Dawn’s Final Mission at Ceres: Navigation and Mission Design Experience

Han, Dongsuk[1], Kennedy, Brian[1], Rush, Brian[1], Grebow, Daniel [1],
Mastrodemos, Nickolaos [1], Whiffen, Gregory[1], Bradley, Nicholas[1], and Karimi, Reza[1],
[1] *Jet Propulsion Laboratory, California Institute of Technology,*
4800 Oak Grove Drive, Pasadena, California 91109-8099, U.S.A

Abstract

On Oct. 31st, 2018, the Dawn spacecraft completed its space journey covering more than 11 years including exploration of Vesta and Ceres, two protoplanets in the main asteroid belt. After successfully completing its prime mission at the dwarf planet Ceres, the Dawn mission was extended twice to pursue new scientific objectives. The second extended mission at Ceres, and the final mission for Dawn, presented a series of challenges that were new to the experienced and accomplished Dawn navigation team. This paper discusses mission design and navigational experiences and challenges during Dawn’s final transfer and orbit at Ceres. Topics include reference orbit design of the final science orbit, mission design and planning for the transfer, periapsis targeting over a surface feature, and analysis for planetary protection requirements.

Keywords: Dawn, Ceres, Low Thrust, Navigation, Mission Design, Extended Mission

I. Introduction

Dawn, a mission belonging to NASA’s Discovery Program, was launched on September 27, 2007 to explore two residents of the main asteroid belt in order to yield insights into important questions regarding the formation and evolution of the solar system. Its objective was to acquire data from orbits around two complementary bodies, Vesta and Ceres, the two most massive objects in the main belt. From July 2011 to September 2012, the Dawn spacecraft orbited Vesta, and returned valuable science data, collected during a total of six different mapping orbits at the protoplanet.

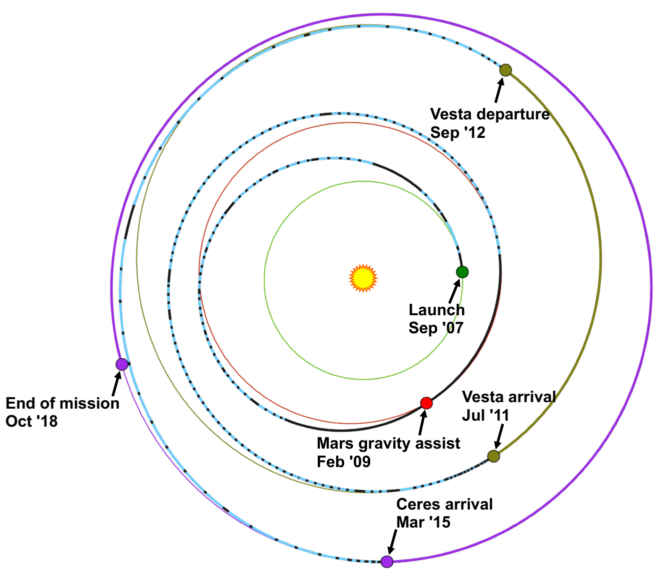

Fig. 1: Dawn's Interplanetary Trajectory

After completing interplanetary cruise, Dawn successfully arrived at Ceres in March 2015, becoming the first mission ever to orbit two different extraterrestrial bodies, as well as the first one to orbit a dwarf planet [1].

After acquiring all the planned data from four circular polar orbits and successfully completing its primary mission goals in June 2016, Dawn's mission was extended. In October 2017, NASA approved the second, and eventually final, extended mission of Dawn at Ceres to collect data at a much lower altitude than any of its previous orbits [2]. A simple timeline and heliocentric trajectory of Dawn's entire mission is depicted in Fig. 1.

Until on-board hydrazine became depleted on October 31, 2018, the Dawn flight team operated the spacecraft with limited fuel controlling the attitude and accomplished all the scientific goals set for Dawn's final mission. Operational challenges in navigation and mission design of the extended mission are further discussed in this paper.

Spacecraft and Payload

Built by a collaboration between JPL and Orbital Sciences Corporation, the Dawn spacecraft was designed to maximize the power available to the ion propulsion system (IPS) in order to meet demanding ΔV requirements. One prominent feature of the Dawn spacecraft is its large solar arrays, which span 20 meters wide. Dawn's on-board electrical power system provides sufficient power to operate the IPS when the spacecraft is at a heliocentric range of 3 au during Ceres operation. The spacecraft's two large solar arrays are designed to provide 10.3 kW at 1 au and 1.3 kW at their end of life at 3 AU. A simple depiction of the Dawn spacecraft is shown in Fig. *2*.

Dawn's IPS is an expanded version of the system used on NASA's Deep Space 1 spacecraft. This low-thrust engine can produce a maximum thrust of 91 mN at peak power and 19 mN at the lowest input power of 0.5 kW, with 112 discrete thrust levels in total. The highly efficient specific impulse range of 3200 and 1900 seconds played a key role in Dawn's feasibility. During the mission's entire operational period, Dawn's IPS system had accumulated 51,385 hours of thrust time and provided 11.5 km/sec of ΔV.

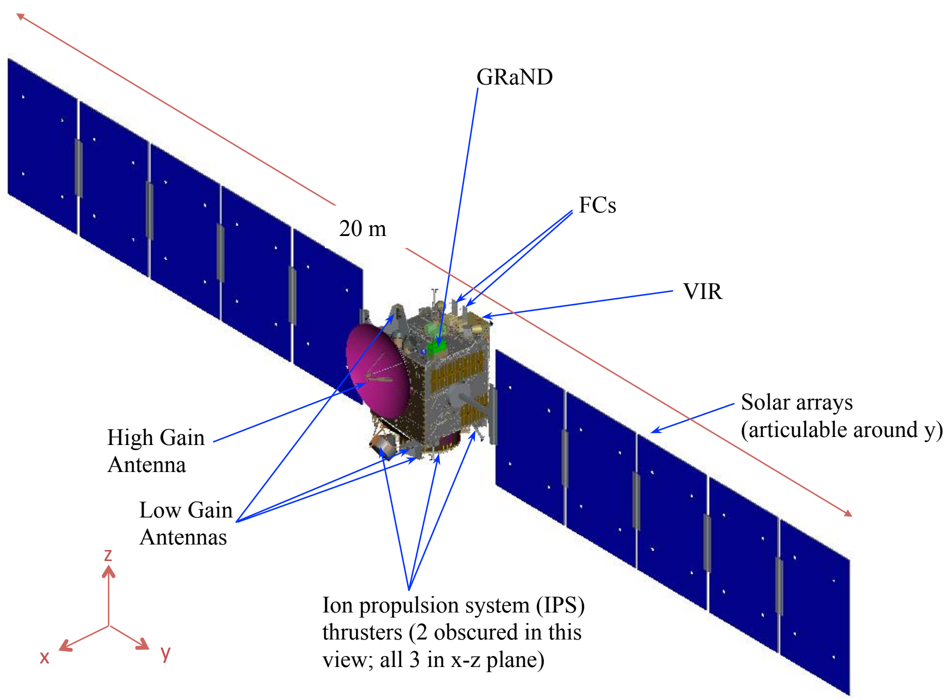

Fig. 2: The Dawn Spacecraft

The attitude control system (ACS) uses three different actuator systems: four reaction wheel assemblies (RWAs), twelve 0.9 N hydrazine fueled reaction control system (RCS) thrusters, and three gimbaled IPS thrusters. RWAs are the primary actuator for attitude control when not using IPS. When used during IPS thrust, the wheels provide control around the thrust vector, with the thrust vector control (TVC) providing control perpendicular to the thrust line. The hydrazine thruster system consists of two redundant sets of six thrusters that can be used for attitude control, or to adjust the momentum of the RWAs. Not all the hydrazine thrusters are coupled; every time the uncoupled thrusters are fired, a small ΔV is imparted to the spacecraft.

Dawn's scientific payload consisted of three instruments. The framing cameras (FC), contributed by Germany (Max Planck Institute for Solar System Research, Katllenburg-Lindau), acquired images for topography and provided images for optical navigation. The visible and infrared (VIR) mapping spectrometer, contributed by Italy (INAF, Rome), collected data to answer questions regarding surface mineralogy. The gamma ray and neutron detector (GRaND) developed by Los Alamos National Laboratory collected data to determine the elemental composition of the protoplanets. Additionally, gravimetric data were measured using the 2-way Doppler data between the spacecraft and Deep Space Network (DSN) antennas. All three science instruments are aligned with the spacecraft +z axis.

Dawn has four RWAs, and the baseline mission assumed the use of three at all times. One of Dawn's RWAs failed in June 2010 during its cruise to Vesta. A second failure occurred in August 2012, while Dawn was spiraling away using IPS after a successful completion of its mission at Vesta. After the third reaction wheel stopped in 2017, Dawn's attitude control was exclusively switched over to RCS using hydrazine.

II. Extended mission at Ceres

Upon completing the prime mission in June, 2016, Dawn began its first extended mission at the Low Altitude Mapping Orbit (LAMO) without changing its orbit. From July 2016 to October 2017, Dawn successfully completed all the goals associated with the first extended mission orbiting around Ceres for four additional mapping orbits. Each mapping orbit in both extended missions was referred to by a generic naming convention: XMO1 to XMO7. A brief timeline, short description of each orbit, and science goal at each mapping orbit phase are summarized in Table *1* and Table *2*.

Table 1: Science orbits in the 1st extended mission (XM1)

	Duration	Key Orbit description	Primary Science Goals
XMO1	2016/07/01 - 2016/09/01	LAMO [8] like, ~385 km circular	GRaND and gravity
XMO2	2016/10/06 - 2016/11/03	HAMO [8] like, ~1480 km circular	VIR's Juling observation
XMO3	2016/12/06 - 2017/02/22	Altitude > 7,200 km	GRaND background measurement
XMO4	2017/04/27 - 2017/06/03	Altitude < 20,000 km at Occator local solar noon	Occator measurement at low phase (2017/04/29, 2017/06/28)
XMO5	2017/06/24 - 2018/04/15	Orbit period 30 days, staging for the second extended mission	GRaND background measurement

As the first extended mission neared completion, the Dawn project studied two options for the second extended mission. One option was to continue investigation of Ceres, while the other was to leave Ceres in order to fly by asteroid 145 Adeona in the second half of 2019. With most of the objectives at XM1 fulfilled, Dawn was placed in a 30-day orbit (XMO5) and collected GRaND data while waiting for the NASA headquarters' decision regarding XM2. The final orbit of the XM1 was a near-optimal staging orbit if the decision was to go to Adeona, and minimized hydrazine consumption.

In late October of 2017, the choice for the XM2 was made by NASA to stay at Ceres. Dawn would be maneuvered to a highly elliptical orbit with a peridemeter under 200 km, well below the 385-km altitude of LAMO/XMO1. (Peridemeter is the term adopted for periapsis at Ceres. Demeter is the Greek counterpart of Ceres, the Roman goddess of agriculture.)

Table 2: Science orbits in the 2nd extended mission (XM2)

	Duration	Key Orbit description	Primary Science Goals
XMO5	2017/06/24 - 2018/04/15	Orbit period 30 days, staging for XM2	GRaND background measurement
XMO6	2018/05/15 - 2018/05/31	Intermediate Orbit	VIR southern observation, VIR Juling observation
XMO7	2018/06/06 - 2018/10/31	Elliptical, 35 km x 4000 km	GRaND observation in low attitude, Occator imaging

The prime objective of XM2 was to reach an orbit with a peridemeter altitude below 200 km. There were other, more specific science objectives in XM2 that affected the design of the orbits and mission timeline. The key drivers for the XMO6 design were the southern hemisphere observation and targeted observation of Juling crater, especially the crater's north wall, via the VIR instrument. XMO6 was constructed from an extended forced-coast period in the optimal transfer from XMO5 to XMO7.

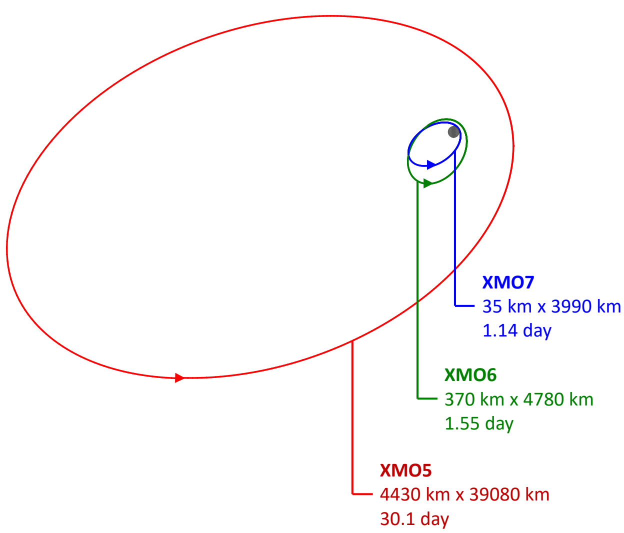

Fig. 3: Science orbits in the 2nd extended mission

XMO7 was the final orbit for Dawn's mission. The main goal of XMO7 was to reach a low enough altitude to significantly improve the resolution and sensitivity of GRaND's nuclear spectroscopy data. There were several issues and factors that were considered in the design of XMO7, including orbit stability for planetary protection, efficient usage of the remaining hydrazine stores, and the targeting of a peridemeter pass over a specific Ceres surface feature (Cerealia Facula in Occator crater).

Navigation challenges for XM2

The Dawn navigation and mission design team encountered and solved a series of challenges during the Vesta [7] and Ceres prime mission [8]. Dawn's second extended mission presented yet another set of technical challenges to the navigation team as listed below:

- Orbit disturbances due to ΔV exerted by RCS control

Three of Dawn's four reaction wheels had failed over the course of the mission, in 2010, 2012, and 2017. Without a one-wheel mode, after the third wheel failure, Dawn's attitude control was accomplished exclusively with the hydrazine-based RCS except for the period of IPS thrusting when the IPS engine controlled two axes and RCS controlled the remaining third axis. Attitude control by RCS posed a sizeable challenge for the orbit determination team. It was more difficult to predict the disturbance of ΔV produced by RCS control than for RWA control due to more frequent and unpredictable thruster firing. The frequency of thruster firings rapidly increased during the low-altitude peridemeter passes.

- Increasingly limited hydrazine stores

The flight team had made major efforts to conserve hydrazine since 2010. Still, the mission had not been expected to be so successful that a second extended mission would be feasible, which required further stretching of an already limited hydrazine supply. Every turn of the spacecraft required RCS thruster firings, and each peridemeter pass increased the frequency of thruster firings. The predicted hydrazine consumption of each potential mission was carefully prioritized before the project selected a final option for the mission extension. This process repeated during the final planning process when each Earth communication period and science observation plan was selected.

- Meeting Planetary Protection requirements with the final orbit

NASA's planetary protection requirement for Ceres was stated as follows: "The Project will provide a spacecraft orbital lifetime around Ceres of greater than 20 years post-orbital-insertion, based on the worst-case credible gravity field model." The Dawn project elected to provide a significant margin on the 20-yr requirement by designing XMO7 to have an orbital lifetime exceeding 50 years with 99% confidence. This requirement was the key driver in choosing the final XMO7 orbit from several possible options.

- Highly elliptical orbit, new to Dawn flight team

All of Dawn's science orbits up to the first extended mission were primarily circular, with the lowest altitude being 385 km at the LAMO. XMO7 was 4000 km x 35 km, a much higher eccentricity with much lower peridemeter altitude compared to any previous science orbits at Ceres. Flying a highly elliptical orbit presented new challenges to the navigation team, especially to the orbit determination with their best gravity field estimated in higher altitude at LAMO. For example, navigating high periapsis speeds has a significant impact on timing errors at periapsis, the primary location of science during XMO7. Timing errors resulted in non-negligible off-nadir camera pointing to image the surface target, because the spacecraft was flying so close to the surface while imaging.

- Targeted fly-over

Another new challenge came from the science team's request for the targeted observation of Juling (XMO6) and Cerealia Facula (XMO7). With Dawn essentially being a mapping mission, flying over a specific surface target had never been attempted during the prime mission phase. With high uncertainty of disturbance forces created by the RCS jets and with the gravity field estimated at an altitude ten times higher, targeted observation campaigns requiring higher delivery accuracy posed new challenges in mission planning.

- Limited preparation time

From NASA's approval of the XM2 mission, the Dawn flight team had less than six months, including the holiday season at the end of 2017, to complete the design of the extended mission before beginning the transfer to the new science orbit. Although preliminary studies of low elliptical orbits were conducted prior to the beginning of XM2, the time available to work through the full trade space and complete a detailed design before operations had to begin was much shorter than for previous phases in the mission. The process included designing both the final science orbits and transfer architecture, while also planning for the precision navigation for the targeted observation. This was by far the least amount of time allowed for the Dawn flight team to design and plan for a new mission. From the initial draft to the final plan, the analysis and design process had to be efficient since there was little margin in the schedule with on-board hydrazine continually being depleted. Also, downsizing of the available flight team and the level of effort, especially toward the end of XM2, had to be factored into the plan.

Mission Design for XM2

As stated earlier in this paper, the prime objective of XM2 was to reach an orbit with a peridemeter below 200 km. Several constraints were applied in the process of designing the final orbits and transfers. The first one was the stability of the final orbit that must fulfil NASA's planetary protection requirement. The Dawn project elected to impose extra margin and chose to demonstrate that the final orbit would remain stable for 50 years after orbit insertion, using the most recent Ceres gravity field and the shape model. A realistic modeling of RCS thrust activities were used to perturb the orbit from the reference orbit for the beginning 100 days, longer than the expected lifetime left of Dawn in XMO7, and the final state was propagated for 50 years. The Dawn project elected to continue science operation in XMO7 until the hydrazine supply ran empty, rendering the final state of the spacecraft unmaneuverable. The summary report of Dawn's final planetary protection plan was delivered to NASA Headquarters in April 2018 [6]. The analysis details of the orbit stability were also presented by Dan Grebow [3].

The second important constraint in designing the orbits in XM2 concerned the remaining hydrazine on-board. From the initial concept design to the final selection, many different orbits and transfer options were studied, and the total hydrazine expenditure of each choice was calculated by Dawn's ACS team and was used as a key discriminator. For instance, the lower the peridemeter of the orbit, the more RCS thruster firings were required to maintain the attitude during the peridemeter pass. Since the end-of-mission was clearly defined by the amount of fuel remaining onboard, a careful balance between the hydrazine consumption in each orbit and the number of expected peridemeter passes was considered in choosing the final orbit.

Another key driver for designing the XMO7 mission was the targeted observation over an area of special interest. Cerealia Facula, at the center of 92 km diameter Occator Crater, had shown large deposits of sodium carbonates and became a very attractive target to the Dawn science team. Aligning one of the peridemeter passes of XMO7 over Cerealia Facula became a key requirement of the XMO7 mission. To provide enough time to prepare for the accurate fly over operations, the Cerealia Facula fly over was planned at the 13th and 14th peridemeters of XMO7.

After the final reference of XMO7 was chosen, the Dawn science team found that the orbit did not allow sufficient low altitude coverage of the southern hemisphere by VIR. The original transfer to XMO7 had an extended coasting period to acquire VIR data. After extensive analysis to determine how to accomplish the VIR objectives, the flight team inserted a new science orbit, XMO6, into the transfer from XMO5 to XMO7. Another targeted observation was included before the XMO6 reference orbit design was completed. Acquiring VIR's spectra of the Juling crater's north wall required a ground track adjustment of XMO6. To allow the flight team to achieve an accurate measurement, the Juling fly-over was designed to be orbit 6 and the backup opportunity was in orbit 7. A summary of the XM2 reference orbits characteristics are shown in Table 3.

Table 3: XM2 orbit elements (Beta is the angle between the orbit plane and the vector to the Sun)

	XMO5	XMO6	XMO7
Inclination	73.40 deg	78.49 deg	84.20 deg
Orbit Period	30.31 days	37.20 hrs	27.28 hrs
Eccentricity	0.78	0.70	0.80
Beta (beginning)	8.22 deg	15.59 deg	26.33 deg
Semimajor axis	22,157 km	3,046 km	2,481 km
Duration	304 days	17 days	145 days
Revolutions	10 orbits	11 orbits	127 orbits

Mission plan for XM2

All spacecraft activities, science and engineering, were controlled by a ground-developed sequence of commands. A background sequence typically spanned four weeks of spacecraft events and included a number of IPS thrust sequences (during the transfer phase), or included science instrument sequences (during the science orbit phases). Developing the architecture of the transfer included selecting the number of thrust sequence and duration of the build cycle. This development was one of the key tasks of the navigation team, and needed to be completed well ahead of the actual sequence building process. This process required a Monte Carlo analysis tool known as Veil as described by Parcher [4]. The design process took multiple iterations before the final architecture was selected. Cost functions in the optimization process were not only a numerical variable (e.g., xenon optimization or time optimization) but often involved a combination of several human factors, such as the flight team's work load and schedule. When the decision of the second extended mission was made to stay at Ceres, no detailed operational plans had been developed other than the high-level science objectives of XM2. The navigation team had to build a detailed XM2 plan, including the reference orbit and transfer architecture in a much shorter time than for previous phases in the mission.

This was not the first time the navigation team developed a new plan in a short period, but yet new operational constraints had become increasingly clear. Since the end of XM2 would be defined by no more usable hydrazine onboard, there was no longer any possibility of any further mission extensions. Flight team members who had been dedicated to Dawn's operations for the past several years or more were beginning to be assigned to other projects. The size of the available flight team and the level of effort decreased, especially toward the end of XM2. The downsizing of available staff needed to be factored into designing the operational plan.

Once uploaded to the spacecraft and activated, completely updating the background sequence would have been difficult and risky due to the long process of review and validation. However, with very careful planning, a simpler and shorter review was possible when only the certain parameters or subset of the sequence were updated. The Dawn flight team used this scheme to improve the timing and pointing accuracy of the instrument operations. Some of these special procedures and techniques used to improve the accuracy of science observations are listed below:

- Short build cycle of thrust sequence

The shorter the ground build time for the thrust sequence, the more accurate estimation of the IPS thrust vector is possible, since the prediction error from the orbit determination is reduced;

however, using a shorter build cycle often required the ground crew to work on a non-prime shift, and repetitive use of the short sequence building would eventually wear down the flight team and increases the risk of human errors. A timeline of several different sequence building processes is described by Han [7]. For XM2, most of the thrust sequence builds were processed in 3 days, and no exception was made for weekends and holidays.

- Short duration thrust sequence

Typically used for a trajectory correction maneuver (TCM), short-thrust sequences can improve delivery accuracy. These sequences are typically developed in a short build time to maximize the delivery accuracy and are used at the last segment of the transfer when more precise delivery is required. Building a sequence, even a short one, requires the entire flight team's support and therefore must be considered sparingly.

- On-board ephemeris update

Dawn's science instrument operation commands typically used a Ceres-relative frame for the instrument pointing, e.g., nadir pointing. Since the science sequence was typically built as part of the background sequence several weeks ahead of execution, the execution could encounter significant pointing errors accumulated from using old orbit determination results. One simple method of reducing this error involved replacing the onboard ephemerides, which define the vector from Ceres' center to the spacecraft, with a new one created by the latest orbit determination. This update process required only a fraction of the flight crew, including navigation and attitude control, and did not require the laborious sequence verification process. This simple method was regularly used throughout the mission for improving science instrument pointing accuracy, especially with imaging activities.

- Sequence timing (epoch) update

Science sequences containing commands that required precise execution times at certain geometric events could not benefit from the ephemeris update process alone. For instance, the FC imaging at peridemeter required both the correct geometric event time and correct pointing vector calculated from the onboard ephemeris. These events were scheduled by using relative time from a key epoch so that updating the epoch would also update the execution time of the command. This ground process, called an "epoch update", essentially updated and replaced the full sequence, and required another iteration of the sequence review process. This method was the most effective way of reducing onboard sequence timing error, but was expensive in terms of the ground crew's labor, and was therefore used only when accurate execution was essential to the instrument observation.

- Science pointing update:

When the desired accurate instrument pointing could not be achieved by using the above sequence updates only, the actual instrument pointing vector is updated. Since targeted observations had not been used, except for the opposition observation at high altitude in XMO4, this process was not used until the last days of the Dawn mission. Only one or two pointing vectors in science sequences were updated by using the latest orbit determination, and the updated science sequence was carefully reviewed before uploading to the spacecraft. The timeline of this process was about 8 hours, including the OD update process.

Below is the breakdown of the XM2 transfer and science orbit sequence timeline. DAxxx is the sequence identifier.

DA940: Transfer sequence from XMO5 to XMO6 (29 days long)

This background sequence contained four thrust sequences. The Dawn flight team has developed and used three different sets of thrust sequence building schedules [7]. The 3 day timeline was constructed with 3 days of prime shift working schedule. The 7 day timeline allowed margin compared to the 3 day version, especially during weekends and holidays. The shortest timeline was the 36 hours which was used only once during Vesta's transfer to LAMO and included no break in the timeline. The first thrust sequence of this particular transfer was a 10-days long thrust built on a 7-day schedule. The second and third thrust sequences were 7-days long each and were built over a 3-day process. The final thrust sequence was 4 days long and built on a 3-day timeline. Since the science activity at XMO6 was not sensitive to the delivery accuracy, by design, no TCM was necessary at the end of the transfer.

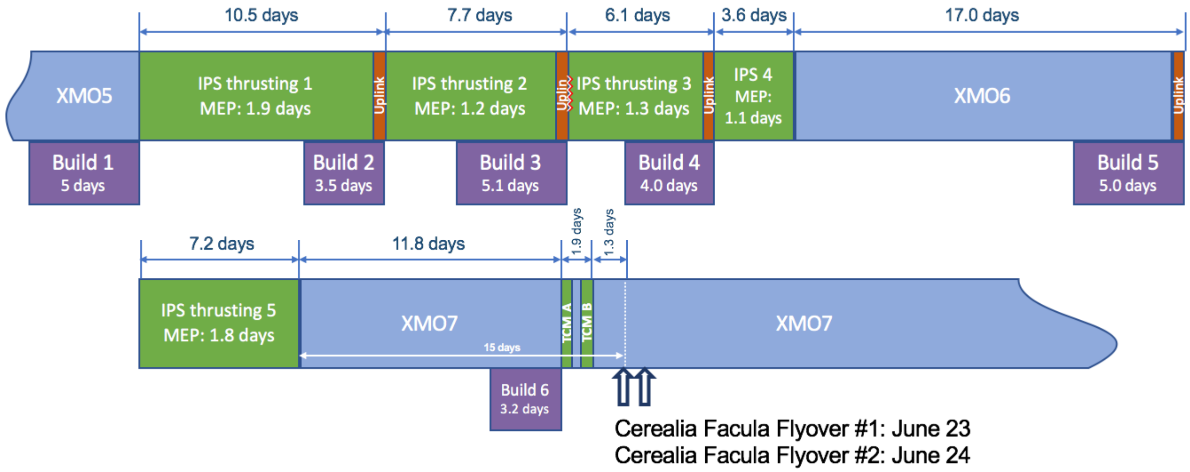

Fig. 4: Transfer architecture from XMO5 to XMO7. The maneuver expansion period (MEP) is an allocation of additional time for statistical IPS thrusting

DA941: XMO6 science activities and transfer to XMO7 orbit (25 days long)

This sequence included science instrument activities for 11 revolutions of the highly elliptical 37.2-hour orbit XMO6. A targeted VIR observation of the north wall of Juling crater was planned at the sixth or seventh orbit, whichever yielded the better geometry. Since the VIR instrument was operated in a "push broom" pattern, only the ephemeris update and epoch update were used to revise the VIR instrument pointing.

DA942: XMO7 science activities and TCM for Cerealia Facula fly over targeting (about 15 day after arrival in XMO7).

The main science goal of XMO7 was to collect GRaND's peridemeter measurements. However, the investigation of Cerealia Facula by close-up imaging was equally important. Since the latitude of peridemeter shifted south with each orbit [3], XMO7 was targeted to place the initial peridemeter north of Cerealia Facula far enough that the flyover would occur at the planned time [3]. In order to provide time for orbit knowledge update after the completion of the transfer, and to allow the TCM to correct the delivery error of the transfer, the Cerealia Facula fly over was planned at the 13th and 14th peridemeters of XMO7. To ensure an accurate fly over and precision pointing by the instruments in a highly elliptical orbit with poorly predictable RCS control, all of the five sequence processes described above were used. A timeline of XMO7 ground activities leading up to the Cerealia Facula observation is shown in Fig. 5.

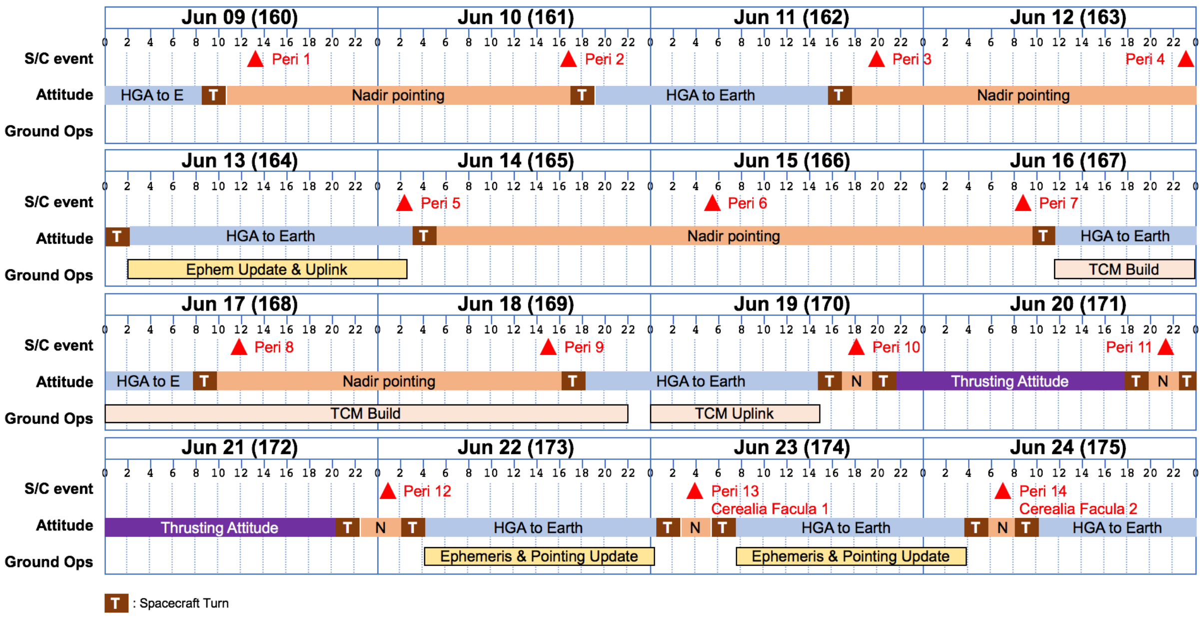

Fig. 5: Navigation operational timeline for Cerealia Facula targeting

Orbit Determination (OD) during XM2

The highly elliptical design of the XM2 orbits was atypical for the Dawn mission and presented some new challenges to the OD team. In order to successfully execute the XM2 mission (primarily XMO7), accurate predictions of the Dawn trajectory were required. These predictions were particularly important during peridemeter, when the peak velocity and acceleration occured. The OD team generated these predicted trajectories using primarily the following inputs:

- OD team's estimate of the spacecraft's state at the end of the latest tracking data
- ACS team's predictions of future thruster firing from the RCS
- Gravity science team's model of the Ceres GM and gravity field harmonics

Of these three inputs, errors in prediction of thruster firing had the greatest impact on trajectory predictions. These thruster firings were due to the on-board ACS providing 3-axis control of the spacecraft attitude. Normally, this control would have been asserted using reaction wheels. However, since the wheels had failed, the control had to be asserted using only the unbalanced RCS. The resultant thruster firing from the RCS continuously perturbed the trajectory. These firings were quite aggressive, generating an order of 1-2 cm/s ΔV during the following events:

- The attitude changes from nadir-pointing to Earth-pointing (and vice versa).
- Through peridemeter to maintain attitude against gravity gradient torques.
- While nadir-pointed through peridemeter, where peak rates reached 0.25 degrees/second.

The primary uses for the orbit predictions were:

- Tracking of the spacecraft with the DSN
- Science sequence implementation
- Real-time knowledge of the Ceres-relative spacecraft position for the on-board ACS
- Corrections to camera pointing for imaging Cerealia Facula

To support the Dawn tracking passes, the DSN required a trajectory prediction to point the antenna and tune the receiver to the expected frequency. During peridemeter, the Ceres-relative velocity of the spacecraft was ~500 m/s. If entirely viewed along the Earth line-of-sight, the change in observed X-band frequency would be over 20 kHz. While a frequency error of this magnitude was not likely to happen, errors of over 1 kHz were possible with predictions that were not updated in a timely fashion. In practice, the OD team provided updates to the DSN at least once per week to avoid unacceptably large frequency errors.

Fig. *6* shows the errors in predicted frequency following delivery of an updated trajectory prediction. The peaks and dips in the data are during peridemeter passages.

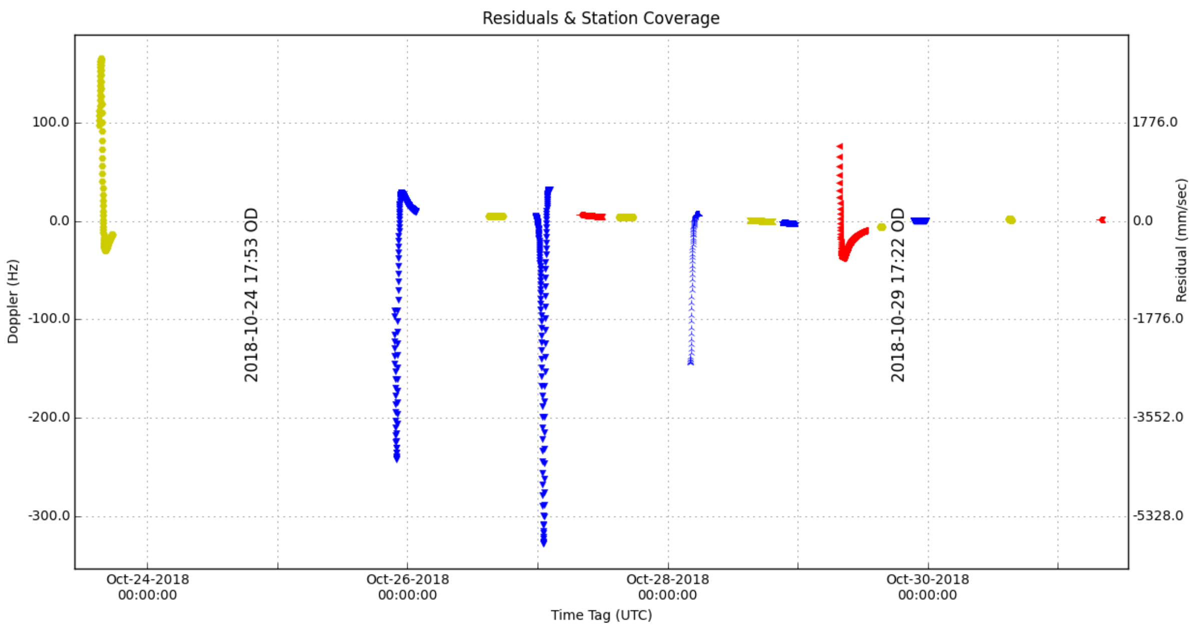

Fig. 6: Ground Doppler frequency prediction performance during a week in XMO7

The science sequences for XMO7 were designed to collect science data during most of Dawn's peridemeter passes. Knowledge of the peridemeter times was necessary to collect data at the correct times. These data were downlinked once every several orbits, through the spacecraft high gain antenna (HGA). During the first part of XMO7, occultations occurred during the HGA passes. If data were to be downlinked while the Dawn view of Earth was occulted by Ceres, the data would be lost because the downlink plan provided little margin for data playback. To avoid this loss of data, the science sequences were implemented with predictions of these occultation times. 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 use the best estimate of the predicted trajectory to update the sequences to reflect the best possible predictions in peridemeter or occultation times. The timing of the commands was set to allow up to ten minutes of error in these predicted 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 peridemeter 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 (usually every six orbits, although the schedule varied), and the pointing performance would be accepted as-is. Fig. *7* shows the pointing performance of the on-board ephemeris against the post-flight reconstructed trajectory during the first several weeks of XM2. All spikes above 1 degree occurred during peridemeter, where the error in predicted position was at a maximum.

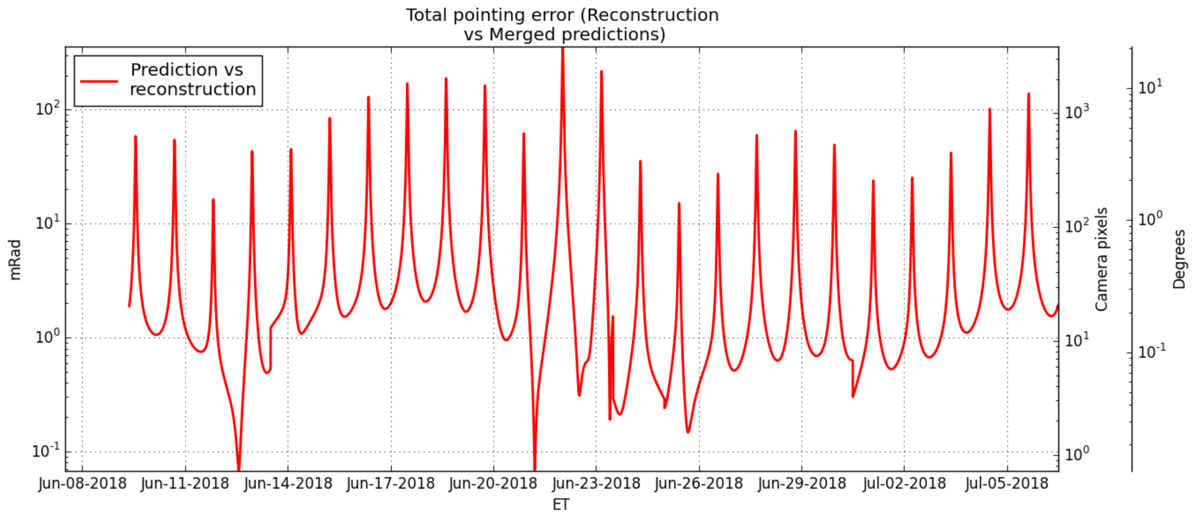

Fig. 7: Pointing prediction performance during first part of XMO7

During the first portion of XMO7, the imaging of Cerealia Facula was carefully planned. Care was taken to mitigate errors in predicting the time of peridemeter; such errors would result in the spacecraft flying over an incorrect longitude at peridemeter.

To prepare for imaging Cerealia Facula, an IPS TCM was planned on June 21, 2018, a day before the first of two planned flyovers. This TCM was designed using a prediction of the effects of RCS thruster activity on the future trajectory, and corrected most of the errors resulting from the IPS thrusting that injected the spacecraft into XMO7. Further details will be published by Whiffen [5]. Most of the residual error in the TCM execution was in the prediction of RCS activity between the design 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 compensate for this error, the OD team had previously planned to provide a prediction of the longitudinal error the day before observations. Based on this prediction, the spacecraft was commanded to point off-nadir at an angle sufficient to point the camera at the target terrain. Using these off-nadir angle corrections, by the previously mentioned science pointing update process, Cerealia Facula was imaged during several peridemeter passes and the results are shown in Fig. 8.

Optical Navigation for XM2

Optical navigation played an essential role in precision navigation during Vesta and Ceres operations. Dawn's optical navigation (opnav) team used a database of landmarks and opnav images to estimate the spacecraft state, as described by Mastrodemos [9]. In the extended mission phases, the Dawn opnav team did not use opnav pictures to construct new landmark maps; that's because the surface coverage of the extended mission images and the imaging geometry were not sufficient to improve the existing database of landmarks. Instead the final reconstructed landmark data based at the end of LAMO was used to process all extended mission images. That database included landmark maps with a range in map scale from 100 m to 2.5 km. Therefore, the new images were used to obtain landmark observables based on the existing landmark database.

During XM1, in particular XMO4, landmarks initially created during approach to Ceres and the Survey orbit that spanned a range in resolution from 500 meters to 2.5 km were used. This was deemed necessary due to that science phase being at similar high altitudes, and landmark observables are best obtained when the resolution of pictures and landmarks are within a factor of 10 but preferably less.

In XM2, landmarks from LAMO with a scale of 100 meters were mostly used. Despite this, given the high eccentricity of the orbit in XMO6 there were still a range of altitudes, which resulted in separating the images into high- and low-range groups. All landmarks were used for the high-range pictures, but for the low-range images only the higher resolution, 100-meter scale landmarks were used. In XMO7 only the 100 m scale LAMO landmarks had been used, since pictures were only taken during peridemeter. This approach was necessary because the highly elliptical and low-peridemeter orbit posed an especially difficult navigation challenge to the team, as noted above, and opnav pictures close to peridemeter provided the most helpful information.

III. Conclusion

Dawn's second extended, and final, mission at Ceres, presented a series of challenges that were new even to the experienced and accomplished Dawn navigation team. The final reference orbit, with unprecedently low peridemeter altitude, needed to meet the science team's objectives while complying with NASA's planetary protection requirements. The complex orbit transfer architecture had to meet the demanding delivery accuracy and had to be designed in limited preparation time. The operational plan had to be robust to nearly unpredictable disturbances from RCS thrusters in order to deliver the spacecraft to accurately fly over the high priority targets on Ceres' surface. Dawn's navigation and mission design team played a key role for Dawn flight team to plan and execute such a challenging mission and accomplishing and ultimately exceeding all science objectives in the final phase of the mission.

IV. Acknowledgments

This paper summarizes the outstanding performance by Dawn's navigation team. A special appreciation goes to Marc Rayman, Dawn's chief engineer and mission manager and the project manager during the extended mission, for diligently providing insightful comments and suggestions from the early development phase to the end of successful operations at Ceres.

The work described in this paper was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

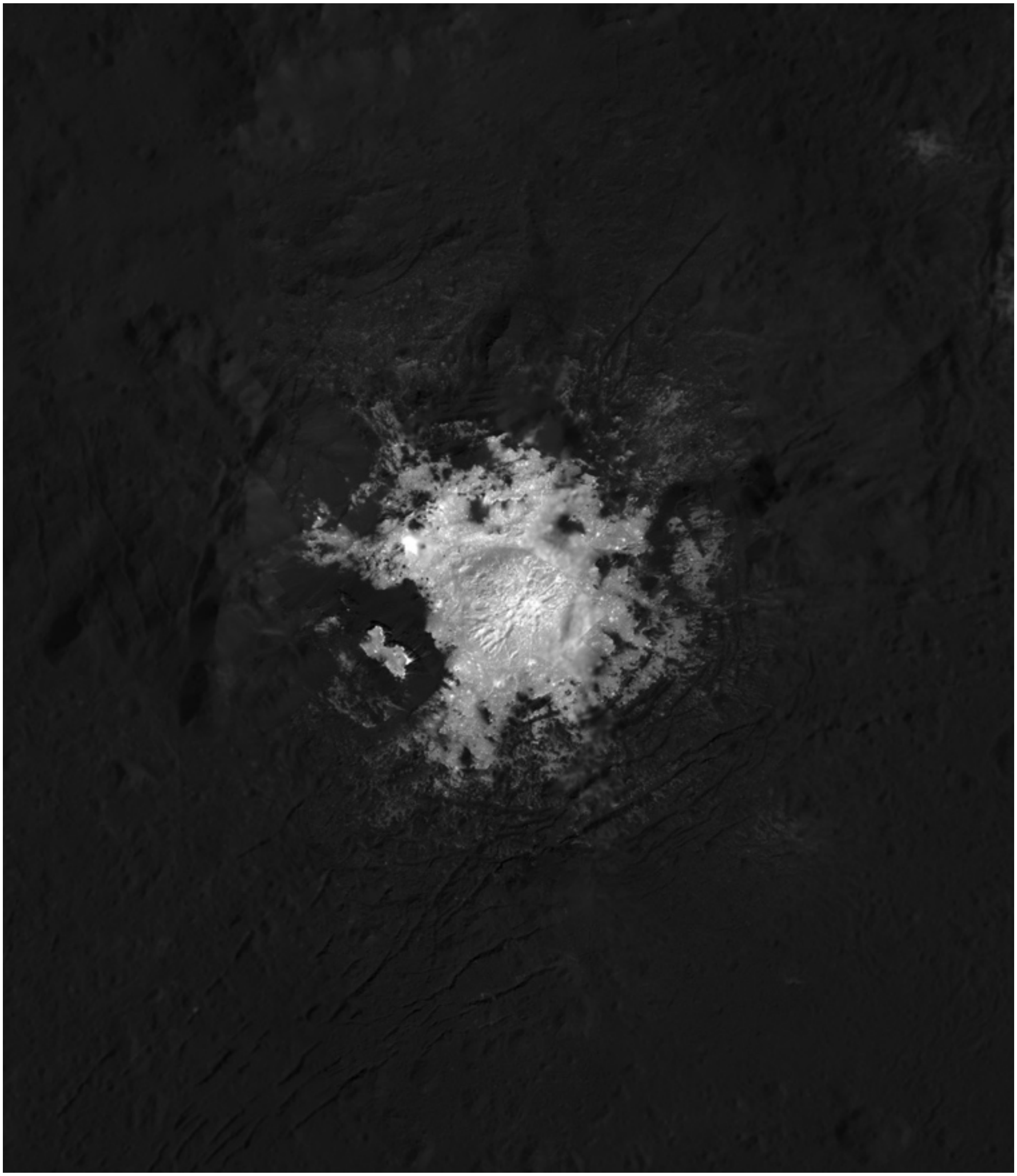

Fig. 8: Cerealia Facula mosaic constructed with images from multiple orbits in XMO7.

V. References

[1] Rayman, M. D., "Dawn at Ceres: The First Exploration of the First Dwarf Planet," 68th International Astronautical Congress, 25-29 September 2017, Adelaide, Australia, Paper IAC-17.A3.4A.2x39024

[2] Rayman, M. D., "Dawn's Second and Final Extended Mission: A New Operational Campaign at Ceres," 69th International Astronautical Congress, 1-5 October 2018, Bremen, Paper IAC-18.A3.4A.1.x46568

[3] Grebow, D. J., et al., "Stability and Targeting in Dawn's Final Orbit," Proceedings of the 29th AAS/AIAA Space Flight Mechanics Meeting, 13-17 January 2019, Kaanapali, Hawaii, Paper AAS 19-254.

[4] Parcher, D. W., et al., "Dawn Statistical Maneuver Design for Vesta Operations," Proceedings of the AIAA/ASS Astrodynamics Specialist Conference, 13-17 February, 2011. New Orleans, Louisiana, Paper AAS2011-180.

[5] Whiffen, G. J., et al., "Design of Dawn's Final Highly Elliptical Transfers Around Dwarf Planet Ceres," (publication in preparation).

[6] Grebow, D. J., "Planetary Protection Report Ceres Second Extended Mission," JPL internal document, D-39729.

[7] Han, D., "Orbit Transfers for Dawn's Vesta Operations: Navigation and Mission Design Experience," 23rd International Symposium on Space Flight Dynamics, Oct. 29 – Nov. 2, 2012, Pasadena, California.

[8] Han, D., et al., "Orbit Transfers for Dawn's Ceres Operations: Navigation and Mission Design Experience at a Dwarf Planet," SpaceOps 2016 Conference, SpaceOps Conferences. 16-20, 2016, Daejon, Korea, Paper No. AIAA 2016-2427.

[9] Mastrodemos, N., et al., "Optical Navigation for the Dawn Mission at Vesta," 23rd International Symposium on Space Flight Dynamics, Pasadena, CA, USA, Oct. 29 - Nov. 2, 2012.