44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference **AIAA-2008-4916**
20-23 July, 2008, Harford, CT

# In-Flight Operation of the Dawn Ion Propulsion System-The First Nine Months

Charles E. Garner,[1] John R. Brophy[2], Steven C. Mikes[31], and Marc D. Raymond[4]
*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Ca 91109*

**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 Δ-V 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 engine design is based on the design validated on NASA's Deep Space 1 mission. However, because of the very substantial (11 km/s) Δ-V 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 also based on the DS1 design. 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 prior to the initiation of long-term thrusting for the heliocentric transfer to Vesta. The IPS hardware, consisting of three ion thrusters and TGAs, two PPUs and DCIUs, xenon feed system, and spacecraft control software, was investigated extensively. Thrust measurements, roll torque measurements, pointing capabilities, control characteristics, and thermal behavior of the spacecraft and IPS were carefully evaluated. The Dawn IPS fully met all its initial checkout performance objectives. Deterministic thrusting for cruise began on December 17, 2007. Over the subsequent approximately 330 days the IPS will be operated virtually continuously at full power thrusting (approximately 91 mN) leading to a Mars flyby in February 2009. The encounter with Mars provides a gravity assist for a plane change and is the only source of post-launch Δ-V apart from the IPS. Following the Mars gravity assist IPS will be operated for approximately one year at full power and for 1.3 years at throttled power levels leading to rendezvous with Vesta in August of 2011. Following nine months of orbital operations with IPS providing the propulsion needed for orbit capture, science orbit transfer and orbit maintenance and Vesta escape, Dawn will transit to Ceres with an expected arrival date of February 2015. As of June 16, 2008 the ion thrusters on Dawn have operated for close to 3,846 hours and have delivered nearly 1 km/s of Δ-V to the spacecraft. Dawn IPS operation has been almost flawless during the initial checkout and six months of cruise. This paper provides an overview of Dawn's mission objectives, mission and system design, and the results of the post-launch Dawn IPS mission operations through June 2008.**

## 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

---

[1] Member of the Technical Staff, Propulsion and Flight Systems Group

[2] Section Staff, Propulsion and Materials Engineering Section, Member AIAA

[3] Member of the Technical Staff, Electronics Design Group

propulsion modules for attitude control and orbit boosting. The Hayabusa spacecraft is returning to Earth after exploring comet Hyabusa [3] and employs cathode-less ion engines for primary propulsion. Several communications satellites including 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 launching many 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 ($\Delta$-V) 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 subsystem checkout. Cruise operations for deterministic thrusting began December 17, 2007 leading to a Mars flyby in February 2009, a rendezvous with Vesta in August 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 system summary, and operations for the first nine months including three months of checkout and six months of cruise.

## II. Mission and Flight System Overview

The mission and flight system are described in detail in References 5-7, 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 three dwarf planets in our solar system, and appears to have survived largely intact since its formation with microwave measurements indicating the possibility of clay and 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 satellite platform series. This platform is used primarily for low Earth orbit and geosynchronous Earth orbit missions but has the design flexibility for use on NASA science missions [8]. 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 but can be used at other times, such as for orbit control or time-critical maneuvers that require faster spacecraft slew rates than ACS can provide. 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 visual and infrared 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 |
|---|---|
| Spacecraft and avionics | 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 Reference 9-11 and is shown in the block diagram in Figure 2. The IPS subsystem is based on the single-engine ion propulsion system flown successfully on the DS1 mission [12,13], that was modified for multiple thrusters and supporting hardware. The Dawn IPS subsystem includes three 30-cm-diameter xenon ion thrusters operated one at a time, two PPUs, two DCIUs, three TGAs for two-axis control, an 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 and radiators.

A titanium composite-overwrap xenon tank, newly 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 at launch. The ratio of tank mass to xenon mass is an astounding 0.05 and represents a true breakthrough in total IPS system mass reduction. The xenon feed system is based on the DS1 design but was modified to operate multiple thrusters. It includes an XCA placed inside 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, 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.

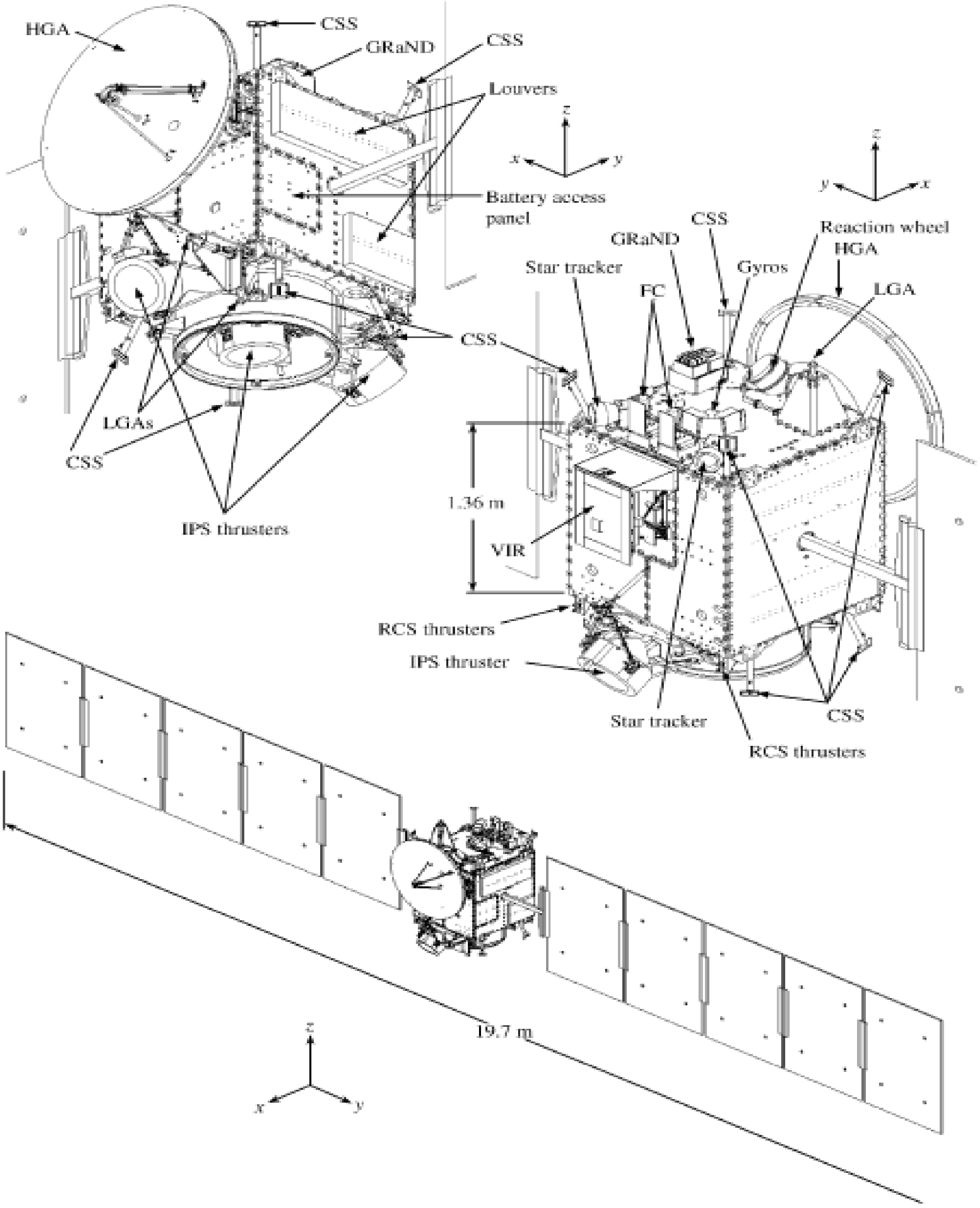

Figure 1. Schematic diagram of the Dawn flight system, from [6].

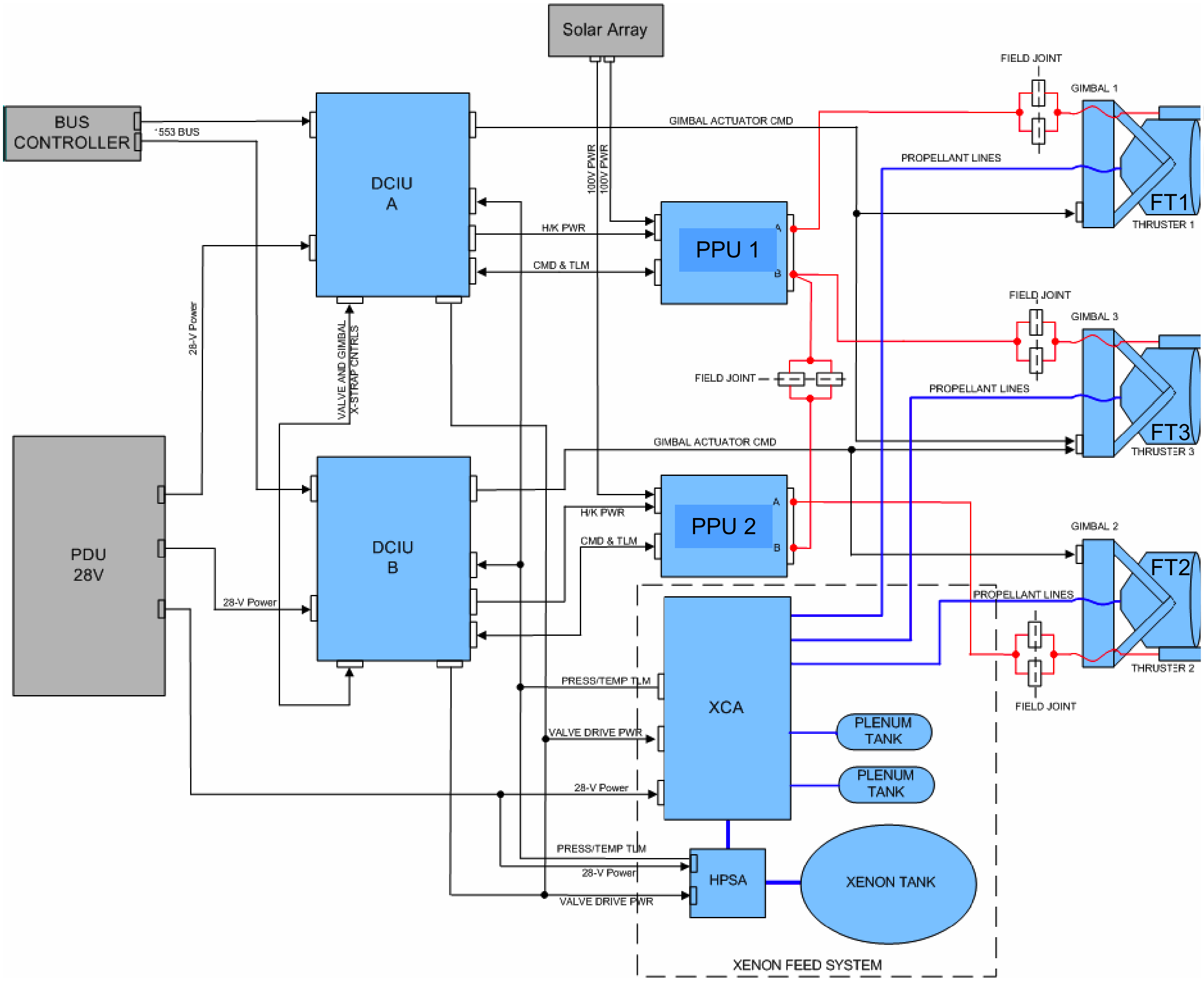

Figure 2. Block diagram of the Dawn IPS subsystem.

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 subsystem 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. One of the thrusters, designated FT3, is mounted to the center of the –Z end of the spacecraft and the other two ion thrusters are mounted externally and are designated FT1 for the thruster on the –X panel and FT2 for the thruster mounted to the +X panel (Figure 2). Each PPU is connected directly to the High Voltage Electronics Assembly (HVEA) which provides unregulated solar array power to the PPUs. 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 Mass Breakdown

| Description | Xenon Allocation (kg) |
|---|---|
| Initial Checkout | 2.7 |
| Diode Mode Operation | 2.7 |
| Xenon Lost to Thruster Restarts | 1.0 |
| 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 | 20.8 |
| 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.

Table 3. Dawn Mission Summary

| Description | Time Period | Distance S/C to Sun AU | Power Level To IPS kW | Comments |
|---|---|---|---|---|
| Launch | 09/27/2007 | 1 | | |
| Initial Checkout | 09/2007--12/2007 | 1--1.16 | 2.6 | Δ-V =0.04 km/s (From IPS) |
| Cruise to MGA | 12/2007--11/2008 | 1.16--1.68 | 2.6 | Δ-V =1.74 km/s (From IPS) |
| Mars Gravity Assist | 11/2008--06/2009 | 1.37--1.60 | NA | Mars flyby February 2009 |
| Cruise to Vesta | 06/2009--08/2011 | 1.40--2.26 | 2.6-1.7 | Δ-V =4.7 km/s (From IPS) |
| Vesta Science Operations | 08/2011--06/2012 | 2.26-2.51 | 1.7-1.3 | Δ-V =0.48 km/s (From IPS) |
| Cruise to Ceres | 06/2012--02/2015 | 2.51-2.84 | 1.3--0.9 | Δ-V =3.55 km/s (From IPS) |
| Ceres Science Operations | 02/2015--07/2015 | 2.84 - 2.93 | 0.9 | Δ-V =0.48 km/s (From IPS) |

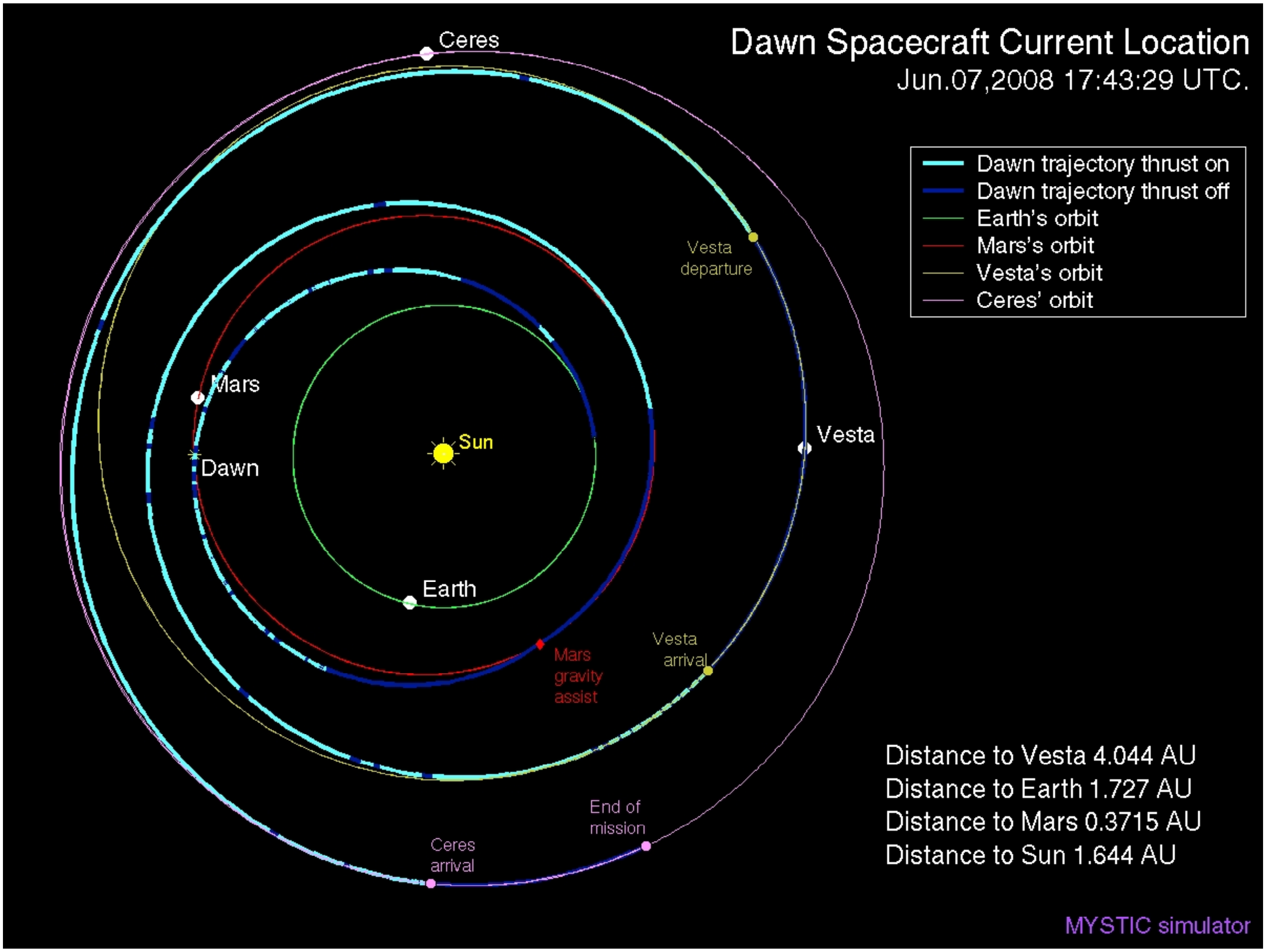

Figure 3. Diagram of the Dawn mission trajectory.

The Dawn mission has a planned duration of approximately eight years. The complete mission Δ-V, from the initial checkout (ICO) through conclusion of Ceres science operations, is approximately 12.0 km/s (Table 3). IPS provides 11.0 km/s of this Δ-V and uses approximately 389 kg of xenon for the complete mission. The ICO to verify all spacecraft subsystems including the IPS required 80 days and was completed within 80 days of launch [16]. Cruise for a Mars flyby commenced in December 2007 and will require approximately 17% of the mission Δ-V (Table 3) and xenon. Low-thrust trajectory design software yields optimum thrust vectors as a function of time throughout the mission (subject to constraints such as the performance of the IPS and the power system, thermally prohibited thrust attitudes, times that activities incompatible with thrusting are scheduled, etc.) The transfer from one heliocentric orbit to another requires a complex profile of spacecraft velocity changes; the result is that at some times in the mission, including the time around the MGA, coasting is better for the mission performance than thrusting [17]. During cruise to the Mars Gravity Assist (MGA) phase of the mission, the IPS will be operated at full power for approximately 295 days of the 335 days allocated for the MGA, which means the IPS will be operated 90% of the time during cruise to Mars. The planned trajectory for this phase of the mission results in going outbound from the sun to a maximum of 1.68 AU in August 2008, then inbound for the MGA maneuver, leading to a Mars flyby in February 2009 with closest approach at approximately 500 km. The MGA will result in a plane change of approximately 3.5 degrees and a change in the mission Δ-V of approximately one km/s.

Thrusting for cruise to Vesta resumes in June 2009 and ends 26 months later with a Vesta rendezvous in August 2011. During the cruise to Vesta, the IPS will be operated at full power until May 2010, resulting in a total of approximately 14,000 hours of IPS operations at full power. After the spacecraft exceeds 2 AU distance from the sun, ion thruster power will be throttled for the remainder of cruise operations to Vesta due to decreased solar array output. 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 duty cycle of approximately 92% at power levels ranging between 2.5 to 1.7 kW. The remaining 8% of the time needed for cruise to Vesta is devoted to communications and data downlink to Earth, spacecraft maintenance activities, other spacecraft activities, and forced coast periods.

Upon rendezvous with Vesta the IPS will be used to spiral the Dawn spacecraft toward the asteroid for orbit capture at an altitude of approximately 15,000 km. Science observations will be conducted in three different orbital altitudes that will be reached with IPS slowly spiraling the spacecraft to the new orbital altitudes. IPS will be used with 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 610 km (following one month of transfer) and 180 km (requiring two months). Within each science orbit, the IPS will be used for periodic orbit maintenance maneuvers. 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, Vesta cruise, science, and deorbit operations will require a Δ-V of 7 km/s and 255 kg of xenon, or approximately 64% of the mission IPS Δ-V 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. For the first four months of cruise to Ceres the spacecraft will continue moving outward from the sun, reaching to a solar distance of approximately 2.55 AU before moving sunward to a distance of 2.44 AU and then travelling outbound again. 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 outermost science orbit at Ceres is planned for an equatorial altitude of 6,400 km, the science orbit following that is at 1,300 km, and the lowest orbit around Ceres is planned for an equatorial altitude of 690 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 Δ-V 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 Δ-V of 11 km/s provided by the IPS.

## III. Mission Operations-Launch Through Initial Checkout

### Launch

The Dawn spacecraft was launched from Cape Canaveral Air Force Station (Cape) on September 27, 2007 on a Delta-II 7925H-9.5 (Delta-II Heavy) launch vehicle that placed the 1,218 kg spacecraft into an Earth-escape trajectory with an aphelion of 1.62 AU, a perihelion of 1.00 AU, and an orbital inclination of 0.53 degrees. An unplanned hold on the launch made necessary by a ship moving into restricted space near the Cape was less than the substantial launch window of 29 minutes, made possible by the versatility of performing missions using the IPS.

The third stage of the launch vehicle with the Dawn spacecraft still attached was spin-stabilized around the spacecraft Z-axis to approximately 48 revolutions per minute (rpm). Through viscous coupling the spin rate of xenon in the storage tank affects the spin rate of the spacecraft in a complicated way that was modeled and tested and is discussed in detail in [18]. After a yo-yo despin and separation from the third stage, the Dawn spacecraft and xenon spin states were very close to the modeled states with the result that the hydrazine expended to place the spacecraft in a 1 revolution per hour roll was close to what was expected. The solar arrays were deployed and the spacecraft began three days of intensive verification of the spacecraft subsystems and to configure the spacecraft for remaining initial checkout activities.

## IPS Initial Checkout

The 80 days following launch were devoted to an initial checkout (ICO) of spacecraft subsystems and the overall system. The IPS was a major focus of this phase of the mission. The IPS checkout is discussed in detail in [16] and is summarized here. The goals of the IPS ICO were to:

1. verify the health and performance of each ion thruster, DCIU, PPU, TGA, xenon tank and the XCA components
2. check ion thruster performance and thrust at five specific throttle levels from 0.95 to 2.5 kW
3. check thrust vector control, thrust pointing and roll torque
4. check autonomous operation of the IPS.

After checking DCIU operation and IPS status, preparing the propellant system for use, conditioning the cathodes, and moving the TGAs from their launch positions to the null location, FT3, then FT1, and finally FT2 were started and operated successfully in diode mode. Start times (from application of the igniter pulses to cathode ignition) for the FT3 neutralizer were 21 seconds for the first start, 13 seconds for the second start, and immediate ignition on all other starts. The other thruster cathodes as well as FT3's discharge cathode ignited immediately with application of the igniter pulses. FT2 operation in diode mode was limited due to the possibility of exceeding allowable thruster temperature limits from solar heating.

## Thruster Performance Characterization Tests in ICO

The key electrical parameters for FT3, FT1, and FT2 over the performance characterization tests are given in [16]. The ICO data indicate that thruster and PPU performance measured in flight for all three thrusters is similar to data measured during acceptance tests. The recycle rate was initially higher than observed in acceptance testing but decreased with operating time over the course of the performance tests. The higher initial recycle rate after launch indicated particulate contamination of the thrusters during the spacecraft assembly, test, and launch operations (ATLO) [16]. The recycle rate decreased with thruster operating time as the high-voltage arcing eliminated the particulate contamination. There are no on-board instruments to measure thrust on the spacecraft. Instead, thrust was measured radiometrically for each thruster at each of five throttle levels (with the exception of FT2 in which the thrust was not measured at 2.12 kW) using the technique described in [19]. In [16] the measured thrust of each thruster is compared to the pre-flight expected values for each thruster. The flight data are in excellent agreement with the pre-flight predictions for thrust.

During normal IPS thrusting operations the spacecraft attitude in the pitch and yaw axes is controlled using a closed-loop thrust vector control system (TVC) whereby the spacecraft ACS uses attitude errors determined from the spacecraft's star tracker to command the thruster TGAs to adjust the thrust vector through the center of mass of the spacecraft. TVC was successfully demonstrated in the ICO with each thruster operating at all throttle ranges including full power with the exception noted above. The TGA duty cycles were within expected limits. Torque generated about the thruster axis (roll torque) was determined from momentum buildup in the RWAs for each thruster over a throttle range of 0.9 to 2.5 kW. The roll torque determined from each thruster meets the mission specification of 60 μN-m at any throttle level, which is important because of limited hydrazine onboard the spacecraft, but the measured roll torque values developed by the thrusters during TVC are greater than expected based on pre-flight screen/accelerator grid hole alignment measurements. As is discussed in the Operations section the roll torque for FT3 decreased over time.

## Long Duration System Test

A long duration system test (LDST) was performed to validate flight system and ground system readiness for cruise operations. In this test the spacecraft performed the following automatic and absolutely timed sequences without intervention from the operations team:

* initiated a slew to place the spacecraft in the correct attitude for thrusting; the slew is completed shortly before the diode mode pre-heat described in the next sentence
* started FT3 for one hour with discharge only (diode mode) to preheat the thruster, then turned FT3 off
* started FT3 at full power (2.5 kW to the PPU)
* operated the IPS at full power in TVC mode for approximately 167 hours--one full week of operations
* shut off FT3 and turned the spacecraft to the telecommunications attitude to transmit spacecraft engineering data and receive new commands (approximately a six hour process)
* initiated a slew of the spacecraft to a new thrust attitude
* restarted FT3 in diode mode for a thruster preheat of one hour, then turned FT3 off
* restarted FT3 at full power and operated the IPS in TVC for four hours to demonstrate readiness to undertake another week's thrusting activity

The results from the LDST are discussed in detail in [16]. The entire IPS subsystem performed extremely well over the course of this test. FT3 started immediately upon application of the igniter pulses to the cathodes, and the thruster's electrical parameters were stable over the duration of the 172-hour thruster burn. As this was the first time the IPS had been operated for any substantial length of time, some unexpected observations were noted, principally that the solenoid valve regulators used to maintain the plenum tank pressures in the XCA to the proper values cycled at an unexpectedly high rate, and the xenon tank temperatures exhibited "spiking" behavior described in detail in [16]. The solenoid valve cycling behavior is discussed in more detail in the Cruise Operations section of this paper. Thrust, roll torque, TGA, PPU, and xenon flow system operations were all nominal. A validation of the spacecraft software that was not included in the LDST followed the LDST. With the IPS and other spacecraft subsystems completely functional, the flight system was ready for cruise operations.

## IV. Cruise Operations-December 2007 through June 2008

The mission plan through mid-2010 is summarized in Section II and calls for IPS operation at full power for 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 IPS will process approximately 71 kg of xenon through the MGA, which is almost half of the 150 kg of xenon mission throughput at full power. Starting in mid-2010 power available to IPS will fall below full-power values and the thrusters will be operated at reduced power. 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 and retrieved during the spacecraft data playbacks in approximately seven day intervals. As of mid-June 2008 only FT3 was operated for deterministic thrusting. Overall IPS reliability is maximized if all three thrusters are operated for equal time durations at full power [15]; the present plan calls for FT1, the thruster on the –X side of the spacecraft (Figure 1) to be operated starting late June 2008.

Cruise operations leading to a MGA started on December 17, 2007 at approximately 1.16 AU from the sun. The spacecraft was oriented such that the spacecraft's Y-axis was perpendicular to the sun/spacecraft line, a spacecraft attitude that is planned for use throughout cruise. FT3 was started with the discharge only for one hour to warm up the thruster, and was then turned off. During the diode mode pre-heat the spacecraft was slowly turned to its thrusting attitude with the thrust vector approximately 102 degrees to the sun/spacecraft line. At the conclusion of the diode mode preheat FT3 was shut off and restarted seven minutes later at full power to begin deterministic thrusting to the MGA. The spacecraft will begin a seven month coast period in November 2008 leading to a Mars flyby in February 2009; during the MGA the IPS will be operated as needed for trajectory correction maneuvers. Deterministic thrusting to Vesta will resume in June 2009. Several engineers were required through the first 80 days of the mission to staff consoles and assess the ICO data, but since the start of cruise operations most Dawn subsystems have been staffed on a part-time basis to minimize mission operations costs. The IPS has been successfully operated through June 2008 using this staffing model.

### IPS Subsystem Performance-PPU, Xenon Flow System, and TGAs

Unregulated high voltage current and voltage to PPU-1 are plotted in Figure 4. The bus voltage increased by approximately 10 V as the solar range to the spacecraft changed from 1.16 AU at the start of cruise to 1.65 AU in late June 2008. PPU-1 input power at the start of cruise was approximately 2.28 kW and near the end of June 2008 was approximately 2.29 W, an increase of approximately 10 W that tracks with an increase in thruster discharge power. The data show that PPU-1 efficiency is similar to the efficiency measured preflight. Data from temperature sensors inside the PPU shown in Figure 5 indicate that PPU-1 temperatures have changed little during cruise. 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 FT3 operating at full power. PPU-1 has performed flawlessly throughout cruise. The temperature of the harness connecting PPU-1 to FT3 is shown in Figure 6. The data indicate that at full power operation the harness temperature has ranged between 37.4 and 39.7 degrees C and is well within the operational temperature limits for the harness.

The xenon flow system has operated perfectly throughout cruise, with the exception of unexpectedly high solenoid valve cycling rates. Differences in pressure measurements between the three pressure transducers on each plenum tank have remained at low values, which implies that there has been no zero shift in the transducers. Solenoid valve pairs are opened and closed to regulate pressure to the xenon flow system plenum tanks. As of late June 2008 the primary solenoid valve pair used to regulate main plenum pressure has been cycled open and closed 76,000 times in cruise, and the primary solenoid valve pair for cathode plenum tank pressure regulation has cycled 22,500 times. The main solenoid valve cycle rate measured during cruise is shown in Figure 7. For both the main and cathode plenum tank regulators the solenoid valve cycle rate measured in flight is greater than expected, which may affect solenoid valve reliability if the number of cycles for the mission exceeds 1,300,000 cycles. Analyses indicate that the solenoid valve cycle rate can be reduced if the temperature of the xenon flowing through the solenoid valves is reduced. In Figure 7 the temperature of the XCA plate was reduced by 0.5 degrees C at 966 hours of cumulative beam-on time, then by 1 degree C more at hours 2,832, 3,113, and 3,433 respectively. Each time the XCA plate temperature decreased the solenoid valve cycle rate decreased. Additional reductions in the solenoid valve cycle rate may be needed pending analyses of the xenon 2-phase flow margin and the expected cycle requirements.

The TGAs have also operated flawlessly in cruise. Cumulative TGA actuator steps are shown in Figure 8. In normal operation the TGAs "dither", or rotate, a small amount around a target center. The TGAs are used to move the ion thruster vector through the spacecraft center of mass to control the spacecraft attitude in pitch and yaw (TVC mode). The spacecraft is operated in TVC mode during normal thrusting, including during desaturations of the RWAs, which occur 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%. Approximately every 2 to 6 months 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

To date FT3 has been started in flight 64 times--48 during cruise operations to MGA--with 24 of these starts with beam extraction. All start attempts on FT3 were successful. The cathode heater preheat duration for all starts was six minutes. Both the neutralizer and discharge cathodes on FT3 have ignited within the ten-second resolution of the data on every start attempt, and data from the ICO taken at smaller time intervals indicate that after the first two start attempts the cathodes on FT3 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, and data taken during cruise indicates actual heater currents have been constant at 8.499 A for the discharge cathode and 8.494 A for the neutralizer cathode. Peak heater voltages for all start attempts with beam extraction during cruise are plotted in Figure 9. Heater voltages at cathode ignition are affected by thruster temperatures, which are a function of sun exposure and time duration between previous thruster operations. A diode mode preheat of the thruster for approximately 54 minutes at approximately 250 W is 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. The thruster has successfully started and operated in diode mode during each of the 24 diode mode start attempts. Thruster operating characteristics during diode mode have remained essentially constant at 12.99 A and 19.3 W over the course of cruise operations.

### Thruster Operation in Cruise

As of late June 2008 FT3 has operated with the discharge on for 3,933 hours and for 3,903 hours with beam extraction. The thruster operating times and xenon used are tabulated in Table 4.

Table 4. Thruster Operating Times and Xenon Consumption Through mid-June 2008

| | All FTs (FT1, FT2, FT3) | FT3 in ICO | FT3 Cruise to late June 08 |
|---|---|---|---|
| Discharge On-time (hrs) | 3688 | 223.0 | 3622 |
| Beam On-time (hrs) | 3955 | 213.6 | 3591 |
| Xenon Consumption (kg) | 40.3 | 2.4 | 37.3 |

### FT3 Performance in Cruise

Data for FT3 operating at full power during cruise are shown in Table 5 and Figures 10-16. Table 15 also includes values from the beginning of life (BOL) throttle table. Thruster operation was very stable throughout all of cruise to date--almost 3,700 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 -199.94 V.

Table 5. Thruster 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 | 1.756 | 1100 | 6.65 | -200 | 14.3 | 23.8 | 194 | 1.5 | 11.5 | 2474 | 2286 | 0.924 |

The accelerator grid current is plotted in Figure 10. 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 Extended Life Test (ELT) [14], which started at a higher level and then decreased over a period of approximately 1,500 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 11. A total of 43 recycles on FT3 operating at full power for 3,300 hours has occurred during cruise. The data indicate that the low recycle rate of approximately one recycle per 77 hours is unchanged over cruise. Most recycles occurred well after the start of beam extraction, indicating that debris accumulated as part of the ATLO process was still being cleared.

The neutralizer voltage, plotted in Figure 12, has decreased by almost 2 V since FT3 was first operated at full power and 1.3 V since the start of cruise. The neutralizer voltage decreased by 0.5 V in the ELT [14] over a similar time period. Neutralizer voltage changes may be related to improved cathode conditioning over time. 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, shown in Figure 13. The plume mode voltage increases to approximately 6 V during the first approximately 30 seconds after cathode ignition, then decreases to approximately 1 V during normal neutralizer operation. The plume mode circuit voltage is monitored continuously to evaluate the health of the neutralizer. Data for the voltage between the spacecraft ground and neutralizer common are shown in Figure 14. Values for neutralizer common voltage in this figure are the values averaged over the complete run for that week and are not the peak values of neutralizer common voltage that can occur on thruster starts. Neutralizer common voltage is affected by the spacecraft attitude to the sun and thruster aging.

Discharge current and voltage are shown in Figure 15; the discharge voltage data do not include drops across the harness between FT3 and PPU-1, which could be as much as 10 W in power. Over the last 2,600 hours of cruise the discharge current has been trending upward at a rate of approximately 0.08 A per 1,000 hours (khr), and the discharge voltage has been trending downward after increasing during the first 1,000 hours of operation in cruise at full power. The discharge loss for cruise is plotted in Figure 16. The discharge loss increased over the first 1,100 hours of operation in cruise, an expected event due to enlargement of the grid holes, and has remained essentially constant since that time. The discharge loss at the start of cruise is greater compared to the discharge loss measured during acceptance testing and during the ICO.

### 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. 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 lack 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 (personal communication from Ian Roundhill, June 10, 2008) . Calculations for thrust during cruise from the Dawn navigation team are shown in Table 6. Uncertainty (1-σ) for all thrust estimates 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. The thrust levels appear to be fairly constant throughout cruise. For mission modeling and future orbit determinations the worst-case thrust for FT3 (89.7 mN) is assumed, so the in-flight performance for FT3 provides margin to the mission in the form of missed thrust days and xenon.

Table 6. Reconstructed Thrust During Cruise

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

The Dawn requirement for roll torque is 60 μN-m at any thruster power level. During the ICO of FT3 the roll torque was measured to be 59 μN-m [16]; at the start of cruise operations the roll torque determined from RWA data was measured to be 52.3 μN-m and has continued to decrease during cruise operations. Roll torque is plotted in Figure 17 as a function of cumulative xenon used during cruise; the magnitude for roll torque appears to be linear with the amount of xenon processed. It is possible that there is a systematic thrust vector pointing error resulting in a torque about the thruster axis that is changing as the spacecraft's center of mass shifts with xenon use. It is also 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. During the ICO when the roll torque was measured for FT1 only 0.8 kg of xenon had been processed by the IPS, and FT1 has not been operated since that time, Operation of FT1 in future cruise operations is an opportunity to distinguish between these two possibilities (personal communication from J. Brophy, June 2008).

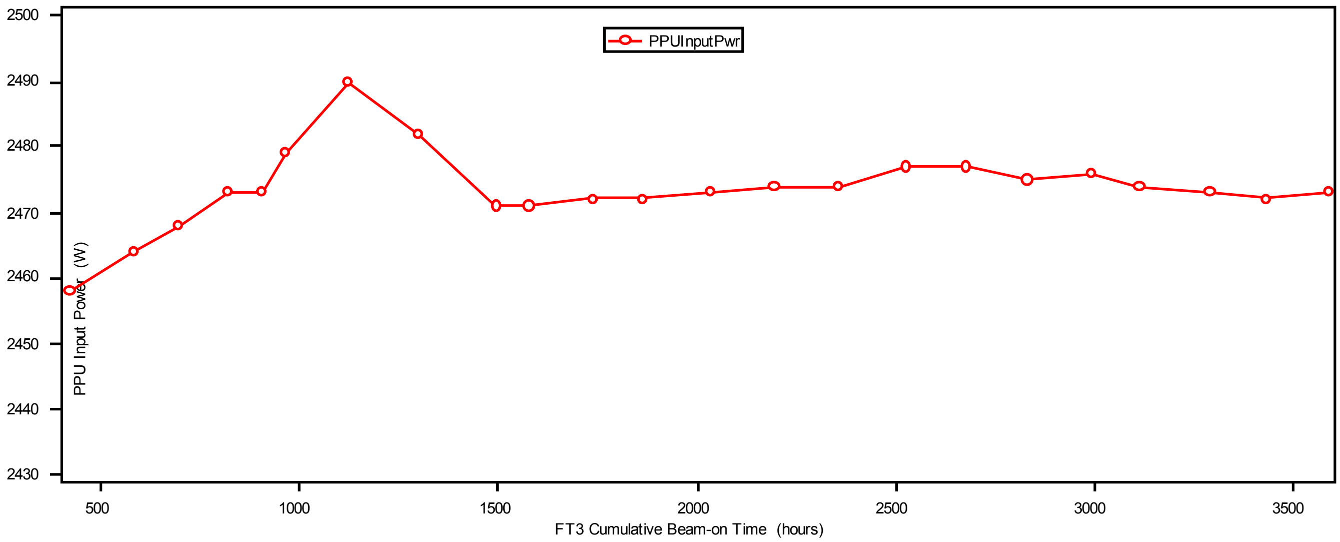

Figure 4. High voltage solar array power to PPU-1

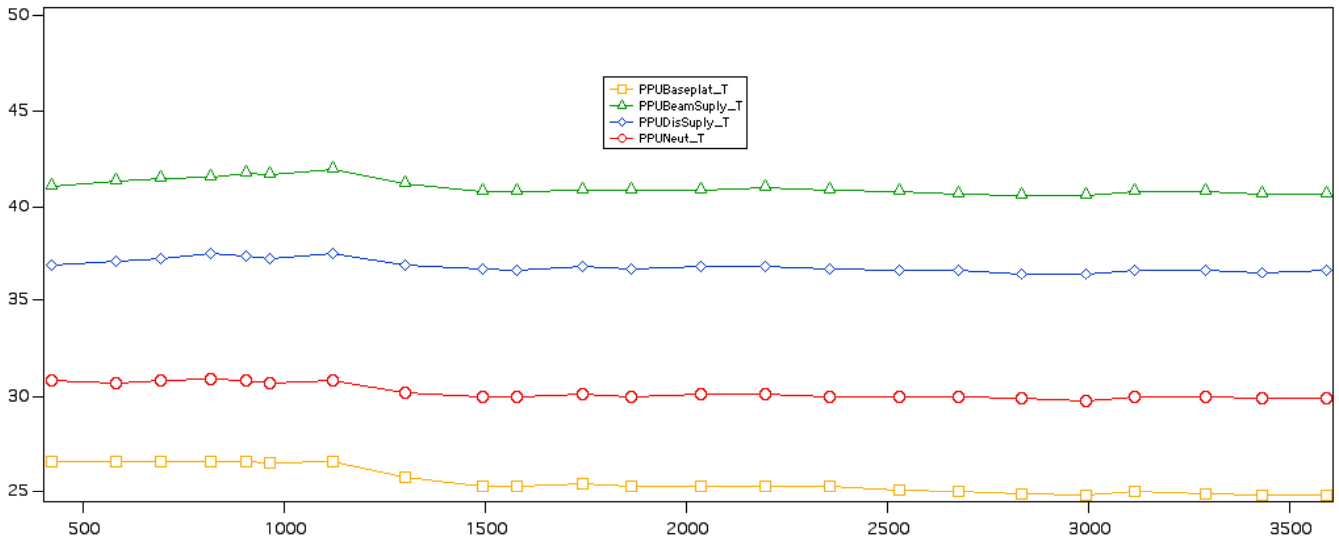

Figure 5. PPU-1 internal sensor temperatures with FT3 at full power operation.

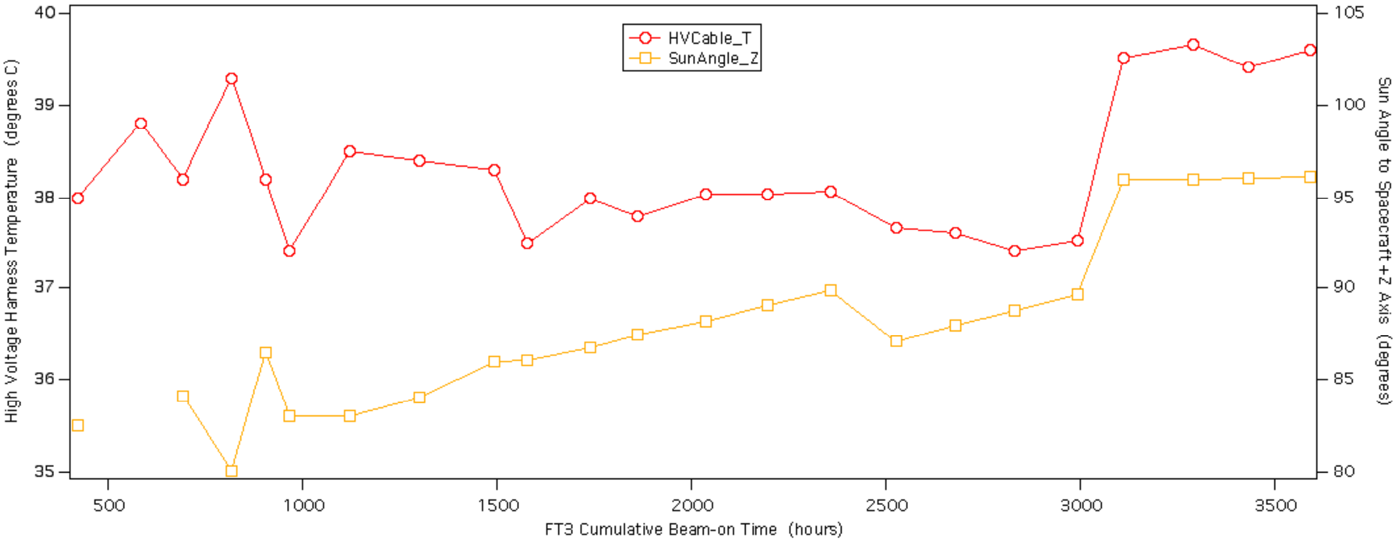

Figure 6. Temperature of the PPU to thruster cable at field joint location.

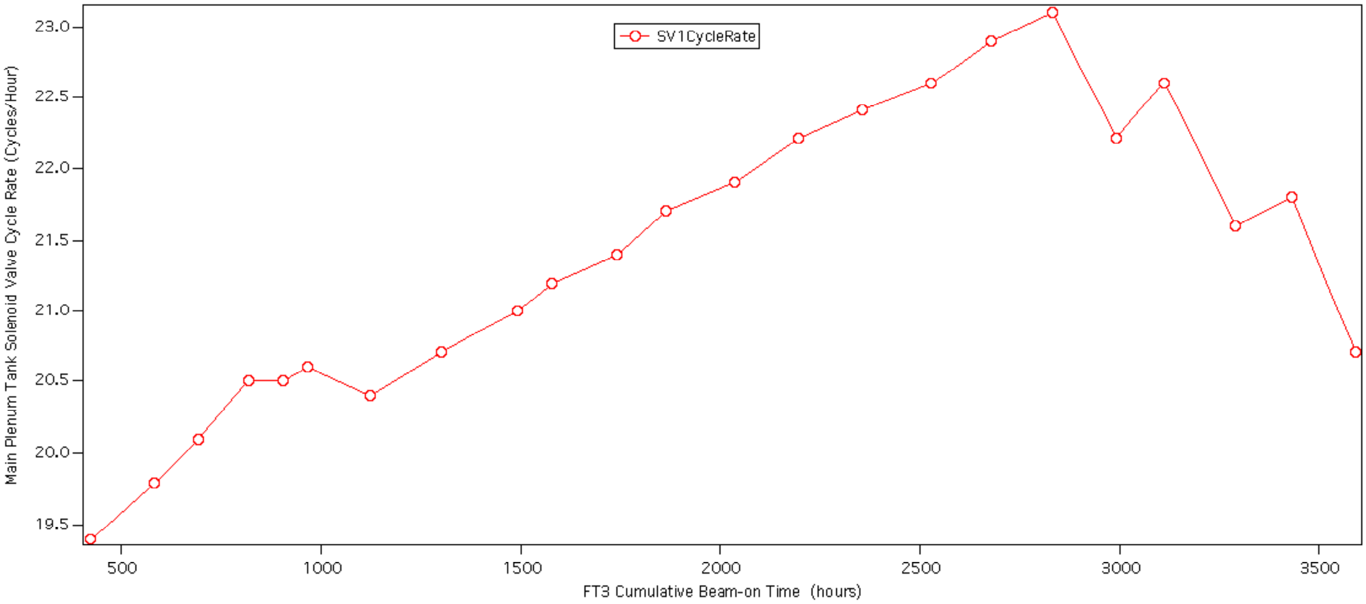

Figure 7. Main plenum pressure regulation solenoid valve cycle rate.

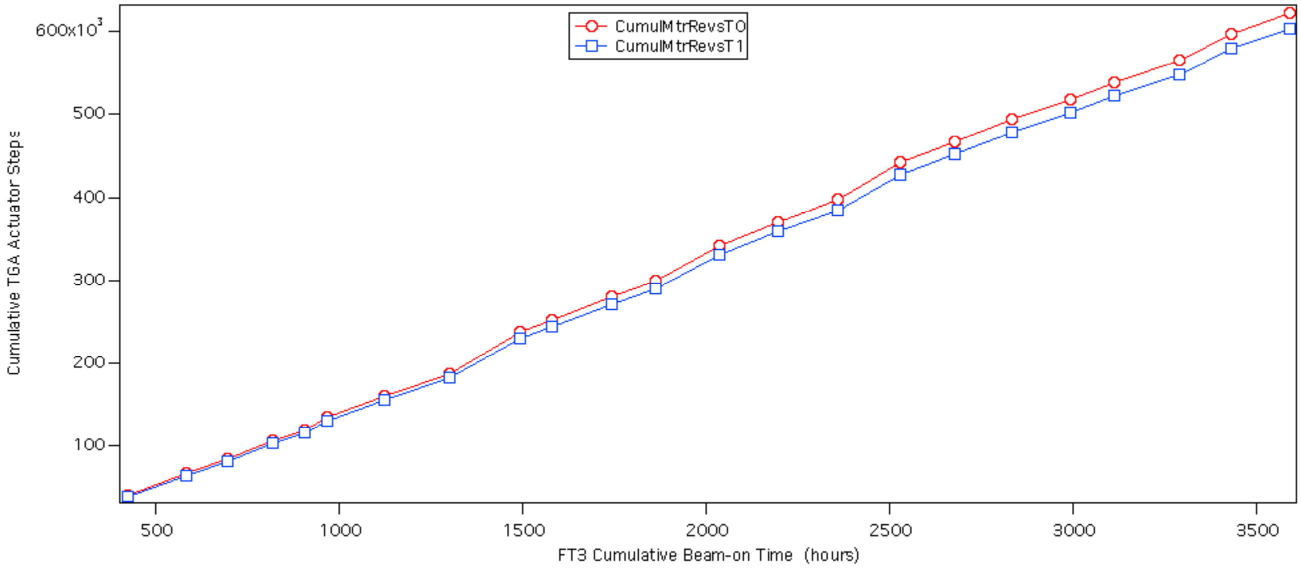

Figure 8. Number of actuator steps on TGA-3 during cruise from December 2007 to June 2009.

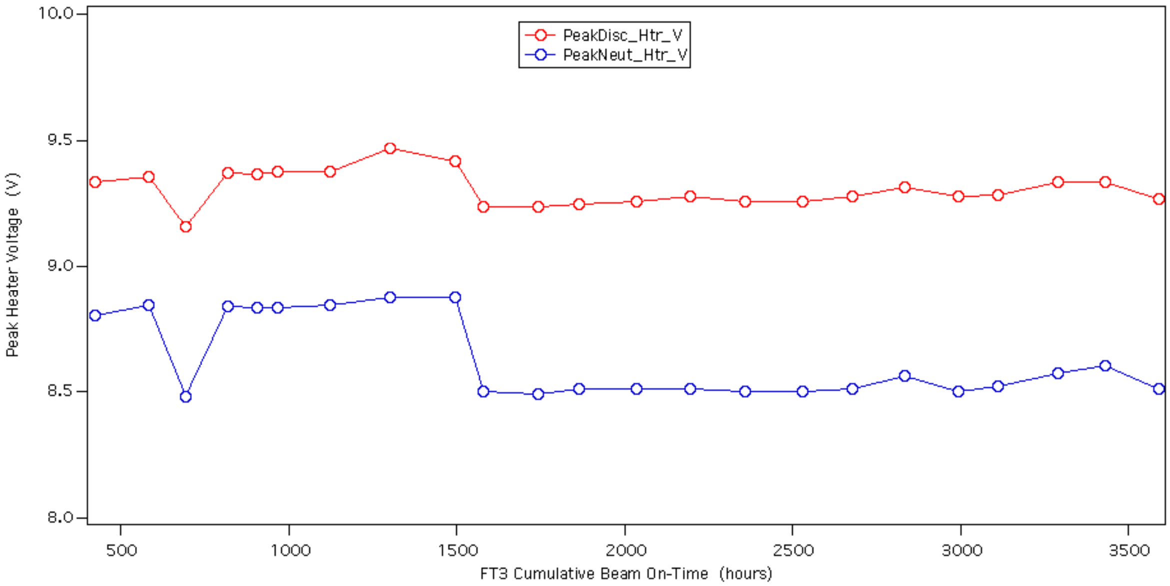

Figure 9. FT3 Peak cathode heater voltage for thruster starts with beam extraction.

Figure 10. FT3 accelerator grid current during cruise.

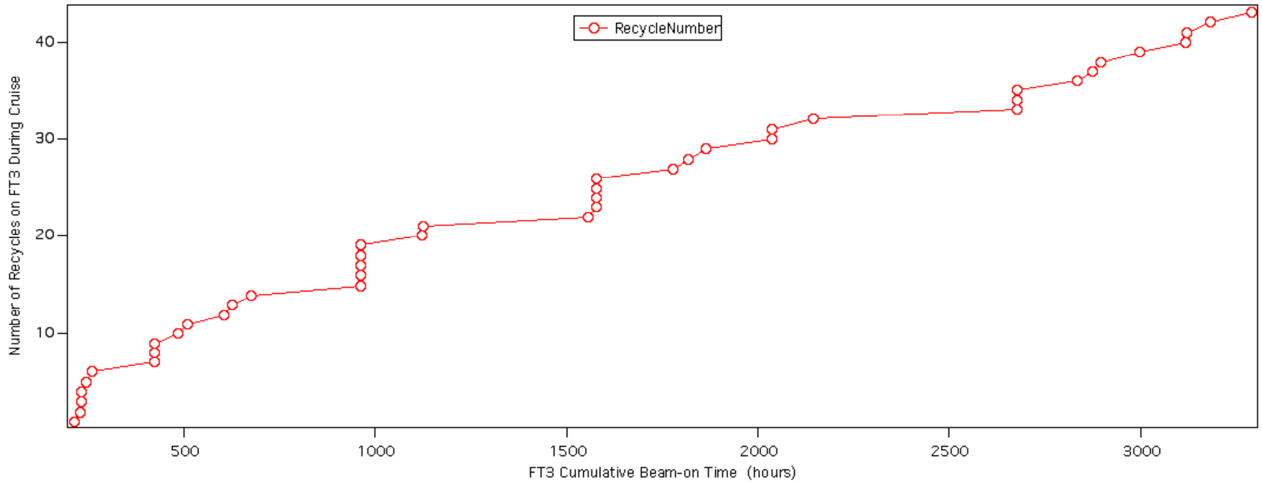

Figure 11. Recycles during cruise with FT3 operating at full power. The recycle rate is app. one recycle per 77 hours.

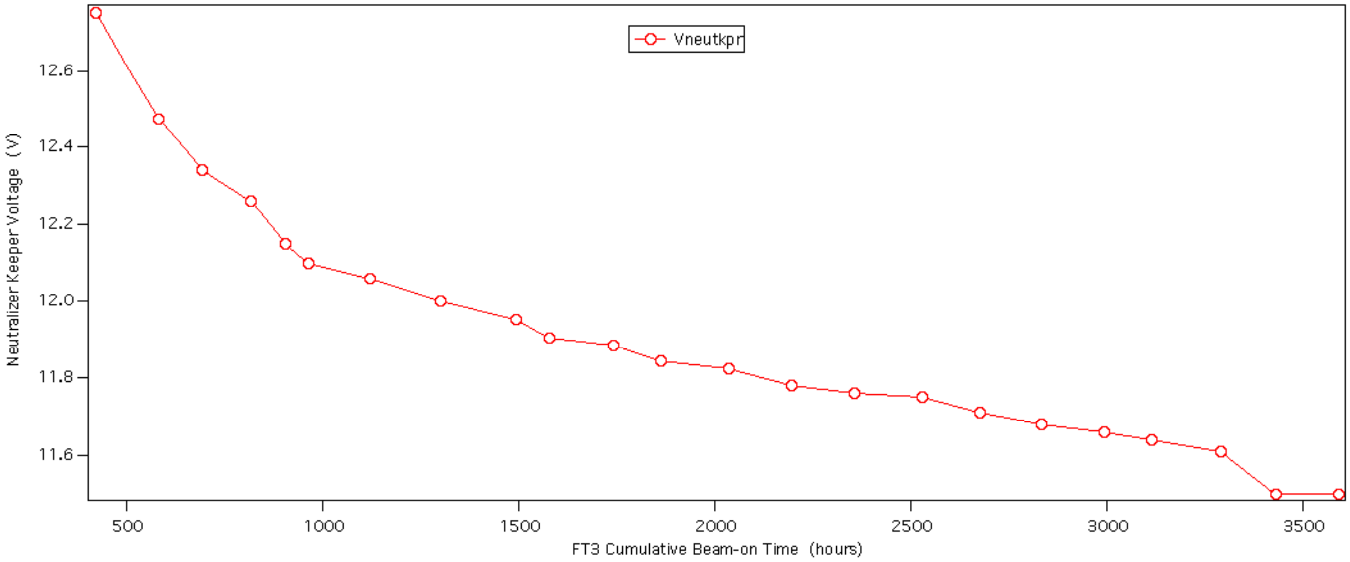

Figure 12. Neutralizer keeper voltage during cruise with FT3 operating at full power.

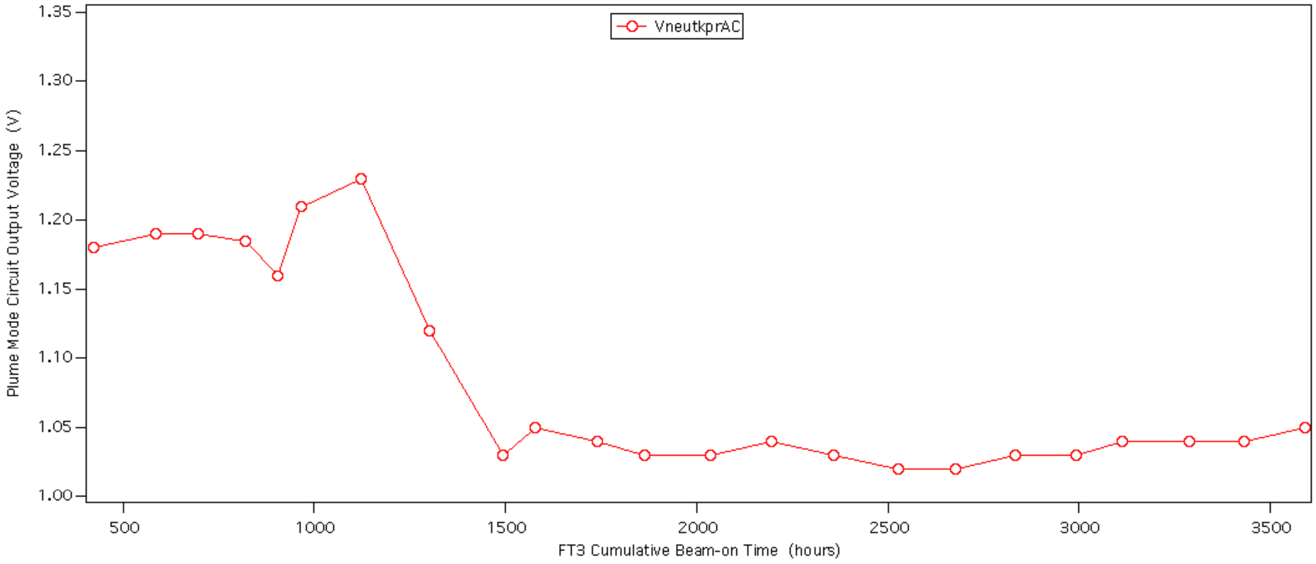

Figure 13. PPU-1 plume mode circuit voltage during cruise.

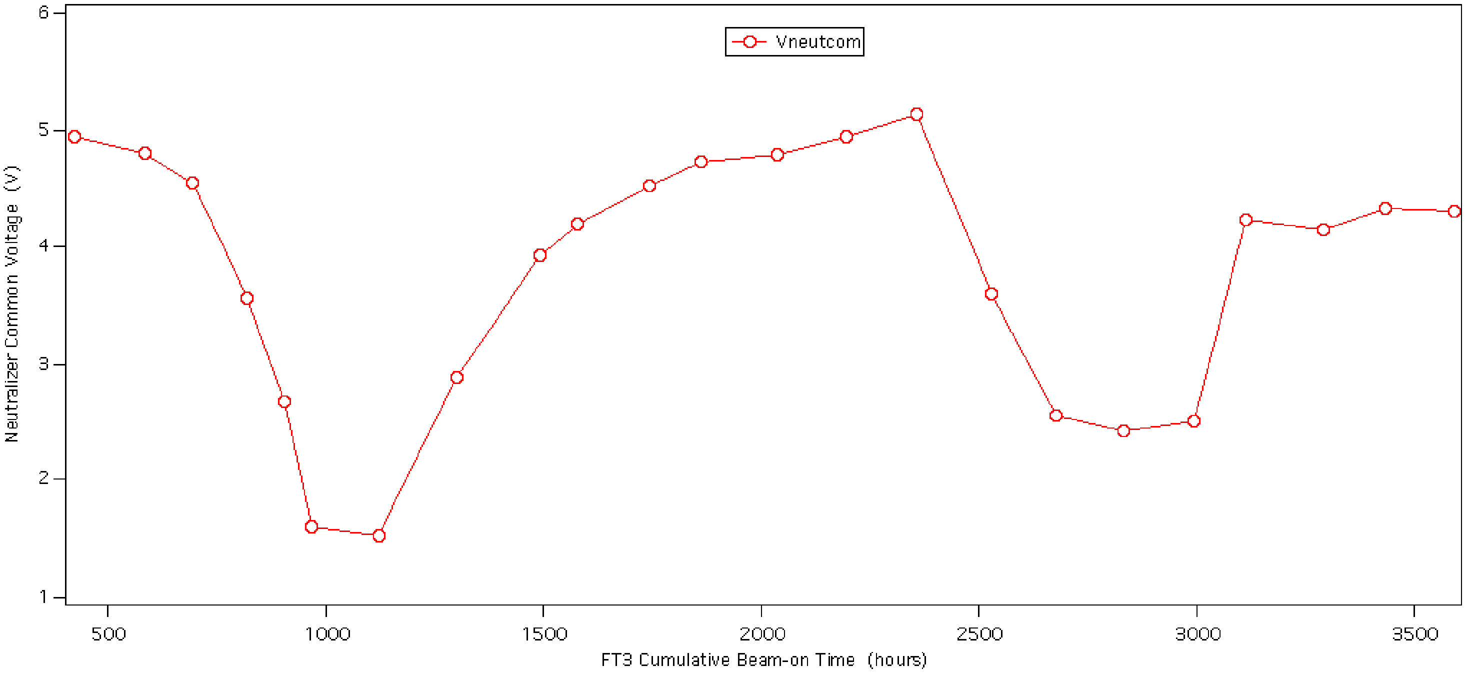

Figure 14. FT3 Neutralizer common voltage during cruise.

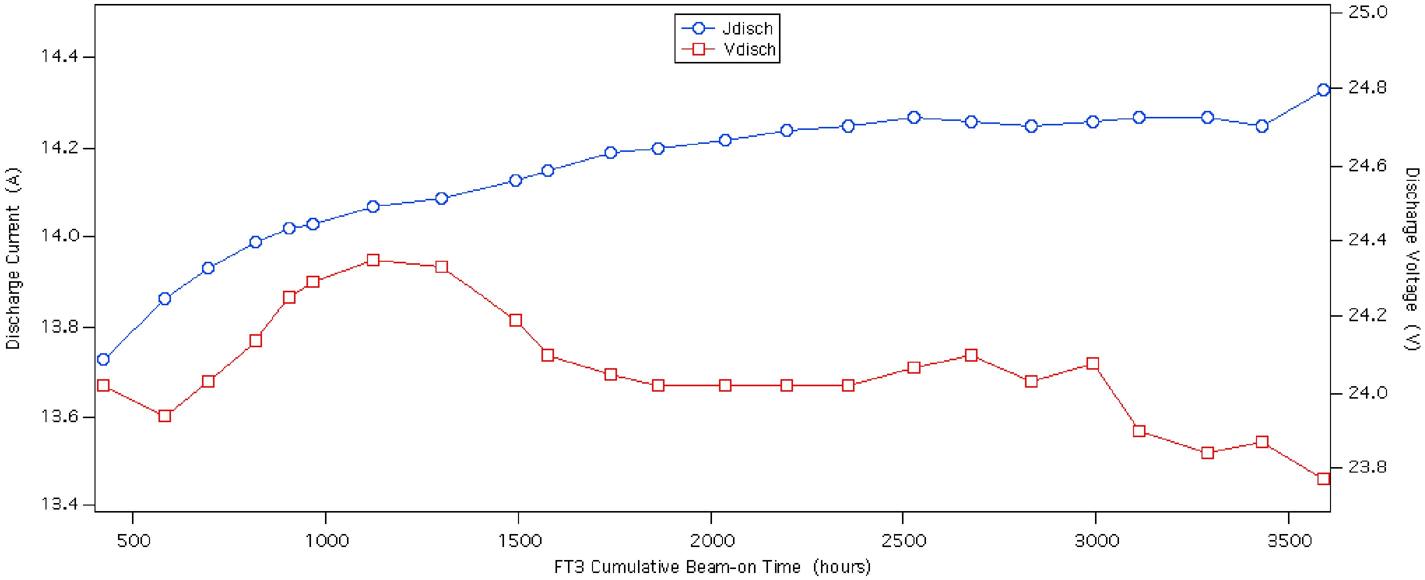

Figure 15. FT3 Discharge current and voltage during cruise.

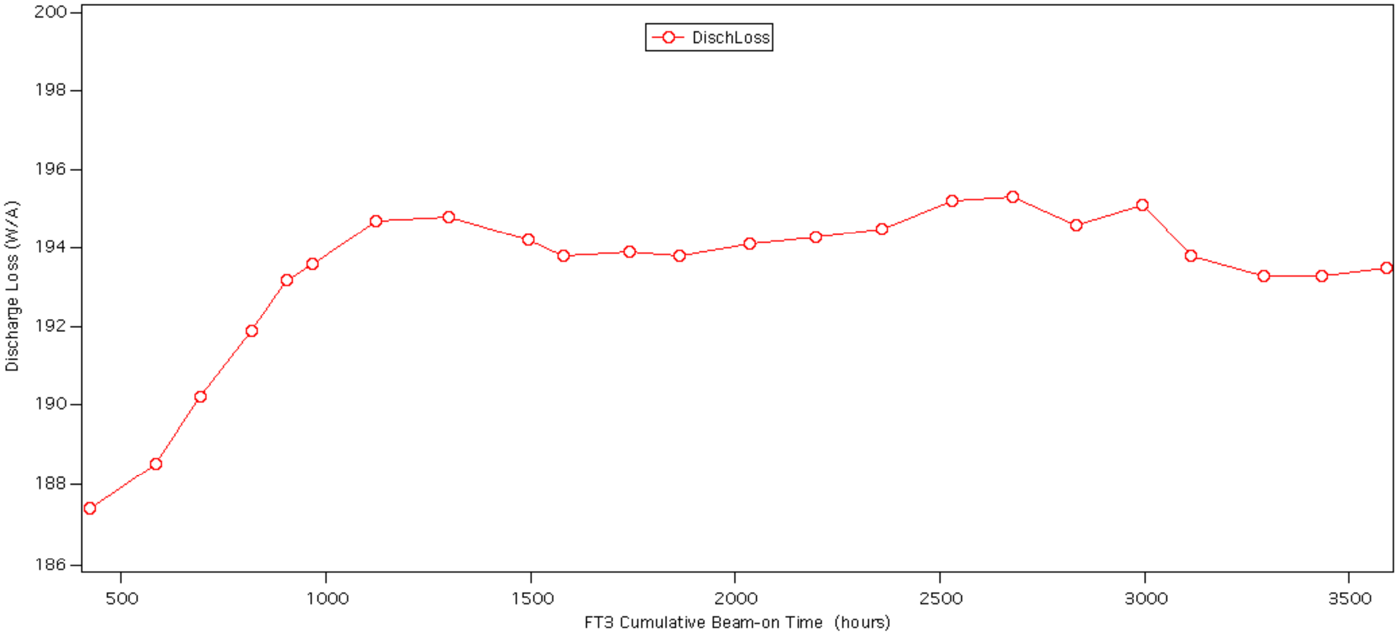

Figure 16. FT3 discharge loss during cruise.

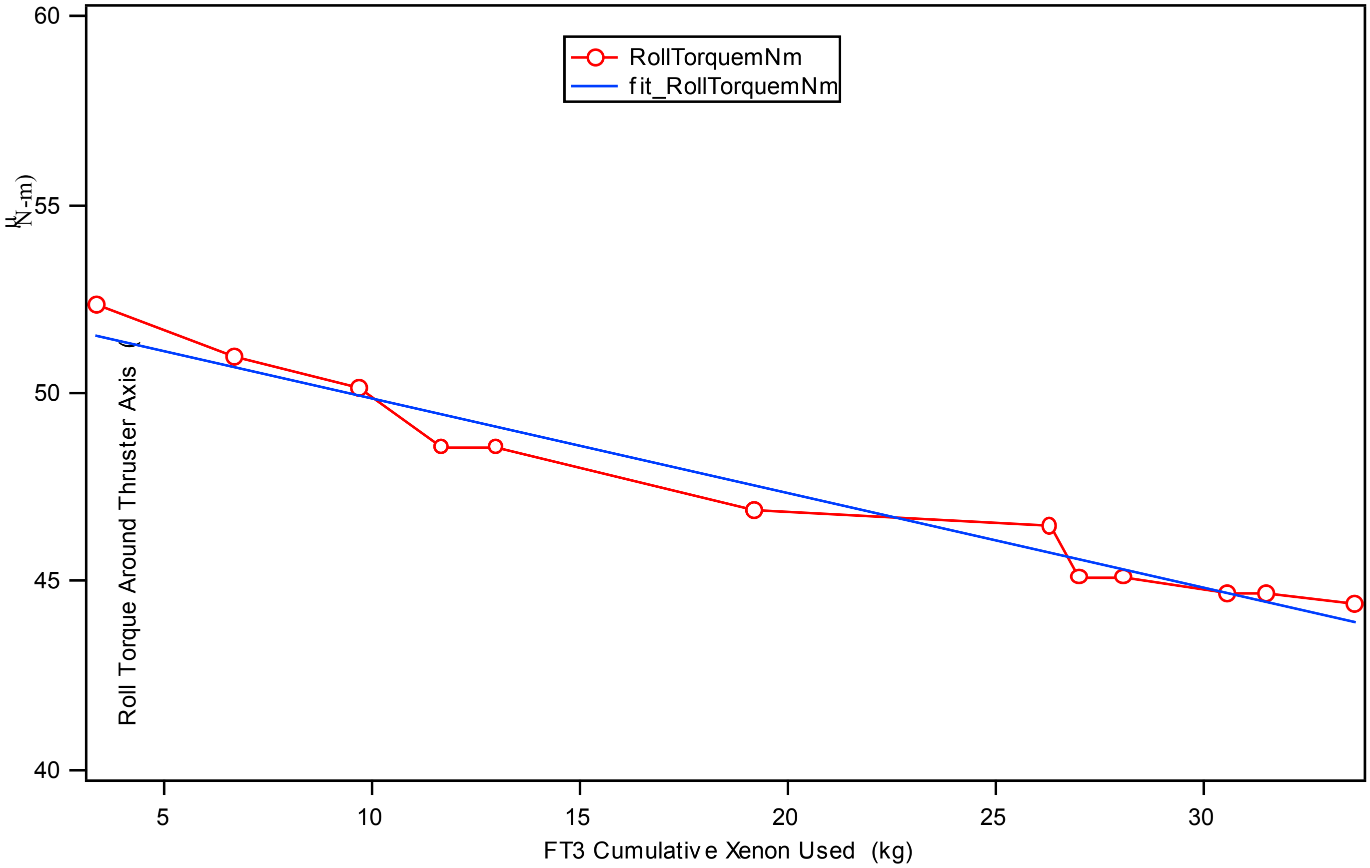

Figure 17. Roll torque about FT3 as a function of xenon use.

## III. Conclusion

The Dawn mission will use an ion propulsion system for heliocentric transfer to the asteroid Vesta and the minor planet Ceres, and for science maneuvers upon arrival. The first 80 days after launch were dedicated to the initial checkout of the spacecraft and the ion propulsion system prior to the initiation of thrusting for the heliocentric transfer to Vesta. The Dawn ion propulsion system completed the initial checkout with all hardware operating as expected with some minor exceptions. Deterministic thrusting for cruise began on December 17, 2007, with a planned Mars flyby in February 2009. The Dawn ion propulsion system has operated almost flawlessly throughout cruise to date, accumulating almost 4,000 hours of beam-on time that resulted in almost 1 km/s of $\Delta$-V to the spacecraft. All the IPS components--the FTs, DCIUs, PPUs, XCA, and TGAs—have operated as expected. The thruster performance characteristics were similar to performance characteristics measured in the thruster acceptance tests. The solenoid valve cycle rates were greater than expected but are not a threat to the successful completion of the mission. Thrust values measured on each thruster during the ICO and on FT3 during cruise were close to expected values. Deterministic thrusting at full power will continue through November 2008, leading to a Mars flyby in February 2009 and a Vesta rendezvous in 2011.

## Acknowledgments

The authors thank the many individuals at the organizations that contributed to the success of the Dawn mission. These organizations are, in no special order: UCLA, JPL, Orbital Sciences Corporation, Glenn Research Center, L3, Moog, Carlton Technologies, Starsys, and Launch Alliance Services. This research was carried out, in part, at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

## References

[1] Rayman, M.D., The Successful Conclusion of the Deep Space One Mission: Important Results Without a Flashy Title, *Space Technology* **23**, Nos. 2-3, p. 185 (2003)

[2] Darnon, Franck et al., "An Overview of Electric Propulsion Activities in France," AIAA-2007-5165, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 8-11 July, 2007, Cincinnati, Ohio.

[3] Kimiya Komurasaki, Kimiya and Kuninaka, Hitoshi, "An Overview of Electric Propulsion Activities in Japan," AIAA-2007-5166, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 8-11 July, 2007, Cincinnati, Ohio.

[4]http://discovery.nasa.gov/

[5]Brophy, John R. et al., "Development and Testing of the Dawn Ion Propulsion System-", AIAA-2006-4319, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 9-12 July 2006, Sacramento, Ca.

[6]Rayman, Marc D., Fraschetti, Thomas.C., Raymond, Carol A., and Russell, Christopher T., "Dawn: A mission in development for exploration of main belt asteroidsVesta and Ceres", Acta Astronautica 58 (2006), 605-616.

[7]C.T. Russell, et al., "Dawn: A Journey in Space and Time", Planetary and Space Science 52 (2004) 465–489.

[8]http://www.orbital.com/ Star- Bus Fact Sheet

[9]Brophy, John R., Rayman, Marc D., and Pavri, Bettina, "Dawn-An Ion-Propelled Journey to the Beginning of the Solar System", paper 2.0406, IEEE Aerospace Conference, Big Sky, Montana, march 1-8, 2008.

[10]Brophy, John R., et al., "Implementation of the Dawn Ion Propulsion System," AIAA 2005-4071, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 10-30 July, 2005, Tucson, Arizona.

[11]Brophy, John R. at al., "The Dawn Ion Propulsion System-Getting to Launch," IEPC-2007-083, presented at the 30th International Electric Propulsion Conference, September 17-20, 2007, Florence, Italy.

[12]Polk, James E. et al., "Validation of the NSTAR Ion Propulsion System on the Deep Space One Mission: Overview and Initial Results", AIAA-99-2274, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 20-24 June 1999, Los Angeles, Ca.

[13]Rawlin, Vincent K. et al., "An Ion Propulsion System for NASA's Deep Space Missions", AIAA-99-4612, AIAA Space Technology Conference and Exposition, 28-30 September 1999, Albuquerque, NM.

[14]Sengupta, Anita et al., "The 30,000-hour Extended-Life Test of the Deep Space 1 Flight Spare Ion Thruster," NASA/TP 2004-213391, March 2005.

[15]Brophy, John R., "Propellant Throughput Capability of the Dawn Ion Thrusters", IEPC-2007-083, presented at the 30th International Electric Propulsion Conference, September 17-20, 2007, Florence, Italy.

[16] Brophy, John R. et al., “Dawn Ion Propulsion System-Initial Checkout After Launch,” AIAA-2008-4917, to be presented at the 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 20-23 July 2008, Hartford, CT.

[17] Rayman, M.D. et al., “Coupling of System Resource Margins Through the Use of Electric Propulsion: Implications in Preparing for the Dawm Mission to Ceres and Vesta,” Acta Astronautica 60 (2007) 930-938.

[18] Ganapathi, Gani B. et al., “Effects Of Xenon Propellant On The Spin Up/Down Of The Dawn Spacecraft”, AIAA-2007-5202, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 8-11 July, 2007, Cincinnati, Ohio.

[18] Misashi, Y., personal communication, September 30, 2007.

[19] McElrath, Tim P., Han, Dongsuk, and Ryne, Mark S., “Radio Navigation of Deep Space 1 During Ion Propulsion Usage,” Paper MS00/57 presented at the 15th International Symposium of Spaceflight Dynamics, Biarritz, France, June 2000.

[22] Personal communication, J. Brophy to C. Garner, June 1, 2008.