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In-Flight Operation of the Dawn Ion Propulsion System Through Start of the Vesta Cruise Phase

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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) which will provide most of the ΔV needed for heliocentric transfer to Vesta, orbit capture at Vesta, transfer to Vesta science orbits, departure and escape from Vesta, heliocentric transfer to Ceres, orbit capture at Ceres, and transfer to Ceres science orbits. The Dawn ion 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. IPS will be operated for over two years at throttled power levels leading to arrival at Vesta in September 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 the start of deterministic thrusting to Vesta.

I. Introduction

Electric propulsion has entered the era of application. Deep Space 1 (DS1), launched in 1998, operated its single engine 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 is returning 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 September 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 the start of deterministic thrusting to 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 vulcanism. 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 beginning of 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, safety and mission assurance, project systems engineering, mission design, and navigation development, and is responsible for mission operations system development and mission operations.

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 18m^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 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.

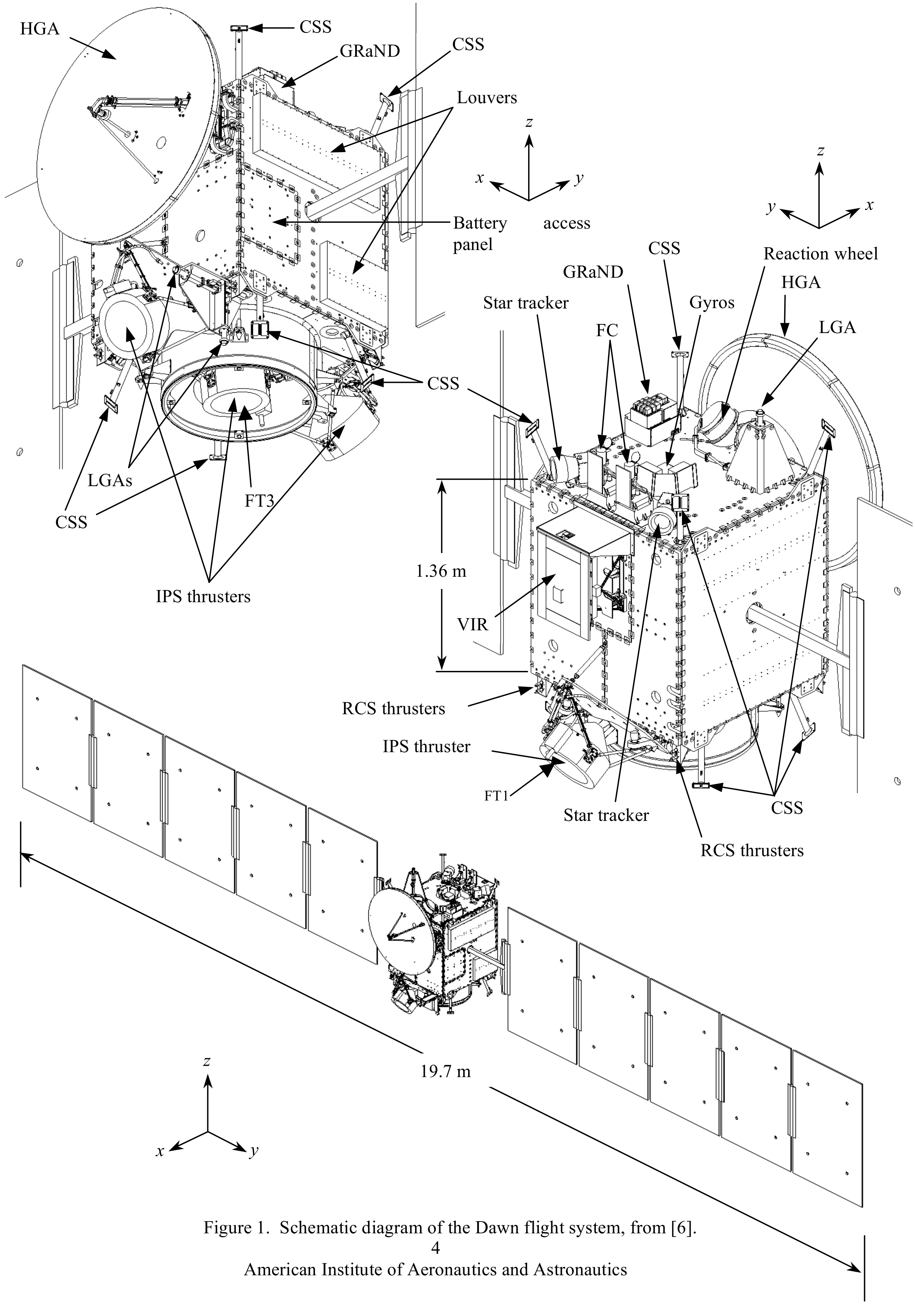

Figure 1. Schematic diagram of the Dawn flight system, from [6].

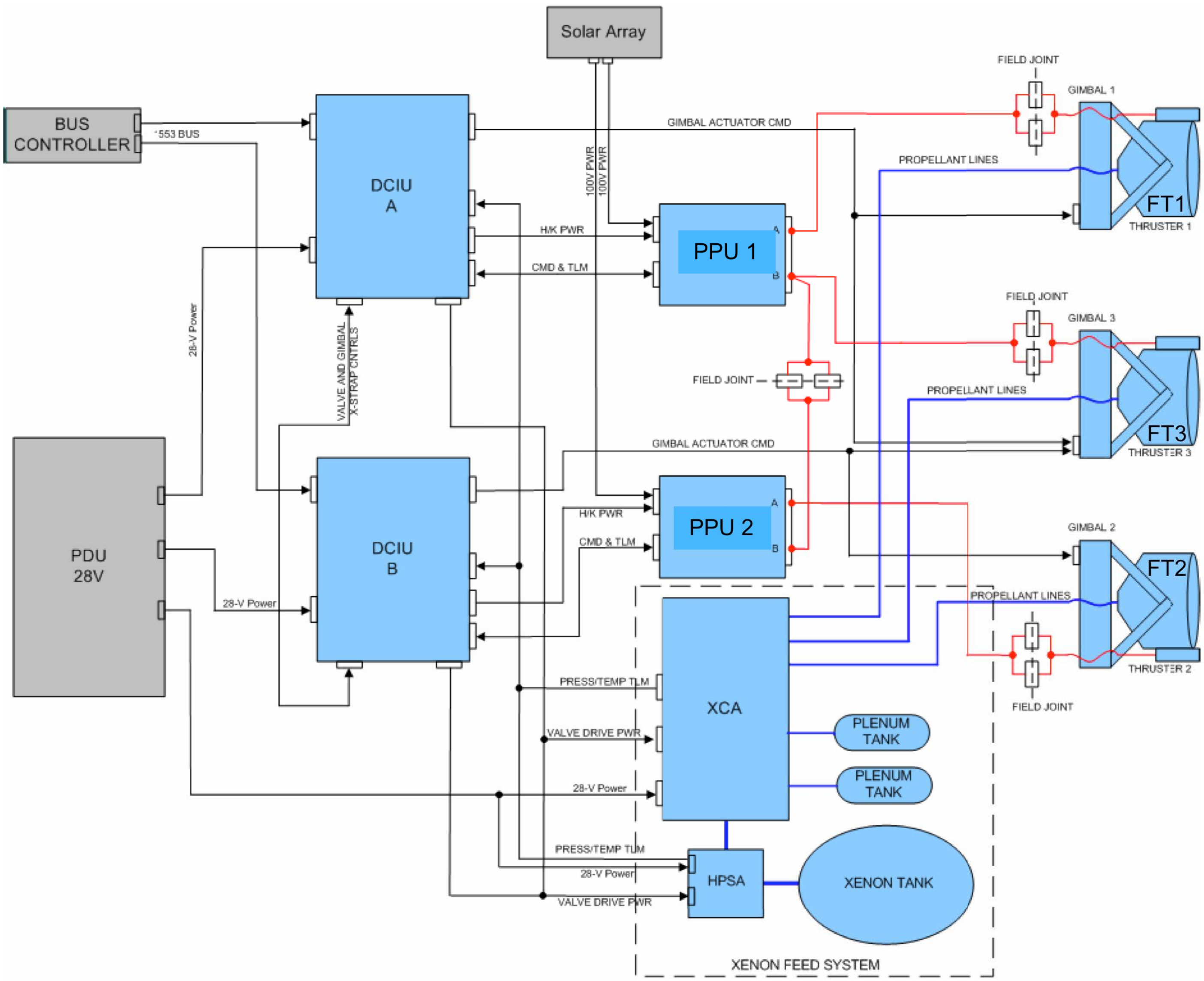

Figure 2. Block diagram of the Dawn IPS subsystem.

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

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.

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 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 =1.6 km/s Plane Change**
MGA	**11/2008--06/2009**	**1.37--1.60**	**NA**	**ΔV =1 km/s Heliocentric Transfer**
Cruise to Vesta	06/2009--08/2011	1.40--2.26	2.6-1.7	ΔV =4.7 km/s (From IPS)
Vesta Science Operations	08/2011--06/2012	2.26-2.51	1.7-1.3	ΔV =0.48 km/s (From IPS)
Cruise to Ceres	06/2012--02/2015	2.51-2.84	1.3--0.9	ΔV =3.55 km/s (From IPS)
Ceres Science Operations	02/2015--07/2015	2.84 - 2.93	0.9	ΔV =0.48 km/s (From IPS)

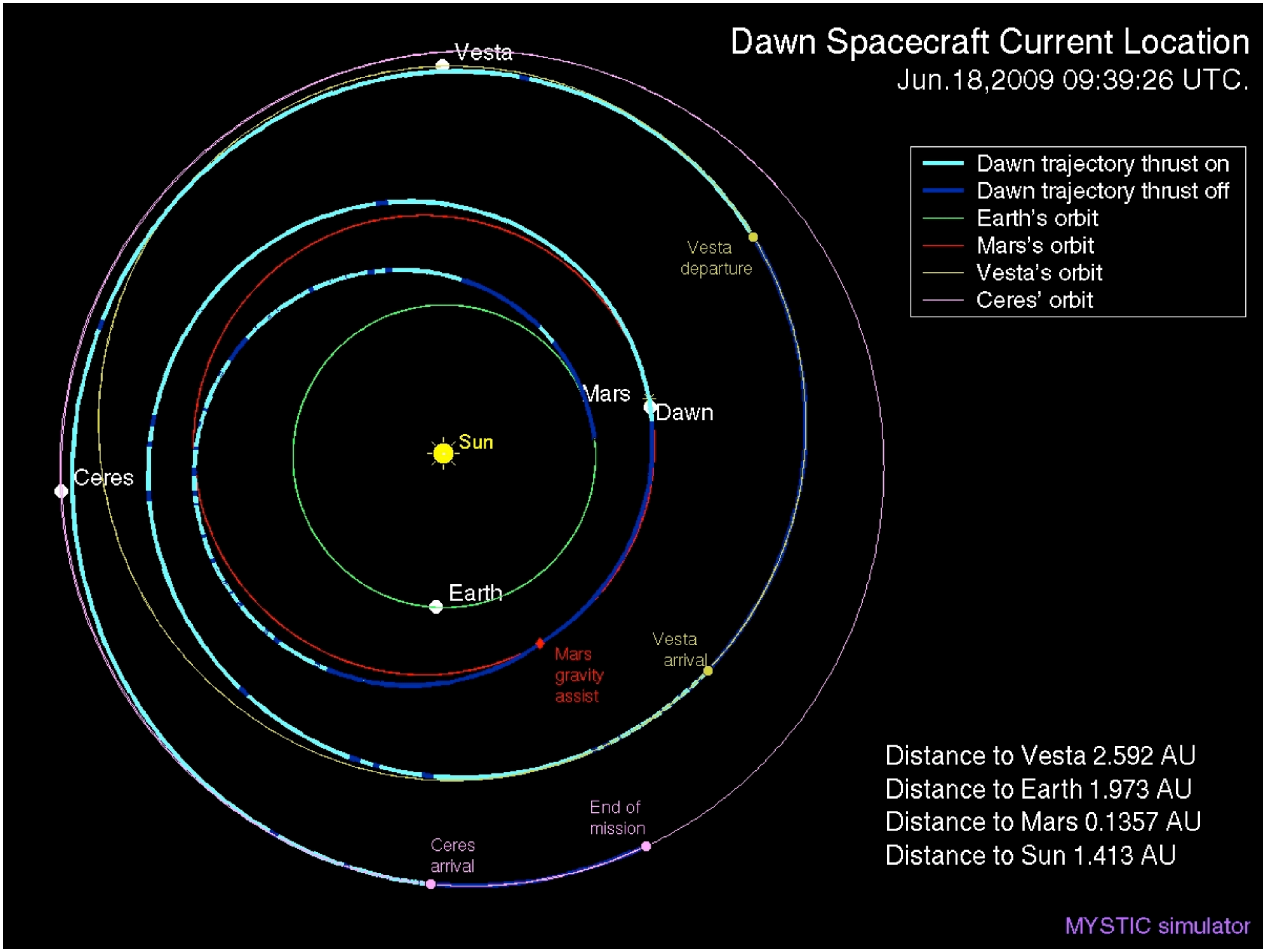

Figure 3. Diagram of the Dawn mission trajectory.

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

III. Overview of IPS Operation During Cruise for Mars Flyby

Cruise Before MGA Mission Plan and Operations Scenario

The goal for this phase of the mission was to modify the spacecraft's heliocentric trajectory leading to a Mars gravity assist in February 2009. This phase of the mission included using IPS for cruise, a trajectory correction maneuver, and spacecraft engineering tests. Cruise before a MGA commenced on December 17, 2007 [17] with the spacecraft at about 1.1 astronomical units (AU) from the sun and was completed successfully on October 31, 2008 with the spacecraft at approximately 1.6 AU from the sun.

The mission plan through mid-2010, a time period which includes all of the cruise before a MGA phase and part of the cruise for Vesta phase, calls for IPS operation at full power for approximately 13,500 hours and utilizing 148 kg of xenon. Thruster operation at full power will be divided uniformly between the three thrusters to maximize the likelihood of mission success.

Thrusting periods during cruise before the MGA were divided into approximately seven day intervals, with off-times for data playbacks and command uplinks limited to approximately six hours. The seven-day thrusting intervals are referred to as thrust arcs. The mission plan included several time periods of no thrusting for engineering activities that are incompatible with the IPS thrust attitude and for coasting times that optimized the mission trajectory. IPS telemetry from the DCIU was stored every ten seconds (except during cathode ignition time periods) and retrieved during the weekly spacecraft data playbacks in approximately seven day intervals. During cathode ignition time periods IPS telemetry from the DCIU was stored at 1 second intervals so that discharge and cathode start times (defined as the time between application of a high-voltage start pulse and cathode ignition) as well as the voltage output of the plume mode circuit could be recorded at high data rates. Real-time telemetry at varying data rates was also available periodically. A low data rate thrust verification pass was typically conducted approximately 3-4 days after thruster ignition to confirm to mission controllers that the spacecraft and IPS were operating as planned.

The sequence of events for all thrusters operated at full power during cruise before the MGA were as follows:

1. The thruster discharge was started for 54 minutes to warm up the thruster, and was then turned off.
2. During the thruster pre-heat the spacecraft was slowly turned to its thrusting attitude.
3. At the conclusion of the thruster preheat the thruster was restarted six minutes later at full power to begin deterministic thrusting for cruise leading to the MGA. Therefore each thrust arc included two separate thruster starts.
4. After approximately one week of thrusting the thruster was shut off, the spacecraft high-gain antenna was re-pointed Earthward, spacecraft engineering data were downloaded and new spacecraft commands were uploaded if necessary.

IPS Operation During Cruise Before the MGA

Thruster operating time and xenon consumption from launch through the start of Vesta cruise are shown in Table 4 and Table 5.

Table 4. Thruster Operating Time Summary Through June 2009*

	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	161.7	3112.6
FT2	22.0	8.0		29.9
FT3	213.7	3579.7		3793.4
Total	277.7	6496.8	161.6	6935.9

* Includes operating time for spacecraft engineering tests and maintenance activities
* Does not include operating time from ground testing

Table 5. Thruster Xenon Summary Through June 2009*

	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	1.79	34.62
FT2	0.27	0.11		0.38
FT3	2.4	39.50		41.89
Total	3.07	72.04	1.79	76.9

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

FT3, the center-mounted thruster, was the first thruster to be operated during the cruise before the MGA phase. By early June 2008 when operation was switched to another thruster FT3 had completed approximately 3,580 hours of full-power thrusting time (Table 4) and utilized 39.5 kg of xenon (Table 5). FT3 thruster operating characteristics are detailed in [17].   FT3 was operated with beam extraction for just over 80% of the total mission time between December 2008 when thrusting on FT3 started and June 2009 when thrusting on FT3 ended.

Operation on FT1, the thruster mounted on the –Y axis of the spacecraft, was started on June 18, 2008 and by October 31, 2008 FT1 had completed approximately 2,909 hours of full-power thrusting time during cruise before the MGA (Table 4) and utilized 32.4 kg of xenon (Table 5).   FT1 was operated with beam extraction for just over 90% of the total mission time between June 2008 when thrusting on FT1 started and October 2008 when thrusting on FT1 ended.

IPS Performance-PPU, Xenon Flow System, and TGAs

Unregulated high voltage current and voltage to PPU-1 for all of cruise for before the MGA are plotted in Figure 4. The bus voltage increased as the solar range to the spacecraft increased. Sun/spacecraft range began decreasing shortly after the beginning of cruise before the MGA using FT1 resulting in a decrease in line voltage. The data show that PPU-1 efficiency is similar to the efficiency measured preflight.

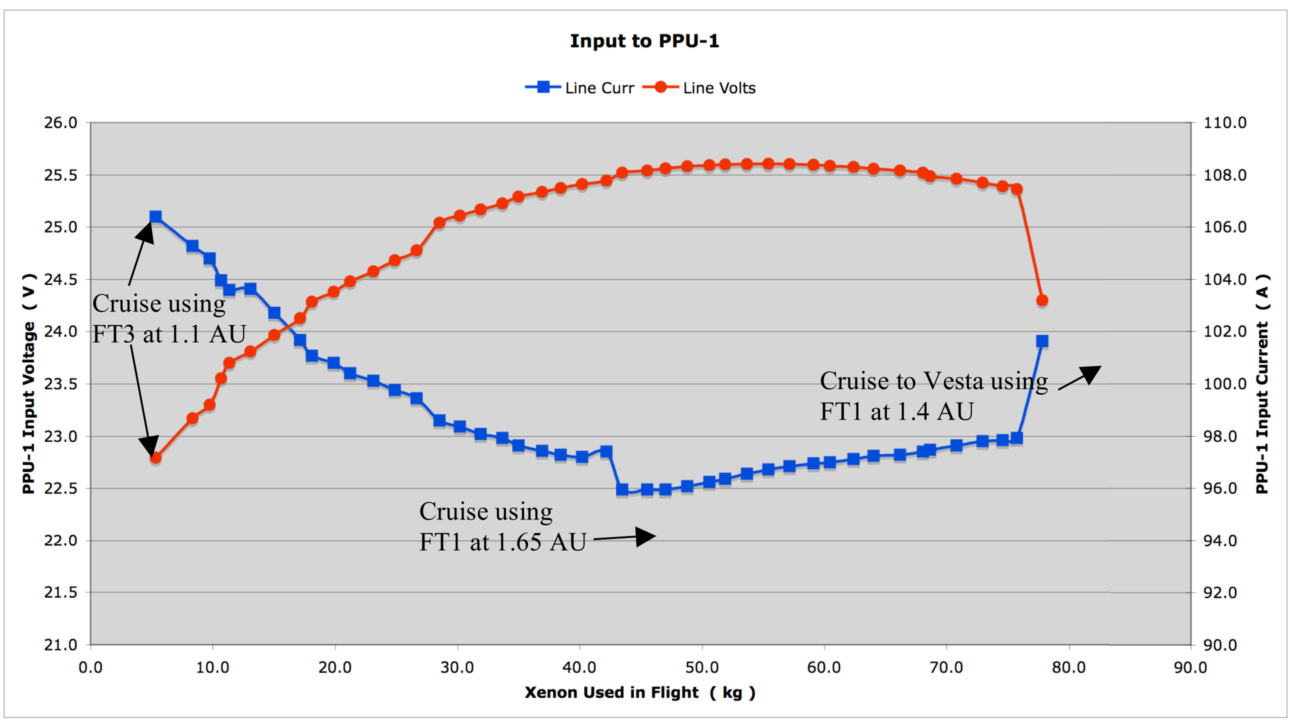

Figure 4. High voltage solar array power to PPU-1

Data from temperature sensors inside the PPU shown in Figure 5 indicate that PPU-1 temperatures have changed little during cruise using FT1. Data for FT3 [17] showed similar results. The PPU baseplate temperature sensor is mounted to the part of the PPU chassis in contact with the spacecraft thermal control surface, and has ranged between 25 and 27 degrees C with the thrusters operating at full power. PPU-1 has performed flawlessly throughout cruise. Temperatures of the connectors mating the PPU-1 harnesses to the thruster harnesses are shown in Figure 6. The data indicate that at full power operation the harness temperature has ranged between 24-42 degrees C and is well within the operational temperature limits for the harness.

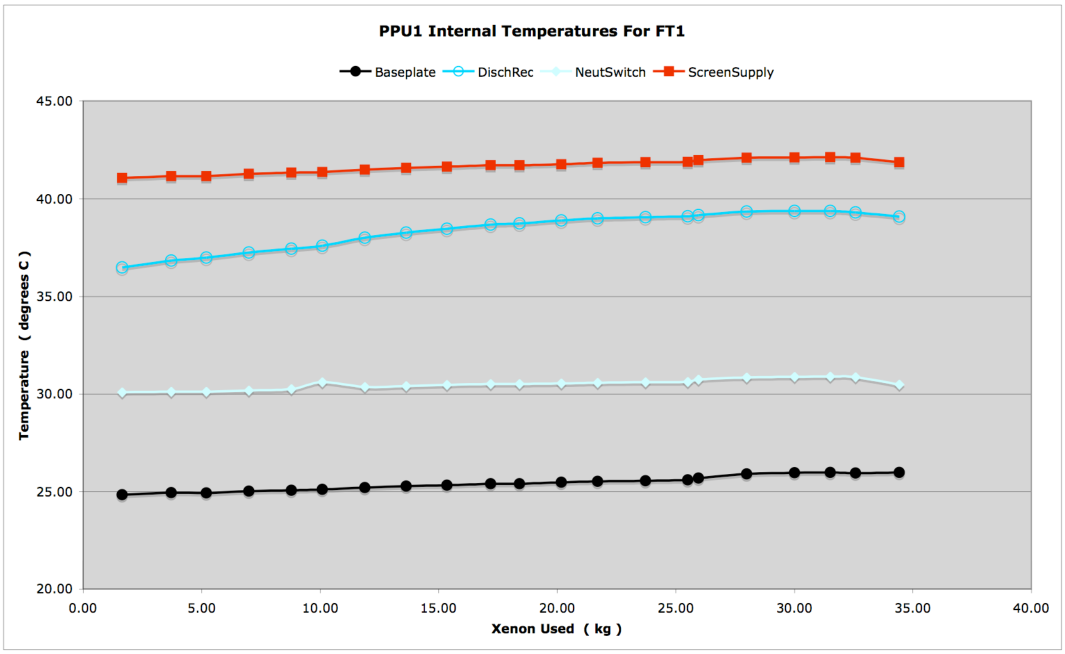

Figure 5. PPU-1 internal temperatures.

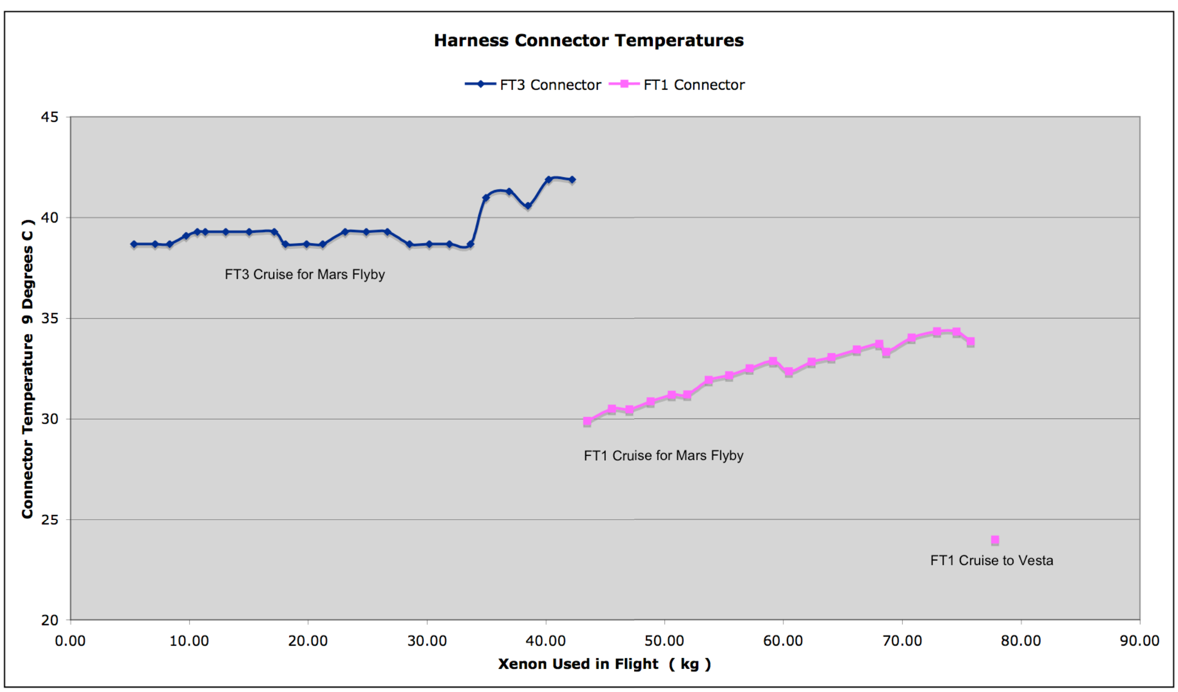

Figure 6. Temperatures of the connectors mating the PPU-1 harnesses to the thruster harnesses.

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 2009 the primary solenoid valve pair used to regulate main plenum pressure has been cycled open and closed approximately 140,000 times in cruise, and the primary solenoid valve pair for cathode plenum tank pressure regulation has cycled approximately 41,000 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. A check of zero-drift of the plenum pressure transducers is discussed in the section of this paper dealing with maintenance activities.

The TGAs have also operated flawlessly in cruise. Cumulative TGA actuator steps are shown in Figure 7. 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 (thrust vector control, or TVC mode). 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.

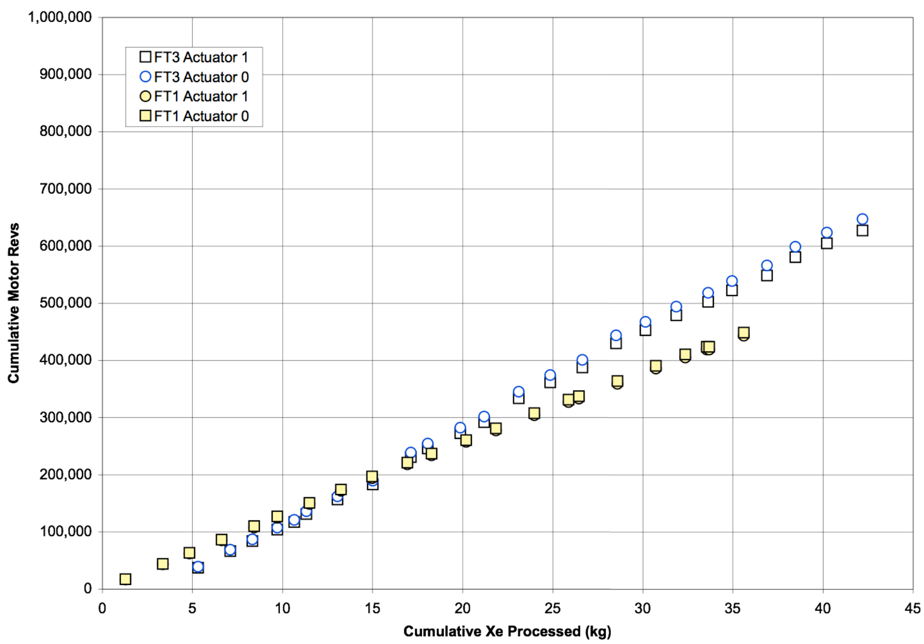

Figure 7. Cumulative thruster gimbal assembly cycles during cruise.

Thruster Starts

To date FT3 has been started in flight 66 times--48 during cruise operations to MGA--with 33 of these starts with beam extraction. FT1 has been started 57 times in flight-42 during cruise operations to MGA--with 29 of these starts with beam extraction The cathode heater preheat duration for all starts was six minutes. All start attempts on FT1 and FT3 were successful. Both the neutralizer and discharge cathodes have ignited within the ten-second resolution of the data on every start attempt, and data taken at smaller time intervals indicate that in every start attempt during cruise the cathodes ignited immediately upon application of the igniter voltage pulses. The nominal cathode heater current for both the neutralizer and discharge cathodes is 8.5 A. Peak heater power for all start attempts with beam extraction during cruise are plotted in Figure 8. Extended Life Test (ELT) heater data have been included in the chart for comparison to Dawn FT heater data. Heater voltages at cathode ignition are affected by thruster temperatures, which are a function of sun exposure 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 FT1 increased by two W over the peak power at start of cruise. The thrusters have been successfully started and operated in diode mode during each of the diode mode start attempts. In diode mode the thruster discharge is operated at 13 A. Over the course of cruise operations discharge voltage at the end of diode mode has increased by approximately 0.2-0.5 V. Extended Life Test (ELT) heater data were included in the chart for comparison to Dawn FT heater data.

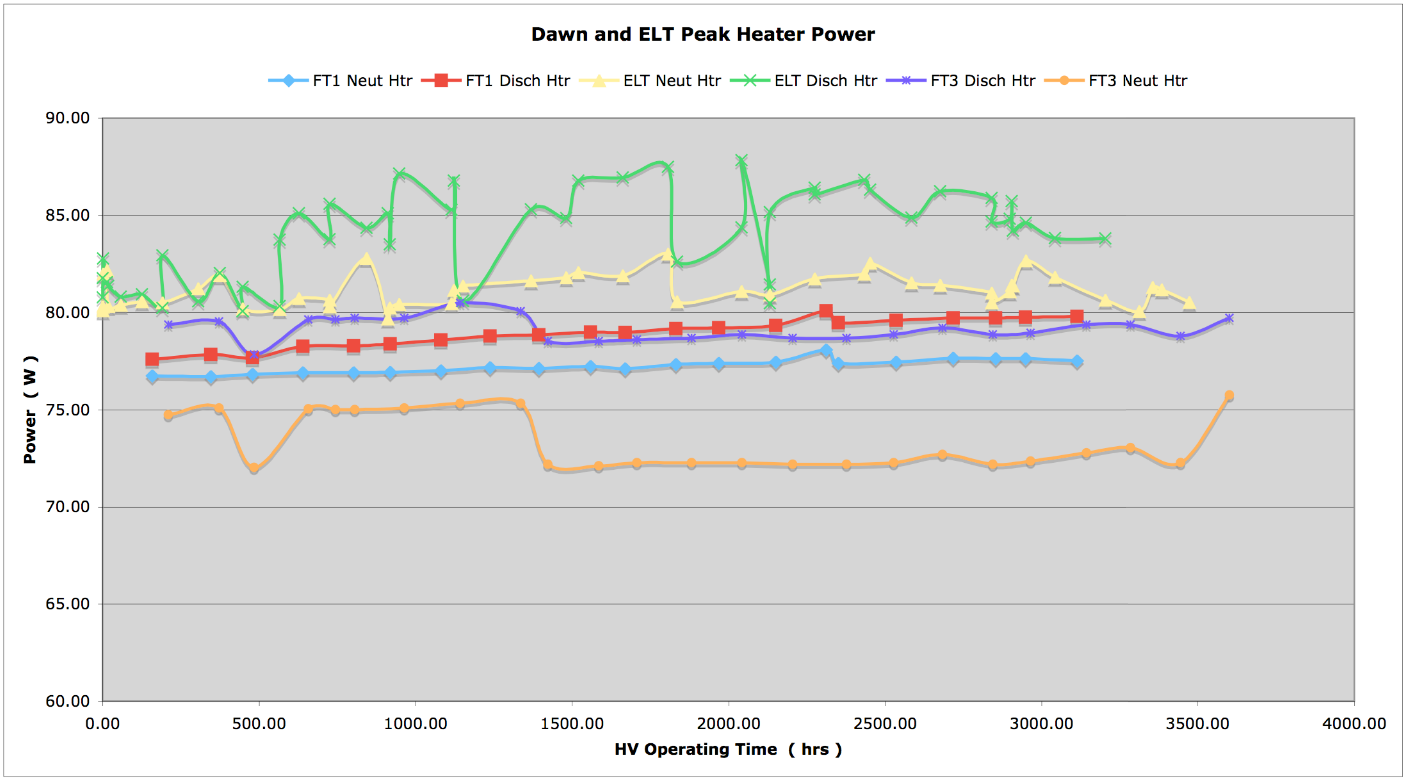

Figure 8. Peak heater power for Dawn FT1, Dawn FT3, and the ELT thruster.

Thruster Performance in Cruise

Data for FT1 and FT3 operating at full power during cruise are shown in Tables 6-7 and Figures 9-16. Table 6 also includes values from the beginning of life (BOL) throttle table. Thruster operation was very stable throughout all of cruise to date--almost 3,400 hours of operation at full power--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, and the accelerator grid voltage is -200 V. 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 6. FT3 Operating Characteristics During the First 6 Months of Cruise

	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	7.05	-200	12.37	25.5	180	1.5	14.54	2483	2275	0.924
Initial Checkout	1.756	1100	4.59	-200	13.09	25.0	186.0	1.5	13.9	2435	2282	0.937
Start of Cruise	1.756	1100	6.1	-200	13.7	24	187	1.5	12.75	2457	2275	0.926
Cruise-June 08	1.76	1100	6.71	-200	14.59	23.67	196	1.5	11.5	2482	2297	0.925

Table 7. FT1 Operating Characteristics Through Cruise for Mars Flyby

	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	198.0	1.5	13.5	2458	2282	0.928
Start of Cruise	1.757	1100	5.97	-200	14.2	24	194	1.5	12.8	2430	2290	0.942
Cruise-June 08	1.758	1100	6.62	-200	15.33	24	210.1	1.5	11.4	2469	2317	0.938

Accelerator grid current for both FT1 and FT3 during cruise is 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, especially given the data on discharge loss that are discussed below. There has been no indication from flight telemetry of electron backstreaming.

Recycles as a function of cumulative operating time 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 81.4 hours of full-power operation for each recycle. FT1 has accumulated 44 recycles at an average of 89.5 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 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.

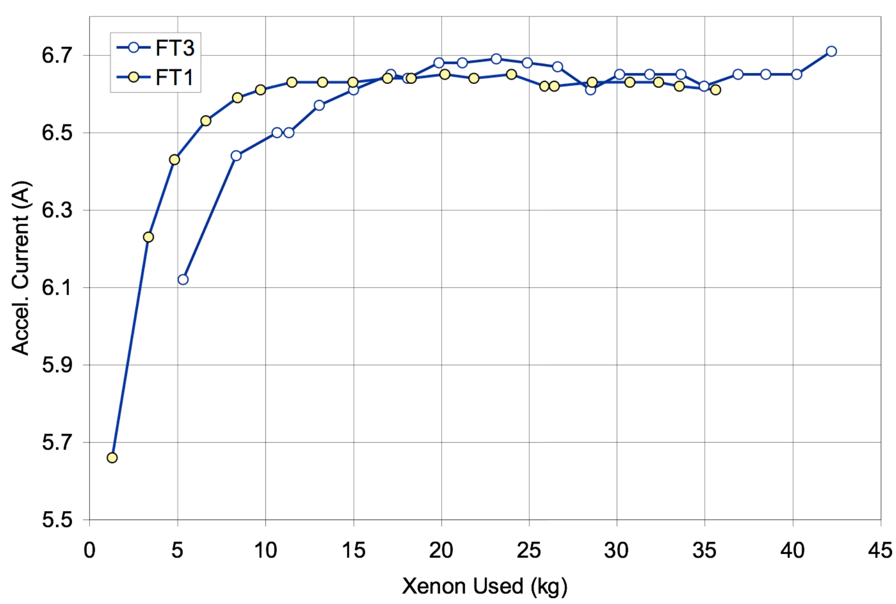

Figure 9. Accelerator grid current during cruise for FT1 and FT3.

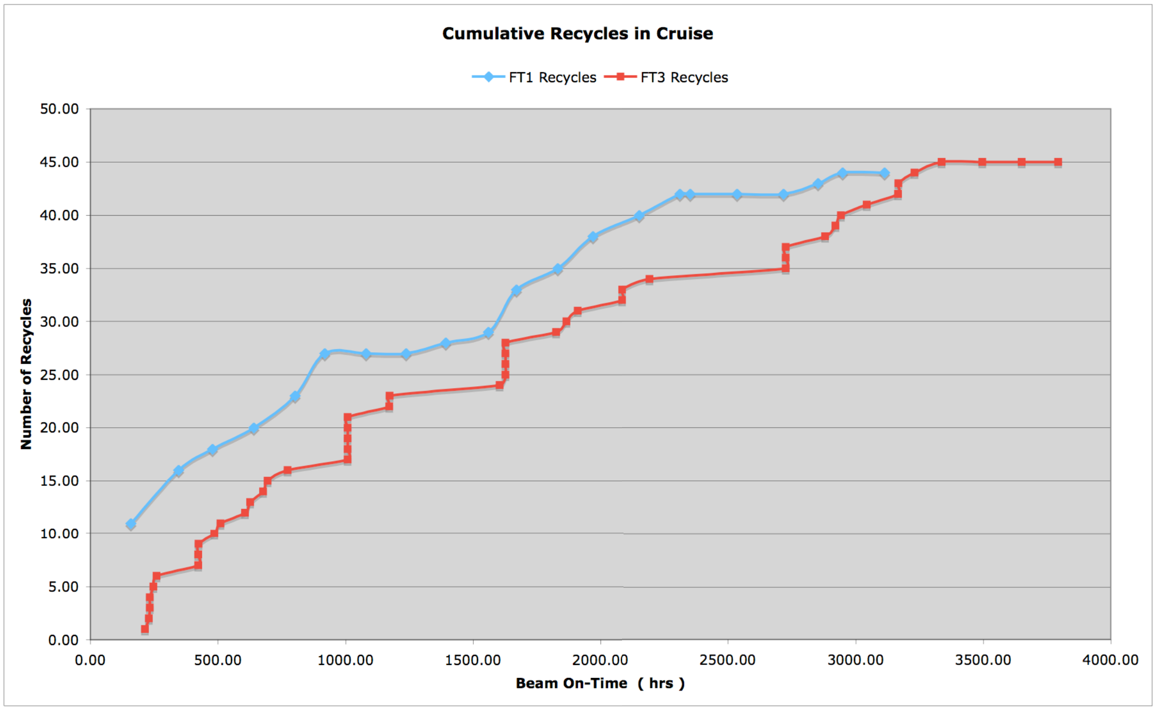

Figure 10. Recycles during cruise for FT1 and FT3.

The neutralizer voltage for operation of FT1, FT2, and the ELT at full power is plotted in Figure 11. Neutralizer voltage for FT1 and FT3 decreased by approximately 1.3-1.5 V since the thrusters were first operated at the start of cruise. The neutralizer voltage decreased by 1.4 V in the ELT [14] over a period of 2,000 hours but then began increasing before leveling off at about 2,600 hours of full-power operation. Neutralizer voltage changes may be related to improved cathode conditioning over time.

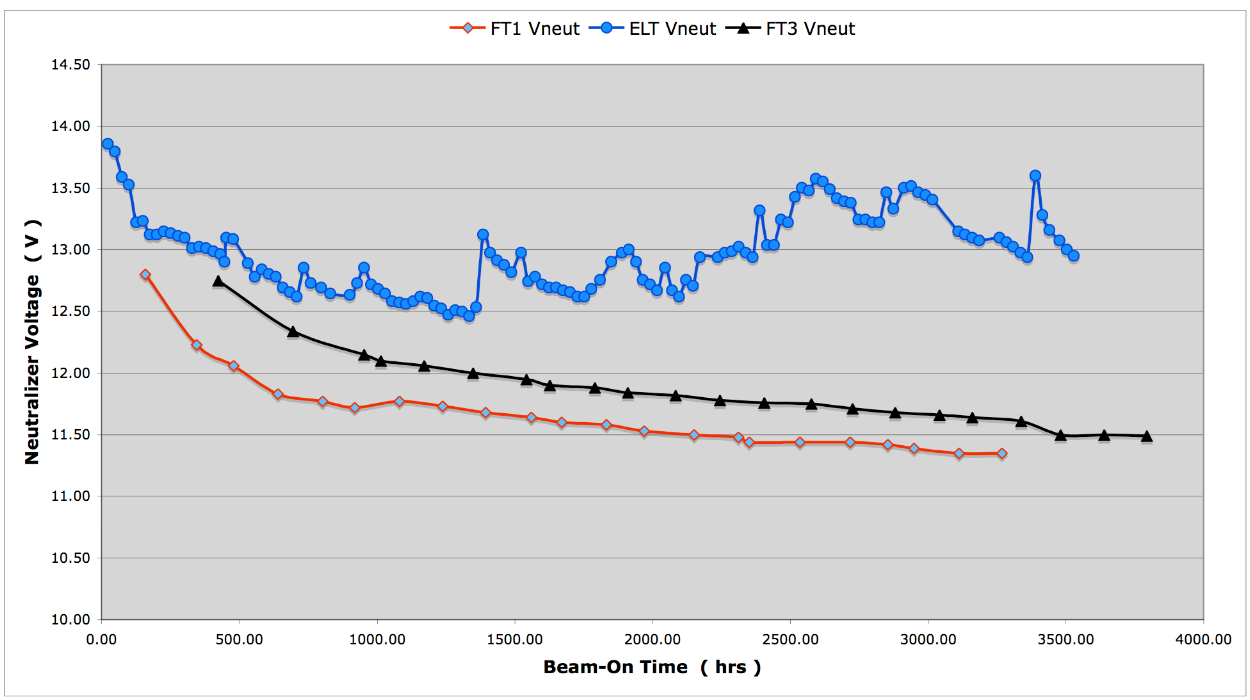

Figure 11. Neutralizer Voltage During Cruise.

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 both FT1 and FT3 are shown in Figure 12. 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, 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.

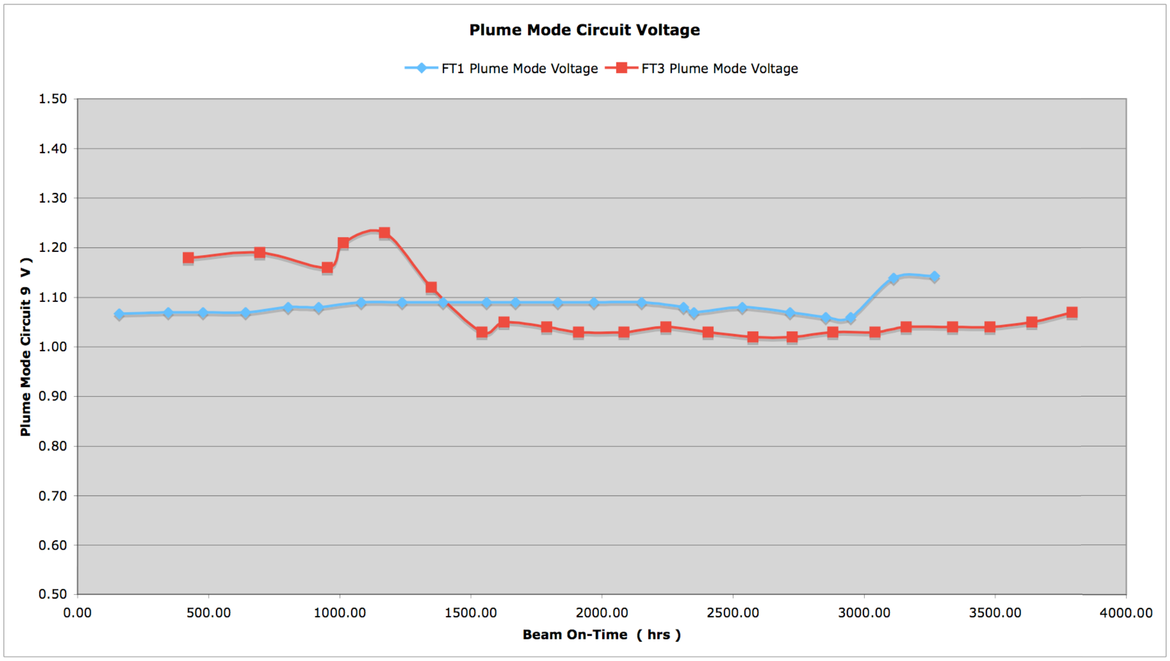

Figure 12. DC output of the plume mode circuit for both FT1 and FT3 during cruise.

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 do not include drops across the harness between the thrusters and PPU-1, which could be as much as 10-15 W depending upon harness temperatures. The discharge current for FT1 exceeds that for FT3 and the ELT because during FT1 assembly two of the permanent magnets for this ring-cusp thruster were installed incorrectly. Initially the discharge current for both FT1 and FT3 increased until the point that both thrusters had processed approximately 22-25 kg of xenon, whereupon discharge current essentially did not change. Similar changes [18] were observed in discharge current for the ELT (Figure 13). 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 FT1, FT3, and the ELT are shown in Figure 14 and track well to changes in discharge current. During cruise discharge power for FT1 increased by 30 W, for FT3 by 10 W, and for the ELT by 25 W over a similar period at full power operation. There was a noticeable increase in discharge current for FT3 for the last two thrust arcs that is unresolved. Data on discharge loss for both FT1, FT3 and the ELT are plotted in Figure 15. Discharge loss tracks with discharge current. During cruise discharge loss increased by 17 W/A for FT1 and 9 W/A for FT3; discharge loss for the ELT increased by 9 W/A over a similar time period.

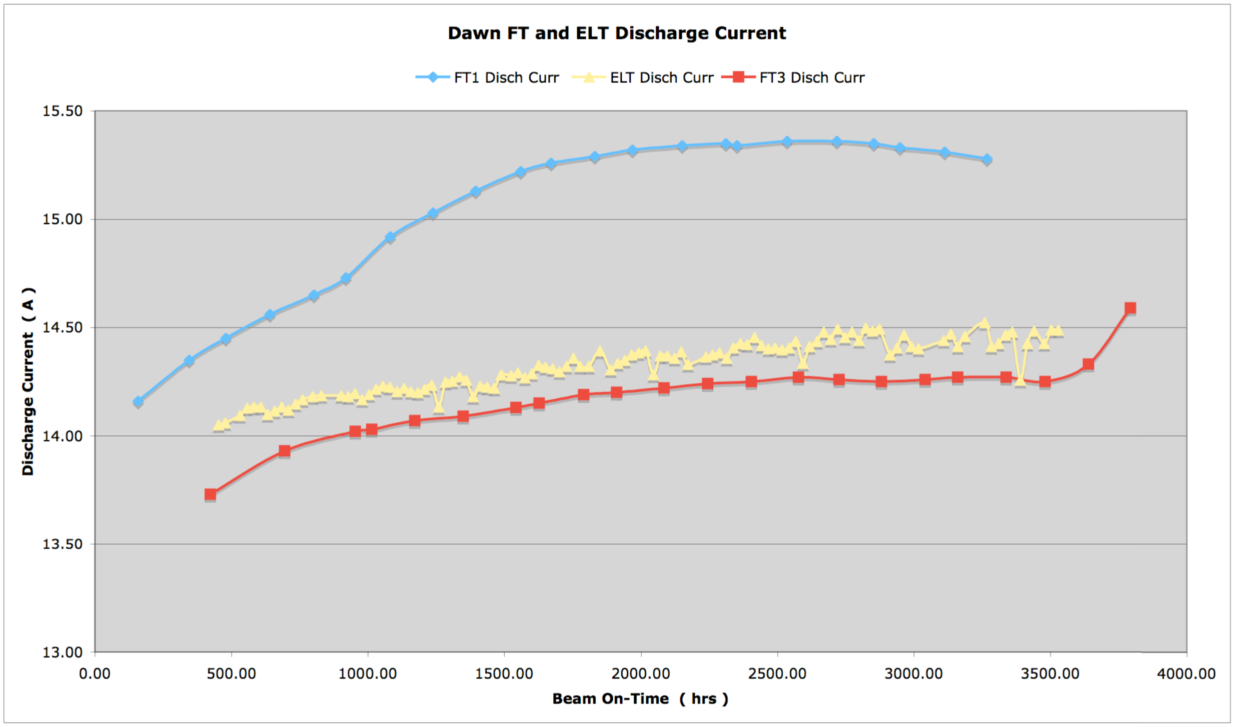

Figure 13. Discharge current during cruise for Dawn FTs and for the ELT.

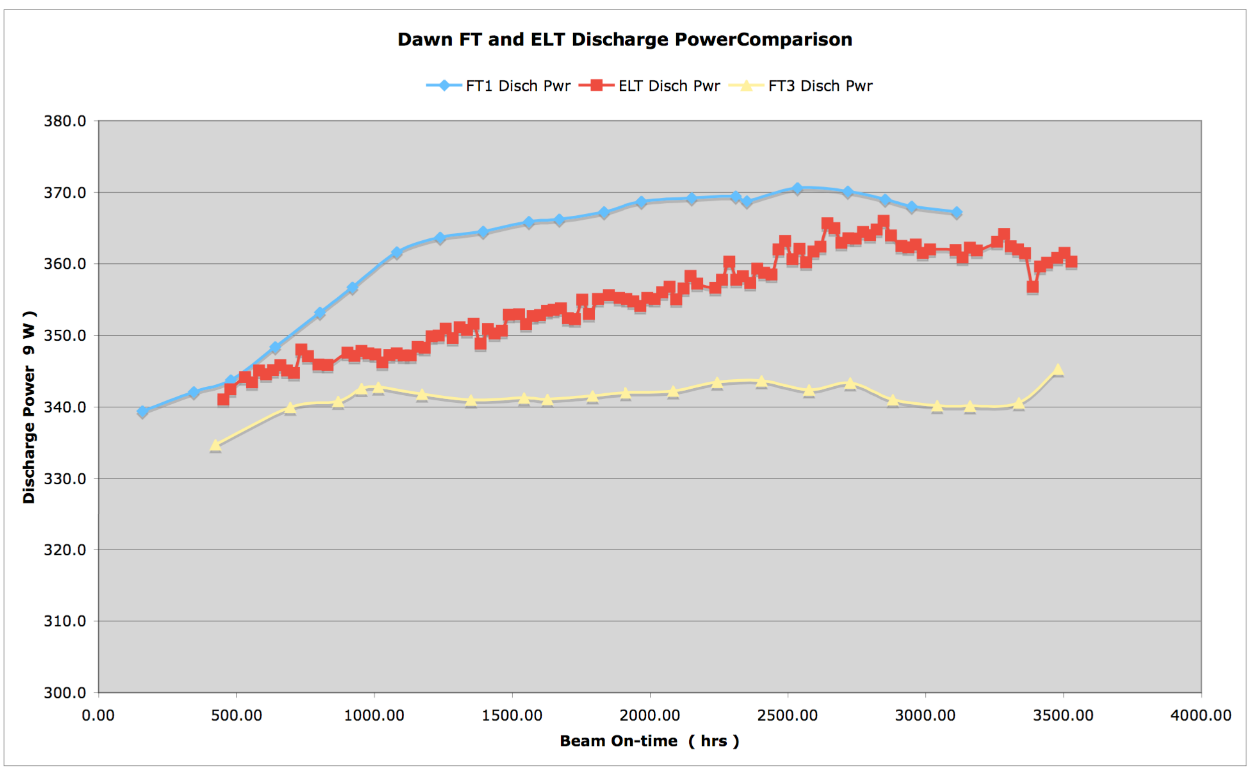

Figure 14. Discharge power during cruise for Dawn FTs and for the ELT.

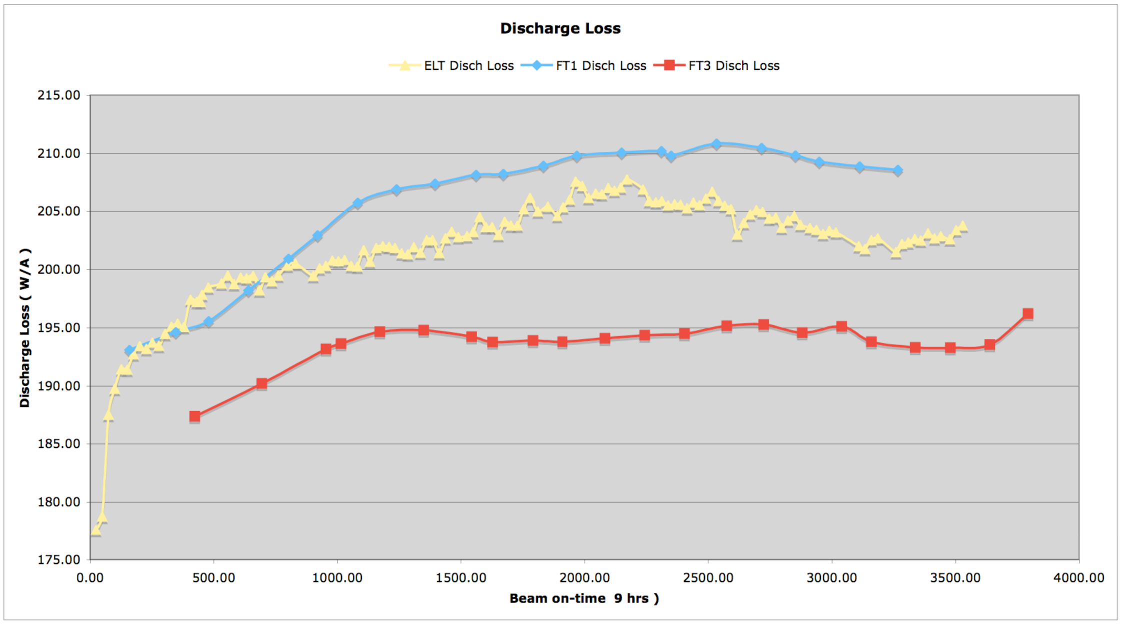

Figure 15. Discharge loss during cruise for Dawn FTs and for the ELT.

Thrust Measurements and Roll Torque

Direct thrust measurements 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 [19]. Calculated (reconstructed) thrust values for FT3 during cruise before the MGA were presented in [17] and are reproduced in Table 8 below for easy comparison to FT1 thrust measurements. Uncertainty (1-σ) for all thrust estimates for FT3 is better than ±0.4 mN. Calculated thrust values are close to but slightly less than the thrust measured on FT3 operating at full power during the ICO [16] and are well within the preflight expected value of 91.0 ±1.65 mN averaging about 91.2 mN.

Calculated (reconstructed) thrust values for FT1 during cruise before the MGA and upon restart for cruise to Vesta are shown in Figure 16. Uncertainty for all thrust estimates for FT1 is better than ±0.4 mN. Reconstructed thrust values for FT1 are close to but slightly less than the thrust measured on FT1 operating at full power during the ICO [16] and are well within the preflight expected value of 91.0 ±1.65 mN averaging about 91.0 mN based on thruster electrical parameters and 90.8 mN based on reconstructed thrust. Most of the thrust values calculated from electrical parameters are within the error bars for reconstructed thrust. For mission modeling and future orbit determinations the worst-case thrust for FT1 (89.7 mN) is assumed, so the in-flight performance for FT1 provides margin to the mission in the form of missed thrust days and xenon.

Table 8. FT3 Reconstructed Thrust During Cruise

Thrust Arc Date	Reconstructed Thrust
	(mN)
01/24/08	91.2 ± 0.2
02/08/08	91.4 ± 0.2
02/26/08	91.2 ± 0.4
03/20/08	91.2 ± 0.4
04/07/08	91.1 ± 0.3
04/14/08	91.1 ± 0.3
05/07/08	91.0 ± 0.2
05/13/08	91.0 ± 0.2

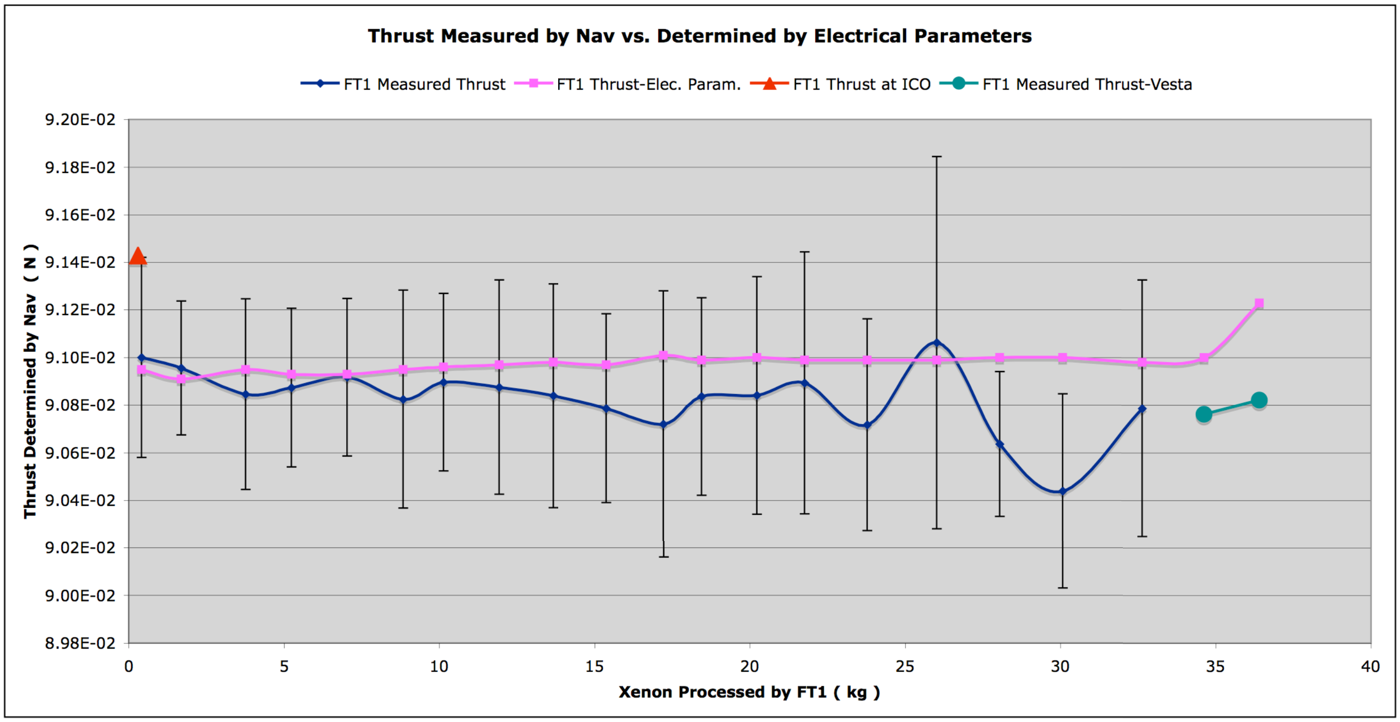

Figure 16. Thrust for FT1 during cruise for a Mars flyby and for start of cruise to Vesta.

The Dawn requirement for roll torque is 60 μN-m at any thruster power level. Roll torques measured about the thruster axis vs. cumulative xenon processed per thruster are shown in Figure 17 for FT1 and FT3. Roll torque measured for both FT1 and FT3 during cruise continue to meet the specification, but instead of being a static value roll torques for both thrusters have changed during cruise before the MGA. At the start of cruise operations the roll torque determined from RWA data was measured to be 52 μN-m for FT3 and 31 μN-m for FT1. The magnitude for roll torque appears to be decreasing as hours are accumulated on the thrusters; roll torque for FT3 has decreased by almost 20% relative to start of cruise while for FT1 the decrease is a more modest 6%. Based on the most recent data the decrease in roll torque per kg of xenon expended is 0.4 μN-m/kg for FT1 and 0.7 μN-m/kg for FT3. 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. 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.

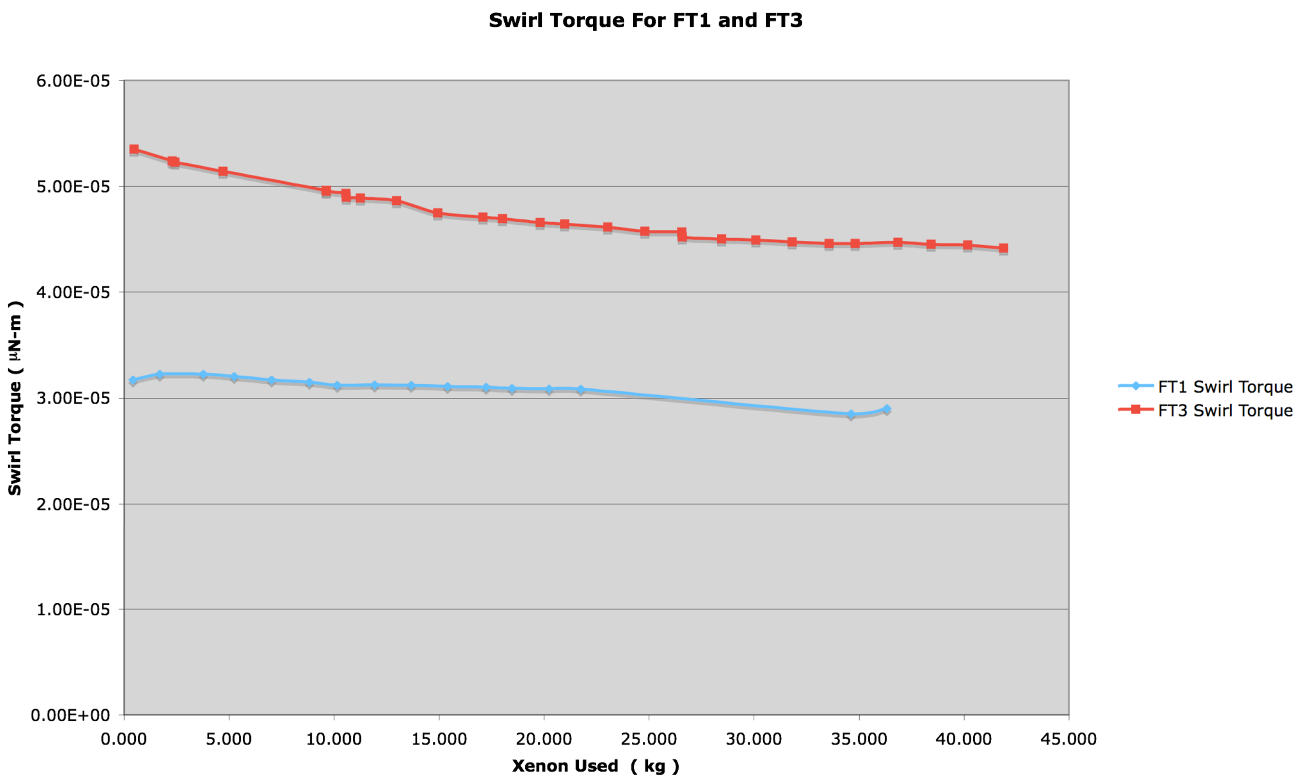

Figure 17. Roll torque for FT1 and FT3 during cruise.

IV. IPS Operations During the Cruise Before the MGA Phase

Cruise operations before the MGA were successfully completed on October 31, 2008. This phase was followed by a coasting phase of approximately 7.4 months. During the coast phase IPS was operated using FT1 twice and FT2 twice. FT1was operated with beam extraction for 2.18 hours at full power for a single trajectory correction maneuver, and for just over 2 minutes with beam extraction for a solar array calibration test. FT2 was used for tests of new spacecraft software.

Because both the IPS thrust and specific impulse are dependent on the power available to the PPU, the design of the mission depends on flight system power models [20]. Dawn's solar arrays are so large that the spacecraft cannot draw as much power as the arrays can produce when within about 2.0 AU of the Sun. To calibrate the array output, on November 4, 2008, at a heliocentric range of 1.62 AU, the arrays were commanded to rotate 60° away from the normal Sun pointing attitude. The IPS provided the load needed to measure the array current as a function of voltage. The off-point angle was chosen to ensure the array would pass through its peak power point and, as expected, that led to the electrical collapse of the array. The resulting data have been used in refining the thrust plan.

On November 20, 2008, Dawn completed the only trajectory correction maneuver (TCM) required to target the MGA. Operations for the TCM were performed using FT1 and were no different from interplanetary cruise thrusting. The maneuver yielded 0.6 m/s and was so accurate that another TCM scheduled for January 15, 2009 (also planned for the IPS) was canceled. The spacecraft flew through the desired target window at Mars on February 17, 2009.

In April 2009, an updated version of the main flight system software was installed in the spacecraft's central computer. There were no planned changes in the software that would affect IPS thrusting. Despite the ground test program, it was deemed prudent to verify that the capability to thrust had not been compromised. Waiting until the resumption of deterministic thrusting in June 2009 would not have allowed time to rectify a problem without missing planned thrusting so a dedicated thrust test was conducted. FT2 was operated on April 27, 2009 and May 1, 2009, each time for almost four hours, demonstrating that all subsystems and spacecraft command files performed as they had with the previous version of the software. A secondary objective of these tests was to measure the off-axis thrust from FT2. Such measurements had been made for FT1 and FT3 during ICO, but thermal constraints when near 1.0 AU prevented the corresponding FT2 test from being conducted. Conventional radiometric Doppler measurements using a spacecraft low-gain antenna during the thrusting provided the needed signal.

Xenon flow rates through the thruster flow control devices (FCD) are a function of FCD temperature and the inlet pressure indicated by the plenum tank pressure transducers. The main flow plenum tank and cathode flow plenum tank both have three pressure transducers installed. The pressure transducers were carefully calibrated pre-flight and have a specification for long-term stability of ± 0.1% full scale output per year. The long coast period after the MGA provided an opportunity to evacuate the plenum tanks and measure any changes in pressure readings at vacuum (zero-drift) for these transducers. This zero-drift check was performed by opening the latch valves to FT3 and 15 days later to FT1. Torque about the spacecraft's Y axis jumped to 16.5 μN-m from the cold-gas thrust developed by the xenon exiting the thruster; torque decreased to nearly zero within 24 hours of the latch valves being opened. The test was completed 24.3 days later and the latch valves were closed. The data obtained from this test indicate no drift in the indicated pressure reading at vacuum.

V. Cruise to Vesta and Ceres

Deterministic thrusting for cruise to Vesta began on June 8, 2009. FT1 was started for the first thrust arc and as of late June 2009 IPS has accumulated 317 hours of operation at full power with beam extraction. IPS will continue to be operated at full power with the goal of distributing full-power operating time evenly between the three thrusters. 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. IPS 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 in case special activities are needed, such as another installation of software or instrument calibrations. These represent no more than 3% of the mission time.

Upon 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 escape and then 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 June of 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 for approximately 94% of the time 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 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 equatorial 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. The Dawn ion propulsion system has operated almost flawlessly throughout the mission to date, accumulating 7,090 hours of beam-on time that resulted in almost 2 km/s of ΔV to the spacecraft. All the IPS components--the thrusters, DCIUs, PPUs, XCA, and TGAs—have operated as expected. The thruster performance characteristics are basically as expected with some exceptions, most noticeably the accelerator grid current behavior, although none of the deciations 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 consistent with thrust values calculated from thruster electrical parameters. 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.

Acknowledgments

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