PREPARING FOR DAWN'S MISSION AT CERES: CHALLENGES AND OPPORTUNITIES IN THE EXPLORATION OF A DWARF PLANET

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After escaping from Vesta in 2012, Dawn is continuing its 2.5-year flight to dwarf planet Ceres. Investigating this second destination promises to provide a view of an intriguing world of ice and rock, likely displaying fascinating geology entirely unlike any body yet orbited by a spacecraft. Dawn spends the significant majority of the time thrusting with its ion propulsion system to deliver the 3.6 km/s required to rendezvous with Ceres. Meanwhile, the operations team has developed the sequences that will be used there. Following orbit capture in March 2015, Dawn will fly to a series of four circular polar science orbits. The orbits, ranging from about 13,500 km to 375 km in altitude, are designed to optimize the scientific observations. The overall strategy for exploring Ceres is based strongly on the extremely successful 16 months of Vesta operations, during which Dawn met or exceeded all of its objectives. Nevertheless, the loss of two of the spacecraft's four reaction wheels has necessitated some important changes. Based on a very productive hydrazine-conservation campaign in the interplanetary cruise and the development of new hydrazine-efficient methods of operating at Ceres, there is good reason to expect that Dawn will be able to accomplish all of its objectives regardless of the health of the reaction wheels. This paper describes the progress in traveling to Ceres as well as the plans for exploring this giant, icy world.

INTRODUCTION

The Dawn mission is designed to conduct detailed orbital explorations of the two most massive objects in the main asteroid belt. Vesta and Ceres may have been in the process of growing to become full-sized planets when Jupiter's gravitational perturbations of the asteroid belt terminated their growth. Studies of these two protoplanets should shed light on the epoch of planet formation as well as the subsequent evolution of the solar system.

Dawn orbited Vesta from July 2011 to September 2012, during which it collected an extraordinary wealth of data including panchromatic and narrowband images in the visible and near infrared, neutron, gamma ray, visible, and infrared spectra, and gravimetry. With a mean radius of 261 km, this body is now recognized to be more like a small terrestrial planet than like the smaller undifferentiated asteroids. A brief overview of Dawn's findings at Vesta is in Rayman and Mase,¹ and many authors have presented more detailed and focused results.²

Dawn is the ninth project in NASA's Discovery Program. It is managed by the Jet Propulsion Laboratory. The principal investigator is from the University of California, Los Angeles. The spacecraft draws strongly from the heritage of previous
projects at Orbital Sciences Corporation, which was responsible for the design, building, testing, and launching. (JPL delivered some subsystems and components to Orbital for integration into the spacecraft.)

The scientific payload includes a visible and infrared mapping spectrometer (VIR). VIR was contributed to NASA by the Agenzia Spaziale Italiana (Italian Space Agency). It was designed, built, and tested at Galileo Avionica and is operated by the Istituto Nazionale di Astrofisica (National Institute for Astrophysics).

The nuclear spectroscopy is accomplished with the gamma ray and neutron detector (GRaND). GRaND was delivered by the Los Alamos National Laboratory and is now operated by the Planetary Science Institute.

A prime and redundant camera (framing camera 2, or FC2, and FC1, respectively) are available for imaging both for science and navigation. The units were contributed to NASA by the Max-Planck-Institut für Sonnensystemforschung (Max Planck Institute for Solar System Research) with cooperation by the Institut für Planetenforschung (Institute for Planetary Research) of the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) and the Institut für Datentechnik und Kommunikationsnetze (Institute for Computer and Communication Network Engineering) of the Technischen Universität Braunschweig (Technical University of Braunschweig).

Details of the spacecraft and payload design, as well as the mission design and scientific objectives, have been presented in detail elsewhere.3,4

Dawn is the only spacecraft to have orbited an object in the main asteroid belt. Now it is in transit to dwarf planet Ceres, the first dwarf planet discovered (in 1801). With a mean diameter of 952 km, it is the largest body between the Sun and Pluto not yet visited by a spacecraft. Vesta and Ceres together contain about 40% of the mass of the entire main asteroid belt.

Dawn's mission is enabled by solar electric propulsion (SEP), implemented as an ion propulsion system (IPS). Without SEP, a mission to orbit either Vesta or Ceres would have been unaffordable within NASA's Discovery Program. A mission to orbit both would have been impossible. This is the only mission ever undertaken to orbit two extraterrestrial targets.

Dawn launched on 27 September 2007. Mission operations in interplanetary cruise through the end of 2013 and at Vesta in 2011-2012 have been described in detail.1,5-7

The loss of two reaction wheel assemblies (RWAs), the first in June 2010 and the second in August 2012 during the departure from Vesta, led to important changes in cruise operations and in planning for Ceres.7 Much of the project's focus in the months following Vesta departure was focused on minimizing hydrazine expenditure.

Cruise Operations

The standard state of the spacecraft in interplanetary cruise is thrusting with one of the three ion thrusters. As of 8 September 2014, Dawn has thrust for 41,300 hours (68% of the time in flight), providing 10.1 km/s since launch. The thrusting has consumed 364 kg of xenon propellant. The interplanetary trajectory is shown in Fig. 1.

Prior to Vesta as well as during the first months after departure, thrusting was suspended once a week to allow the spacecraft to turn from the thrust attitude to point its high gain antenna (HGA) to Earth. To conserve hydrazine, however, the frequency of high-
rate telecommunications sessions was reduced to one in four weeks starting in January 2013. The mission continues to fly this way.

The use of SEP tightly couples mass, power, and thrust time. Moreover, the thrust attitude at any time in the mission is dependent on the thrust at all other times. To design an efficient trajectory from Vesta to Ceres, it is important to know the power available to the IPS throughout the interplanetary cruise. Because Dawn recedes
from the Sun during much of this phase of the mission, the heliocentric-range-dependent power generated by the solar arrays was predicted based on extrapolating from lower ranges. To improve the accuracy of the predictions, dedicated solar array calibrations were conducted.

The first calibration was performed in June 2013 at 2.48 astronomical units (AU) from the Sun. Both solar arrays were rotated to reduce insolation, simulating conditions at greater heliocentric range. IPS thrusting was necessary in order to place a sufficiently large load on the solar arrays to measure their capability. With five angles representing solar distances up to 3.0 AU, data were collected to refine the solar array model.

The calibration was repeated in October 2013 and February and May 2014. The final one is scheduled for September 2014 at 2.71 AU.

Improvements in the solar array model and the model for non-IPS power consumption have allowed an increase in planned power for thrusting. This moves the Ceres arrival earlier.

As part of the campaign to conserve hydrazine after the second RWA failure, all activities other than ion thrusting and regular telecommunications sessions during cruise were reassessed. (Hydrazine consumption is lower during thrusting because two axes of spacecraft attitude are controlled with the gimbaled ion thruster rather than with the hydrazine-based reaction control system.) This led to a reduction in the number and duration of coast periods, which had been included to allow for activities incompatible with optimal ion thrusting. The change in the mission plan not only saved hydrazine, it shifted the Ceres arrival earlier.

As a result of the changes in power and available thrust time, the nominal Ceres arrival date (defined to be when Dawn is gravitationally captured) has moved to early March 2015. The current best estimated arrival is 7 March, although changes of a few days are still anticipated. This is almost a month earlier than was predicted last year.

Anomalies that interrupt thrusting will delay arrival. The principal interest in protecting the arrival date is the cost of hydrazine for extending the duration of the interplanetary cruise. (The flexibility of the mission timeline because of the use of SEP is otherwise accommodated with operational procedures.) To avoid long periods of missed thrust, Dawn has conducted thrust verification (TV) sessions twice each week throughout cruise. For two to five hours, the spacecraft transmits through a low gain antenna while thrusting.

Because of details of the fault protection design, any loss of thrust will invoke one of Dawn's two kinds of safe modes. Further, both kinds of safe mode preclude thrust. In other words, verification that Dawn is not in a safe mode is equivalent to verifying that it continues thrusting. Therefore, only minimal data are required for thrust verification. Indeed, often carrier strength (as a proxy for attitude), telemetry rate (which sometimes is different while thrusting than in a safe mode), or Doppler shift is sufficient by itself to verify thrusting.

Since May 2010, when Dawn was too far from the Sun to thrust at the maximum IPS throttle level and power the 100 W (RF) traveling wave tube amplifier of the telecommunications system without drawing energy from the battery, it has been necessary to reduce the throttle level during the TV sessions. Although the primary objective is thrust verification, data transmitted at 10 or 40 bits/s provide additional insight into the spacecraft state.

The sensitivity of the arrival date to missed
thrust is not a constant but rather varies significantly during cruise. The second and final optimal coast of the mission occurred in November-December 2013, and missed thrust around that time would have had a negligible effect on the arrival. The period of greatest sensitivity was June - August 2014, when the delay in Ceres could have been about nine times the duration of missed thrust. (This ratio applies for thrust interruptions about two weeks long; the effect is highly nonlinear.) Long delays could incur high hydrazine expenses.

To reduce the mean time between a loss of thrust and discovery by the operations team, more frequent TV sessions began in July 2014. Although they could have been implemented exactly like the ones that had already been conducted for years, the project decided to do the new ones differently.

Powering on the transmitter requires reducing the IPS throttle level or drawing energy from the battery. The former introduces tolerable but undesirable complexity to navigation, and the latter puts stress on the electrical power system. Based on those and other considerations, the project, in collaboration with the DSN, devised no-downlink TV (NDTV) sessions.

For NDTV sessions, the spacecraft does not activate downlink, but the DSN looks for a signal to indicate Dawn is in a safe mode. These sessions are short, typically only one hour, so they are easily scheduled. Because the spacecraft is not an active participant, the schedule for the NDTV tracks is independent of the sequence-development process, further simplifying the scheduling of the coverage. They require no commanding on the spacecraft at all, and because they build on new automation capabilities at the DSN, they are relatively easy to implement.

If a downlink were observed, it would mean Dawn is in a safe mode and is not thrusting. The DSN would contact the operations team, which is otherwise uninvolved in the activity.

The absence of an observed downlink can be for one of three reasons. In order of decreasing probability, they are: 1) the spacecraft is not in a safe mode and hence must be thrusting; 2) there is an unrecognized anomaly at the DSN that precludes detection of the downlink; 3) there is a problem so dire that a safe mode cannot be achieved.

The first case is, of course, the one of interest. The third case is sufficiently unlikely that it may be dismissed. To understand the second, we consider that it is the ensemble of NDTV sessions that reduces risk. An unrecognized DSN anomaly that precludes detection of an extant downlink is rare. The probability of any one particular session leading to the discovery of a safe mode is very low, so even if an erroneous conclusion is reached because of a DSN anomaly, it is likely the subsequent NDTV session will detect the condition. With about five NDTV sessions per week (plus scheduled downlink twice a week), the possibility of a false negative is acceptable.

While cruise operations focused on ion thrusting, some other special activities have been conducted as well.

FC2 experienced three unexplained resets during Vesta operations. New software was installed in FC2 in June 2014 (and in FC1 in August) to capture diagnostic data should a reset occur at Ceres.

Thanks to the extraordinary efforts to reduce hydrazine expenditures in cruise and to devise hydrazine-efficient Ceres plans that meet all of the objectives, the two healthy RWAs are not needed. The mission can be accomplished with only the reaction control system (RCS) and RCS in combination with thrust vector control during ion thrusting.
Dawn is expected to have 21.5 kg of usable hydrazine available for Ceres operations. This compares favorably with an estimate of 16.2 ± 4 kg to complete all of the Ceres plans without RWAs. An additional 3.5 kg is held to account for anomalies from the present through the end of the primary mission. No hydrazine has been needed for anomalies since RWA3 failed more than two years ago.

Nevertheless, "hybrid" control, which uses two RWAs plus RCS and hence consumes less hydrazine than pure RCS control, will be used in the final orbit phase at Ceres, as discussed below. To preserve the two remaining RWAs, they are operated twice a year for maintenance. Hybrid control was installed in 2011 in case it was needed at Vesta. It was successfully demonstrated in 2013 and was used operationally for RWA maintenance in 2014.

The final significant cruise activities apart from thrusting will occur in a forced coast during the last week of October 2014. Following the prelaunch plan, radiometric navigation will be used to calibrate the thrust of IPS thruster #3 in the power regime to be used at Ceres. Only thruster #3 is planned for use at Ceres, but the mission can be accomplished with any of the thrusters. All of the IPS hardware is healthy and well within consumables allocations.

The same coast period will be used for the final health check and calibrations for FC2 and VIR before Ceres operations begin in January 2015. (GRaND's final operation before Ceres was in June 2014.) FC2 requires a source a few pixels across for in-field stray light calibration. As it turns out, a very convenient target is Ceres, which at a range of 2.3 million km, will be about 4.5 px in diameter. This engineering activity will not reveal any important new information about Ceres; the best resolution from Hubble Space Telescope (HST) is seven times better.

CERES PLANS

The Ceres plan is based strongly on the plan successfully carried out at Vesta. The principal differences are a result of a few considerations.

The dominant changes are because of the loss of two RWAs. Conserving hydrazine is extremely important, and that has led to the elimination of many turns, as we discuss below. The other two RWAs appear healthy, but confidence in them is low. Based on the assumption that their remaining operational lifetimes are short, we intend to use them where their benefit is the greatest. Hybrid control yields the largest savings in hydrazine (compared to all-RCS control) in the lowest altitude orbit, which is the final phase of the mission. Therefore, the RWAs will not be used in any of the previous phases.

The other significant difference between Ceres and Vesta is that Dawn escaped from Vesta. The mission will conclude with the spacecraft in its lowest orbit at Ceres. At Vesta, there was a special advantage to ascending from the lowest orbit apart from the obvious one of escaping to reach Ceres. Vesta's obliquity is 27°, and the first stereo mapping campaign occurred relatively near the northern hemisphere winter solstice. Following the low orbit phase, Dawn stopped during ascent to repeat the stereo mapping and other observations with the Sun significantly farther north. Ceres' obliquity is considered most likely to be ~ 3°, so the benefit of repeating a mapping campaign would not be significant.

Despite those differences, the structure of the plan for exploring Ceres is very similar to that for Vesta. There are four science phases and separate phases to transfer from one to another.

One of the lessons from the success at Vesta
was the great value of developing command sequences well in advance. Sequences for all phases have been built and reviewed by the operations team. Some key activities have been tested on the flight system testbed as well. All sequences will be updated at Ceres with final epochs and other details.

Ceres approach

The principal objective of the approach phase is to deliver the spacecraft into its first science orbit. Approach lasts about 12 weeks and consists mostly of ion thrusting, very much like the interplanetary cruise.

Thrusting will be interrupted eight times for optical navigation imaging sessions (opnavs). (As a bonus, VIR observations will be collected as well.) Some of the FC2 integration times will be optimized for Ceres and others will be chosen to show stars. The first, in mid-January 2015 in the current plan, will be at a range of about 420,000 km, when Ceres is about 24 FC2 pixels in diameter. By the second observation nine days later, at 290,000 kilometers, the images will be comparable to the best currently available from HST.

Almost three times as many opnavs were planned for Vesta. The number is significantly reduced to avoid the hydrazine expense of the turns and the time without the benefit of TVC. The low risk of having fewer opnavs is acceptable based on Vesta experience.

The first two opnavs will last one hour, and the rest will last two. To observe Ceres throughout a complete 9.1-hour rotation, two more observations will be performed during approach. These rotation characterizations, designated RC1 and RC2, will be at distances of approximately 170,000 and 75,000 km.

Opnavs #3 through #8 all will include extra images designed to search for natural satellites. In addition, there will be two dedicated satellite searches. The first follows immediately after opnav #6 and uses loose all-RCS deadbanding of ±5° (the FC2 field of view is 5.5°) for seven hours to image the space around Ceres. The second includes three-hour observations immediately before and after opnav #8, in this case with intentional pointing away from Ceres.

Capture will occur at a range of between 35,000 and 40,000 kilometers. The distance depends on details of the approach geometry that will be determined in the final few months of thrusting. Orbit insertion is not a critical event and does not even have any special activities associated with it. Downlink will not be scheduled. As at Vesta, the gradual thrust profile differs very little from that of interplanetary cruise. When Dawn thrusts into orbit, it will already have in excess of five years of ion thrusting experience. Thrusting will continue for about two more weeks until the spacecraft is in the first science orbit. Fig. 2 shows part of approach and the entry into the first science orbit.

Figure 2. End of approach trajectory. The dashed sections are where ion thrusting is interrupted for imaging and high-rate telecommunications. The proximity of capture of a coast period is entirely coincidental. Capture occurs during routine thrusting.
Ceres is only the second massive extraterrestrial body (excluding the Sun) that a spacecraft will orbit without first having been visited by a flyby spacecraft. (Vesta was the first.) Because of the uncertainty of the gravity field, the final designs for the science orbits will not be completed until Dawn measures the field. Values presented here are based on the best estimate of the gravity field from observation and theory.

Models of the gravity field are highly uncertain, and the deeper Dawn goes, the greater the effect on the trajectory will be. Other standard sources of trajectory error include determinations of the initial six-state, the IPS thrust vector, and impulses from the (unbalanced) RCS activity.

For all of the spiral descents, a short segment, usually seven days, of the thrust profile is loaded and executed. During a portion of each segment, the operations team uses the latest orbit estimate to update the design of the subsequent segment to keep the spacecraft flying on the reference trajectory to the next science orbit. At Vesta, key radiometric data for each "design cycle" were acquired through the HGA. To conserve hydrazine at Ceres, some of the required navigational data will be acquired through an LGA, avoiding the hydrazine cost of turns and time out of TVC. These LGA sessions are operationally equivalent to TV sessions in interplanetary cruise.

Design cycles are generally seven days at higher altitudes, five days for the intermediate orbits, and three days at lower altitudes. At the end of each design cycle, the spacecraft interrupts thrusting to point its HGA to Earth, the command sequence for the next thrust segment is uploaded, and new radiometric data are acquired.

First science orbit: RC3

The third rotational characterization (RC3) occurs at an altitude of 13,500 km, about two weeks after capture. As all orbits, RC3 will be nearly circular and polar. (The altitudes of the science orbits are shown to scale with Ceres in Fig. 3.) With a period of 15 days, Dawn will have ample opportunity to observe Ceres as it rotates.

Ceres will be 4° in diameter and so will fit comfortably in the FC2 field of view, even with all-RCS control. To minimize hydrazine consumption, deadbands for the two axes of instrument pointing in RC3 and lower orbits are ±0.64°. The third axis is ±5°. (Deadbands of the same size but around different axes are applied for pointing the HGA to Earth, so the antenna boresight can move by ±0.64° in two axes and the rotation around it can be ±5°.) All planning for imaging surface coverage is based on a conservative "reduced field of view," which is the actual field of view minus the deadband. This represents the portion of the view that is guaranteed to be captured, regardless of where the spacecraft is in a deadband. Of course, the full image will be larger, and that extra area observed in lower orbits is treated as bonus. This strategy
ensures that all surface coverage objectives will be met even with the loose deadbands.

Dawn will be targeted to the RC3 orbit but not to any particular phase in the orbit. There is no compelling motivation to include such a constraint. Therefore, of the five major observational periods in RC3, any of them can occur first.

While on the dayside, Dawn will acquire three sets of complete rotation observations of the illuminated surface with FC2 and VIR, one over the northern hemisphere, one near the equator, and one in the southern hemisphere. After each, it will turn to point the HGA to Earth to return the data. (GRaND will collect data for the entirety of the Ceres mission but likely will not begin detecting nuclear radiation from Ceres itself until the penultimate science orbit.)

When over the nightside, the spacecraft will observe the limb at high phase angles both in the southern and northern hemispheres. These two sets of observations also provide the best opportunity during the Ceres mission to search for evidence of water vapor in the space above the surface. Earlier measurements at 557 GHz with Herschel Space Observatory detected water vapor, possibly from cryovolcanism or sublimation of ice at or near the surface. It is not clear whether the number density of water molecules will be high enough for Dawn to detect them, especially with Ceres at about 2.88 AU from the Sun. FC2 and VIR were designed to observe solid surfaces of airless bodies.

Dawn flies most of the time with its radio transmitter powered off to allow the power to be devoted to ion thrusting. When it is not thrusting, however, the transmitter is on. In RC3 and subsequent science orbits, when science observations are being conducted, the spacecraft will transmit low-rate real-time telemetry or, when link margins are lower, carrier only. As the spacecraft points its instruments at the surface, the appropriate LGA will be selected. This will provide radiometric data for both the scientific and engineering measurements of the gravity field.

Second science orbit: survey

Upon completing the data return from RC3, ion thrusting will commence to lower the altitude to survey orbit at 4,400 kilometers. The spiral transfer will include about five revolutions over the course of a month.

Dawn will make seven revolutions in survey orbit with a period of 75 hours. Most of the time over the lit side will be spent pointing to nadir, acquiring FC2 and VIR data. On the first, second, and fourth dayside passes, the spacecraft will point FC2 at the limb for up to nine hours to acquire images for improving optical navigation's shape model and for surface photometry.

Because of onboard data storage limits, both in the instruments and in the spacecraft's memory, extensive effort was devoted to the scheduling of data acquisition in each orbit, even with the same pointing. The timing of VIR data acquisition will allow 80% to 90% of the surface to be covered during the seven revolutions. FC2 will accumulate images of more than 90% of the surface in all channels.

The spacecraft will spend the entirety of its nightside passes with the HGA pointed to Earth, transmitting science and engineering data.

During survey orbit, the updated gravity field will be used to finalize the design of the next science orbit and the trajectory to reach it.

Third science orbit: HAMO

It will take about six weeks to reduce the
altitude from survey orbit to the high altitude mapping orbit (HAMO) at 1,470 kilometers. (The name is not accurately descriptive, given the mapping in RC3 and survey. It is retained from early design concepts as a matter of convenience.) The transfer will include up to 30 revolutions, culminating in the 19-hour orbit period of HAMO. The transfer is illustrated in Fig. 4.

Figure 4. Transfer trajectory from survey to HAMO.

In 12 dayside passes, essentially the entire surface can be mapped with FC2 using the reduced field of view. Dawn will conduct six of these mapping cycles in HAMO. The first will be with the instruments pointed directly to nadir. The other five will map the surface again, each time at a different angle relative to nadir. This strategy provides the data necessary to develop a topographical map. The fifth cycle will be close enough to nadir that it could act as a replacement for a partial or even complete loss of data from the first cycle. But if data from both cycles are acquired, the 3° difference in pointing will aid in establishing the topography. Both cycles will acquire images with the panchromatic and color filters. The other four cycles will use the panchromatic filter only, so more VIR data can be returned.

HAMO is arguably the most scientifically intensive phase of the Ceres mission, as it was at Vesta. In both HAMO1 and HAMO2 at Vesta, every dayside pass in the 12-hour orbit was devoted to data acquisition and every nightside pass was devoted to data return. Turning that often at Ceres is not affordable. It turns out to be more hydrazine efficient to spend longer in HAMO, with some nightside passes pointing the instruments at the undetectable surface and some dayside passes pointing the HGA to Earth. With sufficient time, all required data can be acquired.

Dawn will make three or four (depending on the cycle) dayside passes making observations before a single nightside pass to return data. It will maintain the same cadence within a cycle. For all cycles, after 12 dayside data acquisition passes, interspersed with two or three data return periods over the dark side, the spacecraft will conduct a longer downlink session. Each cycle concludes with 2.5 revolutions (starting on the unilluminated side of Ceres) pointing the HGA to Earth.

With this strategy, HAMO can be completed with only 42 turns in six cycles, only one third as many turns as in the corresponding phase at Vesta. Because of the longer orbit period in Ceres HAMO and the extra revolutions required for returning data, the phase will last about 67 days, compared with half that duration at Vesta.

Fourth science orbit: LAMO

The final phase of the entire Dawn mission will be in the low altitude mapping orbit (LAMO), with a mean altitude of 375 kilometers, where the orbit period will be 5.5 hours. The descent from HAMO will require almost 60 days and 160 revolutions.

The focus of LAMO is on the acquisition of GRaND and high resolution gravity measurements. As a bonus, panchromatic images and
VIR spectra will be collected as well.

With a design based closely on Vesta LAMO, the altitude is chosen for GRaND so that the Ceres solid angle is the same as it was for Vesta, or about $0.34\pi$ sr. Dawn will spend up to three quarters of the time nadir pointed, the best attitude for GRaND, comparable to Vesta. Gravity data will be acquired with the LGAs when nadir-pointed and with the HGA when it is in use.

At Vesta, occasional orbit maintenance maneuvers (OMMs) were required to ensure the spacecraft did not enter eclipse. The gravity field at Ceres is expected not to present such a risk, so the only reason for OMMs would be to improve the ground track for surface coverage. Analysis of the probability of their being needed is ongoing.

LAMO is divided into segments of 20 orbits, or 4.5 days. FC2 and VIR data will be collected during as many as 12 orbits, and three are currently reserved for OMMs. Even if some OMMs are required, others may be canceled, as they were at Vesta. In those cases, the spacecraft will continue pointing to nadir to maximize the GRaND integration time. After 15 orbits, five will be devoted to high-rate data return.

Complete longitudinal coverage for imaging is achieved with 93 orbits. With the additional orbits during which imaging data are not acquired, a complete LAMO cycle lasts 101 orbits, or 21 days. One additional phasing orbit allows for optimal coverage from cycle to cycle. A complete data return from two LAMO cycles will be sufficient to meet the science requirements, but the baseline plan is for four cycles to be robust.

As discussed above, LAMO is the only phase in which RWAs will be used. The two units will be powered on at the beginning of LAMO, and hybrid control will be used as long as both remain fully functional. The plans are independent of the control mode, however, so although an RWA fault will induce a safe mode, the operations team will be ready to recover and resume science activities promptly.

The prime mission concludes with the fourth LAMO cycle. Including reasonable schedule margin (and technical resources to accommodate credible changes), that could be as late as 30 June 2016.

Extended mission possibility and end of mission

With the acquisition of up to four cycles of data in LAMO, Dawn’s nearly nine-year prime mission will conclude. Hydrazine is the most likely limitation on the ultimate lifetime. But if the flight system remains healthy with sufficient consumables and if NASA chooses to continue the mission, the most scientifically productive extension likely would be to continue to operate in LAMO, executing more cycles like those of the prime mission. Additional GRaND data would increase the precision for elemental abundances, and further gravity measurements may improve precision as well. Surface coverage with FC2 and VIR may be increased.

If not for the loss of the two RWAs and the consequent increased consumption of hydrazine, Dawn would have enough hydrazine (and xenon) to depart Ceres. No meaningful studies of such possibilities have ever been conducted however, as they would be too sensitive to when Dawn would be ready to leave. It has always been clear that further measurements at Ceres would be the first priority for an extended mission proposal.

Because of the likelihood of a substantial inventory of water, some of which may even be liquid, and other considerations, Dawn has a planetary protection requirement at Ceres.
Even with the worst-case credible gravity field, impact needs to be precluded for at least 50 years after entering orbit. (The requirement may be changed, based upon Dawn's findings at Ceres.) Extensive analysis was devoted to developing gravity fields based on the shape as determined by HST and stellar occultations and other physical modeling. In all cases, starting from LAMO, the orbit remains relatively stable and far from the surface for times long compared to 50 years.

Even if there were a motivation to reach the surface, it would be virtually impossible. Certainly a controlled landing is not possible, because the surface gravity is nearly 3% of Earth's. At 800 kg, Dawn would need a propulsion system with thrust of more than 200 N. Moreover, orbital velocity in LAMO is 270 m/s. To lower the orbit to the surface would require the same change in velocity as the transfer from HAMO to LAMO, which required two months. Given the limited lifetime, that time could be much more productively devoted to continuing to acquire data with all instruments.

CONCLUSION

Following the loss of two RWAs, the Dawn team has devised very effective methods of conserving hydrazine in interplanetary cruise and at Ceres. There is positive margin for accomplishing all of the Ceres objectives, even if the two remaining RWAs are inoperable.

Building on the outstanding successes at Vesta, Dawn's exploration of the first dwarf planet discovered promises valuable and exciting new insights into the dawn of the solar system.

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REFERENCES


7. Rayman, M. D., R. A. Mase, "Dawn's Op-


