# Dawn Safing Approach to Ceres Re-Design

Daniel J. Grebow*, Gregory J. Whiffen*, Dongsuk Han†, and Brian M. Kennedy†

*Jet Propulsion Laboratory, California Institute of Technology*

*4800 Oak Grove Drive, Pasadena, CA 91109-8099*

**In mid-2014 the Dawn team finalized preparations for the spacecraft's approach to Ceres. The design was the product of careful planning that began several years in advance, when the spacecraft left Vesta in September 2012. However, a few months prior to the anticipated start of approach, the spacecraft entered a safe mode. While temporary loss of thrust for ion propulsion missions is usually not mission-critical, it still presents many challenges. The safing event occurred at a time when thrusting to match Ceres' orbital velocity was most effective, which meant the spacecraft must fly past Ceres before capturing into orbit. The new approach geometry changed the team's strategy for navigating the spacecraft safely into orbit around Ceres with optical data. In this paper we describe the challenges of navigating the Dawn spacecraft into orbit around Ceres, including the safing event and re-design of the approach architecture.**

## I. Introduction

Dawn is a Discovery mission that was selected by NASA in December 2001. The purpose of the mission is to visit the protoplanet Vesta and dwarf planet Ceres to learn more about the *dawn* of the solar system.[1,2] Vesta and Ceres are very unique bodies in the main asteroid belt. In contrast with Vesta which is rocky and heavily cratered, Ceres is icy and believed to contain an abundance of water ice beneath its surface. Unlike other objects in the asteroid belt, both bodies are relatively large and spherical. Vesta and Ceres are the two largest bodies in the main asteroid belt, and together they comprise nearly 40% of the total mass in the main asteroid belt.

With intentions of studying these unknown worlds, the Dawn spacecraft was launched from Cape Canaveral on a Delta II rocket on September 27, 2007. The mission had one gravity assist with Mars in February 2009 while enroute to Vesta. It arrived at Vesta in July 2011 and explored the primitive body for approximately one year before departing in September 2012. The interplanetary cruise from Vesta to Ceres lasted 2.5 years. Dawn arrived at Ceres in March 2015, making it the first spacecraft to visit a dwarf planet.

The mission is unique in that the primary source of inspace propulsion is a set of three ion thrusters. Dawn is the first NASA exploration mission to use ion propulsion. The NSTAR engines on Dawn were first tested in flight on the Deep Space-1 technology demonstration mission.[4] The ion propulsion system (IPS) is truly mission enabling, as Dawn is the first craft ever to orbit two extraterrestrial bodies. To date, the IPS system has logged over 5.5 years of accumulated thrusting, and is capable of providing a total impulse of 11.3 km/s.[3]

In this paper we briefly describe the orbits and science objectives for the Ceres mission. More details can be found in other publications.[5–7] The primary focus of the paper is the approach to Ceres, or the transition from interplanetary cruise to the highest science orbit around Ceres. Approaching a relatively unknown body presents its own unique challenges. We discuss these challenges as well as issues unique to the Dawn mission, specifically to orbit insertion around Ceres. There was the short period of missed thrust due to the safing event a few months before approach. The safing event significantly altered the team's approach strategy. Each day of missed thrust caused a week delay in Ceres arrival. The new, complex approach architecture meant the team needed to re-design the times of imaging Ceres for optical navigation. A strategy of soft

*Outer Planet Mission Analysis Group, Mission Design and Navigation Section, M/S 264-820.

†Outer Planet Navigation Group, Mission Design and Navigation Section, M/S 264-820.

waypoint targeting was developed to guide the spacecraft along the planned course for this new, sensitive approach trajectory.

## II. Overview of Ceres Mission & Approach

Like the Vesta mission, the Dawn Ceres mission had four science orbits: RC3 (Rotational Characterization orbit 3), Survey, HAMO (High Altitude Mapping Orbit), and LAMO (Low Altitude Mapping Orbit). Each orbit had specific science objectives. The purpose of RC3 was to map the shape of Ceres and learn more about the Ceres pole and spin rate. In Survey, HAMO, and LAMO, we planned to obtain a global distribution with the visual and infrared spectrometer (VIR) and global coverage with the framing camera (FC), acquiring high-resolution VIR data in HAMO and LAMO. Additionally, in LAMO the gravity field would be resolved and the gamma ray and neutron detector (GRaND) instrument would be used to study the subsurface structure of Ceres. More details about the science instruments can be found in the following publications.[8,9] A description of the orbits is provided in Table 1, and the orbits are shown in Figure 1. See Polanskey et al.,[5] Han et al.,[6] and Whiffen[7] for more information about the Ceres mission.

**Table 1. Description of Transfers and Science Orbits at Ceres.**

| Mission Phase (Purpose) | Description | Start to End (Duration) |
|---|---|---|
| Approach (Transfer) | End interplanetary cruise and capture to RC3, 5 design cycles, approximately 7-day builds | Dec 27, 2014 to Apr 23, 2015 (117 days) |
| RC3 (Science) | Circular orbit with radius = 14,000 km, period = 15.3 days, beta angle = 5 deg, inclination = 90 deg | Apr 23, 2015 to May 9, 2015 (16 days) |
| RC3 to Survey (Transfer) | 2 design cycles, 4-day builds | May 9, 2015 to Jun 3, 2015 (25 days) |
| Survey (Science) | 47:6 repeat ground track, circular orbit with radius = 4718 km, period = 3.1 days, inclination = 90.74 deg | Jun 3, 2015 to Jul 1, 2015 (28 days) |
| Survey to HAMO (Transfer) | 5 design cycles, 4-day builds | Jul 14, 2015 to Aug 16, 2015 (32 days) |
| HAMO (Science) | 25:12 repeat ground track, circular orbit with radius = 1943 km, period = 18.9 hours, inclination = 90.52 deg | Aug 16, 2015 to Oct 23, 2015 (69 days) |
| HAMO to LAMO (Transfer) | 7 design cycles + 2-day TCM, 4-day and 3-day builds | Oct 23, 2015 to Dec 13, 2015 (51 days) |
| LAMO (Science) | 56:93 repeat ground track, circular orbit with radius = 849 km, period = 5.4 hours, beta angle = 45 deg, inclination = 90.57 deg | Dec 13, 2015 to Jun 30, 2016 (200 days) |

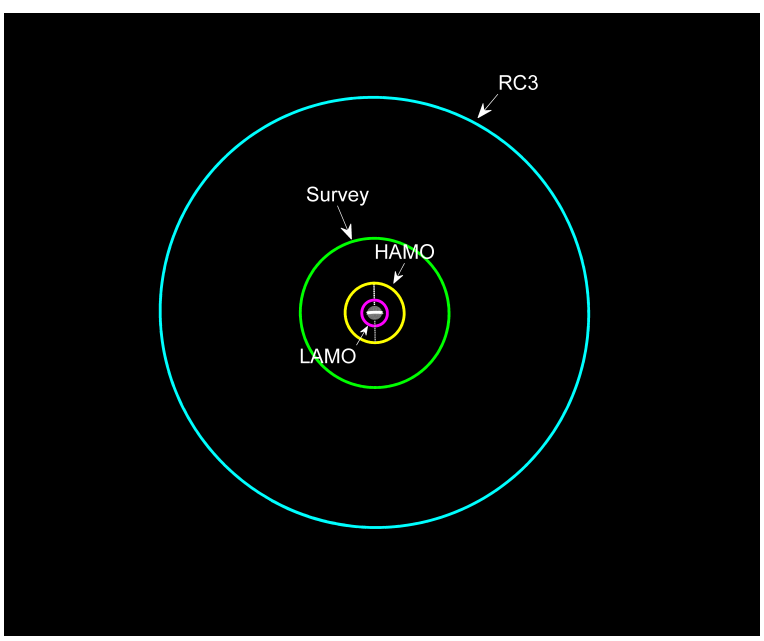


**Figure 1. Ceres Science Orbits.**

### II.A. Challenges of Ceres Approach

One challenge of capturing around a small body is the uncertainty in the physical parameters of the object. The body's ephemeris may not be well-known. There may also be poor knowledge of the body's gravity and pole. The pole is important if the capture orbit has a specific inclination. There is also uncertainty in spacecraft parameters, such as the spacecraft state and thrust modeling.

Deep space interplanetary missions rendezvousing with or flying by small solar system bodies (asteroids or comets) will perform target-relative navigation during an approach phase. Typically, this involves acquiring optical data (Opnavs) using a visible light camera. These data allow the Navigation team to correct the target body ephemeris errors, estimate a target-relative trajectory and design the appropriate targeting maneuvers. In the case of Dawn, the ephemeris errors for Ceres were comparatively well known, but the Dawn trajectory was comparatively less well known due to the frequent use of the low thrust from the Dawn IPS. The value of the Opnavs is related to the approach geometry. Low phases where the body is mostly illuminated are desirable.

After completing successful operations at its first target Vesta, 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. This change required the entire flight plan to Ceres to be redrawn. Conserving hydrazine for the science operation at Ceres became a key objective and the original mission design and plan for Ceres approach was revised. Reduction of spacecraft turns was the key change in the new plan, significantly impacting the optical navigation during Ceres approach. The number of dedicated imaging sessions for Ceres approach optical navigation was reduced to half of the Vesta plan influencing the accuracy of approach orbit determination. During Vesta approach there were 23 Opnavs, where in the first Opnav Vesta occupied only a few pixels. For approach to Ceres, there were 9 Opnavs, and in the first Opnav image Ceres covered 23 pixels.

In a low-thrust mission, there are usually no critical events. However, there are periods where loss of thrust may have a significant impact on the mission. These periods typically occur before flybys or rendezvous. As will be seen, all of these factors combined to make Dawn's approach to Ceres especially challenging.

### II.B. Description of Software

As described in Grebow,[10] the design of Ceres architectures began years prior to arriving at Ceres. Design begins with a reference trajectory that is subsequently decomposed into design cycles, providing a design architecture. Before flying the architecture, its viability is tested with the software Veil, a Monte Carlo tool wrapped around the low-thrust optimizer Mystic.[11,12] Veil is used to help determine the length of design cycles and build times by simulating the effects of unknown parameters, such as spacecraft state knowledge, Ceres gravity, pole, rotation rate, maneuver execution error, and perturbations due to momentum wheel desaturation maneuvers or the reaction control thruster firings. See Whiffen and Parcher[13] and Grebow et al.[10] for a more detailed description of Veil.

### II.C. Planned Architecture Prior to Safing Event

As previously described, the purpose of the approach phase is to safely deliver the spacecraft to the first science orbit around Ceres, RC3. RC3 is a circular, polar orbit with a radius of 14,000 km and a beta angle of 5 degrees that naturally increases with time to avoid going into Ceres shadow. All design cycles in interplanetary cruise and approach target these precise orbit conditions at Ceres.

The final design cycle of interplanetary cruise was planned to be roughly one month in duration, but allowed to expand or contract to eliminate optimal coasting in approach. The cycle interface times determine when the high-gain antenna (HGA) points to Earth to receive data from the Deep Space Network (DSN) for maneuver sequencing commands. Approach to Ceres was an especially busy time for the DSN as New Horizons also was preparing for the Pluto flyby, and therefore times when Dawn communicated with DSN needed to be booked well in advance. During the last cycle of cruise the team planned to lockdown the interface times of approach.

Altogether the approach architecture contained five cycles: the final cycle of cruise, two 28-day cycles followed by two 14-day cycles (architecture shown in Figure 2). For the first Opnav, we planned to slew the spacecraft to image Ceres on February 2, 2015, during the first cycle of approach. In the remaining cycles we allocated coast times for nine additional Opnavs. Veil results showed 100% feasibility for 1950 samples.

Ceres capture was nominally planned for March 7, 2015, and the start of RC3 would occur on March 20, 2015. A summary of the expected delivery is provided in Table 2.

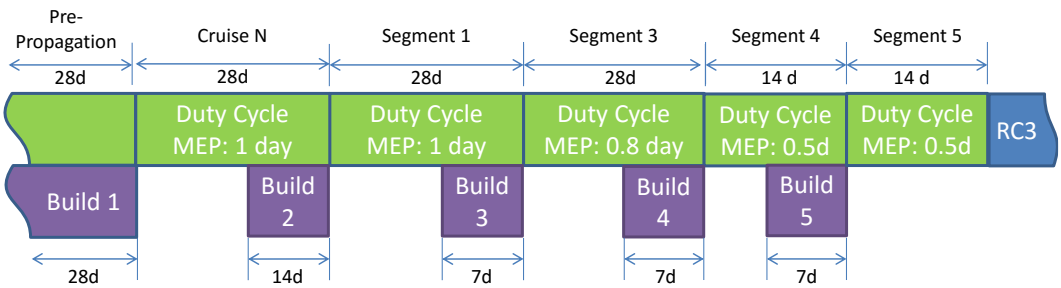


**Figure 2. Approach architecture before safing event.**

**Table 2. Anticipated delivery to RC3 prior to safing event.**

| | Delivery (mean $\pm 1\sigma$) |
|---|---|
| Beta angle (deg) | $5.0 \pm 0.2$ |
| Inclination (deg) | $90.0 \pm 0.2$ |
| Period (hrs) | $364.0 \pm 2.9$ |
| Range (km) | $14006.1 \pm 74.1$ |
| True Latitude Spread (deg) | $40.3 \pm 4.7$ |

## III. Preliminary Missed Thrust Analysis

After losing the second reaction wheel just after departing Vesta it became critical to minimize the amount of coasting because coasting uses more hydrazine than IPS thrusting. Any unnecessary coast for margin was removed from the reference trajectory designs. To better understand the effects of a thruster outage for flying the spacecraft under this lean coasting budget, a missed thrust analysis was performed for the entire cruise reference trajectory. The results of the analysis can be seen in the Figure 3, where the effects of 7-day, 14-day, and 16-day outages are shown. From the figure the most significant impact for a thruster outage occurs in the September-October timeframe in 2014. At these critical times, a 7-day outage would mean arriving at Ceres 50 days later than anticipated, and a 16-day outage would push Ceres arrival back 125 days.

Trajectories for some of the 14-day thrust outages are shown in Figure 4. The approach geometry varies significantly depending on the location of the thruster outage. The $\times$-marker along the trajectory in Figure 4 indicates the location of Ceres capture. A loss of thrust after November 2014 results in trajectories that have close approaches with Ceres before capturing, flying past the body and then approaching it from the opposite side. As shown in the left plot in Figure 4, outage times in December, January, and February result in trajectories with multiple captures at Ceres.

This analysis demonstrates that if there would be an outage during or after September 2014, a quick re-design of the maneuver would be very important, not only for conserving Xenon, but also for approach sequencing and mission planning. An outage would likely have a significant impact on the maneuver design as well, probably requiring a new architecture and additional Veil runs. The adverse change in approach geometry would also affect the placement of Opnavs.

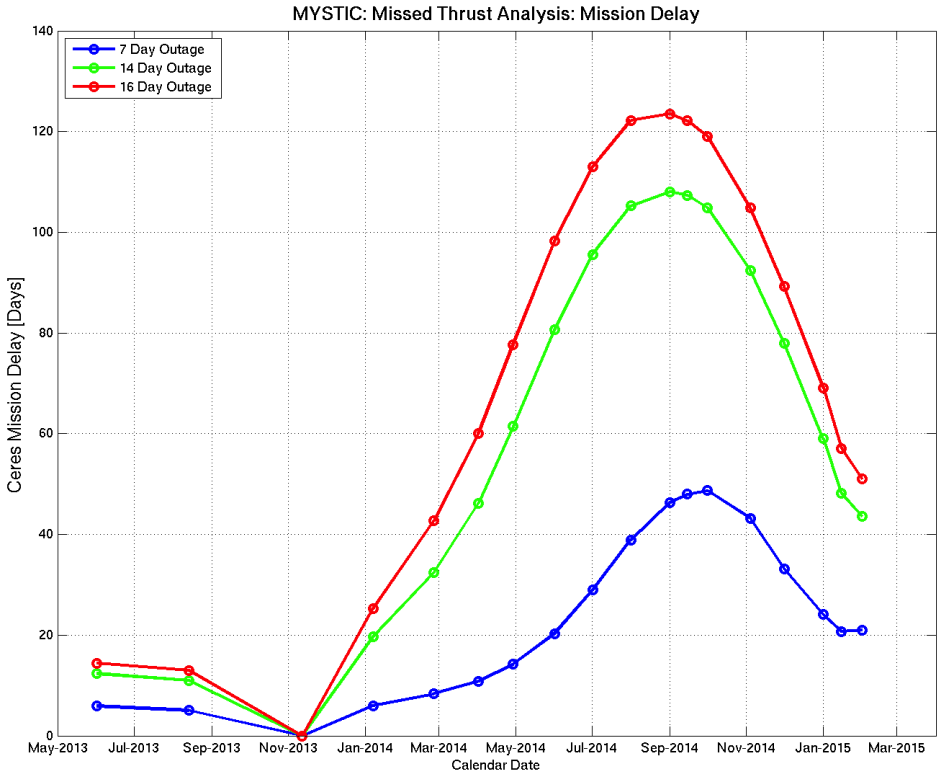


**Figure 3. Missed-thrust analysis for Vesta-Ceres interplanetary cruise. Most significant impact in Ceres arrival date occurs for a thruster outage in September-October of 2014.**

# IV. Safing & Approach Re-Design

## IV.A. Safing Event

During a tracking pass on the morning of Thursday, September 11, 2014, it was discovered that the Dawn spacecraft had entered a safe mode during a period when it was commanded to thrust. In a safe mode the spacecraft overrides all commands, points the spacecraft and panels to the sun and enters a slow roll around the sun vector. Communications with the spacecraft occur via the low-gain antenna (LGA) at a reduced data rate.

To learn more about the spacecraft's state, the Dawn team negotiated with other missions for additional DSN tracking. Meanwhile the Navigation team estimated the orbit of the spacecraft based on the time the spacecraft halted thrust. On Friday evening the maneuver design team performed an analysis to inform the project of the effects of delaying uplinking the recovery sequence. A summary of this analysis is provided in Table 3. From the analysis the team decided to prepare for a Monday uplink provided that the spacecraft was determined to be in a healthy state and responsive to commands. It was found that the new approach geometry would be vastly different from the nominal plan, requiring the Navigation team to reconfigure the placement of Opnavs. The Dawn team also decided collectively to switch to a different IPS thruster in case a problem was discovered with the thruster being used at the time of the safe mode entry. On Saturday, the maneuver design team redesigned the recovery maneuver with the new placement of Opnavs and change in flight thruster.

As of Saturday night, the team was still unsure of the cause of the safe mode entry, and it was decided to reboot the onboard flight computer. The reboot executed nominally, and on Sunday morning, the spacecraft appeared to be in a healthy state. The HGA was commanded to point to Earth, and the Sunday tracking pass showed no alarms. Further testing on Monday morning demonstrated that the spacecraft would respond as expected, and so the team decided to move forward with uplinking the recovery maneuver sequence. During

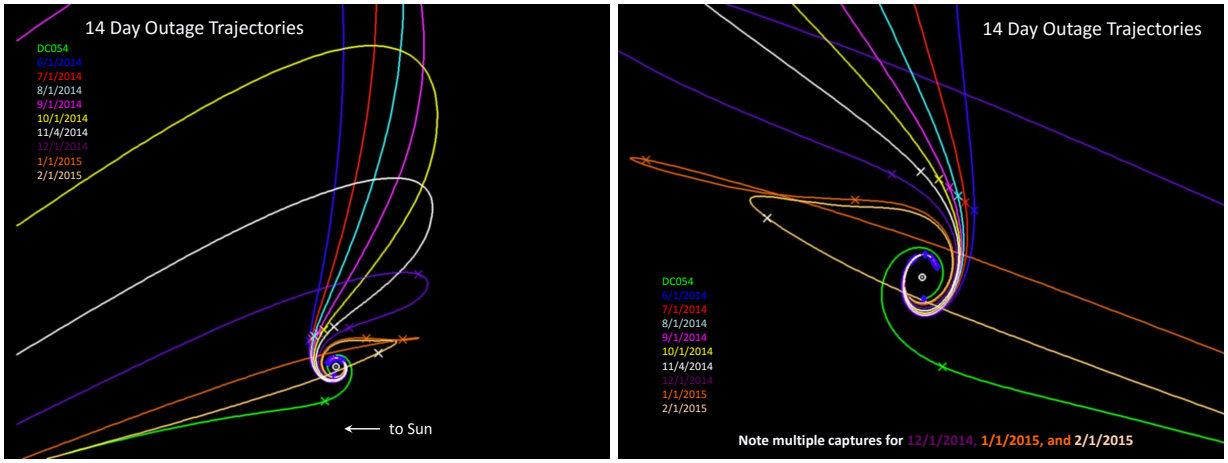


**Figure 4. Change in geometry of approach for recovery trajectories following 14-day outages at times specified in the graphic. The x-marker indicates the location of Ceres capture.**

**Table 3. Expected delay in start of RC3 versus uplink date for recovery maneuver.**

| Uplink Time | Delay (days) |
|---|---|
| September 15 | 28.6 |
| September 16 | 39.5 |
| September 17 | 50.2 |
| September 18 | 60.0 |
| September 20 | 78.2 |
| September 22 | 94.4 |

a tracking pass on Tuesday, thrusting was verified.

The cause of the events that precipitated the safe mode entry was traced back to a disabled valve driver card for the IPS (particular to the thruster being used). The anomaly was deemed a single event upset. It is unknown what disabled the valve driver card, although the exact same phenomenon was experienced three years prior on approach to Vesta.

### IV.B. New Approach to Ceres

The total thruster outage time was roughly 4 days and resulted in a 26-day delay to the start of RC3. Approach trajectories before and after the safing event are shown in Figure 5. Clearly the approach geometry is very different. The post-safing trajectory has a distant close approach with Ceres of 37,000 km, and then turns around and approaches Ceres from the opposite side. A plot of the phase before and after safing is shown in Figure 9 as a function of radius from Ceres. The placement of Opnavs is determined by the Ceres range and the solar phase. For the pre-safing approach, the phase starts low and slowly increases with time and, similarly, the range monotonically decreases as the spacecraft approaches Ceres. For the pre-safing approach trajectory, all Opnavs were scheduled to occur prior to Ceres capture, when the phase is less than 80 degrees. For the post-safe approach, the times and ranges of the Opnavs are shown in Table 4. Opnavs were scheduled for phases as high as 130 degrees, a consequence of the new viewing geometry.

### IV.C. Soft Waypoint Targeting

Every design cycle has statistical margin reserved by way of maneuver expansion periods (MEPs), a period of forced coasting in the reference. During maneuver designs the spacecraft is allowed to thrust during these periods to overcome statistical uncertainty. For Dawn, MEP durations for a cycle are typically around one day, and may be imposed via a duty cycle. (The MEP allocation for the architecture prior to safing is shown in Figure 2.) Freeing MEPs in cycles for the new approach often opened large periods of optimal coasting,

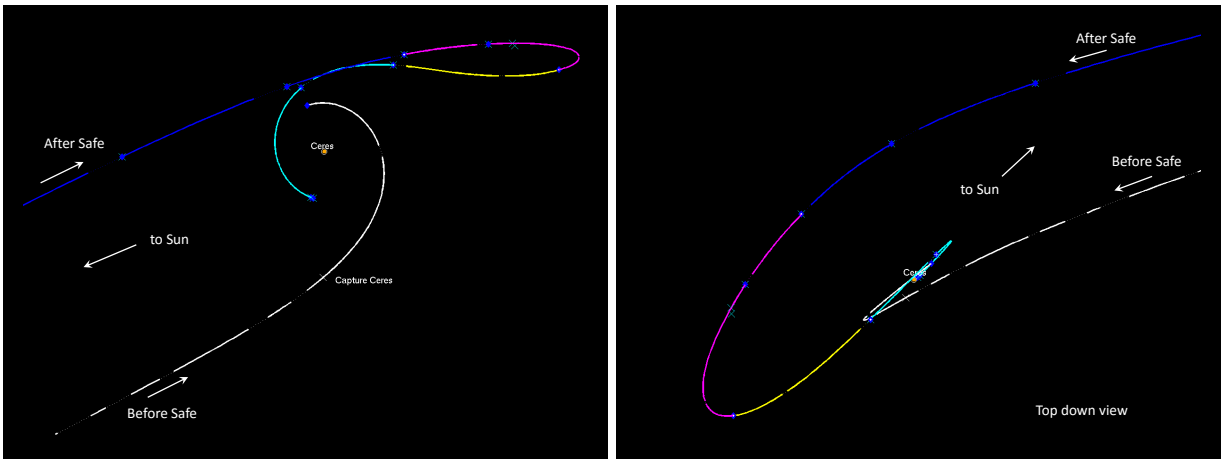


**Figure 5. Trajectory before (white) and after approach (multi-colored); view from Ceres north pole on right.**

**Table 4. Radius and Phase of Opnavs for New Approach.**

| | Time | radius (km) | phase deg |
|---|---|---|---|
| Opnav1 | January 17, 2015 | 336500 | 25 |
| Opnav2 | January 27, 2015 | 216040 | 22 |
| Opnav3 | February 5, 2015 | 136450 | 18 |
| RC1 | February 11, 2015 | 85000 | 17 |
| RC2 | February 19, 2015 | 46000 | 41 |
| Opnav4 | February 24, 2015 | 39490 | 94 |
| Opnav5 | March 2, 2015 | 52010 | 127 |
| Opnav6 | April 10, 2015 | 34240 | 130 |
| Opnav7 | April 15, 2015 | 21560 | 86 |

sometimes several weeks long, significantly altering the approach geometry and compromising the value of the planned Opnavs.

To preserve the approach geometry as closely as possible to designed reference, any extra thrusting available from freeing MEPs was used to 'guide' the spacecraft along the reference via soft waypoint targeting. In Mystic, target states can be inserted along the trajectory (see Figure 7), and each target has a particular weight. A low weight means that Mystic will fly in the vicinity of the target, not satisfying it exactly. This was the method the team adopted for designing maneuvers on approach to Ceres. At the location of every Opnav, a target state was added to pull the trajectory toward the reference that was used to design the Opnav campaign. The weights were adjusted until all optimal coasting was removed and each waypoint target was satisfied to an acceptable tolerance.

### IV.D. Veil Architecture Studies

Due to the increased length in the duration of approach, an extra cycle was inserted into the design architecture, and a new Veil run was completed. The results indicated 71% feasibility. The reduction in feasibility was believed to be due to poor delivery to the start of the fourth cycle leading into the distant Ceres close approach causing a dispersion in the truth trajectory samples. A larger MEP and smaller build time would be needed in the fourth cycle to overcome the poor delivery. It was unclear how large the MEPs should be. Increasing MEPs increases the amount of margin in the trajectory, but it also means delaying the start of RC3 and dealing with more coasting when the MEPs are freed during the maneuver designs. To understand the effects of various MEP sizes, different Veil studies were carried out with different MEP allocations.

The final approach architecture adopted by the team is shown in Figure 8 (compare to Figure 2). Veil

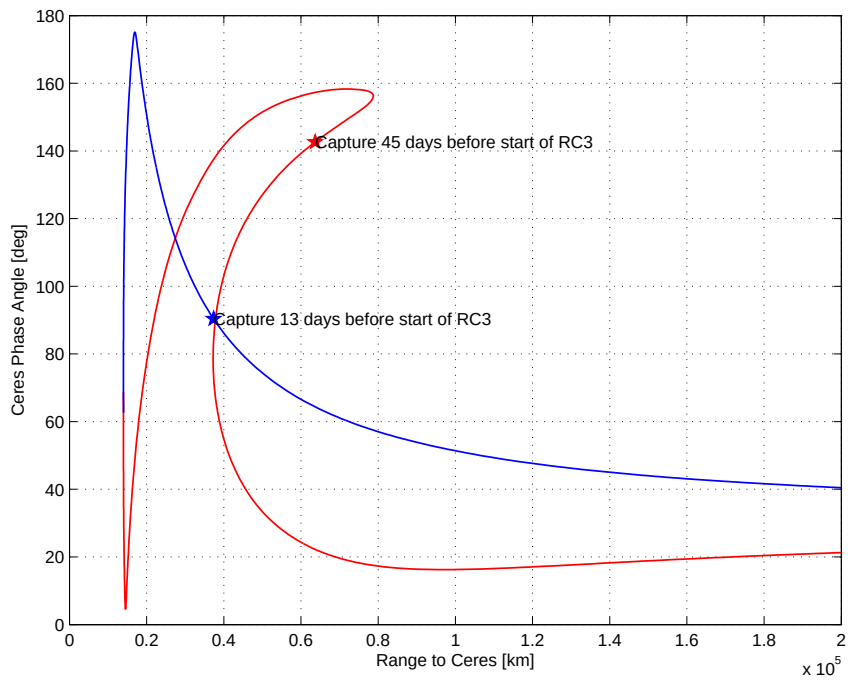


**Figure 6. Phase angle for approach before (blue) and after (red) safing event.**

feasibility showed 99.8% feasibility for 1008 Monte Carlo samples. Range and phase 1-sigma uncertainties for the Opnavs are provided in Table 5. The largest uncertainty was associated with Opnav5 of range = 2150 km, phase = 3.7 degrees. The uncertainties were deemed acceptable for the planned Opnavs. Delivery statistics for RC3 are recorded in Table 6, and are comparable to the pre-safing statistics science was planning to for RC3 (recall Table 6).

**Table 5. 1-sigma uncertainties in location of Opnavs.**

| | Range (km) | Phase (deg) |
|---|---|---|
| Opnav1 | 920.8 | 0.3 |
| Opnav2 | 601.8 | 0.2 |
| Opnav3 | 1341.1 | 1.4 |
| RC1 | 1019.3 | 1.6 |
| RC2 | 1274.9 | 1.6 |
| Opnav4 | 1256.3 | 1.1 |
| Opnav5 | 2148.7 | 3.7 |
| Opnav6 | 97.3 | 0.5 |
| Opnav7 | 537.3 | 1.7 |

## V. Summary & Conclusion

On September 11, 2014, a few months before approach, Dawn experienced a safing anomaly. In the span of four days, the team had diagnosed the problem and determined the spacecraft was healthy enough to resume thrusting on September 15. The loss of thrust occurred at a time when the delay to arrival at Ceres would be greatest, adding 26 days to the mission time to Ceres and significantly altering the approach

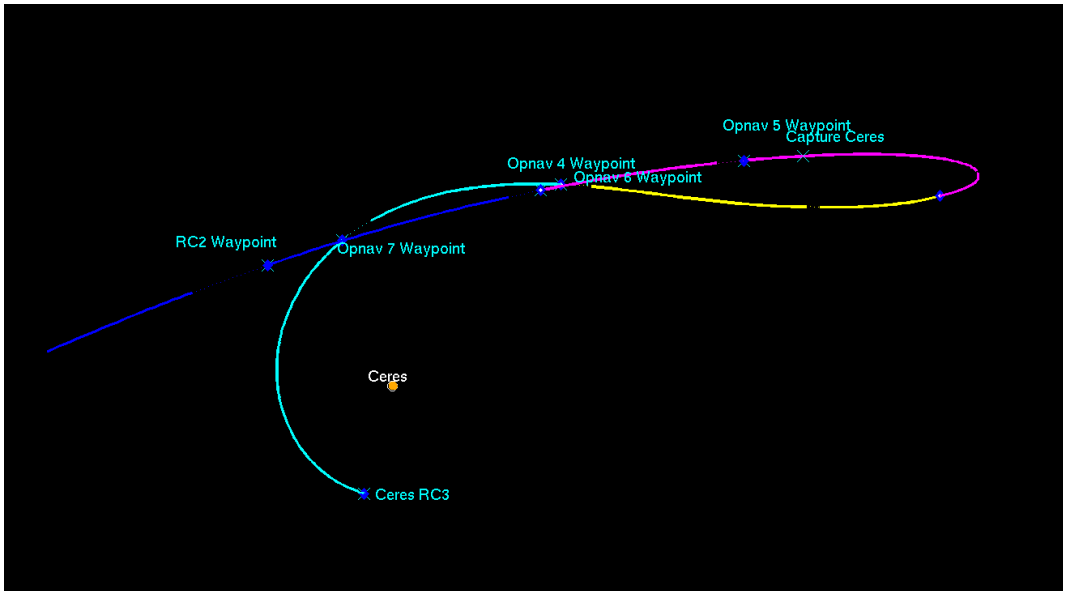


**Figure 7. Approach trajectory with soft waypoint targets annotated (colored by design cycle).**

**Table 6. Delivery to RC3.**

| | Delivery (mean $\pm 1\sigma$) |
|---|---|
| Beta angle (deg) | $5.0 \pm 0.2$ |
| Inclination (deg) | $90.0 \pm 0.7$ |
| Period (hrs) | $374.7 \pm 6.7$ |
| Range (km) | $14277.0 \pm 106.7$ |
| True Latitude Spread (deg) | $-82.3 \pm 5.7$ |

geometry. The new approach trajectory flew past Ceres and then turned to fly back to Ceres from the opposite side. Due to significant changes to the phase, the approach Opnavs needed to be readjusted. The architecture was also re-designed and new Monte Carlo analyses were conducted to test feasibility. The new approach proved to be much more sensitive than the pre-safing approach, and a method was developed to guide the spacecraft along the reference using soft waypoint targeting thereby preserving the anticipated geometry. By early November, the new architecture was adopted by the team and incorporated into the maneuver designs. Approach effectively began on December 2, 2014, and executed as anticipated. Figure 9 shows images obtained from the spacecraft for the first seven Opnavs, including our first image of Ceres taken on January 13, 2015. On April 23 the spacecraft inserted into the RC3 orbit. The delivery error was 205 km and 61 cm/s, significantly lower than the 1-sigma values.

The Dawn mission's ability to adapt to the thruster outage on approach is a true testament to the versatility of the unique ion propulsion system. A safing event during a critical orbit insertion maneuver for a chemical mission would likely result in a failed insertion. However, due to its IPS, the Dawn spacecraft has the unique capability of responding to loss of thrust even during its most important periods of thrusting, as the recovery and re-design of the Ceres approach demonstrates.

## Acknowledgments

The authors thank Dan Parcher for his aid in learning the maneuver design software tools. The initial design architecture approach presented in this paper was created by Dan Parcher. John Smith, Yu Takahashi, and Nick Mastrodemos were all involved the maneuver design recover process. Credits for Figure 9 should go to Marc Rayman.

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute

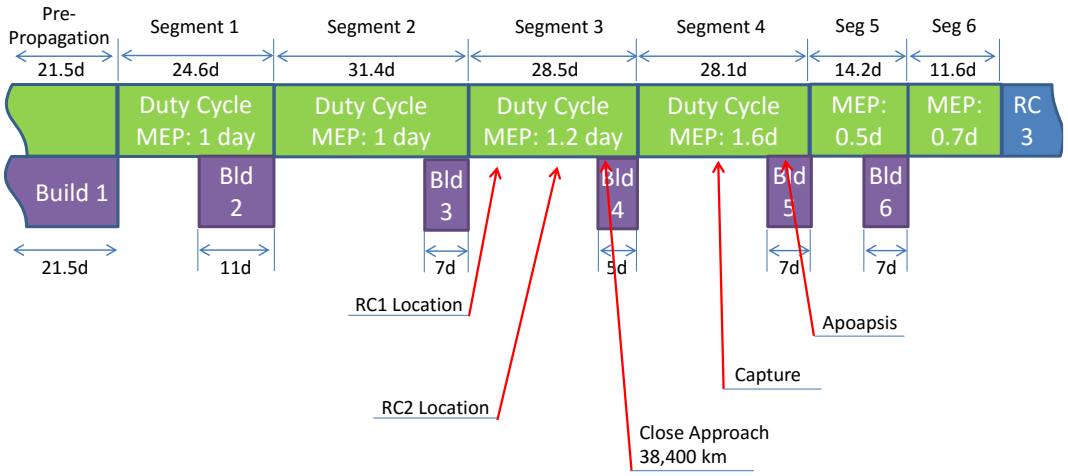


**Figure 8. Final approach architecture.**

of Technology, under contract with the National Aeronautics and Space Administration. Copyright 2016 California Institute of Technology. Government sponsorship acknowledged.

## References

[1]Russel, C.T., et al., "Dawn: A journey in space and time," *Planetary and Space Science*, Vol. 52, No. 5-6, 2004, pp. 465-489.

[2]Rayman, M.D., et al, "Dawn: A mission in development for exploration of main asteroid belt asteroids Vesta and Ceres," *Acta Astronautica*, Vol. 58, No. 11, 2006, pp. 604-616.

[3]Garner, C.E., et al., "The Dawn Vesta Science," *The 32nd International Electric Propulsion Conference, Paper No. IEPC-2011-326*, Wisbaden, Germany, September 11-15, 2011.

[4]Rayman, M.D., "The Successful Conclusion of the Deep Space 1 Mission: Important Results without a Flashy Title," *Space Tecnology*, Vol. 23, No. 2-3, 2003, p. 185.

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

[6]Han, D., et al., "Orbit Transfers for Dawn's Ceres Operations: Navigation and Mission Design Experience at a Dwarf Planet," *The 14th International Conference on Space Operations, Paper No. AIAAA 2016-2427*, Daejon, Korea, May 16-20, 2016.

[7]Whiffen, G.J., "Dawn's Mission at Ceres," *2016 AIAA/AAS Astrodynamics Specialist Conference, Paper No. AIAA 2016-XX*, Long Beach, California, September 13-16, 2016.

[8]Rayman, M.D., and Patel, K.C., "The Dawn project's transition to mission operations: On its way to rendezvous with (4) Vesta and (1) Ceres," *Act Astronautica*, Vol. 66, No. 1-2, 2010, pp. 230-238.

[9]Prettyman, T.H., et al., "Gamma ray and neutron spectrometer for the Dawn Mission to 1 Ceres and 4 Vesta," *IEEE Transactions on Nuclear Science*, Vol. 50, No. 4, 2003, pp. 1190-1197.

[10]Grebow, D.J., et al., "Design & Execution of Dawn HAMO to LAMO Transfer," *2016 AIAA/AAS Astrodynamics Specialist Conference, Paper No. AIAA 2016-XX*, Long Beach, California, September 13-16, 2016.

[11]Whiffen, J.G., "Static/Dynamic Control for Optimizing a Useful Objective," United States Patent No. 6,496,741. Issued Dec. 17, 2002, Filed Mar. 25, 1999.

[12]Whiffen, J.G., "Mystic: Implementation of the Static Dynamic Optimal Control Algorithm for High-Fidelity, Low-Thrust Trajectory Design," *AIAA/AAS Astrodynamics Specialist Conference, Paper No. AIAA 2006-6741*, Keystone, Colorado, Aug. 21-24, 2006.

[13]Parcher, D.W., and Whiffen, G.J., "Dawn Statistical Maneuver Design for Vesta Operations," *AIAA/AAS Astrodynamics Specialist Conference, Paper No. AAS 2011-180*, New Orleans, Louisiana, Feb. 13-17, 2011.

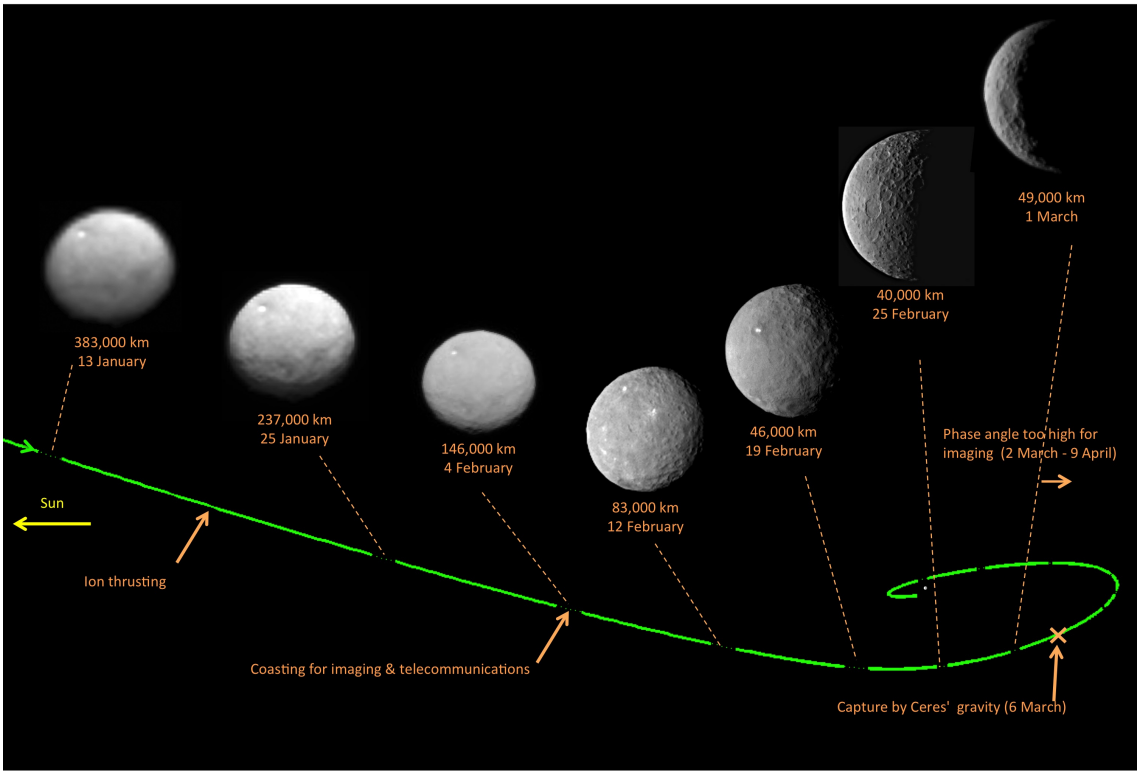


**Figure 9. Actual Opnav image data obtained during approach.**