In-Flight Operation of the Dawn Ion Propulsion System Through the Preparations for Escape From Vesta

Charles E. Garner,[1] Marc D. Rayman, John R. Brophy, and Steven C. Mikes[2]
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, 4 Vesta, and the dwarf planet 1 Ceres. The Dawn spacecraft was launched from the Cape Canaveral Air Force Station on September 27, 2007 on a Delta-II 7925H-9.5 rocket that placed the 1218-kg spacecraft into an Earth-escape trajectory. On-board the spacecraft is an ion propulsion system (IPS) developed at the Jet Propulsion Laboratory which will provide a total delta-V of approximately 11 km/s for the heliocentric transfer to Vesta, orbit capture at Vesta, transfer between Vesta science orbits, departure and escape from Vesta, heliocentric transfer to Ceres, orbit capture at Ceres, transfer between Ceres science orbits, and orbit maintenance maneuvers for all Vesta and Ceres science orbits. Full-power thrusting from December 2007 through October 2008 was used to successfully target a Mars gravity assist flyby in February 2009 that provided an additional delta-V of 2.6 km/s. Deterministic thrusting for the heliocentric transfer to Vesta resumed in June 2009 and concluded with orbit capture at Vesta on July 16, 2011. An additional 231 hours of IPS thrusting was used to enter the first Vesta science orbit, called Survey orbit, on August 3, 2011 at an altitude of about 2,735 km. The IPS was then used over the next year to transfer the spacecraft to the other science orbits: a high altitude mapping orbit (HAMO-1) in September 2011 at an altitude of approximately 673 km, a low altitude mapping orbit (LAMO) at approximately 210 km altitude, and a second high altitude mapping orbit (HAMO-2) at approximately 673 km altitude. To date the IPS has been operated for approximately 24,327 hours, consumed approximately 260 kg of xenon, and provided a delta-V of approximately 7 km/s. IPS performance characteristics are very close to the expected performance based on analysis and testing performed pre-launch. Thrusting for escape from Vesta and cruise to Ceres is planned to start in late July 2012 with a planned arrival date at Ceres in February 2015. This paper provides an overview of Dawn's mission objectives and the results of Dawn IPS mission operations through preparations for departure from Vesta.

I. Introduction

Missions using electric propulsion have attained a high level of success and reliability of operation. Deep Space 1 (DS1), launched in 1998, operated its single thruster ion propulsion system for over 16,000 hours before successfully completing its primary and extended missions [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]. European and U.S. communications satellites have been launched with SPT-100 based propulsion modules for attitude control and orbit boosting. The Hayabusa spacecraft returned to Earth after exploring asteroid 25143 Itokawa [3] and employed ion engines for primary propulsion. The Japanese ETS-VIII uses ion thrusters for north-south station keeping. ESA's GOCE mission, launched in March 2009, employs ion propulsion for precision orbital control in low Earth orbit [4], and ESA's Artemis mission used the RIT-10 ion propulsion system for transfer to a geostationary orbit [5].

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[1]Engineer, Propulsion and Materials Engineering Section
[2] Dawn Project System Engineer and Mission Manager
[3] Principal Engineer, Propulsion and Materials Engineering Section
[4] Senior Engineer, Flight System Avionics Section

Approximately 72 ion thrusters (13-cm-dia and 25-cm-dia) are aboard 32 communication satellites for orbit-raising and station-keeping functions, accumulating ~450,000 operating hours in flight [6]. In 2011 the U.S. Air Force satellite AEHF (Advanced Extremely High Frequency) was successfully placed into a geosynchronous orbit from a highly elliptical orbit around Earth using the spacecraft's Hall thruster station-keeping propulsion system [7] after the propulsion system originally intended for the orbit maneuver failed. As of June 2012 there are over 236 spacecraft successfully using electric propulsion for attitude control, orbit raising, station keeping and for primary propulsion [8].

The Dawn mission is the ninth project in NASA's Discovery Program. The goal of the Discovery Program is to achieve important space science by launching regular smaller missions using fewer resources and shorter development times than past projects with comparable objectives [9]. The combination of low-cost and short development times presents substantial challenges to an ambitious mission such as Dawn.

The Dawn mission has as its goal the scientific exploration of the two most massive main-belt asteroids, Vesta and the dwarf planet Ceres for clues about the formation and evolution of the early solar system. To realize these science goals the Dawn spacecraft must rendezvous with and orbit each body. Dawn is the first mission to orbit a main belt asteroid and will be the first to orbit two extraterrestrial targets. The Dawn mission is enabled by a three-engine ion propulsion system (IPS) that will provide most of the velocity change (ΔV) needed for heliocentric transfer to Vesta, orbit capture at Vesta, transfer to Vesta science orbits, orbit maintenance, orbit escape and departure from Vesta, heliocentric transfer to Ceres, orbit capture at Ceres, orbit maintenance and transfer to Ceres science orbits. Without ion propulsion, a mission to orbit Vesta alone would have been unaffordable within NASA's Discovery Program, and a mission to orbit both Vesta and Ceres would have been impossible.

The Dawn spacecraft was launched from Cape Canaveral Air Force Station on September 27, 2007. The first 80 days of the mission were dedicated to a comprehensive spacecraft and IPS checkout [10]. Cruise operations for deterministic thrusting began December 18, 2007 leading to a Mars flyby in February 2009 [11], and rendezvous and orbit capture at Vesta on July 16, 2011, with a science phase lasting approximately 13 months. At the conclusion of the science phase the Dawn spacecraft will depart Vesta and resume deterministic thrusting leading to 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 through preparations for departure from Vesta.

II. MISSION AND SYSTEM FLIGHT OVERVIEW

The mission and flight system are described in detail in [10-12], and are summarized here. Vesta is the second most massive main belt asteroid with a mean diameter of 530 km. Ceres, with a diameter of 950 km, is the largest and most massive body in the asteroid belt. Ceres is classified as one of five dwarf planets in our solar system, and studies suggest it may have a large inventory of subsurface water. The goal of the Dawn mission is to investigate and compare these two very different bodies in the asteroid belt to answer questions about the evolution of our solar system. The science underlying the Dawn mission have been described in detail elsewhere [13,14]. Dawn is led by its principal investigator, Dr. Christopher Russell, of the University of California, Los Angeles (UCLA), who has overall responsibility for the mission. The Jet Propulsion Laboratory (JPL) was responsible for the spacecraft and science payload development, IPS development and development of other spacecraft components, safety and mission assurance, project systems engineering, mission design, and navigation development, and is responsible for mission operations system development and mission operations which are conducted from JPL.

Orbital Sciences Corporation (Orbital), Sterling, VA, was responsible for developing the spacecraft bus, flight system integration and testing, and launch operations. The Dawn flight system is shown in Figure 1. The spacecraft is based on Orbital's STAR-2 [15] and Leostar [15] satellite platform series. The solar array (SA) consists of two large panel assemblies approximately 18 m^2 each and measuring almost 20 m tip to tip with triple junction cells providing more than 10 kW of electrical power at one astronomical unit (AU) and 1.3 kW for operations at Ceres. Articulation of the solar arrays is about the Y-axis.

The spacecraft attitude control subsystem (ACS) employs mechanical gyros and four reaction wheel assemblies (RWA) for three-axis control of the spacecraft and makes use of the IPS for pitch and yaw control during normal IPS thrusting. The reaction control subsystem (RCS) uses hydrazine thrusters for direct three axis control of the spacecraft and was intended primarily for desaturating the reaction wheels. The spacecraft launched with 45 kg of hydrazine on-board for RCS use on this eight-year-long mission. A mass summary for the Dawn flight system is provided in Table 1.

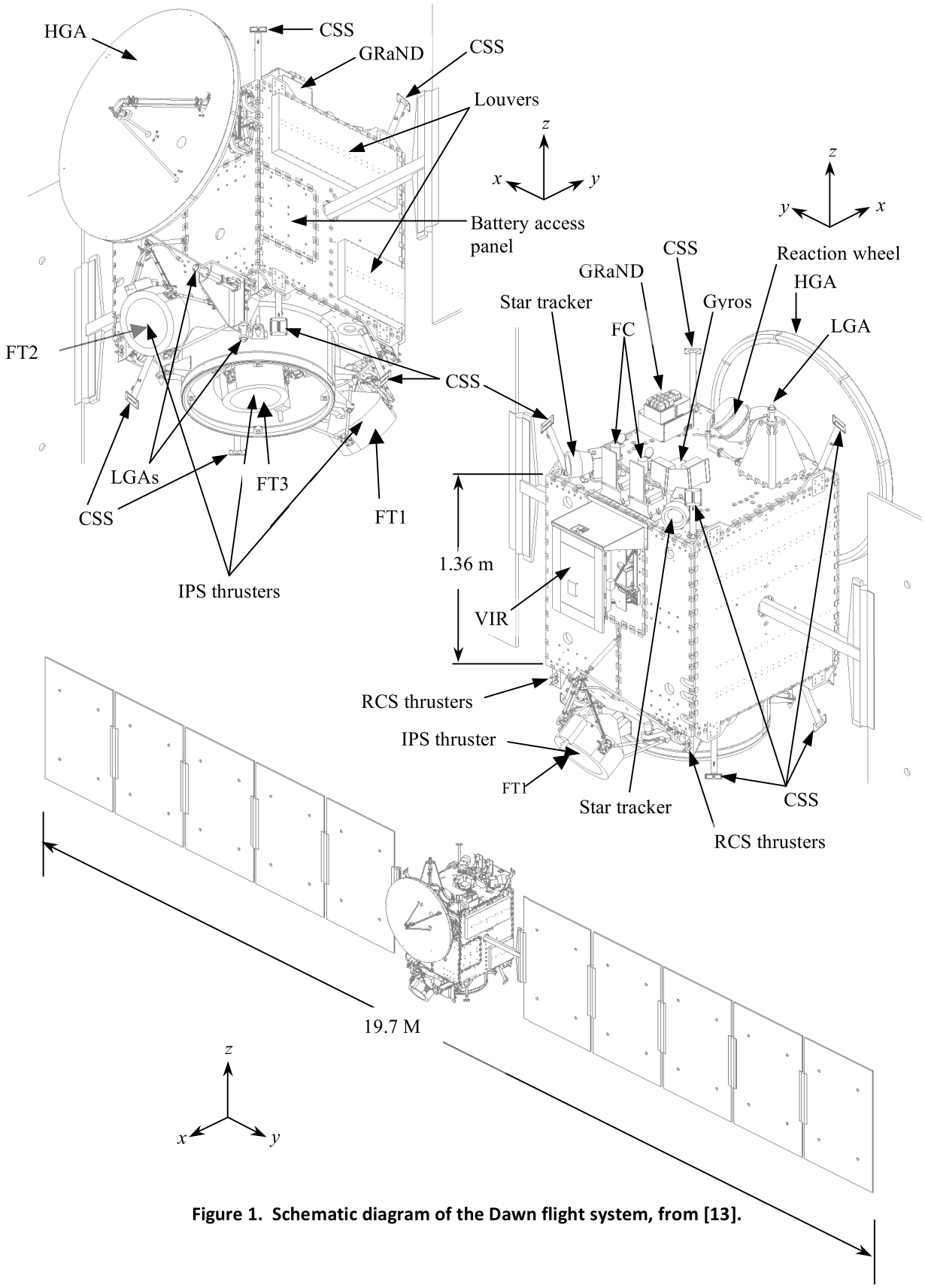

Figure 1. Schematic diagram of the Dawn flight system, from [13].

Table 1. Dawn Flight System Mass at Launch

Description	Mass, kg
Dry spacecraft and avionics (except IPS)	573
Science instruments	46
Hydrazine	45
Ion Propulsion System (IPS)	129
Xenon	425
Flight system mass at launch	**1218**

The Dawn ion propulsion subsystem (IPS) developed at JPL is described in detail in [16] and is shown in the block diagram in Figure 2. The IPS is single-fault tolerant as configured for Dawn and is based on the single-engine ion propulsion system flown successfully on the DS1 mission [17], but modified for multiple thrusters and supporting hardware. The Dawn IPS includes three 30-cm-diameter xenon ion thrusters operated one at a time, two power processor units (PPU), two digital control interface units (DCIU), three Thruster-Gimbal Assemblies (TGA) for two-axis thrust-vector control, a Xenon Control Assembly (XCA) for controlling xenon flow to the engines, and a single xenon storage tank. The ion thrusters and the PPUs are based on technology developed by NASA Glenn Research Center (GRC), and engineered and fabricated for flight by L-3 Communications Electron Technologies (L-3), Inc., Torrance, CA, with minimal modifications to their designs from DS1. The two DCIUs, which accept commands from the spacecraft, command the PPU supplies, operate the valves on the XCA and actuators on the TGAs, and return IPS telemetry, were designed and fabricated at JPL. The design was modified from the DS1 design to meet the multi-engine system functionality and cross-strapping required for Dawn.

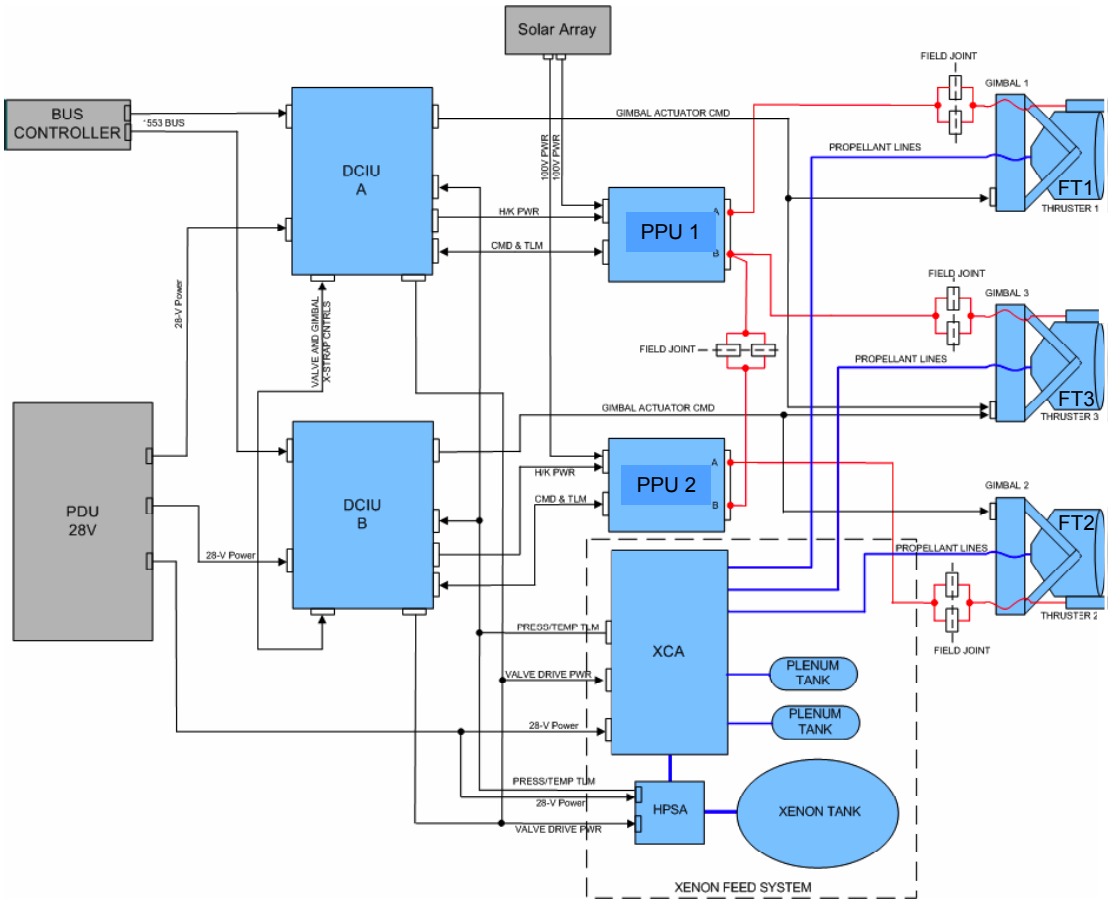

Figure 2. Simplified block diagram of the Dawn IPS.

A titanium-lined composite-overwrap xenon tank developed for Dawn with a volume of 266 liters was mounted inside the core structure of the spacecraft and loaded with 425 kg of xenon prior to launch. A xenon allocation summary is provided in Table 2. The xenon feed system is based on the DS1 design but was modified to operate multiple thrusters and to be single-fault tolerant. Each thruster is gimbaled using the TGA to point the thrust vector through the spacecraft center of mass and to provide pitch and yaw control during ion thrusting.

The mission trajectory for Dawn is shown in Figure 3, and a list of important mission phases is summarized in Table 3 below. The complete mission ΔV, from the initial checkout through conclusion of Ceres science operations and including the Mars gravity assist, is approximately 13.6 km/s (Table 3). The IPS will provide 11 km/s of this ΔV and will use approximately 402 kg of xenon for the complete mission.

Table 2. Xenon Allocation Summary

Description	Xenon Allocation (kg)
Initial Checkout	3.1
Xenon Allocated For Thruster Restarts	3.0
Main Tank Residuals	5.0
Leakage Allocation	10.0
Deterministic Thrusting To Vesta	246.7
Allocation for Vesta Operations	9.8
Deterministic Thrusting To Ceres	114
Allocation for Ceres Operations	10.5
Margin	23.1
Total	**425.2**

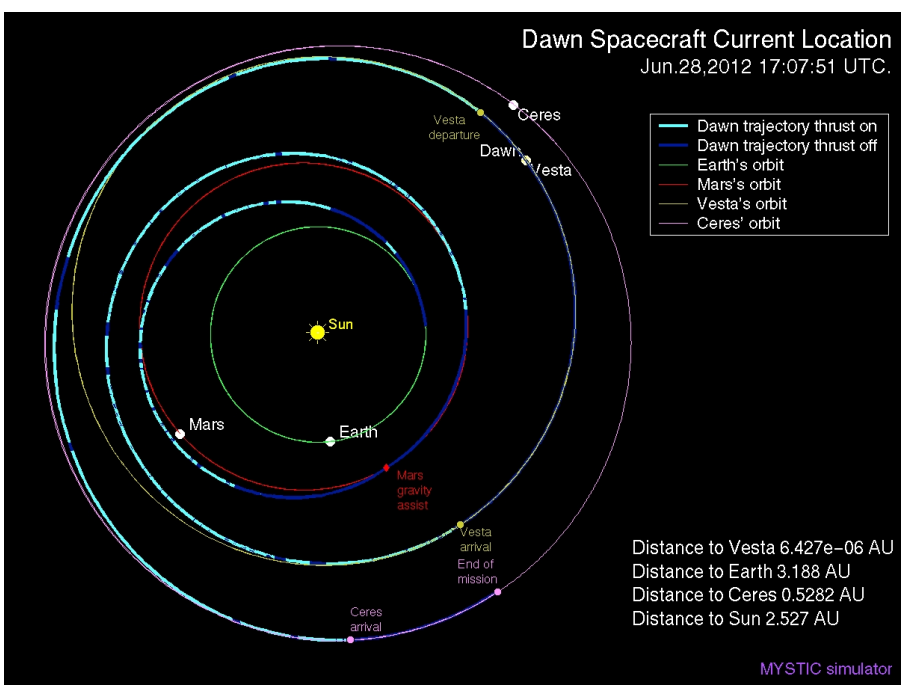

Figure 3. Dawn mission trajectory.

Table 3. Dawn Mission Summary. Bold font indicates the mission phase has been completed.

Description	Time Period	Distance S/C to Sun (AU)	Power Level To IPS (kW)	Comments
Launch	**09/27/2007**	**1.0**	**NA**	
Initial Checkout	**09/2007 - 12/2007**	**1.0 - 1.16**	**2.6**	**ΔV = 0.06 km/s**
Cruise prior to MGA	**12/2007 - 11/2008**	**1.16 - 1.40**	**2.6**	**ΔV = 1.8 km/s**
Mars Gravity Assist (MGA)	**11/2008 - 06/2009**	**1.40 - 1.60**	**NA**	**ΔV = 2.60 km/s (From MGA)**
Cruise to Vesta	**06/2009 - 07/2011**	**1.40 - 2.26**	**2.6 -1.7**	**ΔV = 4.84 km/s ***
IPS Operations at Vesta	**07/2011 - 06/06/12**	**2.26 - 2.53**	**1.7 -1.3**	**ΔV = 0.23 km/**
Cruise to Ceres	07/2012 - 02/2015	2.51 - 2.84	1.3 -0.9	ΔV = 3.55 km/s
Ceres Science Operations	02/2015 - 07/2015	2.84 - 2.93	0.9	ΔV = 0.48 km/s

* From start of cruise to orbit capture at Vesta

III. Overview of IPS Operations At Vesta

Deterministic thrusting to Vesta began on December 18, 2007 and concluded with orbit capture on July 16, 2011 at approximately 04:48 UTC. At capture the spacecraft was approximately 16,000 km altitude above Vesta with a velocity relative to Vesta of approximately 27 m/s, approaching Vesta from its south pole. The low velocity relative to Vesta was a consequence of Dawn's interplanetary ion thrusting approach which reshaped the spacecraft's heliocentric orbit to closely match that of Vesta. In contrast to missions that use high-thrust chemical propulsion, Dawn did not have a typical planetary orbit insertion with a critical short maneuver to achieve a rapid change in the trajectory. Rather, capture by Vesta's gravity occurred during routine thrusting.

The Dawn science plan includes four different near-polar mapping orbits around Vesta to achieve its science goals: Survey orbit, a high altitude mapping orbit (HAMO-1), a low altitude mapping orbit (LAMO), and a second high altitude mapping orbit (HAMO-2). Orbit characteristics such as orbital altitude, orbit plane, etc. were designed to maximize science gathering, orbit stability and spacecraft safety. The IPS was used to transition the spacecraft to all the Vesta science orbits as well as to perform orbit maintenance maneuvers (OMMs). FT2 was used for the transition from orbit capture to Survey orbit, and FT3 was used for all remaining orbit maneuvers at Vesta. Orbit transfers were completed using a series of low thrust maneuvers that spiraled the spacecraft to the required orbits. Uncertainties in ACS pointing of the IPS thrust, IPS thrust magnitude (typically less than 0.25%), thrust from the use of the RCS to desaturate reaction wheels, Vesta's gravity field, and other perturbations resulted in only small errors in performing the orbit maneuvers. Transfers were performed in relatively short segments to minimize the accumulated effect of these error sources. For example, the transfer from HAMO-1 to LAMO required thrusting over approximately 180 orbits around Vesta in ten sequential designs with a total of 31 separate thrust maneuvers. A summary of IPS thrusting activities for Vesta science orbits is shown in Table 4.

The spacecraft's standard near-polar orbit over Vesta at all altitudes took the spacecraft over the north pole (which was in darkness, because it was in northern hemisphere winter at that time), then over the terminator (the boundary between the illuminated and un-illuminated sides), down over the equator, over the south pole, and then across the terminator again to pass over Vesta's night side (Figure 4). The spacecraft was never occulted by Vesta at any time during all operations at Vesta, which prevented shadow on the spacecraft's solar panels. At injection into each science orbit the orbital eccentricity was near-circular. Small forces acting on the spacecraft contributed to maneuver execution errors [20] which overall were remarkably small.

Table 4. Summary of IPS thrusting for Vesta science orbits. Colored rows indicate activities using IPS.

Event	Time Period	Altitude Above Vesta (km)	Number of IPS Maneuvers	Thrust Time (hrs)	Xenon Used (kg)
Transition: Orbit Capture To Survey	07/16/11 to 08/02/11	16000-2735	6	231	2.0
Survey Orbit	08/02/11 to 08/31/11	2735	0	0	0
Transition: Survey To HAMO-1	08/31/11 to 09/28/11	2735-670	16	276	2.5
HAMO-1 Orbit	09/28/11 to 11/02/11	670	0	0	0
Transition: HAMO-1 To LAMO	11/02/11 to 12/12/11	670 - 210	31	288	2.6
LAMO Orbit	12/12/11 to 04/27/12	210			
LAMO OMM*	12/12/11 to 04/27/12	210	11	9	0.2
Transition: LAMO To HAMO-2	05/01/12 to 06/06/12	210-670	22	305	2.4
HAMO-2 Orbit	06/06/12 to 07/23/12	670	0	0	0
IPS Vesta Operations Totals**	07/16/11 to 07/23/12		86	1109	9.8

*Orbit Maintenance Maneuver
**From orbit capture to HAMO-2

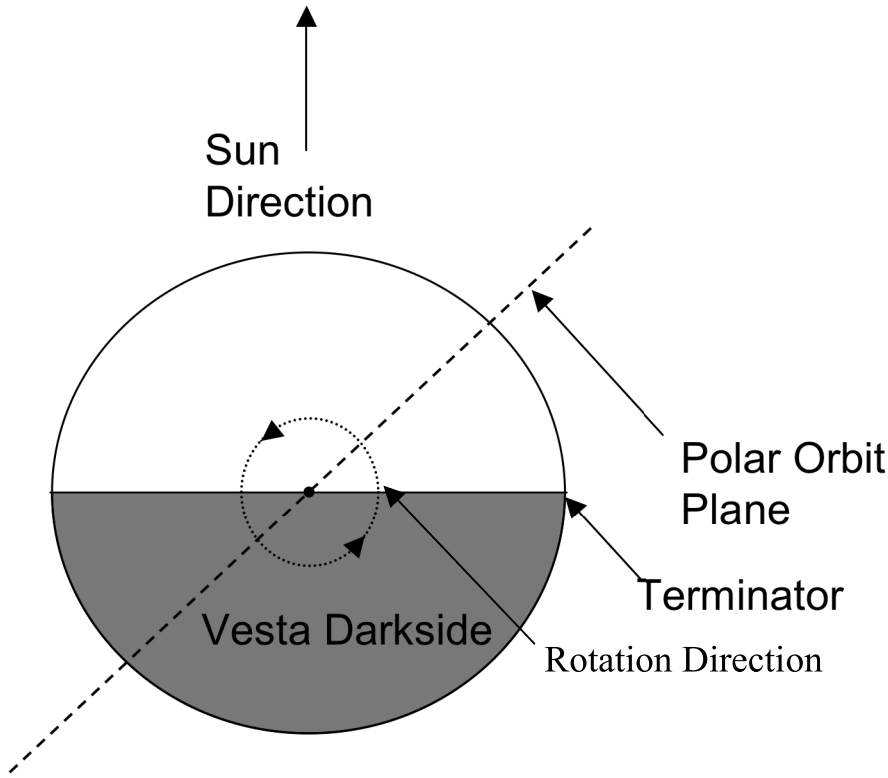

Figure 4. Diagram of Dawn's orbit plane around Vesta as viewed from Vesta's north pole. The angle bet

Two of these error sources merit additional attention. Dawn is the first mission ever to orbit a massive body (apart from Earth or the Sun) which has not previously been visited by a spacecraft. Mercury, Venus, the moon, Mars, Jupiter, and Saturn all were studied with flyby spacecraft before orbiters were sent. Thus, Dawn entered a physical environment with greater uncertainty than is typical. Although there were estimates of Vesta's mass from its perturbations of the orbits of smaller asteroids and even of Mars, its value remained uncertain until Survey orbit.

Survey Orbit Summary

Following orbit capture at Vesta, the IPS was used to transition the spacecraft to the first science orbit, Survey orbit, at an altitude above Vesta of approximately 2,735 km and an orbit plane to sun line angle of approximately 15°. The primary objective of survey orbit was to acquire visible and infrared spectra with VIR camera for mineralogical composition. In addition, survey orbit provided an opportunity to map the surface with the camera and to characterize the gravity field. Photographic measurements and gravity analysis at the Survey altitude were important to better establish the location of Vesta's poles and provide data for a better gravity model, which were not well-characterized prior to arrival at Vesta but needed to minimize maneuver execution errors when using IPS. Vesta's rotational period is approximately 5.3 hours, and each revolution in Survey orbit required approximately 69 hours to complete. Such an orbit allowed the spacecraft a view of virtually every part of Vesta's lit surface at some time. Operations at Survey orbit required 29 days to complete.

Transition from orbit capture to Survey orbit was performed over a period of 16 days using the IPS for 6 thrust maneuvers for 231 hours of beam-on time to spiral the spacecraft to approximately 2,735 km altitude and to modify the orbital inclination and plane. Thrusting periods were established based upon the ease of maneuver planning and execution, the number of different thrusting periods required, and minimizing burn time. Individual thrust times ranged from approximately 29 to 77 hours. Input power to FT2 ranged from 1805 to 1735 W depending upon the solar array output capability, thrust varied from 72 to 70 mN, and Isp varied from 2880 to 2791 s. The IPS provided a total delta-V of approximately 40 m/s and required approximately 2 kg of xenon to transition the spacecraft from orbit capture to Survey orbit.

HAMO-1 Orbit Summary

Following the completion of the science observations in Survey orbit, IPS was used to transfer the spacecraft in a spiral trajectory to a 670-km-altitude orbit called the high altitude mapping orbit (HAMO-1). The goal of HAMO-1 was to obtain higher resolution images using the framing camera, mineralogical analysis using the VIR instrument, and gross elemental composition data using the gamma ray and neutron detector (GRAND) instrument. The final orbital period of approximately 12 hours coupled with Vesta's rotation rate of 5.3 hours resulted in almost complete coverage of Vesta's lit surface every ten orbits. Transition to HAMO-1 included a plane change to establish an angle between the orbit plane and the sun of 30 degrees. The transfer to HAMO-1 required 14 thrust arcs spread over 22 days totaling approximately 268 hours of thrusting at an input power range to the thruster between approximately 1618 W to 1562 W with thrust levels between 65-62 mN and Isp ranging from 2751 to 2731 s. The Survey to HAMO-1 transfer was modeled using the new gravity and pole location data obtained at Survey orbit. Two small trajectory correction maneuvers totaling 7.5 hours of IPS thrusting were required for final orbit injection. Thrust times for orbit transfer ranged between approximately 6 to 34 hours. For all operations to transfer from Survey to HAMO-1 the IPS used 2.5 kg of xenon and provided a delta-V of 67 m/s. The spacecraft spent approximately five weeks at HAMO-1 obtaining the science data. No orbit maintenance maneuvers were required at HAMO-1.

LAMO Orbit Summary

After completion of science at the HAMO-1 orbit, using the improved gravity field developed in this orbit, Dawn began another orbit transfer, targeting the low altitude mapping orbit (LAMO), with a mean altitude of approximately 210 km. As before a spiral trajectory was used to change the orbital altitude of the spacecraft. The transfer included a change in inclination and a plane change to move the Sun 46 degrees out of the orbit plane. Transfer to LAMO included a low-thrust trajectory through the spacecraft orbit/Vesta orbit resonance period where irregularities in Vesta's gravity were particularly effective in perturbing Dawn's trajectory. Nevertheless, the transfer design was robust and the maneuver was performed without incident. The transfer required 22 days for the altitude change, four days for the plane change and ten days for final orbit insertion which included orbit phasing adjustments. For the transfer from HAMO-1 to LAMO the IPS required a total thrusting time of approximately 288.4 hours, used 2.6 kg of xenon and provided a delta-V of 64 m/s. Thrust arcs were up to 62 hours in duration for altitude changes, and typically under five hours in duration for the plane change and under two hours for the final orbit insertion. Input power to the thruster ranged from 1455-1435 W, and the Isp ranged from 2635-2710 s. The LAMO orbit was maintained for approximately 4.5 months, with the highest priority objectives being GRaND and gravity measurements. In addition, data were collected with the camera and VIR, providing better spatial resolution than in HAMO-1. The low altitude of the LAMO orbit was especially important for the GRAND instrument.

It was recognized well before Vesta arrival that although maneuvers to maintain the Survey and HAMO orbits within their requirements would not be needed, it would be necessary to conduct them in LAMO. Vesta's irregular gravity field along with more frequent reaction wheel desaturations using the RCS more strongly perturbed the spacecraft's orbit compared to Survey and HAMO-1. Six orbit maintenance maneuvers (OMM) were needed during the 4.5-month stay in LAMO, implemented with 11 separate thrust arcs totaling 8.9 hours of IPS thrusting and using 0.2 kg of xenon. Input power to the thruster ranged from 1430 to 1250 W; input power available to IPS decreased as Vesta receded from the sun, lowering power available to the IPS.

HAMO-2 Orbit Summary

Following completion of science at LAMO the IPS was used to spiral the spacecraft back to the orbital altitude of HAMO-1, but at HAMO-2 the subsolar latitude was different because of the progression of seasons at Vesta, resulting in different shadowing and illumination conditions compared to HAMO-1. In addition, the angle of the Sun from the orbit plane was chosen to be different from HAMO-1. The transfer included a change in inclination and a change to a sun-orbit plane that varied depending upon the science requirements. Transfer from LAMO included another low-thrust trajectory through the spacecraft orbit/Vesta orbit resonance which completed without incident as expected. Transition from LAMO to HAMO-2 required 35 calendar days, a total thrusting time of approximately 305 hours, and 2.4 kg of

xenon with the IPS providing a delta-V of 56 m/s. Thrust arcs were up to 36 hours in duration, with a final orbit injection thrust period of under 30 minutes. Input power to the thruster ranged from 1254-1220 W, thrust ranged from 50.6-49.9 mN, and the Isp ranged from 2578-2541 s.

The IPS performed flawlessly throughout operations from orbit capture through HAMO-2. Maneuver execution errors were well within mission requirements with thrust typically being within ± 0.25% of the expected value based on delivery of the spacecraft to targeted orbital parameters.

IPS Performance at Vesta

The IPS performance from launch through orbit capture is discussed in detail in [18,19]. Although data presented herein include data from launch, emphasis is on IPS performance during operations at Vesta which includes the period from orbit capture through completion of IPS activities at the HAMO-2 orbit.

A. Operating Time and Xenon Consumption

Thruster operating time and xenon consumption from launch through the end of IPS operations at Vesta are summarized in Tables 5 and 6. Xenon flow rates to the thrusters are calculated from plenum tank pressure/flow control device (FCD) temperature telemetry based on curve fits to FCD calibrations obtained in ground testing. Since almost all IPS operations at Vesta were performed using the center-mounted thruster, FT3 has accumulated the most operating time and processed more xenon than FT1 and FT2.

Table 5. Thruster Operating Time Summary Through End Of Operations at Vesta*

Thruster	Initial Checkout	Vesta Cruise	Vesta Operations	Total
	Beam On-Time (hr)	Beam On-Time (hr)	Beam On-Time (hr)	Beam On-Time (hr)
FT1	42	7583	0.0	7625
FT2	22	7647	231	7900
FT3	214	7711	876	8802
Total	278	22,941	1,109	24,327

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

Table 6. Thruster Xenon Usage Summary Through End Of Operations at Vesta *

Thruster	Initial Checkout	Vesta Cruise	Vesta Operations	Total
	Xenon Use (kg)	Xenon Use (kg)	Xenon Use (kg)	Xenon Use (kg)
FT1	0.4	84.1	0.0	84.4
FT2	0.3	82.3	2.2	84.7
FT3	2.4	80.4	7.6	90.4
Total	3.1	246.7	9.8	259.6

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

B. PPU Performance

Data on power to the PPUs for operation of the thrusters are plotted in Figure 5. Data points are the values for a particular thrust arc averaged over the duration of the thrust arc, which is typically approximately 159 hours for interplanetary cruise and as low as 15 minutes for an OMM. The data include telemetry for unregulated high voltage power from the solar array and include an estimate for PPU housekeeping power of approximately 20 W from the low voltage bus. Input power to the PPUs varied

from 1930 W at orbit capture to 1335 W at HAMO-2. PPU efficiencies were consistently in excess of 92% through operations at Vesta. Both PPUs have operated perfectly throughout the mission to date.

Data (averaged over individual thrust arcs) from temperature sensors inside the PPU are shown in Figure 6 and indicate that PPU temperatures varied during operations at Vesta where there were substantial variations in spacecraft attitude with respect to the sun, total operating times, and times between sequential thrust sequences. The PPU baseplate temperature sensors have ranged between 27 degrees C with the thrusters operating at full power to 16 degrees C with the thrusters operating at 1.7 kW. The fact that the PPU baseplate temperatures are near room temperature even for full power operation is a reflection of the excellent thermal heat rejection system on the Dawn spacecraft.

Temperatures of the harness connectors mating the thrusters to the PPUs are shown in Figure 7. The data indicate that at full power operation connector temperatures ranged between 10 °C and 41 °C, and at lower power the harness connector temperatures were as low as -6 °C, well within operational temperature limits of -55 °C to +90 °C. Harness connector temperatures varied more in operations at Vesta where spacecraft attitude with respect to the sun and operating times varied substantially.

C. XFS Performance

The xenon flow system has operated perfectly throughout cruise, with the exception of the slightly higher-than-expected solenoid valve cycling rates as described in [18]. These higher cycling rates do not pose a threat to the valve cycle life. Plenum tank pressures are controlled by actuation of the solenoid valve pairs between the main xenon tank and plenum tanks. To date the primary solenoid valve pair used to regulate main plenum pressure has been cycled open and closed approximately 623,000 times since launch, and the primary solenoid valve pair for cathode plenum tank pressure regulation has cycled approximately 187,000 times (Figure 8). Solenoid valve cycling rates are increasing at a given throttle level as the density of the xenon in the main tank decreases. The solenoid valves on the Dawn XFS have a flight allocation of 1.4 million cycles, and there are redundant valves that have not yet been cycled in flight but could be used in the event of primary valve failure. There are no indications of solenoid valve or latch valve leakage based on observations of steady-state pressure measurements of the main xenon tank and both plenum tanks. Differences in pressure measurements between the three pressure transducers on each plenum tank have remained at acceptably low values. A check performed in 2009 for changes in the pressure transducer readings at near-zero pressure indicated the pressure transducer values had virtually no measurable shift in output with respect to their pre-launch values [18].

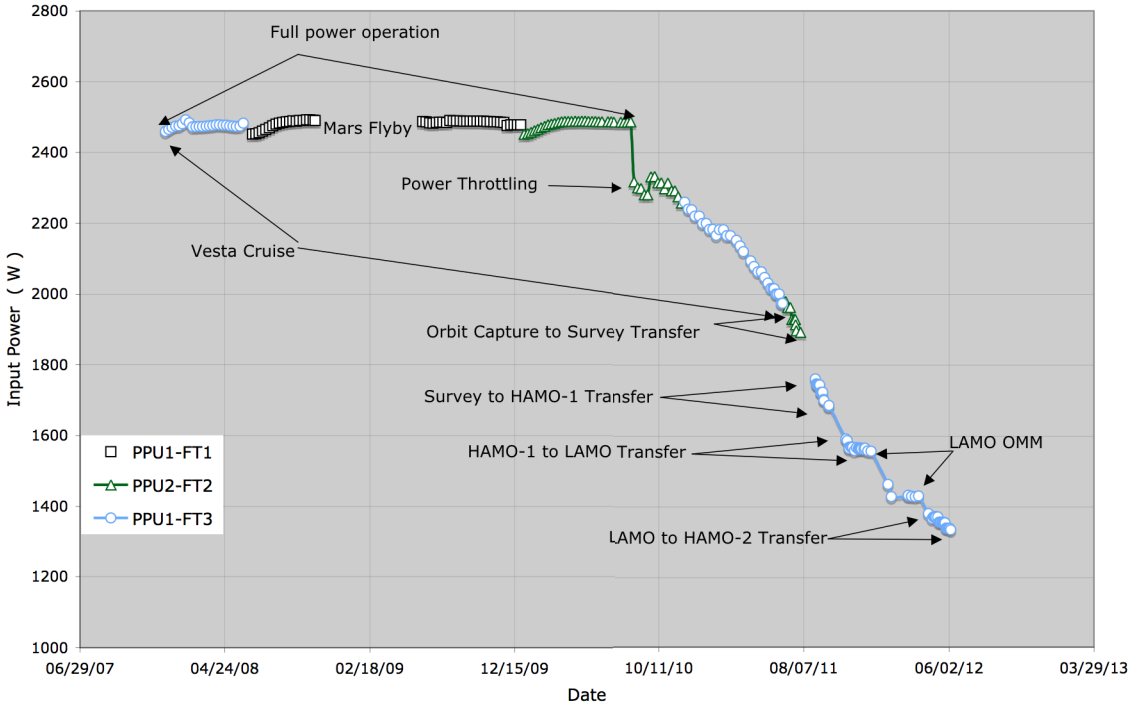

Figure 5. Input power to the PPUs through operations at Vesta.

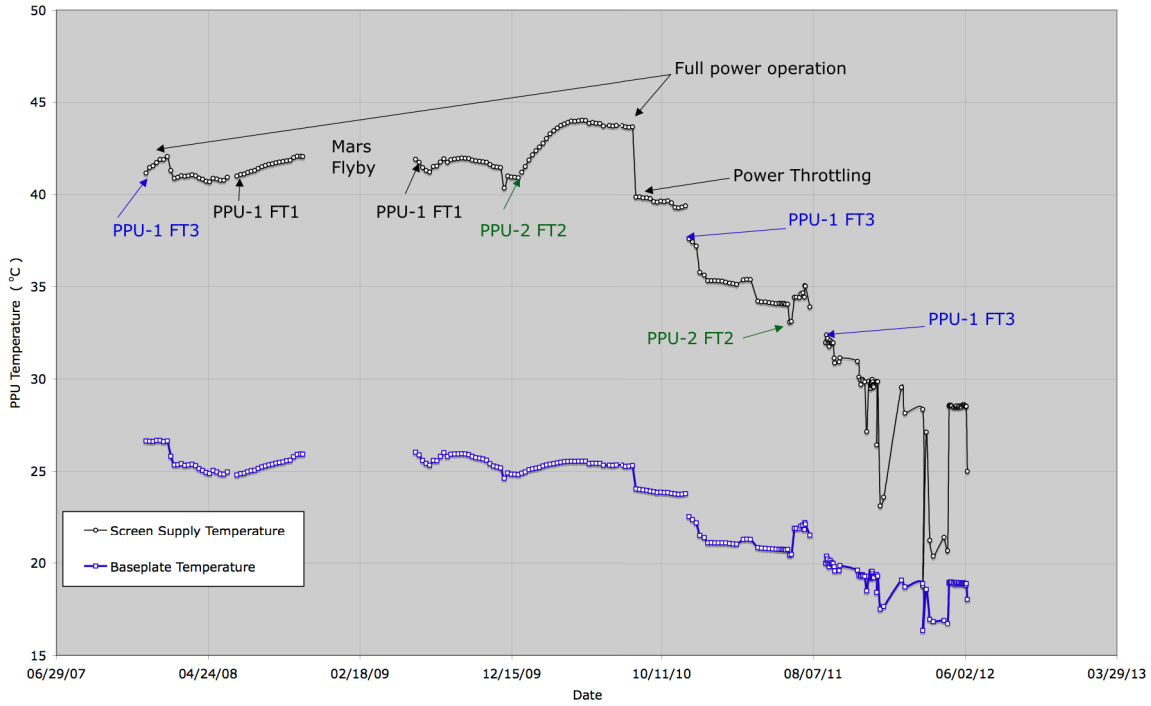

Figure 6. PPU screen supply and baseplate temperatures through operations at Vesta.

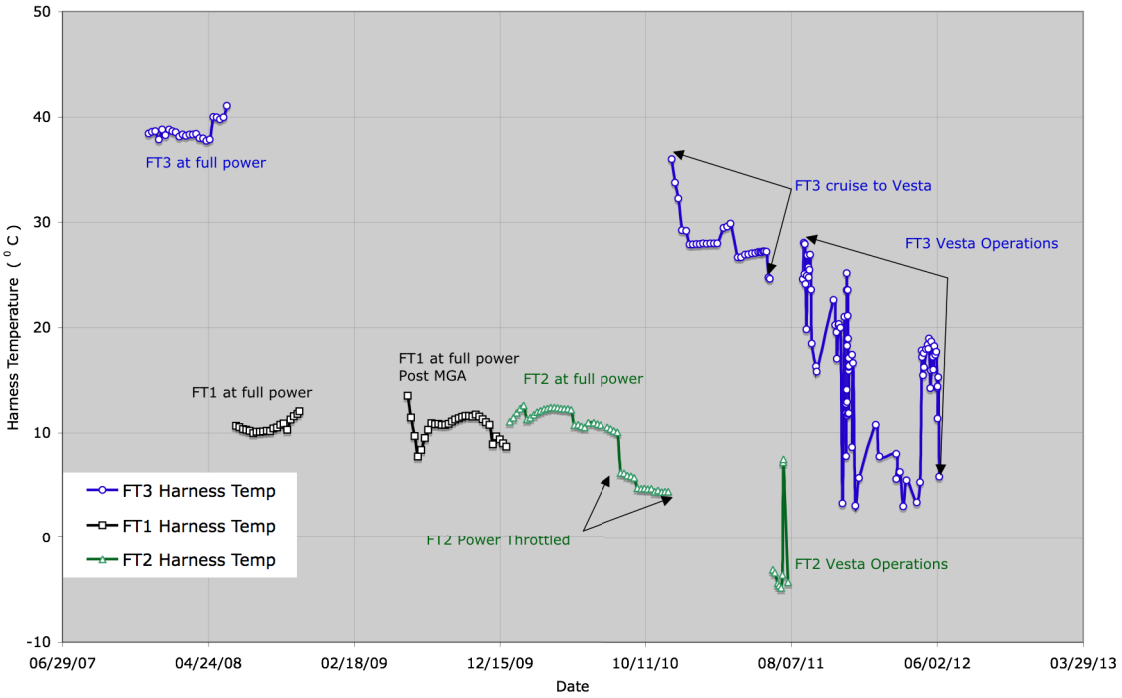

Figure 7. PPU-to-FT harness temperature through operations at Vesta.

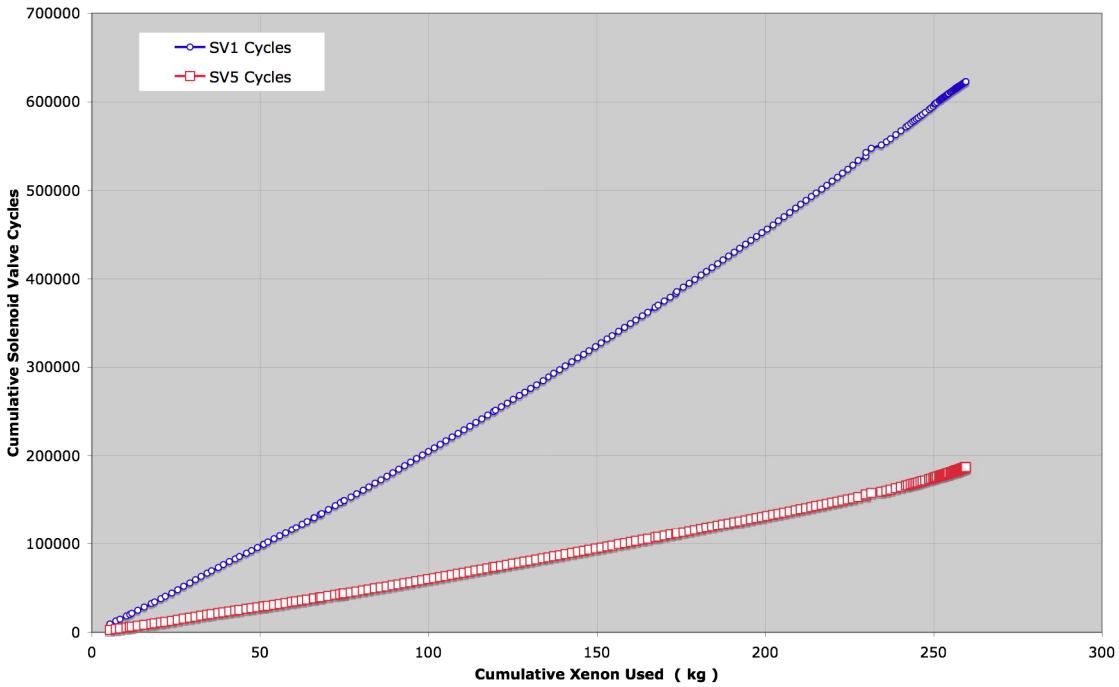

Figure 8. Cumulative open/close cycles on the main (SV1) and cathode (SV5) solenoid valves through operations at Vesta.

D. Thruster-Gimbal Assembly (TGA) Performance

The TGAs have also operated flawlessly during the entire mission. Each TGA consisting of two motor/tripod assemblies (side A and side B) per FT is used to position the thrust vector to control the spacecraft pitch and yaw. This mode is known as thrust vector control (TVC). RWAs or the RCS are used to control the spacecraft roll axis. Cumulative TGA actuator equivalent motor revolutions for the A-side motors (the B-side has used just under the number of motor revs as the A-side) for each FT are shown in Figure 9. The data indicate that the TGA motors have accumulated the equivalent of between 951,000 to over 1,577,000 motor revolutions through HAMO-2. The motor design was life-tested to 30,000,000 revolutions. The spacecraft is operated in TVC mode during normal thrusting, including during desaturations of the RWAs, which are typically sequenced approximately every 12 hours. TGA duty cycle has varied between 0.05% during cruise using RCS and up to 5% during operations at Vesta where RWA was used during TVC. In normal operation the TGAs "dither", or rotate, a small amount around a target center. The duty cycle and number of TGA actuations per kg of xenon used are greater with RWA control. In May 2011 the spacecraft switched to the wheels for attitude control as part of operations for Vesta approach and the TGA duty cycle increased substantially. TGA duty cycle rates under RWA control may increase because under RWA control the spacecraft issues more correcting commands to slew the TGAs than is done under RCS control. 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.

E. Thruster Performance

Detailed thruster performance data from the ICO and cruise through orbit capture at Vesta were presented in [18]. Voltage measurements are determined from telemetry at the PPU and the data have not been corrected for the power drop across the harness, which is estimated to be approximately 15 W for the discharge and 18W total for the thruster at full power. Beginning in March 2011 the discharge cathode and neutralizer flow rates for operation of the FTs at all power levels was changed to 3.7 sccm to address the thrust stability issues that are described [18]. This change resulted in extremely reliable and consistent maneuvers.

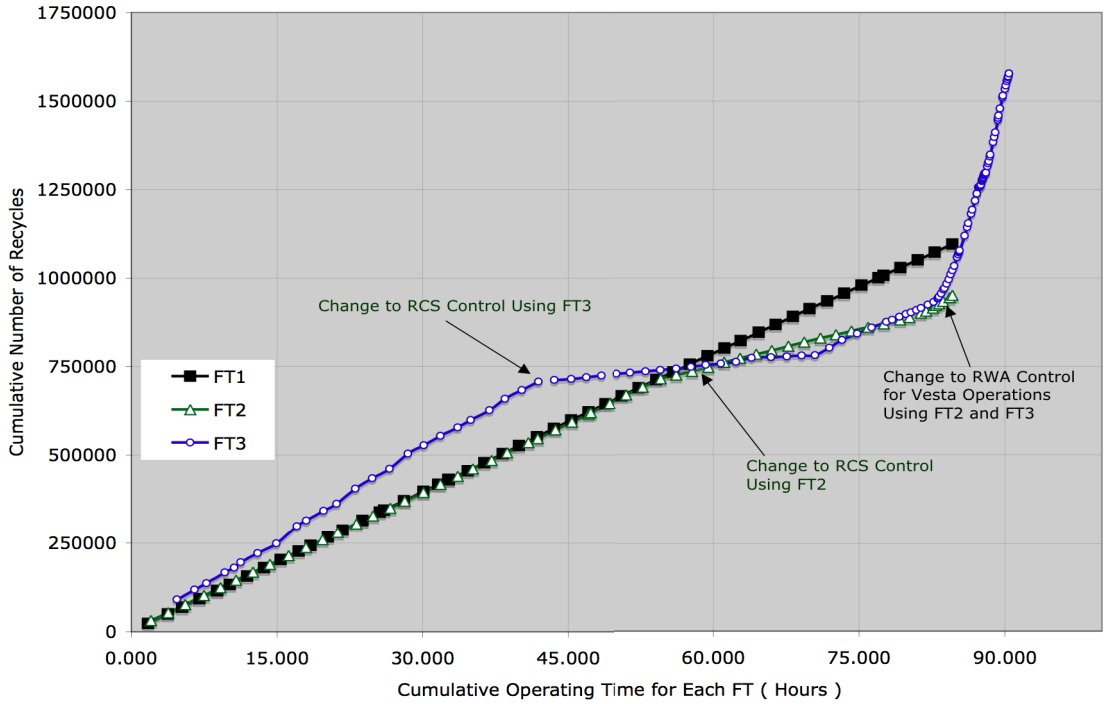

Figure 9. Cumulative equivalent motor revolutions for each TGA through operations at Vesta.

F. Thruster Performance through End of Cruise to Vesta

Detailed thruster performance data from the ICO and cruise through orbit capture at Vesta were presented in [18] and performance data for operations at Vesta are presented below. Voltage measurements are determined from telemetry at the PPU and the data have not been corrected for the power drop across the harness, which is estimated to be approximately 15 W for the discharge and 18W for the thruster at full power. Beginning in March 2011 the discharge cathode and neutralizer flow rates for operation of the FTs at all power levels was changed to 3.7 sccm to address the thrust stability issues that are described [18]. This change resulted in extremely reliable and consistent maneuvers; no thrust reconstructions were available for comparison but in view of the excellent results obtained for the maneuvers it is likely the thrust levels were very close to the values predicted from thruster electrical operating parameters.

G. Thruster Starts

As of completion of IPS operations at Vesta there have been a total of 548 thruster starts in flight. FT3 has been started in flight 299 times, FT1 has been started 115 times, and FT2 has 134 starts in flight. The cathode heater preheat duration for all starts was six minutes. All thruster start attempts have been successful. Data taken at one second intervals indicate that in every start attempt in flight after the ICO, the cathodes ignited within one second of the command for application of the igniter voltage pulses.

H. Thruster Cathode Heaters

The nominal cathode heater current for both the neutralizer and discharge cathodes is 8.5 A. Thruster peak discharge cathode heater power data for all thruster starts are plotted in Figure 10. Heater power at cathode ignition is affected by thruster temperature, which is a function of sun exposure, spacecraft attitude to the sun, and time from a previous thruster operation. A diode-mode preheat of the thrusters for approximately 54 minutes at approximately 250 W was performed before every start attempt.

The variation in peak discharge cathode heater power is similar for each FT. For operations at Vesta there have been more variations in peak heater power, likely due to differing sun angles and times between thrust arcs. Peak neutralizer cathode heater power for all thruster starts is plotted in Figure 11. Neutralizer heater power for each FT has been increasing at a low rate since the start of cruise, but at Vesta, again there has been a wider variation in peak heater power, likely due to differing sun angles and times between thrust arcs.

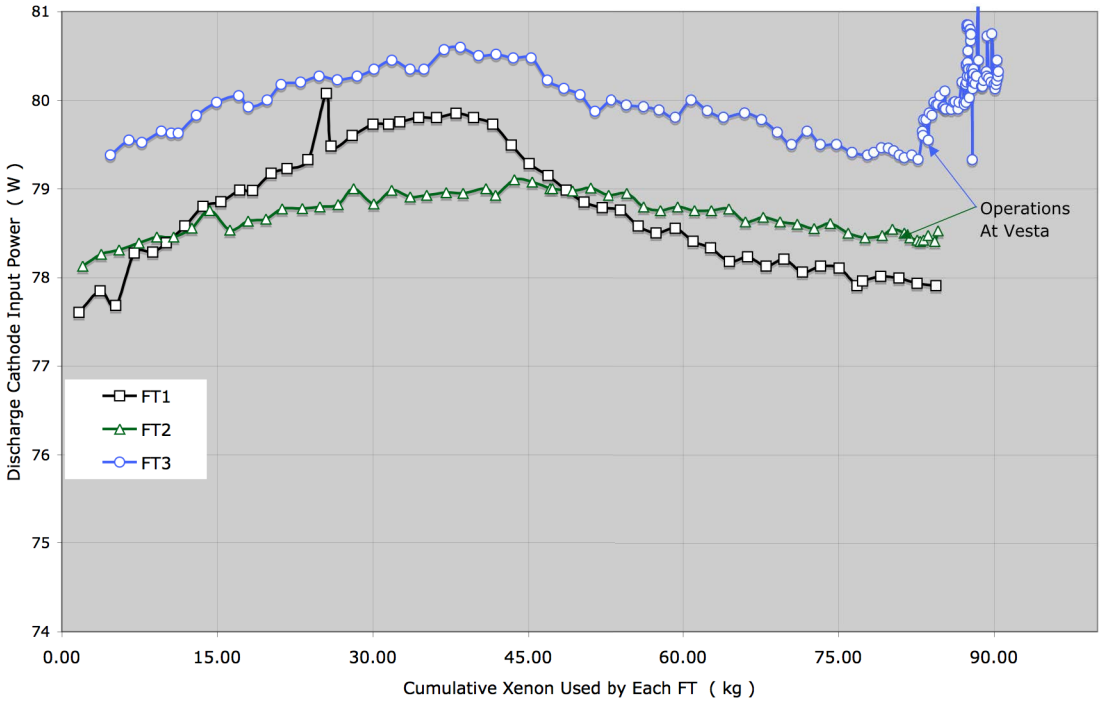

Figure 10. Peak discharge cathode heater power for each FT as a function of xenon use through operations at Vesta.

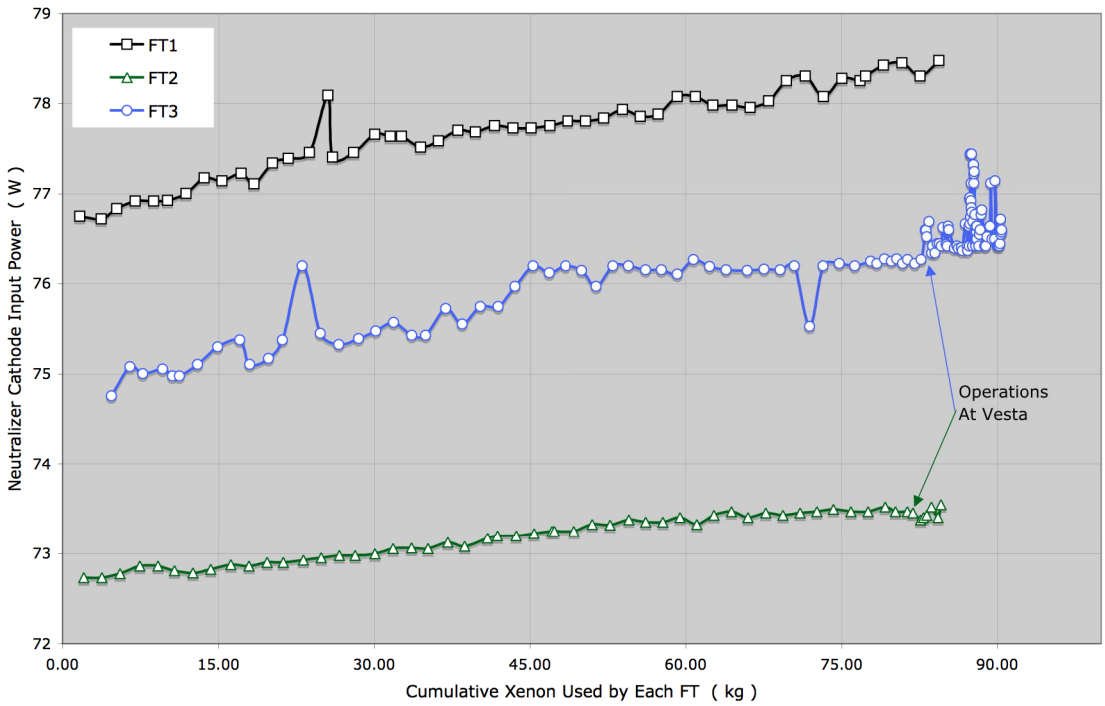

Figure 11. Peak neutralizer cathode heater power for each FT as a function of xenon used through operations at Vesta.

I. Thruster Operating Characteristics

All FTs are now using the end-of-life (EOL) throttle table, which is used once a total thruster has processed more than 70 kg of xenon. It is expected, based on extensive life testing and analysis that each FT can reliably process 195 kg [21] over the Dawn mission profile. Input power to the FTs from start of cruise through completion of IPS operations at Vesta is plotted in Figure 12 as a function of propellant throughput for each thruster. Input power varied from about 2.3 kW at the start of cruise to 1.2 kW at the completion of IPS operations at Vesta. During normal cruise operations to Vesta FT1 was only operated at full power, but FT2 and FT3 were power-throttled beginning in August 2010. For Vesta operations the cathode flow rates were set to the full-power flow rates for all input power levels, thus thruster performance differed from performance values in the end of life throttle table, with lower discharge voltages, lower neutralizer voltages and Isp due to the higher engine flow rates.

Accelerator grid current data for FT1, FT2 and FT3 through IPS operations at Vesta are plotted in Figure 13, with each thruster showing almost exactly the same behavior [18]. The step changes in accelerator grid current evident in Figure 13 are due to changes in the thruster throttle level and accelerator grid voltage. At a fixed flow rate and beam current thruster power is finely controlled with step changes of approximately 10 V in beam voltage, which produces the step changes in accelerator grid current. For operations at Vesta with the thrusters operating at maximum cathode flow rates at all power levels accelerator grid currents were typically about 20% greater compared to the values from the end of life throttle table. It is expected that operation at these slightly greater accelerator grid impingement currents will not substantially reduce thruster operating life. Accelerator grid voltage for each FT was decreased from -200 V to -272 V when FT1 and FT2 reached approximately 70 kg of xenon throughput (65 kg for FT3) in order to provide additional margin against electron backstreaming.

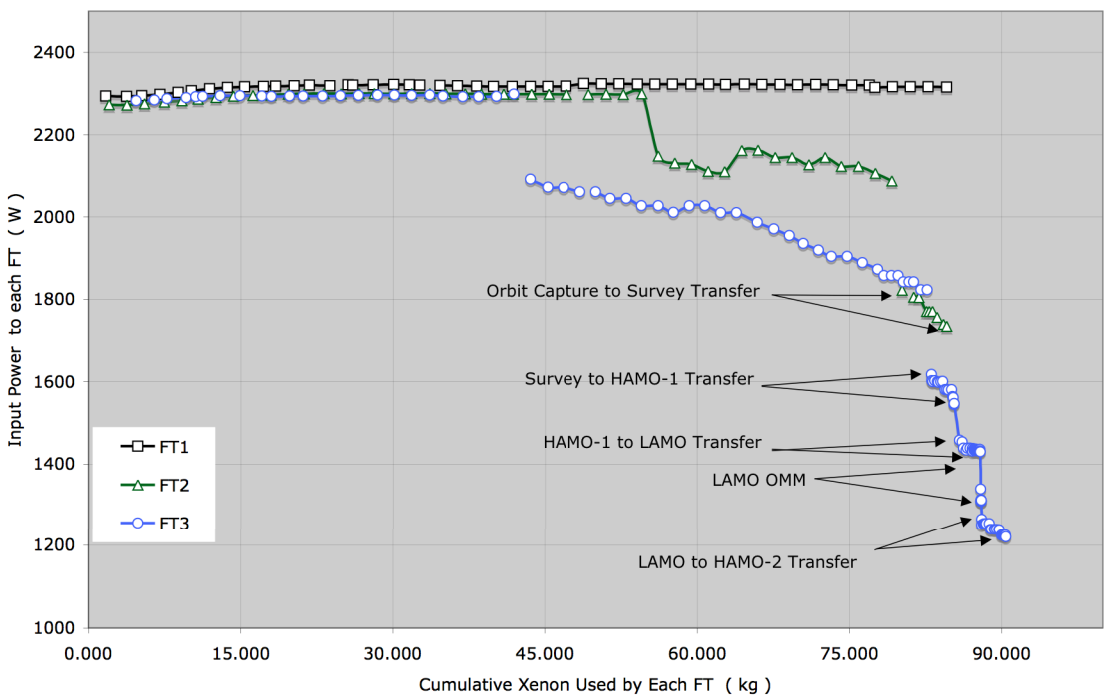

Figure 12. FT input power as a function of xenon throughput per thruster through end of IPS operations at Vesta.

High voltage recycles for each FT through the end of IPS operations at Vesta are shown in Figure 14. FT1, which has only been operated at full power, accumulated 65 recycles in 7625 hours of thrusting. FT2 accumulated 26 recycles in almost 7,900 hours of thrusting, with 24 of those recycles occurring at full power operation. FT3 accumulated 63 recycles operating for 8,802 hours, with 45 recycles occurring at full power. The data suggest that recycle rates have decreased over time and with decreasing power levels. Most recycles in flight occurred within a few hours after the start of beam extraction for each thrust arc.

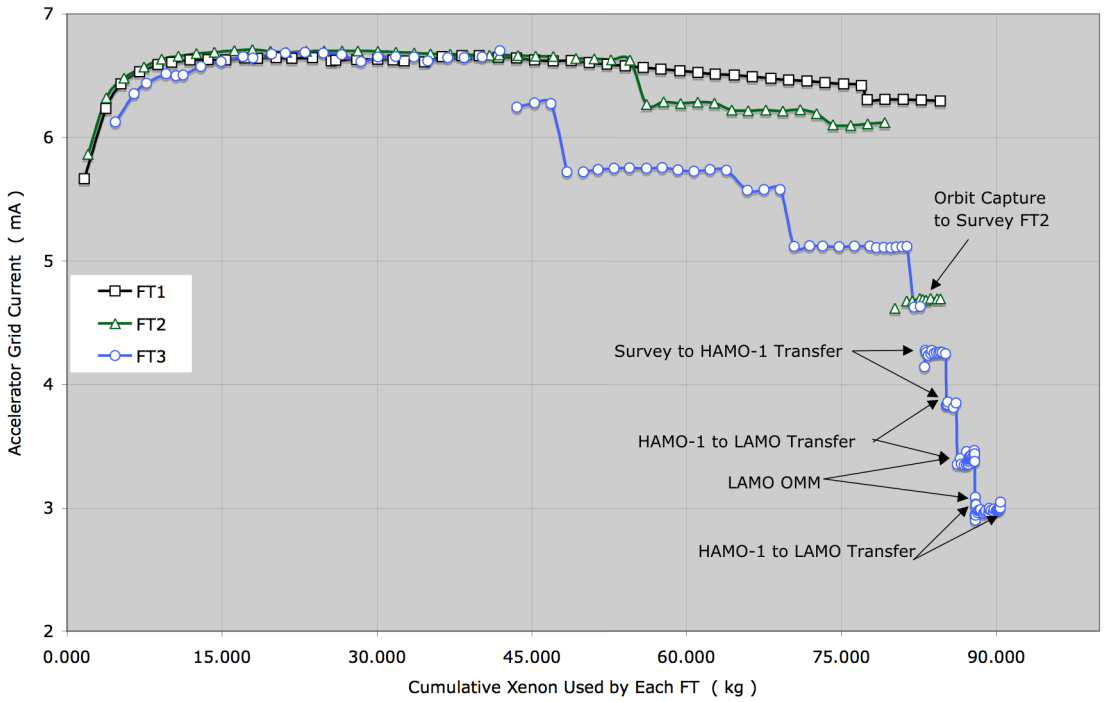

Figure 13. Accelerator grid current through end of IPS operations at Vesta.

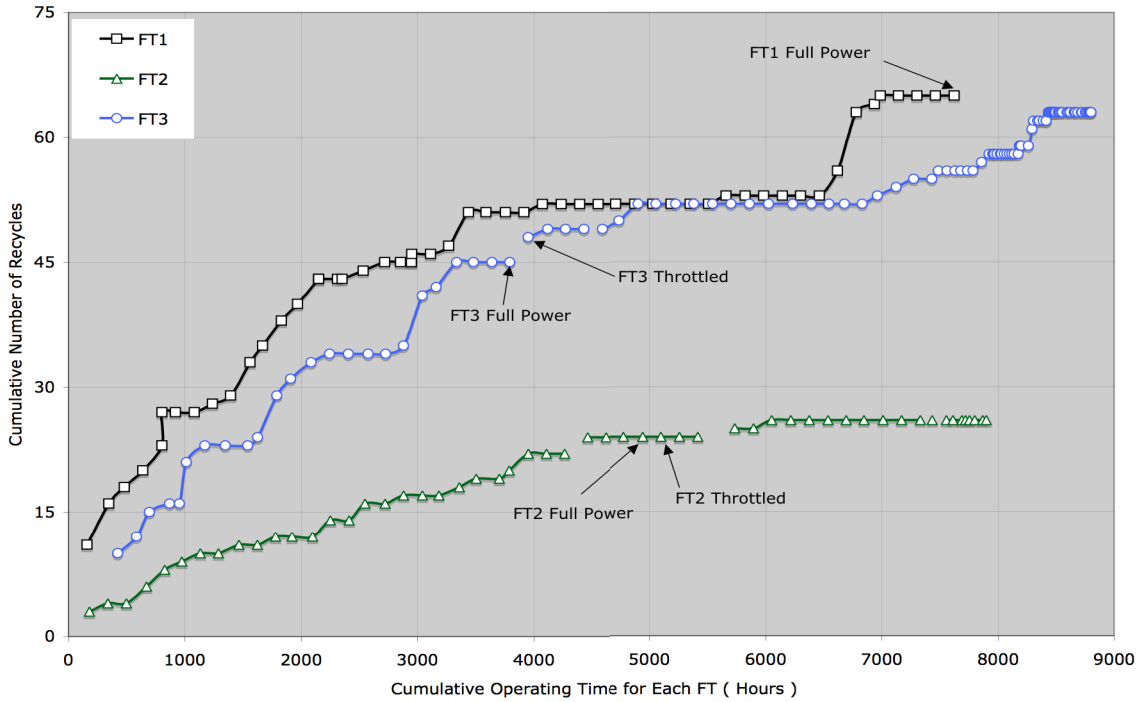

Figure 14. Recycles for each FT through end of IPS operations at Vesta.

Neutralizer keeper voltage data for operation through completion of IPS operations at Vesta are shown in Figure 15. At full power operation the neutralizer keeper voltage decreased in a similar way for all three thrusters. During throttled conditions the neutralizer keeper voltage varied more than during full power operation in cruise where neutralizer current was essentially constant. The greatest changes in neutralizer keeper voltage occurred during operations at Vesta, where there were more frequent changes to power level, spacecraft attitude, thrust arc run times and time between thrust arcs.

The neutralizer cathode must be operated at the proper flow rate and neutralizer keeper emission current to result in the nominal operating mode referred to as "spot" mode. A potentially damaging neutralizer operating condition called "plume mode' is characterized by greater than nominal neutralizer keeper voltage and greater alternating current (AC) noise in the direct-current (DC) neutralizer keeper plasma. This mode can lead to life-limiting erosion in the neutralizer. A plume mode detection circuit in each Dawn PPU converts variations in the AC component of the neutralizer keeper voltage to a DC voltage. The plume mode circuit voltage telemetry is monitored in flight to evaluate the health of the neutralizer. Plume mode circuit output data averaged over individual thrust arcs are shown in Figure 16. In normal operation the plume mode circuit voltage increases to approximately six volts during the first approximately 30 seconds after cathode ignition, when the neutralizer cathode is known to operate in plume mode. Plume mode circuit output then decreases over a period of minutes to approximately 1.0 V to 1.5 V during normal neutralizer operation. During all of Dawn IPS operations since launch there have been no indications of neutralizer cathode operation in plume mode after the initial start-up transients.

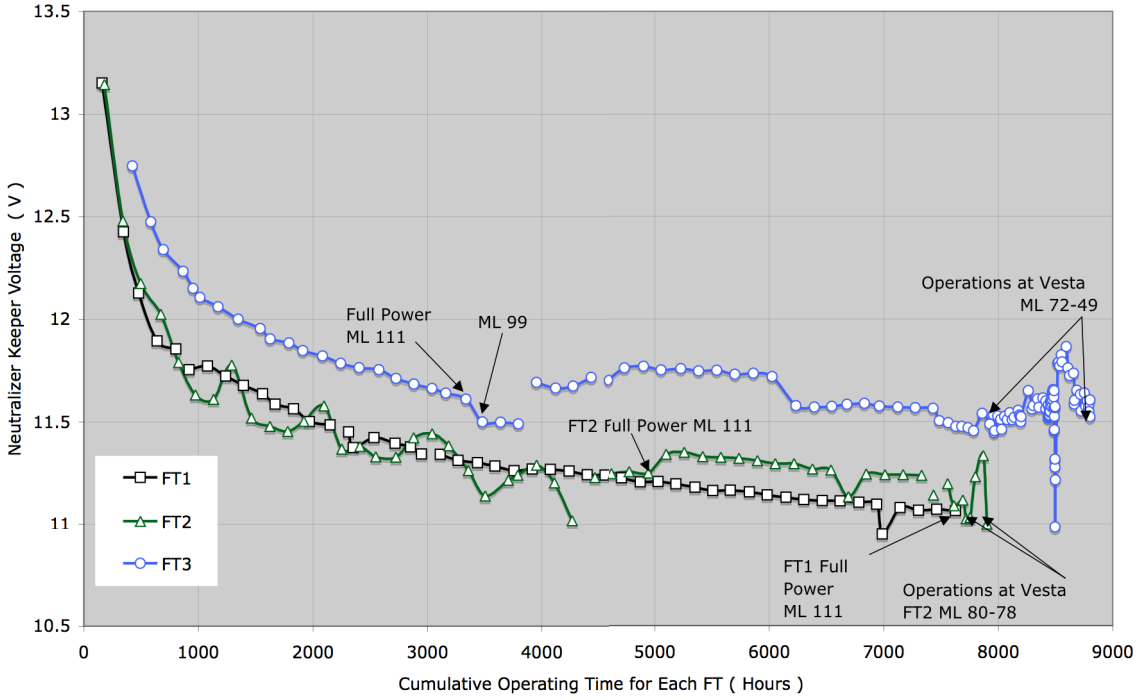

Figure 15. Neutralizer keeper voltage through end of IPS operations at Vesta.

Discharge power and discharge loss for Dawn thrusters through the end of operations at Vesta are shown in Figures 17 & 18. Discharge power and discharge loss behavior through the end of the cruise to Vesta phase are discussed in detail in [18]. The discharge voltage is measured at the PPU and does not include the voltage drop across the harness between the thruster and PPU, which could result in a power difference at the discharge chamber of 10 W to 18 W less depending upon the discharge current and harness temperatures. The discharge current for FT1 exceeds that for FT2 and FT3 because during FT1 assembly two of the permanent magnets for this ring-cusp thruster were installed incorrectly.

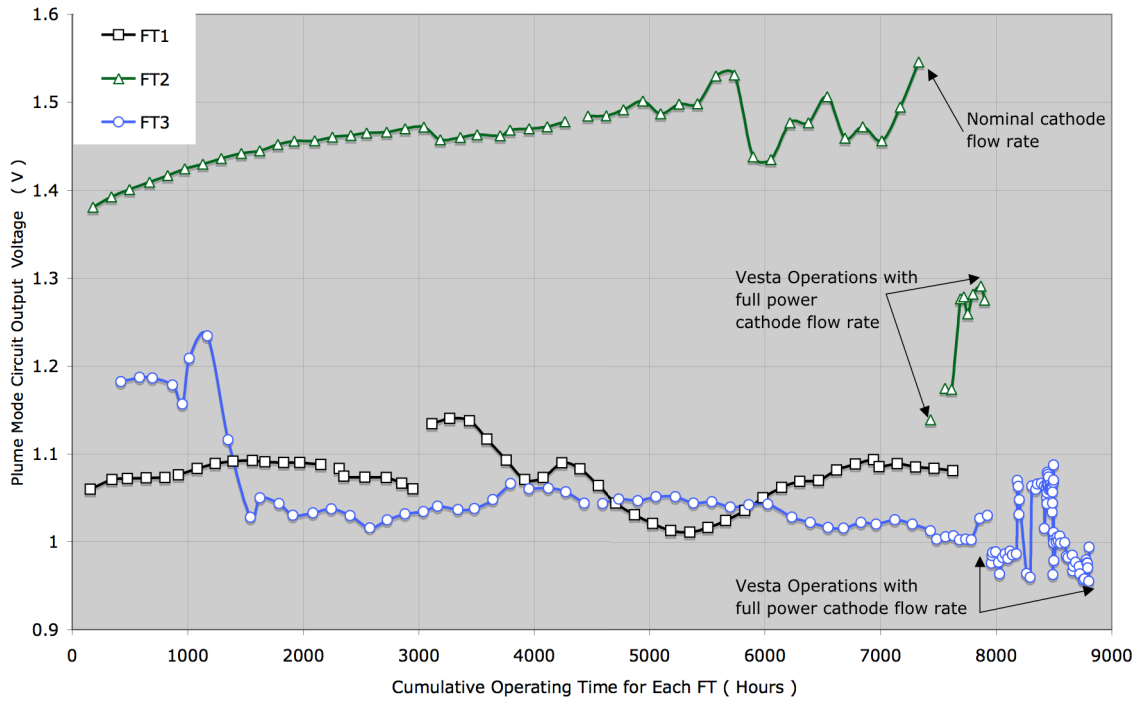

Figure 16. DC output of the plume mode circuit through end of IPS operations at Vesta.

In operations at Vesta discharge power and discharge loss varied with the mission level and was consistently lower compared to the end of life throttle table, due in part to the use of full power cathode flow rates for all thruster input power levels. Thruster temperatures varied at fixed power levels due to variations in sun attitude and thruster operating time between consecutive thrust arcs, affecting discharge power and discharge loss between consecutive thrust arcs.

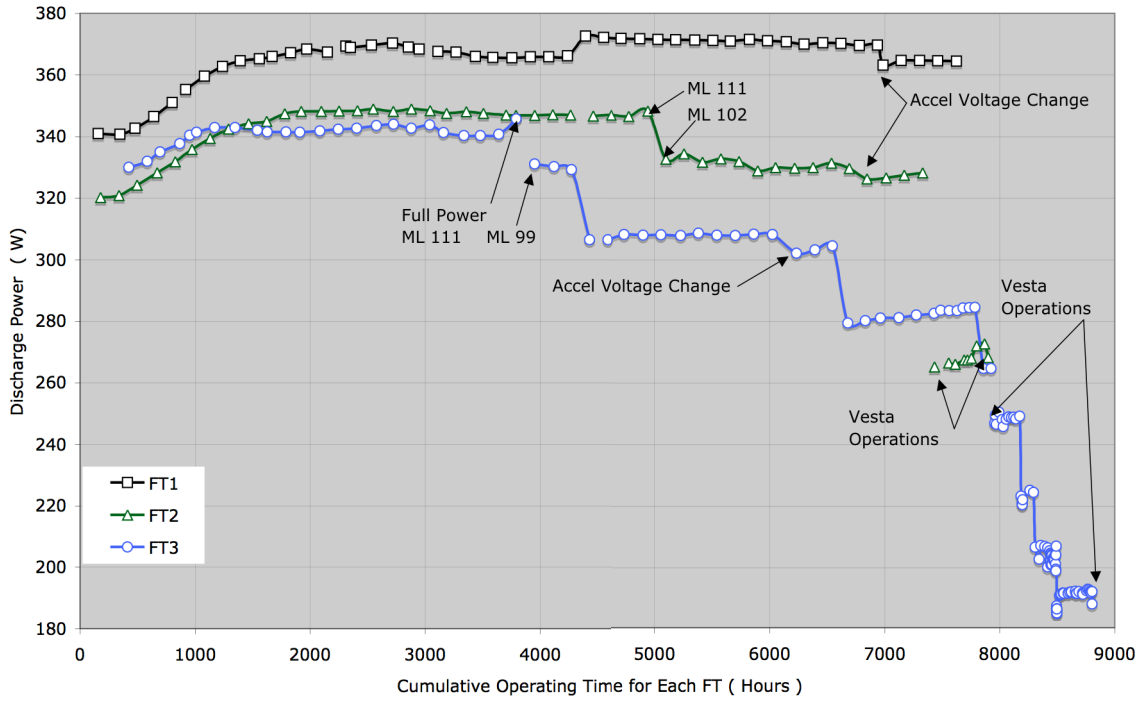

Figure 17. Discharge power for each FT through end of IPS operations at Vesta.

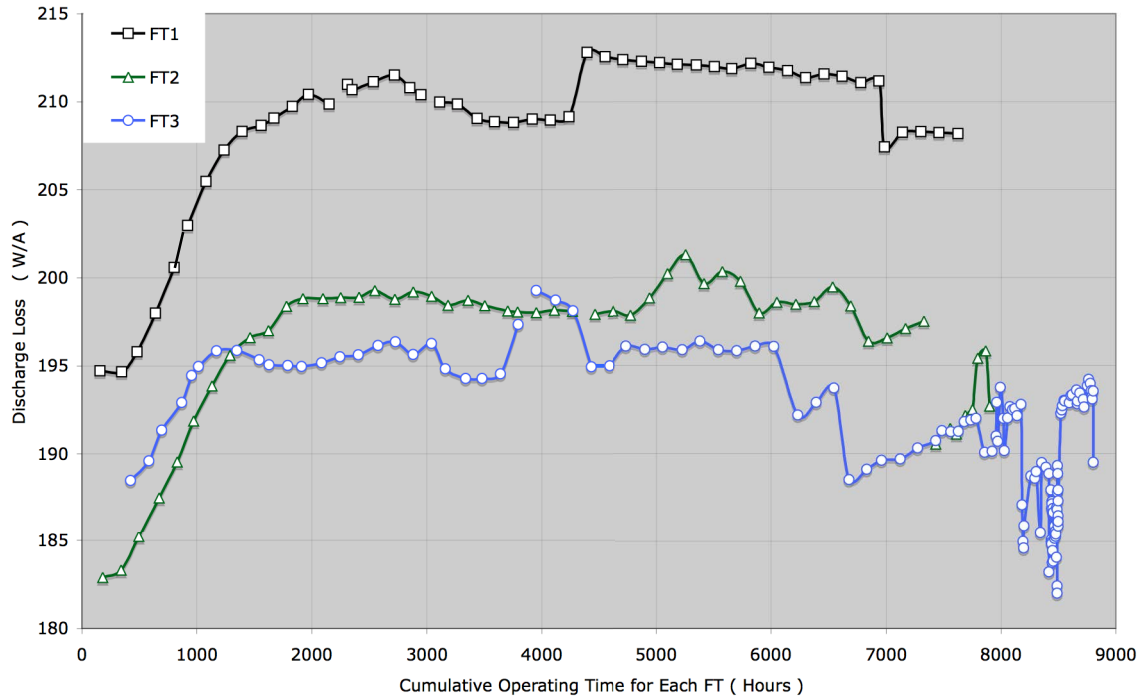

Figure 18. Discharge loss for each FT through end of IPS operations at Vesta.

J. Thrust Measurements

Direct thrust measurements were obtained during the ICO using changes in the Doppler shift of the radio signal from the spacecraft [10]. During cruise, thrust levels developed by the IPS were calculated from thruster telemetry and reconstructed using navigation data as described in [19]. Thrust measurements through entry into Survey orbit are discussed in detail in [19]. In nominal operations thrust transients arising from thruster starts due to cathode flow transients [19] had little effect on the heliocentric transfer to Vesta, but are significant enough during the Vesta orbit phase that the Project investigated low risk ways to minimize their magnitude. The selected approach was to simply maintain the cathode flow rates at the full power mission level (ML) 111 set point for all throttle levels through all IPS operations at Vesta. This maintained the same start-up procedure used successfully throughout the mission but eliminated the cathode flow rate variation after start-up and the corresponding thrust variation. The resulting higher than nominal cathode and neutralizer flow rates resulted in increased xenon consumption. For Vesta operations this translated into approximately one kg more xenon consumed than originally planned which will have no impact on the mission since Dawn currently has ample propellant reserves. To prevent main flow rate transients after start-up, which also contribute to maneuver execution errors, it was also necessary to modify the diode-mode pre-heat procedure. This procedure nominally is executed with both main and cathode plena pressurized to ML 111 levels. The modified procedure changed the main plenum pressure to that corresponding to the intended throttle level after start-up.

Thrust values derived from navigation data for FT2 and FT3 are reproduced in Figures 19-20 along with thrust calculated from thruster telemetry. Thrust values calculated from thruster telemetry were typically averaged over a time period where thruster operating parameters were stable, but for short thrust arcs almost the entire thrusting period (from beam on to beam off) was used. Thrust measurements reconstructed from navigation data include data for FT2 from start of Vesta cruise through entry into Survey orbit, and for FT3 from start of cruise through the start of transition from HAMO-1 to LAMO.

During operations at Vesta thrust values determined from telemetry very closely matched thrust estimated from navigation data, as can be from Figures 19-20. Orbital parameters resulting from maneuvers using the IPS were very close to the intended orbital parameters. It is possible that the increased cathode flow rates suppressed production of double ions, resulting in increased thrust at all mission levels used during Vesta operations. During IPS operation the attitude control subsystem uses the ion thrusters to control the spacecraft in the two axes perpendicular to the thrust direction. The thrusters, however, produce a roll torque about the thruster axis that must be nulled by the RCS or the RWAs. The magnitudes of the

total external torques to the spacecraft during cruise to Vesta were provied in [19]. However, during Vesta operations Vesta's gravity greatly impacts roll torques to the spacecraft and there are no data calculated for roll torque for operations at Vesta.

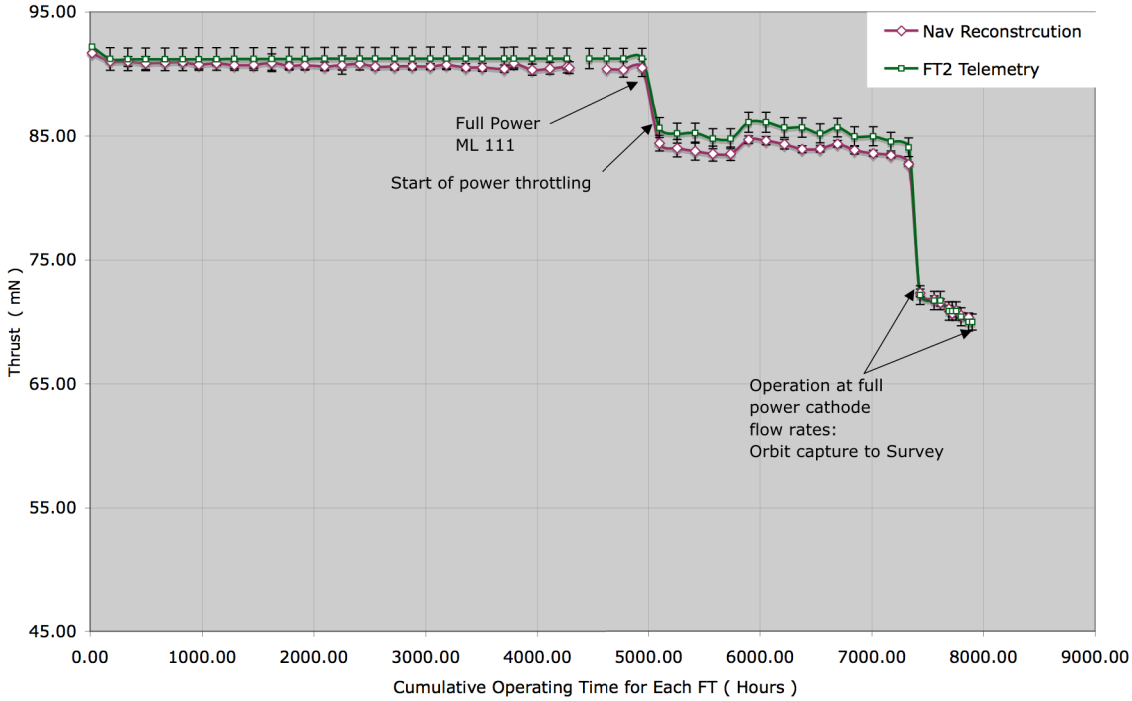

Figure 19. Thrust for FT2 through entry into Survey orbit.

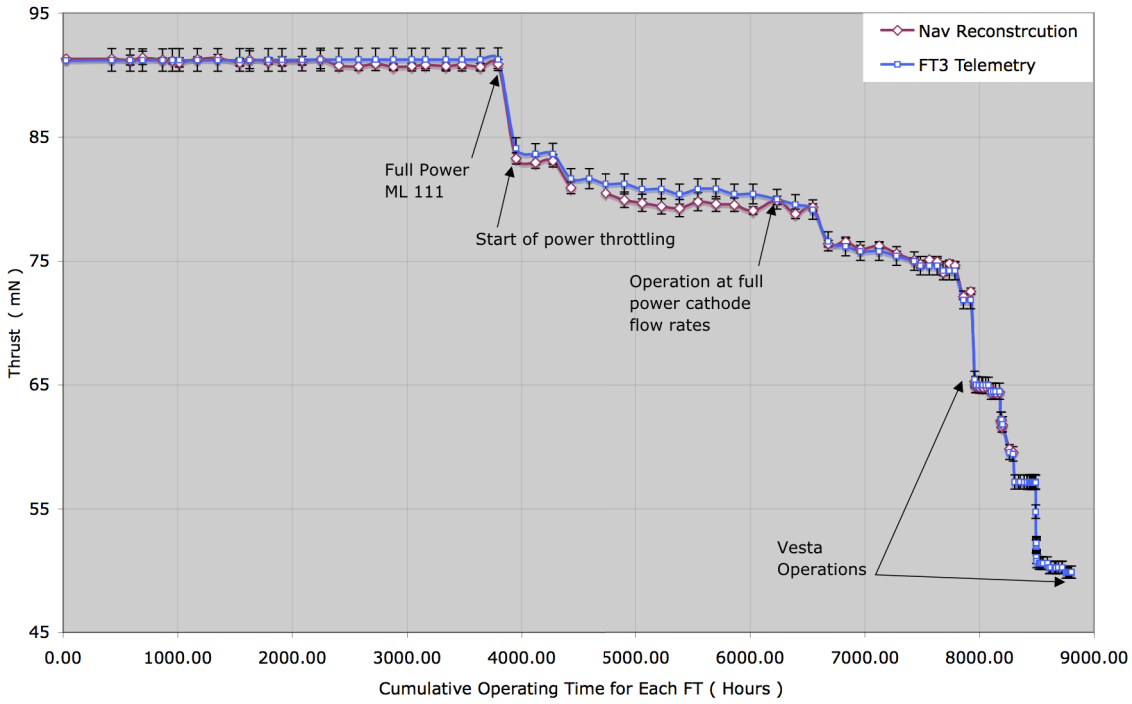

Figure 20. Thrust for FT3 through end of IPS operations at Vesta.

K. DCIUs

Both DCIUs operated flawlessly during operations at Vesta. DCIU-2 was used for six maneuvers and 57 commands to control FT2 from orbit capture on July 16, 2011 to Survey orbit on July 20, 2011. DCIU-1 was used for 80 maneuvers and 573 commands to control FT3 from August 2011 through June 6, 2012 when IPS operations at Vesta were completed. During operations at Vesta all DCIU commands were accepted and executed, and there were no operational errors.

IV. Conclusion

The Dawn mission has successfully used its ion propulsion system for the heliocentric transfer to the main-belt asteroid Vesta and for science operations in orbit. Science orbits included Survey at 2735 km altitude, HAMO-1 at 670 km altitude, LAMO at 210 km altitude, and HAMO-2 at 670 km altitude but with different viewing conditions compared to HAMO-1. Other orbital characteristics such as orbital plane varied depending upon the science requirements. IPS has operated virtually flawlessly throughout the mission to date, accumulating over 23,327 hours of beam-on time and consuming almost 260 kg of xenon that resulted in almost 7 km/s of ΔV to the spacecraft. Maneuver execution errors in reaching the science orbits were low. All the IPS components--the thrusters, DCIUs, PPUs, XCA, and TGAs—have operated nominally. Dawn achieved orbit capture at Vesta on July 16, 2011, reached Survey orbit on August 3, 2011 and the reached the final science orbit HAMO-2 on June 6, 2012. Thrusting to Ceres is scheduled to begin in late July 2012, with escape from Vesta in late August. During the departure phase, Dawn will stop for some final observations of Vesta. Rendezvous with the dwarf planet Ceres is scheduled for February 2015. The Dawn ion propulsion system has shown itself to be extremely reliable and capable and is presently fully operational to begin cruise operations to Ceres.

Acknowledgments

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