In-Flight Operation of the Dawn Ion Propulsion System Through Year One of Cruise to 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 asteroids, 4 Vesta, and the dwarf planet 1 Ceres. The Dawn spacecraft was launched from the Cape Canaveral Air Force Station on September 27, 2007 on a Delta-II 7925H-9.5 rocket that placed the 1218-kg spacecraft into an Earth-escape trajectory. On-board the spacecraft is an ion propulsion system (IPS) developed at the Jet Propulsion Laboratory which will provide an additional delta-V of approximately 11 km/s for the heliocentric transfers to each body and for all orbit transfers including orbit capture/escape and transition to the various science orbits. Deterministic thrusting to Vesta began in December 2007 and concluded with orbit capture at Vesta in July 2011. The transfer to Vesta included a Mars gravity assist flyby in February 2009 that provided an additional delta-V of 2.6 km/s and was the only post-launch mission delta-V not provided by IPS. During the mission at Vesta the IPS was used for all orbit transfers which included six different near-polar science mapping orbits. Thrusting for departure from Vesta and the start of cruise to Ceres began on July 25, 2012 with escape from Vesta occurring on September 5, 2012. To date the IPS has been operated for approximately 31,000 hours, consumed approximately 300 kg of xenon, and provided a delta-V of approximately 8.3 km/s. IPS performance characteristics are very close to the expected performance based on analysis and testing performed pre-launch. Thrusting for cruise to Ceres will continue until the spring of 2015, with a planned arrival date at Ceres in April 2015. This paper provides an overview of Dawn's mission objectives and the results of Dawn IPS mission operations from Vesta departure through the first year of cruise to 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, employs ion propulsion for precision orbital control in low Earth orbit [5], and ESA's Artemis mission used the RIT-10 ion propulsion system for transfer to a geostationary orbit [6]. Approximately 72 ion thrusters (13-cm-dia and 25-cm-dia) are aboard 32 communication satellites 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

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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.

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 asteroids, 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 each body. Dawn is the first mission to orbit a main belt asteroid and will be the first to orbit two extraterrestrial targets. The Dawn mission is enabled by a three-engine ion propulsion system (IPS) that will provide most of the velocity change needed for heliocentric transfer to Vesta and Ceres, orbit capture at Vesta and Ceres, transfer to science orbits, orbit maintenance, orbit escape and departure. 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 [10]. 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 [11]. At the conclusion of the Vesta science phase the Dawn spacecraft departed Vesta for deterministic thrusting leading to a rendezvous with Ceres in April 2015. The end of the primary mission is scheduled for the end of 2015. This paper presents a summary of the Dawn mission operations from Vesta departure through the approximately one year of cruise to Ceres.

II. MISSION AND SYSTEM FLIGHT OVERVIEW

The mission and flight system are described in detail in [12-14], and are summarized here. Vesta is the second most massive main belt asteroid 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 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 are described in [13,14]. 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 [15] and Leostar [15] 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 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.

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. A mass summary for the Dawn flight system is provided in Table 1.

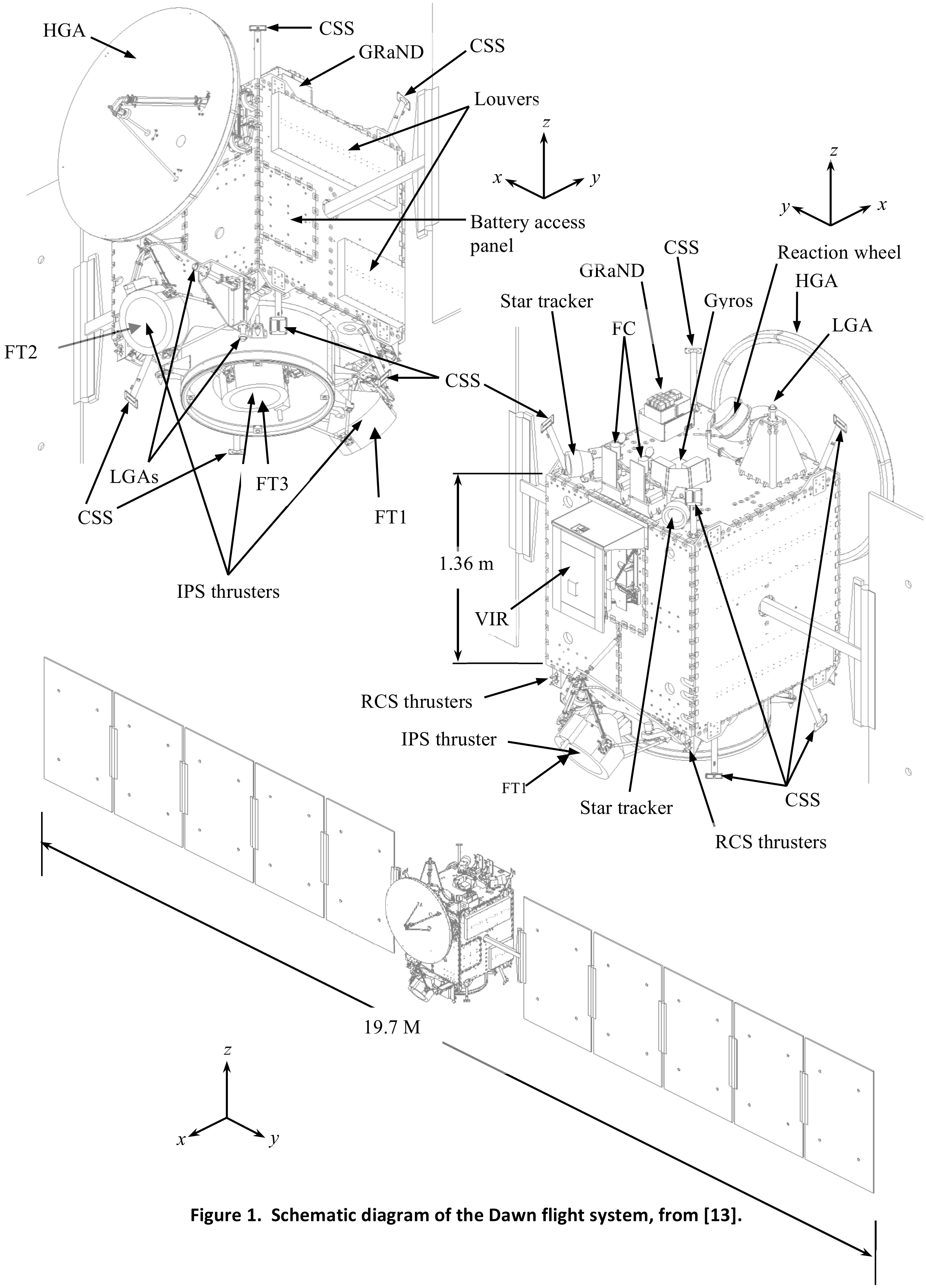

Figure 1. Schematic diagram of the Dawn flight system, from [13].

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 [16] 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 [17], 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, and 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.

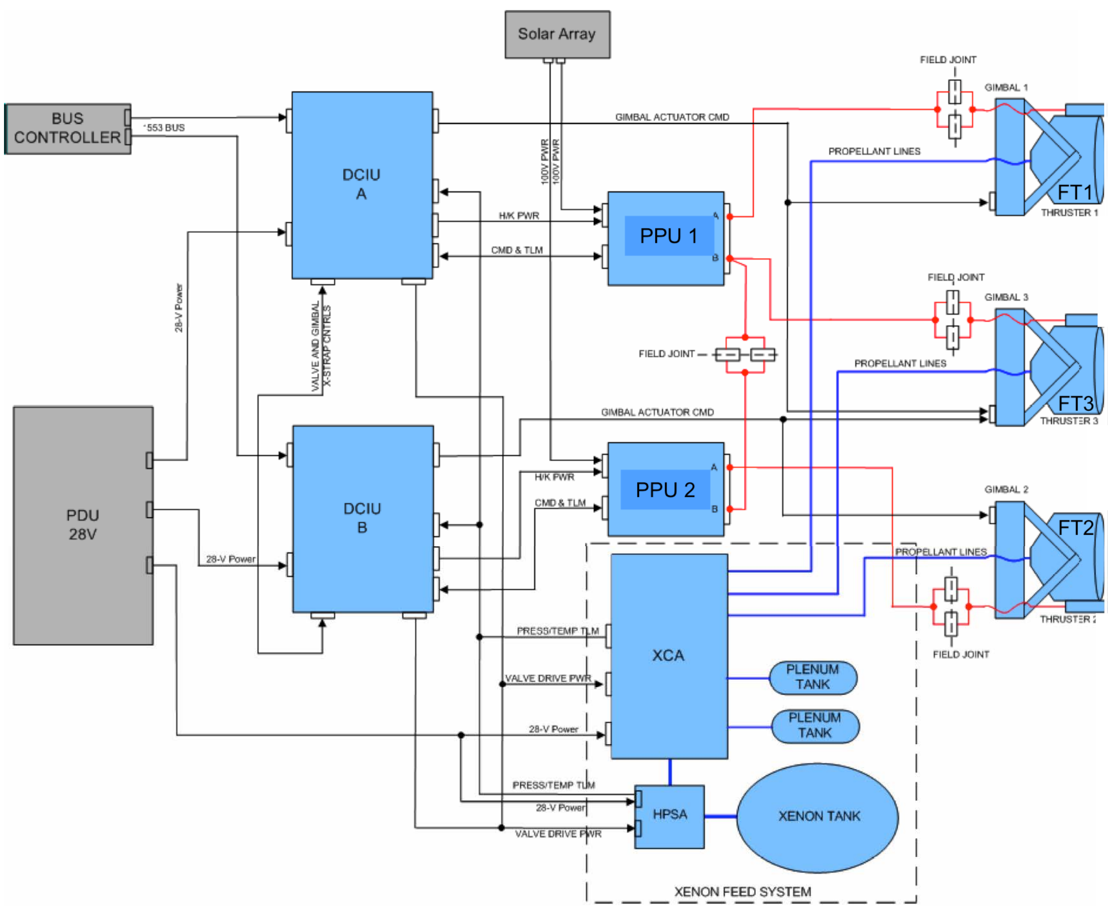

Figure 2. Simplified block diagram of the Dawn IPS.

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. A xenon allocation summary is provided in Table 2. The xenon feed system is based on the DS1 design but was modified to operate multiple thrusters and to be single-fault tolerant. Each thruster is gimbaled using the TGA to point the thrust vector through the spacecraft center of mass and to provide pitch and yaw control during ion thrusting.

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 402 kg of xenon for the complete mission.

Table 2. Xenon Allocation Summary

Description	Xenon Allocation (kg)
Initial Checkout	3.1
Leakage Allocation	10.0
Deterministic Thrusting To Vesta-Actuals	246.8
Allocation for Vesta Operations-Actuals	9.8
Deterministic Thrusting To Ceres	112
Allocation for Ceres Operations	10.5
Xenon Allocated For Thruster Restarts	3.0
Main Tank Residuals	5.0
Margin	25.0
Total	**425.2**

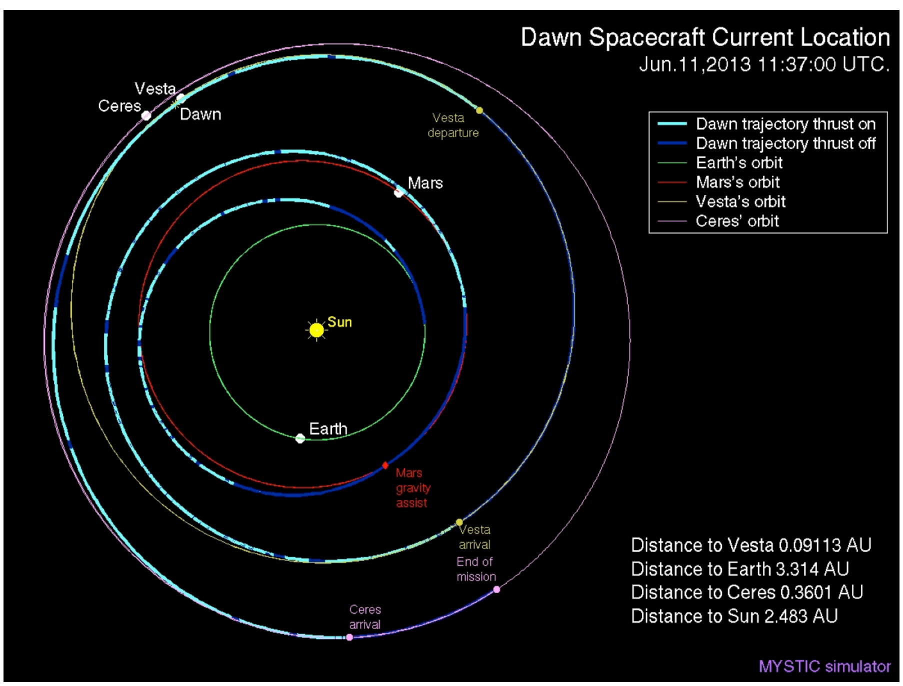

Figure 3. Dawn mission trajectory.

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 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 = 1.8 km/s**
Optimal Coast and 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 - 07/2011**	**1.40 - 2.26**	**2.6 -1.7**	**ΔV = 4.84 km/s ***
IPS Operations at Vesta	**07/2011 - 09/2012**	**2.26 - 2.53**	**1.7 -1.3**	**ΔV = 0.23 km/s**
Cruise to Ceres	09/2012 - 04/2015	2.51 - 2.84	1.3 -0.9	ΔV = 3.55 km/s
Ceres Science Operations	04/2015 - 12/2015	2.84 - 2.93	0.9	ΔV = 0.48 km/s

* From start of cruise to orbit capture at Vesta

III. Overview of IPS Operations July 2012-July 2013

The Dawn spacecraft was inserted into its final science orbit around Vesta on June 6, 2012 at an altitude above Vesta of .approximately 670 km. Thrusting for escape from Vesta began on July 25, 2012. The IPS input power varied as the power generated by the spacecraft solar array change heliocentric range. The spacecraft heliocentric range versus mission time is shown in Figure 4. During the departure phase, thrusting was suspended at various times for final observations of the northern hemisphere of Vesta.

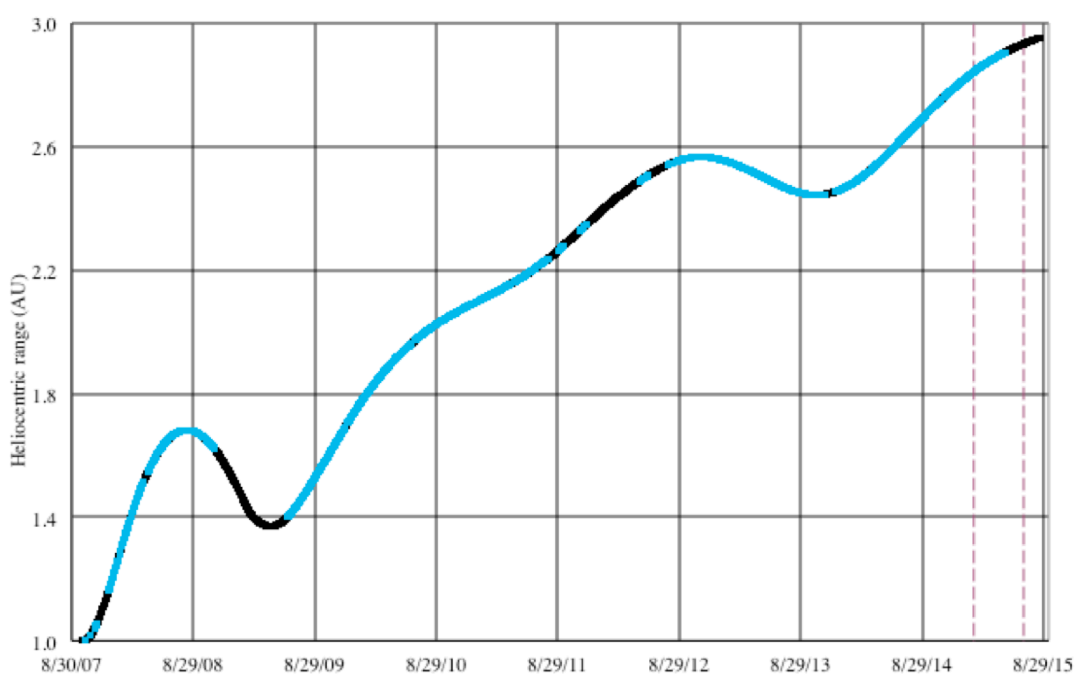

Figure 4. Graph of the heliocentric range over time for the Dawn mission. Blue line color depicts ion thrusting.

The center-mounted thruster, FT3, has been used since August 31, 2011. Input power to the IPS has varied from 1.22 kW at 2.57 AU to approximately 1.4 kW at 2.48 AU. Thrusting segments used during the Vesta escape maneuvers ranged from 46-119 hours depending upon science requirements.

Spacecraft attitude control was provided by the reaction wheels during non-thrusting periods, with spacecraft pitch and yaw controlled by the IPS during nominal IPS thrusting. The plan was to switch to RCS thrusters shortly after achieving escape to minimize the number of reaction wheel revolutions, however on August 9, 2012 during the third thrusting segment for escape from Vesta fault protection on-board the spacecraft detected anomalously high drag torque in one of the three operating reaction wheels, powered off the wheels and IPS, and switched to full RCS thruster control. The flight team then successfully re-planned the departure phase, re-configured the spacecraft for RCS attitude control, and thrusting resumed just eight days later, on August 17, 2012, again with the IPS providing for pitch and yaw control during thrusting periods. The wheels will remain powered off (except for brief testing periods) and spacecraft attitude control will be performed using the IPS plus RCS thrusters for the remainder of cruise to Ceres, as planned last year.

The trajectory used for escape from Vesta resulted in a spiral of slowly increasing radius, reaching escape on September 5, 2012 at an altitude above Vesta of 16,000 km. The departure phase required approximately 593 hours of thrusting at an input power of approximately 1.25 kW and used approximately 4.0 kg of xenon over the seven-week duration of the departure phase. Escape from Vesta occurred during routine thrusting, and in fact the departure phase from Vesta and the start of cruise to Ceres phase were an indistinguishable event during the 7th thrusting segment.

Since escape from Vesta through June 22, 2013 IPS accrued 6,690 hours of thrusting and used 45 kg of xenon in sixteen thrust segments with an input power range of 1217-1400 W. FT3 was used with full power cathode flow rates for the departure phase to reduce trajectory maneuver errors arising from the cathode flow transitions as a result of the bang-bang pressure regulator [11] until the thrust segment beginning 2012-275, where operation with nominal cathode flow rates was resumed.

The IPS has operated for a total of 31,277 hours of operation with beam extraction and has processed 300.1 kg of the 425.2 kg of xenon loaded into the xenon tank at launch. Xenon use to date is well within the allocation for deterministic thrusting to Ceres (Table 2). Times for thrust segments have increased, from seven days to 14-31 days, to reduce hydrazine consumption. The longest continuous operating thrust segment with beam extraction to date was for 748.6 hours.

PPU Performance

Data on input power to PPU-1 for operation of FT3 are plotted in Figure 5. Data points are the values averaged over the steady-state portion for a thrust segment. The data include telemetry for unregulated high voltage power from the solar array and do not include PPU housekeeping power (estimated to be approximately 20 W) from the low voltage bus. Input power to PPU-1 during the Vesta departure and cruise to Ceres phases varied from 1.22-1.34 kW. PPU efficiencies from launch through June 2013 were consistently in excess of 92.5%. There is a small but clearly discernible decrease in PPU efficiency when operating with full power cathode flow rates. Both PPUs have operated perfectly throughout the mission to date. Data (averaged over individual thrust arcs) from the PPU baseplate and screen supply temperature sensors are shown in Figure 6. The data indicate that that the thermal heat rejection system on the Dawn spacecraft that regulates the PPU thermal control surface has operated extremely well. The control setpoint for this surface was decreased several times throughout the mission to reduce total spacecraft power consumption. For cruise to Ceres the PPU thermal control surface setpoint was changed to 10 degrees C.

XFS Performance

The xenon flow system has also operated perfectly throughout the mission. To date the primary solenoid valve pair used to regulate main plenum pressure has been cycled open and closed approximately 747,000 times since launch, and the primary solenoid valve pair for cathode plenum tank pressure regulation has accumulated approximately 262,000 cycles. The solenoid valves on the Dawn XFS have a flight allocation of 1.2 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. 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 acceptably low values.

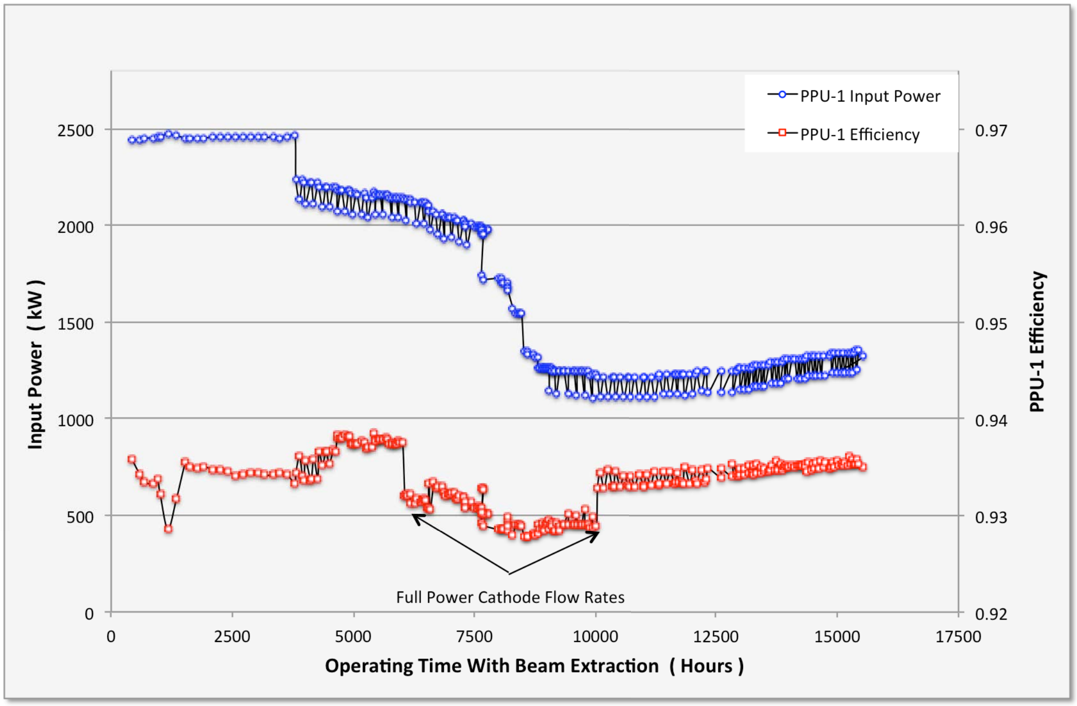

Figure 5. Input power and efficiency for PPU-1 operating on FT3.

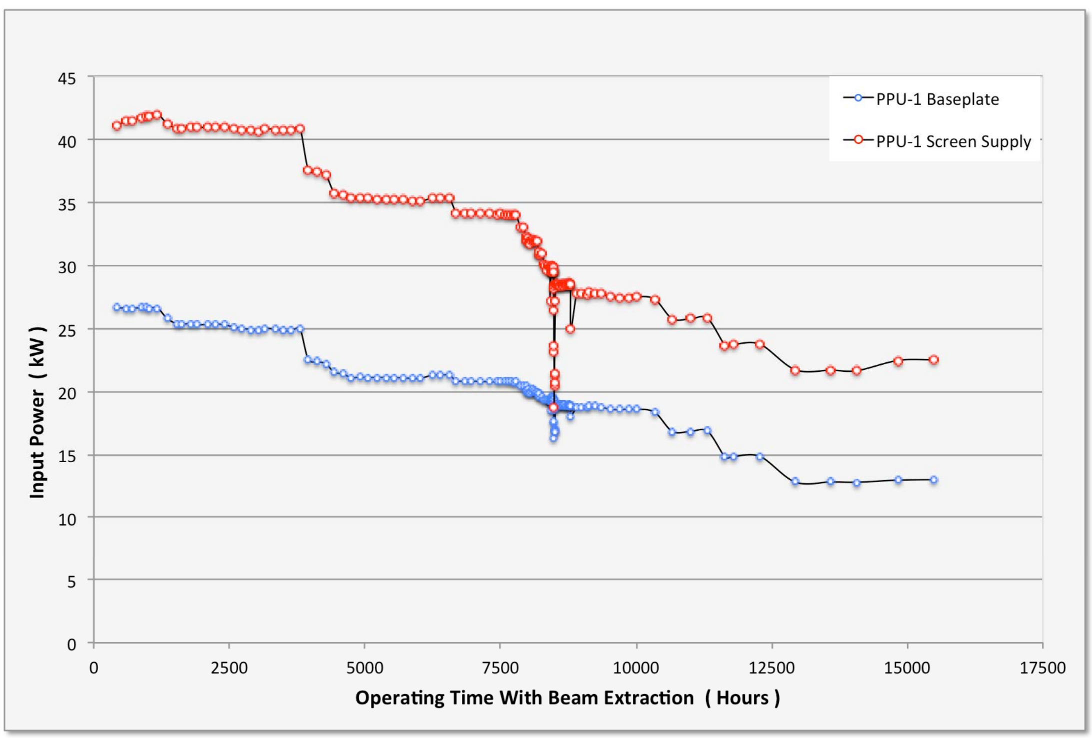

Figure 6. Baseplate and screen supply temperatures for PPU-1.

Thruster-Gimbal Assembly (TGA) Performance

The TGAs have also operated flawlessly during the entire mission. 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 the RCS are used to control the spacecraft roll axis. Cumulative TGA-3 (for FT3) actuator equivalent motor revolutions are shown in Figure 7. The data indicate that the TGA motors have accumulated the equivalent of approximately 2,100,000 revolutions. The motor design was life-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. The duty cycle and number of TGA actuations per kg of xenon used are greater with RWA control [11].

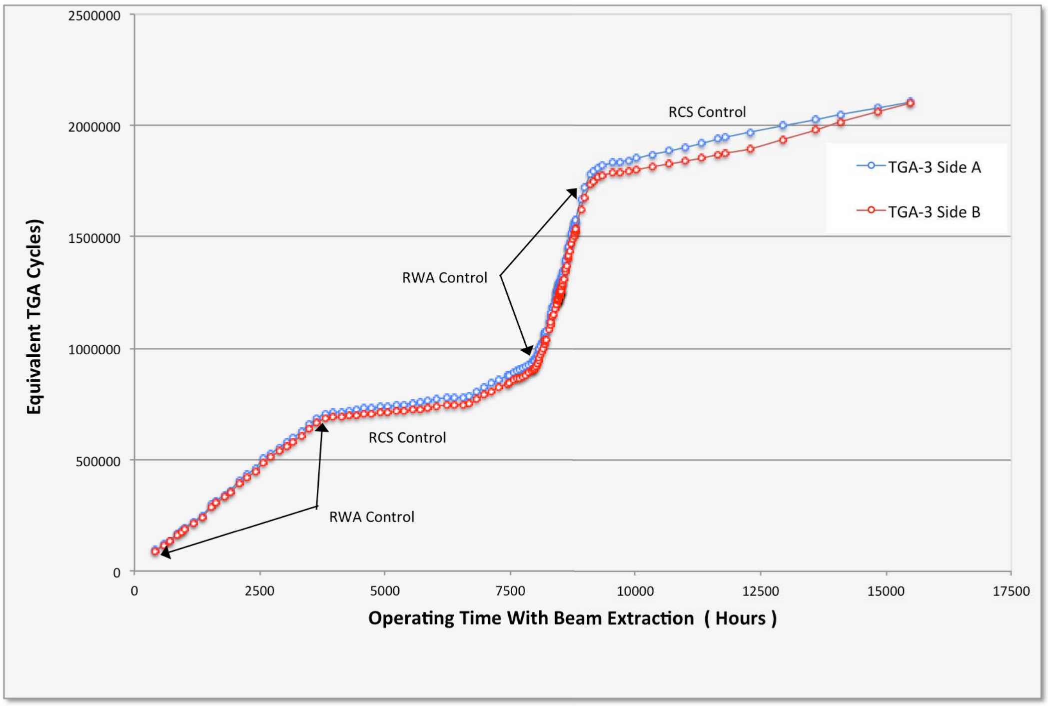

Figure 7. TGA-3 equivalent motor revolutions since launch.

Thruster Performance for FT3

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 total for the thruster at full power. Beginning in March 2011 the discharge cathode and neutralizer flow rates for operation of FT3 at all power levels was changed to 3.7 sccm to address the thrust stability issues that are described in [18]. This change resulted in extremely reliable and consistent maneuvers, and suppressed the discharge voltage (Figure 8). Operation with nominal cathode flow rates was resumed beginning October 1, 2012.

Thruster Starts

Through June 2012 there have been a total of 593 thruster starts in flight, with 344 starts using FT3. 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. The diode mode pre-heat procedure was modified to prevent main flow rate transients after start-up which contribute to maneuver execution errors. This procedure nominally is executed with both

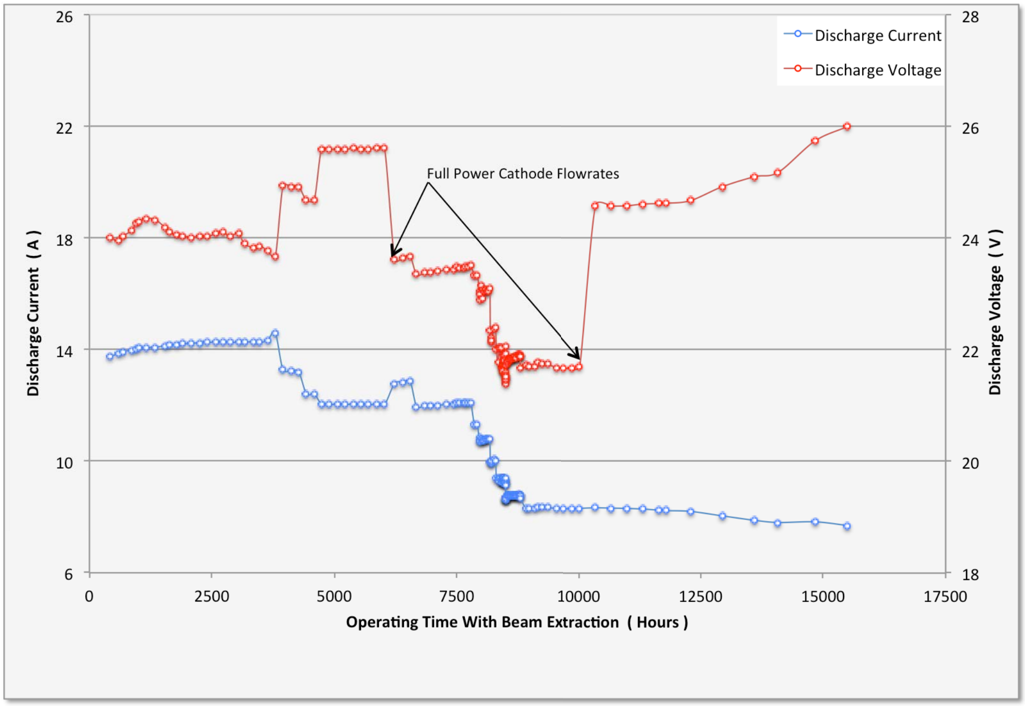

Figure 8. Discharge current and voltage for FT3 from launch through June 2013.

main and cathode plena pressurized to ML 111 levels. The modified procedure changed the main plenum pressure to that corresponding to the intended throttle level after start-up.

Thruster Cathode Heaters

The nominal cathode heater current for both the neutralizer and discharge cathodes is 8.5 A. Thruster peak discharge and neutralizer cathode heater power data for all thruster starts using FT3 are plotted in Figure 9. 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 with beam extraction. Heater power was essentially unchanged during the Vesta departure and cruise to Ceres phases.

Thruster Input Power

All FTs are now using the end-of-life (EOL) throttle table, which is used once a thruster has processed more than 70 kg of xenon. It is expected, based on extensive life testing and analysis that each FT can reliably process 195 kg [18] over the Dawn mission profile. Input power to FT3 from start of cruise to Vesta through June 2013 is plotted in Figure 10 as a function of propellant throughput. Also included in Figure 10 is the end of life input power estimate developed pre-launch. Input power varied from about 2.3 kW at the start of cruise to 1.14 kW at ML 42. Full power cathode flow rates were used between 48.4 through 98.6 kg of xenon throughput, which suppressed the discharge voltage and neutralizer voltage, resulting in lower thruster input power. The effect of full power cathode flow rates on thruster input power is greatest at the lower power levels because the effect of voltage suppression is greatest at lower input powers, which use lower neutralizer and discharge cathode flow rates than the medium to high power levels.

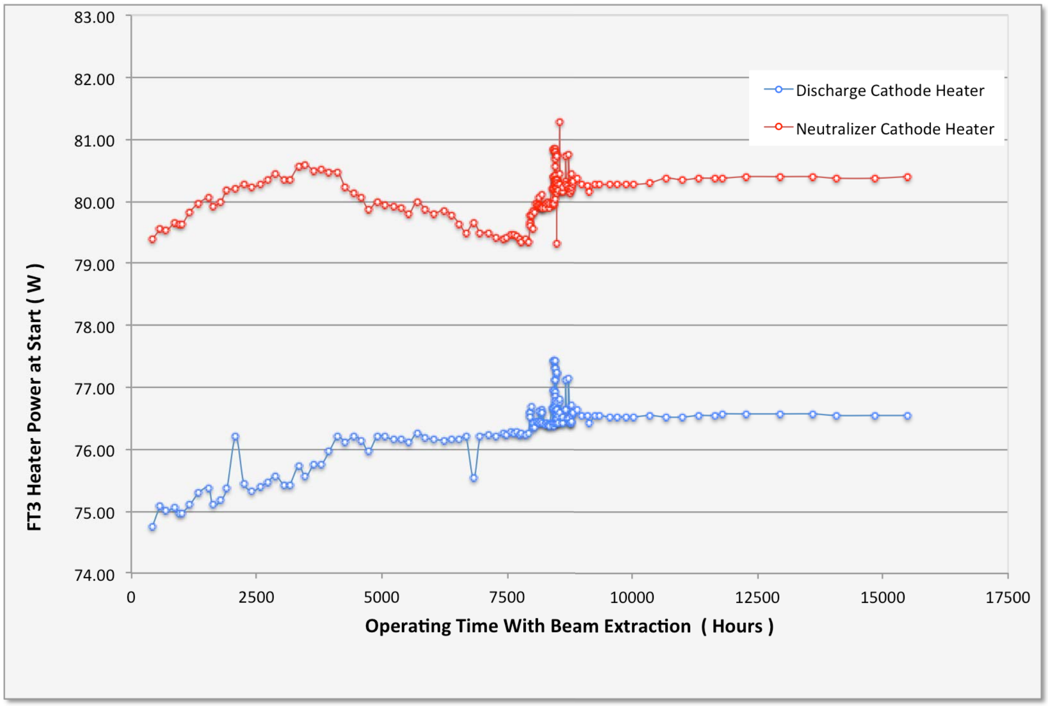

Figure 9. Peak discharge and neutralizer cathode heater power for FT3 from launch through June 2013.

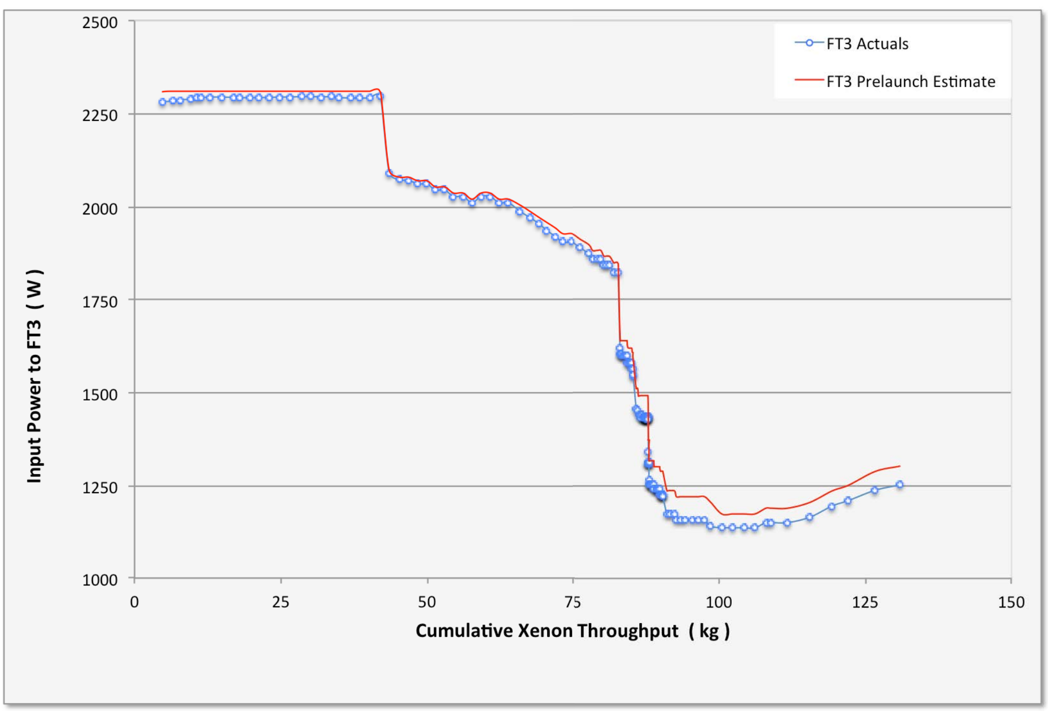

Figure 10. FT3 input power for FT3 from launch through June 2013.

Thruster Accelerator Grid Characteristics

Accelerator grid current data for FT3 from launch through June 2013 are plotted in Figure 11. The step changes in accelerator grid current evident in Figure 11 are due to changes in the thruster throttle level, the accelerator grid voltage, and the cathode flow rate. At a fixed flow rate and beam current thruster power is finely controlled with step changes of approximately 10 V in beam voltage, which produces the step changes in accelerator grid current. At all power levels accelerator grid currents were typically about 20% greater compared to the values from the end of life throttle table. It is expected that operation at these slightly greater accelerator grid impingement currents will not substantially reduce thruster operating life. Accelerator grid voltage for each FT was decreased from -200 V to -272 V when the thrusters reached approximately 70 kg of xenon throughput (65 kg for FT3) in order to provide additional margin against electron backstreaming.

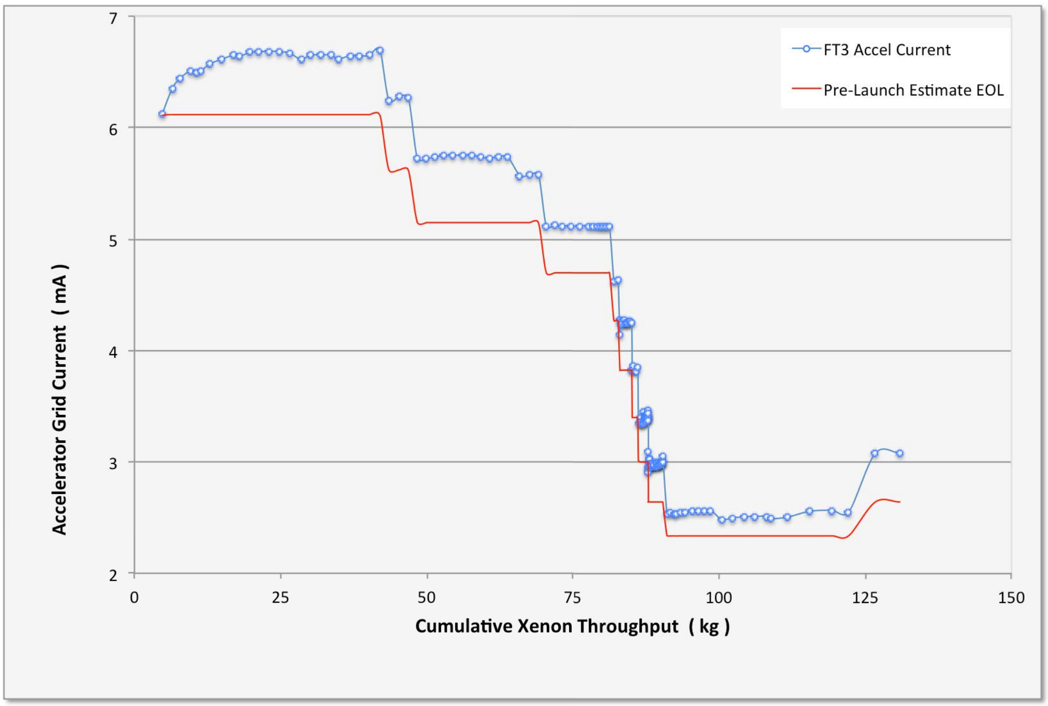

Figure 11. Accelerator grid current for FT3 from launch through June 2013.

Thruster High Voltage Recycles

High voltage recycles for FT3 from launch through the June 2013 are shown in Figure 12. FT3 accumulated 63 recycles operating for approximately 16,000 hours, with 45 recycles occurring at full power. The data suggest that recycle rates have decreased over time and with decreasing power levels. Most recycles in flight occurred within a few hours after the start of beam extraction for each thrust arc. There have been no recycles using FT3 in over 7,500 hours of operation. The last recycle using FT3 occurred in November 2011, when FT3 was operated at an input power of approximately 1.44 kW.

Neutralizer Operation

FT3 neutralizer keeper voltage data for operation from launch through June 2013 are shown in Figure 13. Also shown is the estimate for end of life neutralizer voltage made pre-launch. During throttled conditions the neutralizer keeper voltage varied more than during full power operation in cruise where neutralizer current was essentially constant. The greatest changes in neutralizer keeper voltage occurred during operations at Vesta, where there were more frequent changes to power level, spacecraft attitude, thrust arc run times and time between thrust arcs. Operation at full power neutralizer flow rates suppressed the value for neutralizer voltage, as shown in Figure 13.

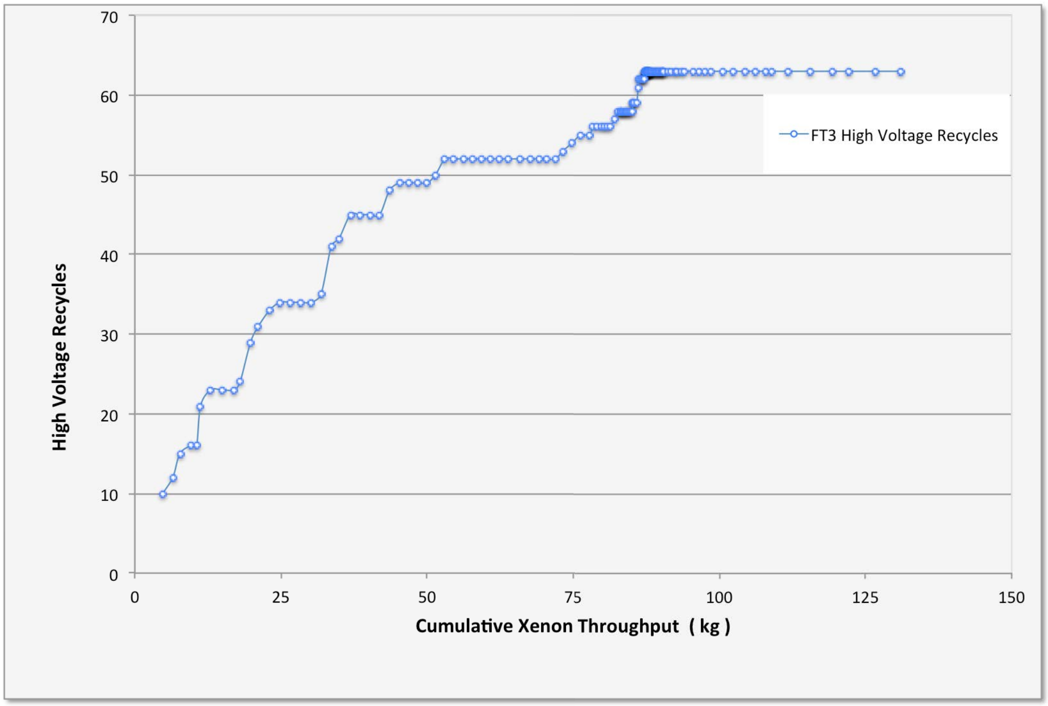

Figure 12. High voltage recycles for FT3 from launch through June 2013.

Figure 13. Neutralizer voltage for FT3 from launch through June 2013.

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. PPU-1 plume mode circuit output data for FT3 averaged over individual thrust arcs are shown in Figure 14. 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 IPS operations since launch there have been no indications of neutralizer cathode operation in plume mode after the initial start-up transients.

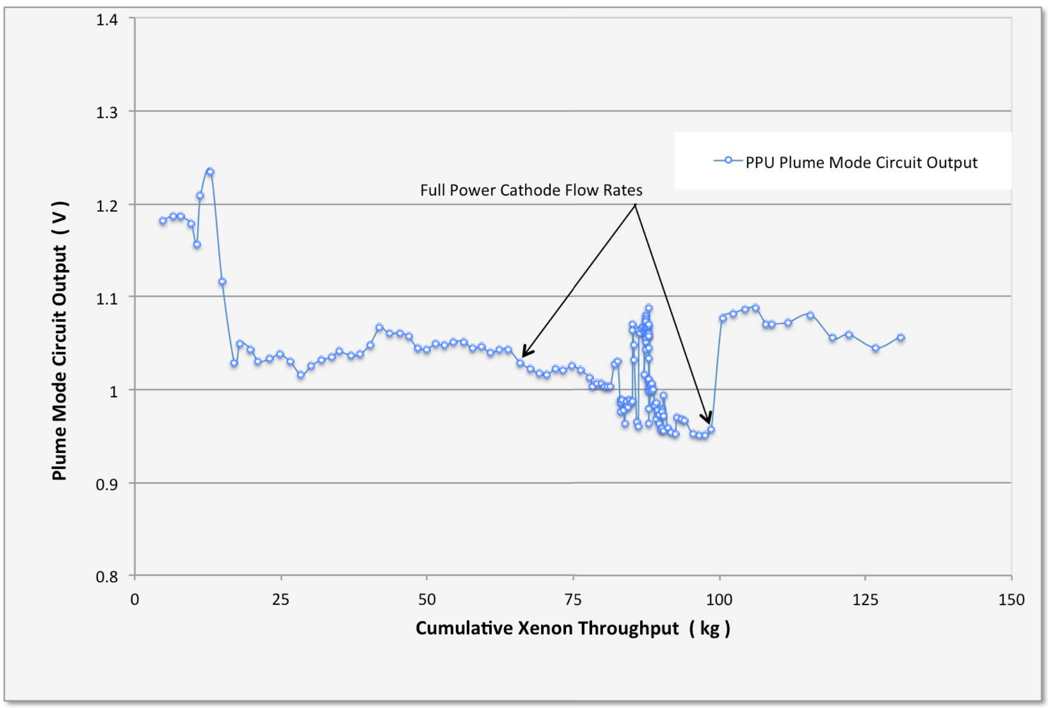

Figure 14. PPU-1 plume mode circuit output for operation on FT3 from launch through June 2013.

Thrust Measurements

Thrust calculated from thruster telemetry and reconstructed using navigation data as described in [19] from launch through the end of June 2013 are shown in Figure 15. Thrust values calculated from thruster telemetry were averaged over a time period where thruster operating parameters were stable. During the departure from Vesta phase and part of the cruise to Ceres phase FT3 was operated using full power cathode flow rates to minimize thrust variations arising from cathode flow transients which contribute to maneuver execution errors (19). Nominal cathode flow rates were used prior to approach to Vesta and starting with the 11th thrusting segment for cruise to Ceres with just over 10,000 hours of total operating time on FT3.

Thrust values determined from telemetry very closely matched thrust estimated from navigation data, as can be from Figures 15. Orbital parameters resulting from maneuvers using the IPS were very close to the intended orbital parameters. With full power cathode flow rates, thrust values determined by radiometric means were the same as values determined using thruster electrical parameters. At nominal cathode flow rates reconstructed thrust values were 99-99.5% of the thrust values expected from thruster electrical parameters. The Dawn mission uses a worst-case thrust degradation factor of 97% of the expected thrust for long-term planning.

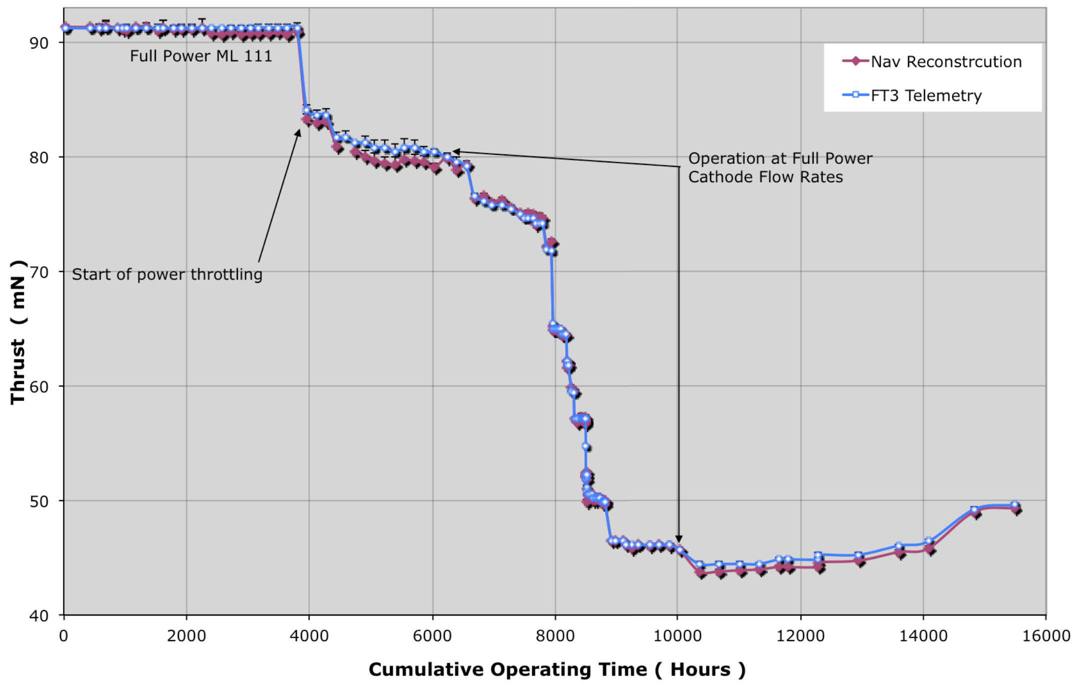

Figure 15. Thrust measurements for FT3 from start of cruise to Vesta through June 2013.

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. During Vesta operations Vesta's gravity greatly impacts roll torques to the spacecraft and there are no data calculated for roll torque for operations at Vesta. For cruise to Ceres, data from the latest nine thrusting segments indicate roll torque values between 20.45-23.95 μN-m for a thruster input power range between 1136-1251 W. 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 under 2 kg for all of cruise to Ceres.

DCIU-1 Operation

DCIU-1 operated flawlessly during the departure from Vesta phase and start of cruise to Ceres phase.. From the period July 2012-June 2013 all DCIU commands were accepted and executed, and there were no operational errors.

Thruster Operating Time And Xenon Throughput Summary

Table 4 summarizes operating time and xenon throughput for each thruster from launch through June 2013. FT3 has accumulated the most number of operating hours and xenon throughput. 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 it is aligned with a 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.

Table 4. Cumulative operating time and xenon throughput for Dawn ion thrusters

Thruster	Neutralizer On-Time (Hours)	Beam On-Time (Hours)	Xenon Throughput (kg)	Thruster Starts
FT1	7678	7625	84.4	115
FT2	7956	7900	84.7	134
FT3	15642	15487	130.9	343
Totals	31277	31011	300.1	592

IV. Conclusion

The Dawn mission has successfully used its ion propulsion system for the heliocentric transfer to the main-belt asteroid Vesta, for science operations in orbit, for departure from Vesta, and approximately 11 months of cruise to Ceres. All the IPS components--the thrusters, DCIUs, PPUs, XCA, and TGAs—have operated nominally during the departure from Vesta and cruise to Ceres phases. Dawn achieved orbit capture at Vesta on July 16, 2011 and escape from Vesta on September 5 2012. To date the IPS has operated for over 31,000 hours with beam extraction, used just over 300 kg of xenon, and imparted a delta-V of over 8.3 km/s to the spacecraft. The Dawn IPS has proven to be extremely reliable and capable with very few operational problems during its almost six-year journey. Thrusting to Ceres will continue until spring of 2015, with approach to Ceres in February 2015 and orbit capture by Ceres expected around May 2015. The Dawn ion propulsion is presently fully operational for continued cruise operations to Ceres.

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