In-Flight Operation of the Dawn Ion Propulsion System: Status at One year from the Vesta Rendezvous

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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 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 into an Earth-escape trajectory. On-board the spacecraft is an ion propulsion system (IPS) developed at the Jet Propulsion Laboratory which will provide most of the ΔV needed for heliocentric transfer to Vesta, orbit capture at Vesta, transfer among Vesta science orbits, departure and escape from Vesta, heliocentric transfer to Ceres, orbit capture at Ceres, and transfer among Ceres science orbits. The Dawn ion thruster [I thought we only called it a thruster. Both terms are used in the paper, but I think a replacement of every occurrence of "engine" with "thruster" would be clearer.] design is based on the design validated on NASA's Deep Space 1 (DS1) mission. However, because of the very substantial (11 km/s) ΔV requirements for this mission Dawn requires two engines to complete its mission objectives. The power processor units (PPU), digital control and interface units (DCIU) slice boards and the xenon control assembly (XCA) are derivatives of the components used on DS1. The DCIUs and thrust gimbal assemblies (TGA) were developed at the Jet Propulsion Laboratory. The spacecraft was provided by Orbital Sciences Corporation, Sterling, Virginia, and the mission is managed by and operated from the Jet Propulsion Laboratory. Dawn partnered with Germany, Italy and Los Alamos National Laboratory for the science instruments. The mission is led by the principal investigator, Dr. Christopher Russell, from the University of California, Los Angeles.

The first 80 days after launch were dedicated to the initial checkout of the spacecraft followed by cruise to Mars. Cruise thrusting leading to a Mars gravity assist began on December 17, 2007 and was successfully concluded as planned on October 31, 2008. During this time period the Dawn IPS was operated mostly at full power for approximately 6500 hours, consumed 71.7 kg of xenon and delivered approximately 1.8 km/s of ΔV to the spacecraft. The thrusting to Mars was followed by a coasting period of approximately 3.5 months that included a Mars flyby in February of 2009. The Mars flyby provided a gravity assist (MGA) for a plane change and approximately 1 km/s of heliocentric energy increase and is the only part of the mission following launch in which a needed velocity change is not accomplished by the IPS. During the coast period IPS was operated for a trajectory correction maneuver and for engineering tests but was not operated for primary propulsion. Closest approach to Mars occurred as planned on February 17, 2009 and was followed by another coasting period of just under 4 months in duration. During this last coasting phase IPS was operated only for routine maintenance activities and for system engineering tests. Deterministic thrusting for heliocentric transfer to Vesta resumed on June 8, 2009. Since resumption of cruise to Vesta IPS has been operated at throttled power levels, most of the time at full power, and with a duty cycle of approximately 93%, leading to an arrival at Vesta in July of 2011 and arrival at Ceres in February 2015. This paper provides an overview of Dawn's mission objectives and the results of Dawn IPS mission operations through one year from the spacecraft's rendezvous with Vesta.

I. Introduction

Electric propulsion has entered the era of application. 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]. There are several European and U.S.-launched communications satellites with SPT-100 –based propulsion modules for attitude control and orbit boosting. The Hayabusa spacecraft returned to Earth after exploring asteroid Itokawa [3] and employs cathode-less ion engines for primary propulsion. Several

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communications satellites based on the Boeing 702 bus and the Japanese ETS-VIII include ion thrusters for north-south station keeping.

The Dawn mission is the ninth project in NASA's Discovery Program. 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 will be the first mission to orbit a main belt asteroid and the first to orbit two extraterrestrial bodies.

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 [4]. The combination of low-cost, cost caps, and short development times presents substantial challenges to an ambitious mission such as Dawn. 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. Cruise operations for deterministic thrusting began December 17, 2007 leading to a Mars flyby in February 2009, a rendezvous with Vesta in July 2011, and 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 one year from the spacecraft's rendezvous with Vesta.

II. Mission and Flight System Overview

The mission and flight system are described in detail in References 5-8, and are summarized here. Vesta is the second most massive main belt asteroid with a mean diameter of 530 km, 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, and shape studies suggest it may have a large inventory of water, making Ceres a valuable body to investigate to determine 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 [6,7]. 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 [8] and Leostar [6] satellite platform series. The four composite panels comprising the X and Y sides of the spacecraft are attached to a graphite composite core cylinder that houses the main xenon tank and hydrazine tank. The solar array (SA) consists of two large panel assemblies approximately $18 m^2$ each and measuring almost 20m tip to tip with triple junction cells providing approximately 10.3 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 electrical power system includes unregulated high voltage power to the IPS and regulated low voltage power for spacecraft subsystems. A nickel-hydride battery provided power during launch and supplements low voltage power to the spacecraft if the spacecraft low voltage bus drops below minimum values.

The spacecraft attitude control system (ACS) employs both reaction wheel assemblies (RWA) and mechanical gyros for three-axis control of the spacecraft and, as will be explained later, makes use of IPS for pitch and yaw control during normal IPS thrusting. The reaction control system (RCS) uses hydrazine thrusters for direct three axis control of the spacecraft and is used 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.

The Dawn spacecraft science instrument complement includes two framing cameras (FC) from Germany for imaging science, navigation, and topographical data, a gamma ray and neutron detector (GRaND) from Los Alamos National Laboratory for determining the location and abundances of key elements including hydrogen, a possible indicator of water, and a visible and infrared mapping spectrometer (VIR) from Italy for surface mineralogy measurements. The FC and GRaND instruments are located on the +Z panel of the spacecraft, and the VIR instrument is located on the –X panel. All instruments are mounted so the centers of their fields of view are aligned with the spacecraft's +*Z* axis. A mass summary for the Dawn flight system is provided in Table 1.

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	129
Xenon	425
Flight System mass at Launch	1218

The Dawn ion propulsion subsystem developed at JPL is described in detail in References 9-11 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 [12,13], 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 control, a Xenon Control Assembly (XCA) for controlling xenon flow to the engines, and a xenon storage tank. The ion thrusters and the PPUs are based on technology developed by NASA [13], 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 system 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 ratio of tank mass to xenon mass is an astounding 0.05 and represents a true breakthrough in total IPS mass reduction. The xenon feed system is based on the DS1 design but was modified to operate multiple thrusters and to be single-fault tolerant. It includes an XCA placed outside the spacecraft core cylinder with two 3.7-liter plenum tanks identical to those flown on DS1, and uses the same xenon flow rate control design to control pressure to flow rate control devices (fixed flow orifices), latch valves and solenoid valves (similar to those used on DS1), service valves, interconnecting tubing, and nine flexible propellant lines (three for each thruster across the TGA interface). The center-mounted thruster is designated FT3 (flight thruster 3), and can be powered by either PPU. The outboard thrusters are designated FT1 on the –X panel and FT2 on the +X panel. Each thruster is mounted to a TGA with two struts to each thruster gimbal pad in a hexapod-type configuration (six struts total per ion thruster). Actuators driven by electronics cards in the DCIU that are commanded by the spacecraft ACS are used to articulate two pairs of the TGA struts for 2-axis control of the thrust pointing vector.

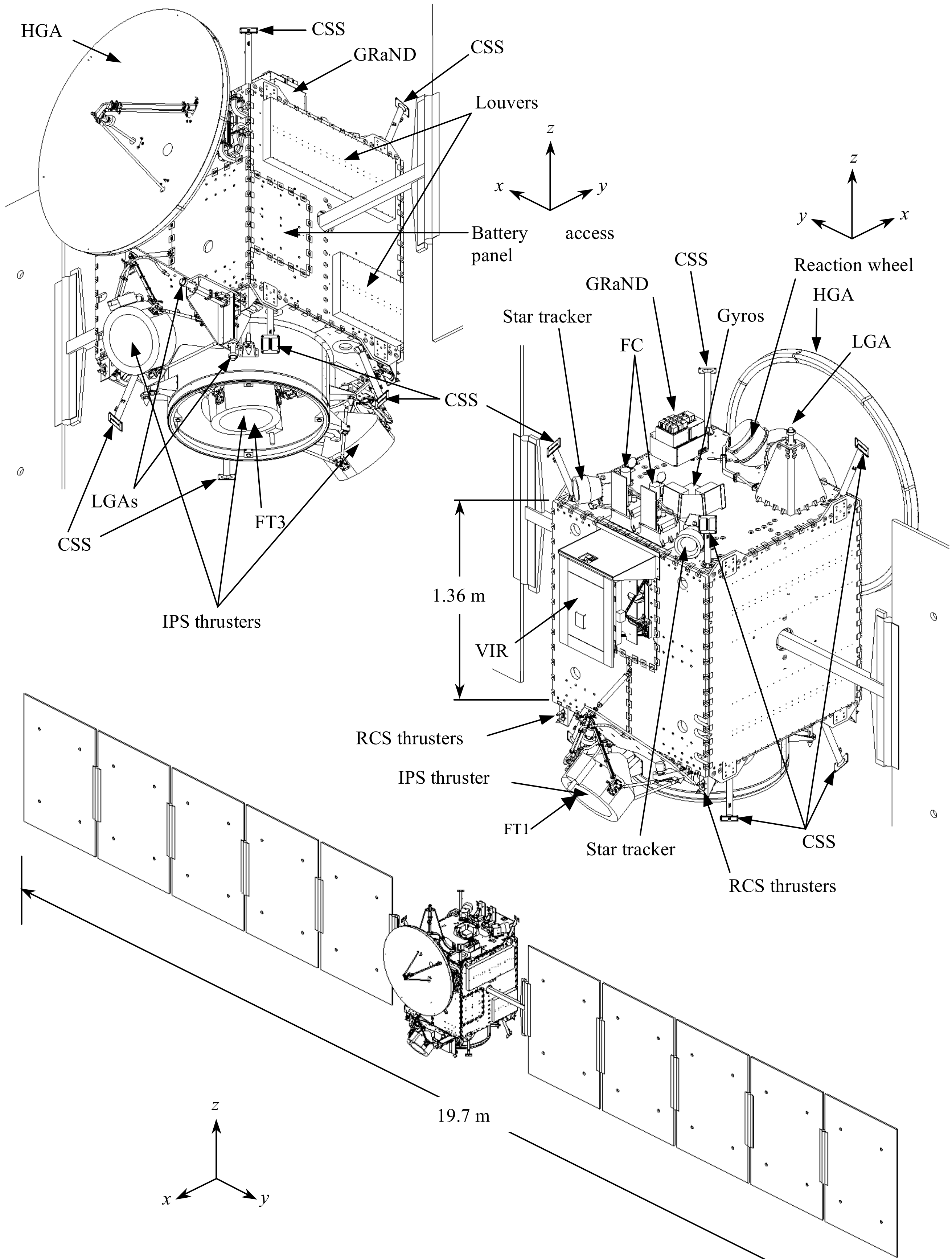

Figure 1. Schematic diagram of the Dawn flight system, from [6].

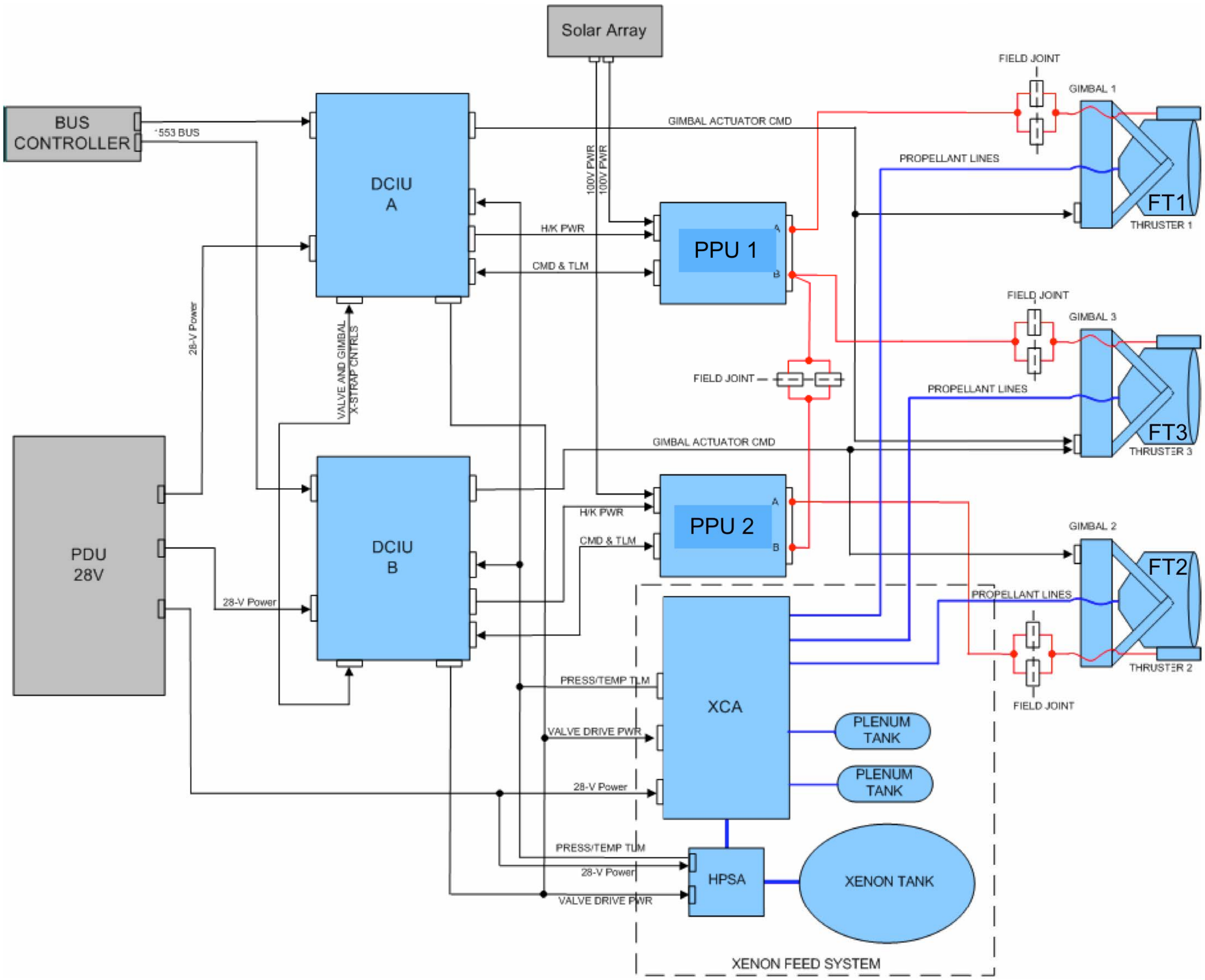

Figure 2. Block diagram of the Dawn IPS subsystem.

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

The Dawn ion propulsion system is designed to be single-fault-tolerant. Ion thrusters using the 30-cm-diameter NASA design were operated for 16,265 hours on the DS1 mission [1] and 30,352 hours in an extended life test [14], however the Dawn mission requires 389 kg (Table 2) or 194.5 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 [11]. Analyses [15] and test data [14] 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 directly to the High Voltage Electronics Assembly (HVEA) which provides unregulated solar array power to the PPUs, and to one DCIU. 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.

Table 2. Xenon Allocation Summary

Description	Xenon Allocation (kg)
Initial Checkout	2.7
Diode Mode Operation	2.7
Xenon Lost to Thruster Restarts	1.9
Main Tank Residuals	5.0
Leakage	10.0
Allocation for Vesta Operations	14.5
Allocation for Ceres Operations	10.5
Deterministic Interplanetary Thrusting	358.0
Margin	19.9
Total	425.2
Total Xenon Used Through June 2010	167.4

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 plane change, is approximately 13.6 km/s (Table 3). IPS will provide 11.0 km/s of this ΔV and will use approximately 389 kg of xenon for the complete mission.

Table 3. Dawn Mission Summary. Bold font indicates the mission phase has been completed. IPS has delivered 4.5 km/s of ΔV as of June 2010.

Description	Time Period	Distance S/C to Sun AU	Power Level To IPS kW	Comments
Launch	**09/27/2007**	**1**	**NA**	
Initial Checkout	**09/2007--12/2007**	**1--1.16**	**2.6**	**ΔV =0.04 km/s (From IPS)**
Cruise prior to MGA	**12/2007--11/2008**	**1.16--1.68**	**2.6**	**ΔV =1.74 km/s (From IPS)**
MGA Plane Change	**02/2009**	**1.4**	**NA**	**ΔV =2.6 km/s (From MGA)**
MGA Heliocentric Energy	**02/2009**	**1.4**	**NA**	**ΔV =1.1 km/s (From MGA)**
Cruise to Vesta	06/2009--07/2011	1.40--2.26	2.6-1.7	DV =4.7 km/s (From IPS)
Vesta Science Operations	07/2011--06/2012	2.26-2.51	1.7-1.3	DV =0.48 km/s (From IPS)
Cruise to Ceres	06/2012--02/2015	2.51-2.84	1.3--0.9	DV =3.55 km/s (From IPS)
Ceres Science Operations	02/2015--07/2015	2.84 - 2.93	0.9	DV =0.48 km/s (From IPS)

Dawn has already completed the initial checkout (ICO) [16], cruise before the MGA, and MGA phases, and in June 2009 Dawn resumed deterministic thrusting leading to a rendezvous with Vesta in July 2011 and Ceres in 2015.

III. Overview of IPS Operations

The ICO, cruise before MGA, the MGA, and optimal coasting phases were completed successfully and are discussed in detail in [17,18]. The effect of the MGA was to alter the direction of the angular momentum of Dawn's heliocentric orbit by 5.2^0, equivalent to a delta-V of 2.3 km/s, and increase Dawn's heliocentric energy by approximately 1.1 km/s [19]. Table 4 summarizes the changes to Dawn's orbital elements and includes values for Vesta's orbit for comparison [19].

Table 4. Summary of orbital characteristics before and after the MGA, from [19].

Orbital Element	Dawn Before MGA	Dawn After MGA	Vesta
Inclination	1.8^0	6.2^0	7.1^0
Longitude of ascending node	49^0	101^0	104^0
Perihelion (AU)	1.23	1.37	2.15
Aphelion (AU)	1.68	1.84	2.57

Deterministic thrusting for cruise to Vesta resumed on June 8, 2009, with the spacecraft at approximately 1.37 AU from the sun. The goal for this phase of the mission is to modify the spacecraft's heliocentric trajectory leading to capture at Vesta in July 2011 and includes using IPS for deterministic thrusting and spacecraft engineering tests[Are we using the IPS for engineering tests during this time?]. The arrival date to Vesta, originally projected to be September 2011, changed primarily due to better than expected solar array performance, allowing IPS operation at higher power and hence thrust levels over time than originally expected.

FT1 was started for the first thrust arc after Mars and was used until January 2010 when thrusting using FT2 began. The mission plan calls for using a combination of FT2 and FT3 until arrival at Vesta in July 2011. Although the Dawn mission can be accomplished with just two ion thrusters, thruster operation has been divided between the three thrusters to minimize wear in a single engine and maximize the likelihood of mission success. IPS will continue to be operated at full power with the goal of distributing full-power operating time as evenly as possible between the three thrusters. Operation at full power is now almost completed. Starting in mid-2010, with the spacecraft at approximately 2.0 AU, power available from the solar arrays will fall below the level needed for the flight system with full power to the IPS and the thrusters will be operated at reduced power (throttled). IPS then will be operated at throttled power levels for the remainder of the mission. By the time the spacecraft reaches Vesta power available to the PPUs will be about 1.7 kW. For Vesta cruise the mission operations plan calls for the IPS to be operated at a weekly duty cycle of approximately 95% at power levels ranging between 2.5 and 1.7 kW. In addition, some periods of forced coasting, typically lasting a week, are included in the trajectory for special activities such as installation of software or instrument calibrations. These represent no more than 5% of the mission time.

Thrusting periods during cruise to Vesta are divided into approximately seven day intervals, with off-times for data playbacks and command uplinks limited to approximately 8.5 hours. The seven-day thrusting intervals are referred to as thrust arcs. The mission plan includes several time periods of no thrusting for engineering activities that are incompatible with the IPS thrust attitude. IPS telemetry from the DCIU is stored every ten seconds (except during cathode ignition time periods) and retrieved during the weekly spacecraft data playbacks. During cathode ignition time periods IPS telemetry from the DCIU is 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 can be recorded at high data rates. Real-time telemetry at varying data rates are also available periodically. A thrust verification pass is typically performed mid-week to verify that IPS and the spacecraft are operating nominally. This activity requires the use of the traveling wave tube amplifier (TWTA), which uses almost 200 W, for communications to the Deep Space Network (DSN) at high data rates.

During normal operations power output from the solar arrays can be supplemented by the on-board low voltage bus battery if the array output is insufficient to power all spacecraft needs. The distance between the sun and Dawn spacecraft will increase throughout the cruise to Vesta phase, starting at 1.37 AU in July 2009 and ending with Vesta capture at 2.26 AU in July 2011. Until approximately April 2010 there was sufficient power generated by the solar arrays to supply all spacecraft functions (about 800 W typically), periodic high power usage when certain spacecraft events occur such as simultaneous use of many heaters, and the 2,500 W IPS requires for full power operation. In April 2010 it was observed that for the first time the battery state of charge (SOC) had decreased for a brief time period (less than 30 seconds), indicating that for this short period of time the arrays were unable to provide full power to IPS and power for all spacecraft functions. In May 2010 the battery SOC decreased by about 1% for the duration of the thrust verification pass, indicating that the solar array output was no longer sufficient for simultaneous operation of IPS at full power and the TWTA. The mission plan calls for elimination of the mid-week thrust verification passes as part of normal spacecraft weekly operations in July 2010 to provide maximum power to IPS for the full duration of the thrust arc.

As the spacecraft's distance from the sun continues to increase the available power output from the sun will decrease to the point where there will be insufficient array power output to operate IPS at full power and the battery SOC will decrease to an unacceptable level. Dawn has on-board control software to automatically and autonomously regulate the power used by IPS to the maximum achievable throttle level that also provides enough power for normal spacecraft activities. The control software, called Autonomous Thrust Reduction (ATR), automatically sends commands to the DCIU to reduce the power level for IPS in approximately 20 W steps when the battery SOC drops below a certain threshold. The control software maintains IPS at this new, lower power level and continues to issue power level command changes to the DCIU for as long as the battery SOC is below the required threshold. In some cases a change to a new, higher power level is included in the command sequences to account for instances where ATR might reduce power to IPS too much due to occasional spacecraft activities such as heavy heater use. First use of ATR is expected in late July 2010.

IPS Operation For Cruise Leading to Capture at Vesta

Thruster operating time and xenon consumption from launch through June 2010 are summarized in Tables 4-6.

Table 5. Thruster Operating Time Summary Through June 2010*

	Initial Checkout	Cruise for MGA	Vesta Cruise	Total
Thruster	Beam On-Time	Beam On-Time	Beam On-Time	Beam On-Time
	hr	hr	hr	hr
FT1	42.1	2908.9	4674.3	7625
FT2	22.0	8.0	3674.0	3704
FT3	213.7	3579.7		3793
Total	277.7	6496.6	8149.3	15123

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

Table 6. Thruster Xenon Summary Through June 2010*

	ICO	Cruise for MGA	Vesta Cruise	Total
Thruster	Xenon Use	Xenon Use	Xenon Use	Xenon Use
	kg	kg	kg	kg
FT1	0.40	32.43	51.8	85
FT2	0.27	0.11	40.5	41
FT3	2.4	39.50		42
Total	3.07	72.04	92.3	167

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

Operation for cruise to Vesta using FT1, the thruster mounted on the –Y axis of the spacecraft, commenced on June 18, 2008 and ended on January 4, 2010. By that time FT1 had completed approximately 7,583 hours of full-power thrusting time and utilized 85.6 kg of xenon. Operation for cruise to Vesta using FT2, the thruster mounted on the +Y axis of the spacecraft, commenced on January 4, 2010. As of June 2010 FT2 had completed approximately 3688 hours of full-power thrusting time and utilized 40.7 kg of xenon.

The duty cycle for IPS is defined as the time with beam extraction divided by the total mission time for thrust arcs, and therefore does not include spacecraft engineering activities. FT1 was operated with a duty cycle of just over 94.2%; the duty cycle for FT2 was just over 94.4% from January through June 2010. Duty cycle can be increased with improved mission planning. FT3, the center mounted thruster, has not been used since June 2008, but the operations plan calls for FT3 to be used in 2011 to maintain an approximately equal distribution of xenon throughput for each engine.

IPS Performance-PPU, Xenon Flow System, and TGAs

Unregulated high voltage power from the solar array to the PPUs for operation of FT1 and FT2 at full power 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 159.5 hours. For both PPUs power increased and then stabilized, following changes to discharge power utilization of FT1 and FT2 as the thrusters wear. PPU efficiencies are similar to the efficiencies measured preflight and are consistently in excess of 92%. The PPUs have operated perfectly throughout the mission to date.

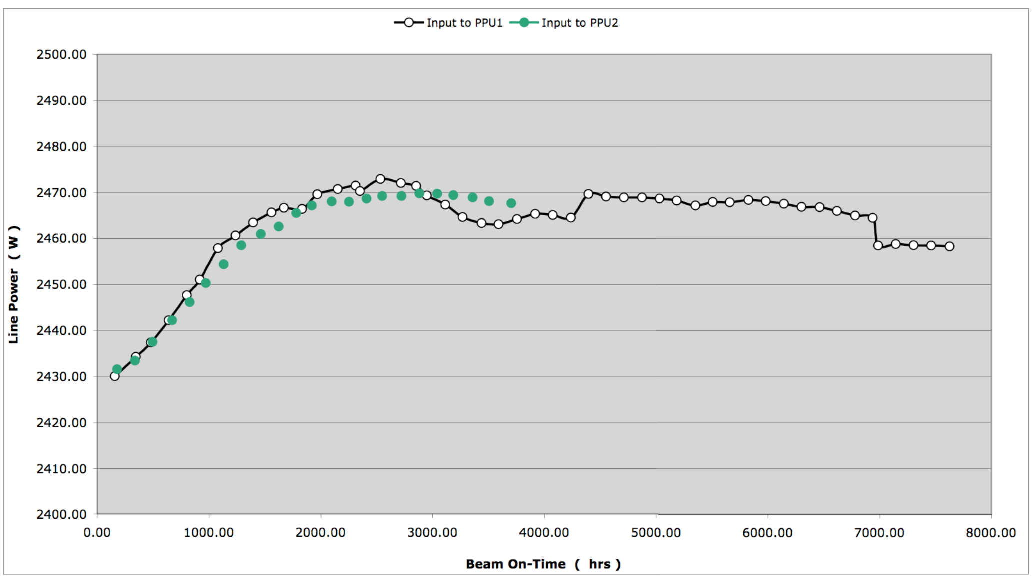

Figure 4. Line power to Dawn PPUs.

Data (averaged over individual thrust arcs) from temperature sensors inside the PPU shown in Figure 5 indicate that PPU temperatures have changed little during cruise. Data for FT3 [17] showed similar results. 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 25-27 degrees C with the thrusters operating at full power. Temperatures of the harness connectors mating the thrusters to the PPUs are shown in Figure 6. The data indicate that at full power operation connector temperatures have ranged between 12-35 degrees C and imply that at full power operation the harnesses are well within operational temperature limits. The change in harness temperature at 2,900 hours of operation on FT1 is due to the spacecraft's increased distance from the sun as a result of the MGA coast.

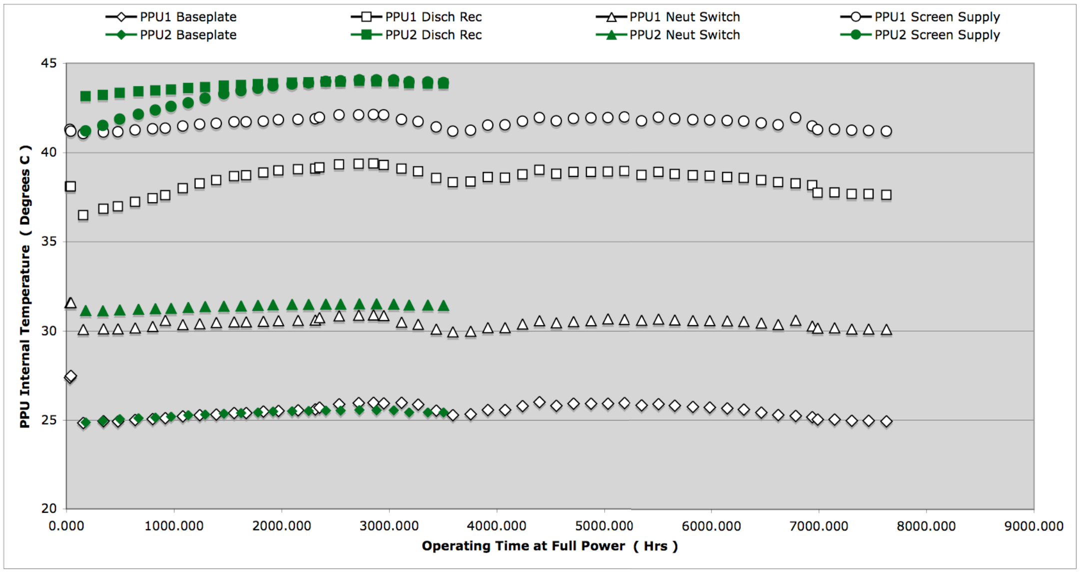

Figure 5. Temperatures measured by the internal sensors with the PPUs operating at full power.

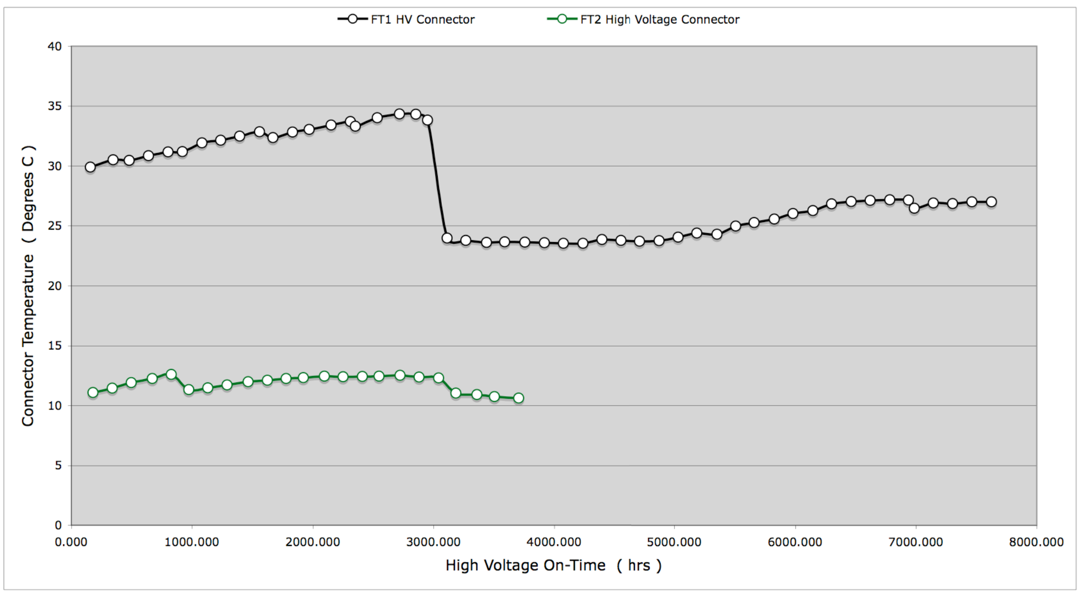

Figure 6. High voltage harness connector temperatures for FT1 and FT2.

The xenon flow system has operated perfectly throughout cruise before the MGA, with the exception of unexpectedly high solenoid valve cycling rates [17]. Solenoid valve pairs are opened and closed to regulate pressure to the xenon flow system plenum tanks. As of mid- June 2010 the primary solenoid valve pair used to regulate main plenum pressure has been cycled open and closed approximately 355,000 times in cruise, and the primary solenoid valve pair for cathode plenum tank pressure regulation has cycled approximately 102,000 times. The controlling temperature for the xenon control assembly plate was reduced early in cruise to reduce the solenoid valve cycle rate [17]. Differences in pressure measurements between the three pressure transducers on each plenum tank have remained at low values.

The TGAs have also operated flawlessly in cruise. Each TGA is used to move the ion thruster vector through the spacecraft center of mass to control the spacecraft attitude in pitch and yaw, called thrust vector control (TVC). Cumulative TGA actuator steps for the A-side motors for TGA-1 and TGA-2 are shown in Figure 7. The B-side motors have almost the same number of steps. The data indicate that TGA-1 motors have accumulated over one million steps through mid-June 2010. The spacecraft is operated in TVC mode during normal thrusting, including during desaturations of the RWAs, which are sequenced approximately every 12 hours. TGA duty cycle has varied between 0.6% and 1%, which is at or less than the expected duty cycle of 1%. In normal operation the TGAs "dither", or rotate, a small amount around a target center. 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.

Thruster Starts

As of June 2010 there have been a total of 239 thruster starts in flight. FT3 has been started in flight 66 times. FT1 has been started 115 times in flight, with 58 of these starts with beam extraction. FT2 has been started 58 times in flight, with 29 of these starts with beam extraction. The cathode heater preheat duration for all starts was six minutes. All start attempts on all thrusters have been successful. Data taken at one second intervals indicate that in every start attempt during cruise the cathodes ignited immediately upon application of the igniter voltage pulses.

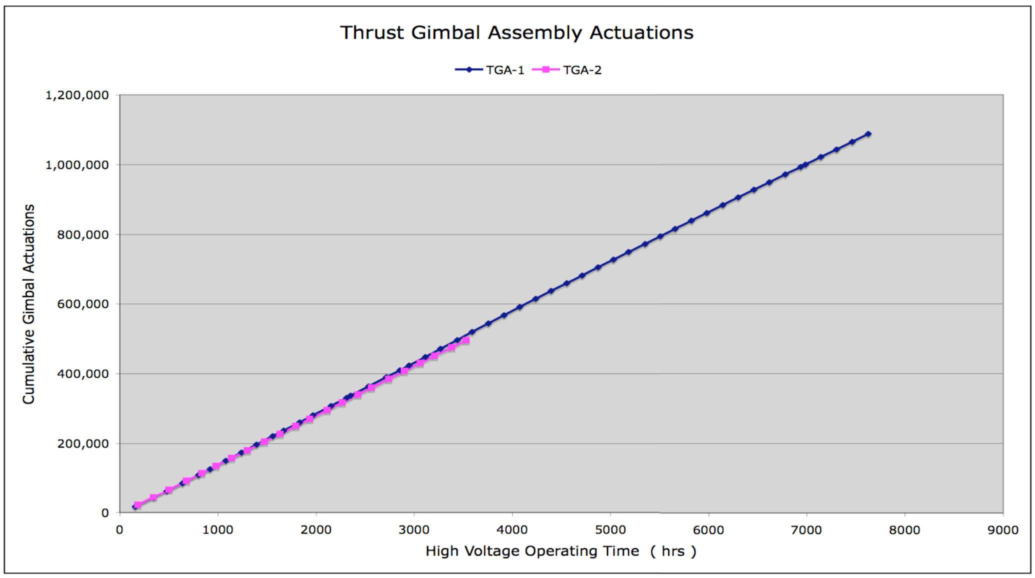

Figure 7. TGA actuations for TGA-1A (gimbals FT1) and TGA-2A (gimbals FT2).

The nominal cathode heater current for both the neutralizer and discharge cathodes is 8.5 A. FT1 and FT2 peak heater power for all start attempts with beam extraction during cruise are plotted in Figure 8. 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 thruster for approximately 54 minutes at approximately 250 W was performed before every start attempt with beam extraction to reduce the risk of thruster recycles (low-impedance arcs between the screen and accelerator grids) from transient screen/accelerator grid spacing changes from thermal expansion. Peak heater power for the FT1 discharge cathode increased by two W over the peak power at start of cruise, but since approximately 3,600 hours of full-power operation heater power has been decreasing. The temperature of the thruster on starts has been relatively constant over time (exceptions are at hour 2,100 for FT1) so the reason for reduced discharge cathode heater power starting around 3,600 hours may be enlargement of the keeper orifice, allowing more radiation to escape so the heater operates at lower power.

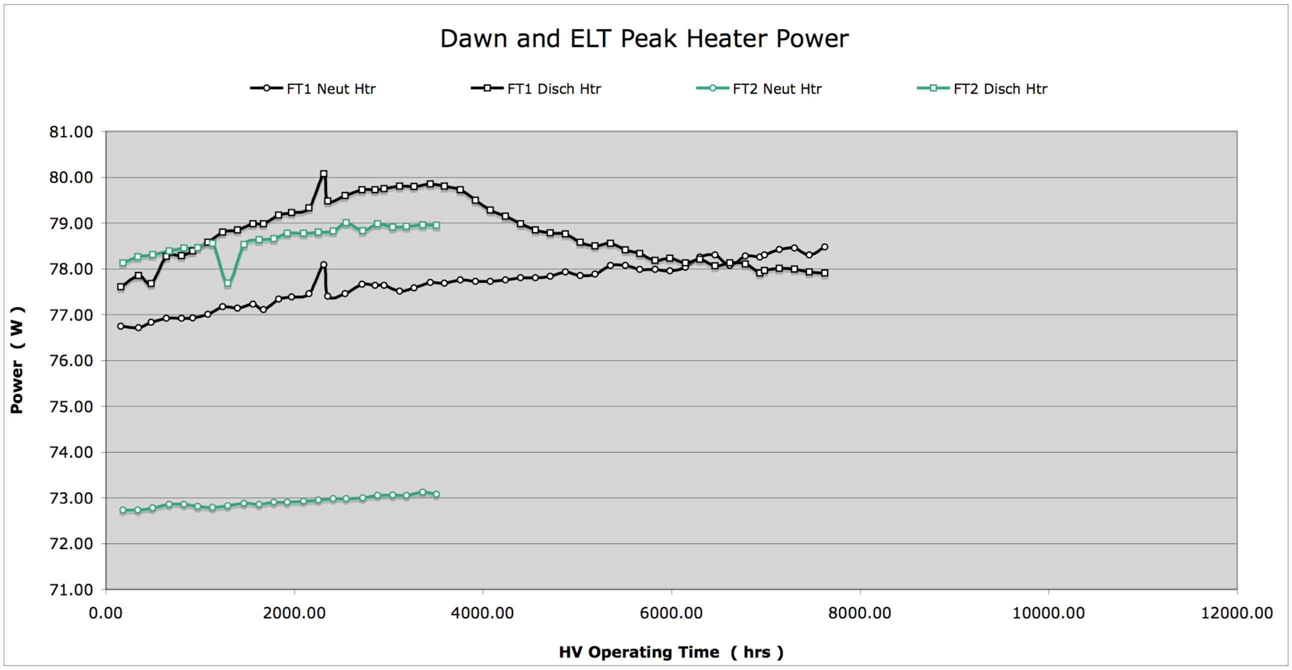

Figure 8. Discharge and neutralizer cathode heater power for FT1 and FT2.

Thruster Performance in Cruise

Data for FT1 and FT2 operating at full power during cruise are shown in Tables 7-8 and Figures 9-16. Table 7 also includes values from the beginning of life (BOL) throttle table. Thruster operation was very stable throughout all of cruise to date, except for the changes noted below. At full power operation the nominal neutralizer current is 1.5 A, the beam current is 1.76 A, the accelerator grid voltage is -200 V, and the total engine flow is just under 3 mg/s [This sounds huge! I'm not sure what you mean, but the total mass flow should be just over 3 mg/s, right?]. During cruise the neutralizer current has been nearly constant at 1.499 A, the beam current has been nearly constant at 1.756 A, and the accelerator grid voltage has been -200 V.

Table 7. FT1 Operating Characteristics Through June 2010

	Beam		Accel.		Discharge			Neutralizer		PPU		
	J_B	V_B	J_A	V_A	J_D	V_D	Disch Loss	J_D	V_D	Input Power	Output Power	Eff.
	(A)	(V)	(A)	(V)	(A)	(V)	(eV/ion	(A)	(V)	(W)	(W)	
Throttle Table BOL	1.76	1100	6.42	-200	13.9	24.6	195	1.5	13.9	2483	2294	0.924
Initial Checkout	1.756	1100	4.84	-200	14	24.9	199	1.5	13.5	2458	2300	0.936
Cruise-June 2008	1.757	1100	6	-200	14.2	24	194	1.5	12.8	2430	2293	0.94
Crusie-Jan 2010	1.757	1100	6.3	-272	15.3	24.6	208	1.5	11.1	2458	2316	0.942

Table 8. FT2 Operating Characteristics Through June 2010

	Beam		Accel.		Discharge			Neutralizer		PPU		
	J_B	V_B	J_A	V_A	J_D	V_D	Disch Loss	J_{NK}	V_{NK}	Input Power	Output Power	Eff.
	(A)	(V)	(A)	(V)	(A)	(V)	(eV/ion	(A)	(V)	(W)	(W)	
Throttle Table BOL	1.76	1100	6.59	-200	13.2	23.9	180	1.5	13.7	2461	2274	0.924
Initial Checkout	1.756	1098	4.67	-200	13.5	24.2	185	1.5	12	2454	2273	0.926
Cruise-Jan 2010	1.756	1100	5.9	-199.9	13.8	23.2	183	1.5	13.1	2433	2273	0.933
Cruise-June 2010	1.758	1100	6.7	-199.9	15	23.1	198	1.5	11.2	2470	2296	0.93

Accelerator grid current data for both FT1 and FT2 during cruise are plotted in Figure 9. The accelerator grid current increased during the first 1,700 hours of operation at full power and leveled off to about 6.6 mA after that. This is unlike the behavior of the accelerator grid impingement current noted in the ELT [14], which started at a higher level and then decreased over a period of approximately 1,000 hours to approximately 6.5 mA after that. It appears from 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. There has been no indication from flight telemetry of electron backstreaming.

Recycles as a function of cumulative operating time at full power are shown in Figure 10. A total of 45 recycles on FT3 operating at full power for 3,793 hours has occurred during cruise, an average of 81 hours of full-power operation for each recycle. FT1 has accumulated 65 recycles at an average of 117 hours of full-power operation for each recycle. FT2 has accumulated 19 recycles for an average of 195 hours of full-power operation for each recycle. For cruise operations after approximately 1,600 hours of beam on-time per thruster the recycle rate is 104 hours per recycle for FT1, 280 hours per recycle for FT2, and 127 hours per recycle for FT3 indicating the recycle rate at full power operation is slowly decreasing. Most recycles occurred well after the start of beam extraction, indicating that debris accumulated as part of the ATLO process was still being cleared.

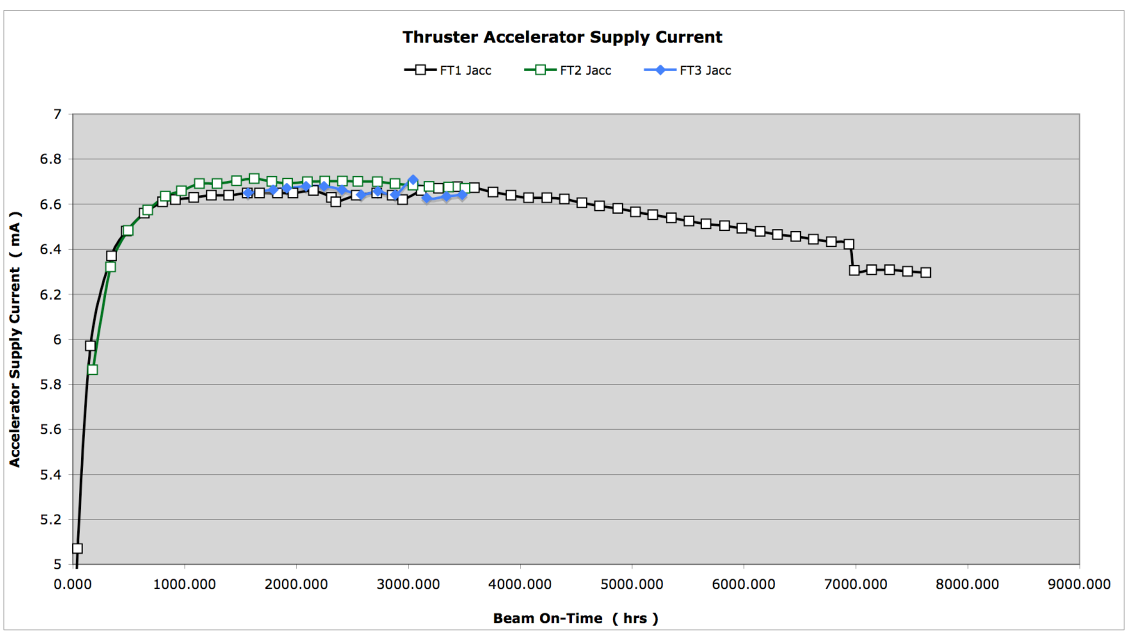

Figure 9. Accelerator grid current for Dawn ion thrusters during cruise.

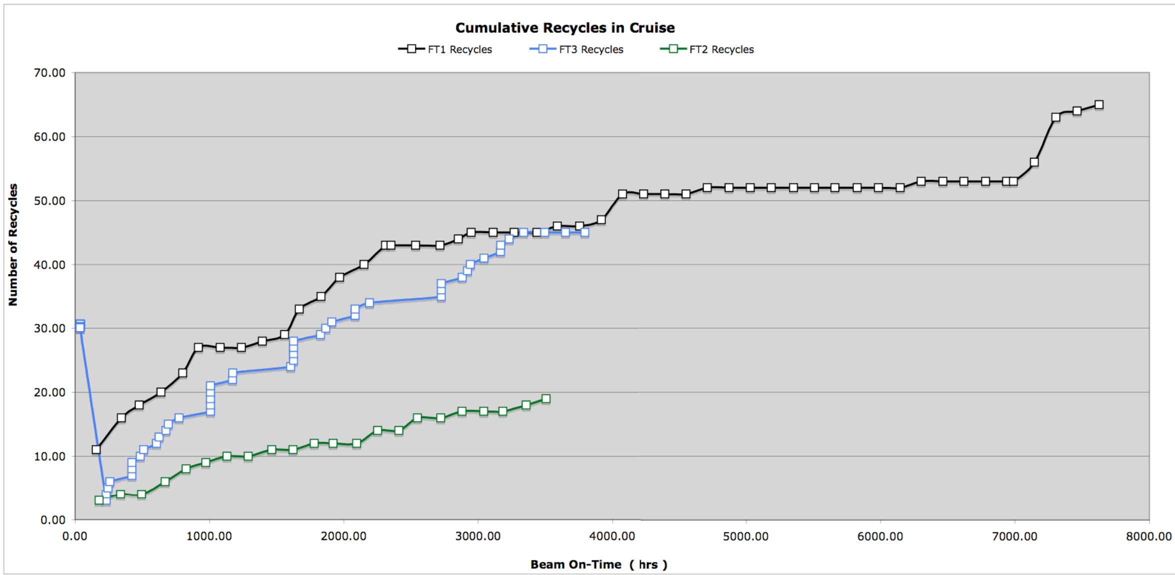

Figure 10. Recycles during cruise for FT1 and FT3.

Neutralizer voltage data for operation of Dawn thrusters at full power and the ELT at full power are plotted in Figure 11. Neutralizer voltage has decreased in a similar way for all three thrusters since the thrusters were first operated at the start of cruise. ELT neutralizer voltage decreased for a time but then increased, however the data from the ELT may be affected by the testing environment. Dawn thruster neutralizer voltage changes may be related to improved cathode conditioning over time or to neutralizer orifice wear. Neutralizer voltage for FT2 has exhibited periodic changes which then change to more nominal values in subsequent thrust arcs. The cause for this neutralizer voltage behavior is not understood.

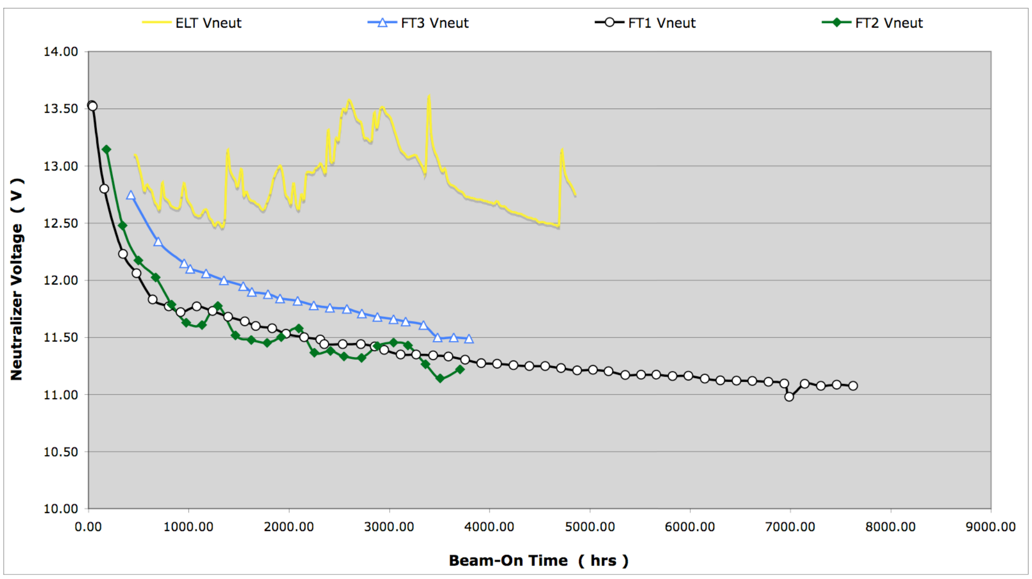

Figure 11. Neutralizer Voltage During Cruise.

A plume mode detection circuit in the PPU converts variations in the alternating current (AC) component of the neutralizer voltage to a direct current (DC) voltage. The plume mode circuit voltage is monitored continuously to evaluate the health of the neutralizer. Plume mode circuit output data averaged over individual thrust arcs for Dawn thrusters are shown in Figure 12. In normal operation the plume mode circuit voltage increases to approximately six volts during the first approximately 30 seconds after cathode ignition, when the cathodes operate with substantial AC variations in their DC voltages. Plume mode circuit output then decreases over a period of minutes to approximately one volt during normal neutralizer operation. Plume mode circuit data show no indication of neutralizer cathode operation in plume mode during cruise.

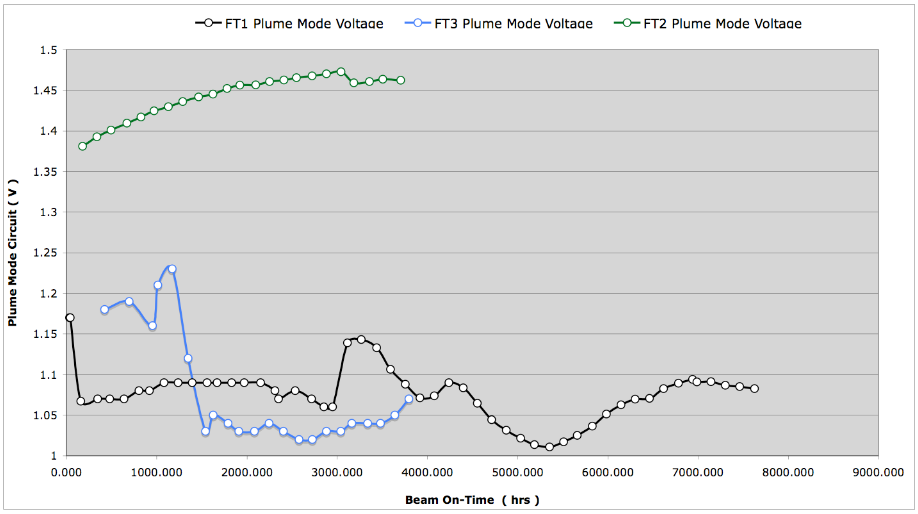

Figure 12. DC output of the plume mode circuit for Dawn thrusters during cruise.

Discharge current, discharge power, and discharge loss for Dawn thrusters during cruise and for the ELT are shown in Figures 13-15; Dawn discharge voltage values are measured at the PPU and do 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 10-18 W less depending upon harness temperatures. The discharge current for FT1 exceeds that for FT2, FT3 and the ELT because during FT1 assembly two of the permanent magnets for this ring-cusp thruster were installed incorrectly.

Initially discharge current increased until the thrusters had processed approximately 22-25 kg of xenon, whereupon discharge current essentially did not change. Discharge current for the ELT [18] continued to increase for a longer period of time but by a lesser amount. The likely cause for the observed increase in discharge current is erosion of accelerator grid hole cusps from direct ion impingement resulting in a greater neutral propellant loss rate. Discharge power for Dawn thrusters and the ELT are shown in Figure 14 and track somewhat to changes in discharge current, although the fact that discharge voltage has been decreasing, due possibly to improved cathode conditioning over time, thruster attitude to the sun and solar distance complicate the thruster power picture. Over approximately 3,600 hours of operation at full power, discharge power increased by 20 W for FT1, by 22 W for FT2, by 18 W for FT3, and by 20 W for the ELT. There was a noticeable increase in discharge current for FT3 for the last two thrust arcs that is unresolved. Data on discharge loss for Dawn thrusters and the ELT are plotted in Figure 15. Discharge loss tracks with discharge power. During cruise discharge loss increased by 15 W/A for FT1 and FT2, and 8 W/A for FT3; discharge loss for the ELT increased by 9 W/A over a similar time period. In [22] it is proposed that discharge loss is a function of both grid hole wear and cathode keeper erosion, which may explain why Dawn thruster discharge loss appeared to level out at lower operating times that observed on the ELT.

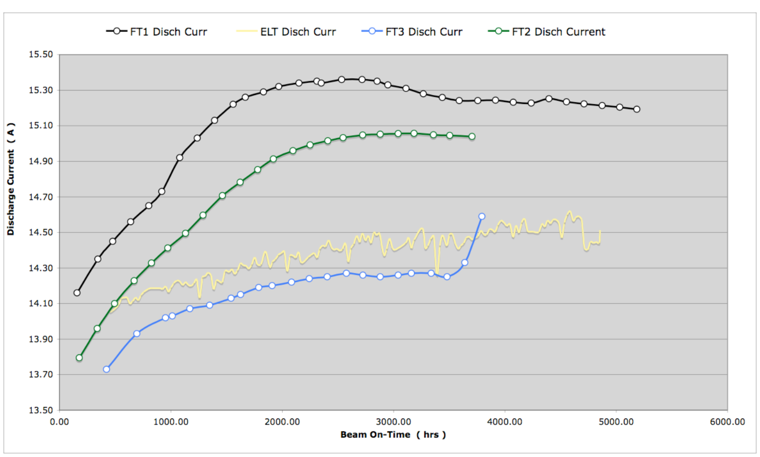

Figure 13. Discharge current during cruise for Dawn FTs and for the ELT.

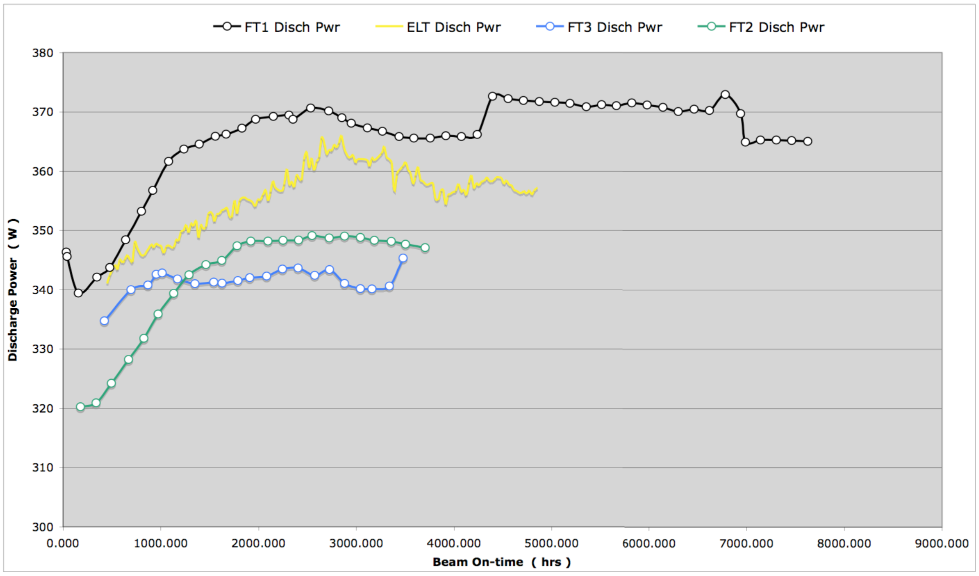

Figure 14. Discharge power during cruise for Dawn FTs and for the ELT.

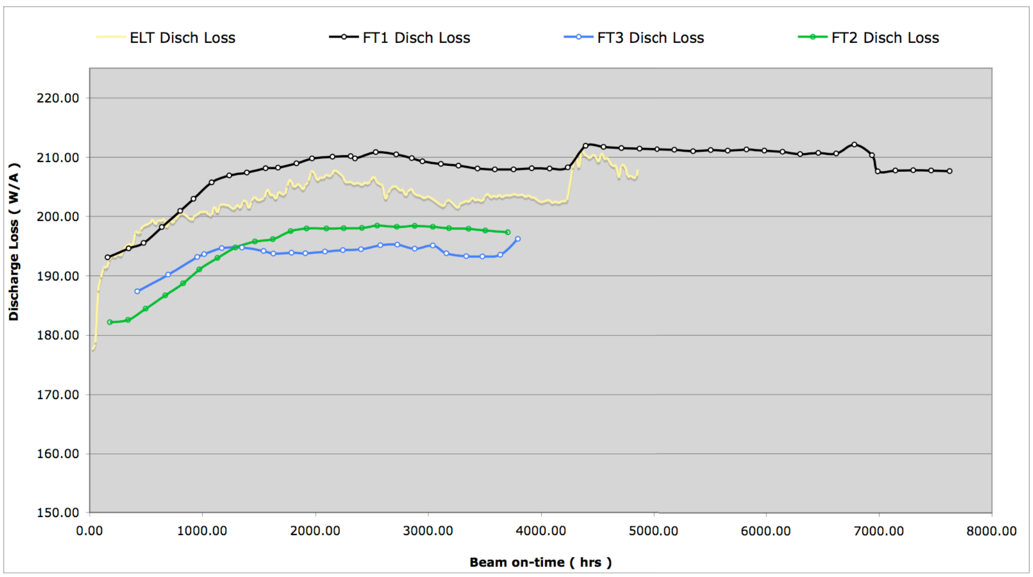

Figure 15. Discharge loss during cruise for Dawn FTs and for the ELT.

Thrust Measurements and Roll Torque

Direct thrust measurements from Dawn thrusters were obtained during the ICO using changes in the Doppler shift of the radio signal from the spacecraft [16]. During cruise thrust levels developed by the IPS are 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 [21]. Calculated (reconstructed) thrust values for Dawn thrusters are reproduced in Figure 16. Uncertainty (1-σ) for all reconstructed thrust determinations is better than $\pm$1 mN. Thrust measurements made during the ICO are included for comparison. Thrust measurements for cruise calculated from thruster parameters are averaged over the entire thrusting period (beam on, beam off) and include a correction to the beam voltage (it is assumed the net beam voltage is 7 V less than the screen supply voltage) and to the thrust loss factor due to operation at greater accelerator grid voltages at thruster end of life resulting in slightly reduced thrust. During cruise at full power thrust calculated from thruster parameters has consistently been 91 ±0.1 mN at beginning of life values and 90.7 ± 0.1 mN for FT1 beginning in early December 2009, when FT1 had reached a throughput of approximately 77 kg of xenon.

Reconstructed thrust values for Dawn thrusters at the start of their cruise thrust arcs (December 2007 for FT3, June 2008 for FT1, and January 2010 for FT2) are generally close to thrust values calculated from thruster parameters but over time reconstructed thrust values have decreased by about 0.6 mN and 1.7 mN per 10, 000 hours of operation at full power for FT3, 0.9 mN and 1.2 mN per 10,000 hours at full power for FT1, and 0.4 mN and 1.1 mN per 10,000 hours of operation at full power 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 over time, an increase in beam divergence over time, a change in beam power telemetry over time, a change in the net accelerating voltage over time, operation at a lower than expected xenon mass flow rate over time resulting in a larger than expected spacecraft mass, and pointing errors through the spacecraft center of mass. [20] 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 of plume divergence changes and the thrust changes were within experimental error. For mission modeling and future orbit determinations the worst-case thrust of approximately 89.5 mN is assumed, so the in-flight performance for Dawn thrusters provides margin to the mission.

The Dawn requirement for roll torque is 60 μN-m at any thruster power level, which caps the amount of hydrazine required to complete the mission. Hydrazine consumption to null out roll torque accumulated due to IPS operations is typically 40 g per week for Dawn thrusters operating at full power and 10 g per week without IPS in operation. Roll torques measured about the thruster axis for Dawn thrusters are shown in Figure 17. Roll torque measured for Dawn thrusters during cruise continue to meet the requirement, but instead of being a static value, roll torques have changed during cruise. Roll torques for FT3 and FT1 have decreased but increased for FT2. It is possible that the change in roll torque observed during cruise is due to changes in alignment of the accelerator grid to the screen grid, but there is no evidence, such as changes in accelerator grid impingement current, to indicate the grid hole alignments are changing. Grid gap changes, however, are possible and were observed on the ELT [20]. Pointing error has also been proposed as a possible source for the change in roll torque. The Dawn project is continuing its study of thruster roll torque changes.

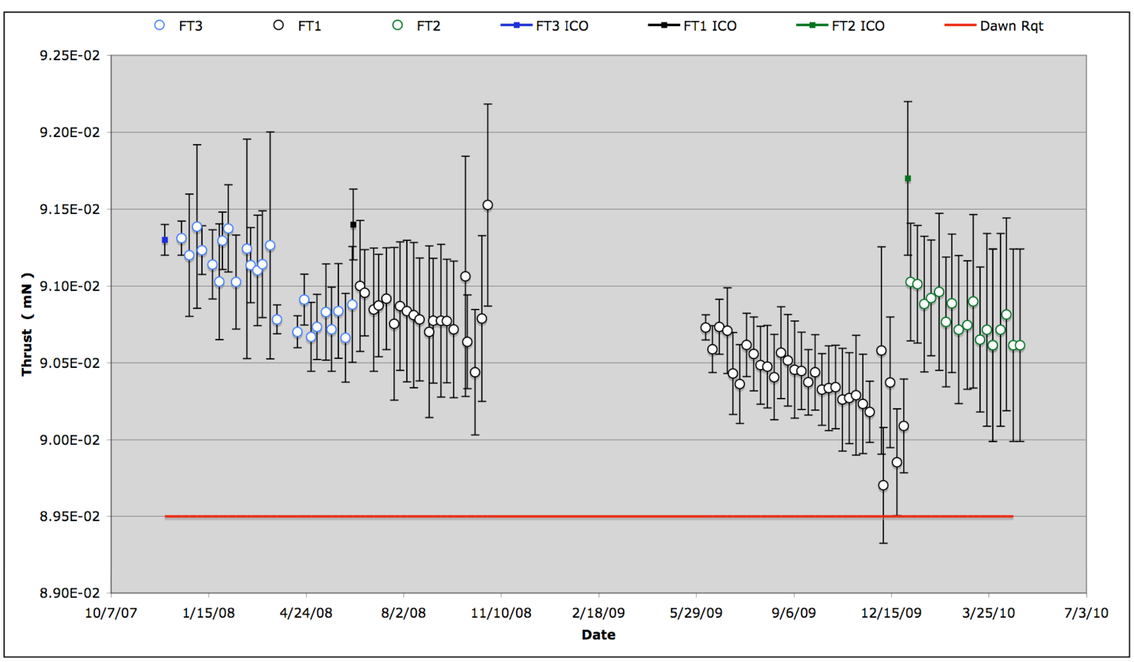

Figure 16. Thrust for FT1 during cruise for a Mars flyby and for start of cruise to Vesta.

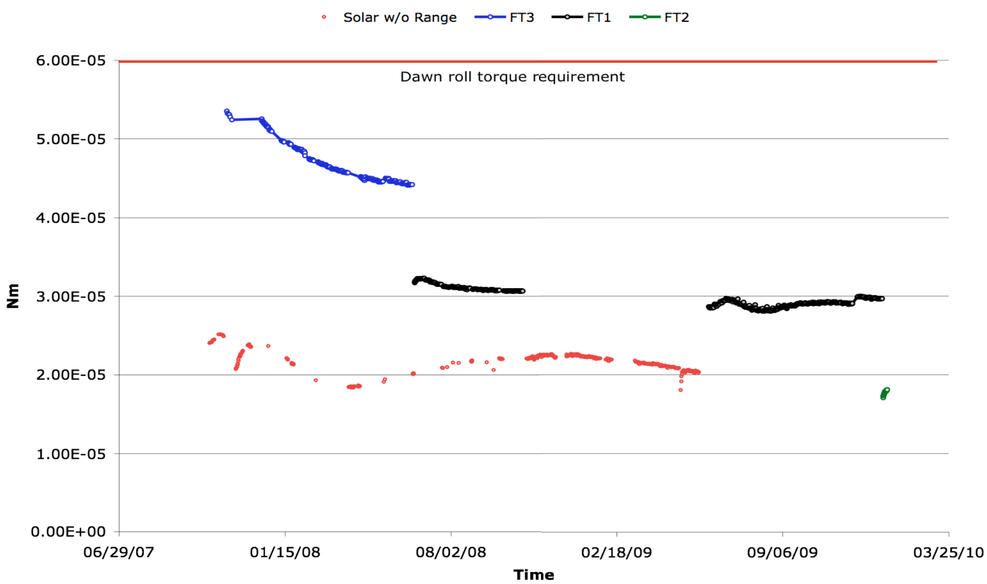

Figure 17. Roll torque for FT1 and FT3 during cruise.

IV. IPS Operations Plan at Vesta

To rendezvous with Vesta the IPS will be used to spiral the spacecraft toward the asteroid for orbit capture at an altitude of approximately 15,000 km. Science observations will be conducted from three different orbits, with the IPS performing all transfers between orbits and any maintenance maneuvers within the orbits. IPS will be used at 1.5 kW input power to spiral down to the first science orbit at an altitude of approximately 2700 km . Spiral orbit transfers will bring the spacecraft to the other two science orbits, at altitudes of approximately 650 km (following one month of transfer) and 200 km (requiring two months). Following the completion of science observations in the lowest altitude orbit, the IPS will be used to raise the orbit to take further observations at 650 km, taking advantage of the Sun being farther north for Vesta, thus illuminating previously unseen terrain. Then the IPS will be used to escape and resume interplanetary operations. ICO activities, MGA, all thrusting to reach Vesta, science, and operations at Vesta will require a ΔV of 7 km/s and 255 kg of xenon, or approximately 64% of the mission IPS ΔV and xenon. The IPS is planned to be operated at full-power and throttled power for a total of approximately 26,000 hours from the start of cruise through Vesta escape.

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. Mission operations plans call for the IPS to be operated power-throttled at a duty cycle of approximately 94% during cruise to Ceres at power levels ranging from 0.9 to 1.37 kW. The remainder of the time during cruise to Ceres is devoted to communications and data downlink to Earth, spacecraft and instrument maintenance activities, etc. 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. The ΔV to be provided by the IPS for all of Ceres operations including heliocentric transfer will approach 4 km/sec, or about 36% of the total ΔV of 11 km/s provided by the IPS.

V. Conclusion

The Dawn mission is using an ion propulsion system for heliocentric transfer to the asteroid Vesta and will subsequently use it for transfer to the dwarf planet Ceres, and for transfer between science orbits at each body. Deterministic thrusting for cruise prior to the MGA began on December 17, 2007 and was successfully completed on October 31, 2008. This phase of the mission was followed by a coast phase lasting approximately seven months and included a Mars gravity assist with closest approach to Mars occurring on February 17, 2009. Deterministic thrusting resumed on June 8, 2009 leading to capture at Vesta in July 2011, earlier than originally planned. The Dawn ion propulsion system has operated almost flawlessly throughout the mission to date, accumulating over 15,123 hours of beam-on time that resulted in over 4.5 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. Deterministic thrusting at full power will continue through mid-2010 and then at throttled power levels afterwards, leading to a Vesta rendezvous in 2011 and a Ceres rendezvous in 2015.

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