The Dawn of Vesta Science

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The Dawn mission is part of NASA's Discovery Program and has as its goal the scientific exploration of the two most massive main-belt asteroids, 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 11.3 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. An additional 210 hours of IPS thrusting was used to enter the first Vesta science orbit, called Survey orbit, on August 3, 2011 at an altitude of approximately 2,735 km. To date the IPS has been operated for 23,621 hours, consumed approximately 252 kg of xenon, and provided a delta-V of approximately 6.7 km/s. The IPS performance characteristics are very close to the expected performance based on analysis and testing performed pre-launch. The only significant issue in over the almost four years of IPS operations in flight was the temporary failure of a valve driver board in the Digital Control and Interface Unit-1 (DCIU-1), resulting in a loss of thrust of approximately 29 hours. Thrusting operations resumed after switching to DCIU-2, and power cycling conducted after orbit capture restored DCIU-1 to full functionality. After about three weeks of Survey orbit operations the IPS will be used to transfer the spacecraft to the other planned science orbit altitudes. After approximately one year of science operations the IPS will be used for escape from Vesta and then for thrusting to Ceres with a planned arrival date at Ceres in February 2015. This paper provides an overview of Dawn's mission objectives and the results of Dawn IPS mission operations through the start of science operations at Vesta.

I. Introduction

The number of missions using electric propulsion is increasing significantly. Deep Space 1 (DS1), launched in 1998, operated its single thruster ion propulsion system for over 16,000 hours before successfully completing its mission [1]. A PPS-1350 Hall thruster was used for primary propulsion on board the European Space Agency's SMART-1 probe, with more flights planned [2]. European and U.S.-launched 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 Itokawa [3] and employed ion engines for primary propulsion.

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Dozens of communications satellites based on the Boeing 702 bus with Xenon Ion Propulsion Systems (XIPS) are now flying. The Japanese ETS-VIII uses ion thrusters for north-south station keeping. ESA's GOCE mission, launched in March 2009, employs ion propulsion for precision orbital control [4], and ESA's Artemis mission used the RIT-10 ion propulsion system for transfer to a geostationary orbit [5].

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 [6]. The combination of low-cost and short development times presents substantial challenges to an ambitious mission such as Dawn.

The Dawn mission has as its goal the scientific exploration of the main-belt asteroid Vesta and the dwarf planet Ceres for clues about the formation and evolution of the early solar system. To realize these science goals the Dawn spacecraft must rendezvous with and orbit both asteroids. Dawn is the first mission to orbit a main belt asteroid and will be the first to orbit two extraterrestrial bodies. The Dawn mission is enabled using a three-engine ion propulsion system (IPS) on-board the spacecraft which will provide most of the velocity change (ΔV) needed for heliocentric transfer to Vesta, orbit capture at Vesta, transfer to Vesta science orbits, orbit escape and departure from Vesta, heliocentric transfer to Ceres, orbit capture at Ceres, and transfer to Ceres science orbits.

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 [7]. Cruise operations for deterministic thrusting began December 17, 2007 leading to a Mars flyby in February 2009 [8], a rendezvous with Vesta in July 2011, and eventually a rendezvous with Ceres in February 2015. The end of the primary mission is scheduled for July 2015. This paper presents a summary of the Dawn mission objectives, mission plan, IPS summary, and operations through the first science orbit at Vesta.

II. Mission and System Flight Overview

The mission and flight system are described in detail in [9-11], and are summarized here. Vesta is the second most massive main belt asteroid with a mean diameter of 530 km. It is the brightest asteroid and is occasionally visible from Earth to the naked eye. Analyses of meteorites thought to originate from Vesta indicate that Vesta is a rocky body with a history of volcanism. 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 appears to have survived largely intact since its formation, with microwave measurements indicating the possibility of clay on or near the surface. Shape studies suggest it may have a large inventory of water. These features make Ceres a valuable body to investigate the materials and processes at work at the formation of the solar system. The goal of the Dawn mission is to investigate and compare these two very different bodies in the asteroid belt to answer questions about the evolution of our solar system. The science underlying the Dawn mission, as well as descriptions of the current understanding of Vesta and Ceres, have been described in detail elsewhere [8,9]. Dawn is led by its principal investigator, Dr. Christopher Russell, of the University of California, Los Angeles (UCLA), who has overall responsibility for the mission. The Jet Propulsion Laboratory (JPL) was responsible for the spacecraft 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 Sciences Corporation (Orbital), Sterling, VA, was responsible for developing the spacecraft bus, flight system integration and testing, and launch operations. The Dawn flight system is shown in Figure 1. The spacecraft is based on Orbital's STAR-2 [12] and Leostar [10] satellite platform series. The solar array (SA) consists of two large panel assemblies approximately 18 m^2 each and measuring almost 20 m tip to tip with triple junction cells providing approximately 11 kW of power at one astronomical unit (AU) and 1.3 kW for operations at Ceres. Articulation of the solar arrays is about the Y-axis.

The spacecraft attitude control subsystem (ACS) employs mechanical gyros and 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. A mass summary for the Dawn flight system is provided in Table 1.

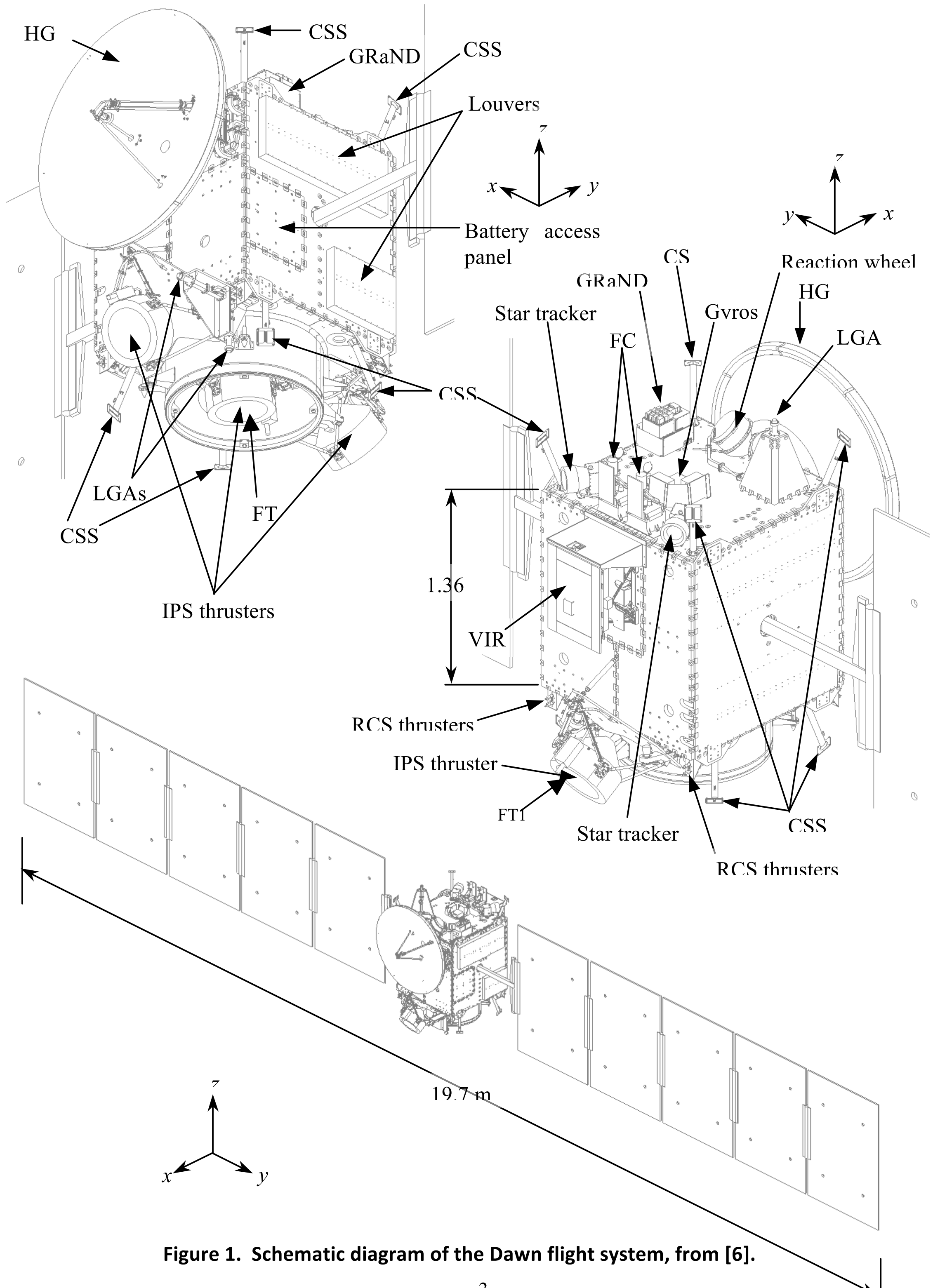

Figure 1. Schematic diagram of the Dawn flight system, from [6].

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 developed at JPL is described in detail in [13] and is shown in the block diagram in Figure 2. The IPS is based on the single-engine ion propulsion system flown successfully on the DS1 mission [14, 15], 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 PPUs, two DCIUs, 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 [15], and engineered and fabricated for flight by L3 Communications Electron Technologies (L3), Inc., Torrance, CA, with minimal modifications to their designs from DS1. The PPUs convert high voltage solar array power to the voltages and currents needed by the ion thrusters and are mounted to a plate on the –Y panel of the spacecraft with temperature controlled by the spacecraft thermal control subsystem using louvers, heat pipes, heaters, and radiators.

A titanium-lined composite-overwrap xenon tank developed for Dawn with a volume of 266 liters was mounted inside the core structure of the spacecraft and loaded with 425 kg of xenon prior to launch. 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 an XCA mounted to the outside of the spacecraft core cylinder, 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 (fixed flow orifices). It also includes 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).

Each of the three ion thrusters is mounted to a TGA with two struts to each thruster gimbal pad in a hexapod-type configuration (six struts total per ion thruster). 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 side and FT2 on the +X side. 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.

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 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.

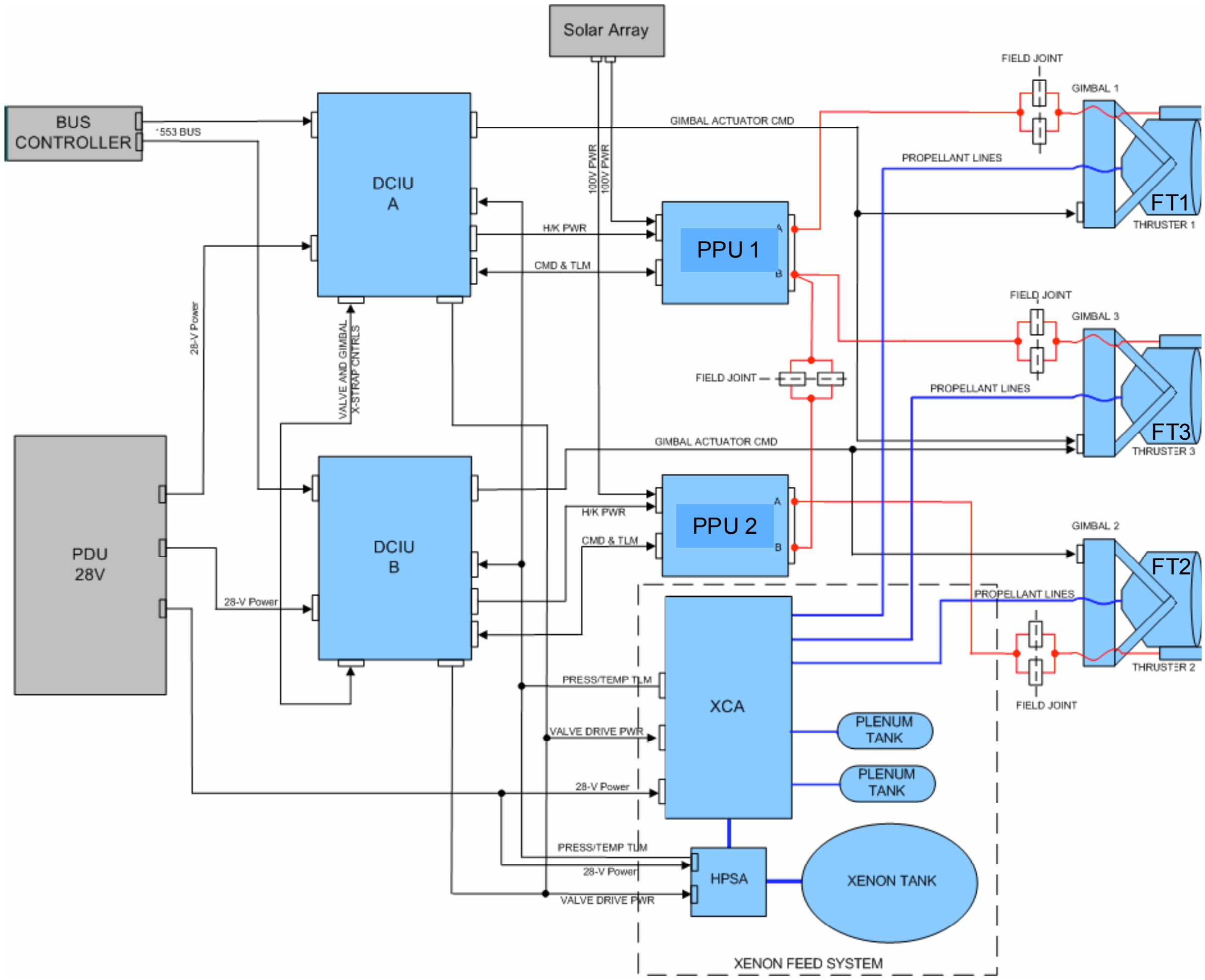

Figure 2. Simplified block diagram of the Dawn IPS.

Both DCIUs are mounted next to the PPUs to the same thermally-controlled plate on 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 [1] and 30,352 hours in an extended life test [16], however the Dawn mission requires 388 kg (Table 2) or 194 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 [13]. Analyses [17] and test data [16] 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 High Voltage Electronics Assembly (HVEA) which provides unregulated solar array power to the PPUs. Thruster 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 13.9 km/s (Table 3). The IPS will provide 11.3 km/s of this ΔV and will use approximately 388 kg of xenon for the complete mission.

Table 2. Xenon Allocation Summary

Description	Xenon Allocation (kg)
Initial Checkout	3.1
Diode Mode Operation	2.7
Xenon Allocated For Thruster Restarts	1.9
Main Tank Residuals	5.0
Leakage Allocation	10.0
Allocation for Vesta Operations	14.5
Allocation for Ceres Operations	10.5
Deterministic Interplanetary Thrusting	358.0
Margin	19.5
Total	**425.2**
Total Xenon Used Through Survey Orbit August 2011	252
Xenon Required for Cruise to Ceres	114

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 Checkout	**09/2007 - 12/2007**	**1.0 - 1.16**	**2.6**	**ΔV = 0.06 km/s**
Cruise prior to MGA	**12/2007 - 11/2008**	**1.16 - 1.40**	**2.6**	**ΔV = 1.80 km/s**
Mars Gravity Assist (MGA)	**11/2008 - 06/2009**	**1.40 - 1.60**	**NA**	**ΔV = 2.60 km/s (From MGA)**
Cruise to Vesta*	**06/2009 - 08/2011**	**1.40 - 2.26**	**2.6 -1.7**	**ΔV = 4.90 km/s**
Vesta Science Operations	08/2011 - 07/2012	2.26 - 2.51	1.7 -1.3	ΔV = 0.48 km/
Cruise to Ceres	07/2012 - 02/2015	2.51 - 2.84	1.3 -0.9	ΔV = 3.55 km/s
Ceres Science Operations	02/2015 - 07/2015	2.84 - 2.93	0.9	ΔV = 0.48 km/s

* Includes approach and insertion into Survey orbit

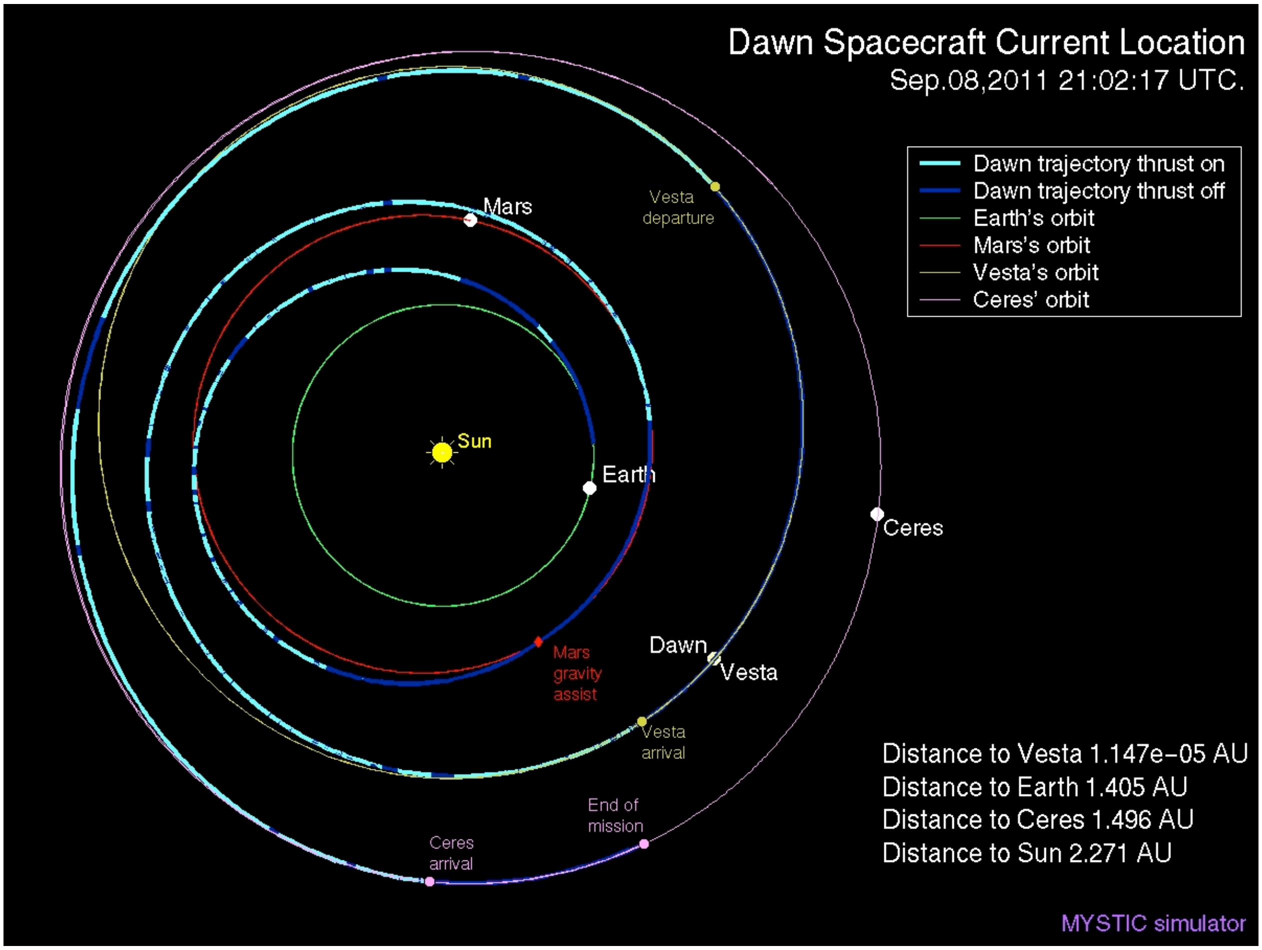

Figure 3. Dawn mission trajectory.

III. Overview of IPS Operations through Orbit Capture and Survey Orbit

The ICO, IPS operations during cruise before the MGA, the MGA, and the optimal coasting phases were all completed successfully and are discussed in detail in [18-20]. The MGA resulted in a plane change of 5.2 degrees and an increase in heliocentric velocity of 2.6 km/s. Deterministic thrusting for cruise to Vesta resumed on June 8, 2009, with the spacecraft at approximately 1.37 AU from the sun. Nominal IPS cruise operations were completed in May 2011. The goal for this phase of the mission was to modify the spacecraft's heliocentric trajectory leading to capture at Vesta in July 2011. The vast majority of this time was used for deterministic thrusting with the IPS with a small amount of time allocated for spacecraft engineering tests. The arrival date at Vesta, originally planned for September 2011, was changed to July 2011 primarily due to better-than-expected solar array performance. This allowed IPS operation at higher power and hence higher thrust levels than originally planned. The Approach phase of the mission began on May 3, 2011 and differs from cruise primarily in the number of hours per week devoted to thrusting. In cruise IPS thrusting was typically 160 hours per week, whereas in Approach the IPS is used for about 100 hours per week to allow frequent stops to perform other functions including optical navigation. Orbit capture at Vesta occurred on July 16, 2011.

Although the Dawn mission can be accomplished with just two ion thrusters, thruster operation was intentionally divided between the three thrusters to minimize wear in a single thruster. The center-mounted thruster, FT3, was used from the start of cruise in 2007 until June 2008. The thruster mounted to the –Y side of the spacecraft, FT1, was then used until January 2010 when the switch to thrusting with FT2 was made. Thrusting using FT2 was completed in December 2010, and thrusting using FT3 was resumed between December 2010 and June 2011. On June 30, in response to the DCIU-1 anomaly (discussed in more detail in a later section of this paper) operations were switched to FT2 for completion of the approach to Vesta.

IPS operation at full power was completed in August 2010 with the spacecraft at just over 2 AU from the sun when power available from the solar arrays fell below the level required for spacecraft needs and IPS full power operation. The IPS has been operated at throttled power levels since that time and will be power-throttled for the remainder of the mission. At Vesta power available to the PPUs will range between 1.9 kW to 1.4 kW. Spacecraft power utilization has been managed through spacecraft subsystem modeling and careful observations of spacecraft power demand. As a result, the fault-protection subroutine (called Autonomous Thrust Reduction), that automatically throttles down the IPS if the spacecraft detects that there is insufficient power to operate at the planned thrust level, has never been used.

During Vesta cruise the IPS was operated at a planned weekly duty cycle of approximately 95% at power levels ranging between 2.0 kW and 2.5 kW. In addition, some periods of forced coasting, typically lasting a week, were built into the trajectory for special activities such as installation of new software, instrument calibrations, or other activities not compatible with IPS thrusting. These special activities represented approximately 5% of the mission time. Thrusting periods during cruise to Vesta were divided into approximately seven-day intervals; off-times for data playbacks and command uplinks were typically allocated 8 to 9 hours per week. The seven-day thrusting intervals are referred to as thrust arcs.

IPS telemetry from the DCIU was stored every ten seconds (except during cathode ignition time periods) and retrieved during the weekly spacecraft data playbacks. During cathode ignition time periods the IPS telemetry from the DCIU was stored at approximately one second intervals so that discharge and neutralizer cathode start times (defined as the time between application of a high-voltage start pulse and cathode ignition), as well as the voltage output of the plume mode circuit could be recorded at higher data rates. Real-time telemetry at varying data rates was also available periodically. A thrust verification pass was typically performed mid-way through a thrust arc to verify that the IPS and spacecraft were operating nominally. This activity required the use of the traveling wave tube amplifier (TWTA), which uses almost 200 W, for communications to the Deep Space Network (DSN). Thrust verification passes were stopped once the mission reached the Approach phase in May 2011.

During normal operations power output from the solar arrays can be temporarily supplemented by the on-board low-voltage bus battery if the array output is insufficient to power all spacecraft needs. Until approximately April 2010 there was sufficient power generated by the solar arrays to supply all spacecraft functions (about 800 W average power), including periods of high power usage when certain spacecraft events occur (such as the simultaneous use of many heaters), and the 2.5 kW required by the IPS for full power operation.

Thruster operating time and xenon consumption from launch through orbit capture are summarized in Tables 4 and 5.

Table 4. Thruster Operating Time Summary Through July 2011*

Thruster	Initial Checkout	Cruise for MGA	Vesta Cruise	Total
	Beam On-Time (hr)	Beam On-Time (hr)	Beam On-Time (hr)	Beam On-Time (hr)
FT1	42	2909	4674	7625
FT2	22	8	7870	7900
FT3	214	3580	4131	7925
Total	**278**	**6497**	**16,675**	**23,450**

*Includes operating time for spacecraft engineering tests and maintenance activities, but does not include operating time from ground testing and discharge-only operation (diode mode).

Table 5. Thruster Xenon Usage Summary through Start of Survey Orbit*

Thruster	Initial Checkout	Cruise for MGA	Vesta Cruise	Total
	Xenon Use (kg)	Xenon Use (kg)	Xenon Use (kg)	Xenon Use (kg)
FT1	0.4	32.4	51.8	84.6
FT2	0.3	0.1	84.2	84.6
FT3	2.4	39.5	40.9	82.8
Total	**3.1**	**72.0**	**176.9**	**252.0**

* Includes xenon used for spacecraft engineering tests, maintenance activities and diode mode burns, but does not include xenon throughput from ground testing.

A. PPU Performance

Data on power to the PPUs for operation of the thrusters are plotted in Figure 4. Data points are the values for a particular thrust arc averaged over the duration of the thrust arc, which is typically approximately 159 hours. The data include telemetry for unregulated high voltage power from the solar array and include an estimate for PPU housekeeping power of approximately 20 W from the low voltage bus. For both PPUs power initially increased and then stabilized, following changes to discharge power utilization due likely to thruster wear. PPU efficiencies, which include low voltage power supplied by the DCIUs, are similar to the efficiencies measured preflight and are consistently in excess of 92% at full power. Power throttling to the thrusters began in August 2010. 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.

Data (averaged over individual thrust arcs) from temperature sensors inside the PPU are shown in Figure 5 and indicate that PPU temperatures changed little during cruise at full power, and decreased somewhat 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 20 degrees C with the thrusters operating at 1.95 kW. The fact that the PPU baseplate temperatures are near room temperature even for full power operation is a reflection of the excellent thermal heat rejection system on the Dawn spacecraft.

Power differences between the EOL throttle table and the flight data for thrusters that have processed more than 70 kg of xenon are shown in Figure 6. Total power used by the PPUs was consistently a few percent less than the pre-launch EOL throttle table values. Beam current was typically controlled to within 0.997 of the set point value, and neutralizer current and accelerator grid voltage were at the set point. Both PPUs have operated perfectly throughout the mission to date.

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 C and 25 C, and at lower power the harness connector temperatures were as low as -6 C, well within operational temperature limits -55C to +90 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.

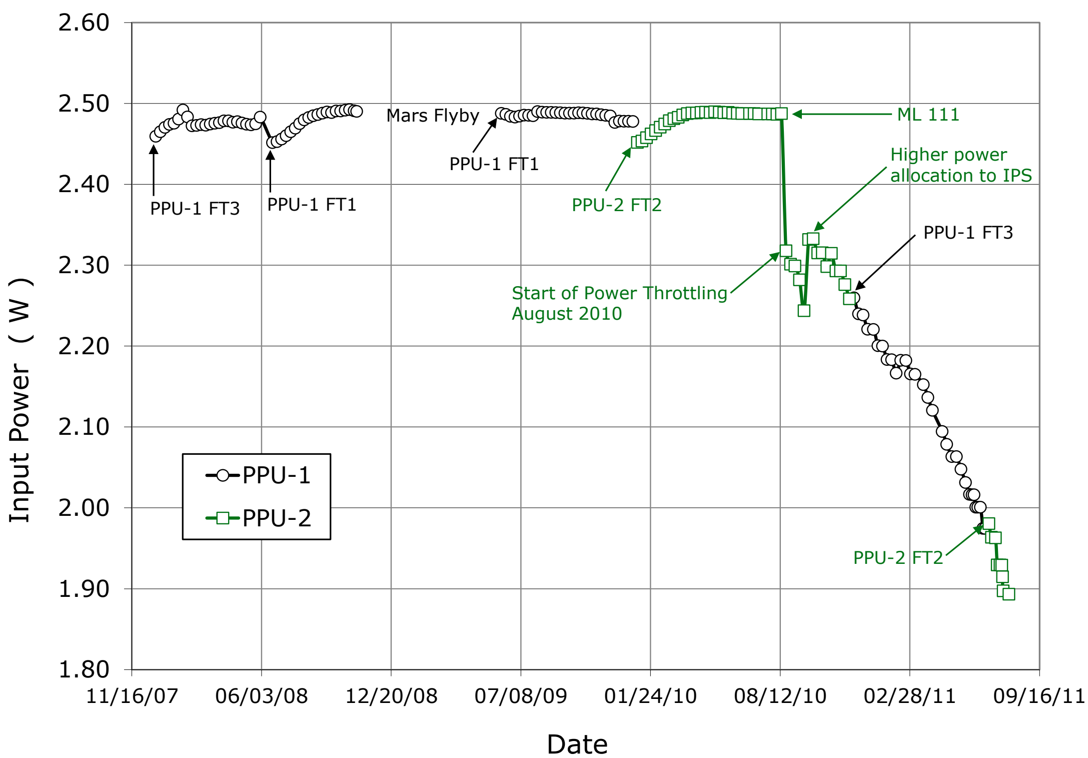

Figure 4. Input power to the PPUs through entry into Survey orbit.

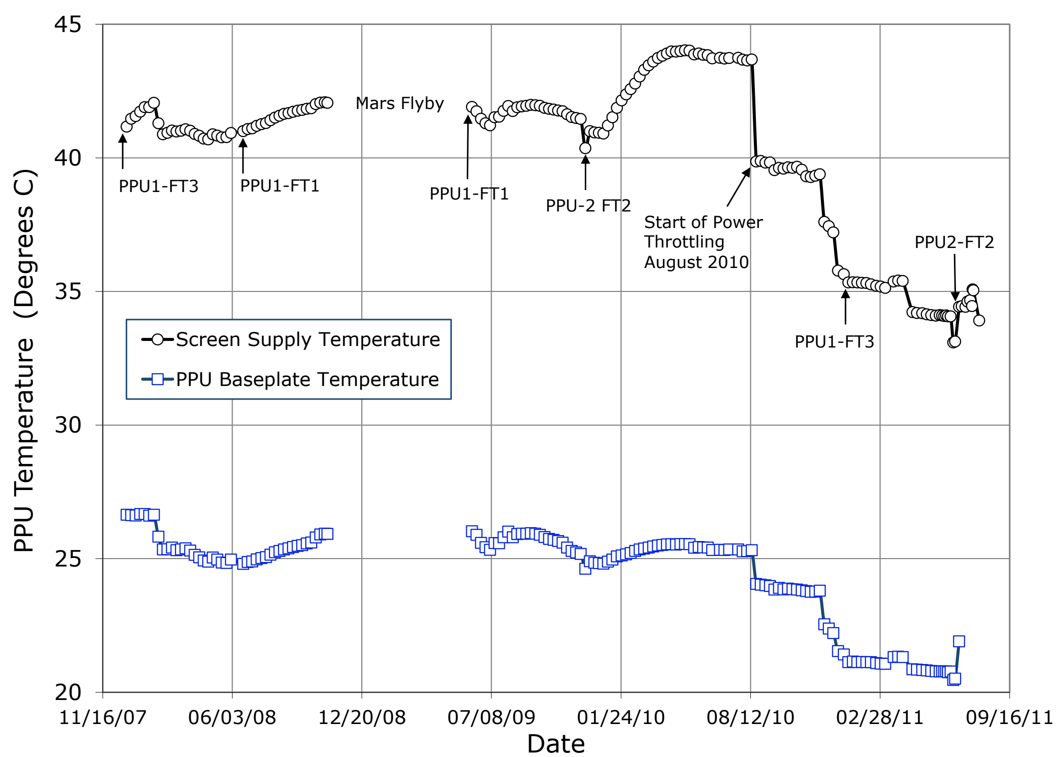

Figure 5. PPU screen supply and baseplate temperatures through entry into Survey orbit.

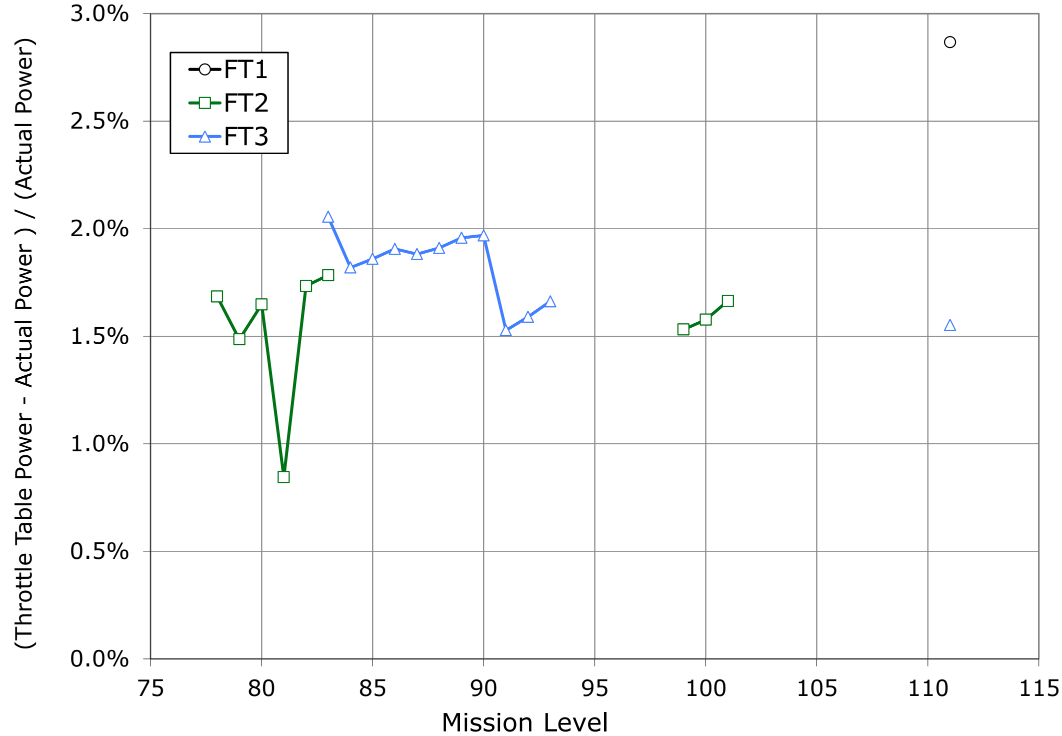

Figure 6. Actual PPU input power is a few percent less than the EOL throttle table values.

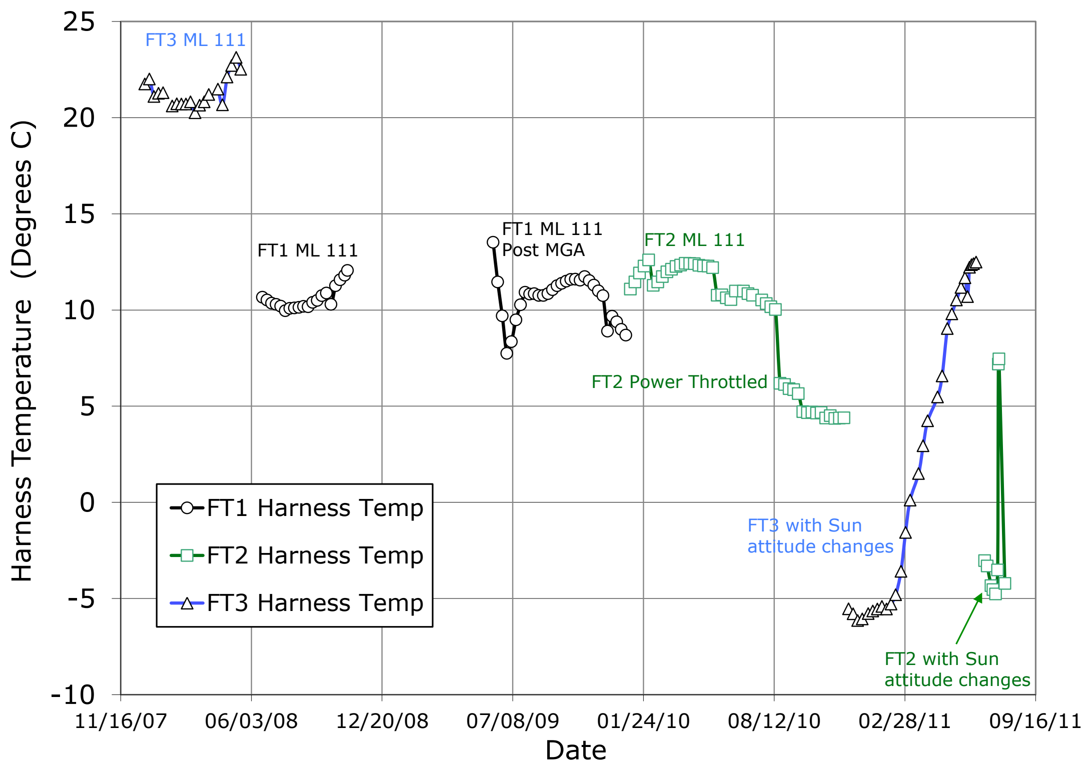

Figure 7. PPU-to-FT harness temperature through entry into Survey orbit.

B. XFS Performance

The xenon flow system has operated perfectly throughout cruise, with the exception of the slightly higher-than-expected solenoid valve cycling rates as described in [18]. These higher cycling rates do not pose a threat to the valve cycle life. 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. The uncertainty in the bulk xenon temperature and pressure 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. 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 602,000 times in cruise, and the primary solenoid valve pair for cathode plenum tank pressure regulation has cycled approximately 172,000 times (Figure 8). The solenoid valve cycling rates increase at a given throttle level as the density of the xenon in the main tank decreases. 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 [17]. There are no indications of solenoid valve or latch valve leakage based on observations of steady-state pressure measurements of the main xenon tank and both plenum tanks. Differences in pressure measurements between the three pressure transducers on each plenum tank have remained at acceptably 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.

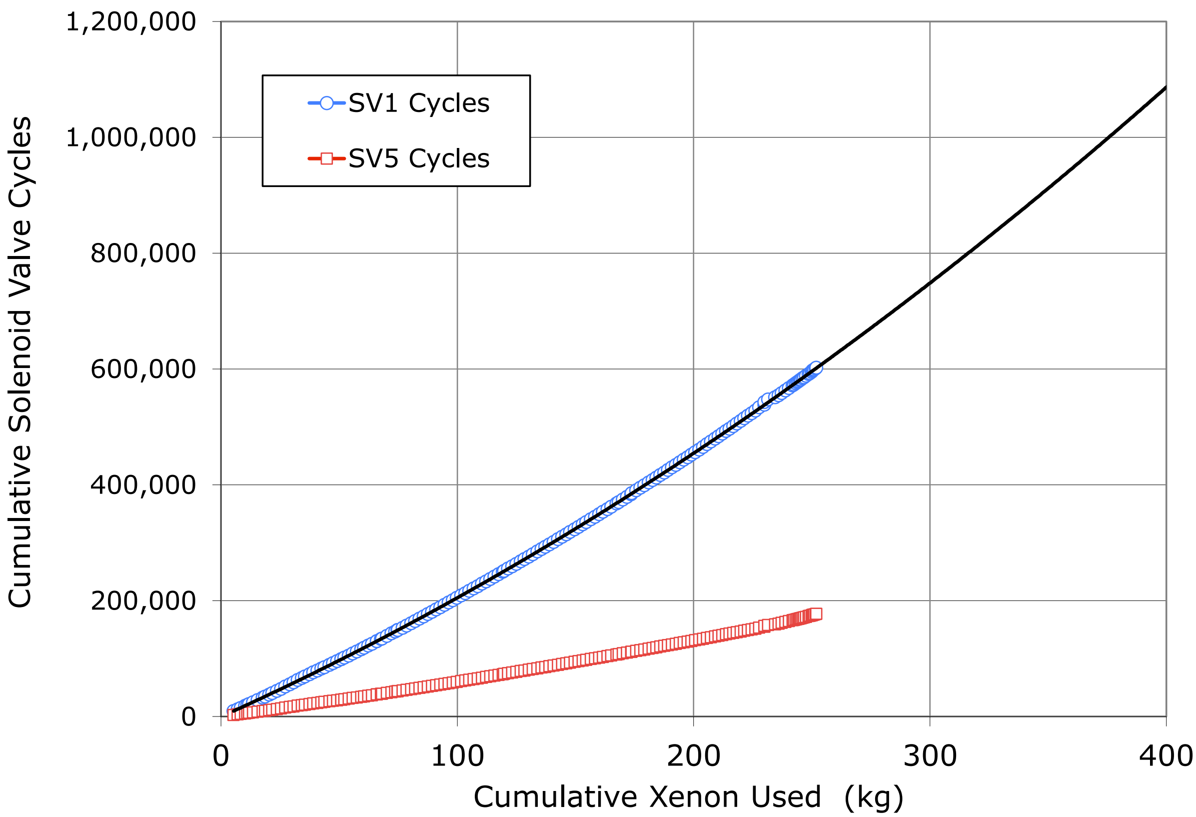

Figure 8. Cumulative open/close cycles on the main (SV1) and cathode (SV5) solenoid valves.

C. Thruster-Gimbal Assembly (TGA) Performance

The TGAs have also operated flawlessly in cruise. Each TGA consisting of two motor/tripod assemblies (side A and side B) per FT is used to position the thrust vector to control the spacecraft pitch and yaw. This mode is known as thrust vector control (TVC). RWAs or RCS hydrazine thrusters are used to control the spacecraft roll axis. Cumulative TGA actuator equivalent motor revolutions for the A-side and B-side motors for each FT are shown in Figure 9. The data indicate that the TGA motors have accumulated the equivalent of between 900,000 to over 1,000,000 motor revolutions through the start of Survey orbit. The motors were tested to 30,000,000 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 RCS attitude control starting in April 2010. In approximately May 2011 the spacecraft switched back to the wheels for attitude control as part of operations for Vesta approach and the TGA duty cycle increased substantially. (Note, FT1 was never operated with RCS attitude control and so it shows the higher duty cycle for its entire operation to date.) 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 RCS 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.

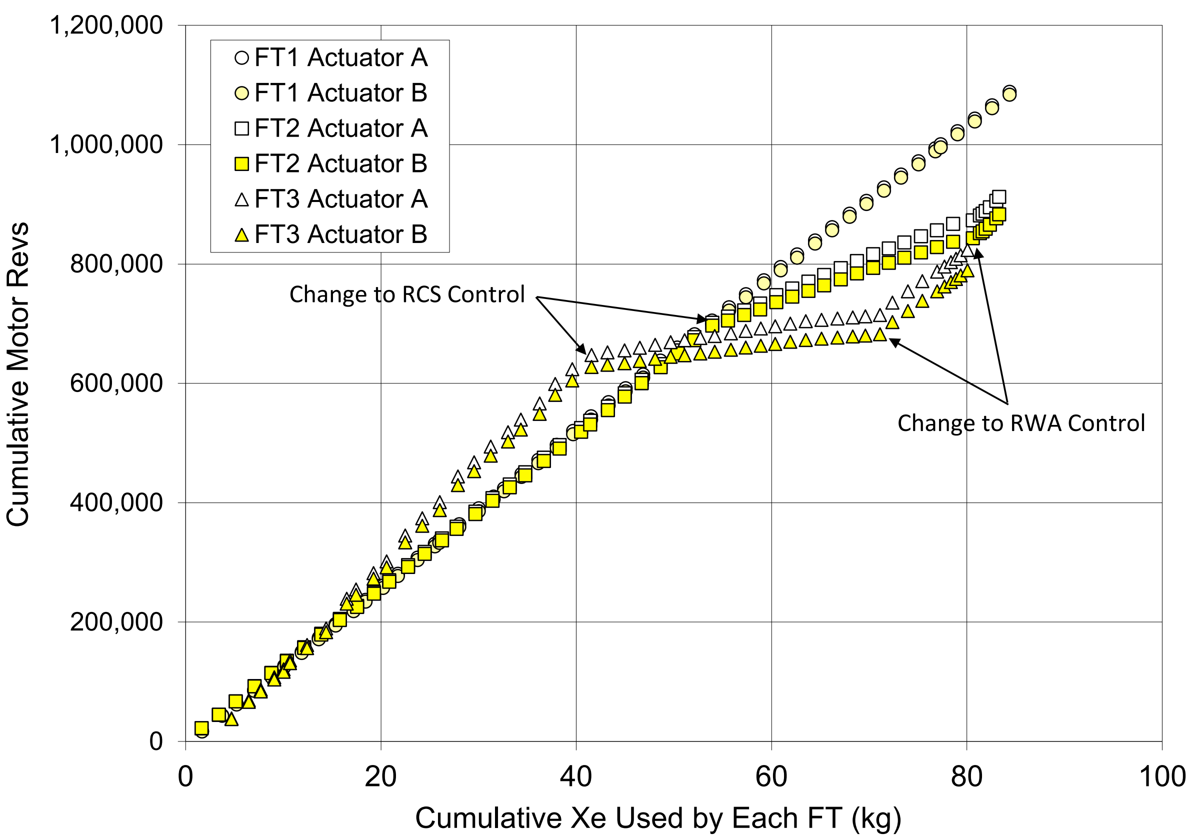

Figure 9. Cumulative equivalent motor revolutions for each thruster-gimbal assembly.

D. Thruster Performance through End of Cruise to Vesta

Detailed thruster performance data from the ICO and cruise through June 2010 were presented in [18]. 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. Beginning in March 201 the discharge cathode and neutralizer flow rates for operation of the FTs at all power levels was changed to 3.7 sccm to address the thrust stability issues that are described in the thrust performance section of this paper.

E. Thruster Starts

As of the start of Survey orbit there have been a total of 388 thruster starts in flight. FT3 has been started in flight 139 times, FT1 has been started 115 times, and FT2 has 134 starts in flight. The cathode heater preheat duration for all starts was six minutes. All thruster start attempts have been successful. Data taken at one second intervals indicate that in every start attempt in flight after the ICO, the cathodes ignited within one second of the command for application of the igniter voltage pulses.

F. Thruster Cathode Heaters

The nominal cathode heater current for both the neutralizer and discharge cathodes is 8.5 A. Thruster peak discharge cathode heater power for all thruster starts are plotted in Figure 10. Heater power at cathode ignition is affected by thruster temperature, which is a function of sun exposure, spacecraft attitude to the sun, and time from a previous thruster operation. A diode-mode preheat of the thrusters for approximately 54 minutes at approximately 250 W was performed before every start attempt.

The variation in the peak discharge cathode heater power is similar for each FT. The heater power increased by a few watts until a xenon throughput of about 40 kg and decreased afterwards. Peak neutralizer cathode heater power for all thruster starts is plotted in Figure 11. Neutralizer heater power for each FT has been increasing at a low rate since the start of cruise.

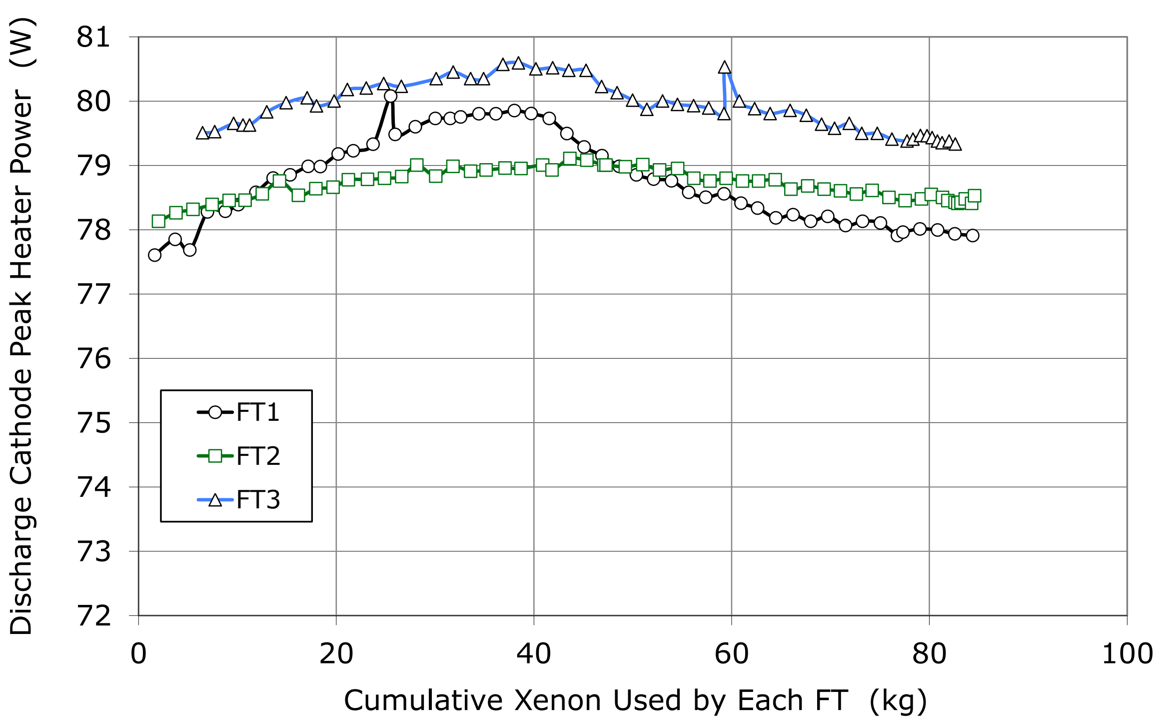

Figure 10. Peak discharge cathode heater power for each FT as a function of xenon used.

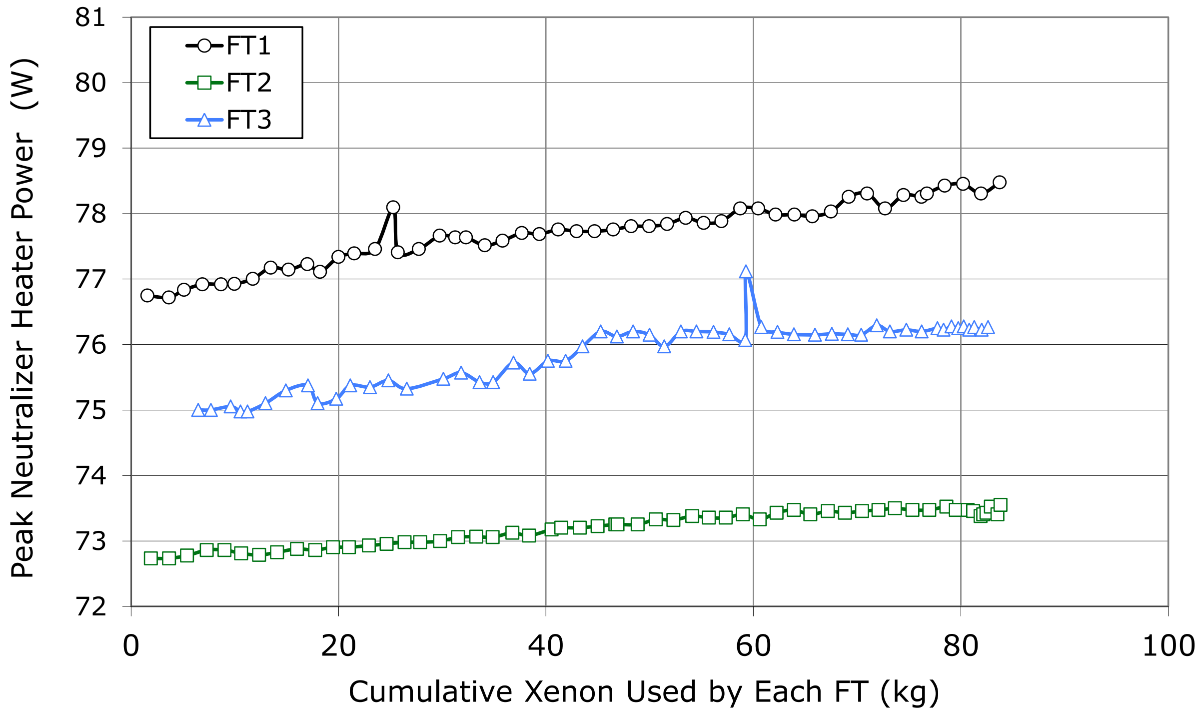

Figure 11. Peak neutralizer cathode heater power for each FT as a function of xenon used.

G. Thruster Operating Characteristics

All FTs are now using the end-of-life (EOL) throttle table, which is used once a total thruster has processed more than 70 kg of xenon. It is expected, based on extensive life testing and analysis that each FT can process at least 195 kg [17] over the Dawn mission profile. Input power to the FTs over the cruise to Vesta is plotted in Figure 12 as a function of propellant throughput for each thruster. Input power varied from about 2.3 kW at the start of cruise to 1.8 kW at the end of cruise. 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 and 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 [21]. During normal cruise operations to Vesta FT1 was only operated at full power, but FT2 and FT3 were power-throttled beginning in August 2010.

The FT operating characteristics including BOL and EOL values and performance obtained from the ICO are shown in Tables 6-8. Thruster operations at full power were conducted from December 2007 to August 2010. The thruster operating characteristics have been very stable throughout all of cruise to date, except for the changes noted below. The BOL set points for full power operation are: a neutralizer keeper current of 1.5 A, a beam current of 1.76 A, an accelerator grid voltage of -200 V, and a total engine flow of approximately 3 mg/s.

Accelerator grid current data for FT1, FT2 and FT3 during cruise are plotted in Figure 13, with each thruster showing almost exactly the same behavior. The accelerator grid current increased during the first 1,700 hours of operation at full power and then leveled off. This is unlike the behavior of the accelerator grid current noted in the Extended Life Test [22], which started at a higher level and then decreased over a period of approximately 1,000 hours to approximately 6.5 mA. 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. The step changes in accelerator grid current evident in Figure 13 are due to changes in the thruster throttle level and accelerator grid voltage. At a fixed flow rate and beam current the thruster power can be finely controlled with step changes of approximately 10 V in beam voltage, which produces the step changes in accelerator grid current.

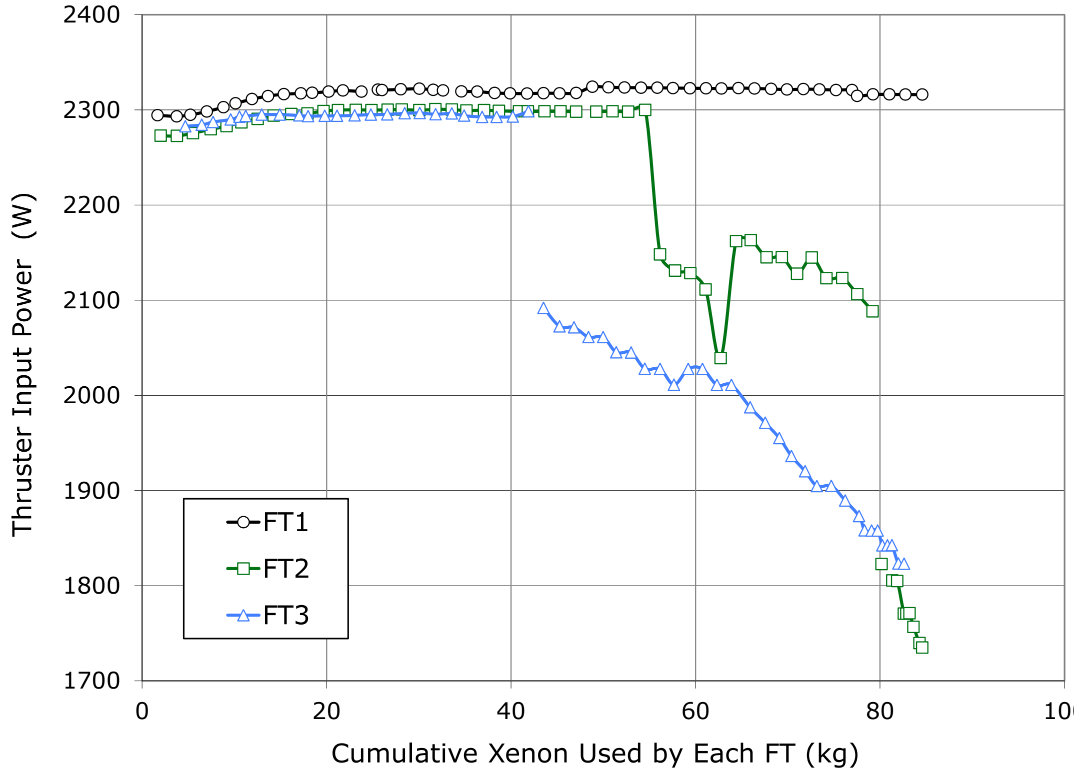

Figure 12. FT input power as a function of xenon throughput per thruster through entry into Survey orbit.

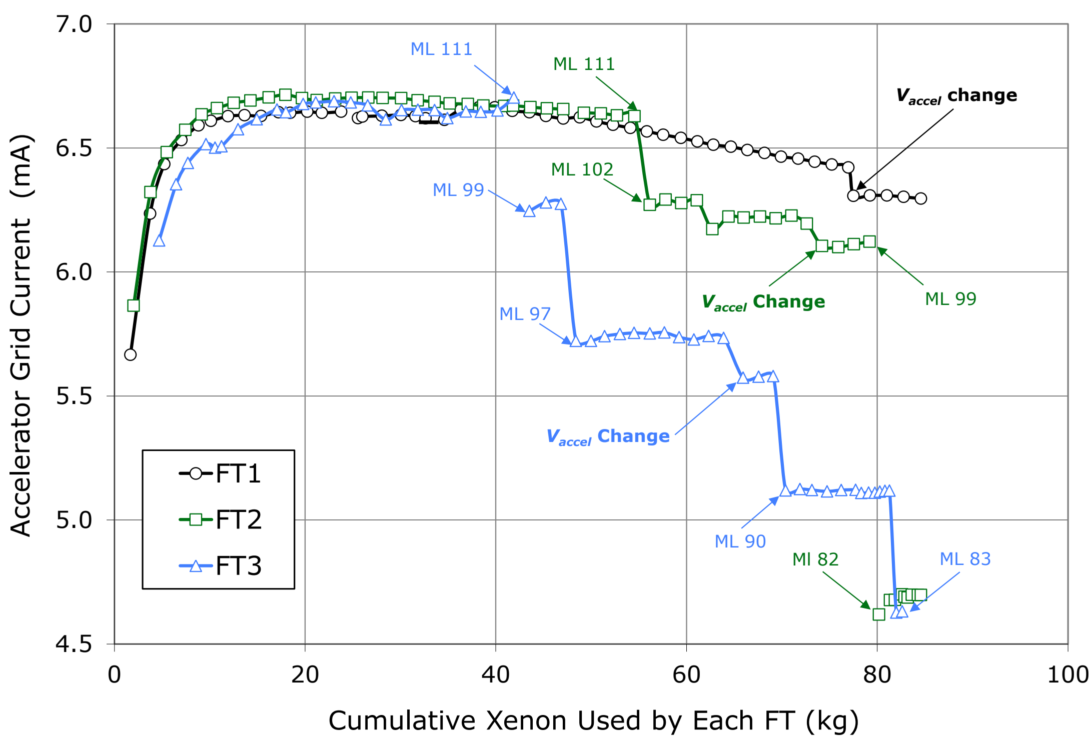

Figure 13. Accelerator grid current through entry into Survey orbit.

Table 6. FT1 Operating Summary for Cruise to Vesta.

	Beam		Accel.		Discharge			Neutralizer		PPU		
	J_B	V_B	J_A	V_A	J_D	V_D	Disch Loss	Jnk	Vnk	Input Power	Output Power	Eff.
	(A)	(V)	(A)	(V)	(A)	(V)	(eV/ion	(A)	(V)	(kW)	(kW)	
Throttle Table BOL ML 111	1.76	1100	7.1	-200	12.4	25.5	180	1.5	14.5	2.48	2.28	0.924
Initial Checkout Ml 111	1.756	1100	4.6	-200	13.1	25.0	186	1.5	13.9	2.44	2.28	0.937
Cruise-June 2008 ML 111 BOL	1.757	1100	6.1	-200	13.7	24	188	1.5	12.8	2.45	2.28	0.932
Cruise-Nov 2009 ML 111 BOL	1.757	1100	6.4	-200	15.1	24.5	211	1.5	11.1	2.48	2.32	0.936
Throttle Table EOL ML 111	1.76	1100	6.1	-270	14.7	24	200	1.5	14.5	2.49	2.33	0.924
Cruise-Jan 2010 ML 111 EOL	1.76	1100	6.3	-272	14.8	24.6	207	1.5	11.1	2.48	2.34	0.942

Table 7. FT2 Operating Summary through Entry into Survey Orbit.

	Beam		Accel.		Discharge			Neutralizer		PPU		
	J_B	V_B	J_A	V_A	J_D	V_D	Disch Loss	Jnk	Vnk	Input Power	Output Power	Eff.
	(A)	(V)	(A)	(V)	(A)	(V)	(eV/ion	(A)	(V)	(kW)	(kW)	
Throttle Table BOL ML 111	1.76	1100	5.6	-200.0	13.0	24.4	180	1.5	13.9	2.48	2.29	0.924
Initial Checkout Ml 111	1.76	1100	4.6	-200.0	13.1	25.0	186	1.5	13.9	2.44	2.28	0.937
Cruise-Jan 2010 ML 111 BOL	1.76	1100	5.9	-200.0	13.8	23.2	183	1.5	13.1	2.45	2.29	0.934
Cruise-Aug 2010 ML 111 BOL	1.76	1100	6.6	-200.0	15.0	23.2	199	1.5	11.2	2.49	2.32	0.932
Throttle Table EOL ML 111	1.76	1100	6.1	-270.0	14.6	24.0	200	1.5	14.5	2.48	2.28	0.925
Throttle Table EOL ML 78	1.40	1035	4.3	-270.0	11.1	26.1	207	1.8	14.7	1.93	1.77	0.923
Cruise-July 2011 ML 78 EOL	1.40	1034	4.7	-272.0	11.8	22.8	193	1.8	11.0	1.89	1.73	0.921

Table 8. FT3 Operating Summary through Entry into Survey Orbit.

	Beam		Accel.		Discharge			Neutralizer		PPU		
	J_B	V_B	J_A	V_A	J_D	V_D	Disch Loss	Jnk	Vnk	Input Power	Output Power	Eff.
	(A)	(V)	(A)	(V)	(A)	(V)	(eV/ion	(A)	(V)	(kW)	(kW)	
Throttle Table BOL ML 111	1.76	1100	5.6	-200	13	24.4	180	1.5	13.9	2.48	2.28	0.924
Initial Checkout Ml 111	1.756	1100	4.6	-200	13.1	25.0	186	1.5	13.9	2.44	2.28	0.937
Cruise-Dec 2007 ML 111 BOL	1.757	1100	6.1	-200	13.7	24	188	1.5	12.7	2.46	2.28	0.928
Cruise-June 2008 ML 111 BOL	1.758	1100	6.7	-200	14.6	23.7	197	1.5	11.5	2.48	2.30	0.927
Throttle Table EOL ML 111	1.76	1100	6.1	-270	14.6	24	200	1.5	14.5	2.48	2.28	0.925
Throttle Table EOL ML 83	1.4	1100	4.3	-270	10.8	26.1	201	1.8	14.7	2.02	1.86	0.923
Cruise-June 2011 ML 83 EOL	1.4	1100	4.6	-272	11.3	23.3	190	1.8	11.5	1.97	1.84	0.930

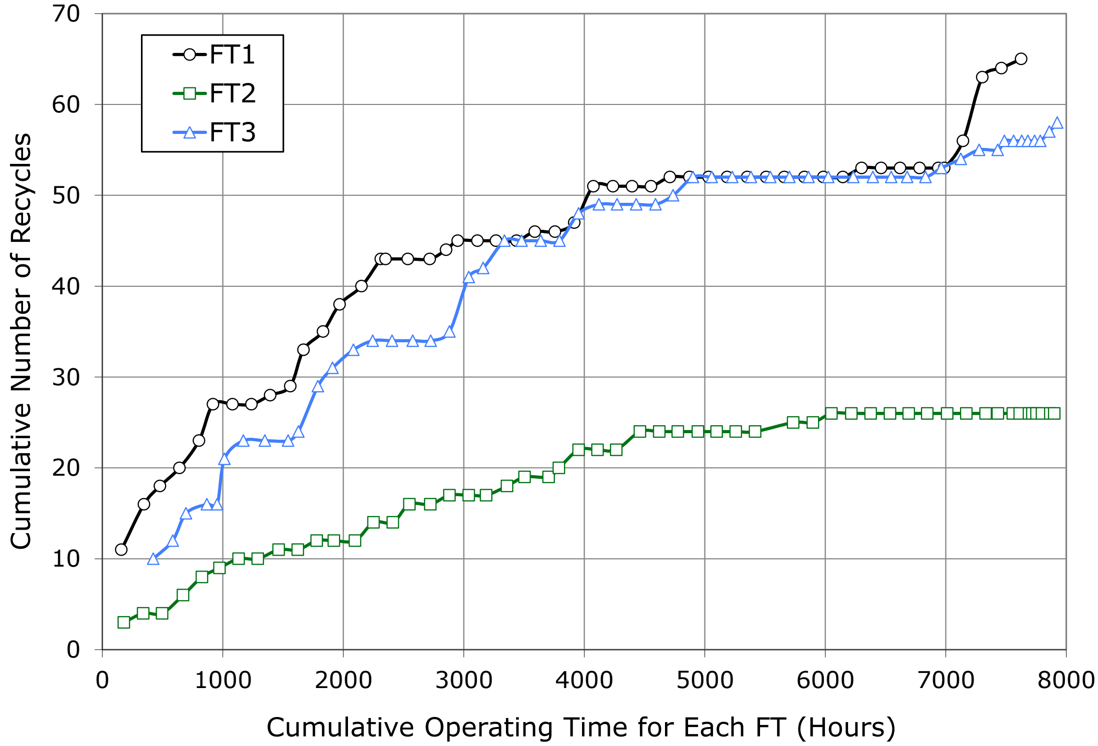

Figure 14. Recycles through entry into Survey orbit. Most operating time on FT1 and FT2 has been at full power.

The Dawn EOL throttle table decreases the accelerator grid voltage from -200 V to -272 V in order to provide additional margin against electron backstreaming as the thruster ages. The decrease in accelerator grid voltage produces a slight increase in beam divergence and a slight reduction in discharge loss. The reduction in discharge loss is caused by an increase in the effective screen grid transparency to ions due to the higher total voltage. The slight increase in beam divergence has a measurable effect on the thrust.

High voltage recycles as a function of cumulative operating time at full power are shown in Figure 14. FT3 has had 58 recycles operating for 7,925 hours during cruise for an average of 137 hours between recycles. FT1 has accumulated 65 recycles at an average of 117 hours of full-power operation between each recycle. FT2 has accumulated 26 recycles in 7,433 hours of operation for an average of 289 hours between recycles. These recycle rates are approximately two orders of magnitude better than those observed in ground life tests. Most recycles in flight occurred within a few hours after the start of beam extraction for each thrust arc. The data suggest that the recycle rate is decreasing with operating time.

Neutralizer keeper voltage data for operation of Dawn thrusters are shown in Figure 15. The neutralizer keeper voltage has decreased in a similar way for all three Dawn thrusters. These changes may be related to improved cathode conditioning over time. Neutralizer keeper voltage for FT2 has exhibited periodic excursions which then revert to more nominal values in subsequent thrust arcs.

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. Plume mode circuit output data averaged over individual thrust arcs are shown in Figure 16. In normal operation the plume mode circuit voltage increases to approximately six volts during the first approximately 30 seconds after cathode ignition, when the neutralizer cathode is known to operate in plume mode. Plume mode circuit output then decreases over a period of minutes to approximately 1.0 V to 1.5 V during normal neutralizer operation. During all of Dawn cruise operations there have been no indications of neutralizer cathode operation in plume mode after the initial start-up transients.

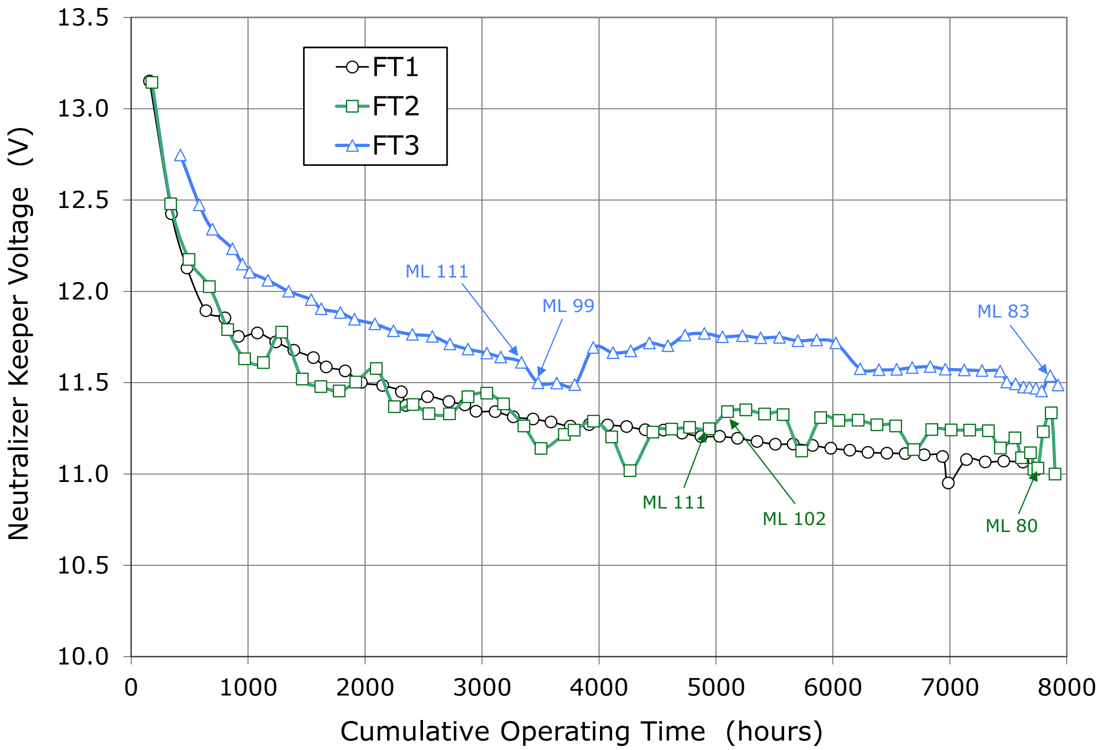

Figure 15. Neutralizer keeper voltage through entry into Survey orbit.

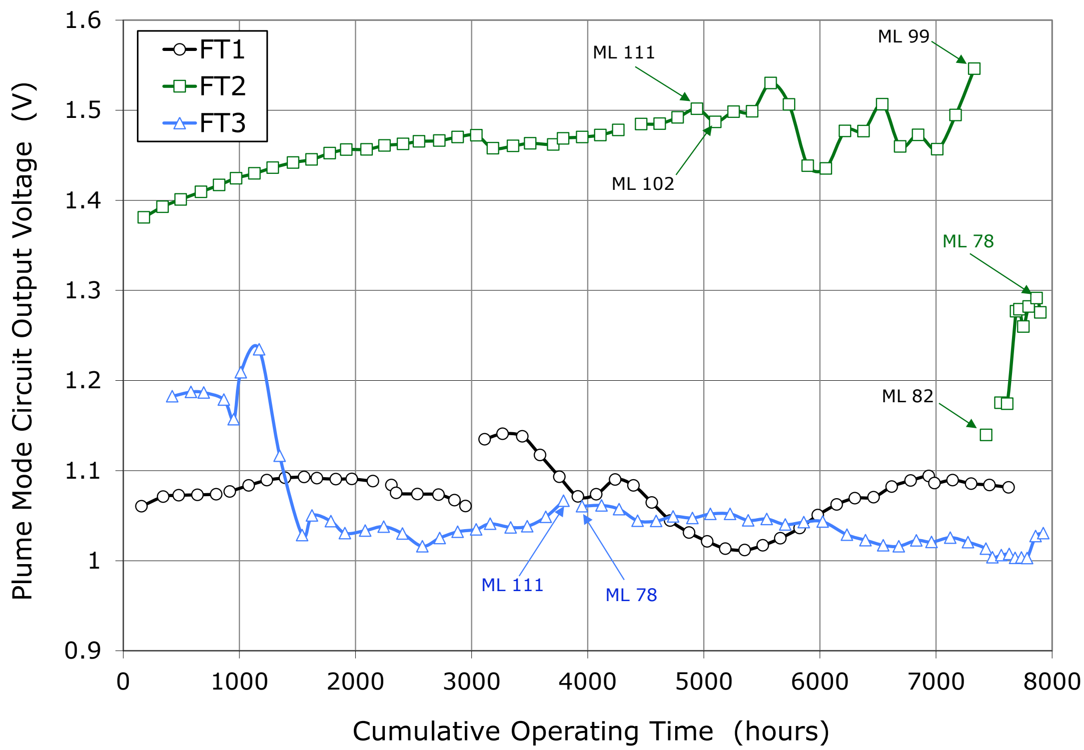

Figure 16. DC output of the plume mode circuit through entry into Survey orbit.

Discharge power and discharge loss for Dawn thrusters during cruise are shown in Figures 17 & 18. The discharge voltage is measured at the PPU and does not include the voltage drop across the harness between the thruster and PPU, which could result in a power difference at the discharge chamber of 10 W to 18 W less depending upon harness temperatures. The discharge current for FT1 exceeds that for FT2 and FT3 because during FT1 assembly two of the permanent magnets for this ring-cusp thruster were installed incorrectly.

Initially the discharge current for each FT increased until the thrusters had processed approximately 25 kg of xenon, after which the discharge current at a fixed beam current essentially did not change. The likely cause for the observed increase in discharge current is erosion of accelerator grid hole cusps resulting in a slight greater neutral propellant loss rate. Discharge power for the thrusters track somewhat to changes in discharge current. Over approximately 3,600 hours of operation at full power, the discharge power increased by 20 W for FT1, by 22 W for FT2, and by 18 W for FT3. There was a noticeable increase in discharge current for FT3 for the last two thrust arcs at ML 111 operation (approximately 6,700 hours of operation) that is unresolved.

Data on discharge loss for Dawn thrusters are plotted in Figure 18. During cruise the discharge loss increased by 15 W/A for FT1 and FT2, and 8 W/A for FT3. The discharge loss for the ELT thruster increased by 9 W/A over a similar time period in the ground life test [22]. In [21] it was proposed that discharge loss is a function of both grid hole wear and cathode keeper erosion, and during the Dawn development phase the keeper material was changed to reduce wear of this component. This fact may explain why the Dawn thruster discharge losses appeared to level out at lower operating times than observed on the ELT.

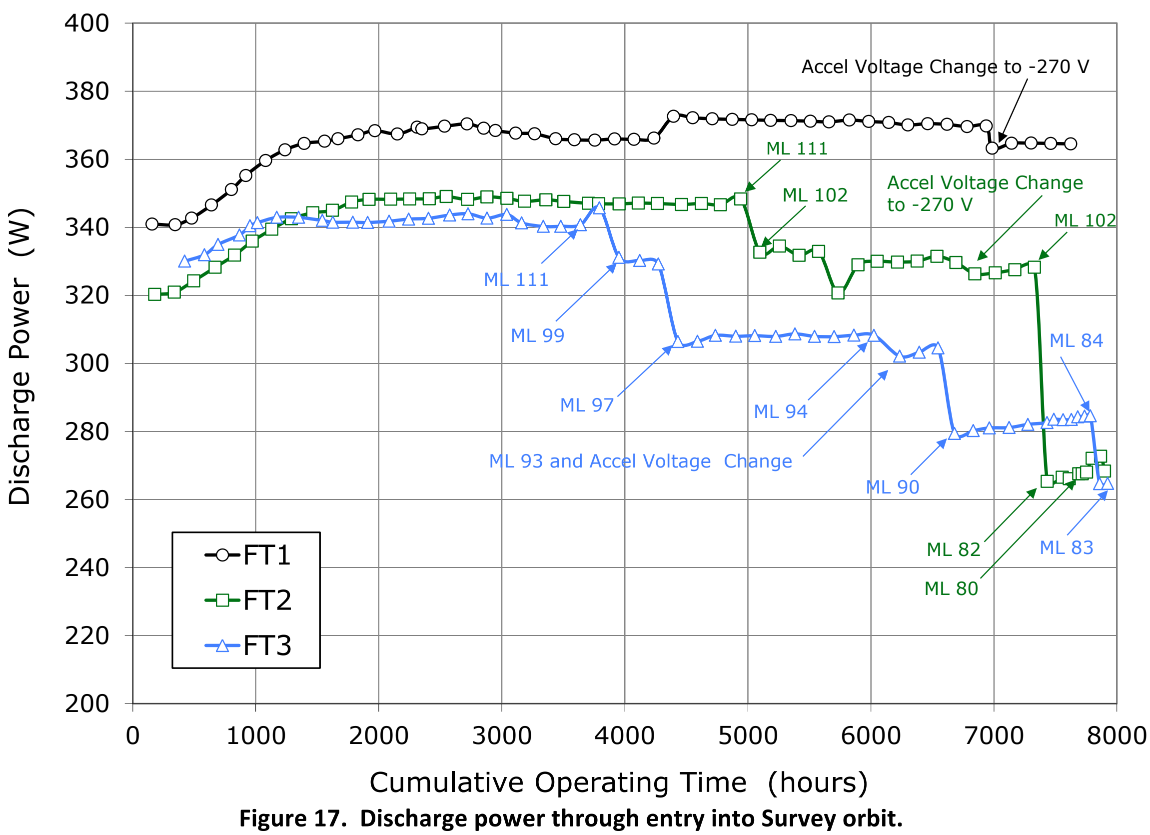

Figure 17. Discharge power through entry into Survey orbit.

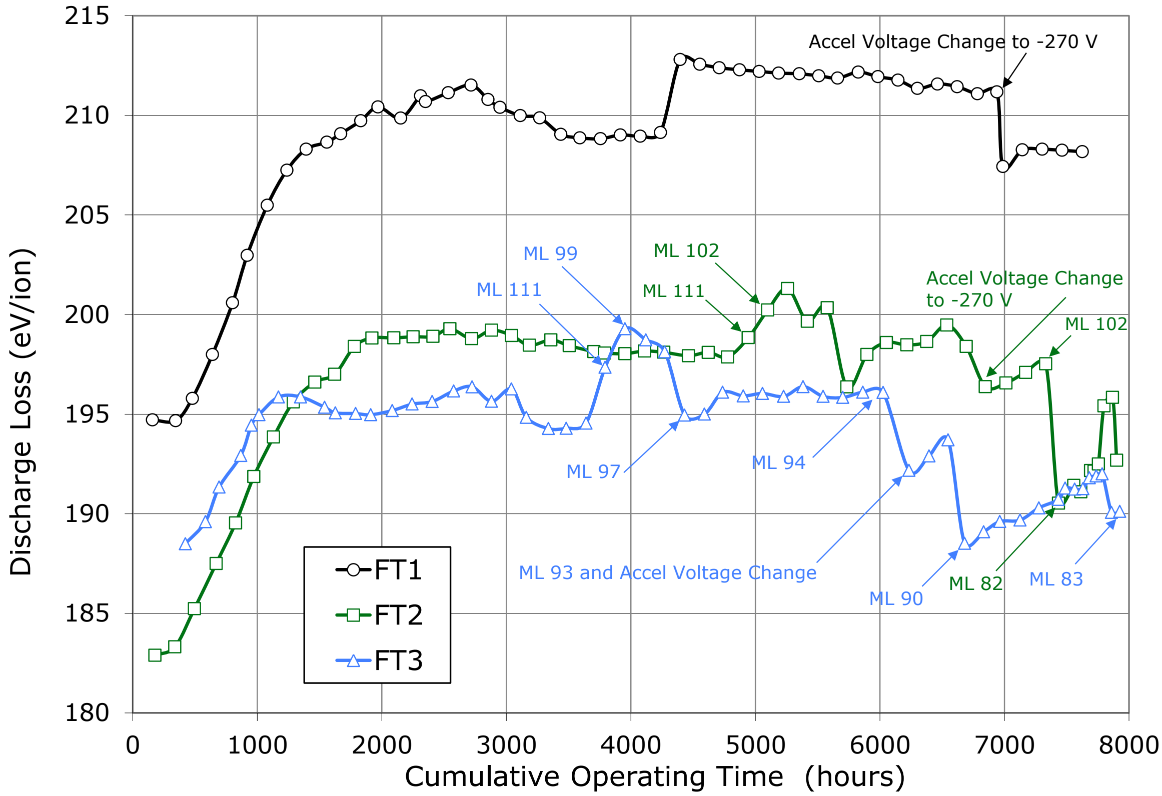

Figure 18. Discharge loss for through entry into Survey orbit.

H. Thrust Measurements

Direct thrust measurements were obtained during the ICO using changes in the Doppler shift of the radio signal from the spacecraft [7]. During cruise, thrust levels developed by the IPS are calculated from thruster telemetry and reconstructed from measurements of the spacecraft's velocity and location made between the approximately seven day thrusting arcs. Uncertainty in these thrust reconstructions is a function of the location of the spacecraft and thrust direction with respect to Earth, the presence and absence of thrusting and thrust variability over time, the ability to correct for solar pressure, effects from the RCS, pointing errors, the tracking precision of the Deep Space Network, and the number of thrust arcs included in the orbit determination process [20]. Uncertainty (1-σ) for all reconstructed thrust determinations is generally better than $\pm$0.5 mN for seven-day thrust arcs. Thrust values derived from navigation data are reproduced in Figures 19-21 along with thrust calculated from thruster telemetry. Thrust measurements made during the ICO are included for comparison. Thrust calculated from thruster telemetry are averaged over the entire thrusting period (beam on, beam off).

Reconstructed thrust values at the start of the use of each thruster (December 2007 for FT3, June 2008 for FT1, and January 2010 for FT2) generally lie within the uncertainty in thrust values calculated from thruster telemetry, but over time the reconstructed thrust values appear to decrease relative to the calculated values. The differences at full power are up to 0.5 mN for FT3, 1.2 mN for FT1, and 1.0 mN for FT2. The cause for the thrust changes over time observed on Dawn is uncertain, with possible explanations being an increase in the double ion content in the discharge chamber, an increase in beam divergence, a change in beam power telemetry, a change in the net accelerating voltage, operation at a lower than expected xenon mass flow rate resulting in a larger than expected spacecraft mass, and pointing errors through the spacecraft center of mass. Reference 22 reports a thrust decrease over time at all power levels, but the observed thrust changes could not be associated to any changes to double ion content or plume divergence changes and the thrust changes were within experimental error. For mission modeling and future orbit determinations a worst-case thrust of approximately 98% of the nominal throttle table thrust value was assumed, so the in-flight performance for Dawn thrusters provides margin to the mission.

Variation in thrust magnitude over a thrust arc is one of the major sources of error in the trajectory propagation during orbital operations at Vesta. The major source of thrust variation in the Dawn IPS is due to the start-up transient associated with the design of the xenon feed system. The thruster start-up procedure requires the flow rate of xenon through the main and neutralizer cathodes to be equal to the full power (ML 111) flow rates, about 3.7 sccm through each cathode (see Table 9). Steady-state operation at throttle levels below ML 105 requires lower cathode flow rates and correspondingly lower cathode plenum chamber pressures. Consequently, when operating at throttle levels below ML 105, there will be a period of time after start-up when the cathode flow rates are greater than the required steady-state values as the cathode plenum pressure blows down to the correct pressure. This period of time can vary from tens of minutes to several hours depending on the target throttle level. Operation with rich cathode flow rates during this transient results in a lower specific impulse, a lower discharge voltage, and fewer multiply charged ions in the exhaust. The effect on thrust is shown in Fig. 22 for start-up to ML 27. The solid line shows the cathode plenum pressure blowing down from the start-up value of approximately 34 psia to the steady-state value for ML 27 of about 23 psia over a period of about six hours. The solid red data points in this figure show the radiometrically measured thrust over this time period. These data indicate a thrust variation of about 0.4 mN during this flow rate transient. Once the plenum pressure (and hence cathode flow rate) reaches its steady-state value, the variation in measured thrust is much smaller.

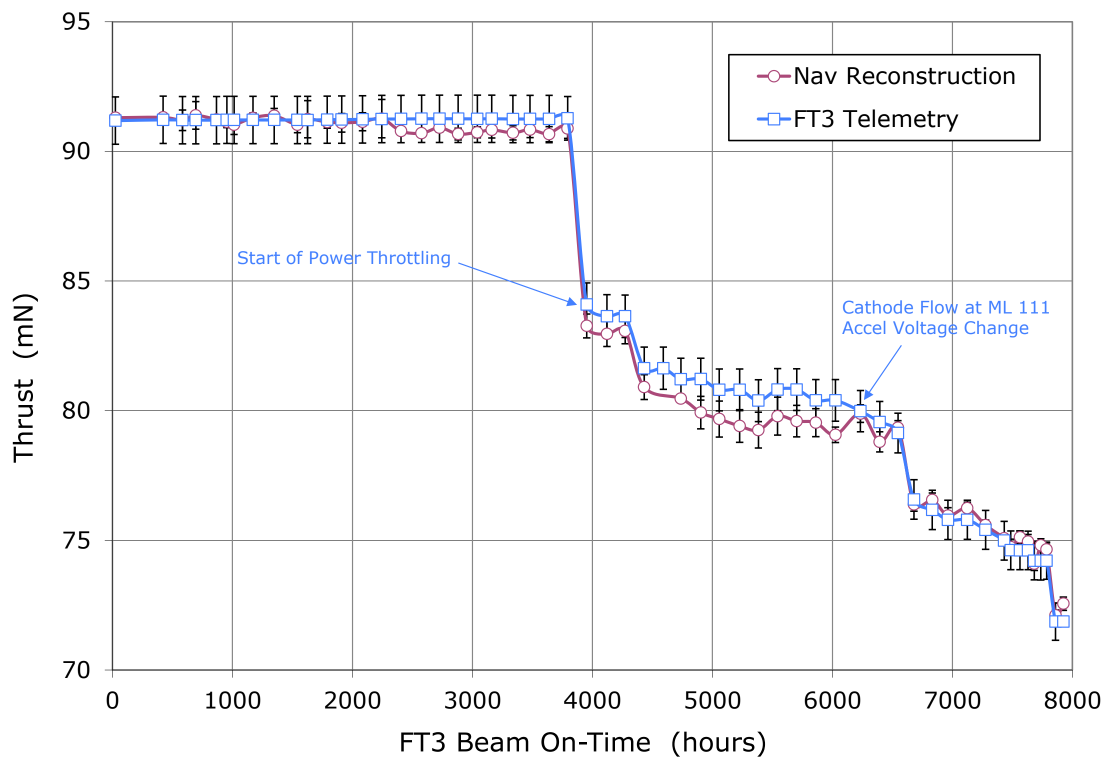

Figure 19. Thrust for FT3 through entry into Survey orbit.

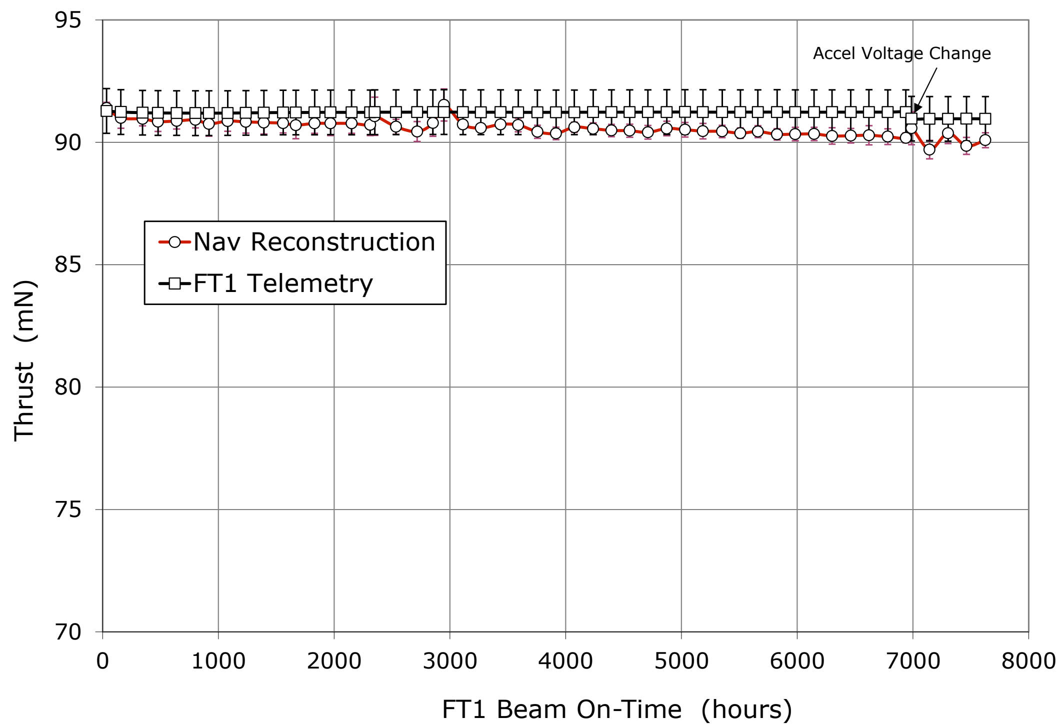

Figure 20. Thrust for FT1 during cruise.

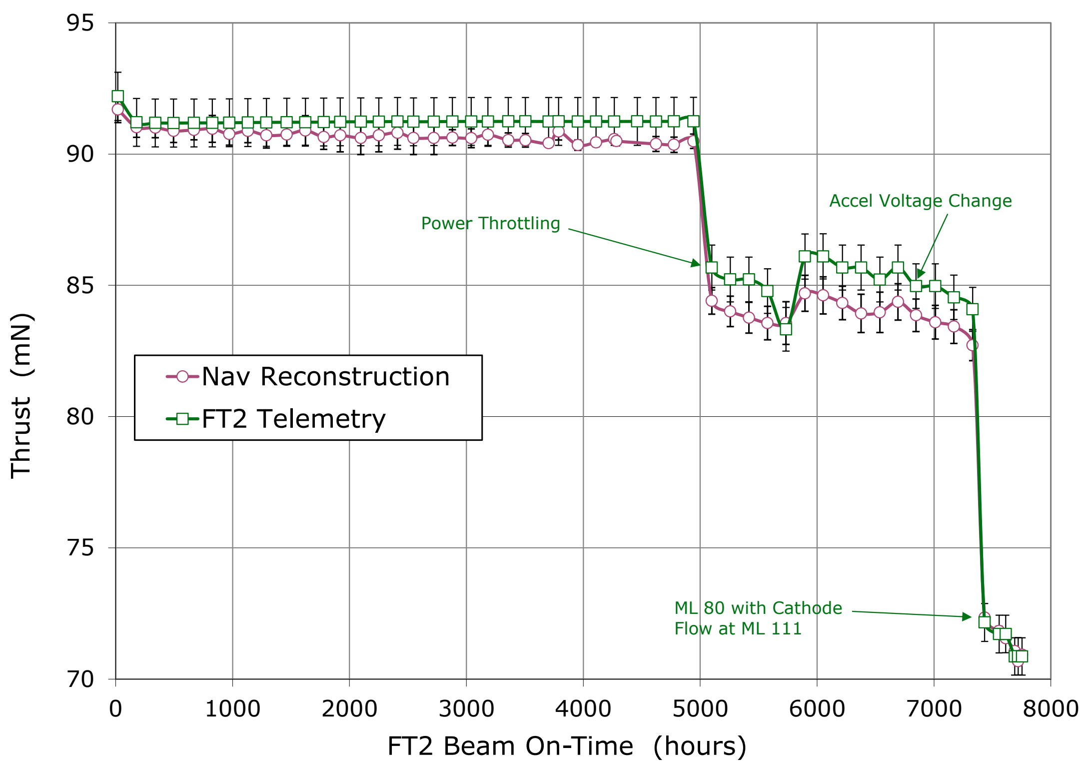

Figure 21. Thrust for FT2 through entry into Survey orbit.

Table 9. Partial EOL Throttle Table for FT3 Operating on PPU-1

Mission Level	PPU Power kW	Main Plenum Pressure (psia)	Cathode Plenum Pressure (psia)	Main Flow Rate (sccm)	Cathode Flow Rate (sccm)
105-111	2.4-2.5	66.5	34.5	23.4	3.7
98-104	2.3-2.4	62.3	31.2	22.2	3.4
91-97	2.2-2.3	58.8	28.4	21	3.1
84-90	2.0-2.2	55.5	26.9	19.9	2.9
77-83	1.9-2.0	51.4	25.3	18.5	2.7
70-76	1.8-1.9	47.5	23.9	17.2	2.6
63-69	1.6-1.8	43.8	23.1	16	2.5
56-62	1.5-1.6	39.3	23.1	14.4	2.5
49-55	1.5-1.5	34.9	23.1	12.9	2.5
42-48	1.3-1.4	30.5	23.1	11.3	2.5
35-41	1.2-1.3	26.3	23.1	9.8	2.5
38-34	1.0-1.1	22.2	23.1	8.3	2.5
21-27	0.8-1.0	18.4	23.1	6.9	2.5
14-20	0.7-0.8	16.5	23.1	6.1	2.5
7-13	0.6-0.7	16.5	23.1	6.1	2.5
0 (Discharge Only)	0.3	66.5	34.5	23.4	3.7

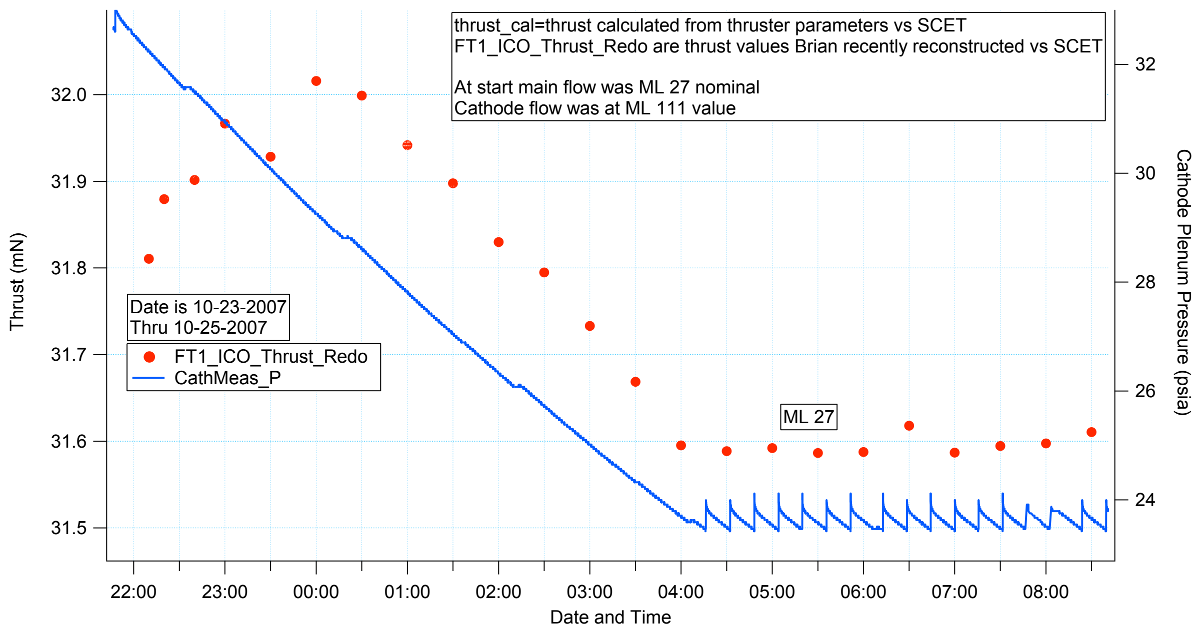

Figure 22. Thrust variation measured during the FT1 start-up transient at ML27 during ICO. Start-up main flow rate corresponded to the ML27 set point and the main and neutralizer cathode flow rates corresponded to the ML111 set points.

This transient variation in thrust had little effect on the heliocentric transfer to Vesta, but is significant enough during the Vesta orbit phase that the Project investigated low risk ways to minimize its magnitude. The selected approach was to simply maintain the cathode flow rates at the ML 111 set point for all throttle levels throughout each thrust arc. This maintained the same start-up procedure used successfully throughout the mission but eliminated the cathode flow rate variation after start-up and the corresponding thrust variation. The resulting higher than nominal cathode and neutralizer flow rates will result in increased xenon consumption. For the Vesta orbital operations this translates into 1.3 kg more xenon consumed than originally planned. The extra xenon consumption will have no impact on the mission since Dawn currently has ample propellant reserves.

Operation with rich cathode flow rates results in high-than-nominal thrust levels. To determine by how much, thrusters FT2 and FT3 were calibrated over the range of throttle levels from ML 27 to ML 83 with rich cathode flow rates as indicated in Figure 23. (FT1 was not calibrated since there were no plans to use FT1 during Vesta orbital operations.) In this figure the difference between the radiometrically measured thrust and the thrust calculated based on the thruster telemetry from the thruster using the nominal thrust-loss factor from the throttle table is plotted against throttle level. For these data the thruster was operating with main flow rates that corresponded to the selected throttle level and cathode flow rates corresponding to ML 111. Within about 0.1 mN the change in thrust is quite consistent across thrusters. The higher thrust with rich cathode flow rates is most likely due to a change in the double ion content of the beam. Complete elimination of double ions would result in a thrust increase of about 0.5 mN at ML25 increasing to about 2.1 mN at ML 83. The observed thrust increases are not this large at the higher throttle levels because the increase in cathode flow rate is relatively smaller at the higher throttle levels and is insufficient to suppress the production of all of the double ions. At ML 25 the relative increase in cathode flow rate is the greatest and it probably does reduce the production of double ions to a negligible level, but there is a smaller double ion fraction to begin with at this throttle level so the thrust increase is smaller than at the middle throttle levels around ML 50.

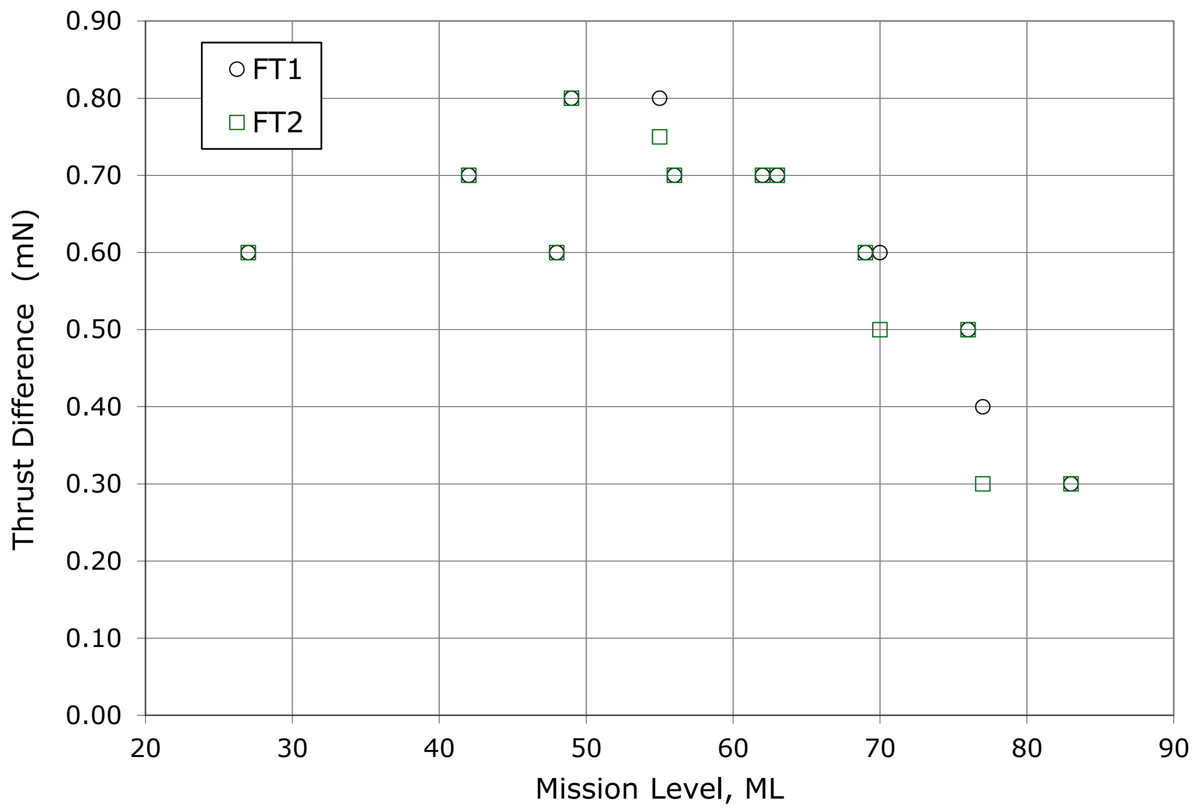

Figure 23. Thrust difference is the radiometrically measured thrust with rich cathode flow rates minus the calculated thrust determined from the throttle table assuming nominal cathode flow rates.

Thrusting with rich main flow (at constant beam current) will also increase the thrust. An example of thrust measurements made using rich main flow is shown in Figure 24 for FT3 operating at ML 83 with ML 111 cathode flow rate throughout the calibration but at a main flow rate that started at ML 111 and decreased over a period of hours to the nominal main pressure. As can be seen from the figure, initial thrust values determined radiometrically are greater than the nominal values and tracked with the main pressure (and main flow rate). Thrust values determined radiometrically reached a steady-state value of the nominal thrust plus 0.3 mN (due to rich cathode flow) when the main pressure and resulting main flow rate stabilized to the nominal value. Based on radiometric data, for a transition from one pressure family to an adjoining pressure family, for example from ML 77 to ML 76, the rich main flow resulted in a thrust increase of a maximum of 0.5 mN for FT2 and 0.7 mN for FT3. However, for both FTs operation at ML 69 using ML 111 cathode flow and ML 111 main flow rates, thrust from radiometric means was approximately 2.2 mN greater than the nominal thrust value. Complete suppression of the double ions at ML 69 would be expected to increase the thrust by about 1.9 mN.

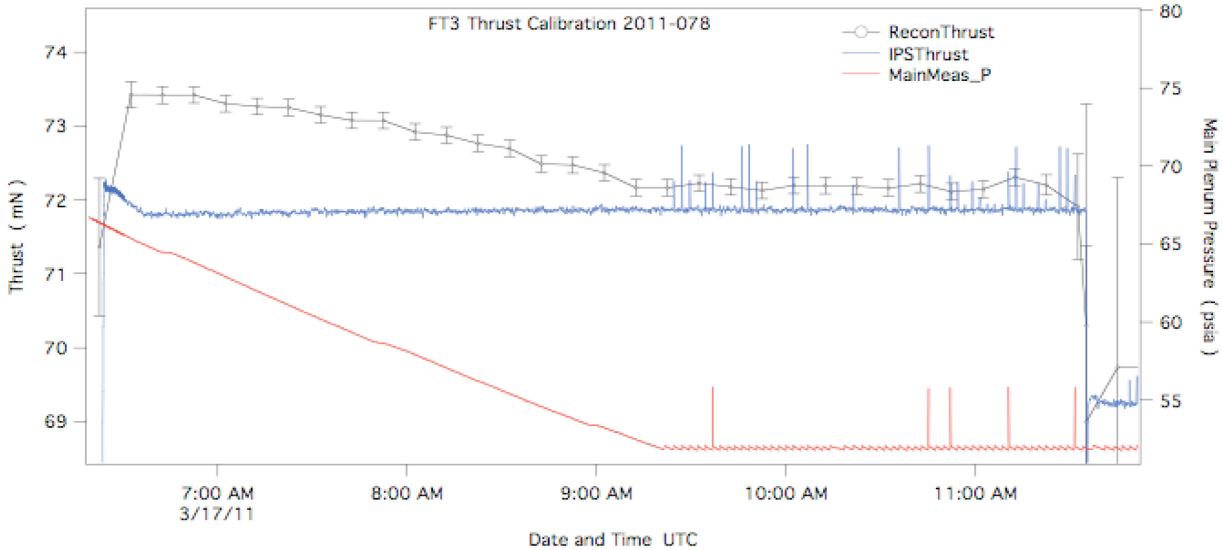

Figure 24. The decrease in thrust measured radiometrically ("ReconThrust") follows the decrease in main plenum pressure during the blow-down to the nominal main plenum pressure set point after startup.

To prevent main flow rate transients after start-up it was also necessary to modify the diode-mode pre-heat procedure. This procedure nominally is executed with both main and cathode plena pressurized to ML 111 levels. The modified procedure changed the main plenum pressure to be that corresponding to the intended throttle level after start-up. Abbreviated diode mode tests were conducted on FT3 at ML 69 and ML 83 main flow rates and ML 111 cathode flow rates. The discharge current was not changed from the 13-A nominal value under the assumption that without beam extraction the discharge chamber will still have an excessive amount of xenon even at the lower main flow rates. Test results indicate that discharge power at the nominal main flow rates, ML 111 cathode flow rates, and 13 A safely provides the necessary heating power for thruster cold starts without risk of over-heating the thruster's permanent magnet rings. Main flow rate variations after startup and the resulting thrust variations can then be eliminated. Plans are for diode modes at main flow rates to be used for upcoming thrust arcs to be implemented before the start of Vesta orbit maneuvers. Operating with diode modes at the main flow rate to be used for a thrust arc combined with operation at a fixed cathode flow rate will minimize IPS thrust transients after startup. Diode mode operation for the final two thrust arcs needed to reach Survey orbit were operated using the main flow rates needed for the upcoming thrust arcs along with a fixed cathode flow rate as described previously. Survey orbital parameters resulting from these two thrust arcs were very close to the intended orbital parameters.

I. Roll Torque

During IPS operation the attitude control subsystem uses the ion thrusters to control the spacecraft in the two axes perpendicular to the thrust direction. The thrusters, however, produce a roll torque about the thruster axis that must be nulled by the RCS or the RWAs. The magnitudes of the total external torques to the spacecraft are plotted in Figure 25. The external torque due to solar pressure is estimated to be typically a few microNewton-meters. The Dawn requirement is that roll torque can not exceed 60 μN-m at any thruster power level, which caps the amount of hydrazine required to complete the mission. Measured roll torques for the Dawn thrusters continue to meet this requirement, but as indicated in Figure 25 the magnitude appears to change as a function of time with each thruster exhibiting a different behavior. The roll torque for FT1 has changed very little over its use, while that for FT2 has increased slightly. The roll torque produced by FT3 has exhibited the largest change, decreasing by about 35% from its BOL value. Hydrazine consumption to null out the roll torque accumulated due to IPS operations is typically 40 g per week for operation at full power and 10 g per week without IPS in operation.

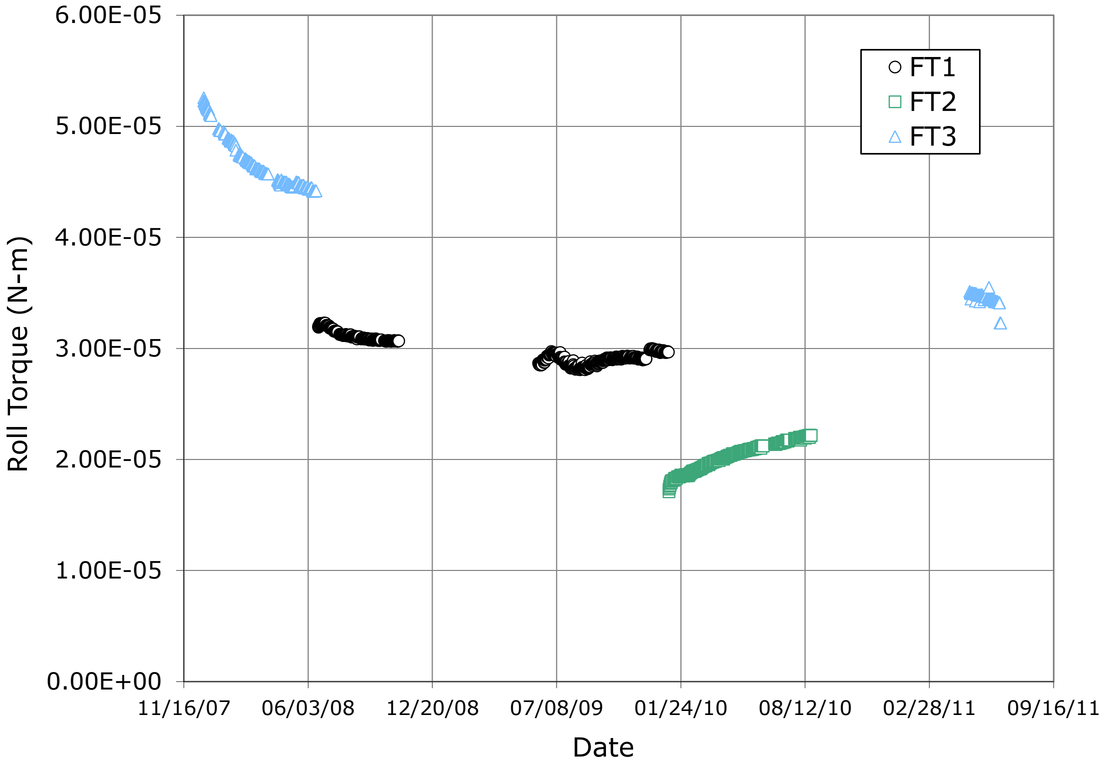

Figure 25. External torques on the Dawn spacecraft during cruise to Vesta.

J. DCIU-1 Anomaly

On June 27, 2011 the spacecraft was thrusting normally until 08:31:32 when it thrusting abruptly stopped and the spacecraft transitioned to safe mode. The fault, which was discovered one day later on a scheduled Deep Space Network track, resulted in a loss of thrusting of approximately 29 hours. A review of the IPS telemetry indicated that a 5-V valve control signal was lost causing the IPS to terminate thrusting. The 5-V signal is used in the DCIU valve driver circuits for control of all latch valves and solenoid valves in the xenon feed system. The solenoid valves are used in the bang-bang pressure regulator that maintains the plenum tanks at the correct pressures to control xenon flow to the ion thrusters. Telemetry indicated that main and cathode plenum tank pressures began to decrease as soon as the 5-V signal was lost. This was accompanied by a gradual increase in the ion thruster discharge voltage and discharge current, as well as changes in the neutralizer cathode keeper voltage, which are consistent with a decreasing of flow rate due to decreasing plenum tank pressures. The DCIU internal fault protection detected the low plenum tank pressure condition, terminated thrusting and transitioned the IPS to safe mode. In safe mode the PPU power supplies are turned off and all latch valves are commanded closed, however due to the 5-V valve driver power failure the latch valves did not close as indicated by the continued decrease in pressure in both plenum tanks. The rate of pressure decrease in the main and cathode tanks was consistent with that expected by the release of xenon through the flow control devices.

An evaluation of the rest of IPS and the spacecraft indicated that other than the 5-V valve power failure the IPS was healthy and fully functional and that the failure of the 5-V valve control power in DCIU-1 had not affected other parts of IPS. This evaluation concluded that it was safe to restart thrusting by switching to DCIU-2, PPU-2 and FT2. DCIU-1 was powered off and DCIU-2 was powered up on June 30, 2011 at 02:30. Valve closure commands are issued by the DCIUs as part of the power-up process, and telemetry indicated the valves closed as commanded. All telemetry indicated IPS was nominal and commands were issued to re-pressurize the plenum tanks. Subsequent telemetry data indicated that the solenoid valves were cycling and were successfully pressurizing the plenum tanks. The following day telemetry indicated that the plenum tanks were at their proper pressures, the solenoid valves had cycled the correct number of times for the pressurizations, and the plenum tank pressures were stable indicating the latch valves were closed. Thrusting using FT2 resumed on June 30, 2011 at approximately 19:45. The Dawn IPS is single-fault tolerant and the full mission to Ceres could be completed with DCIU-2, PPU-2 thrusters FT2 and FT3.

Analysis of the failure indicated a single event upset (SEU) transient as the likely cause of the 5-V valve control signal failure and that power-cycling the DCIU would likely restore its functionality. On July 20, 2011 DCIU-1 was restarted and telemetry showed the 5-V valve control power was nominal. Additional tests were then performed and established that DCIU-1 was once again fully functional.

IV. IPS Operations Plan at Vesta

Dawn's interplanetary ion thrusting has been designed to reshape its heliocentric orbit to match that of Vesta. Extensive thrusting in the years preceding capture by Vesta allowed the spacecraft to approach its target at very low relative velocity. Thus, in contrast to missions that use high-thrust chemical propulsion, Dawn did not have a typical planetary orbit insertion with a critical short maneuver to achieve a rapid change in the trajectory. Rather, capture by Vesta's gravity occurred during routine thrusting. The interplanetary cruise phase ended and the Vesta approach phase that began on May 3, 2011 with Dawn at a distance of 1.2 million km from Vesta. The start of approach was defined by the beginning of optical navigation. Images of Vesta and the background stars provide data for navigation, supplementing conventional radiometrics (Doppler and ranging). Initially Dawn observed Vesta weekly, and the rate increased in the middle of June 2011. Most of the approach phase was devoted to thrusting, the primary difference being that the IPS was operated at a lower duty cycle compared to normal cruise, where the duty cycle was close to 95%. The long-term trajectory design, even before launch, accounted for the reduced duty cycle associated with the optical navigation imaging (as well as the accompanying telecommunications sessions to return the data).

Along with the acquisition of optical navigation images, the principal objective of the approach phase was to continue ion thrusting to complete modifications of Dawn's heliocentric orbit and to achieve the first science orbit at Vesta, known as the "Survey orbit". The trajectory is designed to deliver Dawn to an orbital altitude of approximately 2,735 km. In addition to radius, inclination and other orbital parameters are constraints on the trajectory design, all selected to satisfy requirements from the science data acquisition strategy. Orbit capture at Vesta occurred on July 16, 2011, and the Dawn spacecraft reached Survey orbit on August 3, 2011.

Following the completion of the science observations in Survey orbit, Dawn will transfer to a lower altitude orbit in a different plane. As in the rest of the mission, all the maneuvering is accomplished by the IPS. The second science orbit, known as the high altitude mapping orbit (HAMO), is at an orbital altitude of approximately 685 km. The transfer will take four weeks. Because of uncertainties in ACS pointing of the IPS thrust, IPS thrust magnitude, thrust from the use of the hydrazine-based reaction control system to desaturate reaction wheels, Vesta's gravity field, and other perturbations, the trajectory has to be flown in relatively short segments. The integrated effect of these error sources over the course of more than a few days will be large enough to invalidate the planned thrust profile. In contrast, during interplanetary cruise, the trajectory was updated every five weeks, and the updates tended to be small.

Two of these error sources merit additional attention. Dawn is the first mission ever to orbit a massive body (apart from Earth or the Sun) which has not previously been visited by a spacecraft. Mercury, Venus, the moon, Mars, Jupiter, and Saturn all were studied with flyby spacecraft before orbiters were sent. Thus, Dawn is entering a physical environment with greater uncertainty than is typical. Although there are estimates of Vesta's mass from its perturbations of the orbits of smaller asteroids and even of Mars, its value remains uncertain, and there is no strong basis for estimating higher order gravity terms. Dawn will measure them as the spacecraft gets closer.

The attitude control system uses the IPS to control two axes of spacecraft attitude during thrusting. The third axis is controlled by reaction wheels. To rotate the thrust vector to follow the profile required to accomplish the orbit transfers, ACS commands the IPS TGA to provide the torque required for the flight system. In general, the TGA position to generate the needed torque is not the same as the position needed to aim the thrust in the required inertial direction. Therefore, the navigation design is made flexible enough to accommodate errors in the inertial thrust vector.

Based on the gravity field measured in Survey orbit, a reference trajectory will be designed from Survey to HAMO, and updates during the transfer target the spacecraft to return to the position and velocity along the reference trajectory. Therefore, the thrusting during transfers is a combination of significant components of deterministic and statistical maneuvering, the latter correcting for the error sources identified above.

After spending a month in HAMO, using the improved gravity field developed in the orbit, Dawn will begin another orbit transfer, targeting the low altitude mapping orbit (LAMO), with an altitude of approximately 200 km. (All orbital altitudes may be adjusted based on the gravity field.) Again, other orbit parameters will be changed as well to ensure optimal science data acquisition. The transfer will require about six weeks, with thrust segments being up to three days long before a revised profile of time dependent thrust attitude is generated to account for error accumulation.

Maneuvers to maintain the Survey and HAMO orbits within their requirements should be minimal, but it is likely that maneuvers in LAMO will be required weekly. Vesta, like the Moon, probably has an irregular gravity field that will perturb the spacecraft's orbit. The closer Dawn is to Vesta, the greater the perturbations will be. Moreover, reaction wheel desaturations will be more frequent in LAMO, and they will cause changes to the orbit. Windows for IPS orbit maintenance maneuvers of up to 12 hours per week are built into the LAMO plan.

In the nominal mission, Dawn will spend about two months in LAMO. The project carries 40 days of operations margin for anomalies at Vesta that cause delays in the plan. If any of the margin remains at the end of LAMO, it will be used to extend the duration of that science orbit. Following LAMO, Dawn will spiral back to the orbital altitude of HAMO, although for the second HAMO, the plane relative to the Sun will be different. Because of the progression of seasons at Vesta, this revisit of HAMO will allow the instruments to observe terrain under different illumination conditions from the first HAMO. IPS thrusting for this transfer will be fundamentally the same as for the transfer from HAMO to LAMO, but Vesta (with Dawn in obit) will have receded from the Sun in the intervening time, so the power available to the IPS will be lower. The transfer will take up to seven weeks. After spending about three weeks in the second HAMO, Dawn will spiral out to escape, leaving Vesta in July 2012 to resume interplanetary cruise.

The cruise to Ceres will be much the same as the cruise to Vesta. Cruise to Ceres will commence after escape from Vesta in July 2012 and end with a Ceres rendezvous in February 2015. During cruise to Ceres the IPS will be throttled in power from 1.37 kW at 2.44 AU to 0.9 kW upon arrival at Ceres, resulting in a total of approximately 21,000 hours of IPS operations at throttled power levels. The operations for orbit capture and transfer to science orbits at Ceres will be similar to the procedures described for Vesta orbit activities. The first science orbit at Ceres is planned for an altitude of 5,900 km, the science orbit following that is at 1,300 km, and the lowest orbit around Ceres is planned for an altitude of 700 km. By the end of the mission the IPS will have operated for a planned total of approximately 48,000 hours, and will have used 389 kg of xenon.

V. Conclusion

The Dawn mission has successfully used its ion propulsion system for the heliocentric transfer to the main-belt asteroid Vesta and for capture into Vesta orbit. It will subsequently use its IPS for transfer between science orbits and departure from Vesta, for travel to the dwarf planet Ceres, and for transfer between science orbits at Ceres. The first phase of deterministic thrusting for cruise began on December 17, 2007 and was successfully completed on October 31, 2008. This phase of the mission was followed by a planned coast phase lasting approximately seven months and included a Mars gravity assist flyby with closest approach to Mars occurring on February 17, 2009. Deterministic thrusting resumed on June 8, 2009 leading to capture at Vesta on July 16, 2011, approximately a month earlier than originally planned. The Dawn ion propulsion system is presently fully operational and has operated virtually flawlessly throughout the mission to date, accumulating over 23,200 hours of beam-on time that resulted in over 6.7 km/s of ΔV to the spacecraft. All the IPS components--the thrusters, DCIUs, PPUs, XCA, and TGAs—have operated as expected except as noted. The thruster performance characteristics are basically as expected with some exceptions, most noticeably the accelerator grid current behavior, although none of the exceptions appear to be of concern for subsequent IPS operation. The solenoid valve cycle rates are greater than expected but are not a threat to the successful completion of the mission. Thrust values measured on each thruster during cruise are slightly less than values calculated from thruster electrical parameters but above the thrust levels needed for mission success. The only significant problem to have occurred over the almost four years of IPS operations in flight was the temporary failure of a 5-V control signal in the valve driver board in DCIU-1, resulting in a loss of thrust of approximately 29 hours. Thrusting operations resumed after switching to DCIU-2, and tests conducted after orbit capture indicate DCIU-1 is completely operational. Dawn reached the first science orbit (Survey orbit) on August 3, 2011. After about one year of science operations deterministic thrusting will resume leading to a rendezvous with the dwarf planet Ceres in 2015.

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References

[1] 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)
[2] Darnon, Franck et al., "An Overview of Electric Propulsion Activities in France," AIAA-2007-5165, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 8-11 July, 2007, Cincinnati, Ohio.
[3] Kimiya Komurasaki, Kimiya and Kuninaka, Hitoshi, "An Overview of Electric Propulsion Activities in Japan," AIAA-2007-5166, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 8-11 July, 2007, Cincinnati, Ohio.
[4] Steiger, Christoph, Piñeiro, Juan and Emanuelli, Pier P., "Operating GOCE, the European Space Agency's Low-Flying Gravity Mission," AIAA-2010-2125 SpaceOps 2010 Conference Delivering on the Dream, Marshall Space Flight Center, Huntsville, Alabama, Apr. 25-30, 2010
[5]Killinger, Rainer et al., "Artemis Orbit Raising In Flight Experience with Ion Propulsion," Acta Astronautica 53 (2003) 607-621.
[6]http://discovery.nasa.gov/
[7]Brophy, John R. et al., "Dawn Ion Propulsion System-Initial Checkout After Launch," AIAA-2008-4917, to be presented at the 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 20-23 July 2008, Hartford, CT.
[8]Rayman, Marc D., and Mase, Robert A., "The second year of Dawn mission operations: Mars gravity assist and onward to Vesta", Acta Astronautica 67 (2010), 483-488.
[9]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.
[10]Rayman, Marc D., Fraschetti, Thomas.C., Raymond, Carol A., and Russell, Christopher T., "Dawn: A mission in development for exploration of main belt asteroidsVesta 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] "http://www.orbital.com/NewsInfo/Publications/StarBus_FactSheet.pdf" Star-2 Bus Fact Sheet
[13]Brophy, John R. at 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.
[14]Polk, James E. et al., "Validation of the NSTAR Ion Propulsion System on the Deep Space One Mission: Overview and Initial Results", AIAA-99-2274, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 20-24 June 1999, Los Angeles, Ca.
[15]Rawlin, Vincent K. et al., "An Ion Propulsion System for NASA's Deep Space Missions", AIAA-99-4612, AIAA Space Technology Conference and Exposition, 28-30 September 1999, Albuquerque, NM.
[16]Sengupta, Anita et al., "The 30,000-hour Extended-Life Test of the Deep Space 1 Flight Spare Ion Thruster," NASA/TP 2004-213391, March 2005.
[17]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.
[18]Garner, C.E. et al., "In-flight Operation of the Dawn Ion Propulsion System-The First Nine Months", AIAA-2008-4916, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 20-23 July 2008, Hartford, CT.
[19]Garner, C.E. et al., "In-Flight Operation of the Dawn Ion Propulsion System Through the Start of the Vesta Cruise Phase", AIAA-2009-5091, 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 19-22 July 2009, Denver, CO.
[20]Garner, C.E. et al., "In-Flight Operation of the Dawn Ion Propulsion System: Staus at One Year From the Vesta Rendezvous", AIAA-2010-7111, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 25-28 July 2010, Nashville, TN.
[21]Goebel, Dan M., Polk, James E., and Mikellides, Ioannis G., "Ion Thruster Performance Impacts Due to Cathode Wear", AIAA-2009-5095, 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, August 2-5, 2009, Denver, CO.
[22]Sengupta, Anita et al., "The 30,000-Hour Extended-Life Test of the Deep Space 1 Flight Spare Ion Thruster," NASA/TP 2004-213391, March 2005.
[23]Polk, James E., Brinza, D., Kakuda, R.Y, Brophy, J.R., Katz, I., and Anderson, J.R., , "Demonstration of the NSTAR Ion Propulsion System on the Deep Space One Mission", IEPC-01-075, 27th International Electric Propulsion Conference, October 15-19, 2001, Pasadena, CA.