Orbit Transfers for Dawn's Ceres Operations:
Navigation and Mission Design Experience at a Dwarf Planet

Dongsuk Han[1], John Smith[1], Brian Kennedy[1], Nickolaos Mastrodemos[1], and Gregory Whiffen[1]
Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, California 91109-8099, U.S.A

Dawn, a mission belonging to NASA's Discovery Program, was launched on September 27, 2007 to explore two objects in the main asteroid belt in order to yield insights into important questions about the formation and evolution of the solar system. Successfully completing all mission objectives at Vesta, Dawn arrived at dwarf planet Ceres in March 2015 and continued its journey to a series of four near circular polar science orbits. Dawn became the first mission to orbit around two extraterrestrial targets; such a mission would have been impossible without the low thrust ion propulsion system (IPS). Maneuvering a spacecraft using only the IPS for the transfers between the mapping orbits posed many technical challenges to Dawn's flight team at NASA's Jet Propulsion Laboratory. Failure of the second reaction wheel assembly, shortly before leaving Vesta, added another challenge for Dawn's flight team. This paper discusses the mission design and navigational experience and challenges during Dawn's Ceres operations.

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 about the formation and evolution of the solar system [1]. Its objective is to acquire data from orbit around two complementary bodies, Vesta and Ceres, the two most massive objects in the main belt. From July of 2011 to September of 2012, the Dawn spacecraft orbited Vesta, and returned much valuable science data, collected during the six planned mapping orbits at the protoplanet. Figure 1 depicts the Dawn's interplanetary trajectory and timeline.

Shortly before leaving for the next destination, dwarf planet Ceres, the Dawn spacecraft suffered the loss of second of its four reaction wheels and switched its main attitude control system from reaction wheels to small reaction control system (RCS) thrusters. In the meantime, the flight team quickly devised a new flight plan to minimize the expenditure of hydrazine during the cruise to Ceres. This plan included significant reduction of the high gain antenna (HGA) contact with Earth with the expected adverse effect on Dawn's orbit determination performance.

After completing interplanetary cruise, Dawn was successfully captured by Ceres in March 2015 and began spiraling down to a series of four planned science mapping orbits. Dawn became the first mission ever to orbit around two different extraterrestrial bodies and the first one to orbit a dwarf planet. Maneuvering a spacecraft only using the low thrust ion propulsion system (IPS) for the transfers between the mapping orbits posed many technical challenges to Dawn's flight team at NASA's Jet Propulsion Laboratory. Each transfer needs a robust plan that accounts for uncertainties in maneuver execution, orbit determination, and physical characteristics of Ceres. This plan must meet the requirements of the targeted science orbit, conform to spacecraft safety requirements, and needs to include margin to accommodate unforeseen anomalies. The plan also must be compatible with the capabilities of the operations team, which was small considering the complexity of the mission. The original navigation plan was completely revised with a new scheme for attitude control during operations at Ceres.

[1] *Technical Staff, Mission Design and Navigation Section, M/S 264-820*

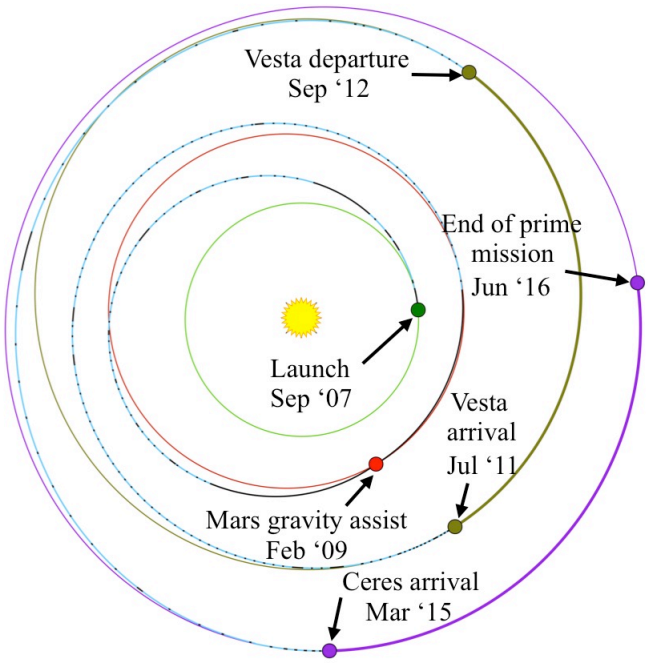

Figure 1. Dawn's Interplanetary Trajectory

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

The following sections will address mission design and navigational experience during Dawn's Ceres operations. Topics include requirements and constraints levied by Dawn's science and spacecraft teams, orbit determination and maneuver design process for transfers, developing timelines for thrust sequence build cycles, and the process of scheduling very demanding coverage with ground antennas at the DSN.

II. Spacecraft & Payload

Built by Orbital Sciences Corporation [4], the Dawn spacecraft is designed to maximize the power available to the IPS in order to meet the very demanding ΔV requirements. One prominent feature of the Dawn spacecraft is the large solar arrays, which extend to a length of 20 meters. Dawn's electrical power system on board provides sufficient power to operate the IPS when the spacecraft is at a heliocentric range of 3 AU during Ceres operation. Dawn's two large solar arrays are designed to provide 10.3 kW at 1 AU and 1.3 kW at their end of life at 3 AU.

Dawn's IPS is an expanded version of the system used on NASA's Deep Space 1 spacecraft. With 425 kg of Xe, the system is capable of providing a cumulative 12 km/sec ΔV for the mission. To add reliability, the spacecraft is carrying three ion thrusters, although only one thruster is operated at a time. All three thrusters are aligned in the spacecraft xz plane with the center flight thruster (FT-3) facing the –z direction and the other two, FT-1 and FT-2, canted 48 degrees from z towards the x-axis. Each thruster is mounted to a two-axis gimbal and has thrust vector control (TVC) to maintain attitude about the two axes perpendicular to the thrust vector. This low thrust engine can produce maximum thrust of 91 mN at peak power and 19 mN at the lowest input power of 0.5 kW, with 112 discretized thrust levels in between. The highly efficient specific impulse range of 3200 and 1900 seconds was the key reason that the Dawn mission was possible. The throttle level of Dawn's IPS is commanded by selecting a mission level ranging from 0 to 111, which correspond to relevant parameters in an on-board throttle table. By the time Dawn arrived at the last science orbit, the lowest orbit at Ceres, the IPS system had accumulated 48,431 hours of thrust time and provided 11.0 km/sec of ΔV.

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

Dawn's scientific payload consists of three instruments. The framing camera (FC), contributed by Germany, acquired images for topography and also provided images for optical navigation. The visible and infrared (VIR) mapping spectrometer, contributed by Italy, collected data to answer surface mineralogy questions. The gamma ray and neutron detector (GRaND) developed by Los Alamos National Laboratory collected data to determine the elemental composition of the asteroid. In addition, gravimetric data are measured using the 2-way Doppler data between the spacecraft and DSN antennas. All three science instruments are aligned with the spacecraft +z face. A simple depiction of the Dawn spacecraft is shown in Figure 2.

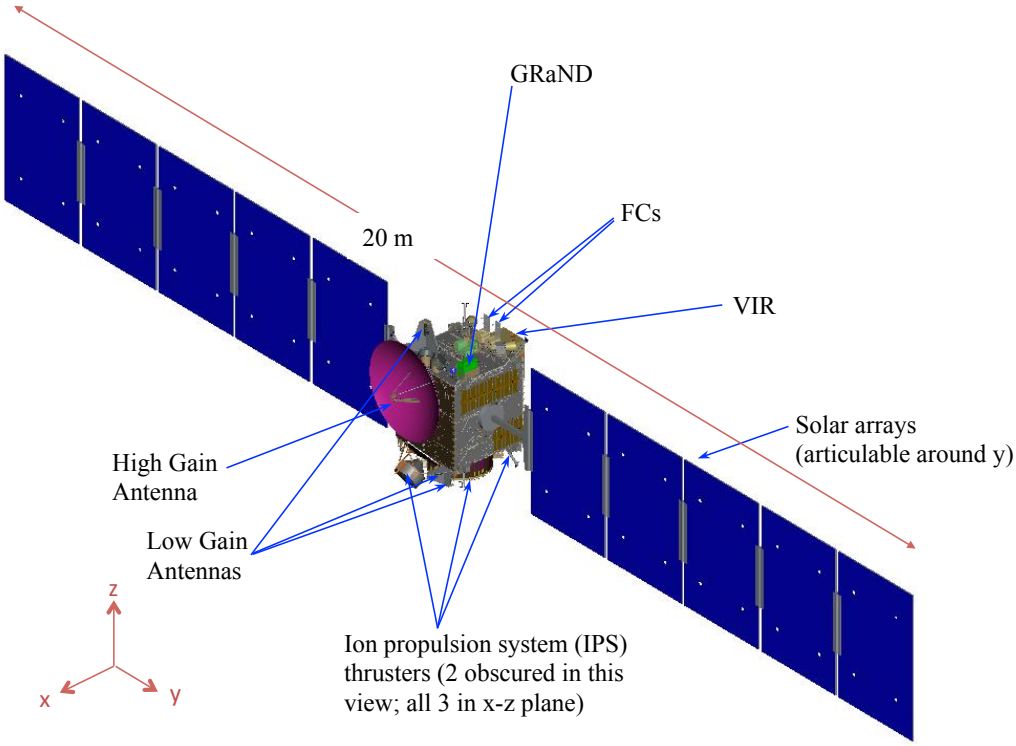

Figure 2. The Dawn Spacecraft

III. Requirements and Constraints

Eclipse constraint

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

Geometric constraint for instruments and thrusters

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

ACS agility constraint

Like any 3-axis controlled spacecraft, Dawn's ACS has dynamic constraints on attitude rate and angular acceleration. While thrusting with the IPS, the designed thrust direction dictates the spacecraft attitude via the power steering algorithm; it is the navigation team's responsibility to design thrust profiles that obey these dynamic constraints. Also, Dawn must avoid pointing the thrust direction in the sun and anti-sun directions to avoid a kinematic singularity in solar array pointing. When the designed thrust vector passes through or near these directions, the always-active power steering will flip the spacecraft attitude by rotating nearly 180 degrees around the spacecraft z-axis. This so-called "power steering flip-over" may violate the ACS agility constraints and must be avoided. Further discussions on this constraint are documented by Smith [12].

Planetary protection for Ceres

NASA's Planetary Protection Office (PPO) required the Dawn project to follow specific guidelines during the mission. The potential for the presence of water on Ceres and other factors that may lead to prebiotic chemistry and the Dawn project's plan of leaving the spacecraft on LAMO orbit after completion of the mission prompted the PPO to impose a specific requirement for Ceres. The primary Ceres planetary protection requirement was that the project provides a spacecraft orbital lifetime around Ceres of greater than 20 years post-orbital-insertion, based on the worst-case credible gravity field model. To maximize the likelihood of executing the Ceres science plan on schedule, the Dawn project elected to exceed the 20-year requirement and instead satisfy an orbit lifetime of 50 years.

Science orbit requirement

The structure of the science plan for exploring Ceres is very similar to that of Vesta. The science observations were concentrated in four campaigns at Ceres, each conducted in a different near-circular, near-polar orbit. These campaigns, designated the third rotational characterization (RC3), Survey, High Altitude Mapping Orbit (HAMO), and Low Altitude Mapping Orbit (LAMO), are depicted in Figure 3. The four orbital altitudes are shown to scale with Ceres, which has a mean equatorial diameter of 952 km. Dawn's operational experiences at all science phases are described in detail by Polanskey [19].

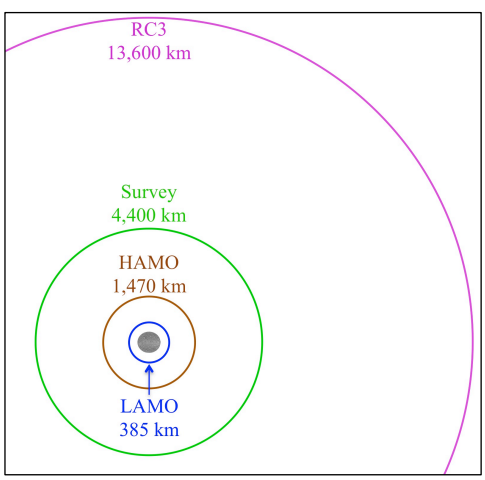

Figure 3. Ceres Science Orbits

The four major science orbit phases were chosen to allow global coverage at a desired spatial resolution. The main objectives in science orbits are: to obtain global spectral mapping of the lit surface with VIR in Survey, to obtain global imaging of the lit surface with FC in HAMO, and to map the gravity field and elemental composition of Ceres in LAMO.

Table 1 provides the desired characteristics of these science orbits. The target radii were specified to achieve the required spatial resolution and orbit periods, and the radius variation represents both a design requirement and a control requirement. The orbit planes are selected to provide good illumination for FC and VIR observations while avoiding eclipses. The angle between the orbit plane and the Ceres-Sun line, beta angle, is used to define desired orbit planes in the requirements. Polar orbit inclination is designed to allow observation of the entire body, and the observing footprints of the instruments allow the variation. The target inclination represents both a design and a control requirement. A minimum orbit period is defined to allow sufficient time for data downlink. Ground track spacing is an important attribute that allows Dawn to map the surface in the most efficient manner with a given instrument at a given altitude. The terminator crossing time uncertainties are control requirements to ensure the download of the science data and represent the tolerance between the predicted orbit, used in building the science sequence, and the actual orbit.

Table 1. Ceres Science Orbit Requirements

	RC3	Survey	HAMO	LAMO
Objective	Map the shape and obtain spin axis orientation and period	Obtain VIR coverage with global distribution; FC global coverage; Achieve VIR low resolution Level-1 requirement	Obtain FC global topography and color coverage; Achieve VIR high resolution Level-1 requirement	Obtain GRaND and gravity coverage; Obtain FC chronology measurements and look for evidence of Ceres-derived meteorites; Achieve VIR high resolution Level-1 requirement
Implementation Strategy	One orbit with at least 3 full rotation observations	Maximum VIR global coverage by acquiring in each subsequent orbit to create a global mosaic	Cyclic coverage with ground track walking around the body with minimum number of orbits to achieve global coverage without gaps	Achieve 70-80% nadir duty cycle for GRaND measurements to achieve global coverage in ~23 calendar days and achieve ~60 days of nadir observing in the science phase
Ground track Walk	No requirement	47:6* Ground track repeat pattern with 3 to 7 petals. Ground track control is not required	27:14* Cyclic coverage with ground track spacing averaging 26 ° for complete FC coverage with minimal gaps within a 14-orbit cycle duration	56:93* Achieve GRaND and gravity global coverage within 93-orbit longitude cycle duration (~22.8 days) and 3.9 ° ground track spacing
Radius Range	14,000 km (+/- 500 km) Full disk within FC FOV accounting for 0.64 ° pointing error	4718 km Survey orbit period to avoid excess time on the dark side while achieving VIR global coverage	1,852 km (1600-2000 km) Maximum by FC resolution and minimum by VIR resolution	839 km Must be < 2 Ceres radii, 825-850 km to meet minimal science objectives
Beta Range	Minimum safe beta	10 ° – 30 ° drifting	25° − 40° drifting	Minimum safe beta for altitude, ideally ≤ 45°, fixed beta
Inclination Range	Same as LAMO	Same as LAMO	Same as LAMO	Inclination that will fix beta for the above orbit radius
Phase duration	1 orbit	Seven 1-orbit cycles	Five 16-orbit cycles	Four 101-orbit cycles
Absolute Timing	No requirement	No requirement	No requirement	No requirement
Dark to Lit Terminator crossing offset	±2 hours	±45 minutes	±10 minutes	±10 minutes
	* Ratio between Ceres rotation and Dawn's orbit count			

IV. Spacecraft anomalies

Reaction wheel failure

Dawn has four RWAs, and the baseline mission assumed the use of three at all times. One RWA failed in June 2010 during the cruise to Vesta. The second failure occurred in August 2012, while Dawn was spiraling away using IPS after a successful completion of mission at Vesta. With only two functioning units, all RWAs were turned off and Dawn continued its path to Ceres using RCS and TVC mode. After the first RWA failure, Dawn's flight team developed hybrid ACS mode using RWA and RCS in combination as described in references [9][14].

Using RCS only as the main attitude control, the hydrazine expenditure rate increased and conserving hydrazine quickly became the key constraint for successfully completing all the mission objectives at Ceres. The Dawn project carefully studied as many as 50 different ideas for hydrazine conservation and immediately adopted a new plan for cruise operations. Rayman [15] describes the operational changes during the cruise from Vesta to Ceres. While cruising to Ceres, the original Ceres operation plan had to be completely revised to ensure all mission objectives at Ceres could be achieved without using any RWAs.

IPS thruster gimbal anomaly

As the mission nears its end, the fuel tanks become progressively lighter and cause the spacecraft center of mass to change, mostly along spacecraft z direction. With the thrust vector going through the spacecraft center of mass, the center thruster (FT-3) is the preferred choice for Ceres orbit transfer operations. Operating non-centered thrusters requires routine updates of the net thrust aim vector estimation and poses more limited operating regions in ACS agility constraints. After completing the first orbit transfer phase, the FT-3 gimbal showed anomalous behavior during the transfer from Survey to HAMO. This anomaly caused Survey to HAMO transfer to be restarted two weeks later than the original plan using FT-2, one of the non-centered thrusters. All remaining IPS thrusting was performed with FT-2.

Anomaly before approach

On September 11, 2014, the spacecraft stopped ion thrusting and eventually went into a safe mode. Diagnostics of the problem and recovery of spacecraft state cost ~4 days of IPS thrusting. This missed thrust happened when the thrust efficiency was very high and each day of delay to resume thrusting resulted in nearly seven days of delay in arriving at the first science orbit RC3. A rapid spacecraft recovery by the flight team and an immediate revision of the approach mission design by the navigation team were essential for Dawn to remain on course to a nominal Ceres operational timeline.

V. Mission Planning

Cruise to Ceres changes:

A crucial difference between the mission prior to Vesta and after Vesta was a result of the loss of two RWAs. With only two functioning RWAs on board, Dawn's baseline ACS mode was switched to RCS and TVC control mode during IPS thrusting and RCS-only control while IPS was not operating during the cruise phase. After the first RWA failure, the Dawn flight team developed a hybrid attitude control mode using two RWA and the RCS jets. When the second RWA failed, it was not evident that accomplishing the Ceres objectives in hybrid control was possible. Although hybrid control yields more efficient use of hydrazine than pure RCS control, it is not nearly as efficient as full RWA control. Moreover, because two RWAs failed so long before their qualified lifetimes had been reached, the project had low confidence in the longevity of the other two RWAs. For this reason, the hybrid mode was not used until Dawn reached its last science orbit, Ceres LAMO.

The Dawn project completely updated the interplanetary cruise and Ceres mission plan after departing from Vesta. Without RWA control, ACS mode consumes more hydrazine and conserving hydrazine became the key objective of the operation. In addition to a programmatic restriction, which defines the end time of Ceres operation, the new mission plan needed to ensure that all science objectives could be accomplished with the remaining hydrazine on board.

Details of the changes in the mission plan for hydrazine conservation are described by Rayman [13] and Polanskey [16]. The key change during the cruise to Ceres phase was the reduction of HGA tracking passes. Among the most hydrazine-costly activities is spacecraft turning. Therefore, a key element of the new plan was a change to having one HGA tracking session every four weeks, rather than one every week. This change itself increased the hydrazine available at Ceres arrival by 4 kg, or about 20% savings. The other weekly HGA passes were converted to LGA passes, where Dawn continued thrusting with IPS while communicating with the DSN using its LGA antenna. To power the on-board transmitter, a lower than maximum available IPS throttle level was used during these contact periods. To reduce the delay in finding a possible spacecraft anomaly, additional thrust verification (TV) passes were added to the plan. The Dawn project also devised a new scheme of no-downlink TV (NDTV) sessions [13]. If it were to enter a safe mode, the spacecraft would send low-rate telemetry through the LGA, while a nominally thrusting spacecraft would not send any signal. During these short sessions, DSN operators were instructed to report to the project if any signal was detected during the session, which would indicate an off-nominal spacecraft state. This NDTV scheme was the key reason for the early detection of a spacecraft anomaly, which occurred during the first thrust sequence, shortly after leaving Survey orbit.

During the interplanetary cruise to Ceres, the mission design team updated monthly the time-optimal solution to arrive at Ceres, using the latest results from orbit determination, and revised the arrival date. The reduction of HGA passes from weekly to once in four weeks affected navigation team's orbit determination accuracy. Only one 12 hour long tracking data in a 4-week period was recorded while the spacecraft was not thrusting with IPS. In addition, poor predictability of small thruster firings from RCS jets impacted navigation performance during the cruise phase. However, additional thrust times converted from HGA coasting times somewhat compensated for the loss of optimality. In the end, Dawn's Ceres arrival time was not significantly changed from the initial plan.

Mission Timeline Development for Ceres Orbit Phase

One special feature of an IPS propelled mission is the flexibility in mission design. Interplanetary cruise design is more dependent upon the performance of IPS and power available to it rather than precise timing requirements dictated by celestial mechanics. This feature made it possible for the Dawn project to complete the Vesta mission timeline well after launch. A similar approach of developing a mission timeline for Ceres was going to be applied, but the new constraint of the limited hydrazine added another complexity to this process.

The mission plan for Ceres operations was entirely re-evaluated [13] and even changing the fundamental design of the science orbits was considered. All possible plans were checked against the expected hydrazine consumption. Fortunately, analysis showed that the original plan of four science orbits, with the change of ACS operation mode, would be feasible with the remaining hydrazine. The detailed timeline for Ceres operations was developed and continuously refined throughout the interplanetary cruise to Ceres.

First, the mission design team designed the reference orbits in compliance with science requirements listed in Table 1. After all science orbit phases were defined, the navigation team developed the architectures for the transfers. Transfers between science orbits are very complex. Part of the complexity is to ensure the intermediate orbits are safe, even in the event of a loss of spacecraft control for as many as 28 days. Also, the transfers are sensitive to the details of the gravity field, which was not known precisely at the time of the architecture design. The architecture defines a complete navigational plan for each transfer and includes total duration of transfer, frequency and duration of each thrust planning cycle, frequency and duration of non-thrusting periods, and strategic placement of statistical maneuvers.

Adding the science orbit phases and transfer phases completed the timeline of Ceres operation, which begins 100 days from the first science orbit and ends at the end of the three-month LAMO science plan. As was practiced before Vesta, the Dawn flight team built sequences of commands for entire Ceres phases during the initial sequence build (ISB) campaign before arriving at Ceres.

Navigation plan for transfer phase and thrust sequence

All spacecraft activities in flight are controlled by a sequence of commands assembled by the ground crew. The basic frame of these commands is the background sequence, which typically spans two to four weeks. Each background sequence contains a placeholder for thrust sequence and blocks of thrusting times were left blank to be later filled by thrust sequences. The begin and end times of these blocks needed to be defined by the mission design team prior to the background sequence build process.

The background sequence is developed four weeks in advance and consists of commands for all spacecraft, and science instrument activities, and also includes IPS thrusting in a format of thrust sequence. While the background sequences takes four weeks to build, the thrust sequences are built in a much shorter time to utilize more up-to-date orbit determination results.

Delivering the thrust profile for the transfer sequence is one of the key responsibilities of the navigation team. Since updating the thrust sequence includes updating the maneuver design, more frequent updates and shorter thrust sequences are ideal for navigational delivery accuracy. However, requiring the small flight team to perform frequent sequence builds for 9 months of operations from approach to LAMO phases would certainly overburden the crew and may have resulted in undesirable mistakes during operations. Careful balancing between navigational accuracy and ground crew workload was an important part of building the mission timeline during asteroid operations. The process of building the transfer architecture is further described in Mission Design section and a list of sequences for Ceres orbit transfers is summarized in Table 2.

Table 2. Summary of Transfer Sequence

Transfer Phase (# of background sequences)	Thrust Sequence (sequence duration / sequence build duration)
Approach to RC3 (4)	28d/7d, 28d/7d, 28d/7d, 16d/7d, 13d/7d
RC3 to Survey (1)	21d/4d, 7d/4d
Survey to HAMO (2)	10d/5d, 7d/4d, 7d/4d, 7d/4d, 7d/3d
HAMO to LAMO (2)	7d/4d, 7d/4d, 7d/4d, 7d/4d, 7d/4d, 7d/3d, 7d/3d, 7d/3d, 2d/3d

Unlike the background sequences, which typically take four weeks to build, thrust sequence builds require faster turnaround for accurate maneuvers. In most cases, the spacecraft continued thrusting while the thrust sequence was

being built. Therefore, the longer the thrust sequence build process takes, the less accurate spacecraft state prediction becomes and the delivery error for the next thrust cycle increases. Three different types of thrust sequence building timelines were used, including a rapid 36-hour timeline, during Vesta operations. With operational experience from Vesta and with the less complex gravity harmonics of Ceres, thrust sequence build timelines were modified to lessen the ground crew's workload but still ensure delivery accuracy to the science orbits.

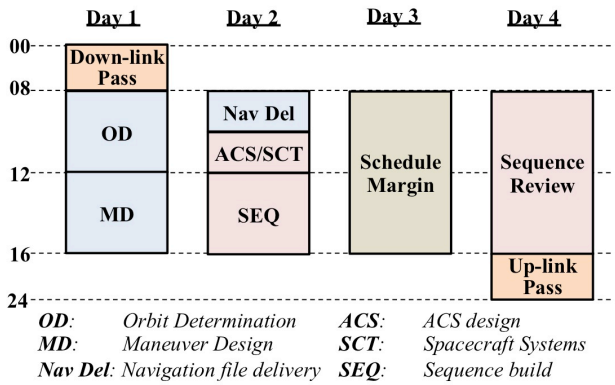

Figure 4. Thrust Sequence Build Timeline

A four-day build timeline was accepted as the baseline and a three-day timeline, created by removing extra margin, was used when a more accurate maneuver was required. In the approach phase, while delivery errors were more tolerable and recoverable by subsequent thrusting, thrust sequences were built in a loose seven day timeline which was essentially the four day building schedule plus a three day weekend.

Building a thrust sequence begins with the tracking data cut-off and ends with the sequence upload to the spacecraft. The baseline timeline allows the flight team to complete their assigned work during the prime shift in nominal cases. The night shift is left as a margin for any contingency situations and allocated to the sequence build process.

One key change from Vesta's timeline was exclusion of the ACS update from the build process. After maneuver design is completed, the resulting flight path deviates from originally predicted trajectory. Therefore the ACS team's initial prediction of ΔV during momentum off loading by RCS is no longer accurate. During Vesta operation, the ACS team revised the predicted RCS ΔV, using the first cut maneuver design, and provided navigation team a chance to update the thrust design. However, with RCS-only control at Ceres, the accuracy of the ACS prediction capability was significantly degraded. With a large uncertainty in prediction, revising the maneuver design with updated ACS prediction was not profitable and was removed from the nominal maneuver design process. Unfortunately, this simplified process resulted in a poor maneuver performance for the final trajectory control maneuver (TCM) prior to LAMO. This will be further detailed in the following Orbit Determination section. The baseline four-day sequence building processes is depicted in Figure 4.

Aligning the thrust sequence build timeline on top of the transfer architecture defines the flight team's ground operational schedule during transfer activities. Before finalizing the work schedule, one more adjustment was made to minimize the work shifts during the weekends. All thrust sequence duration, except for the TCM before LAMO, was seven days to ensure a repeated weekly pattern of ground operations during the transfers. Since the required duration of the Survey science orbit was not a multiple of seven days, the initial timeline required the ground crew to work every Saturday during the following transfer phases. The Dawn project added 6 extra days, taken from operational margin, to Survey science orbit and relieved the flight team from working on many Saturday shifts.

DSN scheduling

Scheduling DSN antenna time is highly correlated with the thrust sequence build process. Since the exact times for thrusting and coasting during the transfer phases are not known until much closer to the event, the conventional strategy of identifying required DSN schedule a month ahead or even earlier was not possible for Dawn.

During Vesta operation, the Dawn project levied a requirement to the DSN schedule team to reserve continuous coverage for the entire Vesta operational period. As the mission timeline became more mature, a strategy to release the unnecessary tracks in two sets was devised as described by Han [10]. This unconventional process was possible since there were not many competing missions for Dawn's geocentric view period during Vesta operations. However, this plan was no longer viable once Dawn began orbiting Ceres. Highly resource-intensive missions like NASA's New Horizons were sharing the same geocentric view from DSN antennas. The Dawn project was requested to provide a more lean and firm schedule, typically in 10 to 12 weeks ahead.

As described earlier, most transfer thrust sequences were in a weekly repeat pattern with one HGA track and one LGA track. Losing any of these tracks would cause significant delay of the transfer or failure to accurately arrive at the next science orbit. To protect these tracking passes, a new strategy of adding extra paddings to the predicted DSN tracks was applied. Each science orbit, during which continuous coverage was required, was padded by one extra week before and after. This scheme was implemented to protect the baseline mission plan from the deleterious

effect of anomalies on the schedule during the transfer. Another type of padding was applied for the tracks during the transfer by padding the required 12 hours up to one day. These extra times were necessary to provide flexibility when the transfer design needed to be revised. Upon completion of the transfer background sequence build, during which thrust and coasting times are defined, these extra tracking times were released by the project after careful reviews. By adopting this new strategy, the Dawn project accepted a risk of not securing necessary DSN tracks in case of a serious spacecraft anomaly. Any anomaly resulting in spacecraft safe mode would take several days to recover and to return to the nominal operating state. If an anomaly occurred during transfer, the entire transfer thrusting architecture may have needed to be completely redeveloped, which may take many days.

Dawn suffered a safe mode entry during the transfer from Survey to HAMO, due to a FT-3 gimbal anomaly. By combination of this schedule padding scheme and a quick detection of the anomaly from an NDTV pass, flight operations were successfully returned to the nominal plan after staying extra two weeks at Survey science orbit.

VI. Mission Design

All of Dawn's launch targets, reference trajectories, and maneuver designs were performed with an in-house software toolset called Mystic [2]. Mystic was built to compute, analyze, and visualize optimal high fidelity, low thrust trajectories. Detailed mission design for the Ceres orbit transfers began before Dawn left the Earth and continued until Dawn was orbiting Ceres at LAMO. The Monte-Carlo trajectory statistical analysis tool Veil [6] was used to design and verify Dawn's approach to Ceres and its orbit transfers. Veil estimates the likelihood that any given thrusting and statistical maneuver plan, or architecture, has to succeed given the expected gravity, orbit determination, and maneuver execution errors the spacecraft may encounter. Veil is designed to link multiple daisy-chained maneuvers, a key requirement for building Dawn's transfer architecture.

Transfer architecture development

Building a transfer architecture begins with designing one trajectory connecting two science orbits. Thrust magnitude is lowered using an average duty cycle of IPS thrusting to model desired total coasting times for the transfer. The next step is to divide the entire transfer into multiple design cycles whose durations are driven by both ground sequence design process duration and the ability to accurately control the thrust direction in the open loop mode in which Dawn is flown.

During operations, for each design cycle, a thrust profile is built with a newly updated set of OD estimations. Intermediate coasting, modeled using a duty cycle, serves several different purposes: recording Doppler data for OD, spacecraft engineering data downlink, sequence upload, and intentional quiet time to reduce the prediction error before thrusting or to update an onboard ephemeris. Coasting was also added to enable statistical maneuvers and provide robustness in the transfer design against uncertainties. A key parameter in deciding the acceptability of the architecture was feasibility. If Mystic failed to find a trajectory using all the available thrusting time, the sample was marked as infeasible. A typical guideline of 99% or higher feasibility was applied in accepting the case. If this criterion was not met, adjustments were made to the architecture and Veil process was repeated.

All pre-developed transfer architectures were successfully implemented at Ceres without significant changes. Operational implementation added additional constraints not present in the Veil studies. The thrust vector profiles designed by the navigation team had to be implementable by the ACS onboard the spacecraft. Since the tight operations schedule precluded navigation iterating with the ACS team, Dawn's ACS team developed a tool, named softSTAT, for the navigation team to verify that the designed thrust profile met the ACS agility constraints.

As described earlier, minimization of hydrazine consumption became a primary goal, since depletion of hydrazine, not xenon, would now determine Dawn's end of mission. Since thrusting using the ion propulsion system uses less hydrazine than coasting, every attempt was made during operations to thrust whenever possible. To accomplish this, Mystic forced thrusting whenever possible and the optimization objective was changed from maximizing final mass to minimizing the angular difference between all thrust vectors and a thrust vector target. Choosing a target direction that satisfied ACS agility constraint, by passing softSTAT, was not easy during the short design process. Prior to the maneuver design process, a Monte Carlo program was run to evaluate many hundreds of direction optimization target candidates for a given trajectory to guide the operational maneuver design. This process was utilized in the majority of thrust sequence building processes in the Ceres operation.

The most challenging transfer both from the standpoint of architecture design and operational implementation was the HAMO to LAMO transfer (Figure 5). This architecture contained 7 design cycles plus a 2-day statistical maneuver. Each cycle was designed to return the spacecraft to a reference trajectory finalized just before operational implementation of the first design cycle. The transfer reduced spacecraft mean semi-major axis from 1939 km to 843 km in 50.6 days, bringing the spacecraft just inside of two Ceres radii and to the final Ceres science orbit.

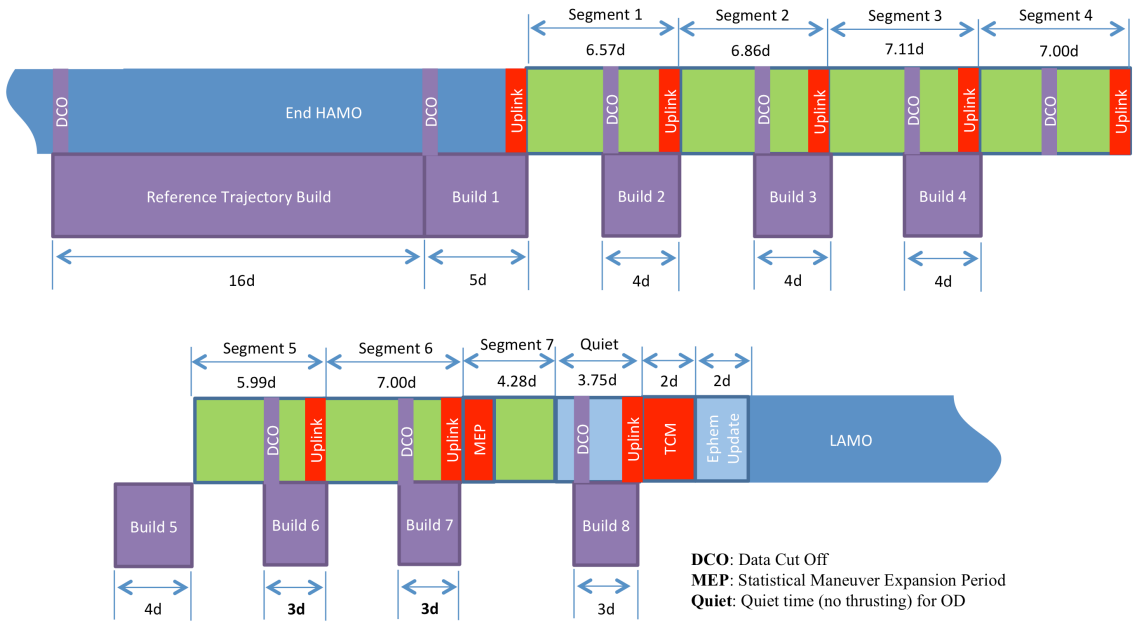

Figure 5. HAMO to LAMO Transfer Architecture

Planetary Protection

The primary Ceres planetary protection requirement was that the project provides a spacecraft orbital lifetime around Ceres of greater than 20 years post-orbital-insertion, based on the worst-case credible gravity field model. To maximize the likelihood of executing the Ceres science plan on schedule, the Dawn project elected to exceed the 20-year requirement and instead satisfy an orbit lifetime of 50 years.

Prior to Ceres arrival, a Monte Carlo analysis was conducted at both the lowest (~375 km) and highest (~13,500 km) distance from Ceres during the orbital mission and confirmed that the spacecraft would not impact Ceres for at least 50 years for the full range of credible Ceres gravity field models. A conservative but credible Ceres gravity field covariance was developed and sampled 10,000 times in the Monte Carlo study. Therefore, the analysis inherently includes the worst-case and best-case credible gravity field models from a lifetime standpoint. The spacecraft is assumed to be unmaneuverable throughout this time period. Variations in solar flux are offset by the conservative assumption that the spacecraft's huge solar arrays continue to remain Sun pointed after loss of maneuverability. No Monte Carlo samples impacted Ceres within the 50 year time period, and minimum radius and maximum eccentricity encountered were always far from the values required for Ceres impact.

The orbital lifetime has been further confirmed to still exceed the 50-year requirement using the latest Ceres gravity field determined by the navigation Team during LAMO operations. The project is in compliance with Ceres planetary protection requirements and guidelines.

Approach redesign following anomaly

Dawn's approach plan to Ceres was designed with 4 design cycles (open-loop control periods). The cycle durations, in chronological order, were planned to be 28, 28, 14, and 14 days long. The first science orbit RC3, polar at a radius of 14,000 km, was the target of the fourth and final cycle. The first design cycle maneuver was to be updated with an orbit determination cut off 14 days in advance. Subsequent cycles were updated with a data cutoff 7 days in advance. On September 11, 2014, just before the approach plan could begin, a spacecraft anomaly ceased thrusting and caused safe mode entry. Previous studies showed that this time was nearly the worst time to lose thrust. For the first week, each day's delay returning to thrust would result in at least a 6.8 day delay in our arrival at RC3. If the delay to return to thrust was between 1 and 2 weeks then the multiplier grew to 7.9 days delay per day of thrust outage.

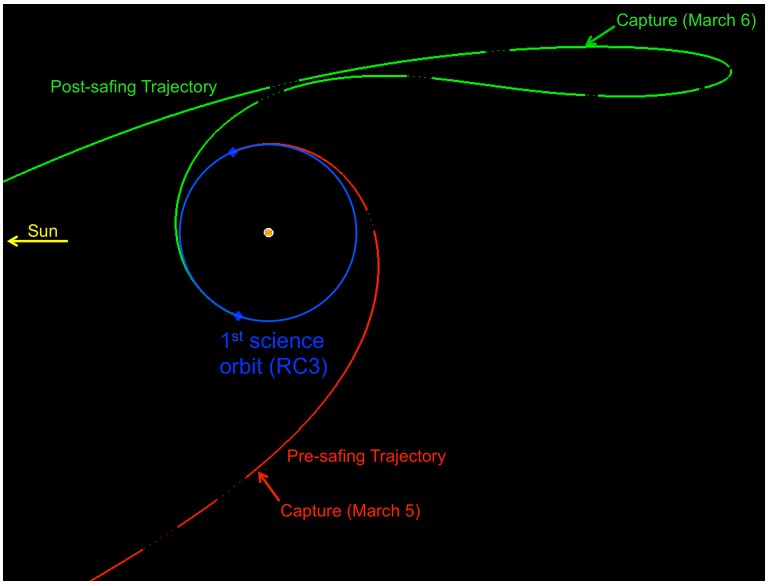

Figure 6. Ceres Approach: Before and After Anomaly

The effect of the thrust outage was that Dawn would not be able to slow enough in a Ceres centered frame to capture without first flying by Ceres and having to fly back. Dawn's Ceres approach was designed to provide low phase opnav imaging, but post-flyby geometry would be at very high phase making optical navigation impossible. A new plan was developed rapidly to account for this "dark side" approach and fine-tuned using Veil in the days following the outage. The thrusting problem was diagnosed and the Dawn flight team quickly recovered the spacecraft state back to normal with total thrust outage of 4 days.

The new approach plan used 5 design cycles. The new overshoot trajectory was very sensitive to OD error and statistical maneuvering. As a result of this sensitivity, the trajectory could change the apparent body phase during planned optical navigation imaging to the point where the data would be nearly useless. Because of this, and unlike the original approach, it was necessary to target Ceres-relative waypoints on approach to guarantee that the planned optical navigation periods would achieve an acceptable phase. The reliability of the approach itself was validated using Veil assuming most of the optical navigation sessions would be successful. Ceres approach trajectories, before and after the anomaly, are shown in Figure 6.

Three different approach plans were tested involving increasing amounts of allocated time for statistical thrusting. Ordinarily a design of this type may take a month or more to develop. Since time was critical three plans were developed based on intuition and tested simultaneously. The plan with the least statistical maneuvering was found to be the most likely to maintain both reliability and obtain acceptable optical navigation images. The revised plan led to a delayed, from the initial plan, but successful entry to the RC3 orbit.

VII. Orbit Determination (OD)

The key contributions by the OD team during Ceres operations were similar to those of Vesta operations. The OD team's pre-Ceres covariance studies were a key input to the transfer architecture design process. At each science orbit, the Ceres physical parameters and gravity field determination prompted an update in the next science orbit design process by the mission design team. Accurate estimation of the spacecraft state and trajectory prediction is a fundamental task for the OD team.

The orbit determination process at Ceres was similar to the process at Vesta, except for two key changes: the plan to leave the spacecraft in the lowest orbit LAMO as part of spacecraft decommissioning, and the use of the all-RCS mode during most of Ceres operations. The disposal of Dawn at LAMO was studied in order to comply with NASA's planetary protection requirements. Developing a "credible worst case gravity model" of Ceres was a key part of validating this requirement.

Switching the ACS mode due to RWA failure resulted in RCS pulsing events that are poorly predicted both in time and magnitude, and these events adversely affected OD performance. Until arrival in the LAMO orbit, the 100% reliance on the RCS would require careful management of the remaining hydrazine. One hydrazine-conserving response was to reduce the number of HGA tracking passes and the number of optical navigation sessions during all transfers, resulting in a significant reduction of tracking data. This change had a significant impact on the OD team's process and ability to accurately estimate the latest Dawn and Ceres parameters.

For Ceres, covariance studies were performed with the assumption of reduced optical and tracking data and increased uncertainty in RCS activity. As with the pre-Vesta studies, the output covariances were scaled by a conservative margin in order to demonstrate robustness. Based on these conservative covariances, the pre-Ceres study by the maneuver team indicated that OD would be able support the transfer with timely delivery of sufficiently accurate information. One key finding from the Ceres covariance studies was that the GM of Ceres is not well

observed using only radiometric data. This observability is especially compromised when the RCS is pulsing frequently. Appropriate use of optical data is needed to obtain an accurate estimate of the Ceres GM [18].

In practice, the transfers into RC3, Survey and HAMO were executed well. The transfer into LAMO went smoothly until the execution of the final deterministic thrust arc. The delivery from this last IPS thrust arc was substantially off from the reference state target. It was determined that two sources of error combined to produce this miss: an underestimation of the gravity field at that altitude, and a failure to account for the increased RCS thruster firing response while under IPS thrust. The underestimation of gravity is due to the OD team estimating only up to degree/order 6 as part of the design of the final deterministic thrust arc. Further description of this result is found in [18]. The RCS activity during this maneuver had a substantial bias that contributed to a net increase in thrust. During the approach to RC3 and transfer into Survey, the center IPS thruster (FT-3) was used. For the transfers to HAMO and LAMO, a non-centered thruster (FT-2) was used to provide thrust. Due to the configuration and orientation of the ship's IPS and RCS subsystems, the net RCS activity is balanced during the use of FT-3, but unbalanced during the use of FT-2. During the earlier phases, the predicted and realized responses of the RCS to FT-2 were not considered to be large, so the thrust build process was streamlined by not accounting for them. However, during the last thrust sequence, the RCS response frequency was twice that of the previous segment, resulting in a biased source of thrust during IPS thrust execution. Combined with the errors in gravity from the OD team, this resulted in a much larger than expected delivery error.

An attempt to clean up this delivery error was undertaken with a TCM. This TCM was a two-day thrust period that had already been built as a statistical maneuver into the LAMO transfer architecture for this type of contingency. Based on lessons learned in the previous thrust arc, the gravity field was estimated with a more appropriate 8th degree/order field. Also, the IPS thrust design was made with a model of expected RCS activity. Nominally unplanned, iteration with the ACS team was added to the process to update the predicted RCS thrusting during the thrust sequence.

In spite of these efforts, the TCM was not able to clean up the entire error. Again, there were two sources of error. The first, and more significant, error was caused by inaccurate prediction of RCS activity between the OD data cutoff and the execution of the TCM three days later. This period between the data cutoff and the TCM is called the "quiet period". During this quiet period, the spacecraft was on a very different trajectory from the designed path due to the delivery errors of the previous thrust arc. While this trajectory was known, the predicted RCS response along this new trajectory was not known. The change in RCS response was not considered and so was not re-calculated. The outdated RCS thrust predictions were used to predict the state at the start of the TCM. Since the actual RCS thrusting resulted in an additional 10 cm/s of ΔV above the earlier RCS predictions, a large state error was observed at the TCM start time, which propagated into another large delivery error. The second source of error was another poor estimation of the Ceres gravity field. This estimation error was of a smaller magnitude than the previous field errors [18], but it resulted in an added delivery error to the TCM. However, in spite of these issues, the Dawn spacecraft arrived at LAMO meeting the science requirements. A minor implication of this delivery error on the science operations at LAMO was that the first imaging cycle missed some of the planned targets and left a few gaps in coverage. Nevertheless, it was quite sufficient for meeting the level 1 requirements. Eventually, the orbit maintenance maneuver in LAMO brought the spacecraft back to the original reference orbit before the second science sequence began and the coverage gaps were filled by ensuing science sequences.

VIII. Optical Navigation (Opnav)

An important component of the orbit determination process is the use of optical observables, created from the images acquired with the framing camera (FC). The most important optical data in proximity navigation are landmarks. Landmarks are constructed with stereo-photoclinometry [8][17], and they are control points on the surface of Ceres, each centered at a small digital terrain and albedo model that extends over part of the surface. Due to the large change in image resolution between approach and LAMO, the number of landmarks necessary to cover the surface increased from 400 to more than 80,000. The key contributions of optical navigation to the orbit determination were in the spacecraft and Ceres state solution, in determination of the rotational parameters and gravity field of Ceres and its detailed topography.

Two spacecraft anomalies significantly impacted optical navigation. Considerable hydrazine savings, necessitated by RWA failures, were achieved by minimizing the total number of turns Dawn would execute. This brought about a number of changes in the opnav and science image acquisition on approach, survey and the orbit transfers. Specifically the number of opnav imaging events was reduced from 23 on approach to Vesta to 12 on approach to Ceres, which was near the absolute minimum to support state estimation for the spacecraft delivery to

the science orbits and the determination of the rotation axis of Ceres. Opnav imaging during the orbit transfers below Survey was removed completely, depriving the navigation team of an independent confirmation of Dawn's accuracy for the next science orbit insertion. Another major limitation was the removal of image mosaics on late approach and Survey. Landmark construction requires the acquisition of images at varying incidence and emission angles, necessitating the use of off-nadir camera pointing in the form of an image mosaic when the body is larger than the camera field of view (FOV), a process that requires a large number of turns. These mosaics were replaced instead with nadir observations, which severely limited the emission angle to less than 30°, from the nominal 60° needed. Detailed simulations of the late approach and Survey phase with nadir observations confirmed that the landmark height accuracy was deteriorated by 50%. Even at this level, however, the optical data were sufficient to support the design of the transfer and science orbit trajectory.

Another anomaly occurred before the beginning of approach phase in September 2014 and prompted a redesign of the approach mission design, as further described in mission design section. As a result the original rendezvous with Ceres became untenable and a new approach trajectory had to be designed that would allow Dawn to catch up with Ceres at a high phase angle. That required a redesign of the approach opnav image acquisition, forcing a number of Ceres observations to be acquired at a high phase angle. Specifically, the 7th opnav was carried out on March 1 2015 at a phase angle of 123° and the 8th opnav on April 10 at 131° phase, as can be seen in Figure 7. The high phase limited the usefulness of these observations, because they utilized only a small part of visible surface to identify landmarks, which were at significantly higher noise level due to the low solar elevation. The revised approach opnav plan, with fewer and noisier observations, provided degraded but enough accuracy in orbit determination leading to a successful arrival at the first science orbit, RC3.

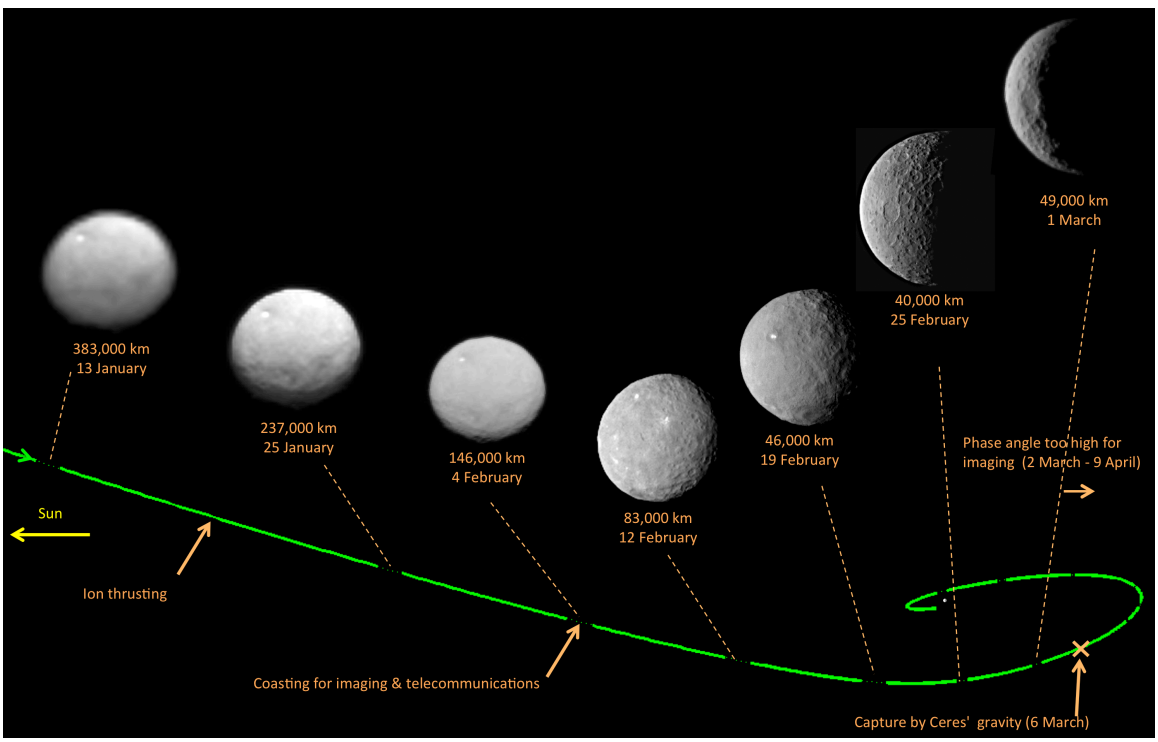

Figure 7. Ceres Approach Geometry

IX. Conclusion

Maneuvering a spacecraft only using the IPS for the transfers between the mapping orbits around a previously unvisited dwarf planet posed many technical challenges to Dawn's flight team. Each transfer needed a robust plan that accounted for uncertainties in maneuver execution, orbit determination, and physical characteristics of Ceres. A number of spacecraft anomalies and incurred changes in spacecraft operations added extra difficulties to Dawn's navigation. Dawn's navigation team at NASA's JPL developed many new techniques and applied them in both the planning and operational phases at Ceres, facilitating the successful operation of the first spacecraft to successfully orbit a dwarf planet.

X. Acknowledgement

This paper summarizes the outstanding performance by Dawn's navigation team. The entire navigation team: Nicholas Bradley, Daniel Grebow, Reza Karimi, Brian Kennedy, Nickolaos Mastrodemos, Daniel Parcher, Brian Rush, John Smith, Yu Takahashi, and Gregory Whiffen, deserves the credit for the technical achievements described in this paper. A special appreciation goes to Marc Rayman, Dawn's chief engineer and mission manager, for diligently providing very insightful comments and suggestions from early development phase to the end of successful operations at Ceres.

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Copyright 2016 California Institute of Technology. Government sponsorship acknowledged.

XI. References

[1] Rayman, M.D., et al, "Dawn: A mission in development for exploration of main belt asteroids Vesta and Ceres", Acta Astronautica, Vol. 58, pp. 605-616, 2006.

[2] Whiffen, G.J., "Mystic: Implementation of the Static Dynamic Optimal Control Algorithm for High-Fidelity, Low-Thrust Trajectory Design", Paper AIAA 2006-6741, AIAA/AAS Astrodynamics Specialist Conference, Keystone, Colorado, USA, Aug. 21-24, 2006.

[3] Vanelli, C.A., et al, "Verification of Pointing Constraints for the Dawn Spacecraft", AIAA/ASS Astrodynamics Specialist Conference, Honolulu, Hawaii, USA, August 17-22, 2008.

[4] Thomas, V.C., et al, "The Dawn Spacecraft", Space Science Reviews, Vol. 163, Nos. 1-4, pp. 175-249, 2011.

[5] Polanskey, C.A., et al, "Dawn Science Planning, Operations and Archiving", Space Science Reviews, Vol. 163, Nos. 1-4, pp. 511-543, 2011.

[6] Parcher, D.W., et al, "Dawn Statistical Maneuver Design for Vesta Operations", Paper AAS 2011-180, AIAA/AAS Astrodynamics Specialist Conference, New Orleans, Louisiana, USA, Feb. 13-17, 2011.

[7] Parcher, D.W., "Low-Thrust Orbit Transfer Design for Dawn Operations at Vesta", Paper AAS 2011-183, AIAA/AAS Astrodynamics Specialist Conference, New Orleans, Louisiana, USA, Feb. 13-17, 2011.

[8] 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.

[9] Bruno, D., "Contingency Mixed Actuator Controller Implementation for the Dawn Asteroid Rendezvous Spacecraft," AIAA SPACE 2012 Conference & Exposition, Pasadena, California, Sep. 11-13, 2012

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

[11] Rayman, M.D., et al, "Dawn's Exploration of Vesta", 63rd International Astronautical Congress, Naples, Italy, Oct. 1-5, 2012.

[12] Smith, B.A., et al, "Understanding Spacecraft Agility for Orbit Transfers on the Dawn Low-Thrust Mission", Paper AAS 12-097, 35th Annual AAS Guidance and Control Conference, Breckenridge, Colorado, USA, Feb. 3-8, 2012.

[13] Rayman, M.D., et al, "Preparing for Dawn's Mission at Ceres: Challenges and Opportunities in the Exploration of a Dwarf Planet", 65th International Astronautical Congress, Toronto, Canada, Sep. 29 - Oct. 3, 2013.

[14] Smith, B.A., "Dawn Spacecraft Operations with Hybrid Control: In-Flight Performance and Ceres Applications", Paper AAS 14-107, 37th Annual AAS Guidance and Control Conference, Breckenridge, Colorado, USA, Jan. 31-Feb. 5, 2014

[15] Rayman, M.D., et al, "Dawn's operations in cruise from Vesta to Ceres", Acta Astronautica, Vol. 103, pp. 113-118, 2014.

[16] Polanskey, C.A., et al, "Architecting the Dawn Ceres science plan", in: Proceedings of the SpaceOps 2014 Conference, 2014.

[17] Mastrodemos, N., et al, "Optical Navigation for the Rosetta Mission, Paper AAS 15-123, Proceedings AAS Guidance and Control Conference, February 2015.

[18] Kennedy, B.M., "Determination of Ceres Physical Parameters Using Radiometric and Optical Data", Paper AAS 16-107, AAS GN&C Conference, Breckenridge, Colorado, USA, Feb. 05-10, 2016.

[19] Polanskey, C.A., et al, "Dawn Ceres Mission: Science Operations Performance", in: Proceedings of the SpaceOps 2016 Conference, 2016.