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STABILITY AND TARGETING IN DAWN'S FINAL ORBIT

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The Dawn spacecraft conducted two extended missions at Ceres following the completion of the primary mission in June 2016. The final orbit of the second extended mission was designed to have a 35-km periapsis altitude for 10x higher-resolution science. The mission ended in this orbit when the spacecraft ran out of attitude control propellant. In this paper, we describe the final orbit and discuss the challenges of flying this low at Ceres. We also include our stability analysis showing the spacecraft will remain in orbit for more than 20 years, as stipulated by the planetary protection requirements.

INTRODUCTION

Dawn was a NASA Discovery mission that was selected to explore the protoplanet Vesta and dwarf planet Ceres to learn more about the origins and evolution of the solar system. The spacecraft was launched from Cape Canaveral on a Delta II rocket on September 27, 2007. The source of post-launch propulsion for the mission was a set of three ion thrusters, first tested in flight on Deep Space 1.[1] The ion propulsion system (IPS) is truly mission enabling. To date, Dawn is the only spacecraft to orbit two bodies other than the Earth and Sun. The spacecraft arrived at Vesta in July 2011. After approximately one year of science operations in orbit around Vesta, the spacecraft departed Vesta to go Ceres, where it remains in orbit today. At end-of-mission, the IPS logged 51,385 hours of thrusting, providing a total impulse of 11.5 km/s.

Dawn's primary mission concluded as planned in the Low-Altitude Mapping Orbit (LAMO) at Ceres in June 2016.[2,3] The spacecraft was healthy and there was sufficient propellant remaining to support two extended missions.[4] After successfully completing the first extended mission in late 2017, the second extended mission was approved with the objective of studying the dwarf planet's surface and subsurface composition in greater detail. For the second extended mission, the spacecraft was commanded into a highly eccentric orbit (e = 0.8), with the orbit oriented such that the spacecraft flew directly over Occator Crater at a pair of targeted periapses, approximately 35 kilometers above Ceres' surface. The remaining usable hydrazine to control the spacecraft's attitude was expended in this orbit as planned. Because of the planned loss of the spacecraft in the final orbit, it was necessary for the team to demonstrate that the orbit is stable and satisfies the planetary protection requirements.

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In this paper we describe how the final orbit was designed, and our processes of verifying the orbit-related planetary protection requirements. We also discuss the mission design and navigational challenges of targeting flying over Cerealia Facula, the “bright spot” in the middle of Occator crater. The spacecraft entered its final orbit on June 8, 2018. Science operations continued in this orbit until loss of communications with the spacecraft on October 31, 2018, caused by an exhaustion of the hydrazine propellant. All scientific objectives for the second extended mission were achieved.

MISSION OVERVIEW

Spacecraft

A diagram of the Dawn spacecraft is provided in Figure 1. As shown in the diagram, the spacecraft has three ion propulsion system (IPS) thrusters, which use ionized xenon for propellant. Only one IPS thruster was operated at a time. The spacecraft, including the IPS thrusters, was powered by two large solar panels spanning a total of 20 meters in length and providing 10 kW of power at 1 AU. Not shown in the diagram are the Reaction Control System (RCS) thrusters, a system of 12 hydrazine thrusters (6 prime, 6 back-up). The spacecraft was also equipped with four reaction wheel assemblies (RWAs) for momentum control. At the time of the second extended mission, three of the four RWAs had failed, and full attitude control was provided by the RCS.

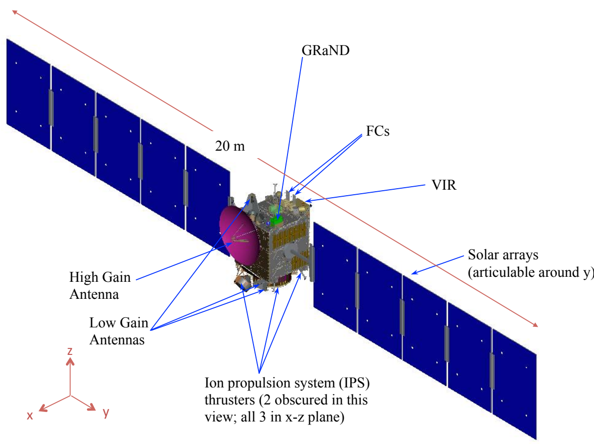


Figure 1. Schematic of the Dawn Spacecraft.

Prime Mission: Vesta & Ceres

For the prime mission, a succession of four science orbits at various orbital radii were successfully performed during Vesta and Ceres operations. The primary mission was a complete success, and all Level 1 requirements were satisfied. For more details about the primary mission, see Han et al.[5] The primary mission ended as planned in the Low-Altitude Mapping Orbit (LAMO) in June 2016. In LAMO, the lowest altitude encountered was ∼360 km.

Ceres Extended Mission: XM1

A primary objective of the first extended mission was to obtain cosmic ray background data to calibrate the Gamma-Ray and Neutron Detector (GRaND) instrument, which was accomplished by raising the orbital altitude. In the first extended mission (XM1), the spacecraft remained in

LAMO (called Extended Mission Orbit 1, or XMO1) for two additional months, after which the orbit was raised successively to three additional science orbits: XMO2, XMO3, and XMO4. To help understand Occator crater's composition, XMO4 was designed to fly directly over the crater when the crater was at opposition from the Sun as seen by Dawn (to see the so-called "opposition surge"). An IPS maneuvering architecture was created to deliver the spacecraft onto a trajectory that passed over Occator crater at phase angle less than 0.1° 3-σ and an altitude less than 20,000 km, while avoiding crossing into shadow when passing over the dark side of Ceres. This observation was the team's first attempt at flying over a targeted spot on Ceres' surface. The opposition surge measurements of Occator crater occurred on April 29, 2017. All science objectives were achieved and the back-up opportunity was cancelled. The final orbit of the first extended mission, XMO4, had a periapsis altitude of approximately 14,000 km.

Ceres Second Extended Mission: XM2

The second extended mission (XM2) began in October 2017. The orbits for XM2 were chosen to obtain additional data to provide further insights into the origin and evolution of Ceres. The first orbit of XM2 is called XMO5, as shown in Figure 2 (red orbit). In mid-April 2018, the IPS was used to successively lower the periapsis to two additional science orbits. For more information about the transfer and delivery to XMO7, see Whiffen.[6] The XM2 orbits are referred to as XMO6 and XMO7, also shown in Figure 1. The spacecraft remained in XMO6 approximately two weeks before maneuvering into XMO7. The final orbit, XMO7, was designed to fly over Cerealia Facula inside Occator crater at periapsis for two consecutive orbits. The planned end-of-mission occured when the spacecraft exhausted its usable supply of hydrazine utilized by the Reaction Control System (RCS) for attitude control during orbit operations of XMO7.

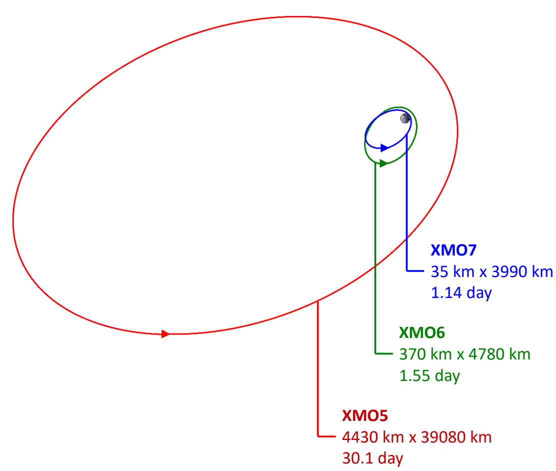


Figure 2. Planned XM2 Science Orbit Altitudes and Periods.

FINAL ORBIT OBJECTIVES & DESIGN

Periapsis Altitude and Resonance

To achieve the highest practicable spatial resolution of scientific measurements in XM2, the Dawn science team desired Dawn's close approach to Ceres (periapsis) to be as low as reasonably achievable for XMO7. In addition, it was deemed scientifically meritorious to design the orbit such that the groundtrack covered approximately the same longitude band during each orbit, particularly to increase the integration time (time spent viewing a given surface section) for the GRaND instrument. The mission design team decided that the XMO7 should be an elliptical orbit with a period equal to an integer multiple of Ceres' rotation, commonly referred to as a "resonant orbit". With a resonant orbit, the low altitudes of the spacecraft trajectory would pass over the same terrain during successive orbits. For XM2 the target spot to fly over was the Cerealia Facula, the "bright spot" inside Occator crater.

Selection of the orbital characteristics was performed in a trade-study fashion, exploring different resonant frequencies and different periapsis altitudes. The team began by evaluating orbits with a periapsis radius of approximately 657 km (a mean altitude 170 km). Recall that in the prime mission, the lowest altitude reached was during the LAMO orbit, with an altitude of $\sim$360 km. This orbit would have brought the spacecraft about twice as close to Ceres' surface as LAMO, for an increase in resolution of approximately a factor of four. Ultimately, the team decided to push the periapsis as close to the surface as feasibly possible while satisfying the planetary protection requirements. After several more studies, the mission design team arrived at an orbit with a mean periapsis radius of 505 km, or a mean altitude of 35 km above Ceres' surface, an altitude approximately ten times closer to the surface than the International Space Station is to Earth's surface.

The team selected a 3:1 resonant orbit, where the Dawn spacecraft orbits once around Ceres for every three Ceres rotations. The 2:1 resonance was deemed too low and too fast to operate comfortably, and the expenditure of xenon to enter the orbit would have been significantly higher due to its lower energy. A 4:1 resonance was also undesirable because the periapsis speed would have been too high for imaging. Therefore, a 3:1 resonant orbit was selected. The selection of a resonance determines the period and semi-major axis of the orbit. For a periapsis altitude of 35 km, the corresponding apoapsis altitude is 3990 km for a 3:1 resonant orbit, near the altitude of the prime mission's Survey orbit. The orbital eccentricity is 0.8. A figure depicting the selected orbit (XMO7) is shown in Figure 3, where Ceres is shown to scale.

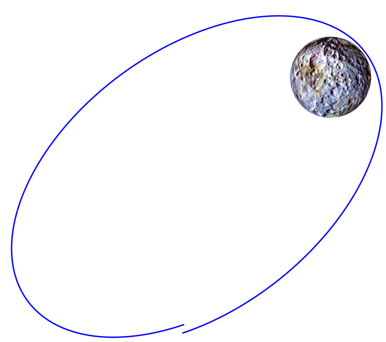


Figure 3. Dawn's final orbit XMO7, with a period of 27 hours. Ceres is shown to scale.

Shadow Avoidance and β-Angle Drift

The selected low-periapsis, high-eccentricity, near-polar orbit is subject to significant non-Keplerian perturbations from Ceres' extended gravity field, especially J_2. Of particular interest are the change in the argument of periapsis, ω, and the right ascension of the ascending node, Ω. Additionally, the quantity referred to as the "β-angle", which is useful for assessing surface lighting conditions, is a measure of how face-on to the Sun the orbit is (related to Ω). The Dawn β-angle is defined as

$$\beta = 90^\circ - \cos^{-1}\left(\hat{\mathbf{h}} \cdot \hat{\mathbf{s}}\right) \tag{1}$$

Here, $\hat{\mathbf{h}}$ is the orbital angular momentum unit vector and $\hat{\mathbf{s}}$ is a the Ceres-Sun unit vector. The time variations of the orbital elements due to J_2 are given by Legendre's planetary equations. From Roy,[7] the disturbing potential F due to J_2 is

$$F = \mu \frac{3}{2}\frac{J_2 R^2}{a^3}\left(\frac{a}{r}\right)^3 \left[\frac{1}{3} - \frac{1}{2}\sin^2 i + \frac{1}{2}\sin^2 i \cos 2(f+\omega)\right] \tag{2}$$

Here, μ is the standard gravitational parameter, R is the mean radius of the body, a is the semi-major axis, r is the orbit radius, i is inclination, and f is true anomaly. Averaging F over mean anomaly and considering only the first order secular perturbations results in the following expressions for the variations in orbital elements

$$\dot{a} = 0 \tag{3}$$

$$\dot{e} = 0 \tag{4}$$

$$\dot{i} = 0 \tag{5}$$

$$\dot{\omega} = \frac{3}{4}\frac{nR^2 J_2}{p^2}(4 - 5\sin^2 i) \tag{6}$$

$$\dot{\Omega} = -\frac{3}{2}\frac{nR^2 J_2}{p^2}\cos i \tag{7}$$

$$\dot{M} = \frac{3}{4}\frac{nR^2 J_2}{p^2}(2 - 3\sin^2 i) \tag{8}$$

In the above equations, e is the eccentricity, M is the mean anomaly, n is the mean motion, and $p = a(1-e^2)$. From Eqs. (3)-(5) there are no first-order secular variations in mean semi-major axis, eccentricity, or inclination due to J_2. The rate of change for ω, Ω, and M depend on the orbit semi-major axis, eccentricity, and inclination. Assuming a fixed semi-major axis, from Eqs. (6)-(7), a low periapsis can lead to relatively fast time variations in ω and Ω, depending on the inclination. A relationship of these two quantities as a function of orbit inclination is shown in Figure 4. For a near-polar orbit (inclination near 90°), there is an appreciable negative $\dot{\omega}$. This means that due to the J_2 perturbation, the sub-latitude of the spacecraft periapsis moves southward by up to 1.7 deg/day. The periapsis quickly rotates around to the opposite side of Ceres. The combination of a fast-moving argument of periapsis and a very low periapsis altitude means that the orbit is in danger of rapidly entering shadow if the orbit plane does not accommodate the rotating argument of periapsis.

For example, consider an exactly polar orbit with a β-angle of 0°, meaning that the orbit plane is perpendicular to the ecliptic plane and lies along the Sun-Ceres line. In this geometry, if the periapsis begins at the equator on the lit side, it will take only 53 days for the periapsis to rotate around to the south pole. Further rotation of the periapsis places that part of the orbit in shadow. Since the Dawn mission was required to avoid flying the spacecraft through shadow, the mission design team investigated time-varying orbit plane solutions.

In Figure 4, the green "node rate" line (representing $\dot{\Omega}$) crosses zero exactly at an inclination of 90°. However, a slight deviation from a purely polar orbit imparts a small time rate of change

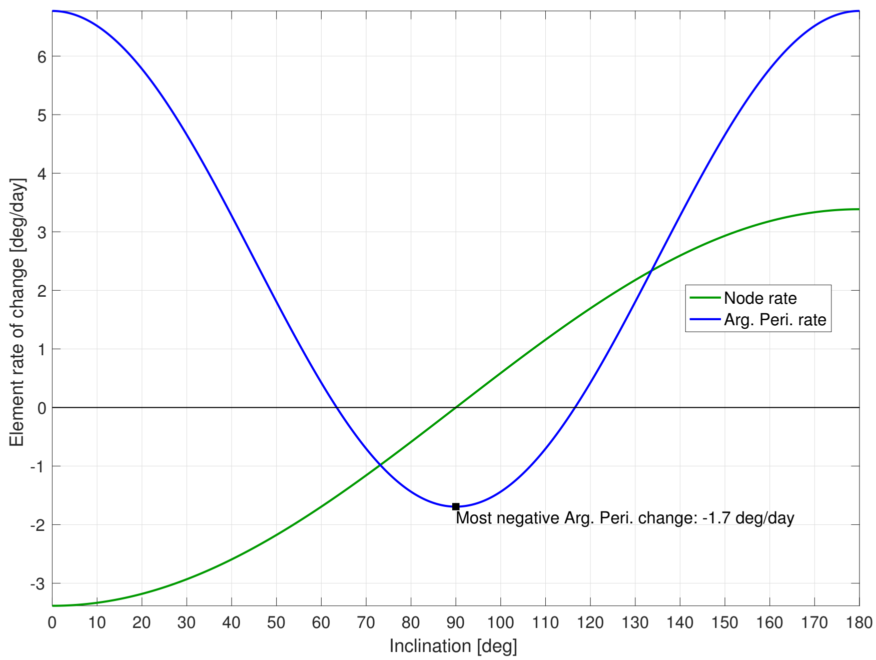


Figure 4. Time rate of change of ω and Ω for 3:1 resonant orbit with 505-km mean periapsis radius.

to the orbit plane, in either the positive or negative direction depending on the selected off-polar inclination. The team determined that a β-angle and corresponding drift rate could be selected so that shadow is avoided for a long time (on the order of several months), even with the relatively fast time variation of the argument of periapsis. As the periapsis rotates around the lit side and approaches the dark side, the orbit plane shifts simultaneously. Selecting the proper inclination allows the β-angle to change just enough so that the periapsis avoids shadow as it rounds the south pole and begins its northward journey.

It was desired to minimize the β-angle at the time when periapsis passed over Cerealia Facula. For optimal lighting conditions and to avoid shadow, the science team initially wanted XMO7 to have a fixed β-angle with β as low as possible to avoid shadow, which was similar to the design of LAMO. A low β-angle provides good lighting conditions for science imagery. The β-angle could not be zero, because such an orbit would place the spacecraft in eclipse when it traversed the dark side of Ceres. The team developed software to select an appropriate orbit inclination that would minimize the β-angle of the observations, while avoiding shadow on the dark side. Figure 5 shows the “admissible regions” of (i, β) pairs. The colored lines on the figure represent two constraints: avoid shadow upon insertion into the science orbit (blue, magenta, and red lines) for varying amounts of coast time between insertion and the Cerealia Facula observation, and avoid shadow when the periapsis rotates around the other side of Ceres (green line). Anything below the green line and to the right of the blue, magenta, or red lines represents an admissible point, where shadow is avoided at both the beginning of the orbit and after periapsis rotates to the other side of Ceres.

The solid black line in Figure 5 shows the inclination required for a fixed β-angle, which allows the orbit plane to drift at a rate exactly equal to Ceres’ rotation rate about the Sun. A small drift in the node of the orbit (Ω) counteracts the natural drift of the orbit plane relative to the Sun-Ceres

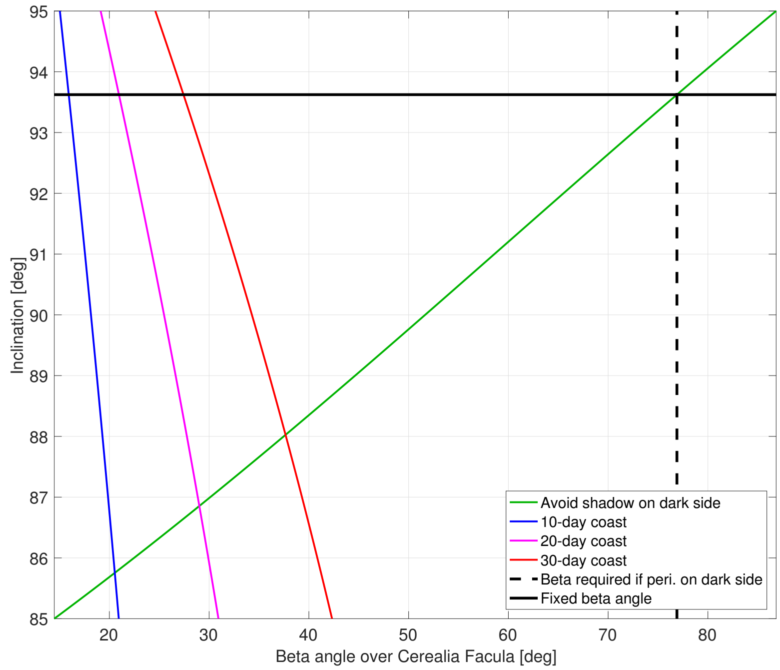


Figure 5. Approximate admissible regions for 3:1 resonant orbit with 505-km mean periapsis radius. "Coast" indicates time from orbit insertion to the first targeted fly-over of Cerealia Facula within Occator crater.

line due to Ceres' rotation about the Sun, allowing for Sun-synchronous orbits. An inclination slightly different from a pure polar orbit provides this required drift. This inclination may be found using Figure 4, where the green "Node rate" line equals the rotation rate of Ceres about the Sun ($\approx$0.2°/day). The second line in Figure 5 (dashed black) is the β-angle at which shadow is avoided on the dark side of Ceres, meaning that an orbit fixed at this β-angle will still avoid shadow, even without a controlled drift. However, the required value of β in this specific case is almost 80° (nearly a terminator orbit), which is much too high for the desired observations of Cerealia Facula. Since the orbital lifetime of XMO7 was expected to be around 100 days because of hydrazine limitations, XMO7 could accomodate an increasing β-angle that eventually crosses into shadow as long as shadow occurs after the expected end-of-mission. Allowing for a non-zero β-angle rate also allowed the team to design an orbit with a relatively small initial β-angle.

For example, the "best" choice of inclination for a 30-day coast between insertion and observation is at the corner where the red line and the green line meet in Figure 5. This choice minimizes the β-angle at the observation, and allows for a sufficient shadow margin to avoid eclipse. For this particular orbit, the choice of inclination is 88°, which provides a β-angle of approximately 40° at the observation of Cerealia Facula.

Because entering XMO7 earlier allowed for a lower β-angle, and because 30 days before the first flyover of Cerealia Facula seemed unnecessarily long, the team elected to have the first flyover occur 15 days post orbit insertion. The science orbit was designed by targeting sub-spacecraft latitude and longitude of Cerealia Facula for two consecutive orbits. The first flyover was constrained to be periapsis and the radius of the second flyover was minimized. The minimum β-angle at the first flyover is realized when the shadow margin at orbit insertion is minimized (shadow margin = 5° at orbit insertion to allow for margin). The following algorithm was used to compute the orbit:

The radius, β-angle, and inclination at the first flyover were all iteratively varied until (1) the mean periapsis radius was 505 km, (2) the initial shadow margin was 5°, and (3) the minimum downstream shadow margin was 5°. Predicted RCS thruster firings were included in the design of XMO7 and iteratively updated with the Dawn Attitude Control System (ACS) team. At the time of the first Cerealia Facula flyover, the converged orbit had an orbital radius of 511.6 km (altitude of 35 km), an inclination of 84.3°, and β-angle of 27.1°. The orbit is shown in Figure 6, where the rotation of the argument of periapsis is quite noticeable.

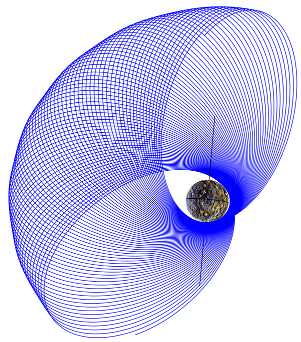


Figure 6. Final design of XMO7. For illustration purposes, only the first 75 orbital revolutions are shown.

Figure 7 shows the time-varying instantaneous shadow margin for the selected science orbit. At orbit insertion, the minimum shadow margin is exactly 5°, and quickly increases due to the β-angle drift. When the periapsis rotates near Ceres' south pole (around day 90), the shadow margin reaches a local minimum of 5°. However, because the β-angle continues to drift, the periapsis does not enter shadow. Instead, the orbit plane progresses to a near-terminator orbit ($\beta \approx 90°$), where the shadow margin is near 90°, around day 125. As the orbit plane continues to precess, the argument of periapsis rapidly moves around Ceres, and eventually shadow cannot be avoided. In the designed orbit, the first umbral crossing occurs on December 26, 2018, or about 199 days into the orbit, well after the usable hydrazine is depleted.

Remarks on Orbital Stability

A previous analysis[3] demonstrated that J_2 had a stabilizing effect on LAMO. J_2 similarly stabilizes XMO7. (Propagating this orbit without J_2 would result in an orbit that crashes within a few days.) From Eq. (3) and (4), to first order, J_2 has no effect on mean periapsis radius, but as previously noted it causes the argument of periapsis to rotate. The relatively high rate of change in ω has a stabilizing effect on the orbit. Orbits with lower $|\dot{\omega}|$ are less robust to solar gravity perturbations. Changing inclination or increasing apoapsis in a way that lowers $|\dot{\omega}|$ can destabilize the orbit. Based on numerical simulations that assume a fixed periapsis radius of 505 km, orbits start to destabilize when the apoapsis radius exceeds 7,000 km, or when orbit inclination is less than 81° or greater than 107°. Furthermore, because of the rotation of the argument of periapsis, the subspacecraft location of periapsis is never in exactly the same place. Thus, despite being in a "resonant" orbit, the resonance is never excited.

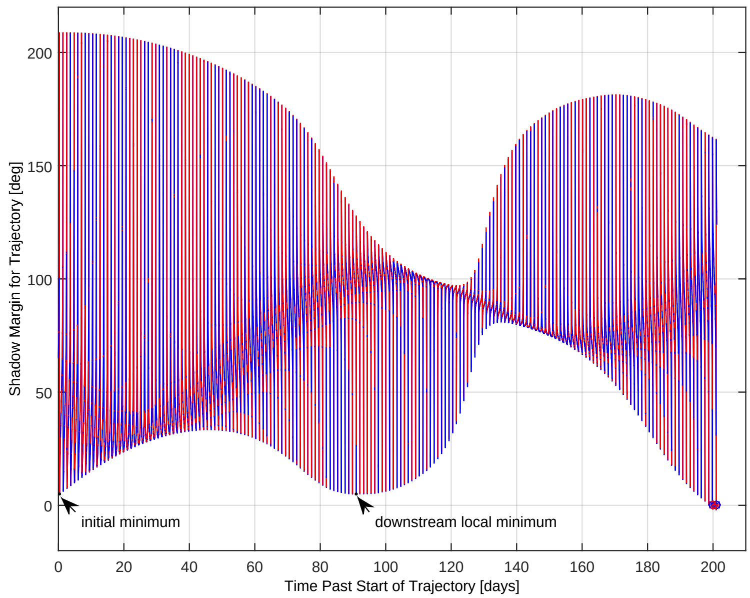


Figure 7. Shadow margin for the final orbit design.

MODELING AND SOURCES OF UNCERTAINTY

A Monte Carlo analysis was performed to assess the impact of all known uncertainty upon the Dawn spacecraft's Ceres orbital lifetime. Injection errors into XMO7 are small and insignificant due to the planned trajectory corrections maneuver at the end of IPS thrusting.[6] Therefore all propagations in the Monte Carlo analysis start at the reference orbit state. The Monte Carlo analysis includes Ceres' gravity field uncertainty and uncertainty from RCS thrusting during science orbit operations.

Mystic,[8,9] a low-thrust trajectory optimization program, was used to propagate Ceres orbital trajectories 50 years into the future. The propagator numerically integrates the equations of motion, models the gravity of the Sun and planets with the latest Ceres gravity field, and uses a flat plate solar radiation pressure model. Atmospheric drag was not considered since Ceres does not have an atmosphere of any significance. To account for variations in solar radiation pressure due to the solar cycle, an extremely conservative assumption was made that Dawn's large (36 m^2) solar arrays would always be Sun-pointed after loss of control of the spacecraft. When the flight system hydrazine supply is exhausted, gravity gradient torque causes the spacecraft to tumble chaotically.[10] The solar radiation pressure force on the spacecraft assuming the solar arrays are continuously Sun-pointed is much greater than that caused by variations in solar flux to a non-Sun-pointed spacecraft.

RCS Small Forces

One of the most significant sources of uncertainty in XMO7 orbit was the modeling of the induced ΔVs from the Reaction Control System (RCS). Since Dawn lost functionality of its reaction wheels, the momentum management and attitude control were entirely dependent on the hydrazine RCS thrusters. To maintain pointing and manage angular momentum, the spacecraft utilized a semi-autonomous control law that kept Dawn's attitude within certain prescribed deadbands. Because the attitude state of Dawn within the deadbands was not deterministic, the RCS system could command a firing of any of the hydrazine thrusters at any time to remain within the deadbands. Because of this lack of determinism, there was a significant uncertainty in how the ΔVs from the RCS system would perturb the final orbit of XM2.

The navigation team studied the effects of the RCS uncertainty on two key quantities: 1) the spacecraft pointing uncertainty as it flew over the targeted Occator flyover, and 2) the perturbation of the orbit periapsis over time. To approach this analysis, the navigation team studied the statistical uncertainty of the RCS system based on inputs from the Attitude Control System (ACS) team.

The ACS team generated RCS predictions for the entire XMO7, simulating constant slewing between pointing the high-gain antenna (HGA) to Earth and pointing the instrument deck to Ceres nadir. This set of predictions provided a large number of samples from which to extract an "expected" performance of the RCS system. In addition to large slews between Earth and Ceres, the ACS team simulated RCS activity around periapsis in XMO7. Because science data acquisition occurred primarily at periapsis in the XMO7, the spacecraft needed to point the instrument suite toward Ceres nadir during the few hours around a periapsis. The nadir vector changed inertially over time, since the spacecraft was rapidly traversing through a wide range of true anomalies, so the spacecraft had to slew at a non-constant rate through periapsis in order to keep the instruments pointed toward nadir. These long turns accounted for more overall ΔV than the slews between Earth and Ceres, so the statistics of the periapsis activity were important to understand. Figure 8 shows an example of the predicted RCS activity in the spacecraft Z-axis over the timespan of several orbits. The "spikes" in activity occur around periapsis, indicating the increased RCS activity before and after periapsis.

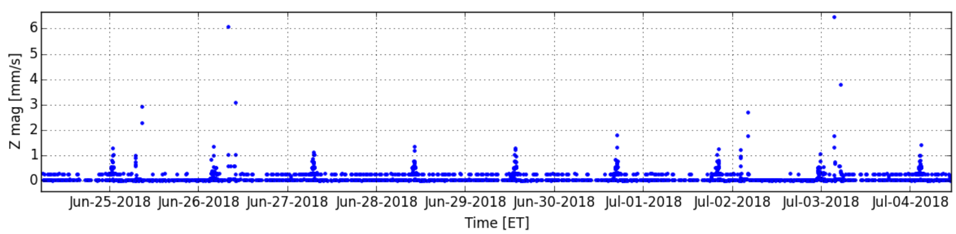


Figure 8. A subset of the RCS activity in the Z-axis predicted by the ACS team. The "spikes" indicate an increase in RCS activity associated with periapsis. The horizontal band just above zero is due to a prescribed minimum thruster pulse width for Z-axis control, with a corresponding minimum magnitude.

The simulated ΔV activity during slew activities between Earth and Ceres is shown as a set of contours in Figure 9 as a function of time since the start of XMO7 and the true anomaly in the orbit. Both of these independent quantities are strong predictors of the magnitude of a slew, because they dictate the relative geometry of Dawn, the Earth, and Ceres. Figure 9 depicts only the spacecraft X-axis RCS activity, for the start of slews from Earth-point to Ceres-point. Similar figures were generated for the other spacecraft axes and for other slew activities, but they are not shown here. Note that only true anomalies from 150°-210° are considered, since the spacecraft is nadir-pointed for several hours around periapsis, and slews only occur in a certain range of true anomalies away from periapsis (to protect science data collection around periapsis).

Figure 9 shows the strong dependence of the RCS ΔV magnitude on the time since the start of XMO7 and the true anomaly in the orbit. Bands of similar ΔVs are clearly visible, and it is relatively straightforward to predict the approximate magnitude of an RCS ΔV given the two independent quantities. Figure 10 shows the simulated predicted ΔVs just after periapsis while nadir-pointed.

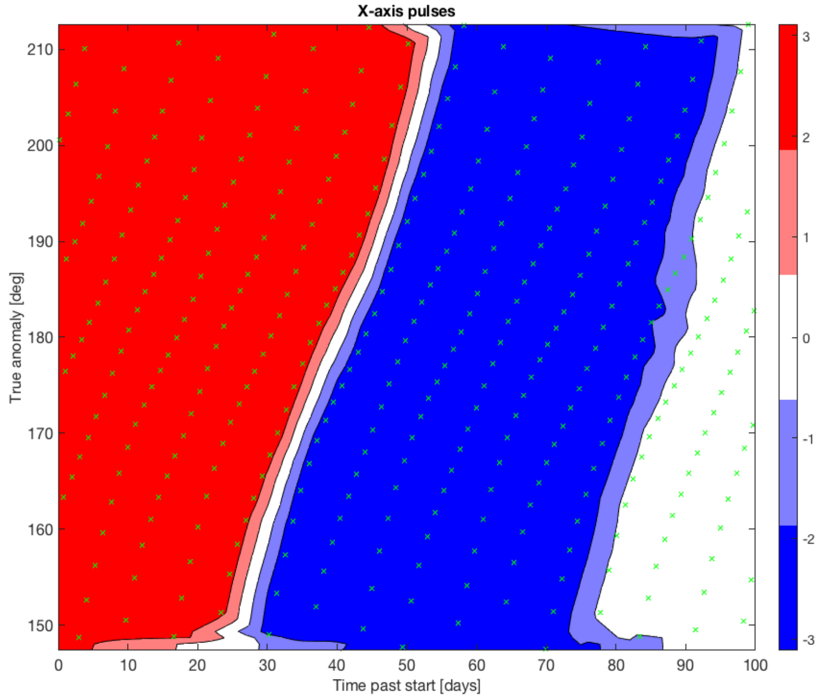


Figure 9. ACS-simulated magnitude [mm/s] of RCS activity along the spacecraft X-axis during the start of slews from Earth-point to Ceres-point.

Note that Figure 10 shows the same type of information as Figure 9, but since periapsis is defined as a true anomaly of 0°, the contour plot collapses to a single two-dimensional line plot.

Figure 10 also illustrates the strong dependence of ΔV magnitude on the time since the start of XMO7. From figures similar to Figure 9 and Figure 10, the navigation team developed predictions of RCS activity that depended on true anomaly in the orbit and time since the start of XMO7. Those models (such as the black line in Figure 10) were compared against the simulated data, resulting in statistics on the expected performance of the RCS activity. Example residuals for the X-axis RCS thrusters during the start of slews from Earth-point to Ceres-point (corresponding to Figure 9) are shown in Figure 11. The standard deviation of the uncertainty between the navigation-derived model and the as-predicted RCS activity is 0.21 mm/s for this particular example.

The navigation-derived model for the final orbit of XM2 is comprised of a nominal predicted magnitude, a bias sampled once per simulation, and a statistical uncertainty for each simulated RCS activity. If an expected RCS perturbation magnitude v is predicted, the modeled achieved magnitude is

$$v_{modeled} = v_{predicted} + b + s \tag{9}$$

where b is a fixed bias (sampled once per simulation) and s is the statistical uncertainty per-activity. For each type of RCS activity, Table 1 gives the per-activity uncertainty (sampled once per RCS ΔV) and per-simulation bias (sampled once per simulation) modeled for the XMO7. Note that there are no RCS thrusters in the Y axis, because the solar panels are mounted to the +Y and -Y decks.

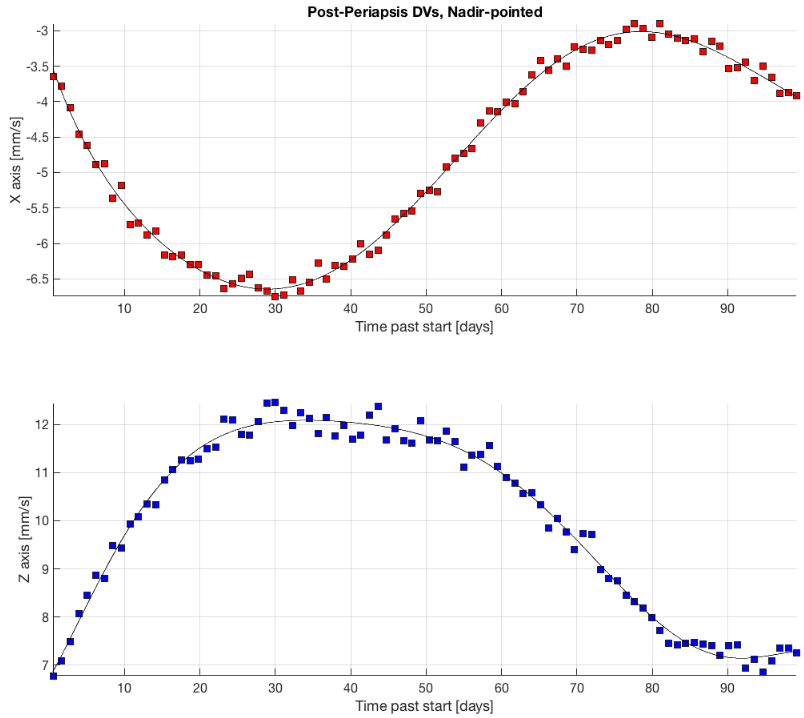


Figure 10. Simulated magnitude of RCS activity just after periapsis, while pointed to Ceres nadir. Note that there are no RCS thrusters in the Y axis, because the solar panels are mounted to the +Y and -Y decks.

Table 1. Error model parameters (Gaussian 1-σ) for RCS activity during XMO7.

Activity type	Spacecraft axis	Bias uncertainty (mm/s)	Per-activity uncertainty (mm/s)
Earth to Ceres start	X	2.0	0.908
Earth to Ceres start	Z	5.0	1.184
Earth to Ceres end	X	2.0	1.199
Earth to Ceres end	Z	5.0	6.120
Ceres to Earth start	X	2.0	0.433
Ceres to Earth start	Z	5.0	0.850
Ceres to Earth end	X	2.0	1.020
Ceres to Earth end	Z	5.0	1.509
Periapsis start, nadir point	X	2.0	0.186
Periapsis start, nadir point	Z	5.0	0.532
Periapsis end, nadir point	X	2.0	0.181
Periapsis end, nadir point	Z	5.0	0.413
Periapsis start, Earth point	X	2.0	0.282
Periapsis start, Earth point	Z	5.0	0.501
Periapsis end, Earth point	X	2.0	0.275
Periapsis end, Earth point	Z	5.0	0.475

With the RCS uncertainty model given by Table 1, and a time- and true-anomaly-dependent model of the nominal RCS ΔV magnitudes, the navigation team performed a Monte Carlo analysis, prescribing for each run a set of slew times relative to periapsis, and sampling the error model to propagate a perturbed trajectory. As previously noted, the quantities of interest were how accurately

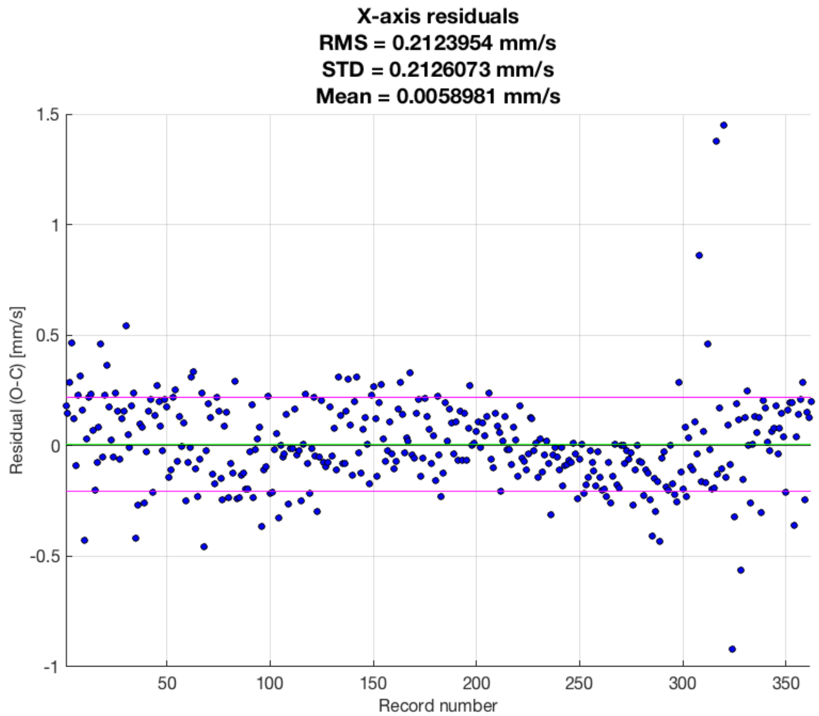


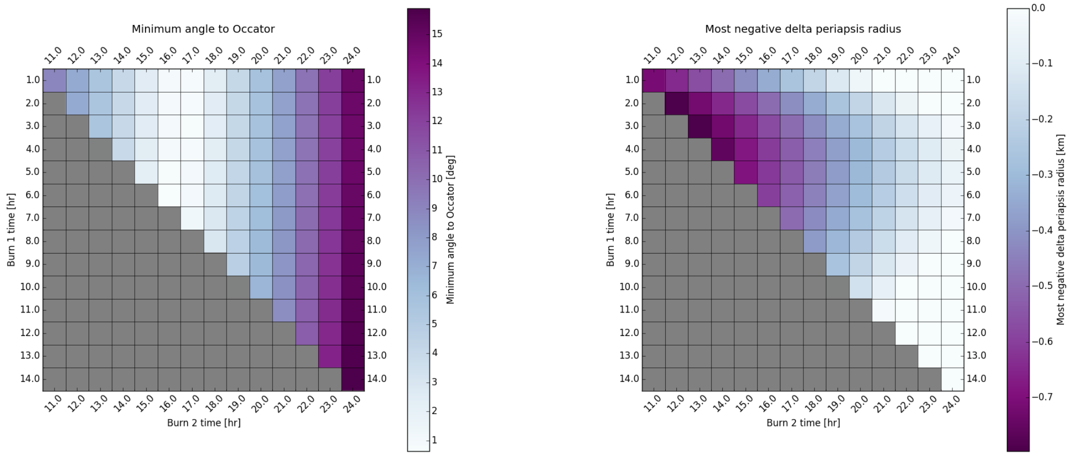
Figure 11. Residuals of ACS-predicted vs navigation-predicted RCS activity. The statistics on this type of thruster activity informs the uncertainty model of the in-flight predicted RCS performance.

the navigation team could expect the spacecraft to fly over the Occator crater, and how much the periapsis radius of the orbit was affected. Figure 12(a) shows the minimum angle achieved between spacecraft nadir and the direction of Cerealia Facula for each pair of slew times per orbit (Burn 1 is from Ceres to Earth, and Burn 2 is from Earth to Ceres). Figure 12(b) shows how much the minimum periapsis radius deviates from the reference depending on when the slews are performed.

Figure 12(a) shows the necessity of using predicted RCS activity in the final trajectory to target Cerealia Facula. The trajectory could conceivably be perturbed enough to place the facula outside the camera's five degree field of view. Figure 12(b) shows that performing the second slew (from Earth to Ceres) later in the orbit perturbs the orbit less than if the slews are placed closer to the beginning of the orbit. In the final design, the slew pairs were placed every six orbits, at approximately 4 hours after periapsis and 6 hours prior to the following periapsis (approximately 21 hours after the previous periapsis).

Ceres Gravity

Uncertainties in Ceres' physical parameters are an important part of the Monte Carlo analysis. The parameters of interest are Ceres' pole orientation, rotation rate, prime meridian at epoch, GM, and gravity field, all of which have been significantly improved from several years of operations in orbit, particularly in LAMO.[11] For the Monte Carlo analysis, the best 18×18 Ceres gravity model is conservatively sampled by inflating the formal uncertainty by a factor of five for harmonics below degree and order 4. Uncertainty for the higher-order terms is inflated by a factor of two.



(a) Minimum angle achieved between spacecraft nadir and the direction of Cerealia Facula in the Occator crater. Zero degrees indicates that the nadir direction passes directly through the faculae.

(b) Most negative variation of periapsis radius compared to the reference XMO7 trajectory. A more negative number indicates the periapsis descends closer to the surface of Ceres than the reference does.

Figure 12. Data for each pair of slew times relative to periapsis (Burn 1 and Burn 2). Note that there is a minimum time of 10 hours between burns, resulting in the gray area.

Shape Model

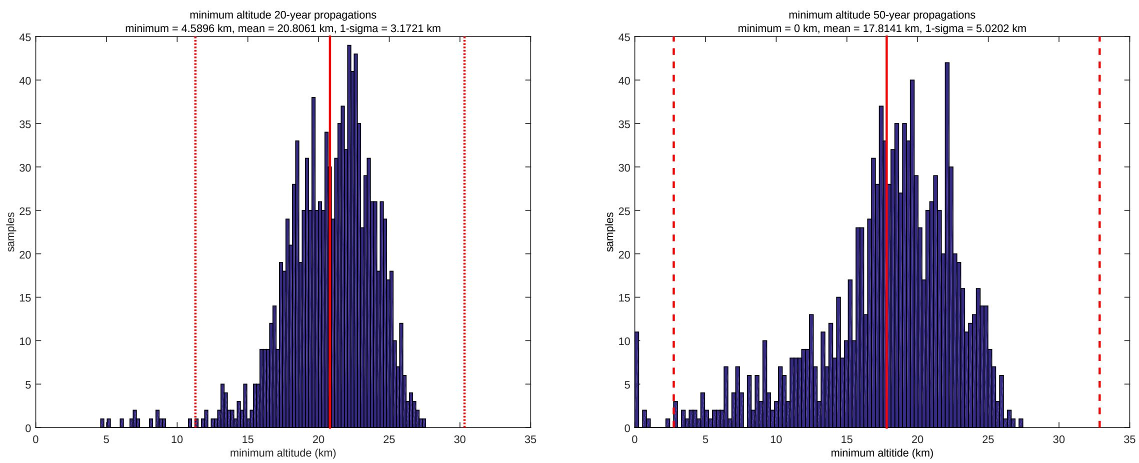
A high-resolution Ceres shape model with over 3 million vertices was created by the JPL Optical Navigation team based on LAMO data. Near the equator the distance from Ceres' center of mass to the surface varies from 475-488 km and at the poles 440-455 km. To account for these variations, for orbital lifetime calculations, altitude is computed with respect to the radius of the sub-spacecraft latitude and longitude. For conservatism, for all altitude calculations the radius was inflated by the formal 3-σ or 300 m, whichever quantity is greater (except at the poles, usually 3-$\sigma \ll 300$ m).

ORBIT STABILITY & PLANETARY PROTECTION

End-of-mission occurred in XMO7 on October 31, 2018, when the spacecraft expended its usable hydrazine to control attitude. Before transferring into this orbit, as stipulated by the Dawn planetary protection plan,[12] the project was required to demonstrate an orbital lifetime around Ceres exceeding 20 years post-orbital insertion. XMO7 was propagated 50 years past the anticipated end-of-mission using the team's best models and predictions. The minimum orbital radius for this propagation was 489.02 km, more than 300 m above the highest point on Ceres' surface, however, during the 50-yr propagation the spacecraft never passed over the highest point at periapsis. Using the high-resolution Ceres shape model, the minimum altitude for the 50-yr propagation was 18.77 km.

To ensure planetary protection requirements were satisfied, the team elected to demonstrate with 99% confidence lifetimes exceeding 50 years using the end of mission operations as the starting point (about 3.5 years after arrival at Ceres). Loss of spacecraft maneuverability was assumed for all lifetime analyses. A Monte Carlo analysis was performed to quantify the impact of known uncertainty parameters. All samples were propagated with JPL's high-fidelity orbit propagation software Mystic. For 1,150 randomly sampled gravity fields, trajectories are propagated from the reference orbit injection state through 100 days of RCS thruster activity, including RCS thrust uncertainty, to model the effects of spacecraft slews during science operations in the final orbit. The trajectories are then propagated post-mission for 20 and 50 years, and the minimum altitude for each sample is stored. Figure 13(a) shows a histogram of the minimum altitude for every sample during the 20-yr propagation. As shown in the figure, none of the 1,150 samples impact Ceres within 20 years. The minimum altitude for 20 years of propagations of all samples was 4.59 km.

A histogram for minimum altitude for 50-yr propagations is provided in Figure 13(b). For simulations up to 50 years post-mission, 99.1% of the samples do not impact Ceres. The few samples that crashed into Ceres impacted far from regions that are biologically interesting. From these results, the Dawn team is 99% confident the Dawn spacecraft will remain in orbit for at least 50 years. A summary of these results were submitted in a NASA report delivery to headquarters in April 2018.[12]



(a) 20-year propagations

(b) 50-year propagations

Figure 13. Histograms of minimum spacecraft altitude from Ceres' surface for Dawn lifetime analyses ($\pm 3\sigma$ lines in red).

RECONSTRUCTED PERFORMANCE

Prediction Performance and Reconstruction

Accurate predictions of the Dawn trajectory were required for the execution of the XM2 mission. The orbit determination (OD) team generated these trajectories using mainly these inputs:

1. OD team estimate of the spacecraft state at the end of the latest available tracking data
2. ACS team predictions of future thruster firing from the RCS
3. Gravity Science team model of the Ceres GM (μ) and gravity field harmonics

The predicted trajectories are used for three purposes:

1. Science sequence implementation.
2. Real-time knowledge of the Ceres-relative spacecraft position for the on-board ACS.
3. Corrections to camera pointing for imaging Cerealia Facula.

The science sequences for XMO7 were designed to acquire imaging, GRaND, and gravity science data during most of Dawn's periapsis passes. Once every several orbits, the spacecraft would pause the collection of science data to download the collected instrument data through the HGA. In order to be successful, the science sequences would have to be implemented with predictions of the times of periapsis, and also the times when Dawn's view of the Earth was occulted by Ceres. Failure to predict the former would result in data being collected at higher altitudes than desired. Failure to predict the latter would result in a loss of data downlink, and a likely loss of instrument data because the downlink bandwidth had little margin for data playback. The science sequences were generated weeks before they were uploaded to the spacecraft, and were designed to be executed over approximately four weeks. One week before upload, there was a planned opportunity to take the best estimate of the predicted trajectory and update the sequences to reflect any changes in periapsis, or occultation times.

The ACS was tasked with pointing the HGA towards the Earth during data downlink sessions, and pointing the instrument payload in the Ceres nadir direction during periapsis passes. The nadir pointing control was implemented using a Ceres-relative spacecraft ephemeris. There was no requirement on the pointing performance of the predicted trajectory. Instead, the performance was capability-driven. It was planned to update the on-board ephemeris every time there was a planned pass using the HGA (every six orbits, approximately), and the pointing performance would be accepted as is. Figure 14 shows the pointing performance of the on-board ephemeris against the post-flight reconstructed trajectory for the first several weeks of XMO7. The spikes in performance (representing worse prediction vs reconstruction performance) are so high because of the proximity of periapsis to the Ceres surface. A small ephemeris error near periapsis results in a large nadir-pointing error.

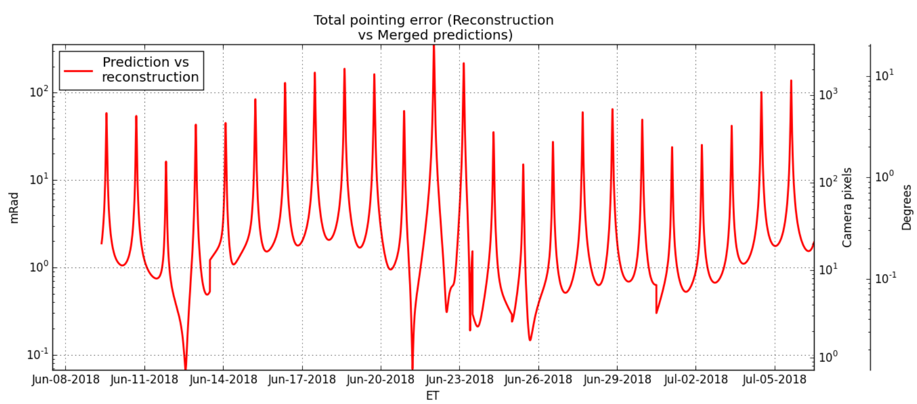


Figure 14. Reconstructed nadir-pointing performance during the first several weeks of XMO7. The spikes of up to 10 degrees occur during periapsis, where the error in predicted position is at a maximum.

Errors in Prediction

Of the three primary errors that impact the trajectory prediction (initial state, gravity and RCS activity) the thruster firings had the greatest impact, and are the only errors to be discussed further.

The on-board ACS provided 3-axis control of the spacecraft attitude. Normally, this control would have been asserted using reaction control wheels. However, since three of the four wheels had failed, the control had to be asserted using only the spacecraft's unbalanced RCS. The resultant thruster firing from the RCS perturbed the trajectory continuously, and these firings were quite aggressive, generating large ΔVs as previously described.

Errors caused by uncertainty in RCS activity resulted in periapsis time prediction errors, which led to compounded errors in predicting future periapsis times, because the predicted RCS activity assumed the spacecraft would be in a different part of its orbit.

Targeting Cerealia Facula

During the first portion of XMO7, the imaging of Cerealia Facula was carefully planned. Care was taken to mitigate errors in prediction of the time of the periapsis, which would result in Dawn being over the wrong longitude at periapsis.

The attempt to image Cerealia Facula began with a low-thrust trajectory correction maneuver (TCM) on June 21 2018, one day before the first of two planned flyovers. The TCM was designed using a prediction of the effects of thruster activity on the future trajectory. This TCM corrected most of the error resulting from the thrust that injected the spacecraft into the lower orbit. Further details can be found in Whiffen.[6]

Most of the residual error in the TCM execution was in the prediction of the thruster activity between the design of the TCM and the execution of the TCM. The pointing error was of order 2 degrees, which could result in the target terrain falling outside of the camera field of view. To accommodate this error, the navigation team had previously planned to provide a prediction of the longitude error the day before the observations. Based on this late-breaking prediction, the spacecraft was commanded to point off-nadir by an angle sufficient to point the camera at the target terrain. Table 2 shows a sample of the targeting information used to generate the pointing commands, based on a navigation prediction.

Time [ET]	Angle [deg]	Range to Occator [km]
22-JUN-2018 00:48:08.1	4.886	34.7
23-JUN-2018 04:01:26.6	9.003	35.1
24-JUN-2018 07:12:09.3	9.095	35.5
25-JUN-2018 10:21:11.1	35.184	44.7

Table 2. Occator (Cerealia Facula) targeting offset angles for the flyovers on June 23rd and 24th.

In this fashion, Cerealia Facula was targeted during several periapsis passes, with resolution improving as the sub-latitude of the periapsis migrated at roughly 1.7 degrees per day. Figure 15 shows a plot of longitude uncertainty at Cerealia Facula's longitude that was later used for planning additional observations. Affectionately known as a "tornado plot", it shows the 1-σ predicted longitude uncertainty at Cerealia Facula's latitude, the altitude at that latitude, and the orbit number. Note that time, not latitude, is on the vertical axis, because the figure shows longitude uncertainty at a specific latitude. The oscillating longitudinal signature is due to the 3:1 resonance of the orbital period with the rotation of Ceres. The trajectory used to generate Figure 15 was reconstructed using data through orbit 28 and the corresponding differences in reconstructed vs. predicted confidence in orbit sub-longitude are apparent. With planning aided by these orbit analyses, successful imaging of Cerealia Facula was performed through several flyovers.

A final reconstruction metric is the predicted vs reconstructed sub-spacecraft location of periapsis for successive orbits. Figure 16 shows latitude/longitude plots of the periapsis location for three different prediction times. Subplot (a) shows the predictions upon entry into the XM2 orbit (before

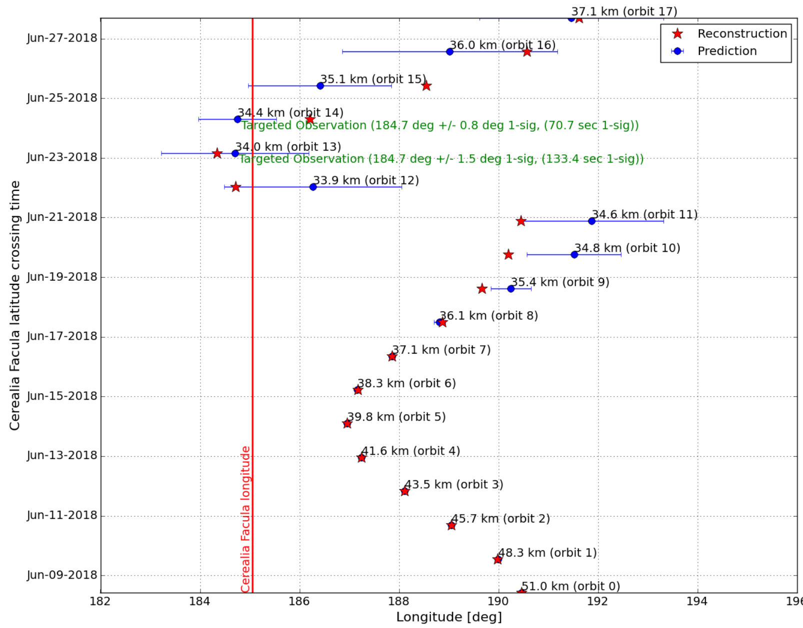
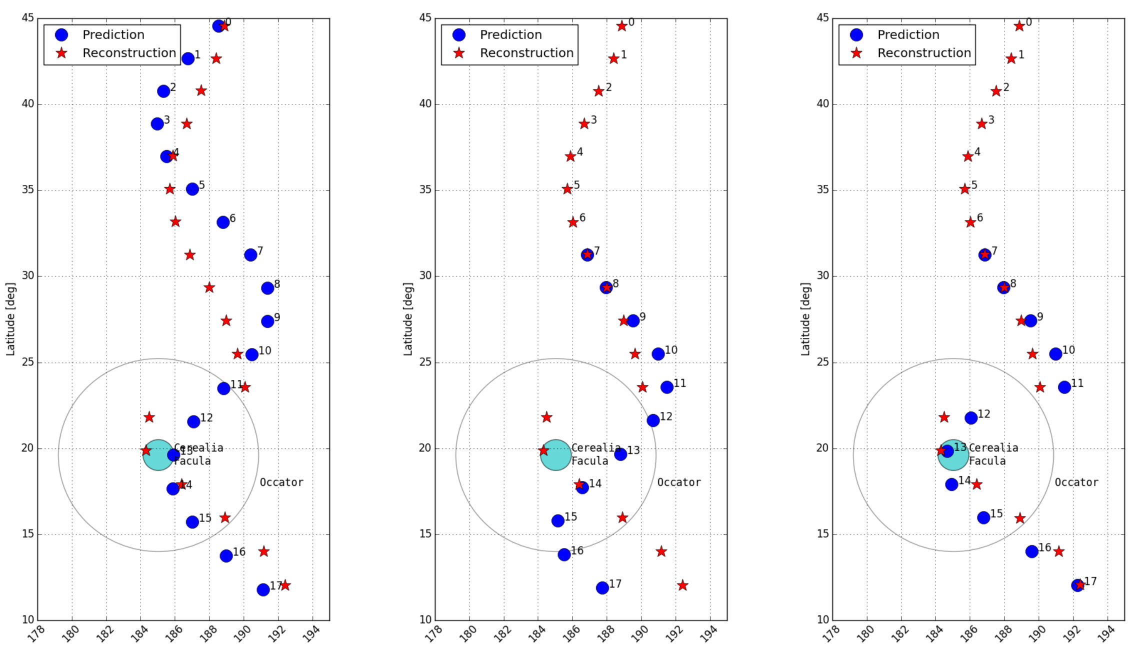


Figure 15. A "tornado plot", showing the predicted and reconstructed longitudes when flying over Cerealia Facula. The sudden westward shift between orbits 11 and 12 is a result of executing the TCM on June 21st.



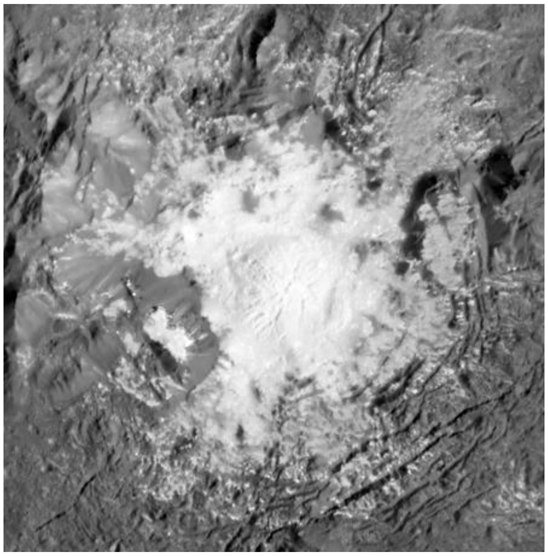
(a) Prediction before Orbit 0

(b) Prediction before Orbit 7, no TCM planned

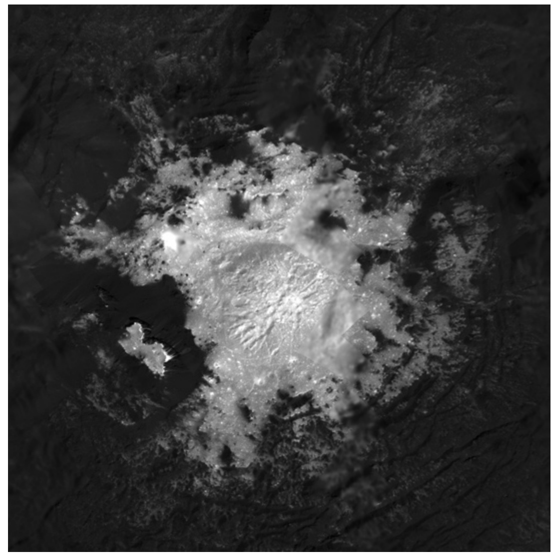
(c) Prediction before Orbit 7, with TCM planned

Figure 16. Sub-spacecraft locations of periapsis for successive orbits, compared to the Occator crater and Cerealia Facula surface features.

the TCM was planned), subplot (b) shows the predictions at the decision point for the TCM design, showing the predicted periapses locations if no TCM was to be performed, and subplot (c) shows the predictions including the TCM design, intended to target Cerealia Facula. Note the large westward shift between periapses 11 and 12 due to the TCM, which achieved its purpose of placing periapsis 13 over Cerealia Facula. Mosaics of Cerealia Facula from LAMO ($\sim$360 km altitude, the highest resolution before XMO7) and XMO7 ($\sim$35 km altitude) are shown in Figure 17. The XMO7 image was stitched together using images collected over multiple low-altitude periapses.



(a) LAMO



(b) XMO7

Figure 17. LAMO and XMO7 mosaics of Cerealia Facula, inside Occator crater. Image credit NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/PSI.

CONCLUSION

This paper describes how the final orbit of the Dawn's second extended mission was designed. The orbit was uniquely challenging to fly because of its low periapsis and high eccentricity. To make sure that the orbit could be safely navigated, all sources of known uncertainty were examined in detail, including uncertainty in Ceres gravity, RCS thrust during science operations, and Ceres topography. The final orbit was designed to have a periapsis as low as possible while ensuring with greater than 99% confidence the spacecraft would not crash into Ceres in 50 years post end-of-mission. The trajectory was designed such that the Dawn spacecraft would fly directly over Cerealia Facula inside the Occator Crator at periapsis in two consecutive orbits, while minimizing the β-angle and avoiding flying into shadow.

The XM2 mission was a complete success. The spacecraft arrived at its final orbit in June 2018. Both passes over Cerealia Facula were completed as planned, and all science objectives for the extended mission were satisfied. Science operations continued in the final orbit until the usable hydrazine was depleted, as planned. During this time, the spacecraft periapsis stayed within the bounds of our Monte Carlo studies, and 50-yr orbital stability is maintained even with the Navigation team's final state knowledge for the spacecraft. Loss of communication with the Dawn spacecraft occurred on October 31, 2018.

ACKNOWLEDGMENT

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