In-Flight Operation of the Dawn Ion Propulsion System Through Year Two 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, 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. From July 2011 through July 2012 the IPS was used to transit to all the different science orbits at Vesta and to escape from Vesta orbit. Cruise for a rendezvous with Ceres began in July 2012 with the spacecraft still in a high altitude mapping orbit at Vesta. To date the IPS has been operated for over 39,237 hours, consumed approximately 350 kg of xenon, and provided a ΔV of approximately 9.8 km/s. The IPS performance characteristics are very close to the expected performance based on analysis and testing performed pre-launch. Cruise to Ceres will require approximately 2.5 years, most of that time with the IPS thrusting at low power. Arrival to Ceres is planned for early 2015. This paper provides an overview of Dawn's mission objectives and the results of Dawn IPS mission operations through the first two years of cruise operations for Ceres.

I. Introduction

Missions using electric propulsion have attained a high level of success and reliability of operation. As of June 2012 there are over 236 spacecraft successfully using electric propulsion for attitude control, orbit raising, station keeping and for primary propulsion [1]. Deep Space 1 (DS1), the first interplanetary mission to use ion propulsion, operated its single thruster ion propulsion system for over 16,000 hours before successfully completing its primary and extended missions [2]. A PPS-1350 Hall thruster was used for primary propulsion on board the European Space Agency's SMART-1 probe, with more flights planned [3]. European and U.S. communications satellites have been launched with SPT-100 based propulsion modules for attitude control and orbit boosting. The Hayabusa spacecraft returned to Earth after exploring asteroid 25143 Itokawa [4] and employed ion thrusters for primary propulsion. The Japanese ETS-VIII uses ion thrusters for north-south station keeping. ESA's GOCE mission, launched in March 2009, employed ion propulsion for precision orbital control in low Earth orbit [5], and ESA's Artemis mission used the RIT-10 ion propulsion system for transfer to a geostationary orbit [6]. Approximately 148 ion thrusters (13-cm-dia and 25-cm-dia) built at L3 Communications, Torrance, CA are aboard 37 communication satellites built by Boeing Defense, Space and Security for orbit-raising and station-keeping functions, accumulating ~450,000 operating hours in flight [7]. In 2011 the U.S. Air Force

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satellite AEHF (Advanced Extremely High Frequency) was successfully placed into a geosynchronous orbit from a highly elliptical orbit around Earth using the spacecraft's Hall thruster station-keeping propulsion system [8] after the propulsion system originally intended for the orbit maneuver failed. Since then two additional satelites with Hall thrusters on-board were successfully launched and operated.

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

The Dawn mission has as its goal the scientific exploration of the two most massive main-belt 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 in July 2012 for deterministic thrusting leading to a rendezvous with Ceres in April 2015. The end of the primary mission is scheduled for the end of June 2016. This paper presents a summary of the Dawn mission operations from Vesta departure through the second 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 Geostar [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.

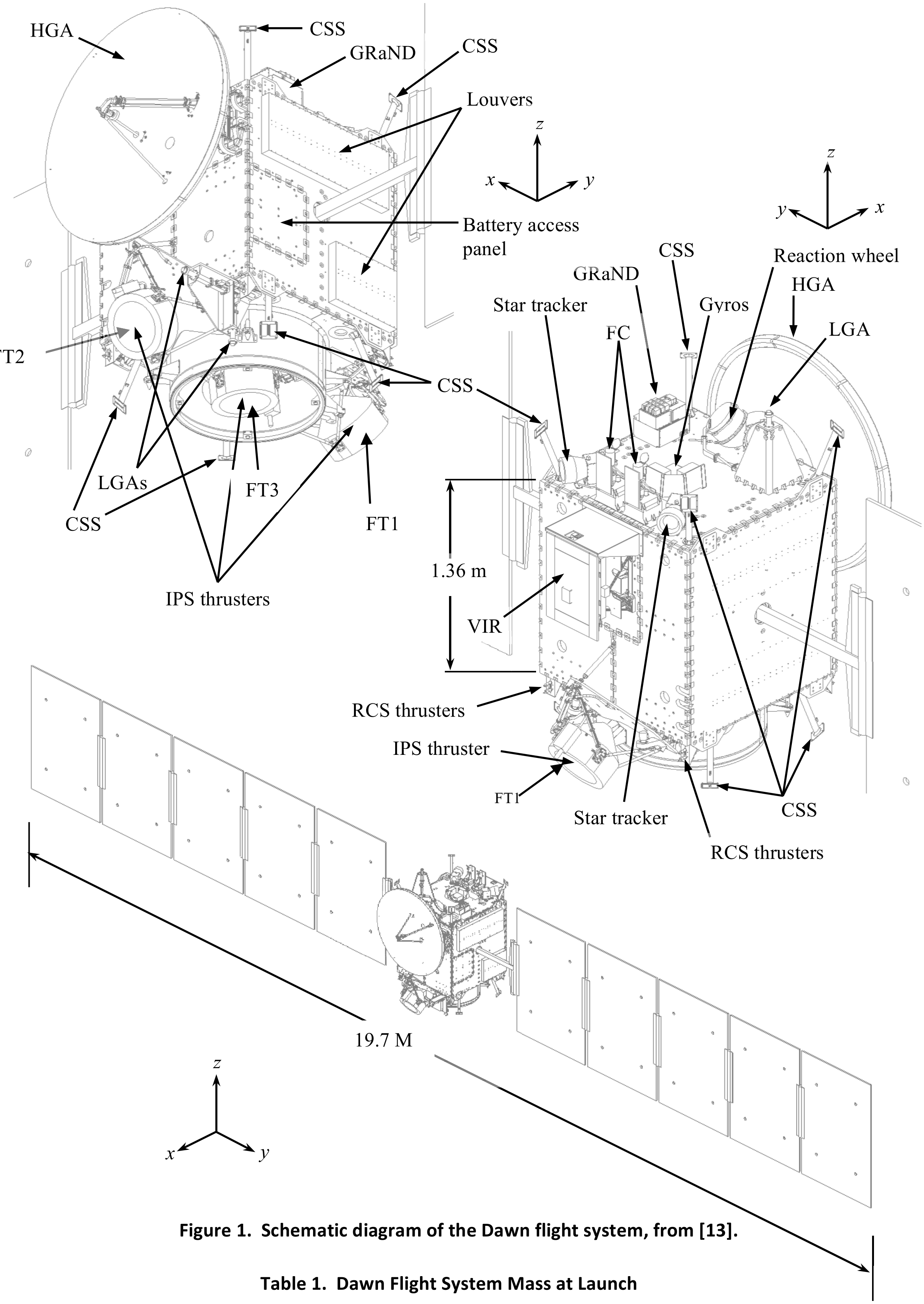

Figure 1. Schematic diagram of the Dawn flight system, from [13].

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.

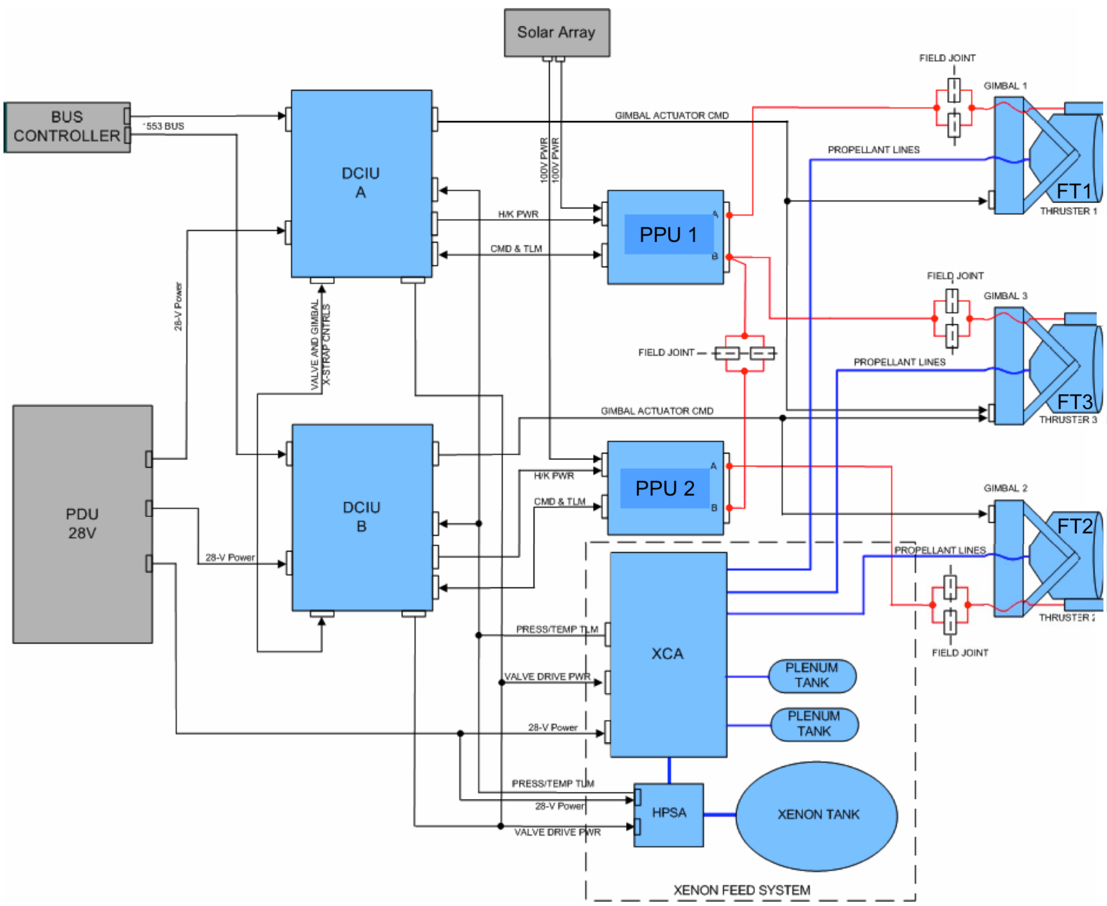

Figure 2. Simplified block diagram of the Dawn IPS.

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 405 kg of xenon for the complete mission.

Table 2. Xenon Allocation Summary

Description	Xenon Allocation (kg)
Initial Checkout	3.1
Leakage Allocation	10
Deterministic Thrusting To Vesta-Actuals	246.8
Allocation for Vesta Operations-Actuals	9.8
Deterministic Thrusting To Ceres	119.7
Allocation for Ceres Operations	10
Xenon Allocated For Thruster Restarts	1
Main Tank Residuals	5
Margin	19.8
Total	**425.2**

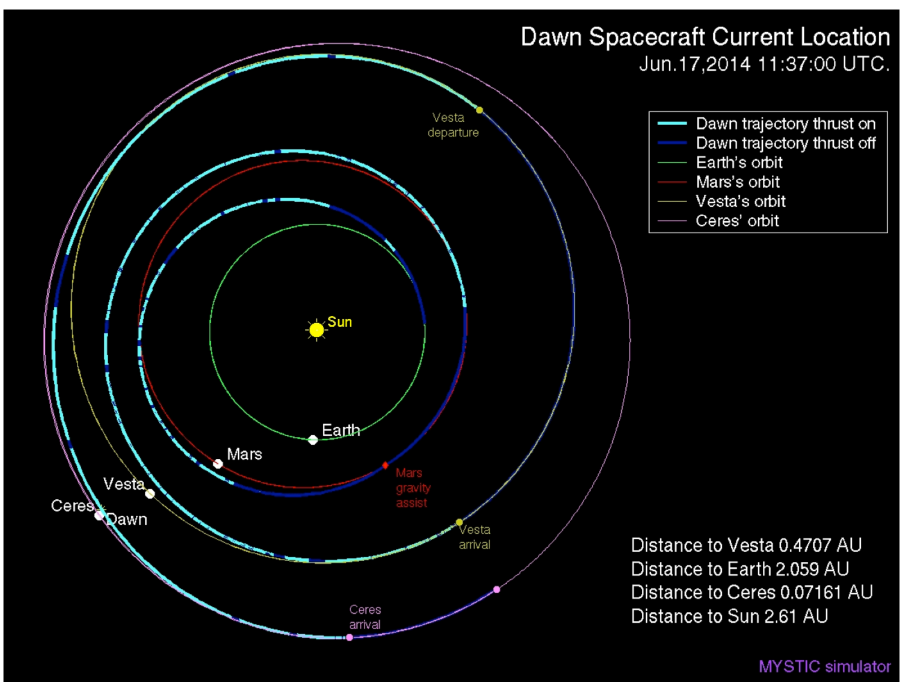

Figure 3. Dawn mission trajectory.

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 June 2013-May 2014

IPS System Overview

Thrusting for escape from Vesta began on July 25, 2012. Since departure from Vesta's high altitude mapping orbit the IPS input power varied as the power generated by the spacecraft solar array changed due to a varying heliocentric range, which in the second year of cruise to Ceres varied from a low of 2.45 AU to a high of 2.62 AU. In the first year of cruise to Ceres FT3 was used, and in the second year of cruise to Ceres (June 2013 through May 2014) FT2 was used, with both FT1 and FT3 used for special spacecraft engineering activities.

Eleven thrusting segments averaging 657 hours in duration were used in the second year of cruise to Ceres. The burn times per thrust segment which were typically substantially longer in duration compared to burn times used previously on Dawn were increased to reduce the number of spacecraft-to-Earth turns, which conserves hydrazine needed for science operations at Ceres. During the second year of cruise to Ceres IPS accrued 7,698 hours of thrusting and used 46 kg of xenon in twelve thrust segments. Since launch the IPS has operated for a total of almost 39,000 hours of operation with beam extraction and has processed 350 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).

Table 4 summarizes operating time for each thruster/PPU and xenon throughput from launch through June 2014. FT3 has accumulated the most number of operating hours and xenon throughput, and Dawn has operated all three thrusters to more evenly distribute the total xenon throughput for each thruster. For transfers from one science orbit to another around Vesta and Ceres, in which the operational schedule requires a rapid design and implementation of the thrust profile, FT3 is preferred because FT3's thruster axis is aligned with 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. FT2 using PPU-2 is the preferred backup to FT3 but effort is made to distribute operating time for the PPUs as well.

Table 4. Cumulative operating time and xenon throughput for Dawn ion thrusters through June 23, 2014

IPS Element	Neutralizer On-Time (Hours)	Beam On-Time (Hours)	Xenon Throughput (kg)	Thruster Starts
FT1	7679	7625	84.4	116
FT2	15192	15126	130.6	156
FT3	16304	16147	135.1	347
Thruster Totals	39175	38898	350.1	619
PPU-1	24029			
PPU-2	15208			
PPU Totals	39237			

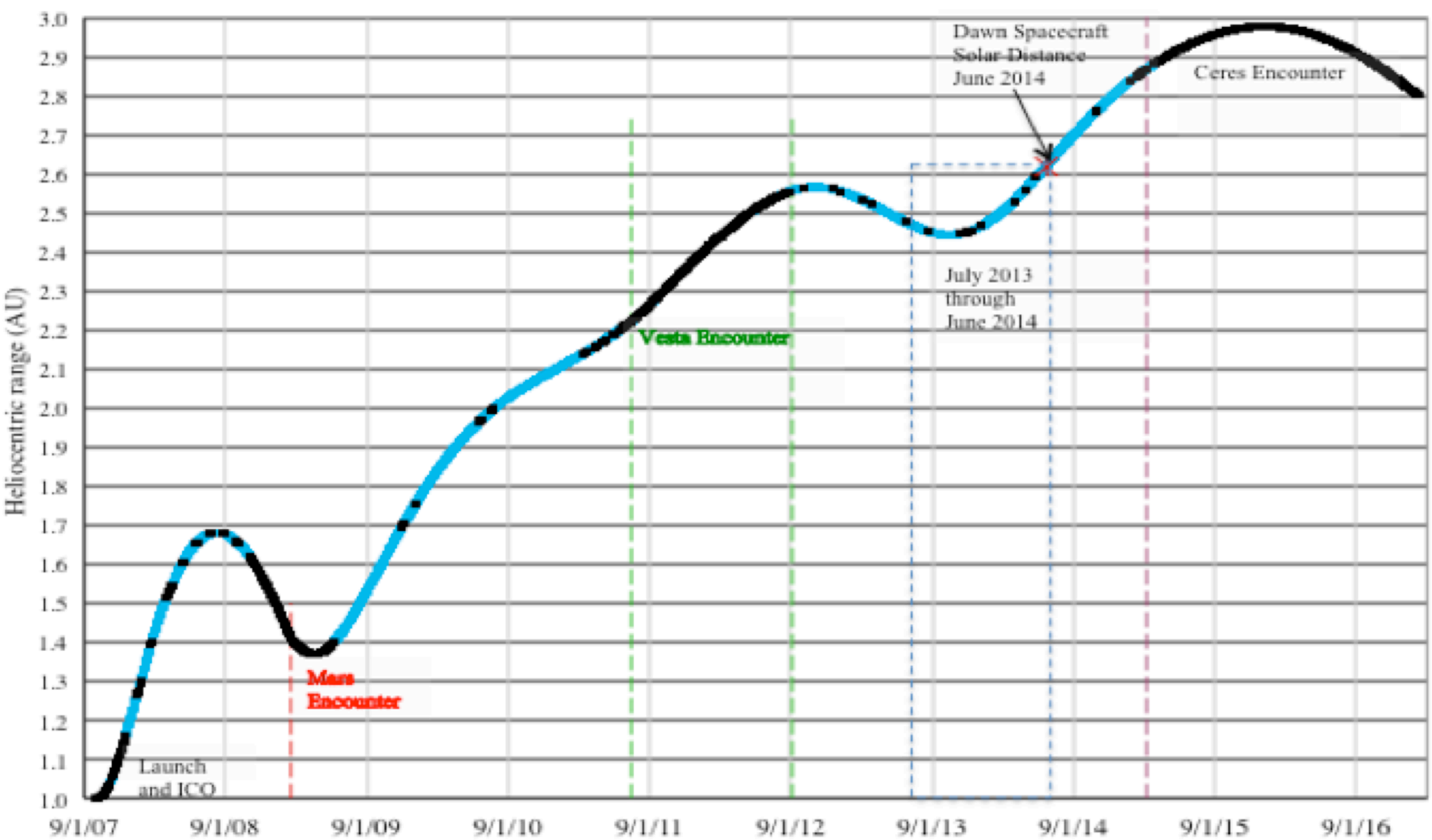

Figure 4. Graph of the heliocentric range over time for the Dawn mission. Blue line color depicts ion thrusting.

Discharge Voltage

Discharge voltage and current for FT2 are shown in Figure 5. 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. At approximately 11,200 hours of operation and 110 kg of xenon throughput the discharge voltage began to increase unexpectedly. A similar change in the discharge voltage was observed on FT3 at the same approximate xenon throughput (Figure 6). The most significant differences in operations on FT2 vs. FT3 are that FT2 has more operating time at lower power levels, fewer starts and substantially less operating time at full power (rich) cathode flow rates Rich cathode flow rates had been used for Vesta operations 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 6). Operation with nominal cathode flow rates was resumed beginning October 1, 2012.

The rate of increase of the discharge voltage for both FT2 and FT3 for the last few thrust segments at nominal cathode flow rates was approximately 0.1 V/kg of xenon throughput at a fixed power level. The mission plan had called for operations on FT3, the preferred thruster for Ceres maneuvers, during the Ceres approach phase, requiring the use of an additional 25 kg of xenon, possibly resulting in an increase in the discharge voltage. Excessively high discharge voltage over a sustained period of time can lead to increased wear and reduced thruster life. A test performed on FT3 operating with the discharge only (diode mode) at rich cathode flow rates confirmed that although the discharge voltage on FT3 had changed substantially at nominal cathode flow rates, the discharge voltage at rich cathode flow rates was virtually unchanged. This test and the fact that the mission had ample xenon reserves led to a decision to operate all thrusters for the remainder of the mission at rich cathode flow rates, where it was expected that both the magnitude and rate of increase of the discharge voltage would decrease. The last two thrust segments using FT2 at rich cathode flow rates totaling approximately 1,500 hours of operation and 8.2 kg of xenon throughput indicated that at fixed power levels the magnitude of the discharge voltage decreased by approximately 2.7 V, and the rate of increase of the discharge voltage dropped to approximately 0.01 V/kg, confirming that operation at rich cathode flow rates had mitigated the unexpected change in discharge voltage behavior. Dawn can expect substantial margin to the discharge voltage going into the approach phase at Ceres.

Thruster Starts

Through May 2014 there have been a total of 619 thruster starts in flight, with 116 starts using FT1, 156 starts using FT2, and 347 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 as discussed in [19] to prevent main flow rate transients after start-up which contribute to maneuver execution errors. The nominal start procedure is executed with both main and cathode plena pressurized to full power pressures and flow rates. 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 7. 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 250-270 W was performed before every start attempt with beam extraction. Heater power was essentially unchanged during the Vesta departure and cruise to Ceres phases.

Figure 5.
FT2 discharge current and voltage for cruise to Ceres June 2013 through May 2014.

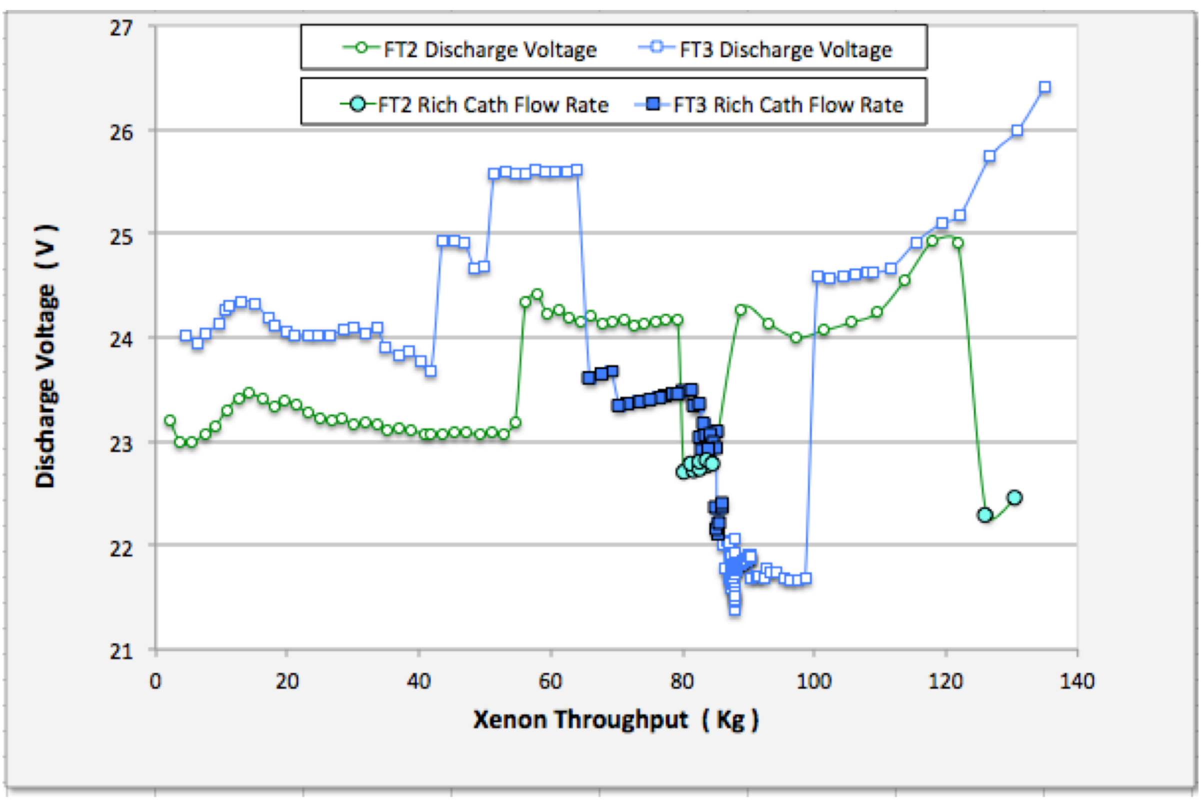

Figure 6. Discharge voltage for cruise to Ceres July 2013 through May 2014.

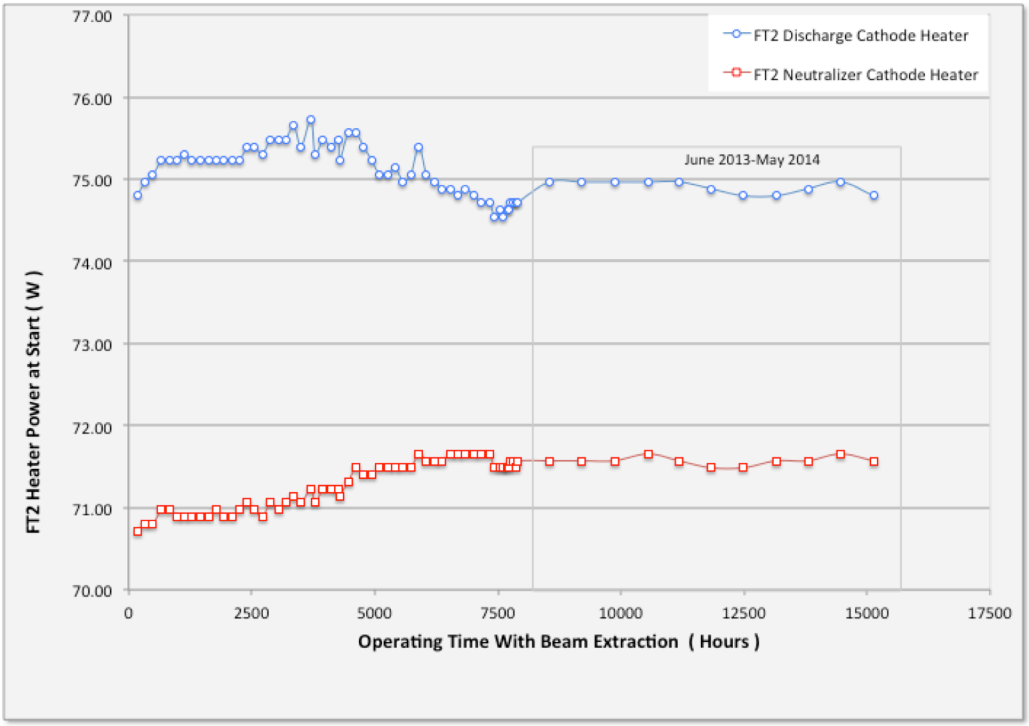

Figure 7. Peak discharge and neutralizer cathode heater power for FT2 from launch through May 2014.

Neutralizer Operation

FT2 neutralizer keeper voltage data for operation from launch through May 2014 are shown in Figure 8. Also shown is the estimate for end of life neutralizer voltage made pre-launch. Operation at full power neutralizer flow rates suppressed the value for neutralizer voltage, as shown in Figure 8. From launch through start of operations at Vesta the neutralizer voltage decreased by approximately 2 V, which may be due to cathode conditioning in the ultra-clean environment of space.

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-2 plume mode circuit output data for FT2 averaged over individual thrust asegments are shown in Figure 9. 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 1.6 V during normal neutralizer operation, with the plume voltage decreasing with FT2 operating at lower power levels. 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.

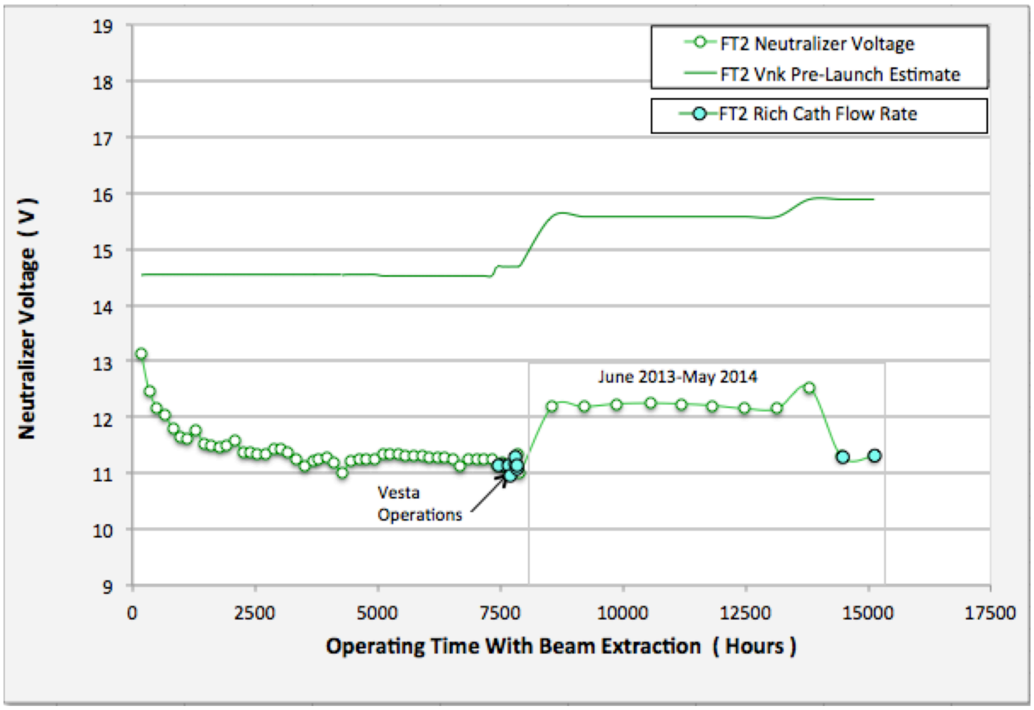

Figure 8. Neutralizer voltage for FT2 from launch through May 2014.

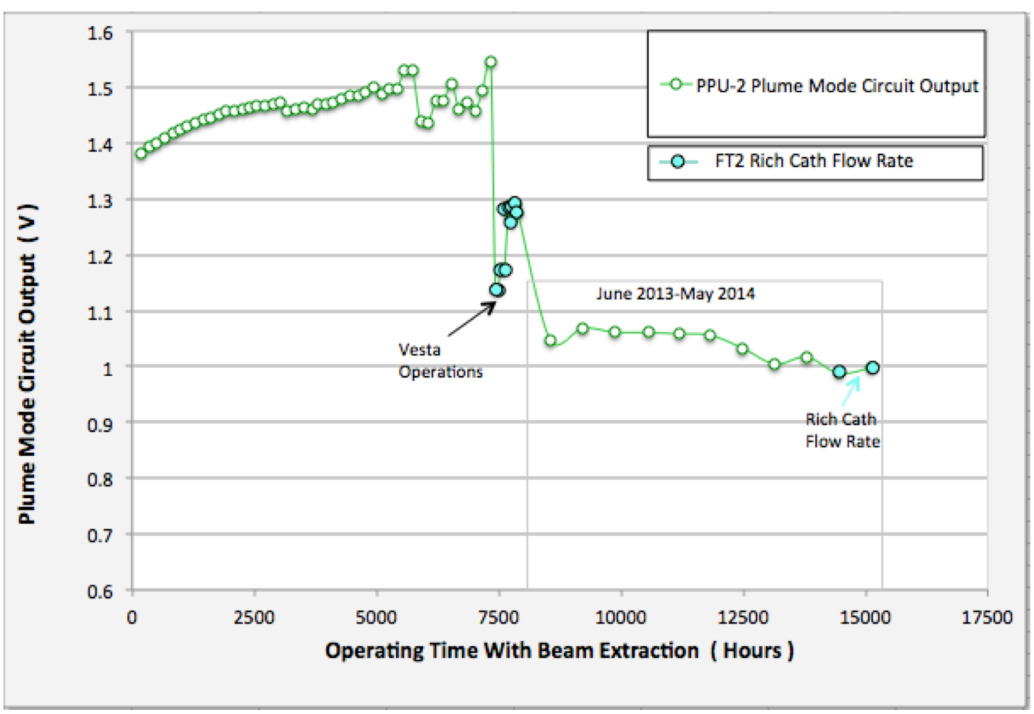

Figure 9. PPU-1 plume mode circuit output for operation on FT2 from launch through May 2014.

Accelerator Grid Current

Accelerator grid current data for FT2 from launch through May 2014 are plotted in Figure 10. The step changes in accelerator grid current evident in Figure 10 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 10-20% 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.

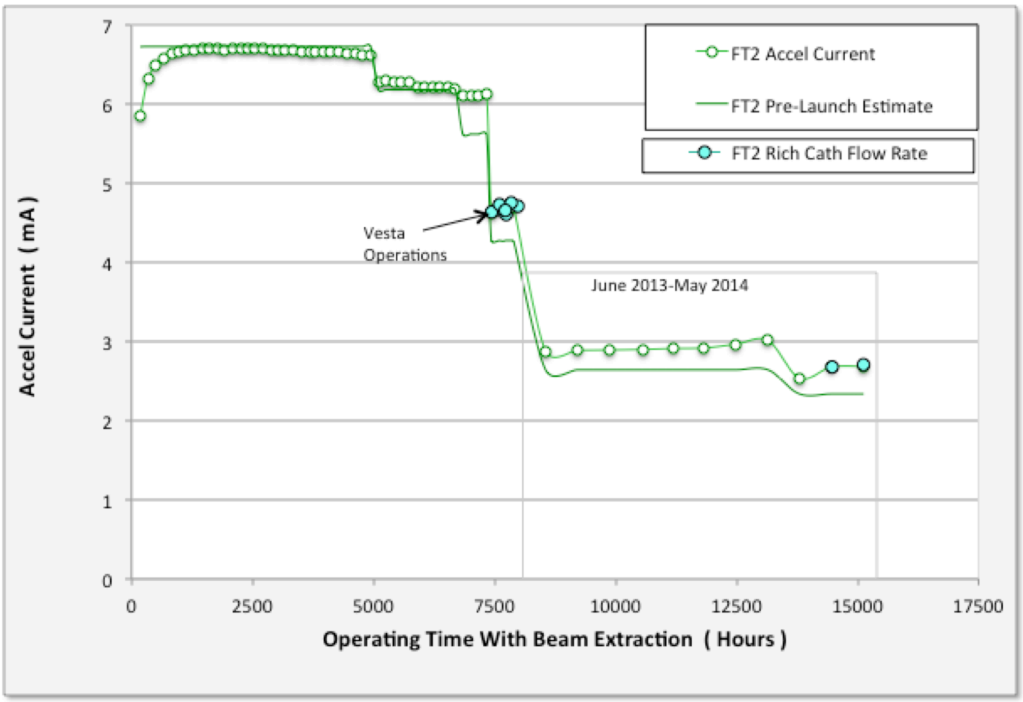

Figure 10. Accelerator grid current for FT2 from launch through May 2014.

Thruster High Voltage Recycles

High voltage recycles for FT2 from launch through the June 2014 are shown in Figure 11. FT2 accumulated 34 recycles operating for approximately 15,125 hours, with 24 recycles occurring at full power. The data suggest that recycle rates have decreased over time and with decreasing power levels, with a rate of one recycle per 236 hours for the first 5,900 hours of beam-on time and one recycle per 1025 hours after 5,900 hours of beam-on time.

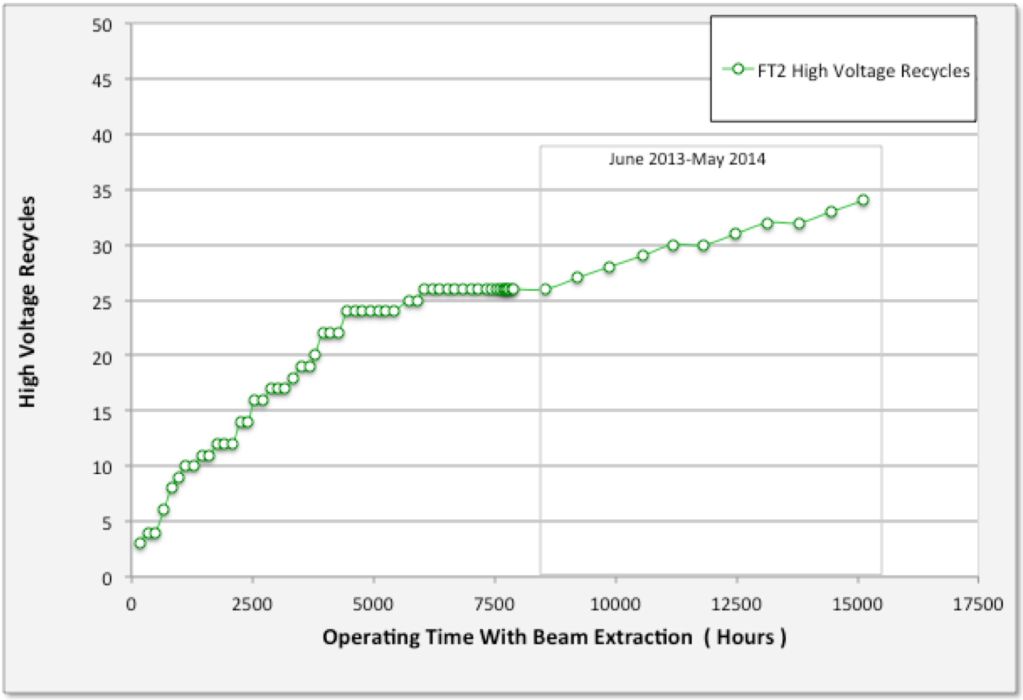

Figure 11. High voltage recycles for FT2 from launch through May 2014.

Thrust Measurements

Thrust calculated from thruster telemetry and reconstructed using navigation data as described in [19] from launch through the end of May 2014 are shown in Figure 12. Thrust values calculated from thruster telemetry were averaged over a time period where thruster operating parameters were stable. During the approach to Vesta phase FT2 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 for cruise to Ceres except for the last two thrust segments where rich cathode flow rates were used as described in the Discharge Characteristics section of this paper. With full power cathode flow rates, thrust values determined by radiometric means 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.

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. 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.

Figure 12. Thrust measurements for FT2 from launch through May 2014.

Thruster and PPU 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 FT2 from start of cruise to Vesta through May 2014 is plotted in Figure 13 as a function of thruster operating time. In the second year of cruise to Ceres input power varied from 1.39 kW at 2.45 AU to approximately 1.1 kW at 2.62 AU, and lower for solar array calibrations where power to the PPU was throttled by tilting the array from the sun.

Data on input power to the PPUs are plotted in Figure 14. Data points are the values averaged at a fixed mission (power) level over the steady-state portion for a thrust segment. The PPU 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-2 during the second year of cruise to Ceres varied from 1.22-1.34 kW, generally lower than the pre-launch poer predict (Figure 14). PPU efficiencies from launch through June 2014 (Figure 15) were consistently in excess of 92%. 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 16. 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, and an example of its effect is the last data point for PPU-2 operations at nominal cathode flow rates (Figure 15).

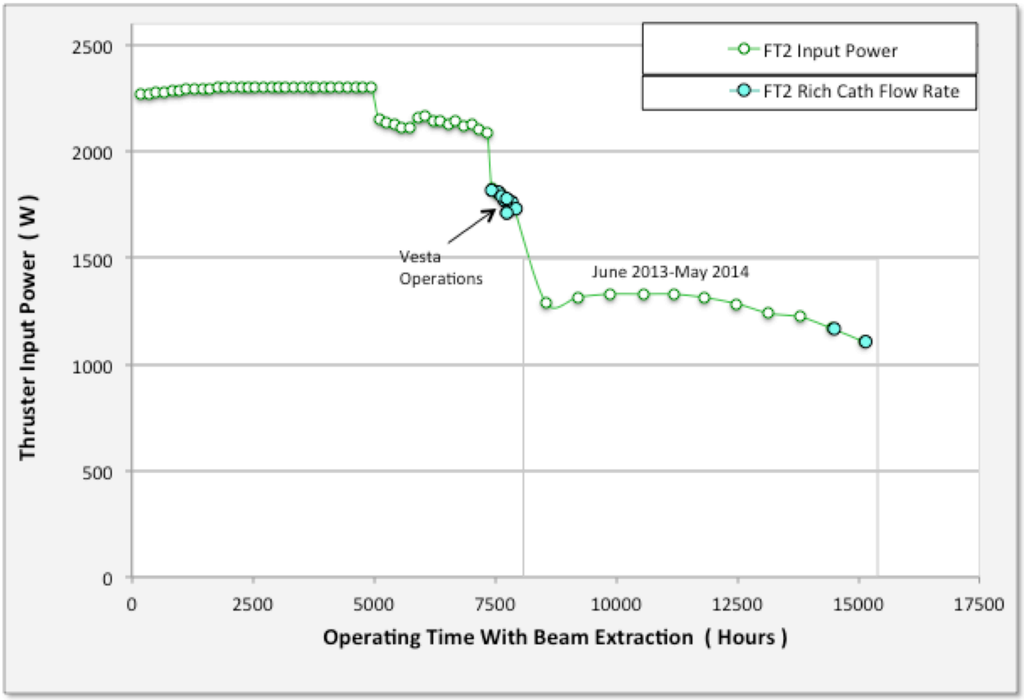

Figure 13. FT2 input power from start of cruise to Vesta through May 2014.

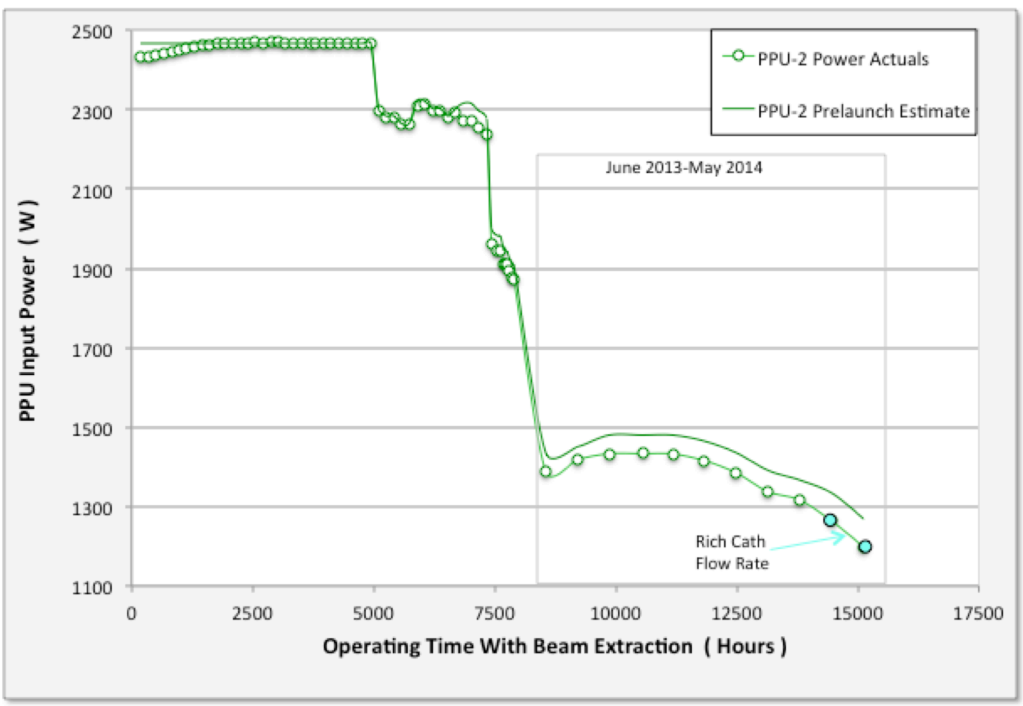

Figure 14. PPU-2 input power from start of cruise to Vesta through May 2014.

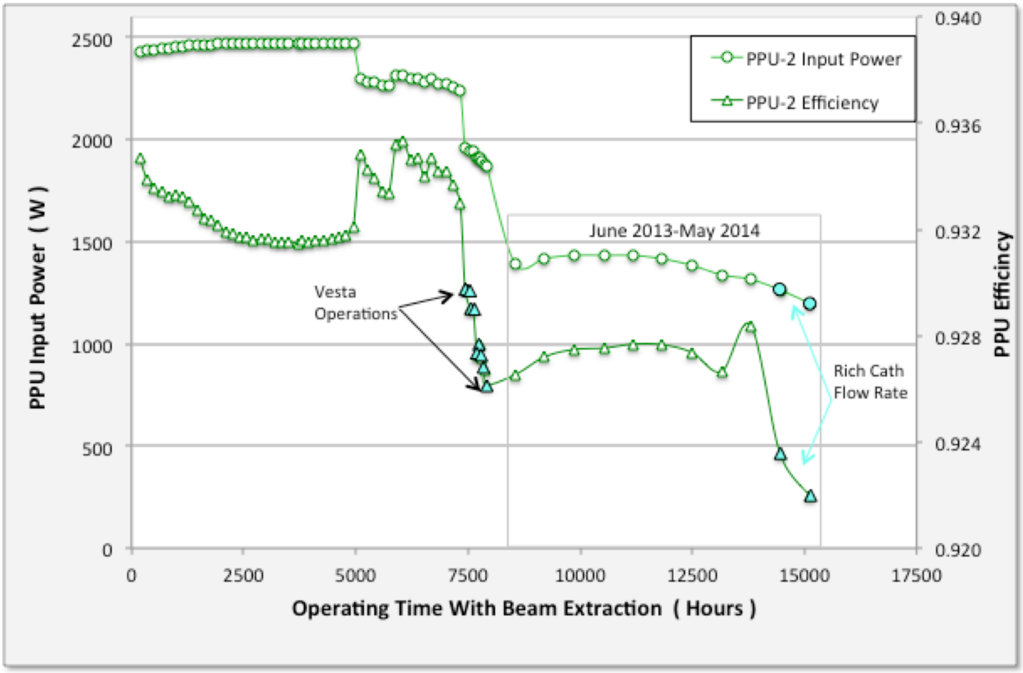

Figure 15. PPU-2 input power and efficiency from launch through May 2014.

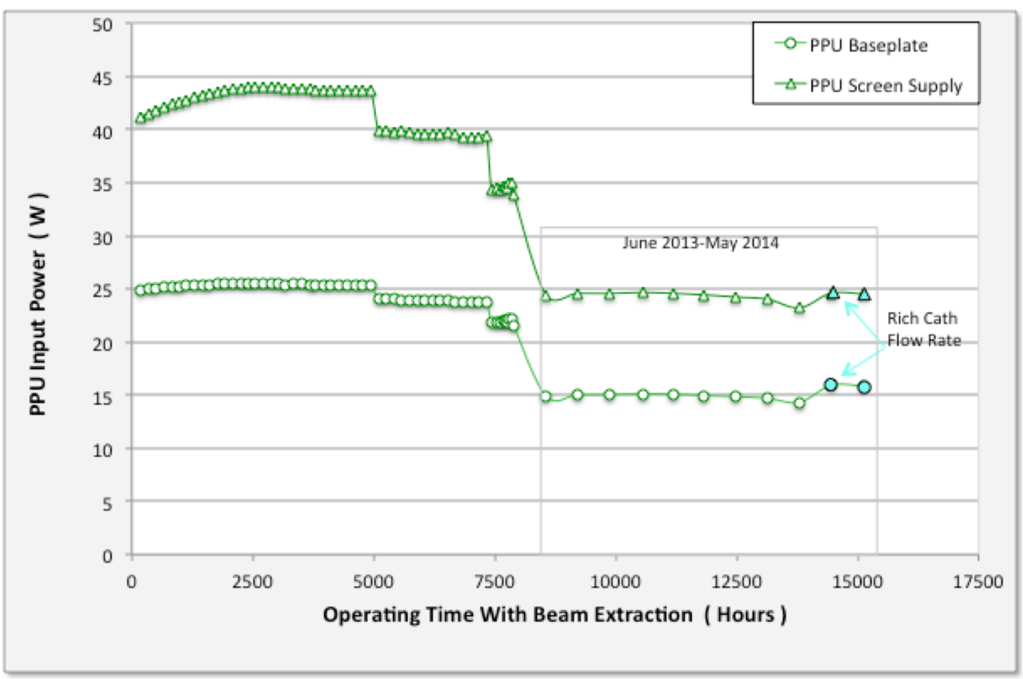

Figure 16. Baseplate and screen supply temperatures for PPU-2 from launch through May 2014.

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 925,280 times since launch, and the primary solenoid valve pair for cathode plenum tank pressure regulation has accumulated approximately 332,256 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.

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-2 (for FT2) actuator equivalent motor revolutions are shown in Figure 17. The data indicate that the TGA motors have accumulated the equivalent of approximately 1,573,000 revolutions. The motor design was life-tested to 30,000,000 revolutions. The duty cycle and number of TGA actuations per kg of xenon used are greater with RWA control [11].

DCIU-2 Operation

DCIU-2 operated flawlessly during the second year of cruise to Ceres. From the period June 2013-May 2014 all DCIU commands were accepted and executed, and there were no operational errors.

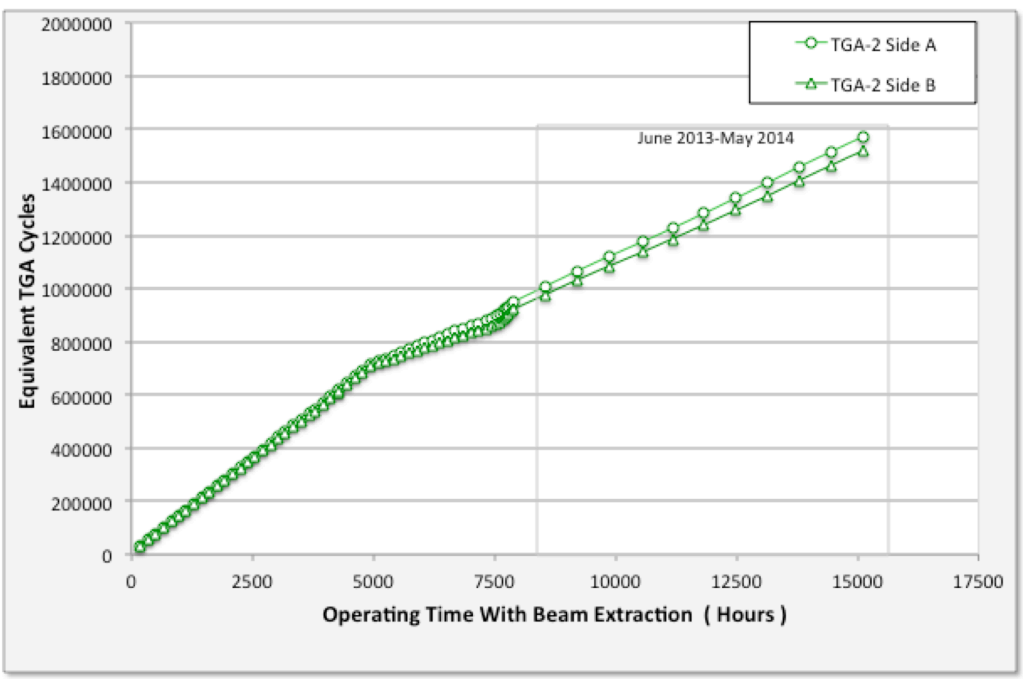

Figure 16. TGA-2 equivalent motor revolutions since launch.

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 23 months of cruise to Ceres. All the IPS components--the thrusters, DCIUs, PPUs, XCA, and TGAs—operated nominally during cruise to Ceres from June 2013 through May 2014. To date the IPS has operated for approximately 38,898 hours with beam extraction, used just over 350 kg of xenon, and imparted a delta-V of over 9.8 km/s to the spacecraft. The Dawn IPS has proven to be extremely reliable and capable with very few operational problems during its almost seven-year journey. Dawn enters into its final nine months of cruise with all IPS subsystem elements healthy. Thrusting to Ceres will continue until spring of 2015, with approach to Ceres in February 2015 and orbit capture by Ceres expected around April 2015. The Dawn ion propulsion is presently fully operational for continued cruise operations to Ceres.

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