Orbit Transfers for Dawn's Vesta Operations: Navigation and Mission Design Experience

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Abstract: *Dawn, a mission belonging to NASA's Discovery Program, was launched on September 27, 2007 to explore main belt asteroids in order to yield insights into important questions about the formation and evolution of the solar system. From July of 2011 to August of 2012, the Dawn spacecraft successfully returned valuable science data, collected during the four planned mapping orbits at its first target asteroid, Vesta. Each mapping orbit was designed to enable a different set of scientific observations. Such a mission would have been impossible without the low thrust ion propulsion system (IPS). Maneuvering a spacecraft using only the IPS for the transfers between the mapping orbits posed many technical challenges to Dawn's flight team at NASA's Jet Propulsion Laboratory. Each transfer needs a robust plan that accounts for uncertainties in maneuver execution, orbit determination, and physical characteristics of Vesta. This paper discusses the mission design and navigational experience during Dawn's Vesta operations. Topics include requirements and constraints from Dawn's science and spacecraft teams, orbit determination and maneuver design and building process for transfers, developing timelines for thrust sequence build cycles, and the process of scheduling very demanding coverage with ground antennae at NASA's Deep Space Network.*

Keywords: *Dawn, Vesta, Navigation, Ion Propulsion system, Low Thrust, Small Body*

1. Introduction

Dawn is the ninth project in the National Aeronautics and Space Administration's (NASA's) Discovery Program. Dawn's main mission goal is to yield a significant increase in the understanding of the conditions and processes acting at the solar system's earliest epoch by examining the geophysical properties of the two most massive and yet complementary bodies, Ceres and Vesta. The scientific investigations will use panchromatic and multispectral imagery, and gravimetry collected while conducting science orbits around Vesta and Ceres [1]. Dawn is the first mission to orbit a main belt asteroid and by mission completion, it will be the first spacecraft to orbit two extraterrestrial planetary bodies.

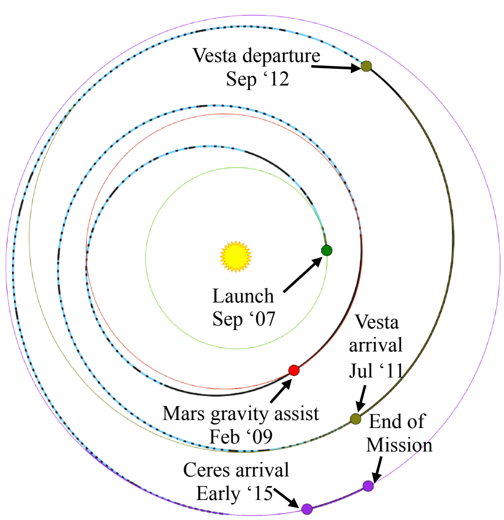

Figure 1. Dawn's interplanetary trajectory

The Dawn spacecraft was launched on September 27, 2007 by a Delta II heavy rocket and began its 8 years long journey. After a Mars gravity assist in February 2009, Dawn arrived at Vesta in July 2011. In Fig. 1, Dawn's interplanetary trajectory is depicted. The trajectory is colored in blue, when thrusting, and in black, while coasting. For fourteen months before leaving Vesta in September 2012, the flight team at the Jet Propulsion Laboratory performed many complex operations and assisted the science team to successfully fulfill all of the objectives at Vesta.

Dawn's mission requires uniquely high post launch delta-V to achieve the mission goals. This requirement is met by using the low thrust solar electric propulsion technology. Previously flown deep space missions, including NASA's Deep Space 1 (DS1), ESA's SMART-1, and JAXA's Hayabusa, have successfully used and demonstrated the effectiveness of this type of propulsion system. With specific impulse much greater than chemical propulsion, the Ion Propulsion System (IPS) provides a mission opportunity that would be too costly with chemically propelled spacecraft. Dawn's IPS design and operations were mostly influenced by the experiences from DS1 mission.

The IPS was used for all nominal post-launch trajectory control, including interplanetary cruise, Mars flyby, asteroid rendezvous and departure, and all orbit corrections and transfers at the asteroids. Maneuvering a spacecraft only using the IPS for the transfers between the mapping orbits posed many technical challenges to Dawn's flight team. Each transfer requires a robust plan that accounts for uncertainties in maneuver execution, orbit determination, and physical characteristics of Vesta. This plan must satisfy the requirements of the target science orbit and spacecraft safety, and it also needs to include margin to accommodate unforeseen anomalies. The plan also must be compatible with the spacecraft capabilities and supportable by the small operations team limited in size by funding. Propulsion by IPS added complexity in orbit transfers much more than missions using chemical propulsion system, and required very different approach in mission design and navigation.

The use of an IPS dictates some fundamental differences from missions that rely on conventional chemical propulsion. Dawn's transfer phases take several weeks of time encompassing many orbits around Vesta and cannot be flown open-loop in one design. Each transfer is broken into several sequences to ensure controllability. The durations of individual thrust sequence vary from one month long during the early approach phase to a short two days in transfer to and from the low altitude mapping orbit. For each sequence, the time-dependent optimal thrust direction and magnitude of the next sequence are updated using renewed spacecraft states and characteristics of Vesta.

Dawn's transfer orbits are mostly filled with powered flight but strategically designed coasting periods are also inserted. These coasting periods are for obtaining tracking data for orbit determination, downloading spacecraft engineering data, and uploading the sequence of commands to the spacecraft using the ground antennae at NASA's Deep Space Network (DSN). The coasting periods dictate the ground operational process cycle of building sequences of commands to be executed by the on-board computer. While the maneuver designs are performed during the sequence building cycles, coasting period placement has to be decided well in advance to meet the DSN's planning schedule and to build the flight team's work schedule. The transfer timeline needs to be completed roughly two months in advance and must be robust to mission design uncertainties and last minute changes in DSN station availability. Human factors also need to be considered in this process by minimizing non-prime-shift work to lessen the flight team's fatigue and stress during the yearlong operation at Vesta.

The following sections will address details of the spacecraft, mission requirements, planning, and operational results of Vesta operations.

2. Spacecraft & Payload

Built by Orbital Science Corporation [2], the Dawn spacecraft is designed to maximize the power available to the IPS in order to meet the very demanding delta-V requirements. One dominant feature of Dawn spacecraft is the large solar arrays, which extends to a length of 20 meters. When the spacecraft is at Ceres at a heliocentric range of 3 AU, the electrical power system on board has to provide sufficient power to operate the IPS. Dawn's two large solar arrays are designed to provide 10.3 kW at 1 AU and 1.3 kW at their end of life at 3 AU.

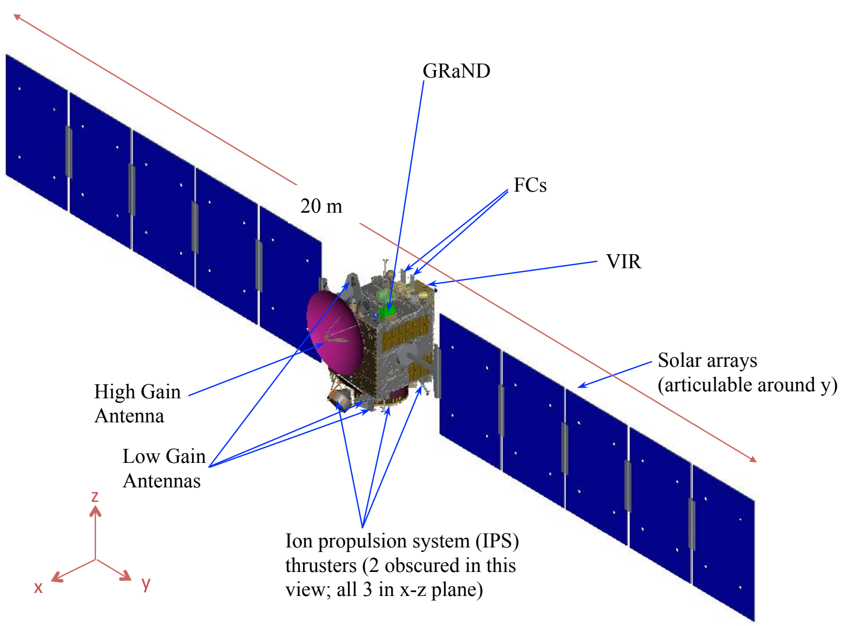

Figure 2. Dawn Spacecraft

Dawn's IPS is an expanded version of the system used on DS1. With 425 kg of Xe gas, the system is capable of providing 12 km/sec delta-V for the mission. To add reliability, the spacecraft is carrying three ion thrusters, although only one thruster is operated at a time. All three thrusters are aligned in the spacecraft xz plane with the center thruster facing –z direction and the other two are canted 48 degrees from z towards the x-axis. Each thruster is mounted to a two-axis gimbal and has thrust vector control (TVC) to maintain attitude about the two axes perpendicular to the thrust vector. This low thrust engine can produce maximum thrust of 91 mN at peak power and 19 mN at the lowest input power of 0.5 kW. The specific impulse ranges from 3200 to 1900 seconds. Throttle level of Dawn's IPS is commanded by selecting a mission level ranging from 0 to 111, with other parameters being looked up from an on-board throttle table.

The Attitude Control System (ACS) has three different actuator systems: four reaction wheel assemblies (RWAs), twelve 0.9 N hydrazine thrusters, and three gimbaled IPS thrusters. RWAs are the primary actuator for attitude control when not using IPS. When used during IPS thrust, the wheels provide control about the thrust vector, with TVC providing control perpendicular to the thrust line. 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. Since not all of the hydrazine thrusters are coupled, every time the uncoupled thrusters are fired a small delta-V is imparted to the spacecraft.

To acquire scientific data, Dawn's payload consists of three instruments. The Framing Camera (FC), donated by Germany, acquired images for topography and also provided images for optical navigation. The Visible and Infrared (VIR) mapping spectrometer, donated by Italy, collected data to address the surface mineralogy questions. The Gamma Ray and Neutron Detector (GRaND) developed by Los Alamos National Laboratory collected data to find the elemental composition of the asteroid. In addition, gravimetric data were measured by 2-way Doppler data between the spacecraft and DSN antennae. All three instruments are mounted toward spacecraft +z direction. A simple description of Dawn spacecraft is show in Fig. 2.

3. Requirements and Constraints

Programmatic constraint:
The Discovery Program places strict limits on the total lifecycle cost of the mission. This programmatic requirement defines the date that Dawn must arrive at Ceres to complete the mission at its second target, which in turn defines the date that Dawn has to leave Vesta for a long cruise to Ceres.

Eclipse constraint:
The Dawn spacecraft was never qualified for eclipses, which restricts the operations from any eclipses. This constraint was motivated by pre-launch cost-savings and has been strictly applied to all mission phases. The orbits and all spiral transfers between science orbits are designed so that even if control is lost for as long as 28 days at any time during the transfer, the flight system will remain safe from the eclipse.

Geometric constraint for instruments and thrusters:
As is common to most spacecraft, a set of instrument pointing restrictions relative to the Sun direction was given. A similar set of constraints was applied for all three IPS thrusters to avoid Sunlight directly reaching the core of the thruster while the thruster is operating. Although the Dawn spacecraft is a 3-axis controlled spacecraft, its onboard attitude commanding algorithm, called "power steering", only permits the operator to command one axis of orientation by specifying a single aiming vector and a corresponding target vector. The remaining axes are determined by power steering algorithm. While IPS thrusting, the one commanded thrust vector fully defines the spacecraft attitude and it is the navigation team's responsibility to ensure the spacecraft attitude, controlled by the designed thrust vector, does not endanger the spacecraft. Dawn's geometric constraints and ACS power steering algorithm are described in Reference [3].

ACS agility constraint:
Like any 3-axis controlled spacecraft, Dawn's ACS has dynamic constraints on attitude rate and angular acceleration. While thrusting with the IPS, the designed thrust direction dictates the spacecraft attitude via the power steering algorithm; hence it is the navigation team's

responsibility to design thrust profiles that avoid these dynamic constraints. Also, Dawn must avoid pointing the thrust direction near the sun to avoid a kinematic singularity in solar array pointing. When the designed thrust vector passes through or near the Sun direction or anti-Sun direction, the always-active power steering will flip the spacecraft attitude by rotating nearly 180 degrees around the spacecraft z axis. This so-called "power steering flip-over" may violate the ACS agility constraints and must be avoided. Further discussions on this constraint are documented by Smith [4].

Science orbit requirement

The science observations were concentrated in four campaigns at Vesta, each conducted in a different circular, near-polar orbit. These campaigns, designated Survey, High Altitude Mapping Orbit (HAMO), Low Altitude Mapping Orbit (LAMO), and High Altitude Mapping Orbit 2 (HAMO-2) are depicted in Fig. 3. In addition to the four science orbit phases, valuable science observations were made in two more targeted science orbits: the rotational characterizations before and after the four major science orbits. Dawn's operational experiences at all science phases are described in detail by Rayman [5].

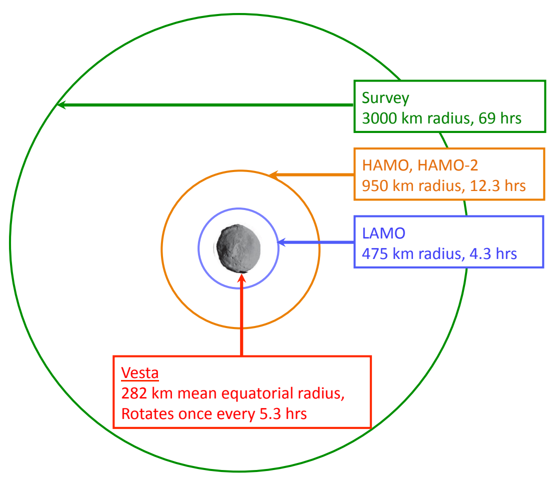

Figure 3. Vesta Orbits

The four major science orbit phases were chosen to allow global coverage at a desired spatial resolution. The main objectives in science orbits are: to obtain global spectral mapping of the lit surface with VIR in Survey, to obtain global imaging of the lit surface with FC in HAMO and HAMO-2, and to map the gravity field and elemental composition of Vesta in LAMO. Table 1, from reference [6], provides desired characteristics of these science orbits.

The target radii were specified to achieve the required spatial resolution, and the radius variation represents both a design requirement and a control requirement. The orbit planes are selected to provide good illumination for FC and VIR observations while allowing the flight system to avoid eclipses. The angle between the orbit plane and the Vesta-Sun line (the "beta angle") is used to define desired orbit planes in the requirements. Polar orbit inclination is designed to allow observation of the entire body, and the observing footprints of the instruments allow the variation. The target inclination represents both a design and a control requirement. Minimum orbit period is defined to allow sufficient time for data downlink. Ground track spacing is an important attribute that allows Dawn to map the surface in the most efficient manner with a given instrument at a given altitude. The terminator crossing time uncertainties are control requirements to ensure the download of the science data and represent the tolerance between predicted orbit, used in building science sequence, and the actual orbit.

Table 1. Vesta Science Orbit Requirements

	Survey	HAMO	LAMO	HAMO-2
Objective	Obtain VIR coverage with global distribution	Obtain FC global coverage at nadir and 3 off-nadir angles, obtain as much VIR coverage as possible	Obtain GRaND and gravity coverage with ideally spaced tracks covering the body at roughly 25 km spacing at equator	Obtain FC global coverage at nadir and 2 off-nadir angles north of 58°
Implementation Strategy	Six orbits (repeating ground tracks OK but not required)	Cyclic coverage with ground tracks covering the body in ten orbits	Achieve global coverage in ~60 days	Same as HAMO
Target Radius	3000 km (spatial resolution)	950 km (spatial resolution). Achieve desired ground track walk within envelope of 925−975 km (60−65 m FC resolution)	475 km (spatial resolution)	Same as HAMO
Target Beta Angle	10°	30°	45° (as low as possible)	≤ 45°
Allowed Beta Range	≤ 15°	25° − 35°	≤ 60°	35° − 47°
Target Inclination	85° − 95°	85° − 95°	85° − 95°	Same as HAMO
Minimum Orbit Period	64 hours	12.0 hours	None	12.0 hours
Ground Track Walk	No requirement	Cyclic coverage with ground track spacing of 36 (full body coverage in ten orbits); maximum equatorial spacing of 42° over one cycle	Achieve global coverage with a maximum equatorial ground track spacing of 6° after sixty days	Same as HAMO
Absolute Timing (target Phasing)	None	None	None	None
Dark to Lit terminator crossing time uncertainty	±45 minutes	±10 minutes	±10 minutes	Same as HAMO

4. Mission Planning

Mission Timeline Development

One special feature of IPS propelled mission is the flexibility in mission design. Interplanetary cruise design is more dependent upon the performance of IPS and power available to it rather than celestial mechanics. This feature made it possible for the Dawn project to complete the Vesta mission timeline well after launch. The detailed timeline for Vesta operations has been developed for more than two years prior to arriving at Vesta and has been continuously refined as the spacecraft moves from one phase to next.

The highest-level requirement affecting the mission timeline is the programmatic restriction on mission duration. Dawn needs to arrive at Ceres by February 2015 to fulfill the mission at its second target. With the best-predicted IPS performance and available power, the mission design team calculated the day by which Dawn had to leave Vesta. During the interplanetary cruise to Vesta, the mission design team updated monthly the time optimal solution to Vesta and revised the arrival date.

Once the beginning and ending dates were defined, the Vesta mission was divided into sub phases. The four science orbits were selected meeting science orbit requirements in Table 1. Once the duration of science orbits were known, the next step was to calculate the time required for the transfers between science orbits. In early design stages, the transfer orbits were designed with a predicted average value of duty cycle, where a duty cycle is the ratio of thrusting to the total length of the arc. Next, a total of 40 days of operational margin was reserved for anomalous situations. Finally, all remaining time at Vesta was allocated to LAMO phase. Activities at LAMO were easily repeatable, and GRaND and gravity science return significantly increased with longer stay at LAMO.

After the durations of all sub phases were defined, the navigation team developed detailed architectures of the transfers. Transfers between science orbits are very complex. Part of the complexity is to ensure the intermediate orbits are safe, even in the event of a loss of spacecraft control for several weeks. Also, the transfer is sensitive to the details of the gravity field, which was unknown at the time of architecture design. The primary objective of the transfer architecture was to generate a plan that is safe and fast. Given finite time available at Vesta, minimum time in transfers will provide maximum time for acquiring science data.

The transfer architecture consists of several design cycles, where each design cycle is controlled by an updated sequence of attitude and thrust commands during the operations. The process of developing the transfer architecture will be further described in later mission design section. Upon completion of architecture design, the mission timeline was updated reflecting the adjusted time for transfers.

Sequence build timeline for transfer

All spacecraft activities are controlled by a sequence of commands built by the flight team and uploaded via DSN antenna. During Vesta operations, Dawn was controlled by two different types of sequences. The background sequence, typically spanning 2 to 4 weeks, contains commands for all spacecraft and science instruments. In the background sequence, blocks of thrusting times were left blank to be later filled by thrust sequences. The begin and end times of these blocks needed to be defined by the mission design team prior to the background sequence build process.

Delivering the thrust profile for the transfer sequence build was the ultimate responsibility of the navigation team. Since updating the thrust sequence includes updating the maneuver design, more frequent updates and shorter thrust sequences result in more accurate navigation to the targeted science orbits. However, requiring the small flight team to perform frequent sequence builds for 14 months of Vesta operations would certainly overburden the crew and may result in undesirable mistakes during operations. Careful balancing between navigational accuracy and ground crews workload was an important part of the transfer designs.

Unlike the background sequences that typically take 2 to 4 weeks to build, thrust sequence builds require faster turnaround for accurate maneuvers. In many cases, the spacecraft continued thrusting while the thrust sequence was being built. Therefore, the longer the thrust sequence build process takes, the less accurate spacecraft state prediction becomes and delivery error by the next thrust cycle will increase. Three different types of thrust sequence building timelines were used for Vesta transfers. In the approach phase, while delivery errors were more tolerable and recoverable by subsequent thrusting, thrust sequences were built in 4 weeks or in one week. For the majority of the thrust sequences during Vesta operations, a 3-day-long build timeline was adopted. On four occasions, when precise path control is required, not only for accurate delivery but also to ensure spacecraft safety, thrust sequences were built in only 36 hours. In table 2, the number of thrust sequences, coverage duration and building timeline per thrust sequence is summarized.

Table 2. Summary of transfer sequences

Transfer (#of thruster sequences)	Thrust Sequence (duration/build timeline)
Approach (5)	28d/28d, 28d/28d, 14d/7d, 14d/7d, 7d/7d
Survey to HAMO (4)	7d/3d, 7d/3d, 7d/3d, 7d/3d
HAMO to LAMO (10)	6d/3d, 4d/3d, 4d/3d, 3d/3d, 4.5d/3d, 4.5d/3d, 4d/36hr, 3d/3d, 5d/3d, 3d/36hr
LAMO to HAMO-2 (11)	3d/3d, 6d/3d, 3d/3d, 2d/3d, 4d/36hr, 4d/3d, 4d/3d, 4d/3d, 4d/36hr, 4d/3d, 2d/3d
Departure (3)	8d/5d, 17d/3d, 24d/3d

Building a thrust sequence begins with the tracking data cut off and ends with the sequence upload to the spacecraft. In the baseline 3-day building process, the schedule allows the flight team to complete their assigned work during the prime shift in nominal cases. The night shift is left as margin for any contingency situations and allocated to maneuver design process and ACS process. This operational margin disappears in the short 36-hour build cycle where work during the night shift is unavoidable. The two sequence building processes are depicted in Fig. 4.

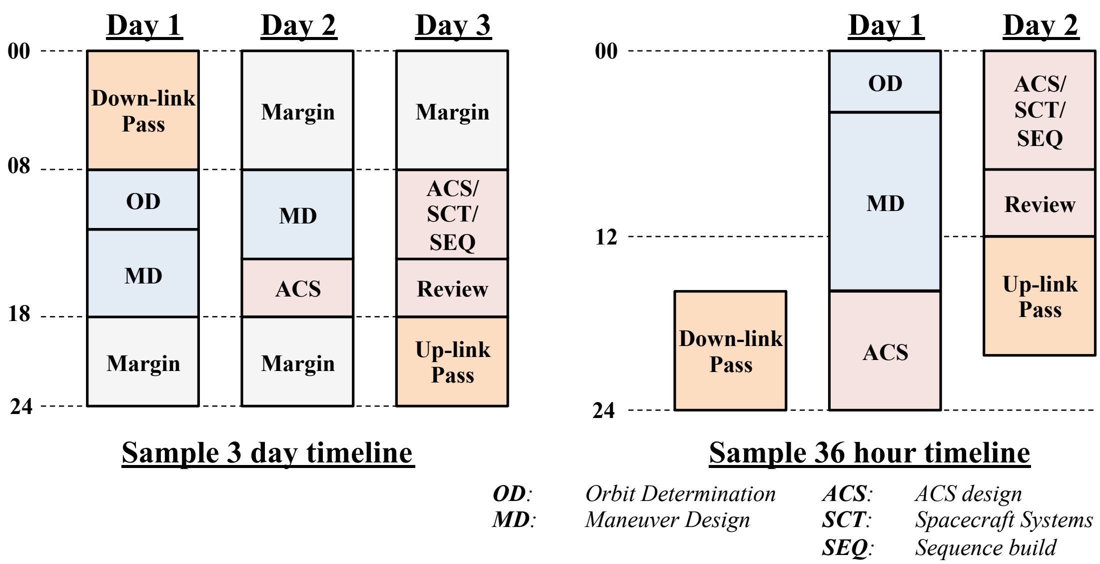

Figure 4. Thrust Sequence Build Timelines

Aligning the sequence build cycle on top of the refined transfer timeline makes the detailed schedule for the flight team. Before releasing the final work schedule, one more adjustment was made to minimize the non-working day shifts. At the time of background sequence build, several options with different transfer start days were reviewed. The option with the least weekend work was a clear choice, if available. If working on weekends and holidays was unavoidable, the option minimizing the number of engineers required for non-working day shift was chosen.

DSN scheduling

Scheduling DSN antenna time is highly correlated with the thrust sequence build process. Since the exact times for thrusting and coasting during the transfer phases are not known until much closer to the event the conventional strategy of identifying required DSN schedule a month ahead or even earlier was not possible for Dawn. Dawn levied a requirement to the DSN schedule team to reserve continuous coverage for the entire Vesta operational period. This was not because Dawn would require contacts to the spacecraft continuously, but because it was impossible to identify the necessary antenna schedule in time for DSN scheduling process requires. This approach is very rare for missions flown by JPL. In consideration to other missions sharing DSN antenna services, Dawn developed a strategy to release the unnecessary tracks as soon as they were identified. At the beginning of the background sequence building process, usually 4 to 5 weeks ahead of sequence execution time, ground tracks were confirmed in near continuous coverage. Using the thrust on/off times provided during the background sequence build, the first cut from the continuous coverage was made. In this process, none of the tracks covering coasting periods and statistical maneuver time blocks were released. The second set of release was made at the thrust sequence build process when the navigation team finalized the actual thrust times to be commanded. Since this release was made only a few days ahead of schedule, some tracks were not picked up by other projects, but many of the released tracks were transferred to other missions. During the process of timeline development, DSN antenna's view periods toward Dawn were not considered. As a result, many of Dawn's tracking passes were covered by several different antennae and often had short coverage gaps, arising from DSN's complex to complex hand over.

5. Orbit Determination (OD)

The key contributions by the OD team in support for Vesta transfer can be grouped as follows: pre-Vesta covariance studies for transfer architecture design, pre-transfer phase gravity field determination for the transfer reference orbit design, and estimation of the latest Dawn and Vesta parameters for each thrust sequence build.

Before arriving at Vesta, the Dawn navigation team performed many studies to identify transfer architectures that would reliably delivery Dawn to each successive science orbit as further described in the following section. To support these studies, the Dawn OD team was tasked with providing full knowledge covariance matrices for every potential design epoch. Each covariance matrix included uncertainties and full correlations between Dawn's Vesta-centered state, the Vesta pole parameters and the Vesta gravity field. In addition to the knowledge covariance, the OD team also provided an injection covariance that was used to seed each sample of the mission design team's Monte-Carlo runs, as described in following section. The knowledge covariances are based on improvements in the knowledge from using the simulated radio and optical observations taken in flight, and assumed *a priori* uncertainty was based on knowledge from the previous phase. For the approach phase, Vesta pole and gravity knowledge were from a study of the Hubble Space Telescope (HST) imagery and shape models derived from that imagery.

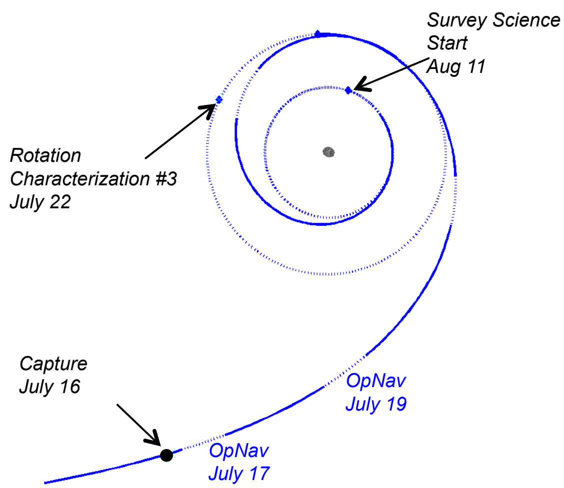

Figure 5. Vesta approach phase

The Vesta approach mission phase spans 100 days prior to the Survey orbit insertion, during which time the range to Vesta decreased from 1.2 million km to 3000 km. Later part of the approach phase is shown in Fig. 5. One key task by the OD team in this phase was estimating the first important Vesta parameter, its rotation axis. In addition to radiometric tracking data, optical image data of Vesta were collected in 23 separate sessions. Among the imaging sessions for optical navigation, the Rotational Characterization imaging events, during which Vesta is observed over a full rotation period, were of particular importance for Vesta's pole estimation. Prior to Dawn's arrival, the pole was only known to about ±8° from HST data, which was not precise enough for the desired science orbit targeting. Optical navigation imaging allowed the pole knowledge to improve enough to keep up with the ongoing targeting to the science orbits. Vesta's pole estimation was a key input to revising the Survey reference orbit and building the last two thrust sequences before Survey insertion. More details on Dawn's optical navigation at Vesta are documented by Mastrodemos [7].

Estimation of Vesta's gravity field began in early approach phase and continued until the spacecraft reached LAMO. The order of estimated spherical harmonic terms increased as the spacecraft spiraled down lower to Vesta. Up to 4th order terms were estimated in Survey, 8th order during HAMO, and up to 15th order terms were detectable by the time the spacecraft arrived at LAMO. The OD team continued estimating gravity fields during the long non-thrusting periods of each transfer phase.

Based on a covariance study, in the Survey orbit, reliable estimation of up to 4^{th} order gravity field was necessary to build the reference transfer orbit to HAMO. A stringent HAMO ground track requirement drove the need to have high confidence in the Survey-level gravity field knowledge. In order to achieve the necessary accuracy in the 4th order gravity field, it was found that additional data and processing time were necessary compared to the original plan. Therefore, an additional orbit was added at the Survey altitude, before the detailed operational plan was set.

Another big effort by the OD team in updating Vesta's gravity field was made during the HAMO phase. A revised gravity field, estimated up to the 8^{th} order harmonics using Doppler data at HAMO, was provided to the mission design team. This was essential for the mission design team to find a stable LAMO orbit and to design the challenging transfer reference trajectory to LAMO.

During transfer phases, the OD team provided state information to the maneuver design team. State information included magnitude modeling for the thrust, any improvements in gravity and pole estimation, and the predicted Vesta-relative state of Dawn at the start of thrusting. Due to the low thrust provided by IPS, Dawn's thrusting duty cycle is very high. Also, Dawn could not be tracked while thrusting because the on-board transmitter had to be turned off to maximize the power to IPS. As a result, the OD team had a very limited amount of radiometric and optical data to estimate a few days long thrust arc. During the orbit transfers, the coast periods were typically 8 hours long. Of these, only 6 hours or less were available for Doppler and ranging data, and the rest were comprised of turns between the IPS thrusting attitude and pointing the HGA to Earth. As a result, most of the IPS thrusting activities were not tracked and OD reconstruction was heavily dependent upon engineering data recorded and downlinked during these infrequent tracking passes. Processing these telemetry data was automated to support the very short time allowed for the OD process.

At Vesta, Dawn's distance from the Sun allowed the IPS to be operated between mission levels 89 (~76 mN thrust) and 45 (~46 mN thrust). Accurate estimation of IPS thruster performance is a key factor for reducing the delivery error for the next maneuver design cycle. IPS thruster performance was calibrated during the early check out period near 1 AU and once more shortly before the Vesta approach. IPS activities were modeled as one finite burn with time varying thrust level changes and estimated with 0.25% *a priori* uncertainty for the magnitude. The estimated performance is passed to the mission design team as a scale factor relative to the previously calibrated thrust magnitude.

6. Mission Design

All of Dawn's trajectories and maneuver designs were performed with an in-house software toolset called Mystic [8]. Mystic was built to compute, analyze, and visualize optimal high fidelity, low thrust trajectories. Detailed mission design for the Vesta orbit transfers began before Dawn left the Earth and continued until Dawn was orbiting at LAMO. None of the pre-existing statistical maneuver analysis tools that rely on linearly mapping a state transition matrix were adequate for studying Dawn's highly nonlinear and complex sequences of maneuvers for the orbit transfers. A new Monte-Carlo low-thrust trajectory statistical analysis tool, named Veil [9], was developed two years before launch and continuously evolved to meet additional requirements. Veil takes random samples from input covariances: state, spacecraft dynamics, Vesta physical parameters, and uses Mystic to find an optimal trajectory to the specified targets. Veil is designed to link multiple daisy-chained maneuvers, a key requirement building Dawn's transfer architecture.

As previously mentioned, building a transfer architecture begins with finding one trajectory connecting two science orbits. In this process, thrust magnitude is lowered based on an average duty cycle, which was calculated by initially predicting the total coasting times for the transfer. The next step is strategically placing coast blocks and dividing the entire transfer into multiple design cycles. During operations, a new thrust sequence is built with newly updated set of OD estimations for each design cycle. Intermediate coasting blocks served several different purposes; recording Doppler data for OD, spacecraft engineering data downlink, sequence upload, and intentional quiet time to reduce the prediction error before thrusting or to update an onboard ephemeris. Two other types of coasting were used for statistical maneuvers; one for pure statistical trajectory correction maneuver and another for maneuver expansion period (MEP) that may be filled in during the operational thrust sequence design. The length of the design cycle varied from 4 weeks at early approach to as short as two days during the transfer to LAMO. The shorter the design cycle is, the more accurate the delivery will be to the next target. However, shorter cycles, hence more frequent designs, will increase the workload to the already burdened ground crew. Balancing between navigational accuracy and minimizing flight teams workload can only be done by iteration of Veil runs and was very time consuming. The design had to be robust against any anomalous situations including spacecraft anomaly, missed tracking passes, and late surprises in Vesta physical characteristic parameters. Changing the architecture after arriving at Vesta, except for post LAMO transfers, was not an option and therefore a more conservative approach was necessary to account for greater uncertainty in Vesta physical parameters before the encounter.

Once a candidate transfer architecture is made, Veil was run on JPL's computing clusters. Even with a cluster of high-end workstations, it took more than a day, or several days for HAMO to LAMO cases, to collect more than 1000 transfers. For example, obtaining one transfer for the HAMO to LAMO took one day using one node. After each Veil run, the data were carefully reviewed and analyzed to make improvements in the architecture. A key parameter in deciding the acceptability of an architecture was feasibility. If Mystic fails to find a trajectory using all the available thrusting time, the sample is marked as infeasible. A typical guideline of 99% or higher feasibility was applied in accepting the case. If this criterion is not met, adjustments were made to the architecture and Veil is run again. This process took a long time and the HAMO to LAMO transfer design was the most difficult and time consuming task by the navigation team. In fact, the final LAMO to HAMO-2 architecture was not completed until Dawn was half way through LAMO operations. More details about the transfer orbit design are described by Parcher [10].

Among all of the transfer designs at Vesta, the most challenging task was finding a transfer to LAMO as described by Whiffen [11]. To reach the lowest science orbit, spacecraft had to pass through the 1:1 resonance where orbit period of the spacecraft matched Vesta's rotation period. At this resonance, a strong coupling between spacecraft's orbital energy and Vesta's rotational energy could change the orbit size rapidly. Also, a strong coupling between spacecraft's angular momentum and Vesta's rotational angular momentum could alter the orbit plane beyond what would have been recoverable by the low thrust engines. Failure to pass through the resonance could significantly delay the science operations at LAMO or lead to the loss of mission due to the spacecraft repeatedly entering Vesta's shadow.

The architecture of HAMO to LAMO was developed before Dawn's arrival at Vesta using a gravity model described in a previous section. Finding a LAMO reference orbit also required rigorous studies. Any unused operational margin would be added to LAMO and the reference orbit must be stable with minimum necessary orbit maintenance maneuvers. The duration of the LAMO science orbit actually increased from the original 60 days to almost 5 months. Over 200,000 different candidate LAMO orbits were studied for long duration orbit stability and also for science ground track requirement during HAMO once adequate gravity knowledge was obtained. The method used is described in [10].

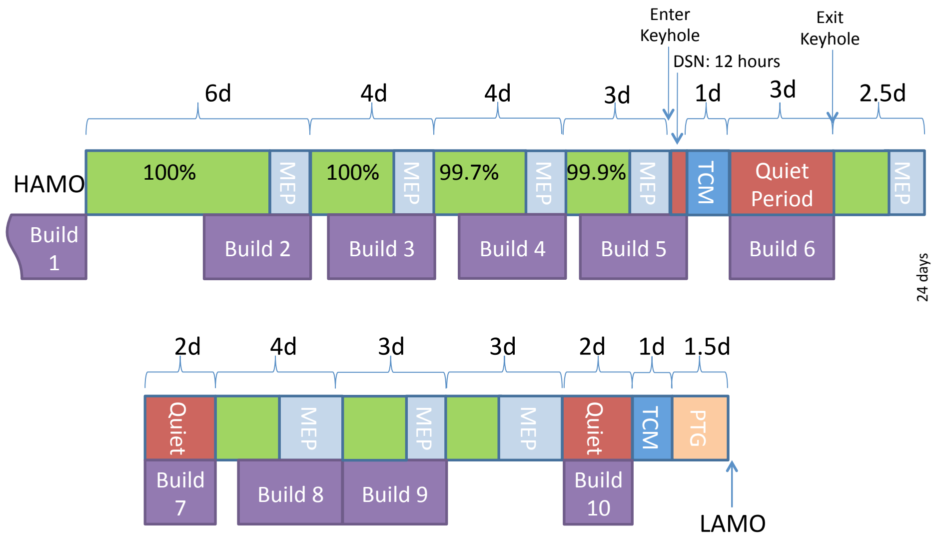

Figure 6. HAMO to LAMO transfer architecture

Upon arriving at HAMO, Vesta's gravity filed was updated with tracking data taken while the IPS was turned off. This ensured that the estimated field would be uncorrupted with noise from the thrust acceleration, and allowed estimation of higher order gravity terms. With the new gravity model with added higher order terms, as a result of studies completed in HAMO, the LAMO orbit mean radius was raised from 465 to 475 km to reduce risk. With the updated LAMO target, a new transfer orbit to LAMO was established for the transfer background sequence build. This transfer was flown in 10 thrust sequences, each one targeting back to the reference trajectory. The most difficult phase of the Vesta operation came to a successful conclusion by entering LAMO on December 12, 2011. A sample of HAMO to LAMO architecture is shown in Fig. 6.

As mentioned above, developing a thrust design that meets spacecraft Sun related geometric constraints and ACS dynamics constraints during IPS thrusting are the navigation team's responsibility. During interplanetary cruise, Dawn's thrust vector was inertially fixed for a week and finding a solution meeting these conditions was relatively easy. However, thrust profiles during Vesta transfers are highly time varying. A conventional maneuver design process would include the navigation team designing the thrust profile within a given set of geometric constraints and then iterating with the ACS team for the dynamic constraint check. This iterative process would not be feasible for Vesta operations due to the very short thrust sequence building time. The constraints needed to be met when the designed thrust profile was delivered to the ACS team the first time.

For this reason, Dawn's ACS team developed a tool named qSTAT [4]. Given the designed spacecraft thrust profile, predicted spacecraft trajectory, and choice of the IPS thruster, qSTAT simulates the spacecraft attitude while following the thrust profile, and predicts momentum state, IPS gimbal angles, and thrust delivery error. At the conclusion of the run, qSTAT provides a simple pass-fail indication as well as plots of the time-history of each variable, showing the thresholds and any violations.

Maneuvers designed using a time optimal or mass optimal solution often violate the ACS constraints, especially during orbit plane changes. To find a solution meeting the ACS agility constraints, several different methods were developed and exercised. The most effective and frequently used was a direction optimization method. The concept was to replace mass or time optimization with new objectives that smoothly alter thrust directions to ones that are acceptable. Development of these new technics were completed in time for Survey to HAMO transfer and were responsible for delivering flyable thrust profile for many thrust sequence builds.

7. Conclusion

Maneuvering a spacecraft only using the IPS for the transfers between the mapping orbits around Vesta posed many technical challenges to Dawn's flight team. Each transfer needed a robust plan that accounted for uncertainties in maneuver execution, orbit determination, and physical characteristics of Vesta. The transfer must ensure spacecraft safety and be fast to maximize the time for acquiring science data at science orbits. Dawn's navigation team at NASA's JPL has developed many new techniques and applied them during more than 13 months of Vesta operations, and contributed to a successful mission at Vesta.

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