THE DAWN PROJECT'S TRANSITION TO MISSION OPERATIONS: ON ITS WAY TO RENDEZVOUS WITH (4) VESTA AND (1) CERES

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Dawn launched on 27 September 2007 on a mission to orbit main belt asteroids (4) Vesta in 2011 - 2012 and (1) Ceres in 2015. The operations team conducted an extensive set of assessments of the engineering subsystems and science instruments during the first 80 days of the mission. A major objective of this period was to thrust for one week with the ion propulsion system to verify flight and ground systems readiness for typical interplanetary operations. Upon successful conclusion of the checkout phase, the interplanetary cruise phase began, most of which will be devoted to thrusting. The flexibility afforded by the use of ion propulsion enabled the project to accommodate a launch postponement of more than 3 months caused by a combination of launch vehicle and tracking system readiness, unfavorable weather, and then conflicts with other launches. Even with the shift in the launch date, all of the science objectives are retained with the same schedule and greater technical margins. This paper describes the conclusion of the development phase of the project, launch operations, and the progress of mission operations.

INTRODUCTION

The Dawn project is designed to investigate the geophysical properties of the two most massive residents of the main asteroid belt, (4) Vesta and (1) Ceres. With mean radii of 265 km and 476 km respectively, these bodies have survived relatively intact from the solar system's epoch of planet formation, yet they have remarkably different characteristics. Detailed comparative studies are expected to yield insight into the conditions and processes of that epoch, at the dawn of the solar system.

The Dawn project is part of the National Aeronautics and Space Administration's (NASA's) Discovery Program. As such, it is led by a principal investigator (PI), Professor Christopher T. Russell of the University of California, Los Angeles. The PI retains leadership of the science team while the Jet Propulsion Laboratory (JPL) has had responsibility for the management of the project, development and delivery of some elements of the spacecraft, mission design and navigation, development of the mission operations system, and mission operations. Orbital Sciences Corporation had primary responsibility for the delivery of the spacecraft, the integration of the science payload (together the spacecraft and the science instruments constitute the flight system), system-level testing, and launch operations.

Two of the 3 science instruments were contributed to NASA. Two essentially identical but physically distinct visible and near-infrared cameras, designated framing camera 1 (FC1) and FC2, were provided by the Max-Planck-Institut für Sonnensystem-forschung (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). A visible and infrared mapping spectrometer (VIR) was supplied by Agenzia Spaziale Italiana (Italian Space Agency). ASI funds the Istituto Nazionale di Astrofisica (National Institute for Astrophysics) for VIR, which was designed, built, and tested at Galileo Avionica. With funding from the Dawn project, the Los Alamos National Laboratory delivered the gamma ray and neutron detector (GRaND).

The first spacecraft planned to orbit a main belt asteroid (and the first planned to orbit two targets), Dawn will acquire panchromatic (in stereo) and multispectral imagery; near ultraviolet, visible, infrared, γ-ray, and neutron spectrometry; and gravimetry. The mission is enabled by electric propulsion, implemented as an ion propulsion system (IPS).

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

CONCLUSION OF DEVELOPMENT PHASE

The assembly, test, and launch operations (ATLO) phase began in January 2005 with the assembly of the spacecraft at Orbital. (Some of the IPS components had been integrated with the core structure at JPL in 2004.) ATLO was suspended from October 2005 through April 2006 as NASA conducted schedule and cost reviews.

Prior to beginning the environmental test program, the fully assembled spacecraft went through a complete set of comprehensive performance tests that demonstrated the health and functionality of each subsystem. Following that, testing at Orbital included electromagnetic interference and electromagnetic compatibility, characterizations of the high gain antenna (HGA) and low gain antennas (LGAs), spin balance, and center of gravity measurements. Acoustic, vibration, and pyro shock tests were conducted as well. Verifications included a fit check of the launch vehicle payload attach fitting (PAF), solar array deployment, and mechanical alignments. Baseline functional tests were performed as appropriate after each test. The flight system also was used to perform mission scenario tests under control of the mission operations system.

All the planned testing at Orbital was completed in December 2006, and the flight system and support equipment were shipped to the United States Naval Research Laboratory (NRL) on 7 - 9 January 2007. The flight system initially was placed in a clean room tent, and support equipment was reconnected. The flight system was moved into the thermal vacuum chamber on 16 January, and vacuum testing started on 23 January.

During operations in the chamber, it was discovered that the high voltage electronics assembly (HVEA) had had a failure. The investigation revealed that the failure had occurred in December 2006, although it was not detected until thermal vacuum testing. The project elected to continue thermal vacuum testing to completion instead of breaking chamber to start the HVEA repair. The testing was completed successfully on 16 February, including operation of each of the ion thrusters. (Prior to the flight system's arrival at NRL, the pumping capacity of the chamber had been increased to support the IPS test firings.)

While the flight system was in the vacuum chamber, an error was recognized in the spin balance data that had been acquired at Orbital in November, thus requiring a new test. After the flight system was removed from the chamber, a spin balance test was conducted at NRL.

When the data quality was verified, the spacecraft was partially disassembled to remove the HVEA, which was shipped to JPL on 27 February for rework. Following completion of the work on the HVEA, it was returned to NRL and reintegrated with the spacecraft on 27 March. Because the HVEA activities had required significant disassembly and reassembly of the spacecraft, a penalty acoustic test was performed to verify workmanship.

On 9 - 10 April the flight system was transported by truck to Astrotech Space Operations in Titusville, FL. At Astrotech the flight system went through its final set of comprehensive performance tests, the remaining mission scenario tests, and end-to-end compatibility tests with the Deep Space Network (DSN). The launch version of the flight software was loaded. The solar arrays, which had not been on the spacecraft since it was at Orbital, were installed, and the battery was reconditioned and installed. After hydrazine and xenon propellants were loaded, a wet spin balance was conducted. Finally, the flight system was mated to the PAF and then to the Delta II third stage. The stack was lifted onto the second stage at the Cape Canaveral Air Force Station (CCAFS) Space Launch Complex (SLC) 17B on 27 June.

LAUNCH PERIODS

Because of the mission flexibility provided by its use of the IPS, Dawn's launch opportunity spanned several years rather than the few weeks more typical of interplanetary missions.[3] As a result, the selection of Dawn's launch period was based on considerations such as project readiness, funding profiles, and availability of the required facilities at CCAFS.

When development began, Dawn targeted a launch in 2006. Following the delay in 2005 - 2006, a new launch period was defined to be 20 June - 10 July 2007.[1,3] The duration was deemed long enough to provide a very high probability of launching, and the end date was chosen to ensure no conflict with the more rigid launch period of Phoenix, which opened on 3 August 2007.

Phoenix was scheduled to launch on a Delta II 7925-9.5 from SLC 17A. Only SLC 17B was qualified for launching a Delta II 7925H-9.5, the vehicle Dawn would use. The proximity of the two launch pads (less than 175 meters apart) and the sharing of some systems between them imposed constraints on the scheduling of the erection of the two launch vehicles and integration of the two spacecraft.

Because of delays in the production of Delta II launch vehicles, in April 2007 the opening of Dawn's launch period was postponed to 30 June. A further delay occurred when a crane at SLC 17B failed on 30 May. When it was repaired, the launch period was set to open on 7 July.

For the original 2007 launch period, a P-3 Orion aircraft had been scheduled for downrange tracking support in the southeast Atlantic Ocean. The aircraft was not available to support the postponed launch period, so NASA planned instead to acquire the launch vehicle telemetry with its ocean-going test and evaluation transportable resource (OTTR).

For the 20 June - 10 July launch period, to limit costs of the launch service, the Dawn project had taken advantage of the mission robustness with the IPS by using only 6 pairs of C_3 and declination of launch asymptote (DLA) and a single launch azimuth across the 21 days. The right ascensions of the launch asymptotes (RLAs), which defined the launch times, varied daily. Unlike the aircraft, the ship carrying the OTTR could not travel far enough in one day to accommodate the intervals between DLAs, so the launch vehicle injection targets were recomputed with a constraint that would enable the ship to be in position to track the launch vehicle on each day of the launch period.

On its way to support the launch, the ship experienced an engine problem, so its arrival at the tracking location was delayed. To avoid another launch delay, a United States Air Force NKC-135 was flown to Ascension Island to provide the tracking for a launch on 7 - 9 July. Unexpectedly rough seas caused the ship further delays, so the launch period would have had a gap between the departure of the aircraft for its prior commitment and the arrival of the ship with the OTTR.

In the final days before the 7 July launch period opened, forecasts of inclement weather at the launch site caused further delays. Once it has been loaded with hydrazine, the second stage of the Delta II must be flown within about 37 days or refurbished before flight is safe. Therefore, fueling of the second stage could not occur until the weather appeared to have a high probability of being acceptable for launch. If the second stage were loaded with hydrazine and it could not launch before Phoenix needed the use of the SLC 17 facilities, neither a replacement second stage nor the refurbished one would be available before November, by which time Dawn's multiyear launch opportunity would close. (The end of the launch opportunity was determined by the synodic period of Vesta and Ceres.[3] Later launches would have required greater mission durations, thus incurring unaffordable extensions of the operations phase.)

With forecasts for weather continuing to be unfavorable and the tracking ship making slow progress, on 7 July it was determined that the probability of launching before Phoenix needed the higher priority at SLC 17 was too low, so Dawn's launch period was shifted to be after Phoenix's. The second stage had not been fueled, so it remained available for the new launch period.

The payload fairing was removed and the flight system and third stage were returned to Astrotech. The rest of the launch vehicle remained in place at SLC 17B. The flight system was maintained in a clean and safe environment with few additional activities. In September it was attached to the third stage again and returned to SLC 17B on 11 September.

The new launch period opened on 26 September in order to allow enough time for Phoenix to have its full launch period and to accommodate other launches already scheduled at CCAFS. In addition, some of the United Launch Alliance personnel who supported Delta II launches at CCAFS also were required for Delta II launches from Vandenberg Air Force Base (VAFB). A commercial Delta II launch from VAFB that had already been scheduled had a higher priority 2-day launch period in September. After those 2 days, Dawn's priority would be higher.

As soon as the crane failed, analysis began on launch vehicle injection targets for September and October as a contingency. The final targets were developed after the decision to change the launch period.

Launches in June or July required DLAs between -24.0° and -11.0°, whereas launches in September and October required DLAs between 26.0° and 28.5°. This significant difference pushed the location for the tracking of second and third stage events from the Atlantic Ocean to the Indian Ocean and Australia. As a result, a substantial modification of the launch support plans was required.

Although the Delta II does not have a yaw steering capability, the mission design's insensitivity to RLA permitted launch windows of 28 to 44 minutes through 15 October. (The window on 1 October was the only one not in that range. It was shortened to 19 minutes to reduce the probability of a minor but undesirable trajectory perturbation from the moon in the event of an injection error.)

Although the IPS permitted a launch opportunity that lasted for years, mission performance was not uniform during that time. For the September - October launch period, technical margins were superior to those for the June - July launch period given the same constraints on the mission. (Constraints included solar array power output and flight system power consumption as functions of heliocentric range and time, thrusting duty cycle, duration of Vesta residence, and Ceres arrival on 1 February 2015.[3])

While not as significant as the effect of launch date itself, another change allowed a modest improvement in mission performance for the new launch period. Because the new injection targets were developed after the final weighing of the wet flight system for the June - July launch, margin that had been included in the original targets to account for uncertainty in the mass was no longer needed. The total flight system mass at launch was 1217.7 kg, including 425.3 kg of Xe and 45.6 kg of hydrazine.

Some of the additional mission performance was used to increase the duration of the Vesta residence from 250 days to 280 days. Spending more time at Vesta allows for a more robust plan for science data acquisition.

Some margin also was expended to insert forced coast periods of about 3 days/month into the plan for IPS thrusting in 2008. With the many changes to the final launch plan, the operations team had less time than expected to prepare for the intensive 80-day initial checkout phase of the mission (see page 8), so these additional forced coast periods were intended to afford additional opportunities to conduct activities incompatible with optimal thrusting.

Despite the significant differences in the launch conditions between June - July and September - October, much of the mission was unchanged from what has been described for the earlier launch period[3] and even for the 2006 launch period.[1] The Mars gravity assist shifted from March 2009 to February 2009. As the duration of the Vesta phase was increased, arrival at the asteroid moved from October 2011 to August or September 2011. Of course, IPS thrust directions changed as well, particularly in the early part of the mission, but by the middle of 2009, the trajectory would be minimally different. Figure 1 is an illustration of the current design for the interplanetary trajectory.

The very different launch and Earth-departure geometry necessitated a number of changes to the initial mission plan. The duration of the coast between firings of the Delta II second stage would have been less than 10 minutes for a June - July launch, but with the significantly higher DLA for September - October, the coast duration grew to more than 40 minutes. Although the launch vehicle does not provide power to the spacecraft, Dawn's 35 A·hour battery provided sufficient margin even for this longer ascent.

Many checkout activities depended upon Earth-relative spacecraft pointing, and these

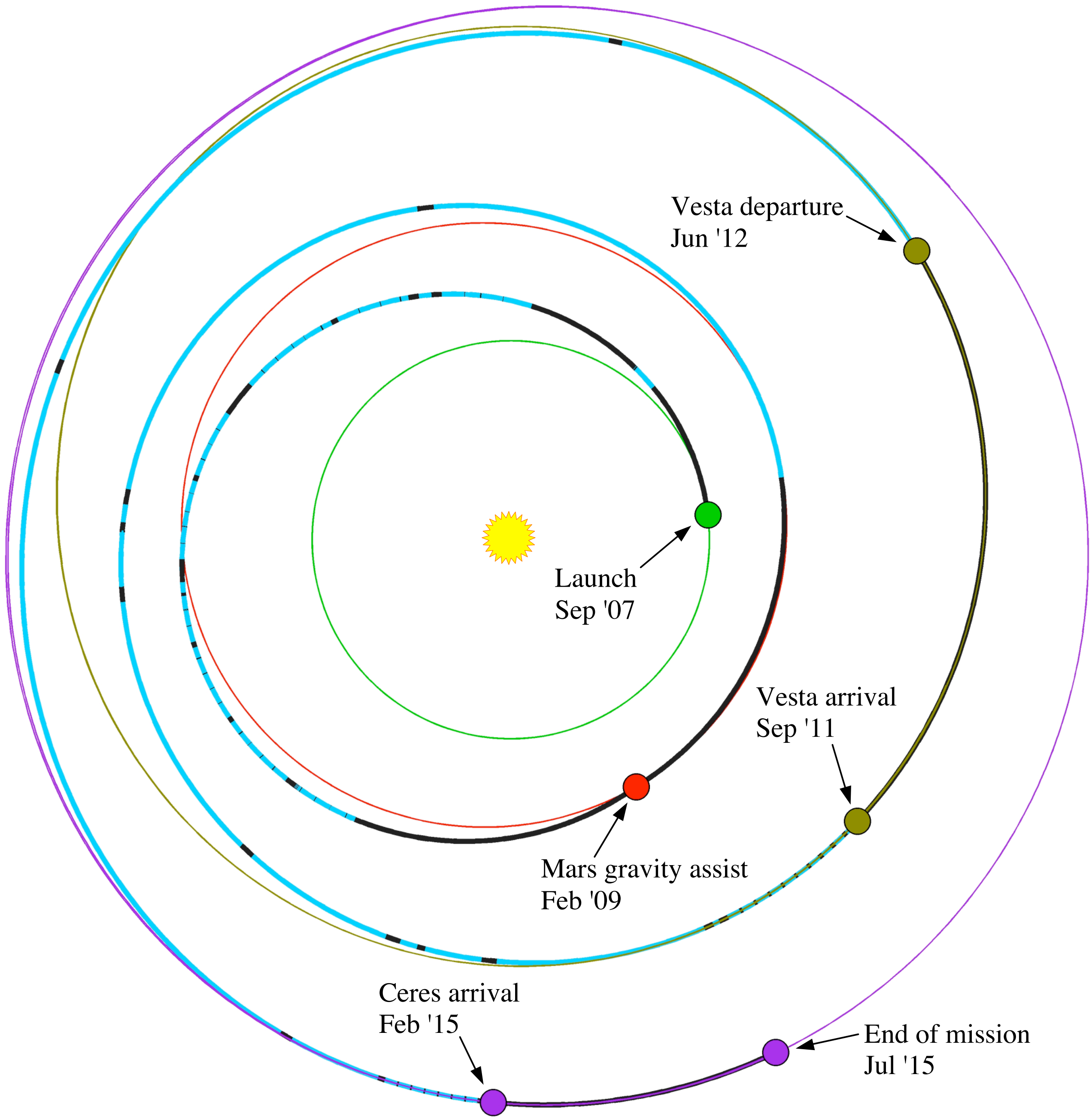

Figure 1. Interplanetary trajectory. Blue is for IPS thrust periods and black is for coasting. The first thrust period is the long duration systems test conducted during the initial checkout phase of the mission; other tests involving IPS thrust during that phase are not shown. Weekly coasts for telecommunications sessions are shown only prior to the Mars gravity assist optimal coast; they are accounted for in the rest of the trajectory design with duty cycle rather than discrete coasts.[3,4]

were redesigned for the new launch period. Planned post-launch reconfigurations of fault protection that were based on geocentric range and Sun-spacecraft-Earth angle were rescheduled, thus requiring an overall adjustment in the early mission schedule.

To maintain proficiency, the operations team conducted additional rehearsals of launch and initial flight operations in preparation for the later launch period.

LAUNCH AND INITIAL ACQUISITION PHASE

Following a one-day delay in loading hydrazine in the Delta II second stage because of weather, Dawn targeted launch on 27 September. Not having an instantaneous launch window, as most Delta II planetary missions do, proved useful, because a ship's unauthorized entry into restricted waters required a delay. That led to a further delay to avoid the risk of collision with an object in orbit. Liftoff occurred at 11:34:00.376 UTC. The launch vehicle delivered the flight system to $C_3 = 11.3\ km^2/s^2$.

The third stage of the launch vehicle was spun by the second stage to about 285°/s for stabilization. Before it released the flight system, the third stage despun, after having spun for about 410 s. The 425 kg of Xe represented 9% of the flight system moment of inertia about the spin axis (z), and the effects of the Xe on the spin profile of the spacecraft were studied in detail during development.[5] At the initiation of despin, the Xe was expected to be spinning at about 245°/s, approximately 30°/s slower than the flight system at that time. The yo-yo despin system on the third stage was designed to achieve a spin rate of the flight system of 18°/s in the opposite direction, by which time the Xe was predicted to be spinning at 230°/s.

Separation from the third stage took place 61.88 minutes after liftoff. Following sensing of separation, a 500-s delay was initiated by the spacecraft before enabling the attitude control system (ACS). The gyros would not yield a meaningful signal with rates greater than 15°/s, so accurate modeling of the Xe behavior was essential. The delay would allow the spacecraft and Xe to approach rotational equilibrium, with the spacecraft rates becoming low enough that the gyros would be useful. The 500 seconds also would let the torque from the Xe diminish so it would neither exceed ACS control authority nor push the rates back above 15°/s, even in a faulted case.

Following the programmed delay, ACS was commanded to bring the rates on all axes to low values. The profile of the spacecraft angular rates following separation was very close to the prediction, but after ACS engaged, it took longer than expected to reach the planned values for reasons that are not fully understood. Nevertheless, the prediction of the spacecraft behavior was adequate to deliver it with rates within the required range for ACS to gain control.

Fault protection allowed 16 minutes for the rates to be controlled at a prescribed level. After that time, it switched to the backup reaction control system (RCS) string and ACS continued for another 6 minutes.

The rest of the post-separation sequence continued as planned. The spacecraft activated thermal knives to release the Kevlar cords restraining the solar arrays. The deployment of the solar arrays was allotted a fixed 12.6 minutes, with no capability to advance to the next activity if the array deployment completed early.

Following the completion of the deployment of the arrays, ACS used its coarse Sun sensors to locate the Sun. About 14 minutes after the arrays were deployed, the spacecraft had its $+x$ axis pointed at the Sun and was rotating at 0.1°/s around that axis as planned.

Apart from the delay for the Xe coupling and the solar array deployment, the post-separation sequence was the one used for achieving safe mode.

The spacecraft has one LGA on its +*x* axis and one each aligned with its +*z* and -*z* axes. With a Sun-spacecraft-Earth angle near 90° early in the mission, safe mode communications were conducted with the -*z* LGA. As the spacecraft rotated, communications would be possible at least half of each hour. Particularly early in the mission, when the geocentric range was low, communications could be supported for a greater fraction of the time.

Dawn uses a 100-W X-band traveling wave tube amplifier (TWTA), which could consume up to about 200 W of spacecraft power. Because of this large load, the TWTA was not activated in the nominal sequence until the spacecraft had its solar arrays pointed at the Sun. (Fault protection was designed to activate the TWTA well before battery energy would have been exhausted, even if Sun-pointing failed.)

The TWTA was powered on 62 minutes after separation and began transmitting 4 minutes later. Initial acquisition at the Goldstone Deep Space Communications Complex occurred less than 1 minute after that.

INITIAL CHECKOUT PHASE

The objective of the initial checkout (ICO) phase of the mission was to prepare for the long-term, high-duty-cycle IPS thrusting required to rendezvous with Vesta and Ceres. The phase was allocated 80 days. Dedicated activities to configure and verify the performance of most subsystems were conducted, and the highlights are described here.

Each of the 3 ion thrusters was planned to be operated at 5 throttle levels from power processor unit (PPU) input powers of 1.0 kW to 2.5 kW, corresponding to thrust of 32 mN (and specific impulse of about 2800 s) to 91 mN (and specific impulse of approximately 3100 s). Operation at one of the intermediate throttle levels on ion thruster #2 (the thruster on the +*x* side of the spacecraft[1]) was not conducted because of the possibility of exceeding temperature limits given the limited range of acceptable attitudes when the heliocentric range was still near 1.0 astronomical units (AU).

Without accelerometers onboard to measure thrust, the thrust of each ion thruster was determined by radiometric navigation. Thrusting was to be conducted in 3 attitudes for each thruster: 1 near parallel to the Earth-spacecraft vector to yield a good Doppler signature and 2 near orthogonal to the Earth-spacecraft vector to measure thrust direction errors. (The latter 2 thrust attitudes were also mutually nearly orthogonal.) Attitude constraints early in the mission precluded operation of thruster #2 in the orthogonal attitudes. These measurements are planned for the optimal coast period after the Mars gravity assist at no cost to mission performance for the deferral.

In addition to verifying that the achieved thrust in all cases was within 1% of the prelaunch predictions, the IPS tests showed all the electronics as well as the xenon feed system and the thruster gimbals to be healthy. Details of the ICO testing and operation of the IPS are presented by Garner *et al.*[6]

Some ICO thrusting activities were focused on testing different ACS control modes rather than the IPS itself. The gyros are not qualified for operation throughout the mission; rather, they are principally for use in safe mode and to achieve accurate pointing in Vesta and Ceres orbit. The gyros also were used for many ICO activities to provide additional robustness as the operations team gained experience with ACS performance. Tests of thrusting were conducted with and without the gyros.

During most of the mission, reaction wheel assemblies (RWAs) are used for attitude control, but ACS can control attitude with the RCS instead. During IPS thrusting, ACS uses the IPS for control of the 2 axes orthogonal to the thrust vector, and either the RWAs or RCS may be used for the third axis. ICO tests verified operation in all modes, as well as desaturating the RWAs while thrusting.

The culmination of thrusting tests in ICO was the long duration systems test (LDST), designed to follow the profile of a typical week of thrusting during the interplanetary cruise phase (see page 10). The purpose was to verify that the flight and ground systems were ready to execute the thrusting necessary to follow the mission plan. Dawn has planned a thrusting duty cycle of 95% during times that thrusting is desired.

On 6 November (local time at JPL), Dawn commenced thrusting for the LDST. After 165 hours, it terminated thrust and turned to a new attitude for a typical weekly telecommunications session. At that time in the mission, the HGA had not yet been tested, so communications continued to use an LGA. Real-time data were returned during the week of thrusting but only to verify that the system remained healthy. The return of stored data at the end of the week of thrusting provided subsystem engineers with a preview of the nature of the telemetry they would have during routine operations.

After a 6-hour communications pass, the spacecraft returned to the thrust attitude and resumed thrusting for another 4 hours. This final part of the LDST demonstrated that standardized command sequences correctly and consistently managed all states across the necessary transitions.

The success of the LDST was an essential milestone in ICO. Weekly thrusting in the interplanetary cruise phase has proceeded much as it did in this test.

While not required for the beginning of the interplanetary transfer to Vesta, each of the science instruments was evaluated during ICO. GRaND was operated continuously for 6 days, during which cosmic rays provided enough signals to demonstrate that the instrument was healthy and operating correctly. Initial tests of FC2 (the prime camera), FC1 (the backup), and VIR showed they also were functioning as intended. These instruments used internal calibrations lamps and observed the sky in the directions they were pointed without dedicated spacecraft attitude changes. Later tests in ICO of FC2 and VIR targeted specific stars, star fields, and planets. (FC1 targeted observations were conducted in the interplanetary cruise phase.)

It had been planned before launch that updated software would be loaded into Dawn's central flight computer after launch. Postponing the installation of software with improvements that were unnecessary for ICO allowed launch to be conducted with a version of software that had received extremely thorough testing. This strategy also provided a convenient opportunity to incorporate fixes identified during the early part of ICO.

Files with the new software were transmitted to the spacecraft on 27 November with the intention of rebooting the computer the next day to begin running the software. Later that day, when the spacecraft was stable and not conducting any special activities, the computer reset. The reason for this unexpected reset has been investigated extensively but has not been determined, and no subsequent instances of similar events have occurred.

After verifying that the spacecraft was safe and the new software was operating as intended, the planned recovery from the reset was completed on 29 November. As an inflight validation of the new software, further IPS thrusting was conducted the next day.

The same software was loaded to the backup computer on 7 December.

The prime and backup central computers each have primary and backup copies of the software. The backup software was loaded to the backup computer on 14 December. The installation of the backup copy on the prime computer was delayed so the investigation into the possible connection between the uploading of the software files and the unplanned reset could continue. (That backup version was loaded on 22 January 2008.)

In addition to the software for the central flight computer, new software was installed in auxiliary computers during ICO. Some of the changes were to fix bugs and others were to modify fault protection to account for previously known needs as the mission geometry changed and operations transitioned to interplanetary cruise.

While all deterministic and statistical trajectory control is planned to be executed with the IPS, the spacecraft has the capability to execute a trajectory correction maneuver (TCM) with the RCS. (A total of 12 m/s is budgeted, distributed for use on approach to Mars and in orbit at the asteroids; in contrast, the Δv from the IPS will be about 11 km/s.) To verify RCS and ACS capability, a test TCM of 0.08 m/s was performed.

The ICO testing included a total of 278 hours of ion thrusting. The IPS expended 3.1 kg of Xe and imparted about 65 m/s to the spacecraft.

INTERPLANETARY CRUISE PHASE

With all required activities for ICO completed and most of the lower priority, optional activities completed as well, the interplanetary cruise phase began on schedule on 17 December using thruster #3 (the one aligned with the spacecraft -*z* axis). Most of the mission will be spent in this phase, either in transit to Vesta or from Vesta to Ceres.

At the beginning of interplanetary cruise, the IPS provided 6.5 m/s/day of thrusting, and that will increase to about 7.4 m/s/day in 2010 as the wet mass decreases. After that, the acceleration will decrease as the heliocentric range increases past about 1.9 AU, requiring the IPS to operate at lower throttle levels. By 25 August 2008, the spacecraft had thrust in interplanetary cruise for almost 5100 hours. This thrusting consumed 56.3 kg of Xe and provided 1.42 km/s.

There have been 2 periods of unplanned coasting. A single event upset in a voltage comparator in the command and data handling subsystem on 14 January caused an auxiliary computer to enter an infinite loop, ultimately leading fault protection to declare a fault and to invoke safe mode. The loss of 85 hours of thrusting, during which the operations team diagnosed the fault and returned the spacecraft to normal thrusting, was insignificant for the mission.

It was subsequently determined that the vulnerability to the upset could be eliminated with a simple software patch. The patch was installed on 22 July during a normal forced coast period.

In the test of thrusting with ion thruster #2 orthogonal to the Earth-spacecraft vector on 8 April (postponed from ICO because of thermal constraints on the attitude), the IPS failed an internal software test and commanded the thruster off. The spacecraft system fault protection detected the unexpected absence of thrust and commanded a high level of safe mode in which the spacecraft would point the HGA to Earth rather than to the Sun as in normal safe mode. Meanwhile, the mission control team, observing the spacecraft through an LGA at 10 bits/s (introducing significant delays in the delivery of telemetry) with a two-way light time of 18 minutes, detected the IPS decision to terminate thruster operation. Commands to halt the test were transmitted, but they conflicted with other commands being issued by fault protection, resulting in an entry into normal safe mode.

In this case, 100 hours of deterministic thrusting was lost; as with the previous incident, the overall effect on the mission was not significant. Indeed, the mission design included forced coasts exclusively for the purpose of providing margin against missed thrust,[3,4] but none of the coasting margin was consumed by either of the missed thrust events.

It was quickly recognized that the software test that had failed was unnecessary. It had been included during development of NASA's previous interplanetary IPS mission, Deep Space 1,[7] when the in-flight behavior had not yet been characterized. Thrusting resumed with thruster #3 on 14 April, and on 21 April the software check was disabled.

At the beginning of interplanetary cruise, sequences were planned to operate for 4 weeks. As operations began to mature, it was recognized that this could be increased to 5 weeks, with the limit on the duration being determined by the combination of sequence development time and how long in advance the DSN could commit to the specific times of coverage.

It was convenient to schedule the forced-coast periods to be at sequence boundaries. As described earlier, forced coast periods were added in 2008 when the launch period was shifted to September - October, but others had already been planned in all years for activities incompatible with optimal thrusting. Based on experience with Deep Space 1, it is expected that as the mission progresses, fewer or shorter interruptions in thrusting will be required in routine operations.

During a forced coast period in January, in addition to the installation of the backup copy of software on the primary central computer, other software changes were made. On 23 and 24 January, the safe mode uplink and downlink rates were lowered because of the increased geocentric range.

FC1 was calibrated with targeted observations during the February coast period, replicating the tests that FC2 had undergone in ICO. (Some of the targets were changed simply because of the different position of the flight system relative to the Sun.)

A longer period of scheduled coasting began on 31 March, devoted principally to additional science instrument work. GRaND was powered on for further characterization tests of the space environment. Software updates for FC1 and FC2, planned before launch, were uploaded to each camera. The installation of software into each camera was followed by a test of the instrument to validate the software. New targeted calibrations were conducted with VIR.

Other engineering activities were conducted during this period as well, with the final planned activity being the thruster #2 Earth-orthogonal thrusting tests postponed from ICO. The safing event prevented them from being completed, so they are scheduled for the coast period after the Mars gravity assist.

Dawn carries 4 RWAs, but only 3 are used at a time in normal operations. Approximately every 6 months, a different one will be powered off, thereby balancing operations across all the units. During the forced coast period in May, the RWA that had had only 11 days of operation since launch was powered on and another was powered off. As with most other periodic maintenance activities, switching among RWAs likely will not require execution during special forced coast periods after having been demonstrated successfully.

Based on known IPS thruster wear-out mechanisms and other considerations, the strategy for thruster utilization includes expending approximately equal amounts of Xe through the 3 thrusters at the maximum throttle level, which should be sustainable until the first half of 2010. The second thruster planned for use in the interplanetary cruise phase was thruster #1 (on the *-x* side of the spacecraft). As that thruster is oriented about 48° from thruster #3, changing to thruster #1 requires a change of 48° in thrust attitude to provide the correct inertial thrust direction. Sun-spacecraft-thruster angles in the first year of the interplanetary cruise phase range from 82° to 102°.

Maintaining acceptable temperatures of RCS and IPS components near the *-z* deck had required restricting attitudes during the early part of the mission, and it was not clear when the change to thruster #1 would be safe for thrusting for a week at a time. Therefore, during the May forced coast period, the spacecraft was rotated to 2 potential thruster #1 thrust attitudes for 5.5 hours each. The duration was chosen to be long enough to verify temperatures but not so long that elevated temperatures might present a health risk. The spacecraft was 1.6 AU from the Sun, and analysis of the tests confirmed that use of thruster #1 was acceptable.

At the beginning of the next 5-week sequence, during a forced coast period in June, Dawn switched to thruster #1, and that thruster has been in use since then. In the 6 months of interplanetary cruise that thruster #3 was used, it provided 0.99 km/s during 3580 hours of thrust, using 39.5 kg of Xe.

Dawn's solar arrays,[1] the most powerful used on a planetary mission, could produce in excess of 10 kW at 1.0 AU. The design of the mission depends strongly on the power available from the solar arrays as a function of heliocentric range and time, because the IPS thrust and specific impulse both depend on the PPU input power.[3] The flight system cannot place a load on the arrays greater than about 3.2 kW (the sum of the maximum IPS power of 2.5 kW and the rest of the engineering subsystems), so the array power output capability could not be measured directly when the spacecraft was less than about 1.9 AU from the Sun. Aphelion in 2008 was on 8 August at 1.68 AU, and that heliocentric range will not be reached again until November 2009. Therefore, a special solar array calibration activity was included in the July forced coast period with a backup opportunity scheduled for the end of September.

In the calibration, the arrays would be rotated far enough that they could not generate sufficient power to operate the IPS. Because the IPS takes about 2 minutes to ramp up to maximum power, high rate telemetry would allow detailed reconstruction of the power *vs.* voltage curve for the arrays. A test of the calibration procedure was conducted on 21 July with the arrays rotated 45° off-Sun, not far enough to reduce their output to as low as the spacecraft loads but enough to test the functionality of the calibration sequence. The sequence operated correctly, but the reconfigurations of the electrical power system and the IPS for the test caused unpredicted behavior that prevented the test from yielding the desired data. A modified version of the calibration test will be conducted in September 2008 and, once the method is verified, will be repeated occasionally during the mission with array rotation angles that depend on heliocentric range.

NEAR-TERM PLANS

Optimal coasting is planned to commence in early November 2008. The spacecraft will pass through its first solar conjunction in December. The Sun-Earth-spacecraft angle will be less than 3° for 19 days, with the minimum elongation being about 0.4° from the solar limb on 12 December. The conjunction period will not impose significant constraints on the mission, as the spacecraft normally operates for periods longer than that without requiring intervention.

Closest approach to Mars will occur on approximately 18 February 2009, with the exact date depending upon the progress of thrusting through the end of optimal thrusting. Several TCM windows are scheduled during the optimal coast prior to Mars. In July the operations team conducted a rehearsal of the development of a TCM to validate the timeline, process, and procedures.

CONCLUSION

The flexibility of the mission design provided by the use of the IPS allowed Dawn to accommodate significant programmatic and technical changes in its launch date. Having completed an ambitious schedule of checkout activities during its first 80 days of operations, the mission is now in stable interplanetary cruise, with all flight and ground systems working well.

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