

In-Flight Operation of the Dawn Ion Propulsion System-Arrival at Ceres

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The Dawn mission, part of NASA's Discovery Program, has as its goal the scientific exploration of the two most massive main-belt objects, Vesta and Ceres. The Dawn spacecraft was launched from the Cape Canaveral Air Force Station on September 27, 2007 on a Delta-II 7925H- 9.5 (Delta-II Heavy) rocket that placed the 1218-kg spacecraft onto an Earth-escape trajectory. On-board the spacecraft is an ion propulsion system (IPS) developed at the Jet Propulsion Laboratory which will provide a total ΔV of 11 km/s for the heliocentric transfer to Vesta, orbit capture at Vesta, transfer between Vesta science orbits, departure and escape from Vesta, heliocentric transfer to Ceres, orbit capture at Ceres, and transfer between Ceres science orbits. Full-power thrusting from December 2007 through October 2008 was used to successfully target a Mars gravity assist flyby in February 2009 that provided an additional ΔV of 2.6 km/s. Deterministic thrusting for the heliocentric transfer to Vesta resumed in June 2009 and concluded with orbit capture at Vesta on July 16, 2011. From July 2011 through September 2012 the IPS was used to transfer to all the different science orbits at Vesta and to escape from Vesta orbit. Cruise for a rendezvous with Ceres began in September 2012 and concluded with the start of the approach to Ceres phase on December 26, 2015, leading to orbit capture on March 6, 2015. Deterministic thrusting continued during approach to place the spacecraft in its first science orbit, called RC3, which was achieved on April 23, 2015. To date the IPS has been operated for over 46,239 hours, consumed approximately 390 kg of xenon, and provided a ΔV of over 10.8 km/s to the spacecraft. The IPS performance characteristics are very close to the expected performance based on analysis and testing performed pre-launch. The IPS will be used for all subsequent orbit transfers and trajectory correction maneuvers until completion of the primary mission in approximately June 2016. This paper provides an overview of Dawn's mission objectives and the results of Dawn IPS mission operations through arrival at the first science orbit at Ceres.

I. Introduction

Missions using electric propulsion have attained a high level of success and reliability of operation. As of June 2012 there are over 236 spacecraft successfully using electric propulsion for attitude control, orbit raising, station keeping and for primary propulsion [1]. Deep Space 1 (DS1), the first interplanetary mission to use ion propulsion, operated its single thruster ion propulsion system for over 16,000 hours before successfully completing its primary and extended missions [2]. A PPS-1350 Hall thruster was used for primary propulsion on board the European Space Agency's SMART-1 probe, with more flights planned [3]. European and U.S. communications satellites have been launched with SPT-100 based propulsion modules for attitude control and orbit boosting. The Hayabusa spacecraft returned to Earth after exploring asteroid 25143 Itokawa [4] and employed ion thrusters for primary propulsion. The Japanese ETS-VIII uses ion thrusters for north-south station keeping. ESA's GOCE mission, launched in March 2009, employed ion propulsion for precision orbital control in low Earth orbit [5], and ESA's

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Artemis mission used the RIT-10 ion propulsion system for transfer to a geostationary orbit [6]. Approximately 148 ion thrusters (13-cm-dia and 25-cm-dia) built at L3 Communications, Torrance, CA are aboard 37 communication satellites built by Boeing Defense, Space and Security for orbit-raising and station-keeping functions, accumulating ~450,000 operating hours in flight [7]. In 2011 the U.S. Air Force satellite AEHF (Advanced Extremely High Frequency) was successfully placed into a geosynchronous orbit from a highly elliptical orbit around Earth using the spacecraft's Hall thruster station-keeping propulsion system [8] after the propulsion system originally intended for the orbit maneuver failed. Since then two additional satellites with Hall thrusters on-board were successfully launched and operated.

The Dawn mission is the ninth project in NASA's Discovery Program. The goal of the Discovery Program is to achieve important space science by launching regular smaller missions using fewer resources and shorter development times than past projects with comparable objectives [9]. The combination of low-cost and short development times presents substantial challenges to an ambitious mission such as Dawn. The Dawn mission is led by the principal investigator, Dr. Christopher Russell, from the University of California, Los Angeles, and the mission is managed for NASA by the California Institute of Technology-Jet Propulsion Laboratory .

The Dawn mission has as its goal the scientific exploration of the two most massive main-belt objects, Vesta and the dwarf planet Ceres for clues about the formation and evolution of the early solar system. Vesta is the second most massive main belt object with a mean diameter of 530 km. Ceres, with a diameter of 950 km, is the largest and most massive body in the asteroid belt. Ceres is classified as one of five dwarf planets in our solar system, and studies suggest it may have a large inventory of subsurface water. The science underlying the Dawn mission is described in [10,11]. To realize these science goals the Dawn spacecraft must rendezvous with and orbit each body. Dawn is the first mission to orbit a main belt object and will be the first to orbit two extraterrestrial targets. The Dawn mission is enabled by a three-engine ion propulsion system (IPS) that provided most of the velocity change needed for heliocentric transfer to Vesta and Ceres, orbit capture at Vesta and Ceres, transfer to Vesta science orbits and orbit maintenance, orbit escape and departure from Vesta, and transfer to science orbits and orbit maintenance at Ceres. Without ion propulsion, a mission to orbit Vesta alone would have been unaffordable within NASA's Discovery Program, and a mission to orbit both Vesta and Ceres would have been impossible with a single launch.

The Dawn spacecraft was launched from Cape Canaveral Air Force Station on September 27, 2007. The first 80 days of the mission were dedicated to a comprehensive spacecraft and IPS checkout [12]. Cruise operations for deterministic thrusting began December 18, 2007 leading to a Mars flyby in February 2009, and rendezvous and orbit capture at Vesta on July 16, 2011, with a science phase lasting approximately 13 months [13]. At the conclusion of the Vesta science phase in July 2012 the Dawn spacecraft departed Vesta for deterministic thrusting to Ceres, leading to a Ceres approach phase lasting approximately seven weeks, orbit capture at Ceres on March 6, 2015, and to the first science orbit on April 23, 2015. The end of the primary mission is scheduled for the summer of 2016. This paper presents a summary of the Dawn mission operations through arrival at the first science orbit at Ceres.

II. MISSION AND SYSTEM FLIGHT OVERVIEW

The mission and flight system are described in detail in [14, 15], and are summarized here. A schematic diagram of the Dawn flight system is shown in Figure 1, with a mass summary for the Dawn flight system in Table 1. The Jet Propulsion Laboratory (JPL) was responsible for the high voltage electronics assembly (HVEA) and science payload development, IPS development and development of other spacecraft components, safety and mission assurance, project systems engineering, mission design, and navigation development, and is responsible for mission operations system development and mission operations which are conducted from JPL.

Orbital ATK (Orbital), Sterling, VA, was responsible for developing the spacecraft bus, flight system integration and testing, and launch operations. The spacecraft is based on Orbital's Geostar [16] satellite platform series. The solar array (SA) consists of two large panel assemblies approximately 18 m² each and measuring almost 20 m tip to tip with triple junction cells providing more than 10 kW of electrical power at one astronomical unit (AU) and 1.3 kW for operations at Ceres. Articulation of the solar arrays is about the Y-axis.

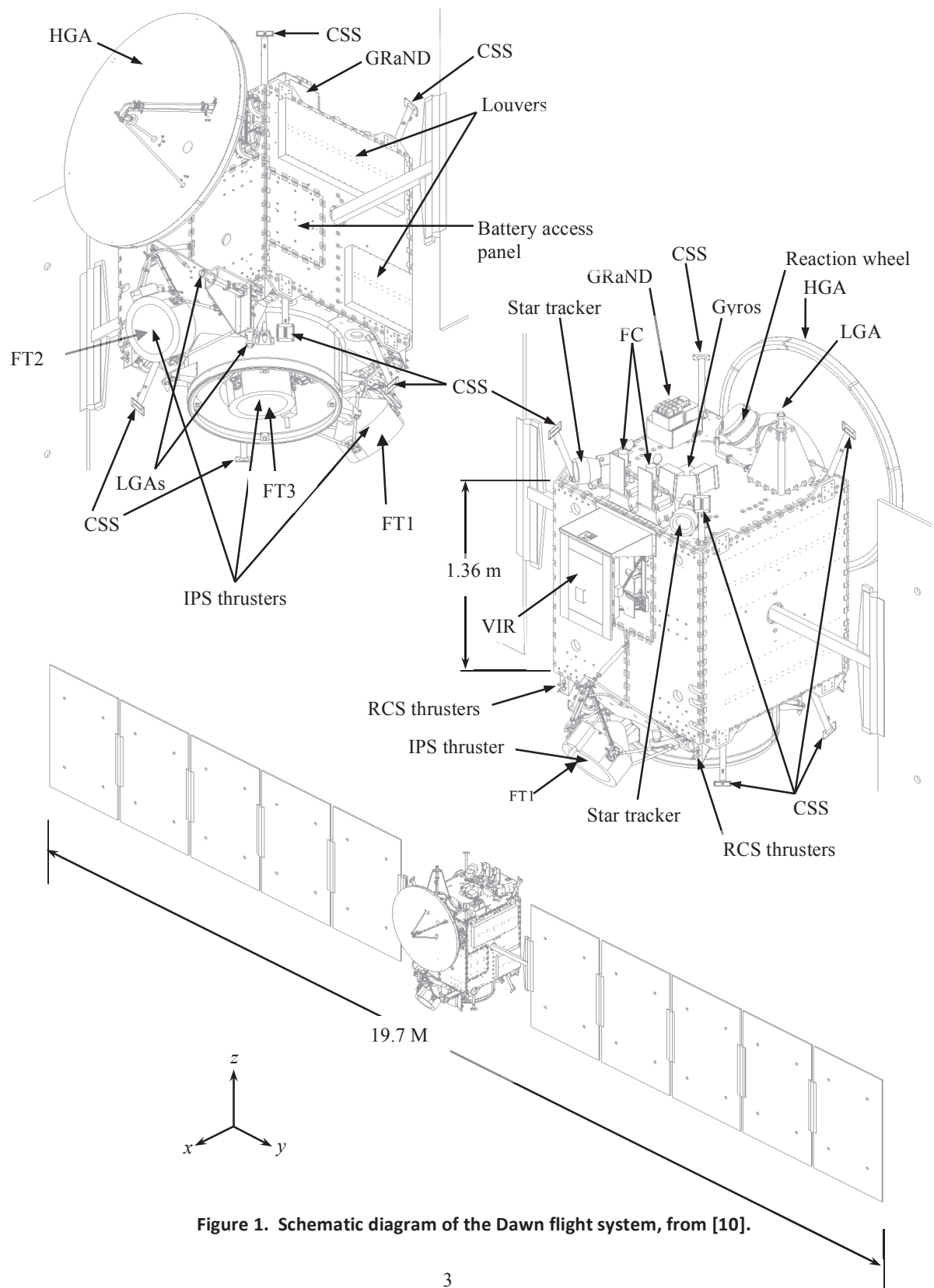


Figure 1. Schematic diagram of the Dawn flight system, from [10].

The spacecraft attitude control subsystem (ACS) employs four reaction wheel assemblies (RWA) for three-axis control of the spacecraft and makes use of the IPS for pitch and yaw control during normal IPS thrusting. The reaction control subsystem (RCS) uses hydrazine thrusters for direct three axis control of the spacecraft and was intended primarily for desaturating the reaction wheels. The spacecraft launched with 45 kg of hydrazine on-board for RCS use on this eight-year-long mission. Two of the four RWAs failed [17], so conservation of hydrazine has been very important, but Dawn is expected to meet its science goals for Vesta and Ceres.

Table 1. Dawn Flight System Mass at Launch

Description	Mass, kg
Dry spacecraft and avionics (except IPS)	573
Science instruments	46
Hydrazine	45
Ion Propulsion System (IPS)	129
Xenon	425
Flight system mass at launch	1218

The Dawn ion propulsion subsystem (IPS) developed at JPL is described in detail in [15] and is shown in the block diagram in Figure 2. The IPS is single-fault tolerant as configured for Dawn and is based on the single-engine ion propulsion system flown successfully on the DS1 mission [12], but modified for multiple thrusters and supporting hardware. The Dawn IPS includes three 30-cm-diameter xenon ion thrusters operated one at a time, two power processor units (PPU), two digital control interface units (DCIU), three Thruster-Gimbal Assemblies (TGA) for two-axis thrust-vector control, a Xenon Control Assembly (XCA) for controlling xenon flow to the engines, and a single xenon storage tank. The ion thrusters and the PPUs are based on technology developed by NASA Glenn Research Center (GRC), and engineered and fabricated for flight by L-3 Communications Electron Technologies (L-3), Inc., Torrance, CA, with minimal modifications to their designs from DS1.

The two DCIUs, which accept commands from the spacecraft, command the PPU supplies, operate the valves on the XCA and actuators on the TGAs, return IPS telemetry and serve as a pass-through for spacecraft commands to the TGAs, were designed and fabricated at JPL. The design was modified from the DS1 design to meet the multi-engine system functionality and cross-strapping required for Dawn. Each DCIU interfaces to a single PPU, to the XCA components and xenon high pressure subassembly, and to each of the three TGAs. Each DCIU provides low voltage power to its corresponding PPU. Only one DCIU is powered up and operated at a time and the unused DCIU is left in an unpowered state. The DCIUs include software needed for automatic and autonomous control of IPS including thruster power levels, flow system valve actuation, and XCA flow control settings. Both DCIUs are mounted next to the PPUs to the same thermally-controlled plate within the core structure of the spacecraft.

The Dawn ion propulsion system is designed to be single-fault-tolerant. Ion thrusters using the 30-cm-diameter NASA design were operated for 16,265 hours on the DS1 mission [2] and 30,352 hours in an extended life test [18], however the Dawn mission requires 400 kg (Table 2, xenon allocation summary) or 200 kg per ion thruster if one thruster fails at the beginning of the mission. To accomplish the mission at least two ion thrusters, two TGAs, one PPU, and one DCIU must be fully functional throughout the mission [10]. Analyses [19] and test data [18] indicate that a two-engine IPS can perform the Dawn mission with a low risk of failure due to ion thruster wear if the thrusters and PPUs are cross-strapped as shown in Figure 2 such that the loss of one thruster or PPU does not impact successful operation of the remaining two ion thrusters or PPU. Each PPU is connected to one DCIU and directly to the HVEA which provides unregulated solar array power to the PPUs. FT3 can be powered by either of the two PPUs, while FT1 is connected only to PPU-1 and FT2 is connected only to PPU-2. The high voltage harnesses connecting the PPUs to the ion thrusters appear as the red lines in Figure 2. Only one of the PPUs is powered on at any time, and the unused PPU is left in an unpowered state. The mission trajectory planned for Dawn is shown

in Figure 3, and a list of important mission phases is summarized in Table 3 below. The complete mission ΔV , from the initial checkout through conclusion of Ceres science operations and including the Mars gravity assist, is approximately 13.6 km/s (Table 3). IPS will provide 11.0 km/s of this ΔV and will use approximately 400 kg of xenon for the complete mission.

The center-mounted thruster is designated FT3 (flight thruster 3), and can be powered by either PPU. The outboard thrusters are designated FT1 on the $-X$ panel and FT2 on the $+X$ panel. Each thruster is mounted to a TGA with two struts to each thruster gimbal pad in a hexapod-type configuration (six struts total per ion thruster). Actuators driven by electronics cards in the DCIU that are commanded by the spacecraft ACS are used to articulate two pairs of the TGA struts for 2- axis control of the thrust pointing vector through the spacecraft center of mass and to provide pitch and yaw control during ion thrusting.

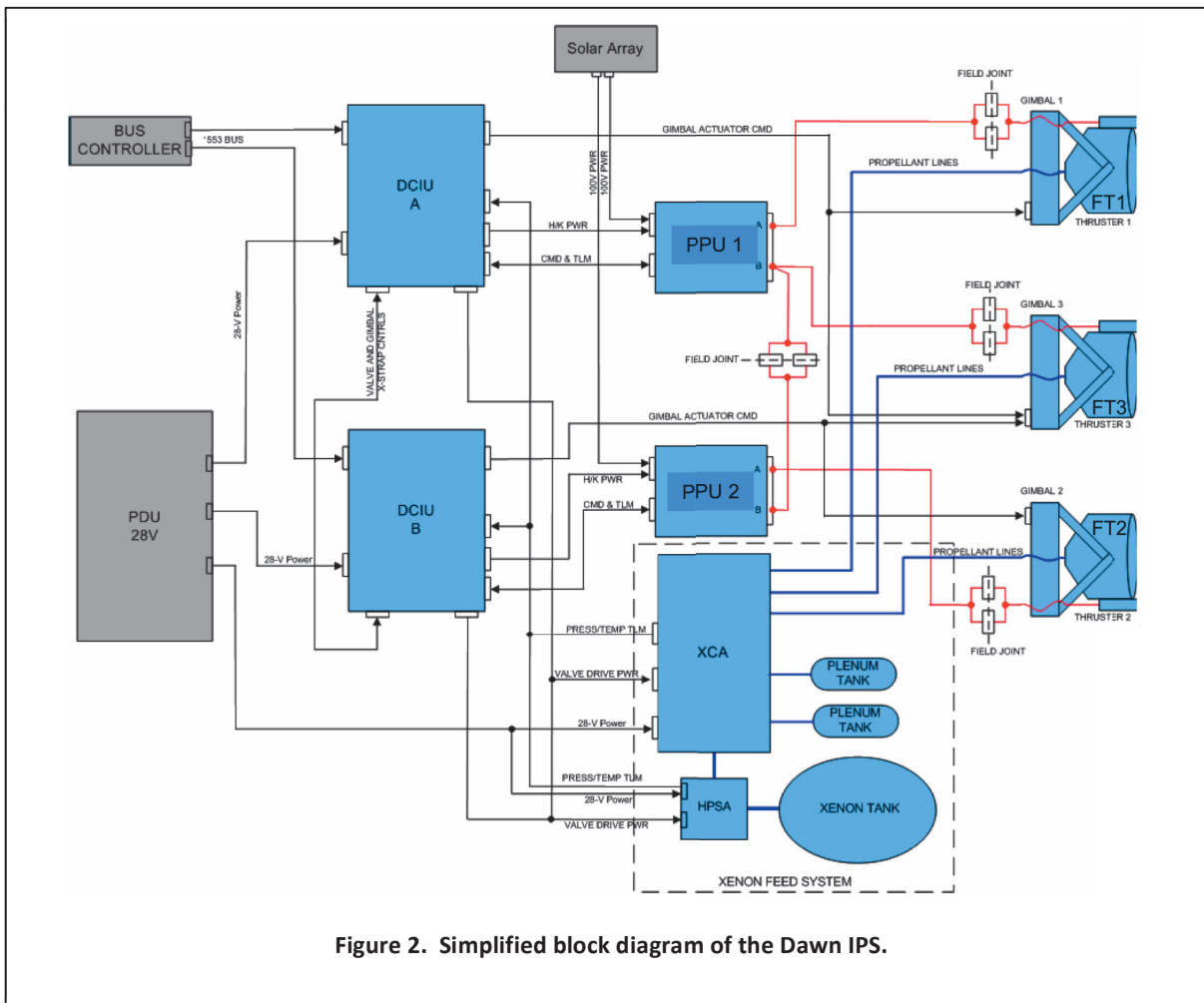


Figure 2. Simplified block diagram of the Dawn IPS.

A titanium-lined composite-overwrap xenon tank developed for Dawn with a volume of 267 liters was mounted inside the core structure of the spacecraft and loaded with 425 kg of xenon prior to launch, with a xenon storage density at launch of approximately 1.6 g/cm^3 . The ratio of tank mass to xenon mass is 0.05 and represents a true breakthrough in total IPS mass reduction.

The xenon feed system is based on the DS1 design but was modified to operate multiple thrusters and to be single-fault tolerant. It includes the XCA placed outside the spacecraft core cylinder with two 3.7-liter plenum tanks identical to those flown on DS1, and uses the same xenon flow rate control design to control pressure to flow rate control devices (flow orifices), latch valves and solenoid valves (similar to those used on DS1), service valves, interconnecting tubing, and nine flexible propellant lines (three for each thruster across the TGA interface). The flow orifices were carefully calibrated pre-flight for flow rate determination based on pressure and temperature at the flow orifices. Total xenon consumption is calculated by integrating the pressure and temperature at the flow orifices. A different but likely less accurate method for calculating total xenon consumption makes use of the xenon storage tank pressure and estimates of the bulk xenon temperature. The two methods agree to within approximately 4 kg, or approximately one percent of the total xenon used. Xenon use appears well within the allocation for all remaining mission phases (Table 2).

The mission trajectory for Dawn is shown in Figure 3, and a list of important mission phases is summarized in Table 3 below. The complete mission ΔV , from the initial checkout through conclusion of Ceres science operations and including the Mars gravity assist, is approximately 13.6 km/s (Table 3). The IPS will provide 11 km/s of this ΔV and will use approximately 400 kg of xenon for the complete mission.

Table 2. Xenon Allocation Summary

Description		Xenon Allocation (kg)
Initial Checkout-	Actuals	3.1
Deterministic Thrusting To Vesta	Actuals	246.2
Vesta Operations	Actuals	10.3
Deterministic Thrusting To Ceres	Actuals	118.0
Approach to Ceres	Actuals	12.4
Allocation for Ceres Operations		9.1
Allocation for Leaks and Thruster Restarts		1.0
Main Tank Residuals		5.0
Margin		20.1
Totals	425.2	

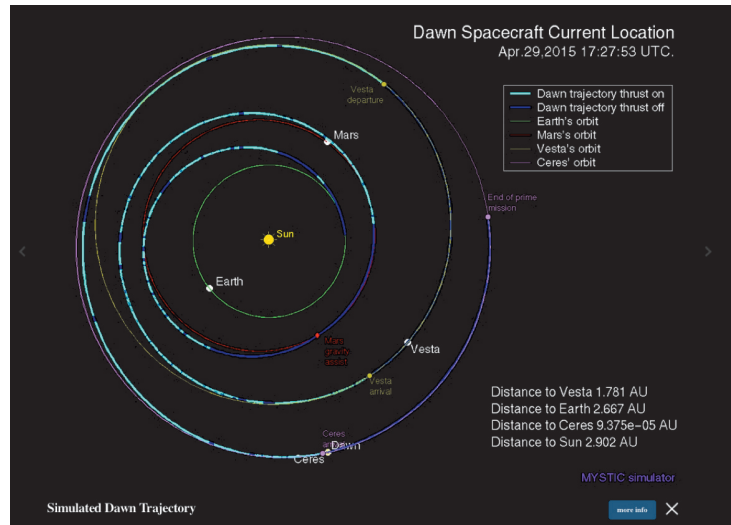


Figure 3. Dawn mission trajectory.

Table 3. Dawn Mission Summary. Bold font indicates the mission phase has been completed.

Description	Time Period	Distance S/C to Sun (AU)	Power Level To IPS (kW)	Comments
Launch	09/27/2007	1.0	NA	
Initial Check-out	09/2007 - 12/2007	1.0 - 1.16	2.6	$\Delta V = 0.07$ km/s
Cruise prior to MGA	12/2007 - 11/2008	1.16 - 1.40	2.6	$\Delta V = 1.80$ km/s
Optimal Coast and Mars Gravity Assist (MGA)	11/2008 - 06/2009	1.40 - 1.60	NA	$\Delta V = 2.60$ km/s (From MGA)
Cruise to Vesta	06/2009 - 07/2011	1.40 - 2.26	2.6 -1.7	$\Delta V = 4.84$ km/s *
IPS Operations at Vesta	07/2011 - 09/2012	2.26 - 2.53	1.7 -1.3	$\Delta V = 0.25$ km/s
Cruise to Ceres and Approach	09/2012 - 04/2015	2.51 - 2.84	1.3 -0.9	$\Delta V = 3.85$ km/s **
Ceres Science Operations	04/2015 - 06/2016	2.84 - 2.93	0.9	$\Delta V = 0.33$ km/s
Total From IPS				$\Delta V = 11.14$ km/s
Mission Total				$\Delta V = 13.74$ km/s

* From start of cruise to orbit capture at Vesta

** From start of cruise to the first science orbit at Ceres (RC3)

III. Overview of IPS Operations To Start of Survey Orbit

Trajectory Description

The ICO, Mars flyby with gravity assist (MGA), and Vesta phases were completed successfully and are discussed in detail in [13, 20-21]. The MGA resulted in a plane change of 5.2 degrees and an increase in heliocentric velocity of 1.7 km/s. Deterministic thrusting for cruise to Vesta resumed on June 8, 2009, with the spacecraft at approximately 1.37 AU from the sun, and nominal cruise operations to Vesta were completed in May 2011. The goal for cruise to Vesta was to modify the spacecraft's heliocentric trajectory leading to capture at Vesta in July 2011 and included using IPS for deterministic thrusting and spacecraft engineering tests. Orbit capture at Vesta was followed by a science phase of just over a year [13].

The trajectory to Ceres is divided into the cruise phase, lasting from 2012 to December 26, 2014, the approach phase, lasting from December 26, 2014 to April 23, 2015, and finally the science orbits phase, from April 23, 2015 to end of mission. Thrusting for cruise to Ceres began on July 25, 2012 with the spacecraft in a high altitude mapping orbit around Vesta at an altitude of approximately 673 km, leading to escape from Vesta on September 4, 2012, and arrival to the Ceres approach trajectory on December 26, 2014. Dawn's interplanetary ion thrusting for cruise was designed to reshape its heliocentric orbit to match that of Ceres. To accomplish this part of the mission trajectory IPS was operated in 43 different thrusting segments averaging about 20.5 days of continuous thrusting per segment, totaling 19,454 hours of beam extraction time and 118.0 kg of xenon throughput to provide a delta-V of approximately 3.56 km/s. The burn times per thrust segment were typically substantially longer in duration for cruise to Ceres compared to burn times used previously on Dawn, to reduce the number of spacecraft-to-Earth turns, which conserved hydrazine needed for science operations at Ceres. During cruise to Ceres Dawn experienced a temporary problem with the IPS, described in the section of this paper discussing the DCIUs, resulting in a very small delay to the arrival time to the first science orbit.

The approach to Ceres phase began on December 26, 2014 with the spacecraft at a distance of approximately 700,000 km from Ceres. The objective of approach was to reach the first mapping orbit at Ceres, designated RC3. During approach, the spacecraft's trajectory was adjusted for achieving orbit around Ceres, and optical navigation was performed. The approach phase differed from cruise in several operational aspects, including more frequent updates to planned IPS thrust vectors and nine periods of imaging Ceres. Imaging during this phase was principally for navigation purposes but provided other engineering and science benefits as well.

An important event during approach was orbit capture, occurring on March 6, 2015 at an altitude of approximately 60,600 kilometers. Dawn's entry into orbit was much like at Vesta but entirely different from orbit insertion for missions using high-thrust propulsion. Dawn spent 92.5% of the 2.5 years from Vesta escape to Ceres capture using the IPS to gradually reshape its heliocentric orbit to match that of its destination. As a result, by the time it was in the vicinity of Ceres, the relative velocity was very low. At orbit insertion, Dawn was traveling only 45 m/s relative to Ceres. Capture occurred as a routine part of ion thrusting and was not associated with any special activities and required no real-time communications to the spacecraft. Upon entering orbit around Ceres, Dawn became the only spacecraft ever to orbit two deep-space bodies. While capture was significant, it was not the focus of the approach phase. The date, altitude, velocity, and other parameters characterizing capture were simply consequences of the trajectory that targeted Dawn to its first mapping orbit. Moreover, because the relative velocity was low, if a problem had occurred that interfered with routine operations, there would have been subsequent opportunities to get into orbit. Dawn would have remained near enough to Ceres that a new trajectory (that is, a new set of IPS thrust vectors) could have been designed that would have delivered the spacecraft to the targeted orbit.

Thrusting continued after capture to reshape the orbit, although then it was the orbit around Ceres that was being modified rather than the orbit around the sun. Ion thrusting proceeded according to plan and concluded on April 23, 2015 when Dawn was in the targeted polar, circular orbit at an average altitude of 13,600 km, marking the conclusion of the approach phase. During the approach phase the IPS was operated in 14 different thrusting segments averaging about 176 hours of continuous thrusting per segment, totaling 2,458 hours of beam extraction time and 12.42 kg of xenon throughput to provide a delta-V of approximately 0.29 km/s.

During cruise to Ceres all three thrusters were used, with FT2 used the most followed by FT3 and FT1. The Dawn mission can be accomplished with just two ion thrusters, but thruster operation was intentionally divided between the three thrusters to minimize wear in a single engine. Only FT3 was used for Vesta escape and approach to Ceres, and FT3 is planned for use for all subsequent orbit maneuvers at Ceres. Although any thruster can in principle be selected for orbit maneuvers, using the center-mounted thruster includes several advantages over using the outboard thrusters including reduced coupling between the RCS and IPS system thrusts.

IPS System Power and PPU Performance

Spacecraft heliocentric range for the complete mission is plotted in Figure 4. The blue line color in the figure depicts periods during the mission when IPS was used for thrusting, and the figure does not include thrusting planned for operations at Ceres. As expected for a low thrust mission, the IPS is on and thrusting for the majority of mission time. The IPS duty cycle, defined as beam-on time divided by total time, was approximately 72.1% for the time period from the start of cruise to Vesta on December 17, 2007 through end of approach on April 23, 2015. The duty cycle for cruise to Ceres, spanning approximately 21,211 hours (start of Vesta departure on July 25, 2012 through December 26, 2014) was 91.7%. The IPS duty cycle for cruise to Ceres was maintained at a high level due to a high degree of IPS reliability and by minimizing the number and duration of high gain antenna passes to Earth, all which served to minimize hydrazine consumption. The IPS duty cycle could have been increased, but this was not necessary-Dawn's mission operation processes allowed ample time for spacecraft engineering and spacecraft testing activities.

Data on power to the PPUs for operation of the thrusters are plotted in Figure 5. Data points in Figure 5 are the values averaged at a fixed power level for approximately 20-100 hours. The data include telemetry for unregulated high voltage and current from the solar array to the PPUs and do not include PPU housekeeping power of approximately 20 W.

Until approximately August 2010 there was sufficient power generated by the solar arrays to supply all spacecraft functions (about 700 W average power), periodic high power usage when certain spacecraft events occur such as simultaneous use of many heaters, and the approximately 2.5 kW IPS required for full power IPS operation. Power throttling commenced in August 2010 as spacecraft heliocentric range increased to 2.6 AU. Initially lower power level allocations to IPS were based on very conservative projections of spacecraft power demand during thrusting; spacecraft power estimates were later refined leading to an increased power allocation to IPS.

During its 2.75-year transit from Vesta to Ceres the spacecraft/solar distance (Figure 4) varied from a minimum of 2.44 AU in mid-October 2013 to 2.9 AU upon arrival to the first science orbit (RC3). Unregulated solar array voltage to the PPUs varied from approximately 97 V to 120.6 V, well within the input voltage range limits for the PPUs (Figure 5). Solar array power available to the IPS varied from approximately 1.43 kW in October 2013 to 0.5 kW upon arrival at Ceres. For both PPUs power initially increased and then stabilized, following changes to discharge power utilization due likely to thruster wear.

Both PPUs have operated perfectly throughout the mission to date, and PPU performance throughout the mission has been excellent. PPU efficiencies at 2.5-1.25 kW are similar to the efficiencies measured preflight and are consistently in excess of 93% at full power. PPU efficiencies at lower power are greater than measured pre-flight, likely due to telemetry calibration inaccuracies at low power. Beam currents controlled by the beam supplies in both PPUs were typically within 0.997 of the setpoint values, and neutralizer current and accelerator grid voltage were at the setpoint.

In Figure 6 data (averaged over individual thrust arcs) from temperature sensors inside the PPU indicate that PPU temperatures changed a few degrees C during cruise at full power, and decreased upon start of power throttling. The PPU baseplate temperature sensors are mounted to the part of the PPU chassis in contact with the spacecraft thermal control surface, and have ranged between 27 degrees C with the thrusters operating at full power to 12.7 degrees C with PPU-1 operating at 0.52 kW. The fact that the PPU baseplate temperatures are near room temperatures even for full power operation is a reflection of the excellent thermal heat rejection system on the Dawn spacecraft.

Temperatures of the harness connectors mating the thrusters to the PPUs are shown in Figure 7. The data indicate that at full power operation connector temperatures ranged between 10 to 45 degrees C, and at lower power the harness connector temperatures were as low as -6 degrees C, well within

operational temperature limits of -55 to +90 degrees C. The temperature excursion experienced by the FT3 harness connector in 2011 is due primarily to changing solar exposure to the -Z deck of the spacecraft where FT3 is mounted, a consequence of orbiting Vesta.

XFS Performance

The xenon flow system has operated perfectly throughout cruise, with the exception of the higher than expected solenoid valve cycling rates as described in [12]. These higher cycling rates do not pose a threat to mission reliability. Total xenon stored in the xenon tank can not be determined accurately using the tank temperature and pressure telemetry because of the non-ideal gas properties of the pressurized xenon and to uncertainties in the bulk xenon temperature. The uncertainty in the bulk xenon temperature and pressure measurements require that the xenon consumption be estimated by integrating total xenon flow over time. Xenon flow rates to the thrusters are calculated from plenum tank pressure/flow control device (FCD) temperature telemetry based on curve fits to FCD calibrations obtained in ground testing.

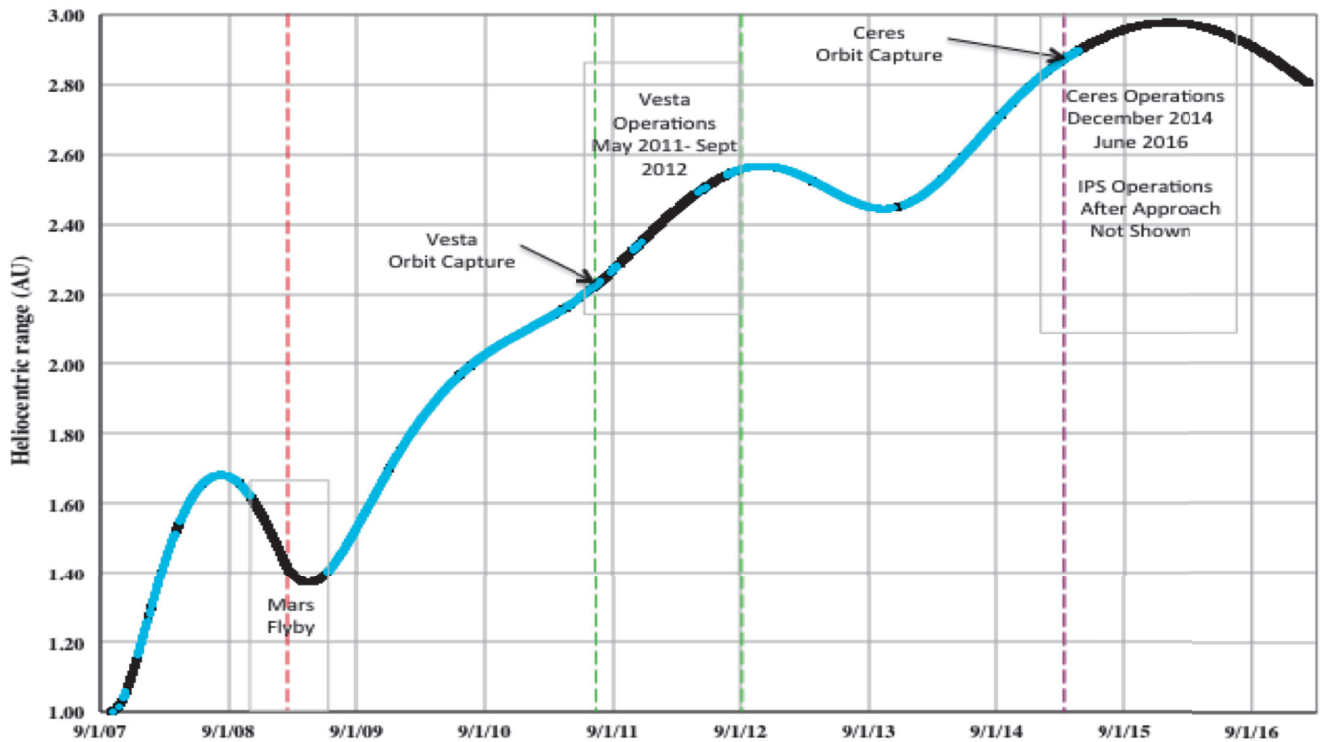


Figure 4. Spacecraft heliocentric range from launch through arrival to RC3 science orbit. Blue line color denotes IPS thrusting.

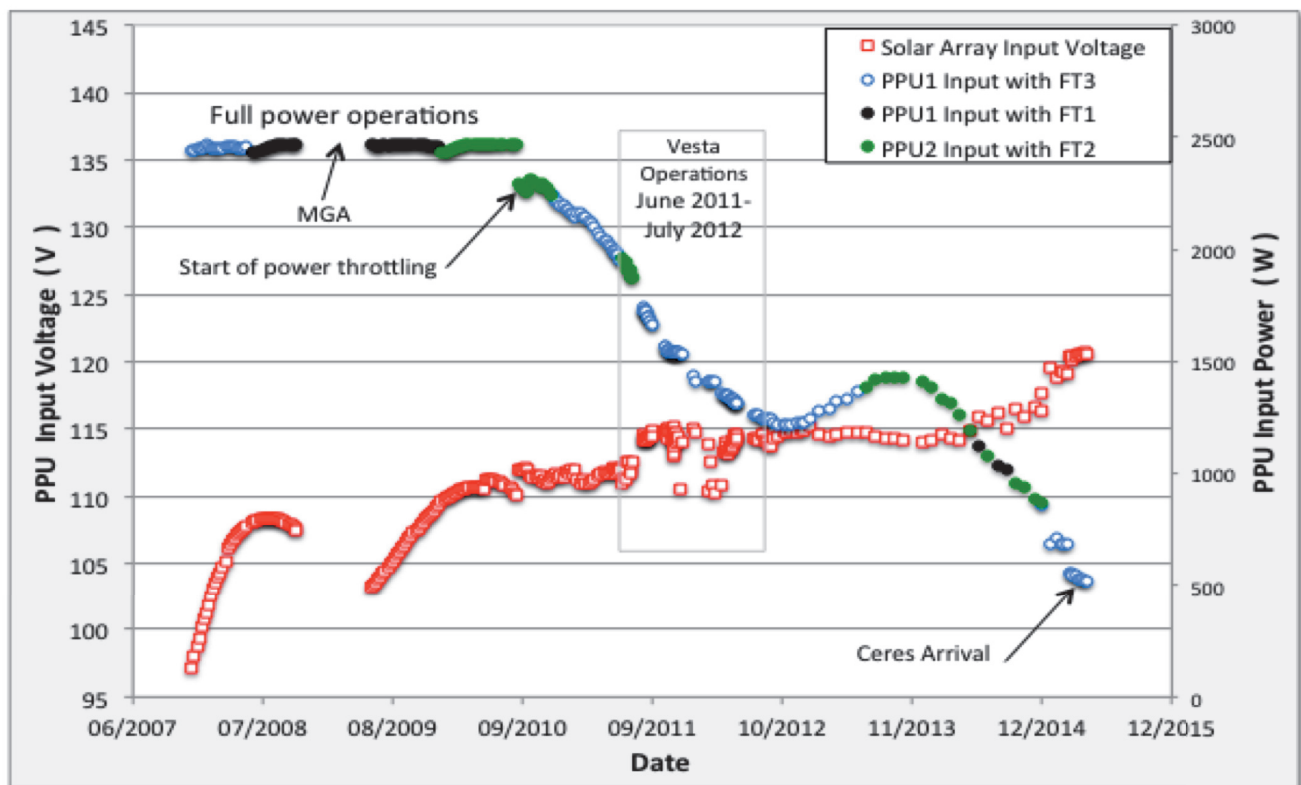


Figure 5. Solar array input voltage and PPU operating power from start of cruise to Vesta through arrival to RC3 science orbit.

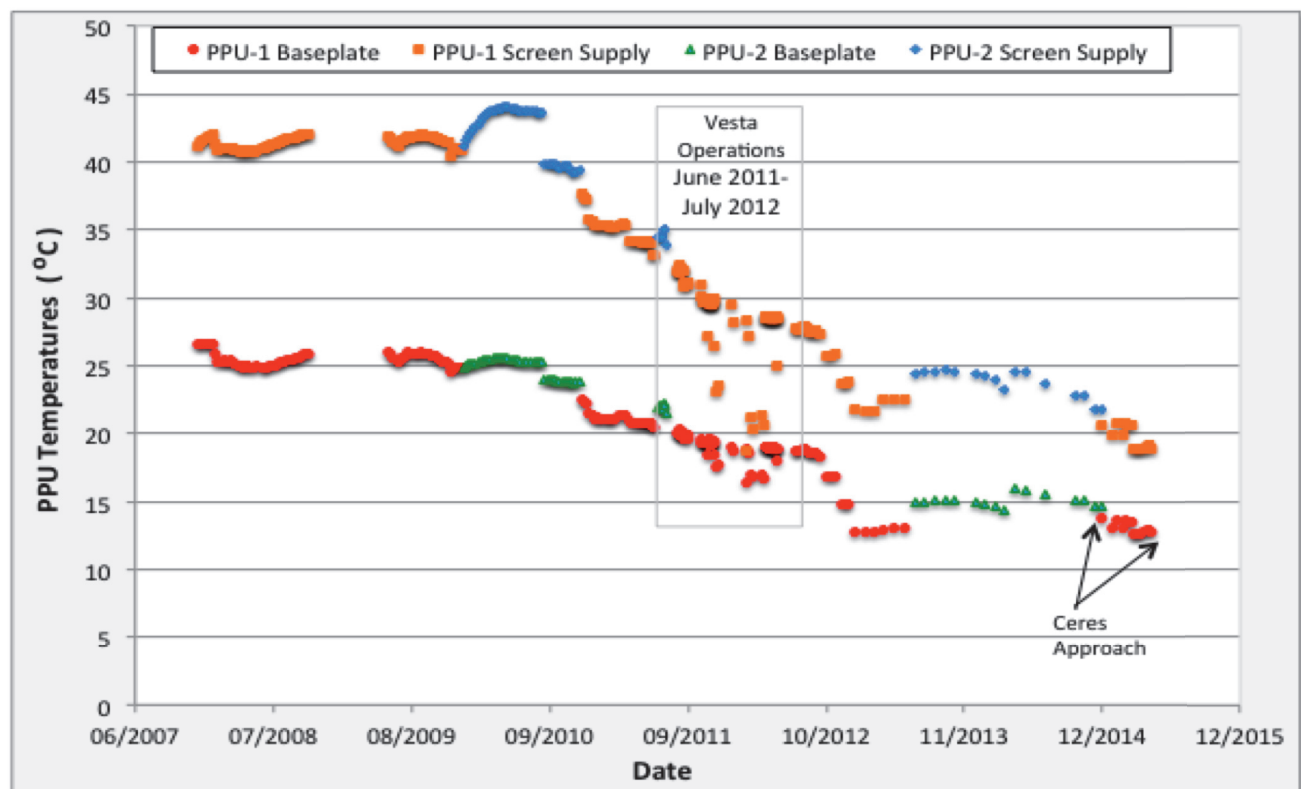


Figure 6. PPU-1 and PPU-2 temperatures from start of cruise to Vesta through arrival to RC3 science orbit.

Plenum tank pressures are controlled by actuation of the solenoid valve pairs between the main xenon tank and plenum tanks. To date the primary solenoid valve pair used to regulate main plenum pressure has been cycled open and closed approximately 1.16 million times in cruise, and the primary solenoid valve pair for cathode plenum tank pressure regulation has cycled approximately 532,000 times (Figure 8). It is expected that solenoid valve cycling rates at a given throttle level will increase as the density of the xenon in the main tank decreases and as the pressure differences between the inter-solenoid valve space and plenum tanks decrease. The solenoid valves on the Dawn XFS have a flight allocation of 1.4 million cycles, and there are redundant valves that have not yet been cycled in flight but could be used in the event of primary valve failure. The controlling temperature for the xenon control assembly plate was reduced early in cruise to reduce the solenoid valve cycle rate [20]. There are no indications of solenoid valve or latch valve leakage based on observations of steady-state pressure measurements of both plenum tanks. Differences in pressure measurements between the three pressure transducers on each plenum tank have remained at low values. A check performed in 2009 for changes in the pressure transducer readings at near-zero pressure indicated the pressure transducer values had virtually no measurable shift in output with respect to their pre-launch values.

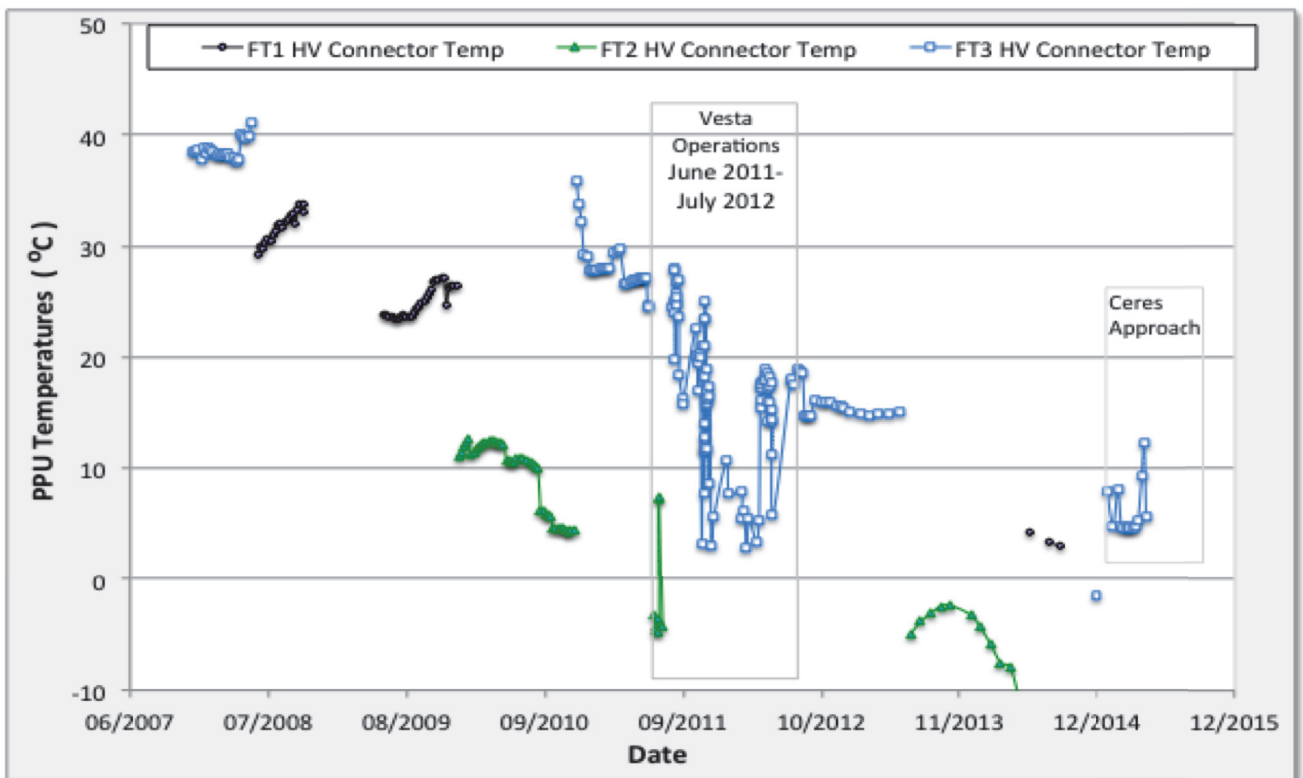


Figure 7. Harness connector temperatures from start of cruise to Vesta through arrival to RC3 science orbit. Flight allowable lower limit is -55 °C.

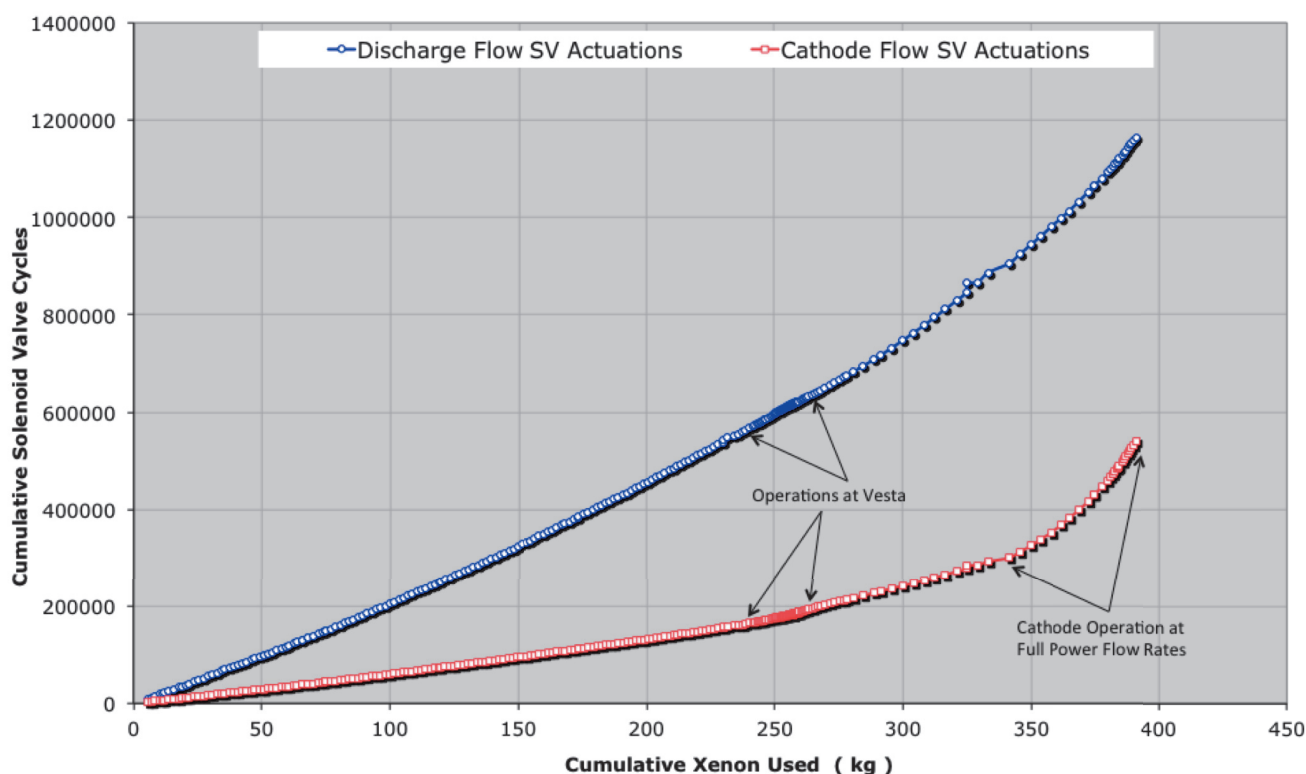


Figure 8. Cumulative number of discharge and cathode SV cycles vs. xenon consumed from launch through arrival to the RC3 science orbit.

TGA Performance

The TGAs have also operated very well in cruise. Each TGA consisting of two each motor/tripod assemblies (side A and side B) per FT is used to move the ion thruster vector to control the two axes normal to the thrust direction. This mode is known as thrust vector control (TVC). RWAs or RCS hydrazine thrusters are used to control the axis around the thrust vector. Cumulative TGA actuator motor revolutions for the A-side motors for each FT are shown in Figure 9. The B-side motors have almost the same number of revolutions. The data indicate that through arrival to RC3 the TGA motors have accumulated the equivalent of over 1.28 million motor revolutions for TGA-1, 1.81 million motor revolutions for TGA-2, and 2.26 million motor revolutions for TGA-3. The motors were qualified to 30 million revolutions. The spacecraft is operated in TVC mode during normal thrusting, including during desaturations of the RWAs, which are typically sequenced approximately every 12 hours. TGA duty cycle has varied between 0.05% and 1%, which is at or less than the expected mission duty cycle of 1%. In normal operation the TGAs “dither”, or rotate, a small amount around a target center. The duty cycle and number of TGA actuations per kg of xenon used are greater with RWA control. In Figure 9, the actuation rate for FT2 and FT3 decreased when the spacecraft switched to hydrazine thrusters for attitude control starting in June 2010. In May 2011 the spacecraft switched to the wheels for attitude control as part of operations for Vesta approach and the TGA duty cycle increased substantially. TGA duty cycle rates under RWA control may increase because under RWA control the spacecraft issues more correcting commands to slew the TGAs than is done under jet control. Approximately every two months for TGAs in use (and six months for unused TGAs) lubricant in the actuators is redistributed by vectoring the thrusters from their null locations to the hard stops and then back to their null locations.

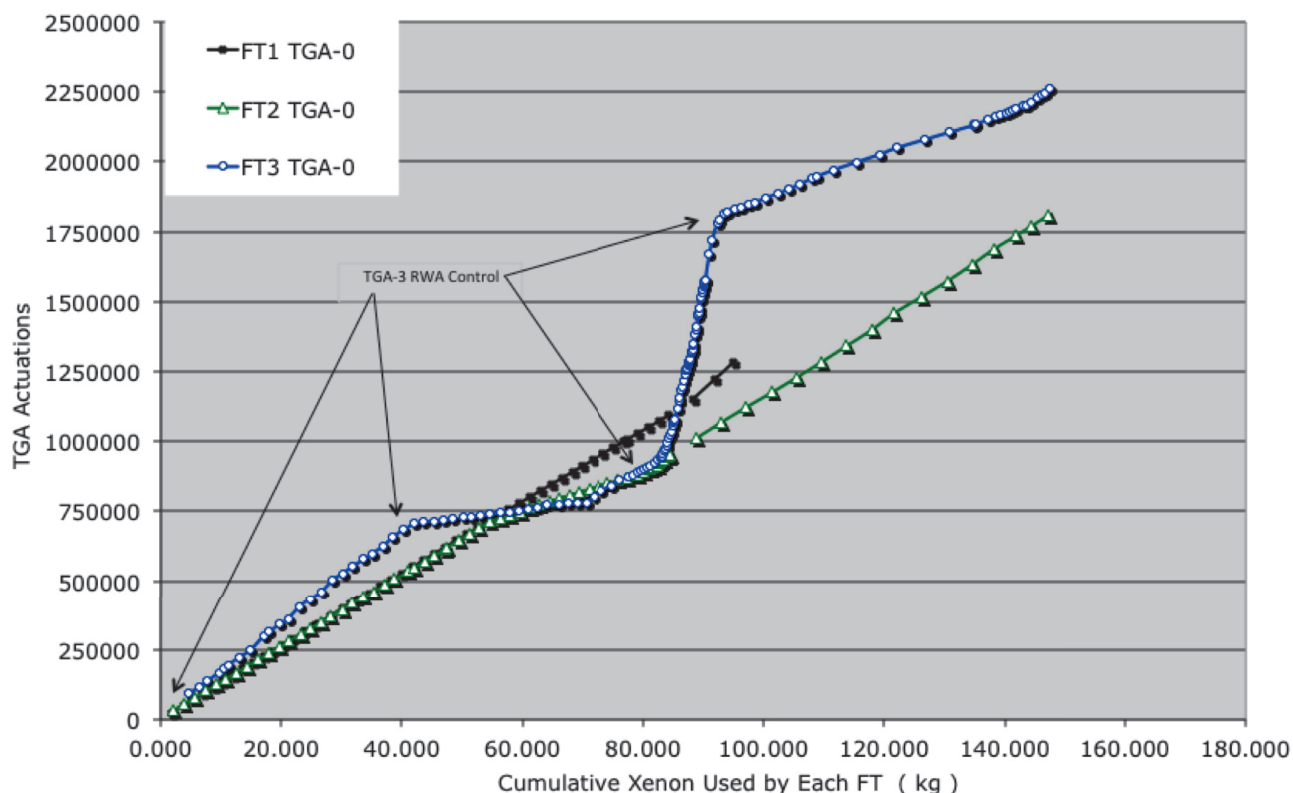


Figure 9. Cumulative number of TGA side A cycles vs. xenon consumed, from launch through arrival to the RC3 science orbit.

Thruster Performance Through Arrival to RC3

Thruster performance data from the ICO were presented in [12] and detailed thruster performance from the start of cruise to Vesta to arrival at RC3 are presented here. Voltage measurements are determined from telemetry at the PPU and the data have not been corrected for the power drop across the harness, which is estimated to be approximately 15 W for the discharge and 18W for the thruster at full power. During operations at Vesta and for some of cruise to Ceres thrusting sequences the discharge cathode and neutralizer flow rate for operation of the FTs at all power levels was changed to 3.7 sccm, the flow rate for full power operation, for thrust stability issues that are described in the thrust performance section of this paper.

IPS Operating Time and Xenon Consumption

Table 4 summarizes operating time for each thruster/PPU and xenon throughput from launch through arrival to RC3 on April 23, 2015. FT3 has accumulated the most number of operating hours and xenon throughput, and Dawn has operated all three thrusters to more evenly distribute the total xenon throughput for each thruster. For transfers from one science orbit to another around Vesta and Ceres, in which the operational schedule requires a rapid design and implementation of the thrust profile, FT3 is preferred because FT3's thruster axis is aligned with the principal axis of the spacecraft. Nevertheless, transfers with the other thrusters are feasible and any of the three Dawn thrusters can be used for any maneuver. FT2/PPU-2 is the preferred backup to FT3, to distribute operating time for the PPUs as well.

Table 4. Operating time and xenon throughput for Dawn ion thrusters from launch through April 23, 2015

IPS Element	Neutralizer On-Time (Hours)	Beam On-Time (Hours)	Xenon Throughput (kg)	Thruster Starts
FT1	9524	9468	95.2	122
FT2	18235	18165	147.3	165
FT3	18353	18607	147.5	362
Thruster Totals	46112	46240	390.0	649
PPU-1 (Hours)	28288			
PPU-2 (Hours)	18252			
PPU Totals (Hours)	46540			

All Dawn FTs have reached end of life (EOL) operation, which is defined as reaching a total thruster throughput of 70 kg of xenon. It is expected based on analysis that each FT can process at least 195 kg [19]. Input power to the FTs from start of cruise to Vesta through arrival to RC3 is plotted in Figure 10 as a function of propellant throughput for each thruster, and in Figure 11 as a function of beam-on time for each thruster. It is likely that thruster power telemetry calibrations at low power are inaccurate. Input power varied from about 2.3 kW at the start of cruise to 0.5 kW at arrival to RC3. All three FTs exhibited increases in thruster power of approximately 11-26 W over the first approximately 20 kg of xenon throughput then leveled off. By the end of full-power operation each FT had increased in power by 16-26 W compared to thruster power used at the start of cruise. Increased thruster power may be related to thruster wear including enlargement of grid holes and the discharge cathode keeper orifice diameter. During normal cruise operations to Ceres all thrusters were operated at end of life conditions, where the accelerator grid voltage was decreased to approximately -275 V to enhance margin to electron backstreaming. In Figure 10-11 power used by FT3 during cruise to Ceres increased due to decreasing heliocentric range (Figure 4) resulting in more power available to IPS.

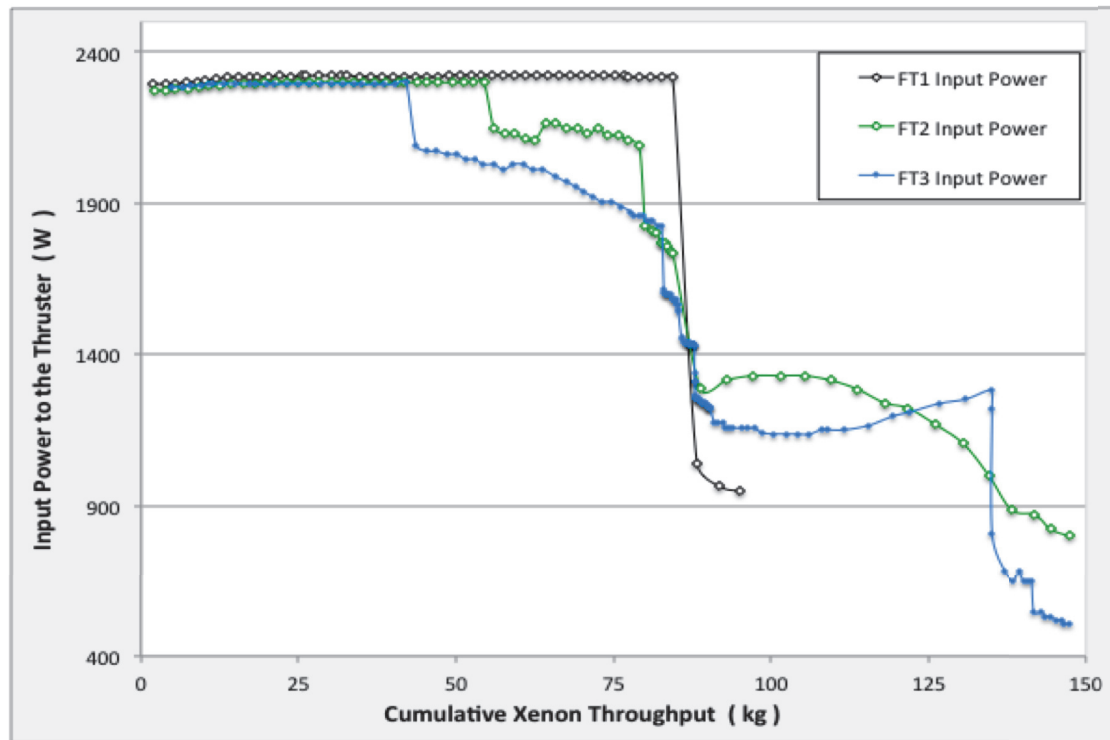


Figure 10. Dawn thruster input power from start of cruise to Vesta through arrival to RC3 science orbit.

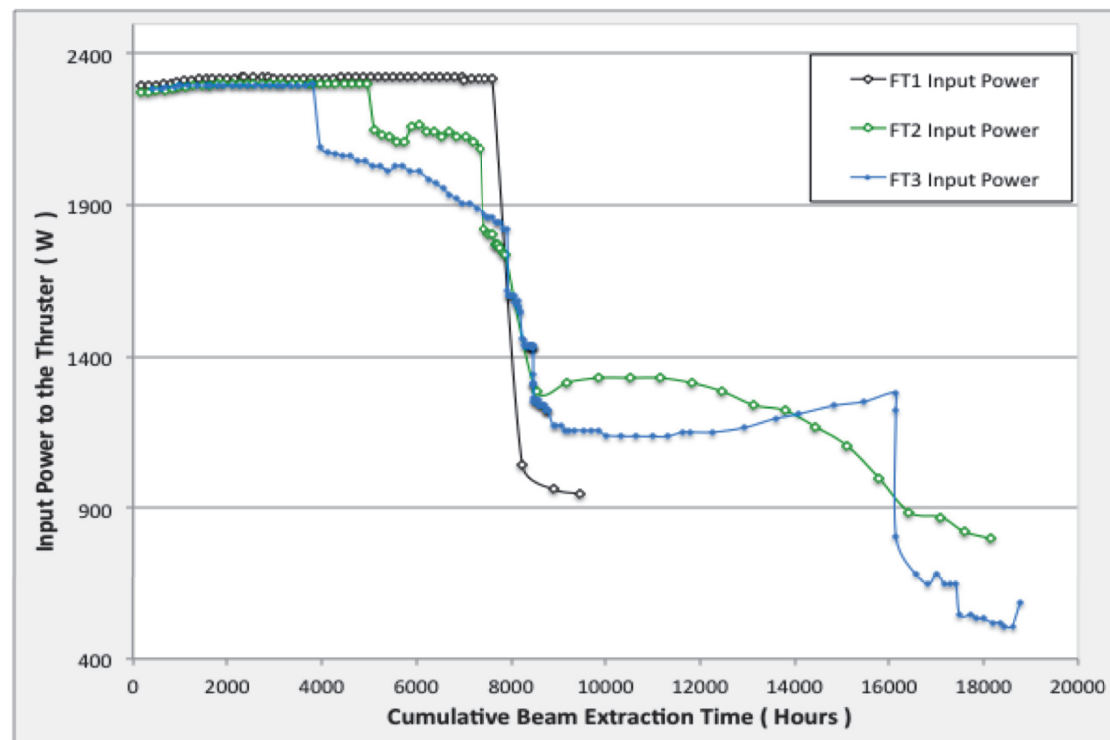


Figure 11. Dawn thruster input power from start of cruise to Vesta through arrival to RC3 science orbit.

Discharge Voltage

Discharge voltage and current for the three Dawn ion engines are shown in Figure 12. Telemetry with closed symbols indicate operation of an engine at high cathode flow rates, and during approach to Ceres through arrival to RC3 both high cathode and discharge flow rates were used while thrusting with FT3. Voltage measurements are determined from telemetry at the PPU and the data have not been corrected for the power drop across the harness. Full power (rich) cathode flow rates were used for Vesta operations to address the thrust stability issues that are described in [20]. This change resulted in extremely reliable and consistent maneuvers, and suppressed the discharge voltage (Figure 12). Operation with nominal cathode flow rates was resumed beginning October 1, 2012, until April 2014 when all three engines were switched to operations at rich cathode flow rates (the closed symbols in Figure 12).

For all three engines at full power, discharge voltage initially increased then stabilized. This is likely related to accelerator grid hole wear characteristics, which result in higher grid transparency to ions. Abrupt changes in discharge voltage exceeding approximately one volt are related to changes to the cathode flow rates from nominal values to full power values or to power level changes. For example during the Ceres approach phase using FT3 when the power level changed by approximately 16 W (one level in a power throttle table consisting of 112 power levels), the discharge voltage changed by approximately 2.4 V.

At approximately 101 kg of xenon throughput for FT2 and 111 kg of xenon throughput for FT3 the discharge voltage for both FT2 and FT3 began to increase at a rate of approximately 0.1 V per kg of xenon throughput. Both engines were operating at nominal cathode flow rates when the discharge voltage characteristics began changing. The most significant differences in operations on FT2 vs. FT3 are that FT2 has more operating time at lower power levels, fewer starts and substantially less operating time at rich cathode flow rates.

The mission plan had called for operations on FT3, the preferred thruster for Ceres maneuvers, during the Ceres approach phase, requiring the use of an additional 25 kg of xenon through end of mission, possibly resulting in an increase in the discharge voltage. Excessively high discharge voltage over a sustained period of time can lead to increased wear and reduced thruster life. A test performed on FT3 operating with the discharge only (diode mode) at rich cathode flow rates confirmed that although the discharge voltage on FT3 had changed substantially at nominal cathode flow rates, the discharge voltage at rich cathode flow rates was virtually unchanged. This test and the fact that the mission had ample xenon reserves led to a decision to operate all thrusters for the remainder of the mission at rich cathode flow rates, where it was expected that both the magnitude and rate of increase of the discharge voltage would decrease. Since the change in flow rates to the cathodes, FT2 has processed 25.3 kg and FT3 has processed 12.5 kg. Data from thrusting performed since the change to rich cathode flow rates indicate that the magnitude of the discharge voltage decreased by approximately 2.7 V, and at fixed power levels the rate of increase of the discharge voltage dropped to approximately 0.025 V/kg, confirming that operation at rich cathode flow rates had mitigated the unexpected change in discharge voltage behavior. Presently at approximately 500 W of thruster input power the discharge voltage is at 19.4 V. Dawn can expect substantial margin to the discharge voltage for orbital operations at Ceres.

Thruster Starts

From launch through arrival to RC3 there have been a total of 649 thruster starts in flight, with 122 starts using FT1, 165 starts using FT2, and 362 starts using FT3. Almost half of these engine starts were on the discharge only for one hour (called "diode mode") to prepare the engine thermally for beam extraction. The cathode heater preheat duration for all starts was six minutes. Data taken at one second intervals indicate that in every start attempt in flight after the ICO, the discharge and neutralizer cathodes ignited within one second of the command for application of the igniter voltage pulses. Discharge cathode and neutralizer cathode heater power appear unchanged over time, possibly indicating low levels of keeper electrode erosion over time. Beginning in December 2014 all thrusters were started without using a thruster discharge pre-heat cycle. The highest power level for a thruster start without a thruster discharge pre-heat was at approximately 800 W on FT3.

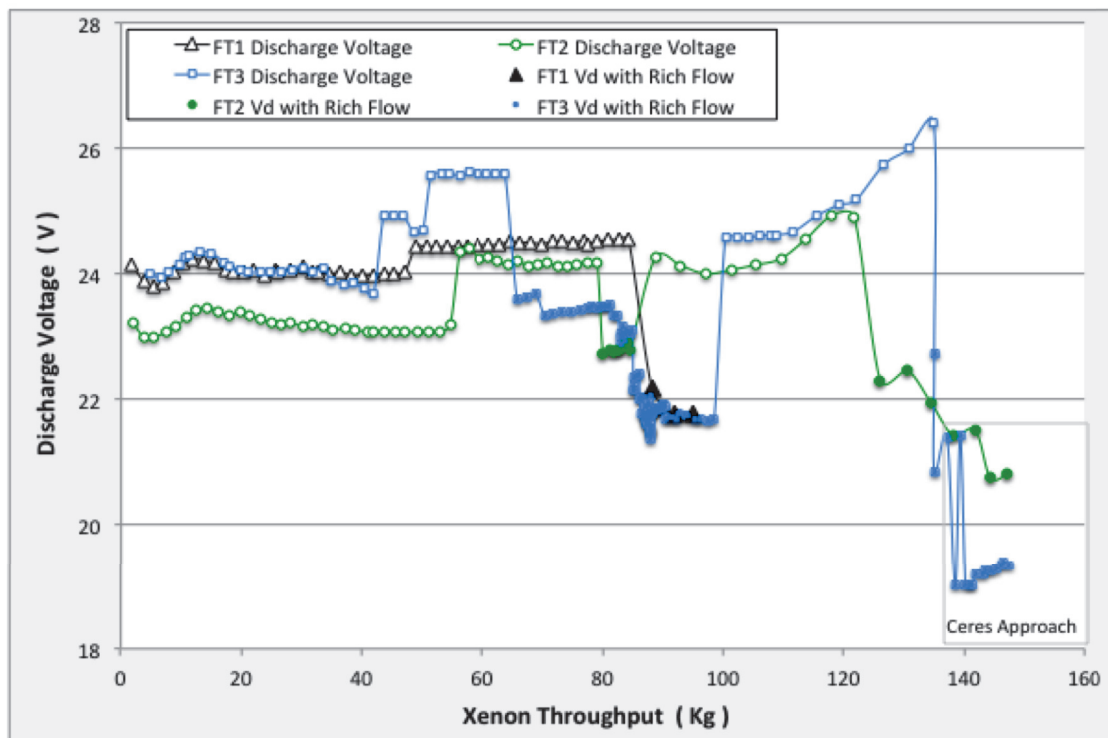


Figure 12. Dawn thruster discharge voltage from start of cruise to Vesta through arrival to RC3 science orbit.

Neutralizer Operation

Dawn thruster neutralizer keeper voltage data for operation from start of cruise to Vesta through arrival to RC3 are shown in Figure 13. From the start of cruise to approximately 80 kg of xenon throughput neutralizer keeper voltages decreased in a similar way for all three Dawn thrusters. Dawn thruster neutralizer voltage changes may be related to improved cathode conditioning over time in the clean environment of space. Smaller changes to the neutralizer voltage appear to be due to thruster power changes, while larger changes are related to operating the engines at moderate to low power with rich cathode flow rates, which suppresses the neutralizer voltage (Figure 13).

The neutralizer cathode must be operated at the proper flow rate and neutralizer keeper emission current to result in the nominal operating mode referred to as “spot” mode. A potentially damaging neutralizer operating condition called “plume mode” is characterized by greater than nominal neutralizer keeper voltage and greater alternating current (AC) noise in the direct-current (DC) neutralizer keeper plasma. This mode can lead to life-limiting erosion in the neutralizer. A plume mode detection circuit in each Dawn PPU converts variations in the AC component of the neutralizer keeper voltage to a DC voltage. The plume mode circuit voltage telemetry is monitored in flight to evaluate the health of the neutralizer. Dawn thruster plume mode circuit output data for each engine averaged over individual thrust segments are shown in Figure 14. In normal operation the plume mode circuit voltage increases after cathode ignition, when the neutralizer cathode is known to operate in plume mode. Plume mode circuit output then decreases to a lower, steady-state voltage during normal neutralizer operation, with the plume voltage decreasing at lower power levels and rich cathode flow rates. During all of Dawn IPS operations since launch there have been no indications of neutralizer cathode operation in plume mode after the initial start-up transients.

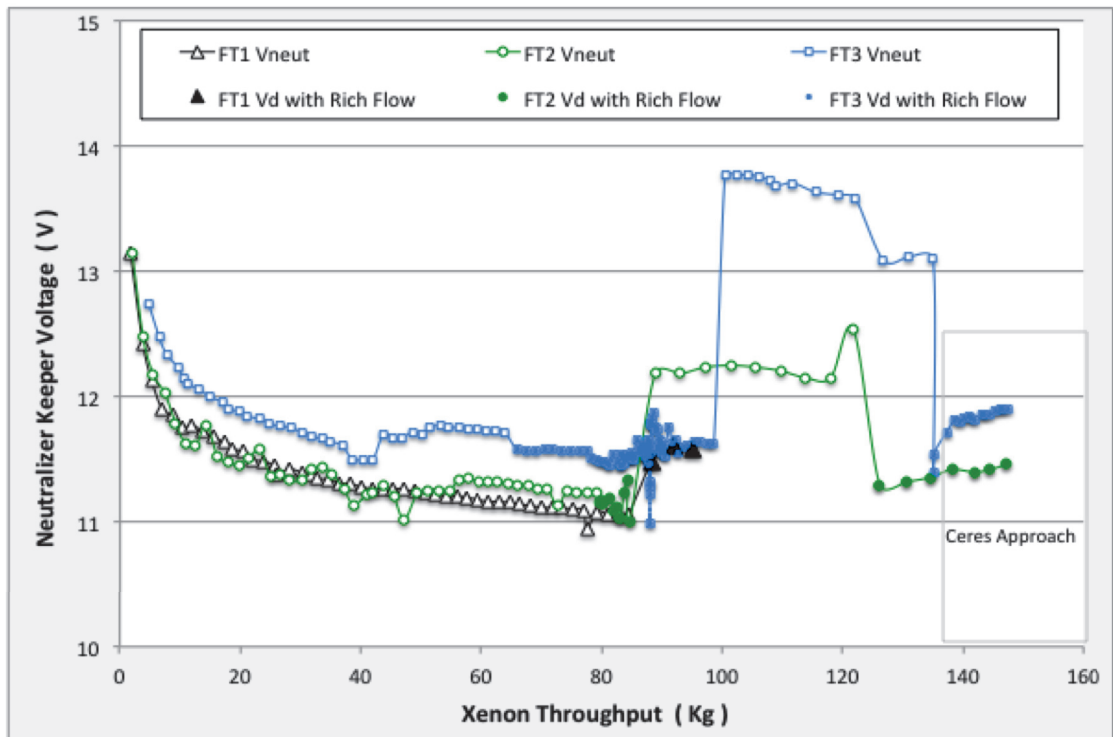


Figure 13. Dawn thruster neutralizer voltage from start of cruise to Vesta through arrival to RC3 science orbit.

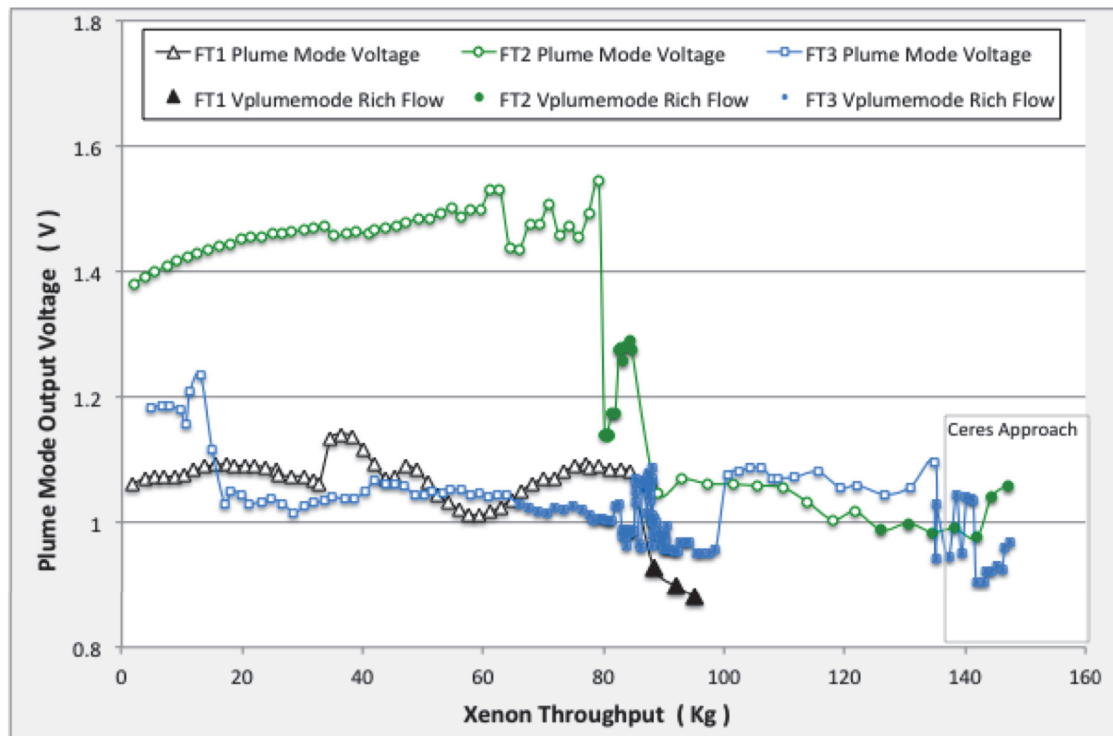


Figure 14. Dawn thruster plume mode circuit output voltage from start of cruise to Vesta through arrival to RC3 science orbit.

Accelerator Grid Current and Thruster Recycles

Accelerator grid current data for Dawn ion thrusters from start of cruise to Vesta through arrival to RC3 are plotted in Figure 15. The accelerator grid current increased during the first 1,700 hours of operation at full power and leveled off after that. This is unlike the behavior of the accelerator grid impingement current noted in the ELT [18], which started at a higher level and then decreased over a period of approximately 1,000 hours to approximately 6.5 mA after that. It appears from thruster ground testing that the higher values of the accelerator grid current are due to hole cusp wear that decreases over time as the cusps are eroded away. The accelerator grid current behavior observed during cruise is not understood at this time. The observed behavior could be a result of changes to grid-to-grid hole spacing, but there has been no indication from flight telemetry of electron backstreaming. Step changes in accelerator grid current are related to changes in thruster operating power and accelerator grid voltage. At a fixed flow rate and beam current thruster power can be finely controlled with step changes of approximately 10 V in beam voltage, which explains the step changes in accelerator grid current. All Dawn FTs have reached end of life (EOL) xenon throughput, which is defined as reaching a total thruster throughput of 70 kg of xenon. After reaching approximately 65-75 kg of xenon throughput the accelerator grid voltage was changed for each FT, from -200 V to -272 V, to provide additional margin to electron backstreaming from thruster wear. The effect of changing the accelerator grid voltage was a slight increase in beam divergence and reduced discharge loss, caused by an increase in the grid transparency to ions. Arcing or other faults can occur from grid spacing changes or from debris that bridges the gaps between the grids. The PPU is designed to clear these faults by quickly reducing discharge power, power-cycling the beam supplies, then re-establishing the discharge and beam currents to their nominal values, a process called high voltage recycling. High voltage recycles from start of cruise through arrival to RC3 are shown in Figure 16. FT1 accumulated 66 recycles, FT2 34 recycles, and FT3 64 recycles. The data indicate that after initially increasing over a period of thousands of hours of operation, recycle rates have decreased over time and with decreasing power levels. There have been very few recycles from cold starts with the thruster front masks at temperatures below -80 degrees C. There have been a very few recycles on thrusters that were unused over periods of years and then re-started.

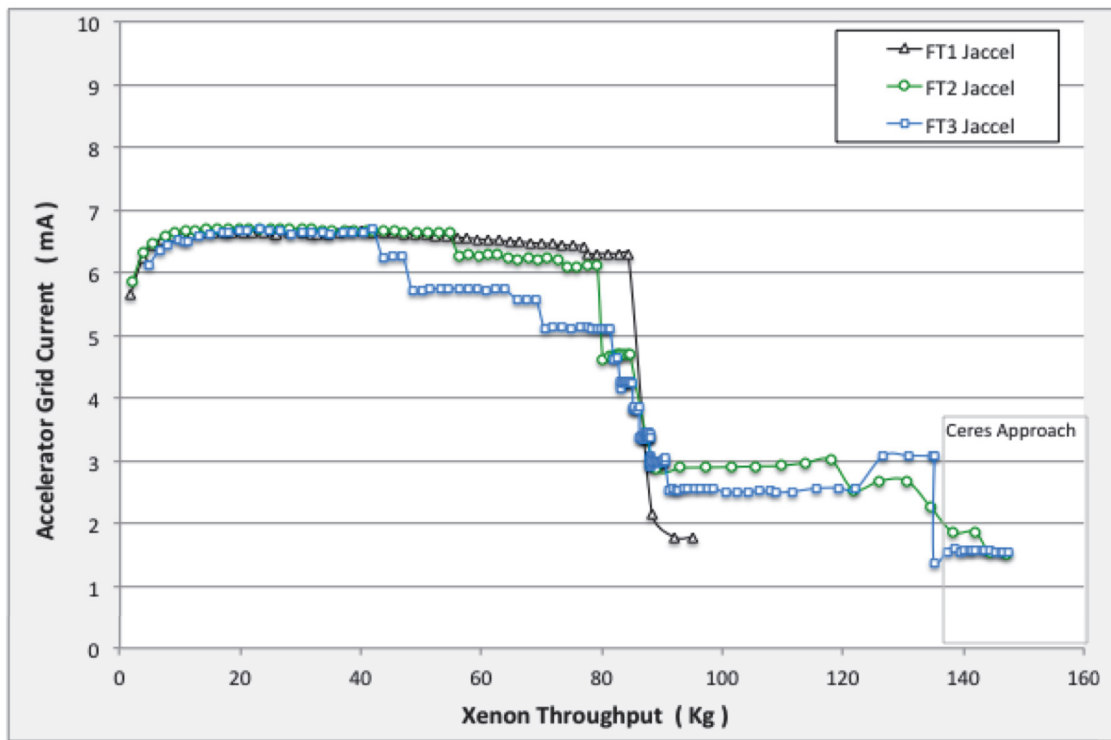


Figure 15. Dawn thruster accelerator grid currents from start of cruise to Vesta through arrival to RC3 science orbit.

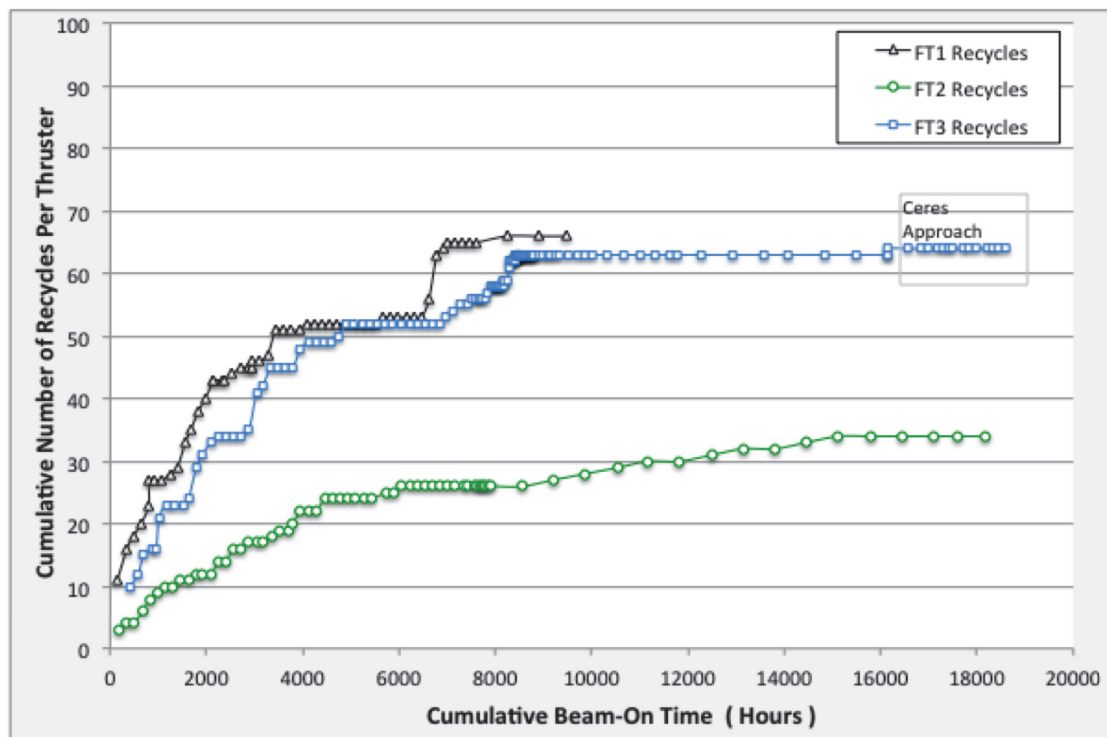


Figure 16. Dawn thruster grid recycles from start of cruise to Vesta through arrival to RC3 science orbit.

Thrust Measurements

Thrust calculated from thruster telemetry and reconstructed using navigation data as described in [20] from start of cruise to Vesta through arrival to RC3 are shown in Figures 17-19. Thrust values calculated from thruster telemetry were averaged over a time period where thruster operating parameters were stable. During approach to Vesta FT2 and FT3 were operated using full power cathode flow rates to minimize thrust variations arising from cathode flow transients which contribute to maneuver execution errors (20). During some portions of cruise to Ceres the thrusters were operated with rich cathode flow rates, and for approach to Ceres FT3 was operated with rich cathode and discharge flow rates, again to minimize maneuver execution errors. Nominal cathode flow rates were used for cruise to Ceres except for the last two thrust segments where rich cathode flow rates were used as described in the Discharge Characteristics section of this paper. With full power cathode flow rates, thrust values determined by radiometric means for each of the three engines were the same or slightly greater (by 1-2%) as values determined using thruster electrical parameters, the opposite of results from nominal cathode flow rates. At nominal cathode flow rates reconstructed thrust values were 98-99.5% of the thrust values expected from thruster electrical parameters depending upon the thruster, thruster throughput, and input power level. The Dawn mission uses a worst-case thrust degradation factor of 97% of the expected thrust for long-term planning.

During IPS operation the attitude control subsystem uses the ion thrusters to control the spacecraft in the two axes perpendicular to the thrust direction (pitch and yaw). The thrusters, however, produce a roll torque about the thruster axis that must be nulled by the RCS or the RWAs. Roll torque values have been the same or lower than pre-launch estimates throughout the mission. The combination of low roll torque values and use of the IPS for pitch and yaw control have resulted in a very small demand for hydrazine consumption during normal IPS thrusting. Hydrazine consumption during normal IPS thrusting is presently estimated to be approximately 4.4 kg for all of cruise to Ceres.

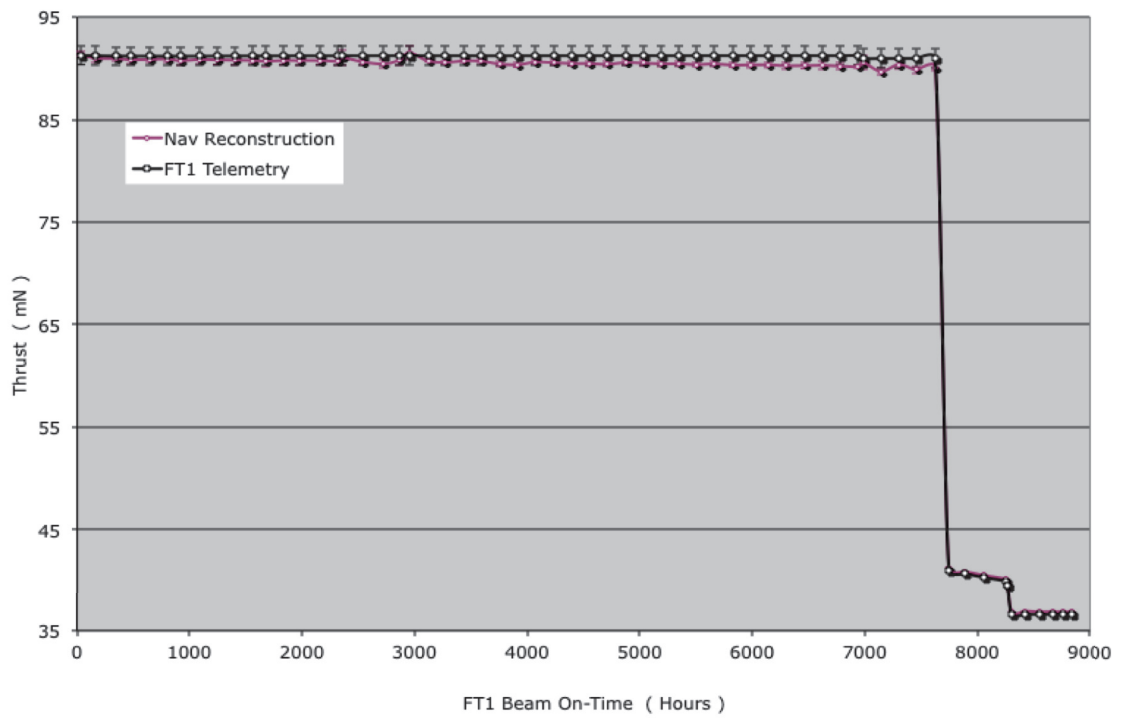


Figure 17. Dawn FT1 thrust from start of cruise to Vesta through arrival to RC3 science orbit.

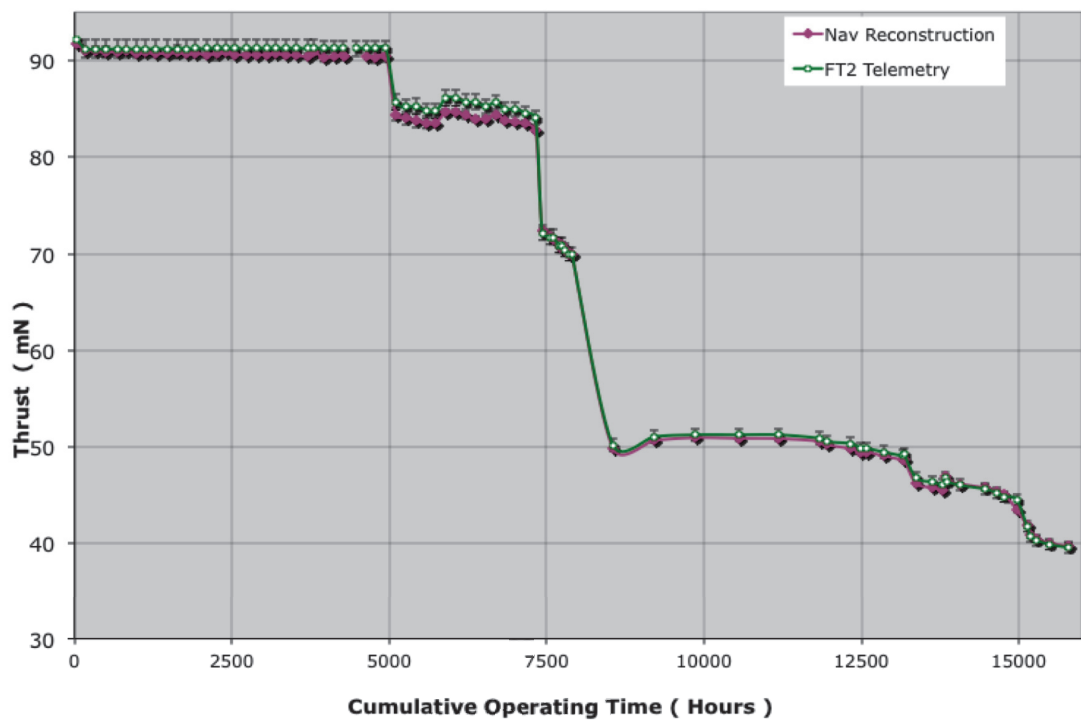


Figure 18. FT2 thrust from start of cruise to Vesta through arrival to RC3 science orbit.

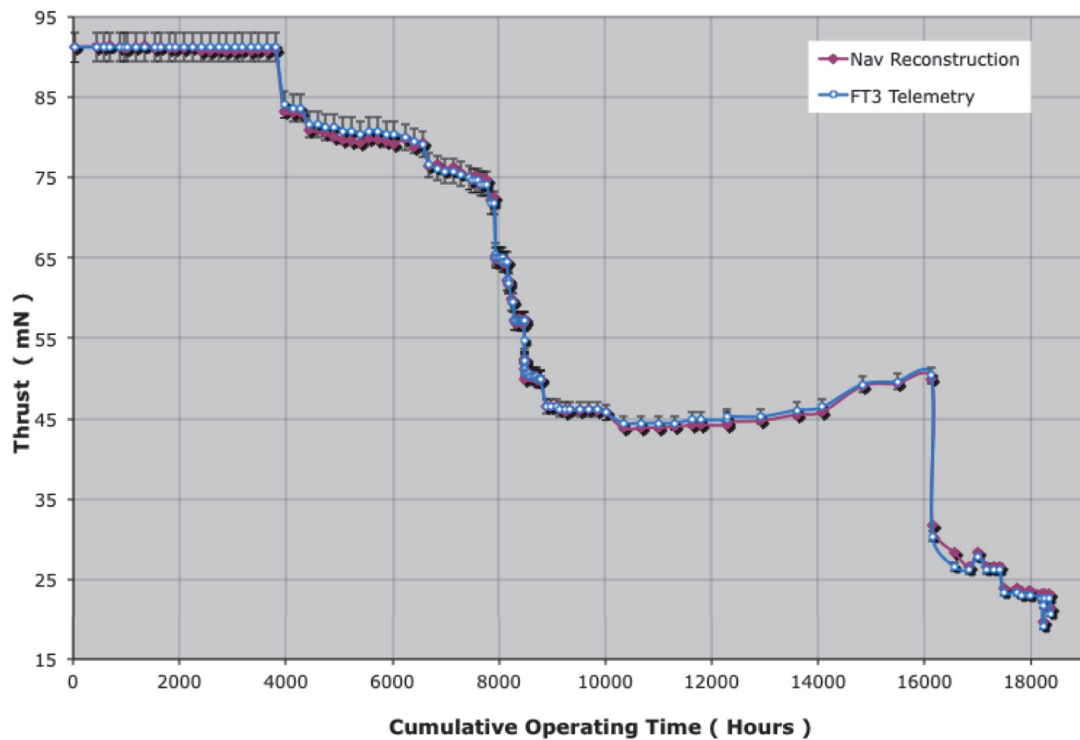


Figure 19. Dawn FT3 thrust from start of cruise to Vesta through arrival to RC3 science orbit.

DCIU Operation

The DCIUs control the PPUs and the XFS, including valve control and flow rates to the engines. The DCIUs include fault protection software to turn off the power supplies and close the solenoid valves and certain latch valves if certain fault conditions are detected. Generally one of the DCIUs is kept powered on because main xenon storage tank and plena tank pressure and temperature telemetry come from the DCIU. Only one DCIU is powered on at any time. Since being powered on during the initial check out phase in the fall of 2007 the DCIUs have been on for approximately 66,000 hours. In that time, a period spanning just over 7.5 years, the DCIUs have operated almost flawlessly. All DCIU commands were accepted and executed, and there were no operational errors, with the exception of two incidents regarding DCIU-1, one in 2011, and the other in 2014. These operational errors were likely related to Dawn's space environment. Recovery from these faults was performed quickly, and new operational plans were implemented including revising the trajectory of the spacecraft, resulting in no loss of science to the mission.

IPS Operations Plan at Ceres

A top-level summary of planned use of the IPS for orbit maneuvering and maintenance at Ceres is shown in Table 4. The Dawn spacecraft completed cruise to Ceres on December 26, 2014, entered orbit around Ceres on March 6, 2015, and completed the approach phase reaching the first science orbit at Ceres, called RC3, on April 23, 2015. RC3 is a circular, polar orbit at an altitude of approximately 13,500 km and an orbital period of about 15.3 days. Science collection included high-phase observations as Ceres is back-lit by the Sun, gravity measurements to refine the mass estimate, spin axis, spin rate, and shape, and search for plumes. In early May 2015, Dawn will be on the sun-lit side collecting full-frame observations of the fully illuminated surface. This first science acquisition phase will complete on May 9 and Dawn will then use the IPS to spiral down to the next science orbit, called Survey orbit, at an altitude of approximately

4,400 km. This is followed by transfer to the high altitude mapping orbit (HAMO), and finally to the low altitude mapping orbit (LAMO). Transfer to HAMO requires about 36 days followed by a 71 science phase. Transfer to LAMO, Dawn's final orbit, requires about 55 days followed by an approximately three month science phase. The IPS will be used for orbit maintenance in the LAMO orbit to the end of mission. The number of orbit maintenance maneuvers is expected to be low. There are no plans to move the Dawn spacecraft from its LAMO orbit.

Table 4. Summary of IPS thrusting for Ceres science orbits. Colored rows indicate activities using IPS.

Event	Time Period	Altitude Above Ceres (km)	Expected Xenon Consumption (kg)
RC3	04-23-15 to 05-09-2015	13,600	
Transfer: RC3 To Survey Orbit	05-09-2015 to 06-04-2015	13,600 to 4,400	1.9
Survey Orbit	06-04-2015 to 07-01-2015	4,400	0
Transfer: Survey To HAMO	07-01-2015 to 08-06-2015	4,400 to 1,470	2.6
HAMO Orbit	08-06-2015 to 10-16-2015	1,470	0
Transfer: HAMO To LAMO	10/16/2015 to 12-10-2015	1,470 to 375	3.9
LAMO Orbit	12-10-2015 to End of Mission	375	0
LAMO Orbit Maintenance	12-10-2015 to End of Mission	375	0.8

IV. Conclusion

The Dawn mission has successfully used its ion propulsion system for the heliocentric transfer to the main-belt protoplanet Vesta, for science operations in orbit, for departure from Vesta, cruise to the dwarf planet Ceres, Ceres approach, orbit capture at Ceres, and arrival to RC3, the first science orbit at Ceres. All the IPS components--the thrusters, DCIUs, PPU's, XCA, and TGAs—operated virtually flawlessly through arrival to RC3. To date the IPS has operated for approximately 46,239 hours with beam extraction, used just over 390 kg of xenon, and imparted a delta-V of over 10.8 km/s to the spacecraft. The IPS will provide the delta-V needed for all remaining Ceres orbit transfers and orbit maintenance until the summer of 2016 which marks the end of Dawn's primary mission. The Dawn IPS has proven to be extremely reliable and capable with very few operational problems during its over seven-year journey. The Dawn ion propulsion is presently fully operational for continued orbital operations at Ceres.

Acknowledgments

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References

- ¹ "Aerojet Redmond Operations Propulsion Capabilities", 2011-H-4231, Aerojet Corporations, June 2012.
- ² Rayman, M.D., "The Successful Conclusion of the Deep Space 1 Mission: Important Results Without a Flashy Title," *Space Technology* **23**, Nos. 2-3, p. 185 (2003)
- ³ Darnon, Franck et al., "An Overview of Electric Propulsion Activities in France," AIAA-2007-5165, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 8-11 July 2011, Cincinnati, Ohio.
- ⁴ Kuninaka, Hitoshi and Kawaguchi, Junichiro, "Lessons Learned from Round Trip of HAYABUSA Asteroid Explorer in Deep Space," IEPC-2011-1771, 32nd International Electric Propulsion Conference, 11-15 September 2011, Wiesbaden, Germany.
- ⁵ Wallace, Neil et al., "The GOCE Ion Propulsion Assembly-Lessons Learnt From the First 22 Months of Flight Operations," IEPC-2011-327, 32nd International Electric Propulsion Conference, 11-15 September 2011, Wiesbaden, Germany.
- ⁶ Killinger, Rainer et al., "Artemis Orbit Raising In Flight Experience with Ion Propulsion," *Acta Astronautica* **53** (2003) 607-621.
- ⁷ Personal communication from Kuei-ru Chien, L-3 Communications Electron Technologies Inc., Torrance, CA, May 29, 2014.
- ⁸ "Rescue In Space" by Robert S. Dudley, *Air Force Magazine*, January 2012, pgs 38-41.
- ⁹ <http://discovery.nasa.gov/>
- ¹⁰ Rayman, Marc D., Fraschetti, Thomas.C., Raymond, Carol A., and Russell, Christopher T., "Dawn: A mission in development for exploration of main belt asteroids Vesta and Ceres", *Acta Astronautica* **58** (2006), 605-616.
- ¹¹ C.T. Russell, et al., "Dawn: A Journey in Space and Time", *Planetary and Space Science* **52** (2004) 465–489.
- ¹² Brophy, John R. et al., "Dawn Ion Propulsion System-Initial Checkout After Launch," AIAA-2008-4917, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 20-23 July 2008, Hartford, CT.
- ¹³ Garner, Charles E. et al., "In-Flight Operation of the Dawn Ion Propulsion System Through the Preparations for Escape From Vesta", AIAA- 2012-4182, 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 29-August 3, 2012, Atlanta, GA.
- ¹⁴ Brophy, John R. et al., "Development and Testing of the Dawn Ion Propulsion System-", AIAA-2006-4319, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 9-12 July 2006, Sacramento, Ca.
- ¹⁵ Brophy, John R. et al., "The Dawn Ion Propulsion System-Getting to Launch," IEPC-2007-083, presented at the 30th International Electric Propulsion Conference, September 17-20, 2007, Florence, Italy.
- ¹⁶ "http://www.orbital.com/NewsInfo/Publications/StarBus_FactSheet.pdf" Star-2 Bus Fact Sheet
- ¹⁷ Rayman, Marc D. and Mase, Robert A., "Preparing for Dawn's Mission at Ceres: Challenges and Opportunities for the Exploration of a Dwarf Planet", IAC-14, 65th International Astronautical Congress, 29 September-3 October 2014, Toronto, Canada.
- ¹⁸ Sengupta, A. et al., "An Overview of the Results from the 30,000 Hr Life Test of Deep Space 1 Flight Spare Ion Engine", AIAA-2004-3608, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 11-14 July 2004, Ft. Lauderdale, FL.
- ¹⁹ Brophy, John R., "Propellant Throughput Capability of the Dawn Ion Thrusters", IEPC-2007-083, presented at the 30th International Electric Propulsion Conference, September 17-20, 2007, Florence, Italy.
- ²⁰ Garner, Charles E. et al., "The Dawn of Vesta Science", IEPC-2011-326, 32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 11-15, 2011.
- ²¹ Garner, C.E. et al., "In-Flight Operation of the Dawn Ion Propulsion System Through Year One of Cruise

to Ceres", AIAA-2013-2498, 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 14-17 July 2013, San Jose, CA.