THE SECOND YEAR OF DAWN MISSION OPERATIONS: MARS GRAVITY ASSIST AND ONWARD TO VESTA

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Dawn launched in September 2007 on a mission to orbit main belt asteroids (4) Vesta in 2011 - 2012 and (1) Ceres in 2015. The mission is enabled by an ion propulsion system, which will be operated for the majority of the interplanetary cruise. Following 10.5 months of thrusting that concluded in October 2008, the spacecraft began a period of optimal coast that ended in June 2009. A Mars gravity assist in February 2009 provided an effective Δv of 2.6 km/s. The mission flexibility afforded by the use of ion propulsion provided relatively simple targeting at Mars. Additional engineering activities were conducted during the coast period after Mars, including loading new software into the spacecraft's central computer. This paper describe the progress of the mission, including the approach to Mars, the encounter itself, special activities conducted prior to the resumption of ion thrusting, and the continuation toward Vesta.

INTRODUCTION

The Dawn mission is designed to investigate (4) Vesta and (1) Ceres, the two most massive residents of the main asteroid belt. The characterization of the geophysical properties of these bodies is expected to help elucidate the physical and chemical processes and conditions during the epoch of planet formation at the dawn of the solar system. Dawn will acquire panchromatic (in stereo) and multispectral imagery; near ultraviolet, visible, infrared, γ-ray, and neutron spectra; and gravimetric data.

Dawn is the ninth project in the National Aeronautics and Space Administration's (NASA's) Discovery Program. The project is managed by the Jet Propulsion Laboratory (JPL). Mission operations is conducted at JPL, and scientific leadership is provided by the principal investigator, from the University of California, Los Angeles.

Dawn's scientific payload comprises a γ-ray and neutron detector (GRaND), a visible and infrared mapping spectrometer (VIR), and a pair of identical framing cameras (FC2, the prime unit, and FC1, the backup). A redundant camera is required because of the need to acquire optical navigation data in addition to essential scientific data at Vesta and Ceres. The gravimetry is accomplished without dedicated flight hardware.

GRaND was delivered by the Los Alamos National Laboratory. VIR was contributed to NASA by the Agenzia Spaziale Italiana (Italian Space Agency, or ASI). ASI funds the Istituto Nazionale di Astrofisica (National Institute for Astrophysics) for VIR, which was designed, built, and tested at Galileo Avionica. The framing cameras were

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contributed to NASA by the Max-Planck-Institut für Sonnensystemforschung (Max Planck Institute for Solar System Research) with cooperation by the Institut für Planetenforschung (Institute for Planetary Research) of the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) and the Institut für Datentechnik und Kommunikationsnetze (Institute for Computer and Communication Network Engineering) of the Technischen Universität Braunschweig (Technical University of Braunschweig).

The Dawn spacecraft was designed, built, and tested by Orbital Sciences Corporation. Together the payload and the spacecraft compose the flight system.

The mission to orbit both Vesta and Ceres is enabled by the use of solar electric propulsion, implemented on Dawn as an ion propulsion system (IPS). Without it, even a mission to only one of these bodies would not be affordable within the Discovery Program.

The design of the flight system and of the mission as well as the scientific objectives have been presented in detail elsewhere.[1,2]

Dawn launched on 27 September 2007. It will reach the first science orbit at Vesta in August 2011. Following escape in July 2012, it will rendezvous with Ceres in February 2015. To accomplish this, most of the mission is devoted to thrusting with the IPS. The first major thrust period was conducted from 17 December 2007 to 31 October 2008. The progress of mission operations from launch through the end of 2008 was described by Rayman and Patel.[3]

MARS APPROACH

The need for a Mars gravity assist (MGA) arose when Dawn's launch moved from 2006 to 2007.[1] The MGA enabled the Vesta rendezvous to occur early enough that Dawn would be able to rendezvous with Ceres in February 2015 to satisfy programmatic constraints.

Just as the IPS provides a significant degree of flexibility in the design of the complete mission,[4] it made targeting for the MGA quite flexible. Because the overall mission performance depended relatively weakly on flyby conditions, much of the targeting was driven by considerations of easing the operations team workload. (Mission performance generally is measured by how much time Dawn can spend in orbit at Vesta subject to all constraints including the Ceres arrival date.[4])

Analyses considering closest approach altitudes as low as 300 km found no risks to flight system health or safety. No further studies were conducted, so 300 km was adopted as the lowest acceptable altitude. A target of 500 km was chosen because it was low enough to obtain significant mission benefit from the encounter and allowed for relatively simplified targeting, thus permitting the project to devote its resources to other tasks.

Dawn launched with 425 kg of Xe propellant for the IPS, and the Xe margin to complete the mission is well above requirements. The mission was designed to reach its two targets nearly as early as possible at the expense of Xe. Therefore, if an anomaly delayed the arrivals, it would lead to a reduction in the expenditure of propellant. Additional Xe would be of importance principally only for a possible extended mission and in the unlikely event of a significant leak. The benefits to the primary mission of conserving Xe are of such low value that the effects of the MGA targeting on the Xe consumption did not affect the MGA design.

The more valuable resource for the project was the duration of the optimal coast pe-

riod that included the MGA. The initial plan was to continue to coast after the 18 February MGA until 15 June, and many special activities had been scheduled for this time (see page 6). Therefore, in addition to the safety constraint, Mars targeting was designed to preserve enough coasting after the encounter to complete these other activities on the comfortable schedule that had been set earlier in the mission. Although greater reductions in the coast duration could have been accommodated, the criteria for performing a trajectory correction maneuver (TCM) were based on allowing for no more than a 6-day advancement in the planned resumption of thrusting.

The decision to execute a TCM depended upon satisfying two criteria: 1) the 3σ knowledge ellipse must cross or be completely outside the boundary defined by the minimum altitude and the 6-day contour, and 2) the required trajectory correction must be greater than 1σ in the delivery error.

As the flight system had spent the majority of time since launch thrusting, a TCM was not considered to be an unusually difficult operation. A TCM differs from interplanetary IPS thrusting in only two regards. Because the TCM attitude and duration cannot be determined long in advance, the timeline and processes used to design, build, and test the sequence are slightly different from those used in normal operations. In addition, a TCM is; typical thrust periods are about 160 hours long (leaving enough time each week for a telecommunications session through the high gain antenna).

The first window for a correction (TCM1) was scheduled for 20 - 21 November 2008. This was sufficiently long after the conclusion of deterministic thrusting on 31 October to do enough tracking to develop a good estimate of the orbit and then to design and execute the TCM. Two days were allocated in case the maneuver had to be decomposed into two thrust periods to comply with attitude constraints. The window also was scheduled to allow the maneuver to be completed well before solar conjunction in December.

During IPS thrusting, the attitude control system (ACS) controls the two axes orthogonal to the thrust vector by gimbaling the ion thruster. The thrust axis is controlled with reaction wheels. Because of ACS transients when thrusting is initiated, the minimum thrust duration at that time in the mission was set to 2 hours. Terminating thrust much earlier was likely to trigger an attitude fault and hence a safing.

The operations team is investigating methods to reduce the transient behavior to permit shorter thrust periods, but the present constraint was satisfied easily at Mars. Because the mission was not sensitive to the time of closest approach (TCA), thrusting that changed only the TCA had virtually no cost. Therefore, even if only a short TCM were needed to change the encounter coordinates, the duration could be increased by adding to the TCM thrust vector another thrust vector in the direction that changed only the TCA.

The predicted delivery at Mars with and without TCM1 are illustrated in Figure 1.

Ion thruster #1 was the last one in use for deterministic thrusting in 2008.[3] As switches were already configured to select this thruster, it was chosen as the prime thruster for TCM1.

The maneuver was designed to be 121 minutes and provide a $\Delta v = 0.63$ m/s. It was executed successfully on 20 November.

For solar conjunction, the project imposed a conservative command moratorium for 5 - 17 December, approximately corresponding to the time that the Sun-Earth-probe angle was less than 2.3°. The minimum elon-

gation from the center of the Sun was 0.6°.

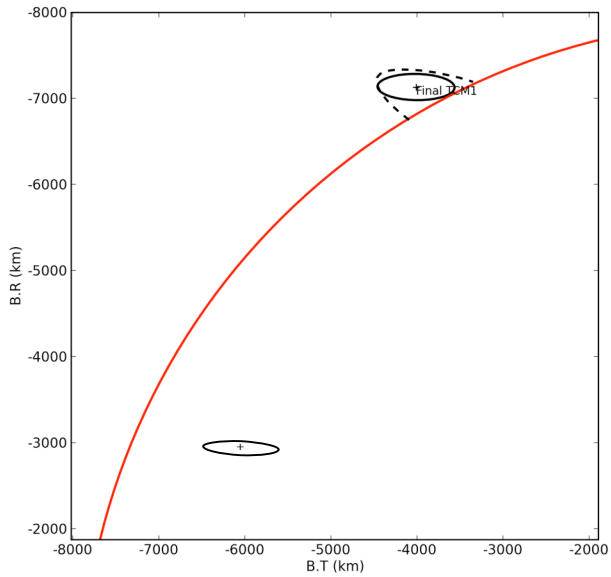

Figure 1. TCM1 targeting in the B-plane. The B-plane is normal to the approach asymptote and contains the center of Mars. The red contour represents the 300-km altitude for safety. The dashed contour corresponds to a 6-day reduction in the duration of the optimal coast period after Mars. The upper ellipse is the 3σ uncertainty in the delivery for the TCM1 design. The lower ellipse is the 3σ uncertainty at the time of the TCM1 design in the uncorrected encounter.

The window for TCM2 was chosen to be 15 - 16 January 2009, allowing enough time for acquisition of radiometric navigation data after conjunction and avoiding interference with holidays and associated vacation times. When designed at the beginning of January, the maneuver did not satisfy the criteria for execution, because the 3σ uncertainty in the prediction of the trajectory was completely contained within the boundary defined by safety and reduction in coast time. As a result, TCM2 was not implemented.

GRAVITY ASSIST

Dawn approached Mars over the northern hemisphere with $v_\infty = 2.5$ km/s. Closest approach occurred on 18 February at 00:28 UTC at an altitude of 542 km. The angle between the incoming and outgoing v_∞ vectors was 78°.

One effect of the MGA was to alter the direction of the angular momentum of Dawn's heliocentric orbit by 5.2°. This was equivalent to a $\Delta v = 2.3$ km/s. The MGA also raised Dawn's heliocentric energy with an equivalent $\Delta v = 1.1$ km/s. In total, Mars provided an equivalent of 2.6 km/s to Dawn. For comparison, the IPS will provide a total of about 11 km/s over the course of the mission. Table 1 shows how the MGA changed some of Dawn's orbital elements (in the absence of any subsequent ion thrusting) and includes the values for Vesta's orbit for comparison.

Orbital element	Dawn before MGA	Dawn after MGA	Vesta
Inclination	1.8°	6.2°	7.1°
Longitude of ascending node	49°	101°	104°
Perihelion (AU)	1.23	1.37	2.15
Aphelion (AU)	1.68	1.84	2.57

Table 1. Effect of MGA on Dawn's heliocentric orbit. (AU is astronomical unit.)

PAYLOAD CALIBRATIONS

While the objective of the MGA was to obtain the gravity assist in order to reach Vesta on the required schedule, it presented an opportunity to conduct further calibrations of the science instruments. All instruments had been calibrated and operated on several occasions, and all have been operating well. The project planned to use the MGA for additional calibrations of GRaND, FC2, and VIR.

Dawn's aphelion prior to the MGA was 1.68 AU in August 2008, outside the orbit of Mars. The encounter with Mars occurred at 1.41 AU. The spacecraft approached at a phase angle of 162°, precluding observations with FC2 or VIR because of thermal constraints. The instruments could not be pointed at Mars until significant gravitational bending

increased the angular separation between it and the Sun.

GRaND was activated on 20 January and measured the space background prior to reaching Mars. FC2 and VIR were powered on a few hours before closest approach.

Following the attitude profile for the calibration observations temporarily placed Mars in the field of view of Dawn's star tracker. (The spacecraft has two star trackers, with only one powered during normal operations.) In anticipation of this causing the tracker to lose lock, the inertial reference units were used during the encounter. (In normal operations, they are powered off to preserve their life for use in science data acquisition at Vesta and Ceres.) As a further mitigation, the system fault response to an indication from ACS of invalid tracker data was disabled during the time Mars was close enough to the tracker that stray light might lead to loss of stellar reference.

The star tracker operated well, losing lock at closest approach (CA) + 2 minutes, with Mars well inside the predicted stray light cone. As expected, the loss of lock triggered ACS to set a flag monitored by system fault protection, but with the response disabled, the spacecraft continued to operate as planned, following the sequence for acquiring FC2 and VIR calibration data. At CA + 13 minutes, the star tracker regained lock and resumed reporting valid quaternions to ACS, which correctly incorporated them into its attitude estimate. Because of a software bug, however, the flag ACS had set was not cleared when the tracker began providing good data again.

At CA + 20 minutes, the stored sequence reenabled the fault response for the tracker data. Because the flag persisted in indicating the tracker's data were invalid, the response was invoked. System fault protection activated the backup star tracker so the sequence could continue. Because of another bug, insufficient time was allowed for the backup tracker to begin operating, and fault protection declared it unhealthy. The response was to invoke safe mode, thus terminating the calibration sequence. Of course, safe mode did not compromise the required gravity assist.

Neither bug by itself would have been adequate to interrupt the calibrations. Limitations in the encounter sequence testing had prevented the first bug from being identified. The second bug had been recognized earlier in flight and was already incorporated in new software scheduled for uploading in April 2009.

GRaND was powered off when safe mode was invoked, but all the data it had collected were preserved in the spacecraft's memory, which was unaffected. The instrument acquired an excellent set of nuclear spectroscopy data, observing γ-rays and neutrons from the surface and atmosphere. The data have been correlated with spectra acquired by 2001 Mars Odyssey, providing the desired calibration. This was GRaND's only opportunity prior to Vesta to observe a specific body that had been characterized with γ-ray and neutron spectroscopy. The data were of particularly high value because the energetic particle background was low during the encounter.

When VIR was powered off by the safing, the data it had acquired were lost from its internal volatile memory. A few FC2 images had already been transferred to the spacecraft's memory. Because the flight system had so recently passed over the terminator, however, the images were not of regions that provided significant value for calibration.

POST-MARS COAST PERIOD

Among the special activities scheduled for the coast period after Mars was a measurement of stray light in FC2 images on 31 March. The camera acquired images from 90° to 30° from the Sun. (The lower limit was determined by thermal constraints at 1.37 AU from the Sun. These constraints will be relaxed at greater heliocentric ranges.) The flight system stopped every 2.5° and collected images with integration times of 1 s, 10 s, and 100 s through the clear filter. Every 5° between 90° and 45°, the same triplet of images was acquired through each of the other 7 filters as well. Below 45°, all 8 filters were used at every 2.5° image station. The data showed that the stray light performance of the camera is excellent.

The central flight computer's software had been updated earlier in the mission.[3] Development of a subsequent version of the software began in January 2008, containing bug fixes (including the correction to ensure the backup star tracker could be used by fault protection), improved robustness for some fault scenarios, and operational enhancements.

The software files were uploaded on 13 April, and the primary computer was commanded to reset on 14 April to begin running it. The reset invokes safe mode, and all activities required to return the flight system to normal cruise configuration were completed on 16 April.

Most of the Dawn mission is devoted to IPS thrusting. Although none of the software changes was expected to affect thrusting (and ground testing verified this), the criticality of this capability to the accomplishment of the mission motivated a test in flight. Dawn thrust on 27 April and on 1 May, showing that the flight system and the ground-generated command products performed with the new software just as they had with the previous version. After the successful operation of the new software, primary and backup copies were installed in the backup flight computer on 11 May, and the backup copy was installed in the primary computer on 13 May. The architecture of the system requires each copy to be separately uplinked and installed. It is not possible to copy the software from one location to another.

A secondary objective of the thrust test was to use radiometric navigation to measure the off-axis thrust of ion thruster #2. Such data had been planned to be acquired in the initial checkout phase of the mission, but the test then was postponed because of thermal constraints at 1 AU. (Similar tests were performed on thrusters #1 and #3, which did not have the same constraints by virtue of their different locations on the spacecraft.) The measurements were planned for April 2008 but were prevented by the failure of a software check that was later established to be unnecessary and was removed.[3] The measurements were completed successfully as part of the flight system thrust verification.

The thrusting on 27 April was the first time the cathodes in thruster #2 had been operated in more than 12 months and the first time the unit had been operated with beam extraction in 17 months. Thruster performance was nominal.

By the end of the system thrust test, thruster #2 had accumulated 30 hours of thrust in flight. In contrast, thruster #1 had 2951 hours and #3 had 3793 hours. The operation of the thrusters will be balanced over the lifetime of the mission.

The coast period around the MGA is the longest planned for the mission and hence the longest interval during which the IPS will not be operated. Therefore, it presented a unique opportunity to measure the long-term drift of

pressure transducers in the low-pressure section of the system for delivering xenon to the thrusters. The section was allowed to vent to space from 2 May to 28 May, and the resulting data showed the drift in each transducer since the prelaunch calibrations was very low.

CONTINUATION OF DETERMINISTIC THRUSTING

Deterministic thrusting recommenced on 8 June. Mission performance was only weakly sensitive to the date for the resumption of thrusting, so it could have been later without significant consequence for the mission, as planned during the MGA targeting. Nevertheless, the special activities scheduled for the optimal coast period had been completed on schedule, and 8 June fit well with the normal schedule for development of sequences.

As of 31 August, Dawn had thrust for 8720 hours since launch, or 52% of its time in space. The IPS had imparted 2.4 km/s and expended 97 kg of Xe.

In 2008, coast periods of about 3 - 5 days were included in each 5-week sequence to allow for activities incompatible with optimal IPS thrusting. These regular intervals were inserted only for the first year to allow extra time for the operations team to gain experience and to provide additional margin after the late change in the mission timeline following the rescheduling of the launch in 2007.[3] It is no longer necessary to include these frequent extended gaps in thrusting. Only occasional coasts are included in the plan for new software loads and extended engineering tests and calibrations.

The use of the IPS strongly couples the design of the mission to the performance of the flight system.[4] The pertinent models of the flight system performance were updated in the first half of 2009. For most of development and the first part of operations, the greatest uncertainty in the definition of the nominal mission timeline was the power available to the IPS, dominated by the uncertainty in the solar array output power as a function of heliocentric range and time. The solar array could produce in excess of 10 kW at 1 AU, and even at the aphelion in 2008, it generated more than the 3.2 kW the flight system could draw. Nevertheless, based on telemetry, higher fidelity thermal and electrical modeling, and refined radiation estimates, a new model of the solar array was formulated, showing that it would yield 8 - 10% more power than had been anticipated.

Models for hydrazine and Xe expenditures (both affecting wet mass) and IPS thrust and specific impulse also were revised, but the change in the solar array power dominated the effect on the mission. In addition, the schedule of coast periods was modified slightly, including adding some coasts between Vesta and Ceres.

The combined effect of the changes was to allow the mission to increase the time in orbit around Vesta from 9 months to 12 months and still satisfy all other constraints. This extra time is very important in the continuing development of the plans for Vesta, principally in providing the margin needed to formulate a more robust design. A plot of the trajectory is in Figure 2.

CONCLUSION

The return to quiet interplanetary thrusting, with relatively few new activities planned, allows the operations team to focus more on planning for Vesta. A great deal of work remains to develop the operational strategies for acquiring the intended science data.

The first test of the development of Vesta sequences was initiated in July 2009. The team used the project's standard operations

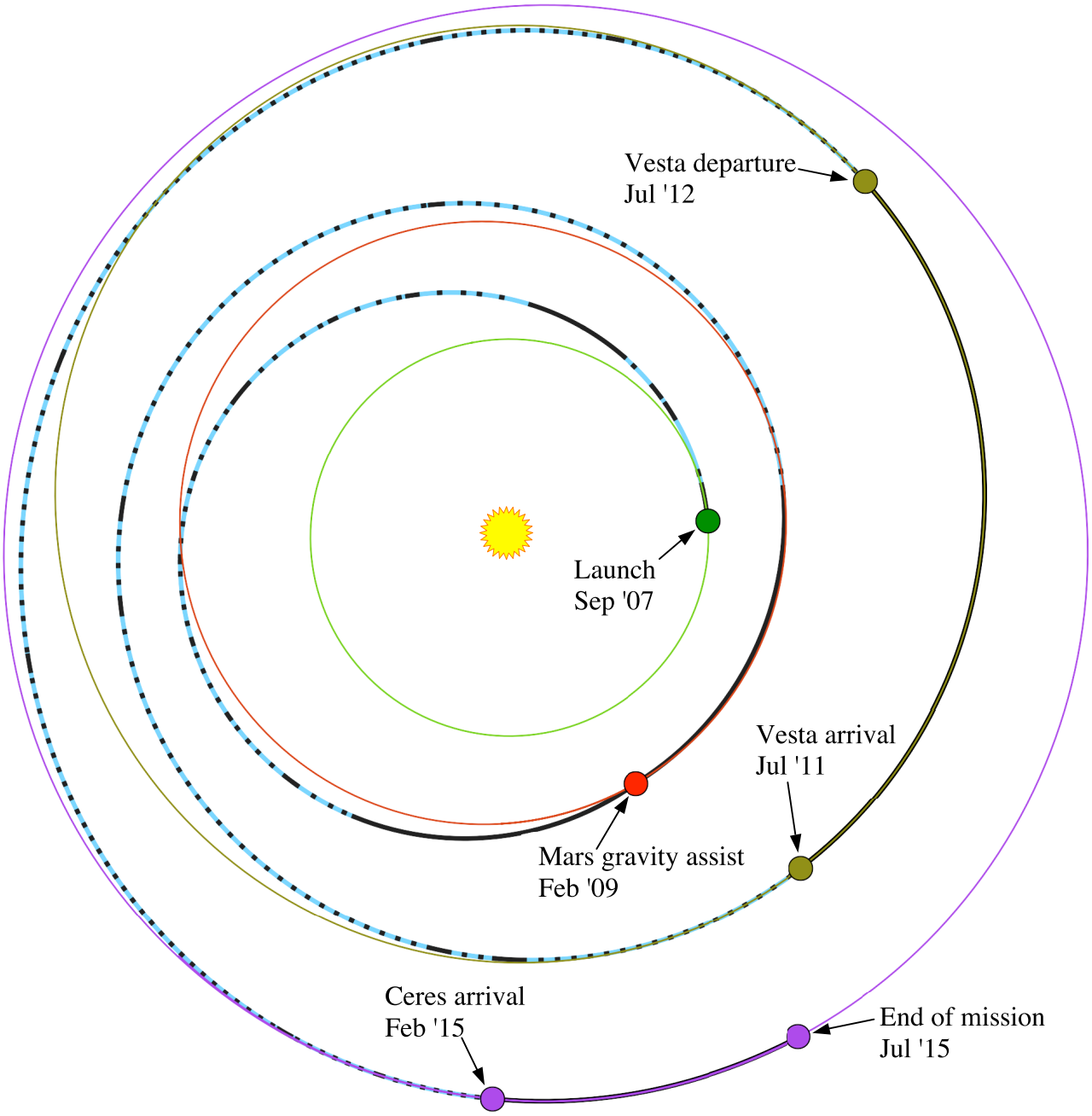

Figure 2. Dawn interplanetary trajectory. Blue is for IPS thrust periods and black is for coasting.

processes to build sequences from the preliminary plan for one of the Vesta science orbits, and then ran them successfully in the flight system testbed in August. More operational tests are planned to be conducted in parallel with the ongoing design work.

ACKNOWLEDGMENTS

The continuing success of the Dawn mission has been achieved by the dedicated and talented members of the operations team. Their work is acknowledged with gratitude.

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