Dawn's Mission at Ceres

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Dawn is NASA's ninth Discovery class mission. The Dawn spacecraft was designed to orbit both the giant asteroid Vesta and the dwarf planet Ceres in succession, a mission only made possible by the high efficiency of ion propulsion. While the same spacecraft visited both bodies, the mission planning and maneuver execution at the two bodies were necessarily very different. The mission at Vesta benefited from at least three functioning reaction control wheels. At Ceres, all maneuvering and coasting during transfers was done without reaction wheel control due to the loss of the second of four wheels while departing Vesta. Loss of the second wheel made conserving attitude control propellant (hydrazine) critical to achieving mission success at Ceres. To save hydrazine, avoiding unnecessary coasting and attitude turns became essential during the interplanetary cruise to Ceres and for all transfers once at Ceres. In contrast, operations at Vesta did not need to avoid coasting. Operating at Ceres requires being farther from the Sun. Greater heliocentric distances (approaching 3 A.U.) make Dawn's attitude control constraints while maneuvering more restrictive as a result of reduced control authority.

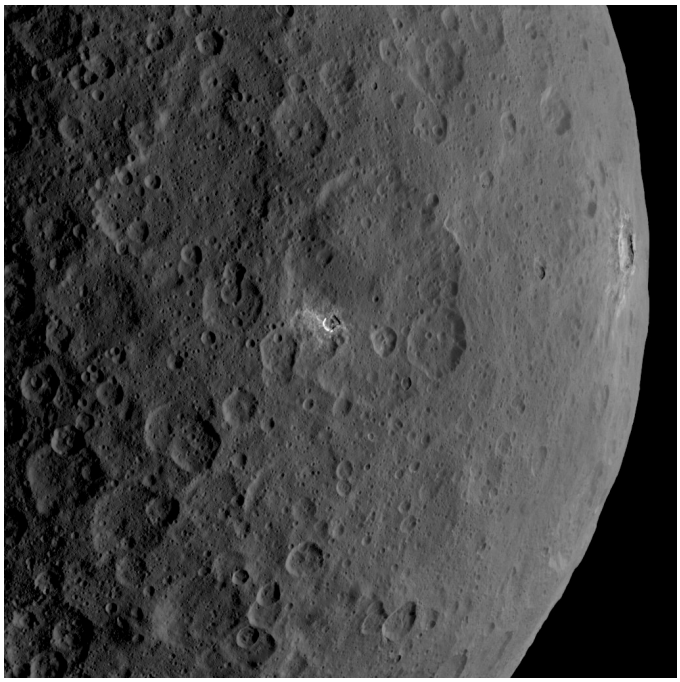

Figure 1. A view of the dwarf planet Ceres from Survey Orbit, altitude 4,381 [km]. Image credit NASA/JPL-Caltech, UCLA, MPS, DLR, and IDA.

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Nomenclature

ΔV	Change in spacecraft velocity due to propulsion
β	Sun - spacecraft orbit plane Beta angle
$v(t)$	A unit vector in the thrust acceleration direction
$\hat{D}$	Thrust direction objective
X_{sc}	Spacecraft position in an inertial frame
V_{sc}	Spacecraft velocity in an inertial frame
X_{body}	Central body position in an inertial frame
V_{body}	Central body velocity in an inertial frame
$\hat{r}$,$\hat{t}$,$\hat{n}$	Radial, Transverse, and Normal frame unit vectors
x	state vector
w	Static control vector
t	Time

I. Introduction

The Dawn spacecraft was launched in September of 2007 on an unprecedented journey to orbit the giant asteroid Vesta and dwarf planet Ceres, two different Sun orbiting bodies in the main asteroid belt. Together Vesta and Ceres constitute nearly one half of the entire mass of the main asteroid belt between Mars and Jupiter. Vesta and Ceres have more in common with the differentiated terrestrial planets and the large icy moons of the outer solar system, respectively, than with the vast majority of the other asteroids in the main belt. Dawn is the ninth Discovery class mission launched under NASA's Discovery cost-capped program. After a Mars gravity assist in 2009, Dawn captured into orbit around Vesta in 2011. Dawn orbited Vesta for a little more than one year in a variety of different near polar orbits optimized for different science instruments and acquisition objectives. Dawn left Vesta in September of 2012 and began an almost 3 year cruise to rendezvous with Ceres in March of 2016. Capture at two extraterrestrial bodies has never before been achieved and was made possible by Dawn's very efficient Ion Propulsion System or IPS.[6] Dawn's IPS has a specific impulse of approximately 3000 seconds. The IPS has provided Dawn with more than 11,000 [m/s] of post-launch ΔV. This amount of ΔV is nearly 3 times more than any other deep space mission to date.

The unprecedented maneuvering capability of Dawn and low-thrust in general require very different design and operational procedures than conventional chemical propulsion missions. The challenges of maneuvering in the strong and highly asymmetric gravitational field of Vesta is described in references 3 and 4. This paper focuses on the challenges of operating Dawn at the dwarf planet Ceres. Though the same spacecraft was operated at both Vesta and Ceres, the mission planning and maneuver execution at the two bodies had to be very different.

Unlike Vesta, Ceres has a planetary gravitational field that is nearly rotationally symmetric, but it is further from the Sun than Vesta which reduced the solar power available for maneuvering. Weaker thrust compounded with a body that is 3.5 times more massive than Vesta made orbital transfers more onerous. The spacecraft had three or more functioning reaction control wheels throughout Vesta operations. The Dawn spacecraft lost its second of four wheels during the final stages of Vesta escape. With only two remaining functional wheels, we relied solely on attitude control jets to reach Ceres and maneuver to all of the science orbits planned for the prime mission. A hybrid two-wheel plus jets mode was developed and used in the final, lowest science orbit at Ceres where it was calculated to provide the greatest benefit. Attitude agility was a limiting factor in designing maneuvers at Vesta. Attitude agility is more limiting at Ceres due to the reduced control authority at lower thrust levels available further from the Sun. Dawn uses thrust vector control for attitude control in two axes orthogonal to the nominal thrust direction while ion propulsion is in use. The ion thrusters can be gimbaled to thrust through points outside of the center of mass to create attitude control torques. Reduced ion propulsion thrust levels resulted in significantly reduced attitude agility.

The loss of the second reaction control wheel departing Vesta also made conserving hydrazine for attitude control crucial for the completion of the mission. Less hydrazine is used when the IPS is operating because two axes can be controlled using xenon. When coasting, all three axes must be controlled with hydrazine jets. It was therefore of interest to reduce or eliminate optimal coasting from IPS maneuver designs to conserve

as much hydrazine as possible. There was no such objective applied at Vesta. At Vesta the objective was to thrust as little as possible while still satisfying attitude agility constraints, and avoiding unnecessary thruster on/off cycling. Xenon conservation was not the leading reason for near mass optimal maneuvering at Vesta, rather low propellant usage corresponding to small maneuvers will generally have less total execution error and therefore better delivery. At Ceres, the objective was to thrust as long as allowed to conserve hydrazine while still have an acceptable delivery accuracy. The difficulty of maneuver design at Ceres was compounded by the reduced attitude agility at Ceres.

Plane changes are one of the most demanding maneuvers to complete with low-thrust from an attitude agility viewpoint. A continuous thrust plane change invokes two high-rate attitude changes each revolution. The high rates required for plane change maneuvers combined with the desire to avoid optimal coasting and non-essential forced coasting made large propulsive plane changes difficult or impossible. This fact drove the overall mission design plan at Ceres to reduce or eliminate plane change maneuvers. The natural evolution of the orbital plane was used in lieu of propulsive plane change maneuvers.

All flight maneuvers and mission design trajectories implemented at Ceres were developed using JPL's high-fidelity low-thrust software called Mystic[2] ("Mystic" is not an acronym). Mystic uses an algorithm called Static Dynamic Control[7] linked to high-fidelity fully integrated propagation. The propagation models continuous thrust, gravity harmonics, multi-body gravity, solar radiation pressure, and nonlinear solar power and ion propulsion models. Mystic allows the user to specify multiple complex objectives, state targets, and constraints.

One mathematical trajectory design objective function that was essential for Ceres operations is called thrust direction optimization.[8] Thrust direction optimization refers to finding a thrust profile that is optimally close to thrusting in a single fixed inertial direction or, more generally, a specified time varying direction. The objective is applied while constraining the trajectory to reach a fixed terminal state condition and meet any other needed operational constraints. Thrust direction optimal solutions are not generally mass optimal. The amount of thrusting time in excess of the mass optimal thrusting time is typically a user selected parameter termed "slack". The more slack, the closer thrusting can become to any user specified thrust direction objective typically. Thrust direction optimization was developed for Dawn's operations at Vesta to satisfy attitude agility. The application of thrust direction optimization at Ceres was critical, but also fundamentally different than at Vesta because at Ceres the amount of slack was much greater. Slack at Ceres was expanded to eliminate all coasting and thereby conserve attitude control propellant. In contrast, at Vesta slack was sized to be only large enough to find a thrust profile that satisfied attitude agility constraints.[8]

II. Ceres Operations

II.A. Science Orbits Design at Ceres

The prime mission at Ceres was designed to include four different, circular, near polar mapping orbits. The first and highest orbit was named for its main purpose of determining Ceres rotation (pole and rate). The Rotational Characterization orbit (or RC orbit) radius was 14,000 [km]. This orbit also allowed for an initial determination of the J2 gravity term and a low resolution shape model. The second orbit was named the Survey orbit, and it was the first to be designed to have a repeat ground track for repeat global mapping. The third orbit was named High Altitude Mapping Orbit or HAMO. HAMO radius was 1946 [km]. The main objective of this orbit is the visual and infrared mapping of Ceres' surface including stereo imagery for topography. The final and lowest orbit during Dawn's prime mission was named the Low Altitude Mapping Orbit or LAMO. LAMO's altitude was 360 [km]. The main purpose of LAMO was for the acquisition of data from Dawn's Gamma Ray and Neutron Detector or GRAND instrument and for high resolution gravity measurements to infer the interior structure of Ceres. Beyond the original requirements set for the mission, Dawn obtained a visual global high resolution map and high resolution topography while in LAMO. Targeted visual and infrared spectroscopy was also conducted while in LAMO. Global mapping with Dawn's infrared and visual spectrometer was not possible given the small footprint of the instrument at LAMO altitudes. Table 1 provides a summary of the characteristics of each science orbit of the prime mission at Ceres. Figure 2 illustrates the relative scale of the science orbits around Ceres. The science campaign at Vesta used an analogous set of four science orbits with Vesta HAMO being visited on the way down to Vesta LAMO and again on the way up from LAMO toward escape.

The Survey, High-Altitude Mapping, and Low-Altitude Mapping orbits were all designed to have repeat

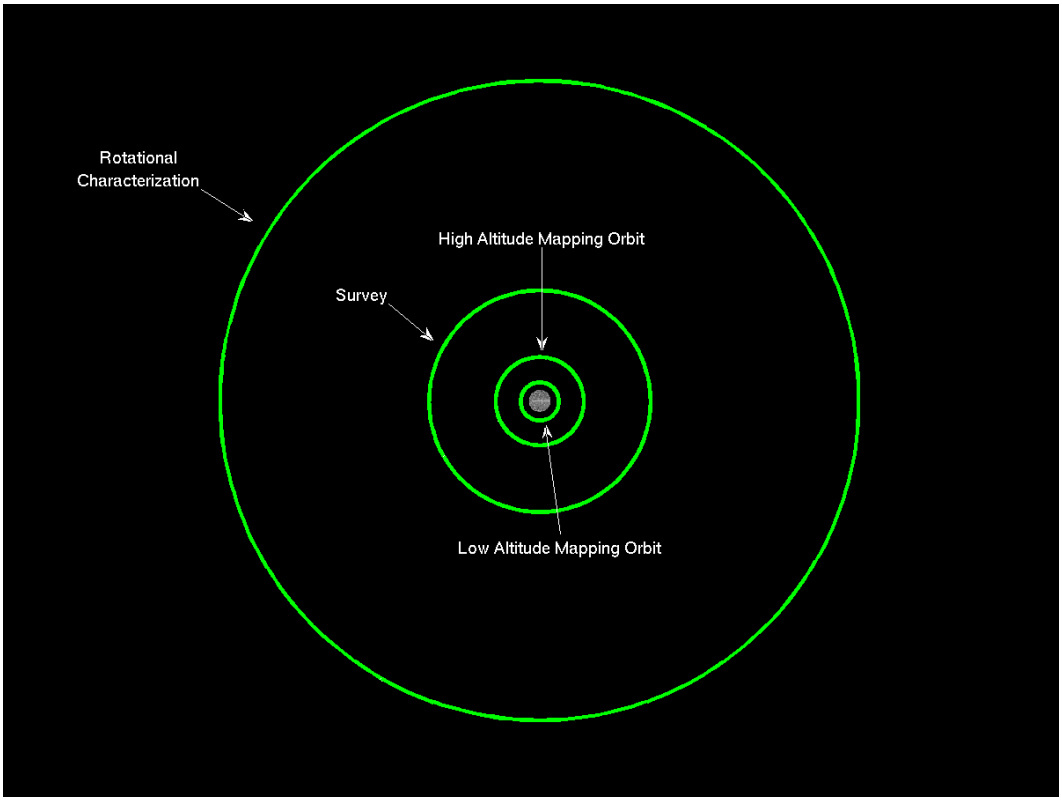

Figure 2. The relative sizes of the executed prime mission science orbits at Ceres.

ground tracks to facilitate global mapping coverage. The cadence of downlink, onboard data storage capacity, and prime instrument foot print and resolution requirements drove the selection of particular altitudes and repeat ground tracks. It was also necessary to investigate the properties of all orbits dynamically near a candidate science orbit for the purposes of orbit selection. This was done to be sure the neighborhood as a whole was well behaved. The final selection of a repeat pattern was subject to an evaluation of the proximity to low-order orbit-spacecraft resonances. Some low-order resonances will attract or repel the spacecraft through interactions with gravity harmonics. The attraction or repulsion will drive the orbit period and hence ground track well away from what was planned. In addition to low-order resonances, the close proximity to highly undesirable ground tracks (generating poor or failing to achieve global coverage) were also avoided. Even though these poor ground track orbits may not be dynamically attractive, they could be entered through maneuver execution errors leading to orbit delivery error. Figures 3 and 4 illustrate the ground track repeat pattern targeted for the High-Altitude Mapping and Low-Altitude Mapping orbits respectively.

To meet planetary protection requirements at Ceres the Low-Altitude Mapping orbit and its dynamic

Table 1. Ceres Prime Mission Science Orbits. Ground track resonances are reported in the form of Ceres revolutions:spacecraft revolutions. Orbit duration is the total time spent in each orbit including time spent before and after science acquisition was completed. The RC orbit did not target a repeat ground track. *Footnote a:* **This time is from LAMO injection to the end of prime mission on June 30, 2016. Dawn, however, continues to operate in LAMO in its extended mission as of the writing of this paper.**

Orbit Name	Radius [km]	Altitude	Ground Track	β Range [deg]	Duration [days]
Rotational Characterization	14,000	13,517	na	5 - 8	15
Survey	4,864	4,381	33:4	13 - 21	41.3
High Altitude Mapping	1,948	1,465	25:12	24 - 36	68.8
Low Altitude Mapping	843	360	56:93	45	197[a]

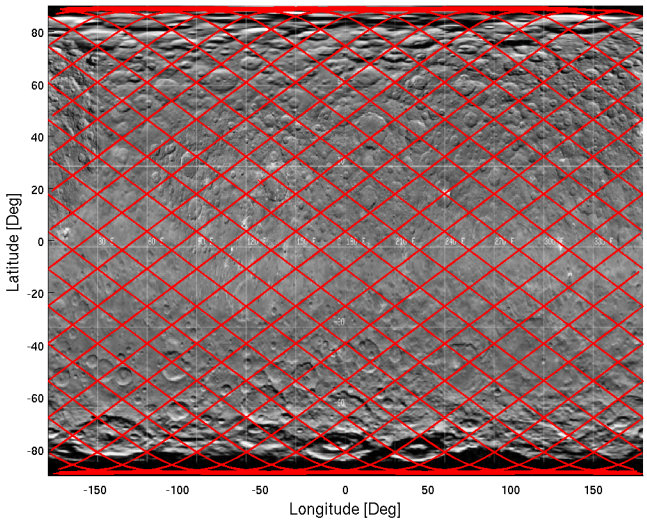

Figure 3. The reference High-Altitude Mapping Orbit (HAMO) ground track repeat pattern at Ceres.

vicinity was shown to be stable for at least 50 years. The possibility of some form of life existing on Ceres requires that the Dawn spacecraft be entirely sterile if there were to be an impact. 50 years was calculated to be more than enough time for the space radiation environment to completely sterilize the spacecraft. Long-term propagations beyond 50 years did not show any secular decay of the orbit that would lead to impact. It is expected that if Dawn were to remain in LAMO it would be stable there for a very long time.

II.B. Transfers Between Science Orbits at Ceres

The science orbit radii in Table 1 were selected primarily for science requirements. However, this set of orbits visited in succession from outermost to innermost provided adequate determination of gravity to successfully design and navigate to each successively lower orbit. Had this not been the case, we would have added intermediate non-science orbits to adequately determine the gravity field before moving lower. Orbit determination and gravity field determination is generally very difficult during powered flight. The ion propulsion execution error and more particularly the attitude jet firing can easily alias into the determination of the gravitational field. Each transfer and the next science orbit reference trajectories were therefore designed without updating the gravity harmonics during the transfer.

The trajectory flown during the approach and capture into the Rotational Characterization orbit is illustrated in Figure 5. The peculiar shape is the result of an unexpected loss of thrust that occurred beginning September 11, 2014 and lasting several days. This unexpected outage resulted in an over shoot of Ceres costing an extra 30 days to return. Details about the approach and its complex redesign after the loss of thrust event is provided in reference 1. The transfer from the Rotational Characterization orbit to the Survey orbit is illustrated in Figure 6. This transfer only required just short of five orbital revolutions around Ceres as a result of the high altitudes. Figure 7 illustrates the transfer from Survey orbit to the High Altitude Mapping orbit. The Survey to HAMO transfer required 23.9 revolutions around Ceres. Figure 10 illustrates the reference trajectory transfer from HAMO to LAMO. The HAMO to LAMO transfer required 143 revolutions around Ceres.

In all orbits and transfers, entering Ceres' shadow had to be avoided with an added margin of safety of at least 5 degrees. This requires an increasing minimum Sun β angle with successively lower orbits. The Sun β angles listed in Table 1 indicate the designed and flown β angle evolution during the Ceres science campaign. Positive β angle, AM local time descending node orbits were used to ensure the natural change in β angle is always positive. At high altitudes, the natural β angle evolution corresponds to the angular rate of Ceres in its orbit around the Sun (about 0.2 degrees per day). Another requirement is that at no time during planned thrusting can the spacecraft enter shadow if there is a loss of thrust for 28 days. This constraint is always met because of the avoidance of plane changes (discussed below) and the naturally increasing β angle of the

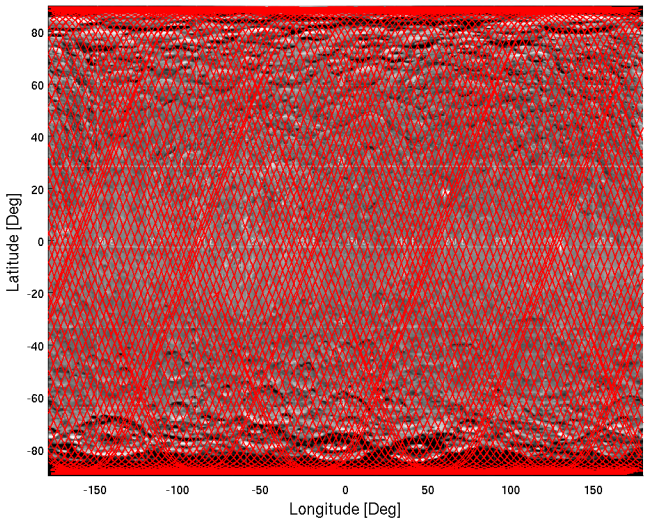

Figure 4. The reference Low-Altitude Mapping Orbit (LAMO) ground track repeat pattern at Ceres.

+AM local time orbit.

Propulsive plane change maneuvers (for example to change β angle) are both expensive and also strain attitude agility when combined with the desire to thrust at all allowed times for hydrazine (attitude control propellant) conservation. For this reason, the entire mission at Ceres was designed to involve essentially no planned propulsive plane change maneuvers. This was achieved by exploiting the natural β angle evolution at high altitudes (0.2 degrees per day) to increase β angle during each science orbit and subsequent transfer. The final and lowest science orbit was able to obtain a frozen Sun β angle using Ceres' gravity harmonic J2. J2 was anticipated to be large enough to freeze the β angle at LAMO altitudes based on shape models created using Hubble imagery well before Dawn's arrival. J2 was not anticipated (and in actuality was not) large enough to freeze β angle at HAMO altitudes in orbits near enough polar to facilitate global mapping coverage. The frozen β angle inclination target for LAMO was 0.6 degrees off of a polar orbit. This inclination was initially obtained at Survey and refined at HAMO as J2 determination improved. Figure 8 illustrates the time evolution of the Sun β angle during the HAMO to LAMO transfer. The orbital inclination required to freeze the β angle at LAMO altitudes was achieved much higher up so essential no propulsive plane change maneuver was required to end up in the frozen orbit when LAMO altitude was achieved. The flattening out of the β angle evolution at the end of the transfer (targeting 45 degrees) is evident at the right side of the plot in Figure 8. Some long term low amplitude cyclical change to β angle in LAMO is unavoidable due to Ceres' eccentric orbit around the Sun.

Once LAMO orbit was achieved, orbit maintenance maneuvers were allowed on a 22 day cycle (corresponding to the ground track repeat period). Orbit maintenance maneuvers (OMMs) were not planned or needed in any of the higher science orbits. The anticipated perturbations from attitude control jet firing are the most severe in LAMO as a result of the high attitude rates necessary for instrument pointing and strong gravity gradient torques. An analogous orbit maintenance strategy was used at Ceres as was used at Vesta.[9] The orbit maintenance plan consists of two 12 hour maximum sized maneuvers separated by approximately 8 days designed in pairs once every 22 days. OMMs were targeted to either return to the reference orbit six-state (position and velocity) at the end of the second maneuver, or a state nearby that was optimized by Mystic to stay close to the reference trajectory over the next week or two given the predicted perturbations of attitude jet firings and improved gravity knowledge. If the delivery from a designed orbit maintenance maneuver was shown to be statistically indistinguishable from future state knowledge uncertainty or if it provides a statistically unreliable improvement, then the OMM was cancelled. Most OMMs were cancelled, only 3 of 9 possible OMMs were executed.

Table 2 summarizes several characteristics of each transfer between science orbits at Ceres. All transfers were designed end-to-end to be time optimal with allocations for statistical thrusting throughout. Conservation of Xenon propellant for ion thrusting was not necessary because by this point in the mission it was

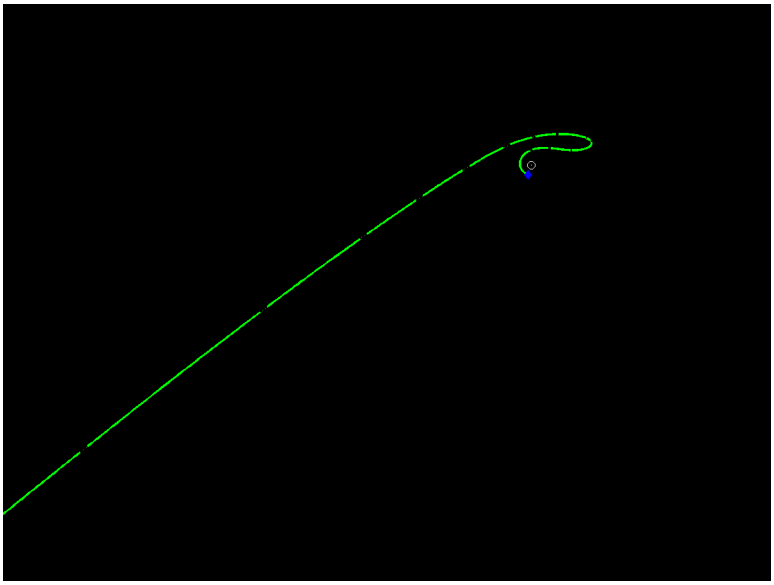

Figure 5. The approach, capture, and injection into the Rotational Characterization orbit at Ceres.

clear Dawn had significantly more Xenon remaining (unused propellant margin) than we could reasonably use at Ceres. While all transfer reference trajectories were optimized end-to-end, each transfer was broken up into open loop "design cycles" to be flown. Each design cycle was targeted to the corresponding reference trajectory 6-state (position and velocity) at the end of each cycle. Each design cycle was redesigned based on current orbit determination data typically 3 to 5 days before the cycle's maneuvering began. Generally the goal in designing the transfer architecture was to minimize the number of design cycles required while maintaining adequate reliability against uncertainty and adequate science orbit delivery accuracy at the end of the completed transfer.

Table 2. Ceres Prime Mission Orbital Transfers.

Transfer	Radius [km]	Revolutions	β Range [deg]	Duration [days]	Design cycles
RC orbit to Survey	14,000 to 4,864	4.85	8 - 13	25.2	2
Survey to HAMO	4,864 to 1948	24.6	21.8 - 24.3	32.2	5
HAMO to LAMO	1,948 to 843	143.0	36.2 - 45.0	50.6	8

The durations of the 2 design cycles used to transfer between the RC orbit and Survey were 21 days and 3.5 days. The final cycle was short to ensure an accurate delivery to Survey. The durations of the 5 design cycles used to transfer between Survey and HAMO were 9.3, 7, 7, 7, and 2 days. Again the short final design cycle was intended to provide an accurate delivery to HAMO. The durations of the 8 design cycles used to transfer between HAMO to LAMO were 6.55, 7, 7, 7, 6, 7, 4.25, and 2 days. The final cycle of 2 days was allocated entirely to statistical thrusting (a trajectory correction maneuver). It was found that a trajectory correction maneuver was needed to ensure an adequate delivery to LAMO. The commonality of 7 day design cycles was to create a work schedule that was consistent week to week.

II.C. Avoiding Unnecessary Coasting At Ceres While Satisfying Attitude Agility Constraints

Low-thrust transfer reference trajectories have to be designed to account for several uncertainties including unbalanced and generally unpredictable attitude jet firing ΔVs, orbit determination errors, maneuver execution errors, and physical parameter (gravity) determination errors. Given the low acceleration associated with low-thrust, statistical thrusting to compensate for these uncertainties must be accounted for with a significant amount of additional thrusting time beyond what a deterministic error-free transfer requires. The amount of extra time required for each design cycle of each transfer was computed using JPL's Veil software.[5] At Vesta, the additional thrusting time was incorporated into transfer reference trajectories as periods of

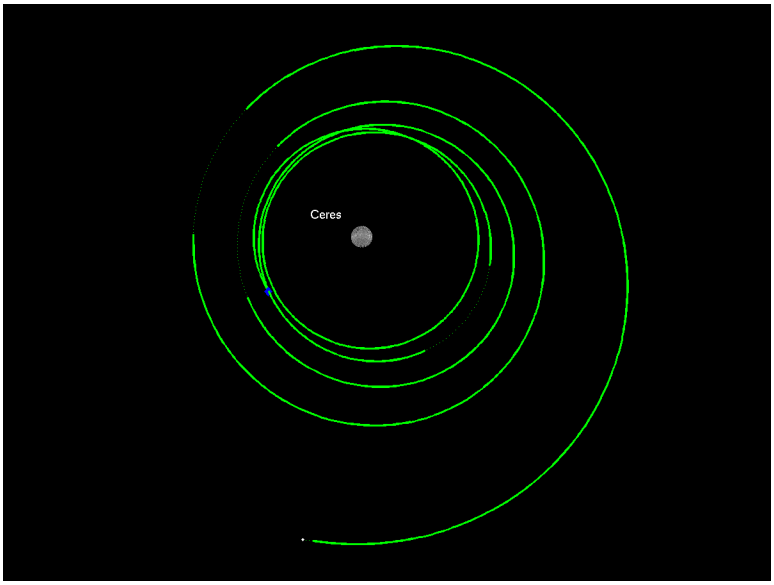

Figure 6. The transfer spiral-in from the Rotational Characterization Orbit (RC) to the Survey Orbit at Ceres.

forced coasting. During operations, these periods are"freed" to allow additional thrusting and/or a temporal shift to the thrusting as needed. Incorporating forced coasting in reference trajectories to account for statistical thrusting results in the phenomena we coined "ghosting" during operations. "Ghosting" is the strong tendency or even necessity of any operational maneuver design to include at least some coasting (a ghost of the reference trajectory's forced coast) during the times held in reserve as forced coasting in the reference transfer. Deliberately reducing the thrust magnitude available during operations does not generally remove a ghost of coast present in a reference trajectory. Often deliberately reducing the allowed thrust magnitude to remove a ghost coast results in points in time with very high attitude rates well beyond what the spacecraft can support. Coasting in low-thrust trajectory design can be just as essential as thrusting is to reach some six-states - especially if high thrust direction angular rates and angular accelerations have to be avoided.

Unlike operations at Vesta, at Ceres it was important to reduce attitude jet firing to conserve hydrazine. Less hydrazine is required during ion thrusting than during coasting. Therefore the goal was to avoid non-essential coasting during orbit transfers at Ceres. This goal lead us to a different approach to reference transfer design. Rather than book statistical thrusting as forced coasts in the reference trajectory as was done at Vesta, the thrust magnitude used in the reference was reduced by an amount corresponding to the fraction of additional time needed for statistical thrusting at Ceres. This procedure resulted in "ghost" free reference state targets making it much easier to achieve continuous thrust solutions during operations.

Ion thruster thrust magnitude calibration was important to achieving accurate delivery to targets. To best facilitate ongoing improvement to thrust magnitude knowledge accuracy, most transfers were conducted using a single throttle level. This was done despite the fact that changing heliocentric distances often allowed different throttle levels. Using a single throttle level improved our prediction ability and allowed continuous improvement in our knowledge of the thrust magnitude. Typically the throttle level was selected near the maximum possible for each transfer. Choosing a high throttle level provides the most attitude control authority. Selecting a maximum or near maximum throttle level and thrusting at all available times also creates a great deal of "slack". The term "slack", introduced above, is the amount of thrusting time in excess of the mass optimal thrusting time. Obviously, transfers with slack cannot be designed using either a mass or time objective.

During Vesta operations, a minimal amount of slack was introduced in many maneuver designs to find solutions that satisfy attitude agility constraints when a mass optimal solution resulted in agility constraint violations. At Ceres most maneuvers ended up being designed with a great deal of slack. The slack was the result of the high throttle level used for attitude control authority and the desire to thrust at all allowed times - including using up all of the unused statistical thrusting allocation. The allocations for statistical thrusting were typically generous to ensure conservatism, and therefore the great majority of the allocation was left unneeded during operations creating excess slack.

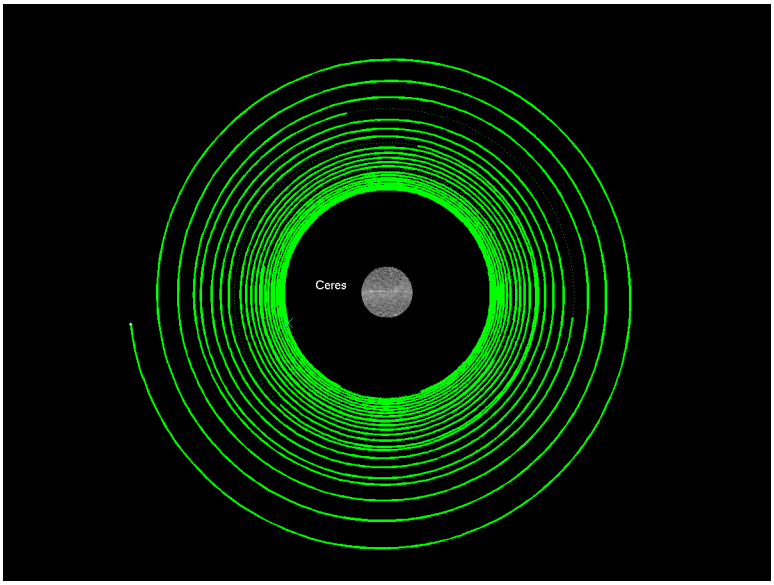

Figure 7. The transfer spiral-in from the Survey orbit to the High Altitude Mapping Orbit (HAMO) at Ceres.

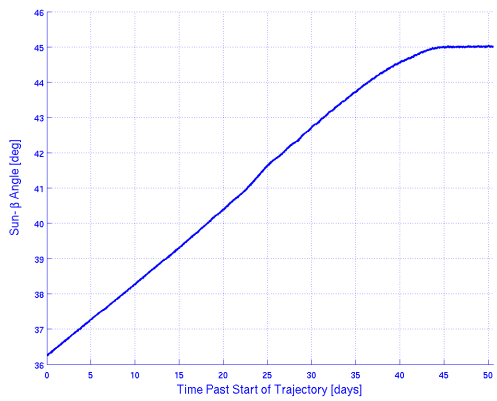

Figure 8. The Sun β angle time evolution during the transfer spiral-in from the High-Altitude Mapping Orbit (HAMO) to the Low-Altitude Mapping Orbit (LAMO) at Ceres. The frozen β angle targeted at LAMO is evident at the right side of the plot.

Thrust direction optimization[8] was used to compute most transfer maneuvers at Ceres. A thrust profile is said to be "Direction Optimal" if the thrust profile is closest to (or furthest from) a thrust direction target and the thrust profile meets all other constraints and the trajectory still achieves the required state targets. The direction target can be either inertially fixed or the direction can be a function of time. The direction objective can be applied to part or all of the transfer. Direction objectives can be used in combination with each other and with mass objectives to create a Pareto optimal front. The general form of a direction "attractor" objective is

$$min_{v,w} \int_{t\in\tau} \left[1 - \hat{v}(t) \cdot \hat{D}(x(t), v(t), w, t)\right]^2 dt, \tag{1}$$

where $\hat{v}(t)$ is a unit vector pointing in the same direction as the thrust acceleration at time t and $\hat{D}$ is unit vector function that provides the target thrust direction at time t. The set of times τ need not be continuous or include all of the trajectory time horizon. The vector function of time x is the spacecraft position, velocity, and mass. The parameter vector w are parameters that are not functions of time (so called "static" control parameters[2]) that are part of the control space along with the vector control function of time $\hat{v}(t)$. Examples of static controls include flight time, initial spacecraft state, etc.

The most useful target type and the one used almost exclusively at Ceres was an attractor objective to

find thrust directions to be as close as possible to a fixed point in a spacecraft - Ceres relative rotating frame called the Radial, Normal, and Transverse (RTN) frame. The radial, transverse, and normal unit vector directions are defined as

$$\hat{r} = (X_{sc} - X_{body})/||X_{sc} - X_{body}||,$$
$$\hat{t} = (\hat{V} - (\hat{r} \cdot \hat{V})\hat{r})/||\hat{V} - (\hat{r} \cdot \hat{V})\hat{r}||,$$

and

$$\hat{n} = \hat{r} \times \hat{t},$$

where the body relative spacecraft velocity is defined as

$$\hat{V} = (V_{sc} - V_{body})/||V_{sc} - V_{body}||.$$

The variables X_{sc} and V_{sc} are the spacecraft position and velocity in an inertial frame and X_{body} and V_{body} are the central body's (Ceres') position and velocity in the same inertial frame. The RTN attractor thrust direction objective can be written

$$min_{v,w} \int_{t \in \tau} \left[1 + \hat{v}(t) \cdot (a\hat{r} + b\hat{t} + c\hat{n})\right]^2 dt. \tag{2}$$

The constants, a, b, and c in equation (2) are chosen to define the fixed direction objective in the RTN frame. Selection of a, b, and c are subject to the constraint $||a\hat{r} + b\hat{t} + c\hat{n}|| = 1$ or equivalently $a^2 + b^2 + c^2 = 1$. Since there are only two degrees of freedom in specifying the direction, it is convenient to specify the objective direction as a right ascension angle and a declination angle in the RTN frame.

Finding values of right ascension and declination for the RTN target that result in feasible maneuvers when given a large amount of slack is generally difficult. Often direction optimal maneuvers with lots of slack include short periods with very high attitude rates and accelerations. During operations, time was of the essence and the number of possible thrust direction targets that could be tried was very large. Software was constructed to test each of a grid of possible RTN frame right ascension and declination angles simultaneously using a computer cluster. The results were ranked based on multiple criteria including the attitude rates required, the maximum ion thruster gimbal excursions required for attitude control, and the thrust angular pointing error resulting from thrust direction excursions for attitude control. Figure 9 is an example of

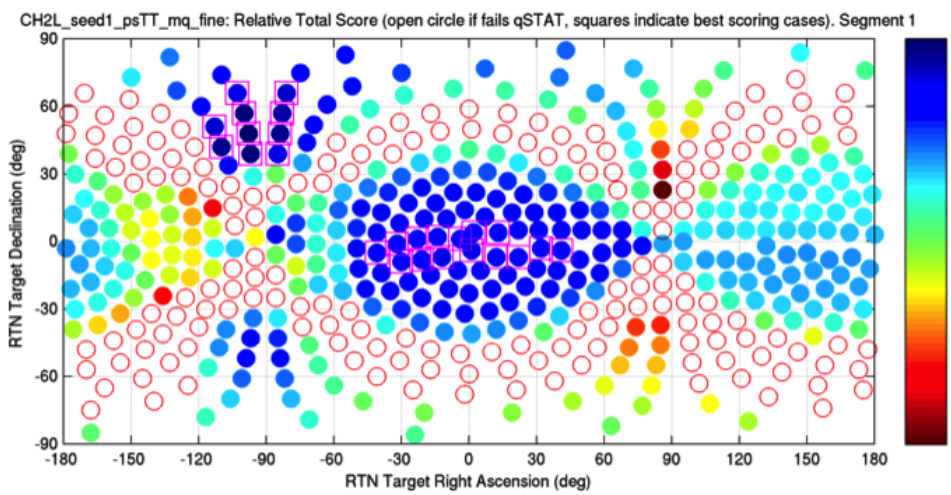

Figure 9. An example of right ascension angle and declination angle search.

results of a search over right ascension and declination for an RTN target for the first design cycle of the HAMO to LAMO transfer. The multiple criteria for good attitude control solutions were combined into a single value and color coded, blue being best and red being worst. Red empty circles indicate failure to satisfy the attitude agility limits on the Dawn spacecraft. The overall best solutions are enclosed in square boxes. Often preliminary orbit determinations days in advance of the final design time were adequate to identify a good right ascension and declination for use in the final maneuver design. Frequently, the target (0,0) performed well. This direction corresponds to radial (outward) thrusting.

A detailed discussion of the most challenging transfer at Ceres between HAMO and LAMO is given in reference 11. This transfer involved over 140 powered revolutions and the attitude agility constraints were by far the most difficult to satisfy due to the intrinsically high attitude rates necessary for the low-altitude spiral inward.

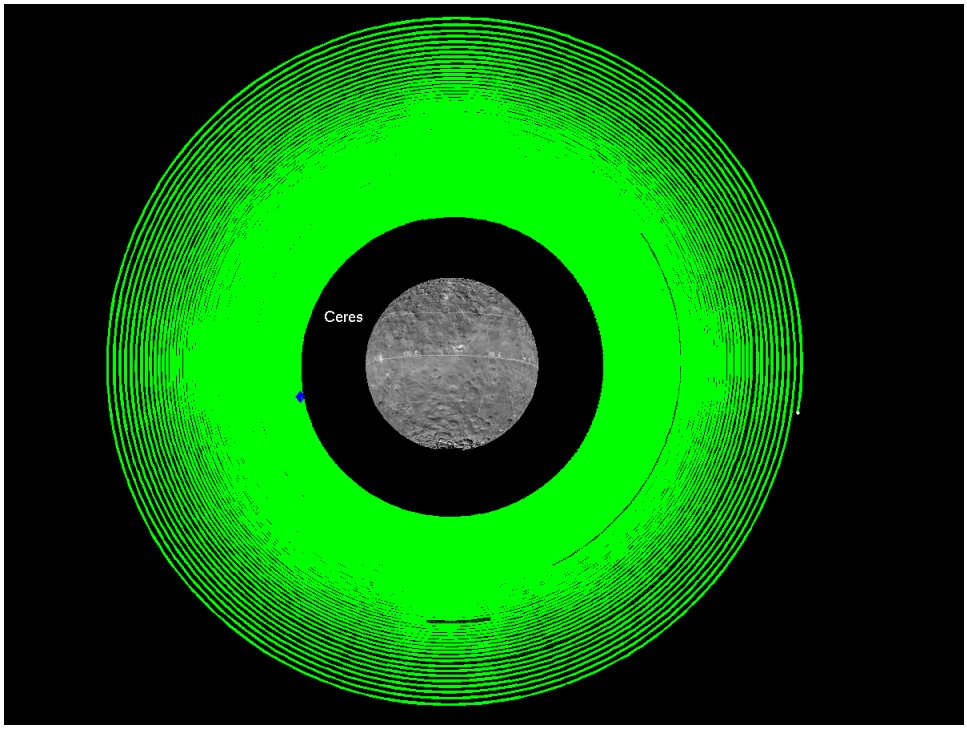

Figure 10. The transfer spiral-in from the High-Altitude Mapping Orbit (HAMO) to the Low-Altitude Mapping Orbit (LAMO) at Ceres.

III. Conclusion

The Ceres prime mission ended June 30, 2016. Successful deliveries to all science orbits allowed all science requirements to be met and ultimately exceeded. Hydrazine conservation throughout the interplanetary cruise to Ceres and all orbital transfers at Ceres left the spacecraft with more than enough hydrazine to complete its prime mission and commence its extended mission at Ceres. As of the writing of this paper, Dawn continues to operate in its lowest science orbit at Ceres, productively gathering additional science data from the dwarf planet. Plans are being made to optimize the science return for the remaining extended mission. The remaining two reaction control wheels continue to function in the Low Altitude Mapping Orbit in the hybrid jet/wheel mode saving hydrazine. The lessons learned operating at Ceres were in many ways very different than Vesta owing in large part to the different operational goals after the loss of Dawn's second reaction control wheel during departure from Vesta. Many of these lessons may have applicability to future missions where continuous thrusting is preferable and/or when attitude agility is limited.

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