46.8 to 50.6 mN (Figure 13). Thrust decreased during the transfer since the heliocentric range increased. The initial spacecraft mass was 948.8 kg and Xenon propellant mass flow rates varied from 1.8E-6 to 2.9E-6 kg/s resulting in a total propellant mass expenditure of 2.1 kg during the transfer. Most of the thrust was applied in the vicinity of the spacecraft Vesta relative velocity vector (Figure 14) but there was also considerable out of plane thrusting to change inclination and beta angle. Thrust vector directions in an inertial frame (Figure 15) are nearly great circle arcs (at most one complete arc per rev). These figures were quite helpful during the design stage since they display the minimum angle between thrust vectors and the Sun/anti-Sun direction. This angle was greater than 30˚ throughout the transfer, well above the threshold likely to trigger rapid "power steering flips".

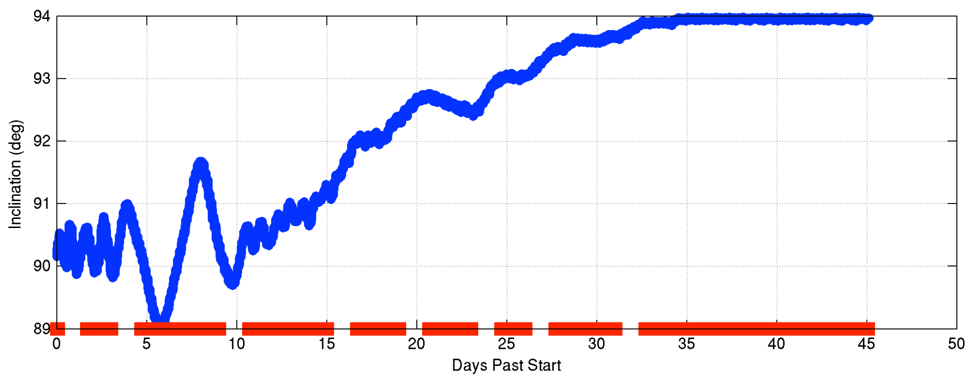

Figure 11. Inclination Profile.

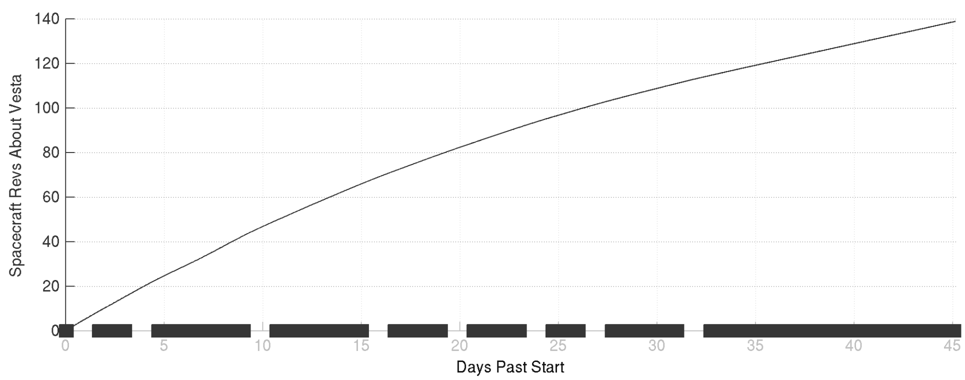

Figure 12. Spacecraft Revs About Vesta.

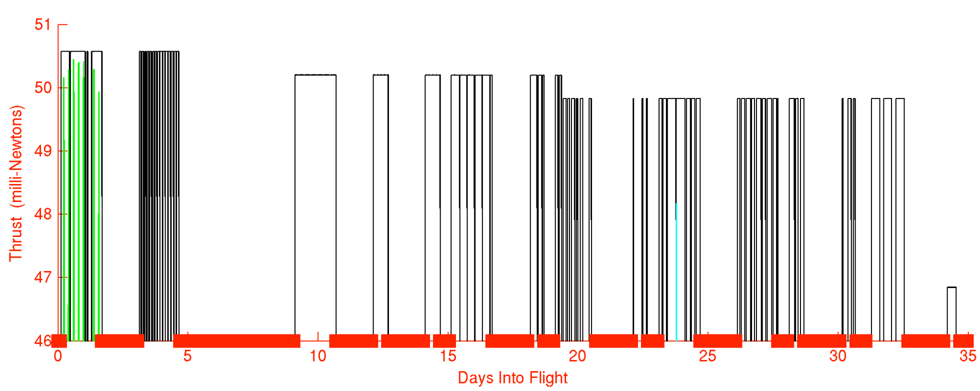

Figure 13. Thrust Magnitude Profile.

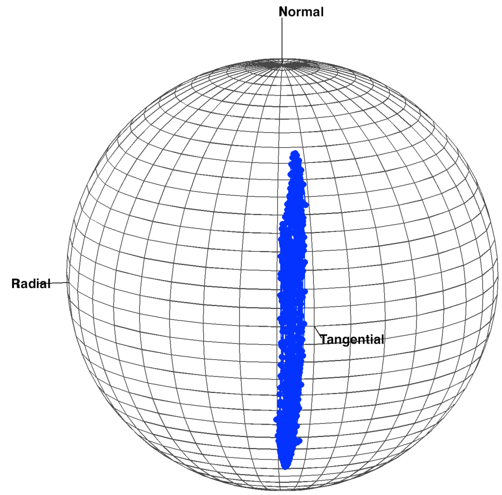

Figure 14. Thrust Direction In Radial, Tangential, Normal Frame.

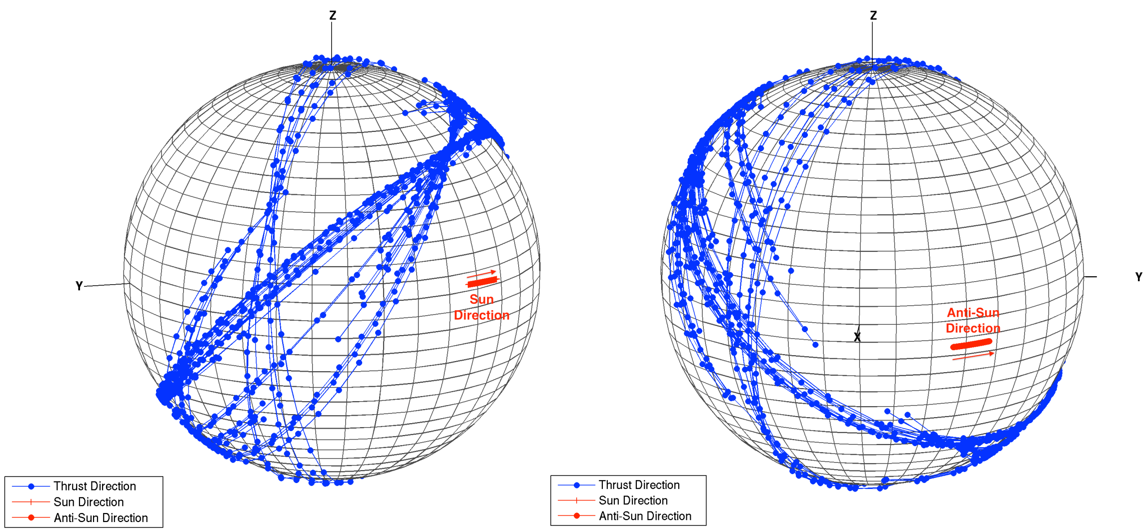

Figure 15. Thrust Direction In Inertial (EMO2000) Frame.

Figure 16 displays the initial margin against the spacecraft entering eclipse during the transfer. For Dawn, initial eclipse margin was given in terms of beta angle margin. At each point along the reference trajectory, the 6-state is sampled and the beta angle computed which results in the orbit just entering eclipse. This beta angle is compared against the nominal beta angle profile to compute the beta angle margin. Figure 15 does not address the requirement that the spacecraft remain eclipse free for 25 days – see Figure 4 instead.

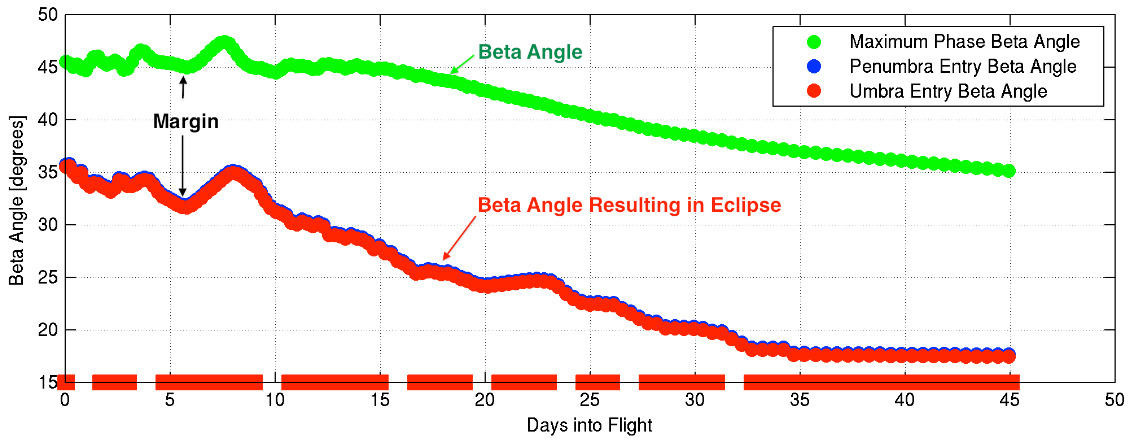

Figure 16. Initial Eclipse Margin in Terms of Beta Angle Margin.

All of the HAMO-2 science requirements (Tables 2 and 4) were met. The 10-rev repeat ground track for all 6 cycles is shown in Figure 17. One cycle is ~5.1 day since orbit period is ~12.3 hours. The small spread in ground tracks is due to non-zero eccentricity and was acceptable to science. The radius during HAMO-2 varied by +/-31 km (Figure 18), which though slightly above the +/-30 km requirement, was quite acceptable to science. Orbit eccentricity remained less than 0.045 throughout.

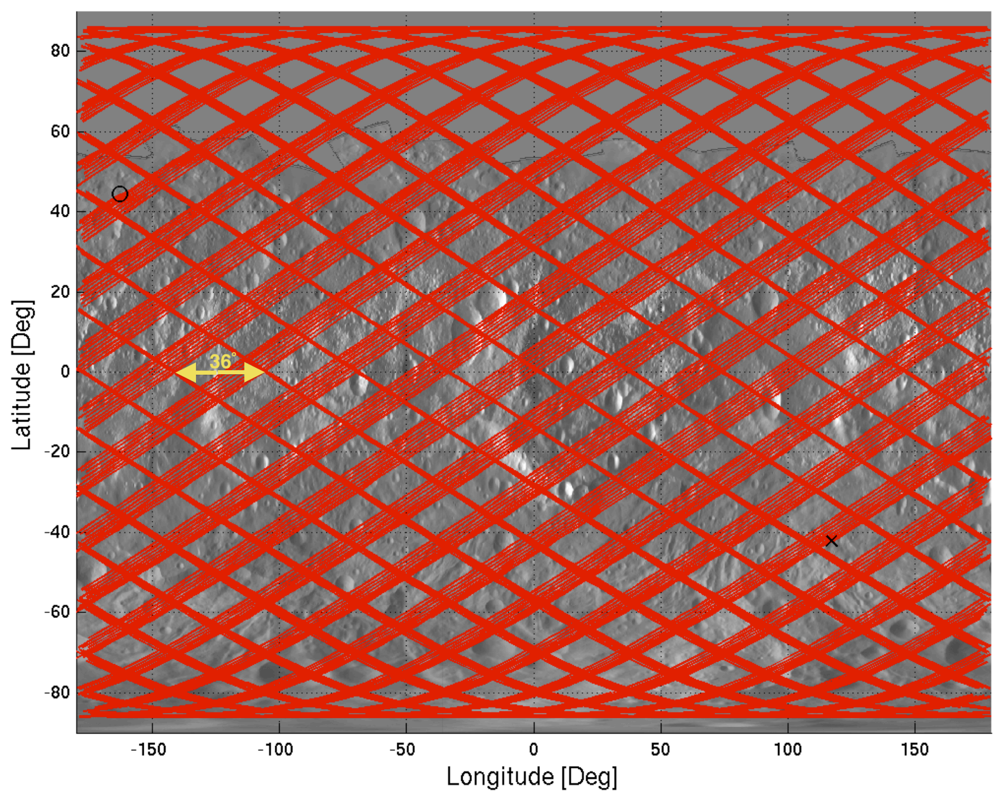

Figure 17. HAMO-2 10-Rev Repeat Ground Track (6 repeat cycles).

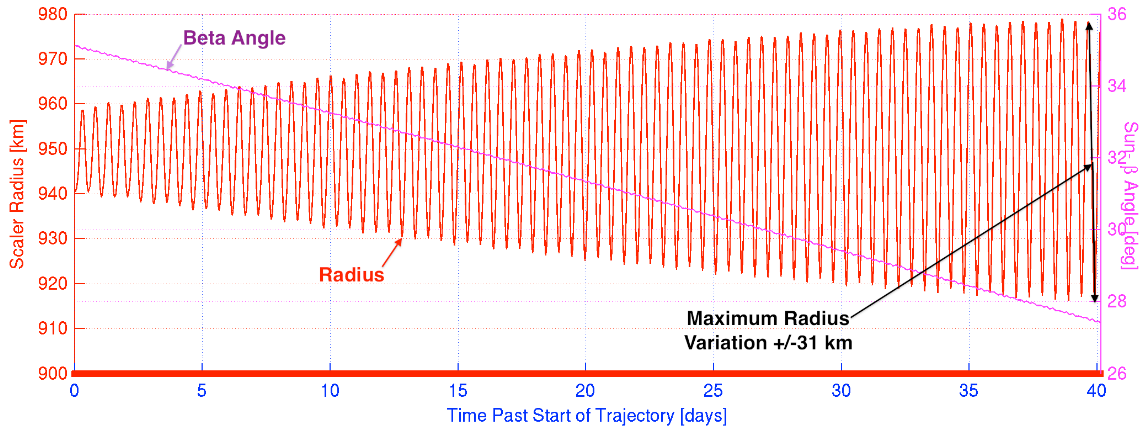

Figure 18. HAMO-2 Radius Variation.

CONCLUSIONS

Design of the LAMO to HAMO-2 reference trajectory was a complex and time-intensive task that was the culmination of many stages of prior design work. Many potential candidates were developed and it is likely than several of the top candidates could have been implemented successfully. Design process intuition was difficult to develop due to the non-linear nature of stability and low-thrust trajectory design. Independent development efforts by the three authors provided a wider diversity of candidates enabling selection of a robust and operationally implementable reference trajectory. The reference trajectory was successfully implemented and flown in May and June of 2012[7,8,9,13]. Science acquisition during HAMO-2 was highly successful wetting appetites for the upcoming Ceres encounter in 2015.

ACKNOWLEDGEMENTS

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