Attitude Determination and Control Subsystem (ADCS) Preparations for the EPOXI Flyby of Comet Hartley 2

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ABSTRACT

On November 4, 2010 the former "Deep Impact" spacecraft, renamed "EPOXI" for its extended mission, flew within 700km of comet 103P/Hartley 2. In July 2005, the spacecraft had previously imaged a probe impact of comet Tempel 1. The EPOXI flyby was the fifth close encounter of a spacecraft with a comet nucleus and marked the first time in history that two comet nuclei were imaged at close range with the same suite of onboard science instruments. This challenging objective made the function of the attitude determination and control subsystem (ADCS) critical to the successful execution of the EPOXI flyby.

As part of the spacecraft flyby preparations, the ADCS operations team had to perform meticulous sequence reviews, implement complex spacecraft engineering and science activities and perform numerous onboard calibrations. ADCS contributions included design and execution of 10 trajectory correction maneuvers, the science calibration of the two telescopic instruments, an in-flight demonstration of high-rate turns between Earth and comet point, and an ongoing assessment of reaction wheel health. The ADCS team was also responsible for command sequences that included updates to the onboard ephemeris and sun sensor coefficients and implementation of reaction wheel assembly (RWA) de-saturations.

Acronyms

ADCS = Attitude Determination and Control Subsystem
AutoNav = Autonomous Navigation subsystem
DEC = Declination
DI = Deep Impact
EFB = Earth Flyby
EME2000 = Earth Mean Equator J2000 coordinates
EPOXI = Extrasolar Planet Observations and Characterization + Deep Impact Extended Investigation
ET = Ephemeris Time

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HGA = High Gain Antenna
HRI = High Resolution Imager
ICV = Initial conditions vector (heliocentric position/velocity)
IR = Infrared spectrometer
ITM = Impact Targeting Maneuver
LGA = Low Gain Antenna
MPDF = Maneuver Performance Data File
MPF = Maneuver Profile File
MRI = Medium Resolution Imager
NCP = North Celestial Pole
RA = Right Ascension
rpm = revolutions per minute
SCU = Spacecraft Control Unit (flight computer)
SIRU = Scalable Inertial Reference Unit
SPE = Sun-probe-Earth angle
TCM = Trajectory Correction Maneuver
TWTA = Traveling Wave-Tube Amplifier, a device that amplifies radio frequency signals to higher power
VTC = Vehicle Time Code

1 Introduction

The Deep Impact (DI) spacecraft, consisting of a three-axis stabilized Flyby spacecraft and a 3-axis stabilized Impactor spacecraft (see Figure 1 below), was launched on January 12, 2005 from Cape Canaveral Air Force Station in Florida on a Delta II-7925. At launch it had a total mass of 601 kg (517 kg dry mass and 84 kg wet mass) and was capable of generating up to 750W of power through its body-mounted 7.5m^2 solar arrays(EPOXI Project). The Flyby spacecraft was equipped with two Ball CT-633 star trackers, one Litton Scalable Inertia Reference Unit (SIRU) with four hemispherical resonator gyros and four accelerometers, thirteen Adcole sun sensors, four Ithaco reaction wheels, four 4-N RCS thrusters, and four 22-N TCM thrusters. The Impactor spacecraft was equipped with one star tracker, one SIRU, four 1-N RCS thrusters, and four 22-N Divert thrusters.

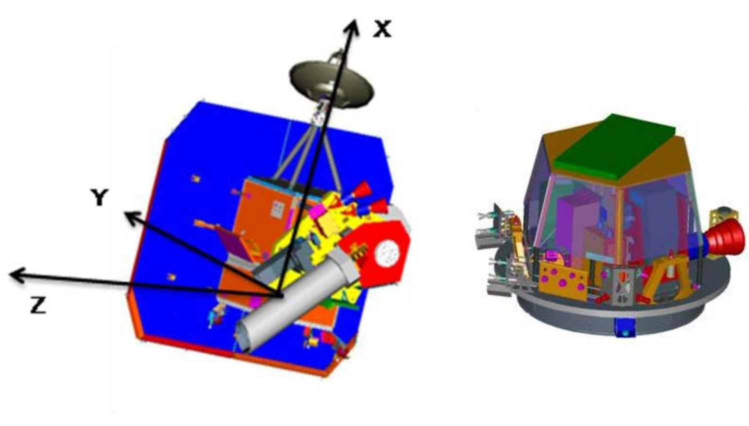

Figure 1. Deep Impact Flyby and Impactor spacecraft

The combined Flyby-Impactor spacecraft were sent on a trajectory toward comet Tempel 1, when 24-hrs before impact with Tempel 1 it released a copper-plated probe on an impact-bound trajectory. Shortly thereafter the Flyby spacecraft performed a divert Delta-V maneuver to avoid colliding with the comet itself. The probe then executed three impact targeting maneuvers (ITMs) using data provided by its impact targeting sensor (ITS) camera and an onboard autonomous navigation system known as AutoNav.

The AutoNav onboard the Impactor spacecraft used the observed center-of-brightness of the Tempel 1 nucleus via a scene analysis algorithm operating on the ITS optical navigation images. By determining the error relative to the predicted pixel location of the comet in the ITS camera frame, the Impactor AutoNav system was able to perform onboard orbit determination. This onboard OD refined the expected position of the comet, nominally provided as a set of time-varying Chebyshev polynomials (position/velocity vectors), to update the desired pointing of the spacecraft that was sent to the ADCS.

The Impactor's Autonav also used the estimated distance to the comet plus the time-to-impact to compute and execute the three ITMs. These ITMs lead to a successful impact of Tempel-1 on July 4, 2005, while the impact crater/ejecta plume formation was imaged by the Flyby spacecraft's high- and medium-resolution imagers (HRI and MRI telescopes[3], both mounted on a common platform), and infrared (IR) spectrometer (co-aligned with the MRI).

The Flyby spacecraft simultaneously downlinked impact images via X-band to Earth through its steerable high gain antenna (HGA). This was a unique feature of the Tempel 1 encounter given the flyby/impact geometry (the HRI/MRI were pointed at the impact point while the gimbaled-HGA was pointed at Earth, which was in the opposite direction of the sky).

The Flyby spacecraft also carried its own version of the AutoNav software, which was used to update the expected impact point on the comet, using the center-of-brightness computations taken from the MRI images, and pointing information provided by ADCS. This allowed the Flyby spacecraft to properly track the impact point throughout the encounter.

In late July 2005, shortly after the Tempel 1 encounter, the spacecraft executed a Delta-V trajectory correction maneuver (TCM-8), to target the spacecraft toward comet Boethin. The spacecraft was then placed in hibernation mode for 25 months—and then briefly awakened every 6 months only to monitor health and safety. On September 26, 2007 the spacecraft was taken out of hibernation to initiate the EPOXI mission. The **EPOXI** name is a combination of two NASA extended missions begun on July 3, 2007: the **EPOCh** (Extrasolar Planet Observations and Characterization) search for known extra-solar planets transiting their parent stars, and the **DIXI** (Deep Impact Extended Investigation) flyby of comet Hartley 2.

For the extended mission, when it came time to locate Boethin for Navigation purposes it could not detected and was assumed to have broken into pieces. Comet 103P/Hartley 2, of the Jupiter family of

[3] Both the HRI and MRI have a nine-position filter wheel to permit imaging in different parts of the visible spectrum. The HRI is a 30-cm diameter telescope. The MRI is a 12-cm diameter telescope with a wider field of view for context imaging of stars and the comet's coma.

comets[4] , discovered by astronomer Malcolm Hartley[5], was then selected to replace comet Boethin. The primary reason for selection was that its short period (6.46 years) meant an exceptionally close pass near Earth on October 20, 2010, and thus made it a spectacular target for the flyby mission. By measuring two different comets (Tempel 1 and Hartley 2) with the same instruments onboard the Flyby spacecraft, scientists would be able to determine which cometary features were primordial and which represented the comet's evolution as it regularly passed through the inner solar system(EPOXI Project).

2 EPOXI Mission Sequence of Events

The EPOXI mission was broken up into the following phases, beginning in late 2007:

Cruise-1: As previously mentioned, the spacecraft was taken out of hibernation mode on September 26, 2007. Ground controllers executed TCM-9 on November 1, 2007 to direct the spacecraft toward the newly selected comet Hartley 2. This new trajectory would require the spacecraft to fly by Earth 3 times before reaching Hartley 2.

The first Earth flyby gravity assist after TCM-9 occurred on December 31, 2007, bounded by TCMs 10 and 11. During this encounter, the HRI/IR instruments were used to observe the moon as part of a re-calibration exercise. At closest approach to Earth, the spacecraft reached an altitude of 15,567.63 km above Eastern Asia.

Cruise-2: Following the successful Earth flyby, Cruise-2 began in January 2008 until the Hartley 2 approach phase in September 2010. During this time the EPOCh portion of the extended mission was executed, from January 22, 2008 to August 2008. Other activities during this time frame included spacecraft instrument and subsystem calibrations, Earth flybys 2 and 3, two distant Earth flybys, and an interplanetary internet test in October/November 2008 (Feaga). In mid-2008, TCM-12 directed the Flyby spacecraft on a more optimized trajectory toward Hartley 2. This slightly adjusted the encounter distances for Earth flybys 2 and 3, as well as those for the distant Earth flybys. The Earth flybys during cruise 2 occurred on the following dates:

- Earth Flyby #2: December 29, 2008 (bounded by TCMs 13, 14, 15)
- Distant Earth Flyby #1: June 29, 2009 (no TCMs required to aim or correct for gravity assist)
- Distant Earth Flyby #2: December 28, 2009 (bounded by TCMs 16, 17)
- Earth Flyby #3: June 27, 2010 (bounded by TCMs 18,19)

Approach: About 2 months after EFB 3, the approach phase began—60 days (starting September 5, 2010) before the Hartley 2 encounter (November 4, 2010). During this phase, the science team took images of the comet to watch for any outbursts of volatile material. Navigation data was also gathered to plan TCMs and refine the spacecraft's trajectory toward the comet. The spacecraft sequences were broken up into the following segments(Rieber):

[4] Comets with orbital periods < 20 years
[5] Using the UK Schmidt Telescope in Siding Spring Observatory, Australia

- E-60 to E-50 days: A repeating ~6-hour imaging/downlink cycle.
    - Fast 6.25min (375sec) turn from Earth-point to comet point. The turn duration was constrained by thermal requirements.
    - 25min HRI/MRI imaging of the comet
    - Fast 6.25min (375sec) turn back to Earth point
    - 5 hr 22min 30sec downlink at the playback attitude
- E-50 to E-40 days: A repeating 2-hr imaging/downlink cycle was permitted during this period as the spacecraft was less thermally constrained. This allowed more frequent imaging of the comet.
    - 20 min (1200 sec) turns from Earth-point to comet point
    - 25min HRI/MRI imaging of comet
    - 20 min (1200 sec) turns back to Earth point (playback attitude)
    - 55 min downlink at the playback attitude
- E-40 to E-34 days:
    - 30min turn from the playback attitude to the nominal cruise attitude for a 3-day IR spectrometer cool-down period. The playback attitude was different from the nominal cruise attitude in order to minimize the slew angle. As such, the playback attitude definition had to be updated once per week to keep the slew angle small and to satisfy other attitude constraints (power, thermal, etc.).
    - **TCM 20** occurred at the end of this period, after the IR cool-down.
- E-34 to E-8 days: A repeating ~16-hr imaging/downlink cycle
    - 10min turn from the Earth-point playback attitude to comet point
    - ~16.5hrs HRI/MRI imaging of comet, including IR scans
    - 10min turn back to Earth point (playback attitude)
    - 5.5 - 7hr downlink at the playback attitude. Only 5 hours was actually needed to playback all images.
    - **TCM 21** occurred at the end of this sequence
    - A standard Cruise Calibration was conducted at the end of this window in September 2010 after TCM-21.
- E-8 to E-1 days: A repeating ~17-hr of comet imaging followed by seven 1-hr do-si-do's.
    - Each do-si-do consisted of:
        - A brief period of comet imaging
        - Fast 6.25min (375sec) turn to the Earth-point (playback attitude)
        - A brief period of downlink at the playback attitude
        - Fast 6.25min (375sec) turn back to comet point
    - This sequence was stopped briefly for the contingency **TCM 22**. This TCM refined the spacecraft's flight path (nominal reference trajectory) to meet the comet closest approach distance of 700km. The actual flyby distance was 694 km.
    - This sequence ended at the E-26hr mark at the cruise attitude

Encounter: The critical encounter sequence began at E-18hrs and lasted until E+2hrs. During this critical sequence, the science observations were tailored to: obtain spectral maps of gas outbursts as the comet rotated; obtain spectral maps of the distribution of gas and dust in the coma; search for frozen volatiles such as water-ice; map the topographical features for comparison with other comets; and finally map the surface temperature variation(Feaga). In order to receive this science data, the following events had to occur:

- The HGA had to be pre-positioned at the gimbal positions it was expected to have upon return to Earth-point at E+7min. Due to the design of the spacecraft for the Tempel 1 encounter, the HGA could not be pointed at Earth during the closest approach to Hartley 2. In other words, the geometry of the flyby relative to Earth meant that the comet could not both be imaged and images downlinked to Earth through the HGA. Thus the HGA had to be turned off for the closest approach.
- The spacecraft executed a 30min turn from cruise attitude to comet point
- The first set of IR scans began at E-2hrs
- The spacecraft's attitude was propagated on the IMUs only and AutoNav was turned on at E-50min
- AutoNav OD updates began at E-40min
- The spacecraft was transitioned to the Image/Protect mode at E-35min, where the HRI/MRI were kept on comet point but the spacecraft rotated about the HRI/MRI line-of-sight such that the solar arrays were edge-on to the comet relative velocity vector. This was to prevent any particle impacts onto the solar arrays, which would otherwise damage them.
- Flyby and track comet Hartley 2 with the HRI/MRI at a nominal 700km miss distance, 80deg south of the Sun direction. This occurred on Thursday, November 4, 2010 at **13:52:35** UTC (6:52:35 AM PDT). At this time, the Flyby spacecraft flew past the comet at a speed of 12.32 km/s.
- Swap from TWTA-A to TWTA-B to switch from the LGA to the HGA at E+2min
- Operate on TWTA-B to re-enable HGA communications with Earth (@ 2000 kbps) at E+7min.
- Stop AutoNav OD updates at E+10min.
- At E+30min, return to Image/Sun configuration, with HRI/MRI boresights on comet but the spacecraft rotated about the HRI/MRI line-of-light so that the Sun would be nearly normal to the solar arrays.
- At E+30min, the spacecraft began downlinking images and data from spacecraft control unit A (SCU-A) covering the period E-18hr to E+30min.

Departure: This sequence began at ~E+2days and continued to ~E+22days. It consisted of look-back imaging of the comet while simultaneously downlinking data to the ground. The activity ended at the cruise attitude. Following the completion of this phase, another standard Cruise Calibration was uplinked at the end of November 2010.

3 ADCS Sequence Review and Activities

Each of the above-mentioned sequence segments was merged with a general background sequence that commanded regular engineering maintenance activities. As part of the normal sequence review process, the ADCS team had to review each merged background sequence/sequence segment to ensure it complied both with the ADCS checklist and ADCS review tools. As part of the general background sequence review, the ADCS team had to check the correctness of the following items:

ICV: The initial conditions vector, loaded via ground command, represented the Sun-to-spacecraft position and velocity vector in heliocentric coordinates with a valid start time (ICV epoch) in ephemeris time (ET)(Schira). The ICV epoch was converted to a vehicle time code (VTC) using a VTC-to-ET offset that had to be commanded along with the ICV.

The ICV was derived from the latest ground-based navigation orbit determination solution and used for onboard orbit propagation of the spacecraft when the spacecraft clock reached the valid ICV epoch. It also enabled the propagator to estimate the positions of the Sun and Earth, and magnitudes of the perturbing forces, such as the Sun's gravity, solar radiation pressure, and thruster forces. The ICV was used to determine the spacecraft attitude and HGA pointing. The HGA pointing also required an Earth ephemeris, which was generated from a set of Keplerian elements.

The values of each of the vector components were independently checked on the ground in a program called Tball. Tball is a JPL-developed 3D visualization program that depicts the celestial sphere with the spacecraft at the center, and permitted computation of the Sun-to-spacecraft position/velocity vectors at the desired epoch using the latest ground-based spacecraft ephemeris.

In contrast to the ICV, the Chebyshev polynomials were only used when the Flyby spacecraft was in a special comet reference frame mode, which defined a frame with the HRI/MRI pointed at the comet but one of the other body axes pointed as close as possible to the Sun (Image/Sun) or the comet relative velocity vector (Image/Protect).

Coarse Sun Sensor Coefficient updates: The Deep Impact Flyby spacecraft is equipped with 13 Adcole sun sensors spread across the spacecraft. Each sun sensor outputs a voltage in units of counts that is a function of the angle from the boresight to the Sun, determined by a modeled sun vector, and two coefficients. The measurements from each sun sensor are then combined to compute a measured sun vector, which can be compared to the modeled sun vector. The coefficients are a function of spacecraft distance from the Sun and are updated periodically to ensure proper sun sensor calibration and small errors in the measured versus modeled sun vectors(Larson). ADCS checked the background sequence to ensure the proper sun sensor coefficients were being loaded based on the expected distance of the spacecraft from the Sun.

RWA Desaturations: Throughout the EPOXI mission, the spacecraft's attitude was controlled by a set of 4 reaction wheels. As the spacecraft is commanded to turn from one target to another and external torques (such as solar radiation pressure) act upon the spacecraft, each reaction wheels adjusts its speed and the net momentum contribution from the wheels changes. To keep the total spacecraft momentum constant per the law of conservation of angular momentum, the spacecraft reacts by turning to counter the change in the wheel momentum. As the wheel speeds change, the net wheel momentum varies and can rise toward the limit of 2.5 Nms. To prevent the wheels from exceeding their net momentum capacity, they must be de-saturated—that is, spun back down to low-rpm while thrusters maintained attitude control. RWA desaturations are normally performed during downlink windows when the spacecraft is at an attitude where the HGA can be pointed toward Earth.

To ensure that RWA de-saturations were properly spaced in the background sequence, the ADCS team ran each sequence through two tools: a momentum accumulation tool dubbed Scanner, and a kinematic predictor tool dubbed SlewDogg. Scanner functioned by using a midpoint epoch in the sequence under review and calculated the amount of solar torque acting on the spacecraft while Earth-pointed. Scanner reported the net momentum accumulation per day and thus the total number of days to reach 2.5 Nms. If the de-saturations were scheduled more frequently than the number of days to reach the momentum limit, then the de-saturation strategy was deemed acceptable. In comparison, the SlewDogg tool, which normally models spacecraft turns, was modified to read de-saturation commands. Upon recognition of each de-saturation command, the total wheel angular momentum was reset to 0.25 Nms. SlewDogg reported the wheel momentum before and after each de-saturation command, as well as periodically without de-saturation commands, as a check that the maximum wheel momentum capacity was not breached. This served as another check that the RWA de-saturations were properly spaced in the background sequence.

Trajectory Correction Maneuvers: The EPOXI mission required several trajectory correction maneuvers, coupled with all the Earth flybys, to keep the spacecraft on target to encounter comet Hartley 2, as shown in Table 1. Note that the largeness of the TCM-12 maneuver was due to a redesign for an alternate mission encounter geometry. TCMs are normally conducted by the 4 sets of Divert thrusters, which are mounted nearly parallel to the spacecraft X-axis. There are also 4 sets of RCS thrusters used during RWA de-saturations, as depicted in the following figure.

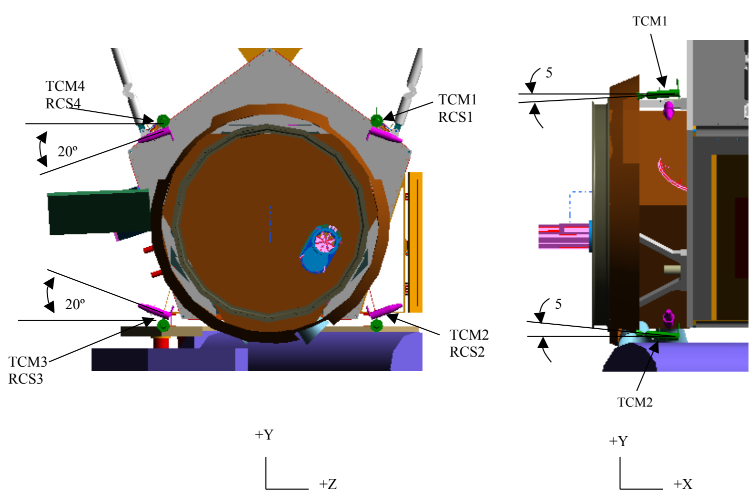

Figure 2. Flyby spacecraft thruster positioning

TCM	Burn Time	Delta V (m/s)	Status
TCM-9	01-NOV-2007 18:00:00	14.49176	0.977% (-- sigma) overburn
TCM-10	11-DEC-2007 18:00:00	0.03093	CANCELED

TCM-11	16-JAN-2008 18:00:00	0.72021	CANCELED
TCM-12	19-JUN-2008 18:00:00	31.54328	0.062% (1.2 sigma) overburn
TCM-13	11-DEC-2008 18:00:00	0.59365	0.005% (0.2 sigma) underburn
TCM-14	19-FEB-2009 00:00:00	0.82824	0.15% (0.4 sigma) overburn
TCM-15	18-MAR-2009 18:00:00	--	CANCELED
TCM-16	08-DEC-2009 18:00:00	0.49361	0.44% (0.2 sigma) overburn
TCM-17	21-JAN-2009 21:00:00	--	CANCELED
TCM-18	28-MAY-2010 18:00:00	0.10861	0.58% (0.3 sigma) overburn
TCM-19	19-JUL-2010 18:00:00	0.84468	0.18% (0.6 sigma) overburn
TCM-20	29-SEP-2010 18:00:00	1.53302	0.07% (0.3 sigma) overburn
TCM-21	27-OCT-2010 18:00:00	1.58746	0.15% (5.3 sigma) overburn
TCM-22	02-NOV-2010 15:00:00	1.35988	0.08% (0.8 sigma) overburn

Table 1. List of TCMs planned during EPOXI Extended Mission

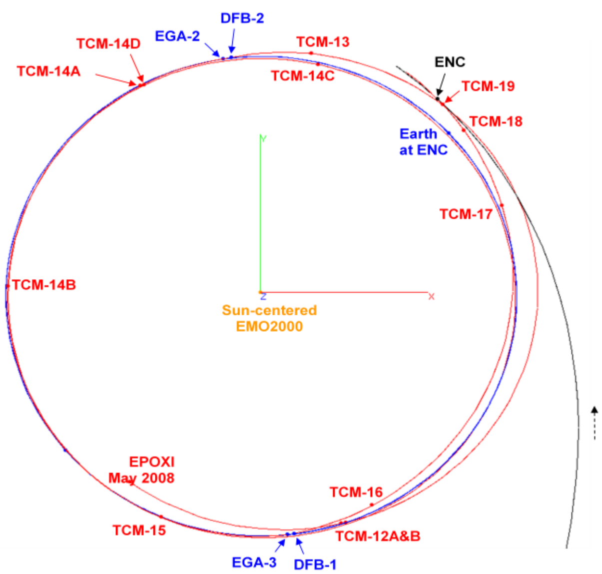

Figure 3. TCM trajectory plot for EPOXI Extended Mission

For each TCM, the process first began with the Navigation team providing to ADCS an input known as an MPF (maneuver profile file) which contained the RA/DEC of the Delta-V vector, the desired DV magnitude, and the burn time, among other parameters. The ADCS team would then use this input in a tool named Diburn, which produced an output known as an MPDF (maneuver performance data file), containing the burn time; spacecraft mass at the start of the maneuver; usable propellant at the start of the maneuver; effective thrust direction unit vector with respect to the spacecraft X,Y,Z coordinates; effective thrust magnitude fourth degree time-varying polynomial coefficients; and mass flow rate third degree polynomial coefficients(Legerton, Deep Impact Maneuver Performance Data File). This would be passed to the Navigation team to refine their maneuver estimate. Navigation would then redeliver a final MPF to ADCS, who would then re-run the Diburn tool to generate an MIF (maneuver implementation file). The MIF contained the spacecraft team's implementation of the Navigation team's requirements as given in the MPF. The contents of the MIF are very complicated and are only briefly summarized here: RA/DEC of Delta-V vector, magnitude of the total Delta-V, total Delta-V vector in EME2000 coordinates, EME2000 to spacecraft XYZ attitude transformation matrix, start time of first burn in the block, end time of last burn in the block, mass at start of the first block, mass at end of the last block, and various covariances, etc (Legerton, Deep Impact Maneuver Implementation File).

To run the Diburn tool, the ADCS team had to request several burn parameters from Ball Aerospace & Technologies Corp, the manufacturer of the spacecraft. The Ball propulsion team supplied these parameters in an Excel spreadsheet. The only parameters of direct use to ADCS were the fuel mass remaining in the tank and the tank pressurant temperature. Other assumptions in the use of the Diburn tool were the Divert Thruster duty cycle, and minimum duty cycle scale factor. With these inputs, both an MPDF and MIF can be generated and sent to the Navigation team.

Also part of building TCM commands was the generation of the Delta-V target table entries—which define the attitude at which the Delta-V maneuver was to be executed. These consisted of control frame target tables specifying quaternion offsets in a pair of commands. The first target table command specified the quaternion offset relative to the spacecraft body axes; the second target table command specified the quaternion offset relative to the reference frame, whether inertial, standby (Sun/Earth) or comet point. Target entry 22 was used to specify the Delta-V pointing direction, and a separate Delta-V table entry was used to specify the Delta-V magnitude.

Cruise Calibrations: Several instrument calibrations were conducted during the journey to Hartley 2: in June 2008, June 2009, February 2010, one at the end of the E-34 to E-8 day period (at the end of September 2010) and the other after the Departure sequence (at the end of November of 2010). The cruise calibrations offered the scientists an opportunity to calibrate the science instruments to improve the quality of their data. There were also several IR detector calibrations conducted during the lead-up to the Hartley 2 encounter, including calibrations using the Moon, which lead to the discovery of water forming on the lunar surface regolith.

The cruise calibrations involved two sets of stellar observations, separated by a downlink period at the playback attitude. During the observations, the HGA was taken out of autotrack as the spacecraft could not both conduct the observations and point at Earth. The observations involved pointing the HRI/MRI spectral filters at several well-known stars (Vega, Canopus, and Achernar), and performing several IR spectrometer scans of the stars. The purpose of this stellar data was to perform radiometric calibration of the instrument spectral response, to determine the HRI/MRI boresight alignments, to measure the electrical cross-talk of the visible wavelength instruments, and to verify the IR spectrometer's wavelength map (verifying that the expected spectral emission lines of well-known stars showed up properly on the IR detector).

During the first of the instrument calibrations, stellar target geometry caused one of the spacecraft's two star trackers to be pointed near the sparsely starred North Celestial Pole (NCP), where an idiosyncrasy of the tracker's embedded software caused the tracker to lose lock. This resulted in degraded pointing performance for a short time, but did not impact the accuracy of the calibration.

Do-si-do Demo: A few months before the actual encounter, an in-flight demonstration of the 7-hr do-si-do campaign during the E-8d to E-1d approach period was conducted. There was considerable risk in performing the seven 1-hr do-si-dos as it had never been done before on the Deep Impact spacecraft and occurred right before the actual comet encounter. Thus, the demonstration was conducted essentially to mitigate the risk of jeopardizing the encounter science. As such, the purpose of the "do-si-do" demo was two-fold: 1) to verify that the spacecraft ADCS system could rapidly execute the 6.25min, ~140deg turns between Earth-point and the comet imaging attitude and 2) to verify that the DSN could rapidly lockup on the downlink signal upon returning the HGA to Earth-point. The rapid DSN lockup was contingent upon a continuous uplink via the LGAs during the turns, allowing the ground station to stay coherent and thereby enabling a quick downlink lockup. The ability of three wheels to track the comet, should one of them have failed, was also analyzed and found to be acceptable if the wheels were pre-loaded with a specific momentum level.

Opposition: Following the departure sequence and after the November 30, 2010 cruise calibration, the geometry between the Sun, spacecraft and Earth was such that the SPE (sun-probe-Earth) angle would be small. This meant that the spacecraft could not simultaneously keep its solar arrays normal to the Sun while pointing the HGA at Earth. As a result of this opposition scenario, the HGAs had to be turned off, frozen in their final gimbaled positions, until the SPE angle was sufficiently large as Earth crossed the Sun to allow direct-to-Earth communications. This was verified in Tball by setting the time to a particular date/time (such as December 1, 2010 08:00:00 AM PST) , placing the spacecraft at an attitude with the sun 0deg off of the arrays, commanding the HGA to point to Earth, and then repeating these commands at successive times until the HGA could no longer track the Earth.

Using this method, it was found that the HGA reached its Z-gimbal limit of +65.89deg on December 03, 01:00:00 AM PST, when the SPE angle was 24deg and decreasing. The SPE angle reached a minimum of 4.7deg on December 16, 07:00:00 AM PST. Through opposition, the SPE angle increased to 24.69deg, on January 7, 2010 07:00:00 AM PST, at which time the HGA Z-gimbal could again reach +65.89deg. Thus, with some margin, the HGA was taken out of autotrack from December 4, 2010 to January 10, 2011. During this period, no telemetry was received from the spacecraft, and the background sequence simply commanded several RWA de-saturations and an ICV update.

4 RWA Health Assessment

The Flyby spacecraft is equipped with a set of four Ithaco TW-2A40 reaction wheels, whereas the Impactor spacecraft had none. During both the Deep Impact and EPOXI missions, the performance of the wheels relative to their lifetime limitations had not been monitored. For Deep Impact, the mission was so short that pre-launch analysis lead to the conclusion that there was no risk of violating the lifetime capability. However, for the EPOXI mission, the need to monitor RWA health & safety became apparent following reaction wheel lifetime concerns on other spacecraft. To monitor the health and safety of the EPOXI reaction wheels, both the total dwell time at low-rpm (< 150 rpm) and total accumulated revolutions of all four wheels had to be determined. Wheel performance during past TCMs was also investigated, as the wheels are left to coast down toward zero after each TCM burn, while the spacecraft attitude was controlled by the RCS thrusters. Faster coastdown times (both from positive and negative speeds) from one TCM to the next would indicate an increase in RWA friction.

For the RWA friction investigation, the coastdown range had to be limited to a region of speeds experienced by the most TCMs (all the way back to TCM-8 before the EPOXI mission began). Thus the coastdown range was limited to 25 -10 rad/s (283 rpm – 95 rpm), capturing the linear range of coastdown[6]. As depicted in the following two figures, no consistent trend was found for the coastdown speeds when comparing coastdown from positive speeds and coastdown from negative speeds. For the positive coastdown speed cases (see Figure 4), the applicable TCMs demonstrated generally decreasing coastdown times for all wheels except RWA4 (where only two data points were available). This indicated that RWAs 1 to 3 were experiencing increased friction over time, but nothing alarming. No identifiable trend could be found for the negative coastdown TCMs either (see Figure 5).

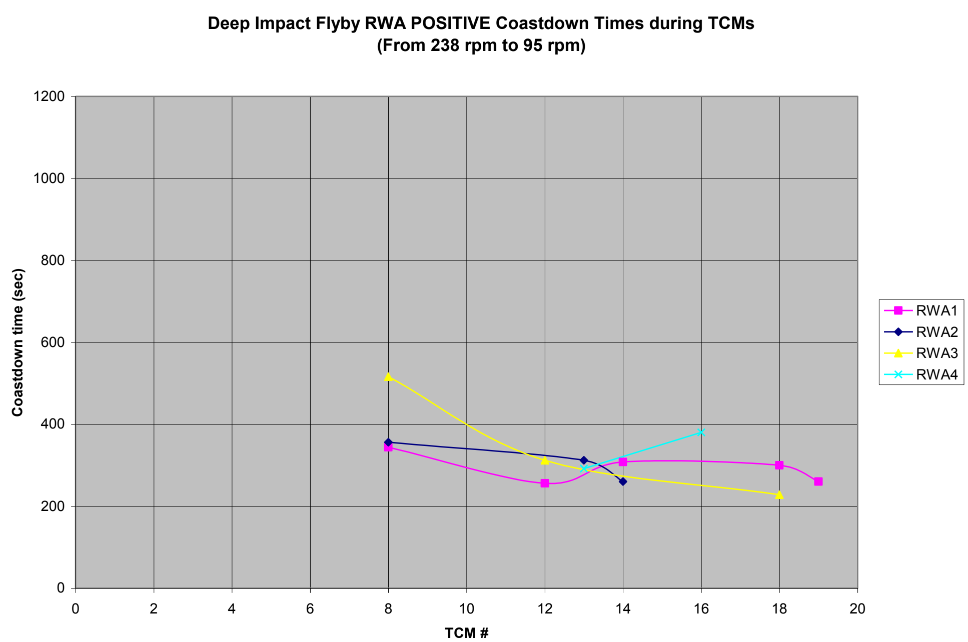

Figure 4. EPOXI Positive Coastdown Times during TCMs

[6] The coastdown has a linear contribution and exponential contribution.

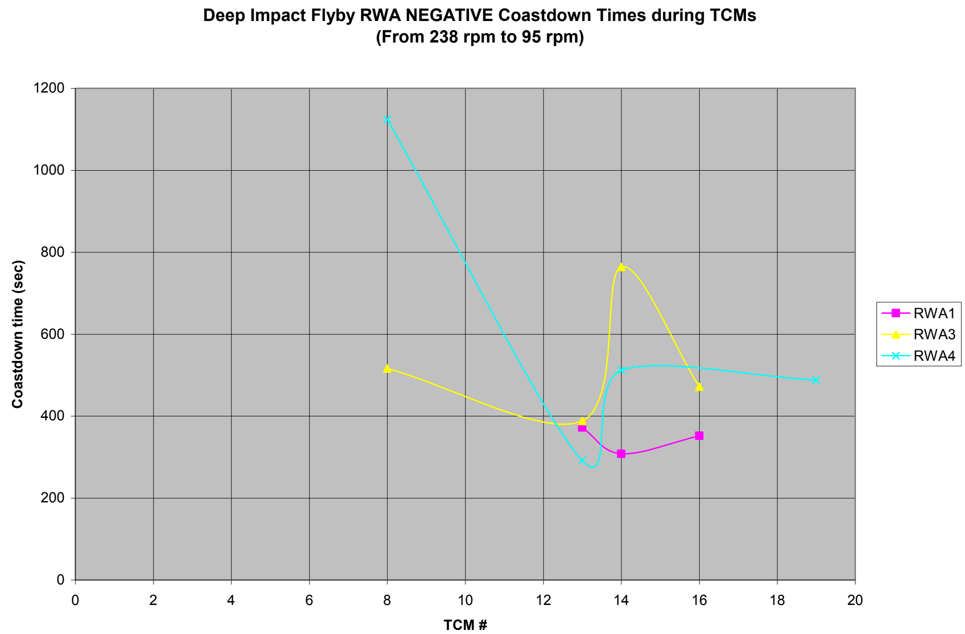

Figure 5. EPOXI Negative Coastdown Times during TCMs

Another method of characterizing the behavior of the EPOXI RWAs was to look at modeling the wheel coastdown as a function of friction parameters Coulomb friction C and T_{dahl} friction. The Coulomb friction determines the high-speed exponential region of coastdown, and T_{dahl} controls the low-speed linear region of coastdown.

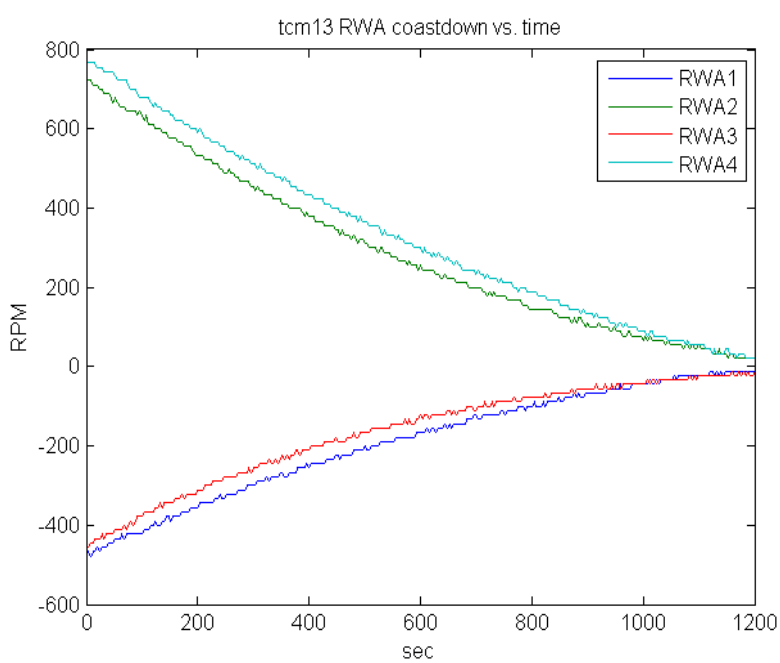

Figure 6. TCM13 RWA Coastdown (showing expontential and linear regions)

By fitting the coastdown plots to C and T_{dahl} for both positive and negative coastdown, the ADCS team could thereby determine whether there was any noticeable trend in the friction parameters. The coastdown model can be characterized by the following equation(Sarani):

$$w(t) = \frac{-T_{Dahl}}{C} sign(w_0) + \left(w_0 + \frac{T_{Dahl}}{C} sign(w_0) \right) e^{-t/\tau}$$
$$\tau = J / C$$

where J = 0.0076 kg-m^2 is the moment of inertia of a given reaction wheel, w_0 is the initial wheel speed, C is in the range 1e-5 to 1e-2 Nms/rad and T_{dahl} is in the range 1e-5 to 1e-3 Nm(Luna). The following four figures depict the Coulomb friction and T_{dahl} friction parameters for several TCMs during the EPOXI mission. As can be seen from these diagrams, the variation in friction parameters is unique for each RWA. For example, the Coulomb friction parameter in the positive coastdown direction appeared to increase for RWAs 2 and 3, slightly increased for RWA1 then remained constant, and remained constant for RWA4. For the negative coastdown cases, the Coulomb friction essentially remained constant for RWAs 1, 3, and 4, but jumped around for an overall increase for RWA2. These Coulomb friction trends did not represent anything alarming regarding the health of the reaction wheels.

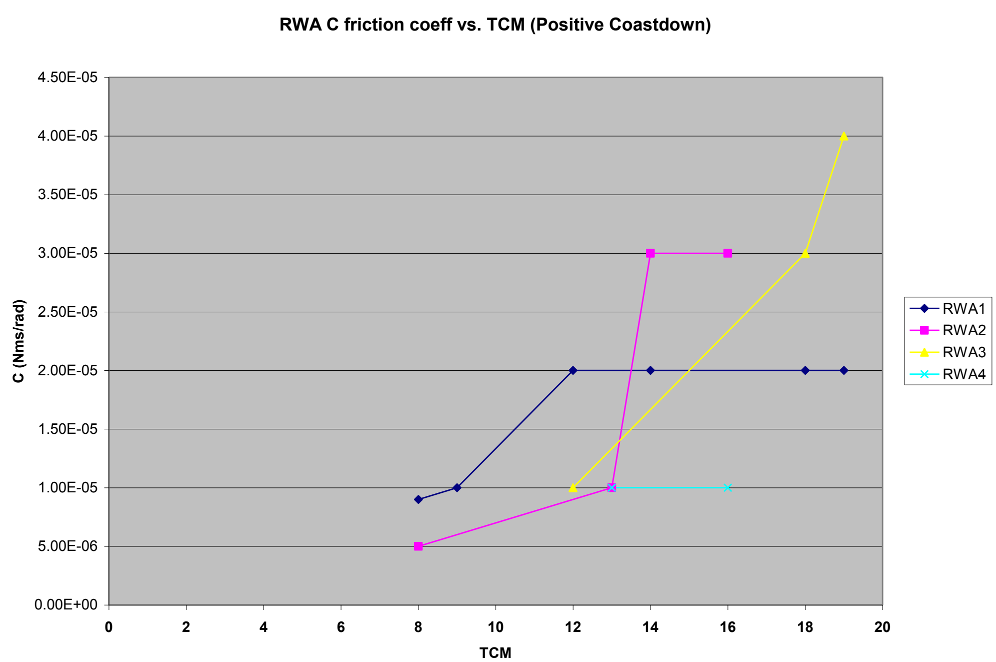

Figure 7. EPOXI RWA Coulomb friction coefficient (Positive Coastdown)

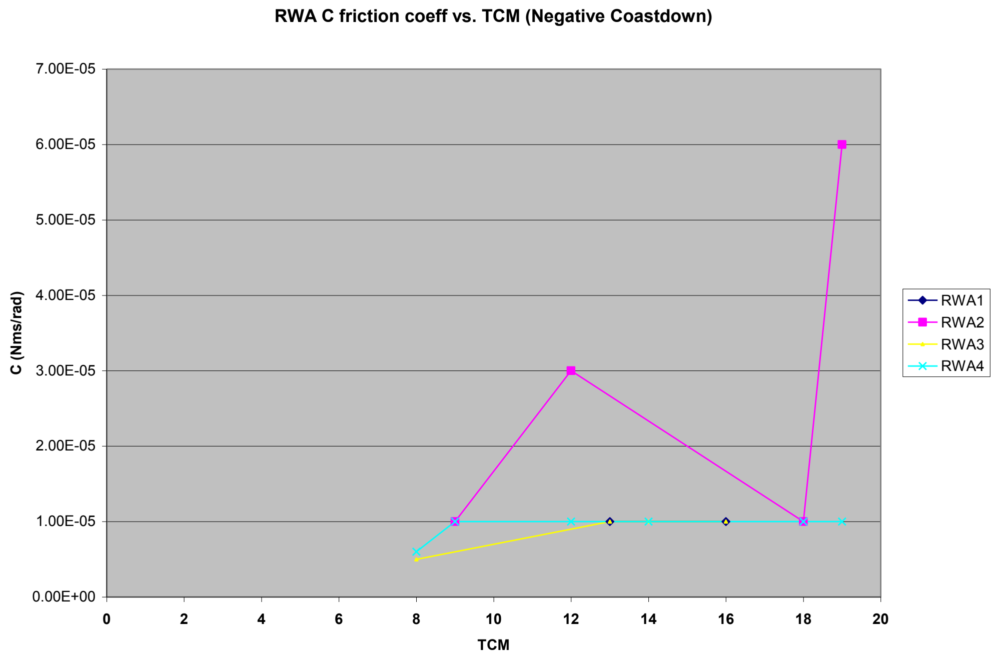

Figure 8. EPOXI RWA Coulomb friction coefficient (Negative Coastdown)

As for the T_{dahl} friction, in the positive coastdown direction the parameter appeared to decrease over time for RWAs 2, 3, and 4, but essentially remained constant for RWA1 (after a small sharp dip at TCM9). For the negative coastdown direction, there was no identifiable trend for all the wheels. With only 2 data points RWA1 appears to decrease, RWA2 jumps around, RWA3 jumps around, and RWA4 has a steady increase. None of these trends presented anything alarming regarding the health of the RWAs beyond normal wear and tear.

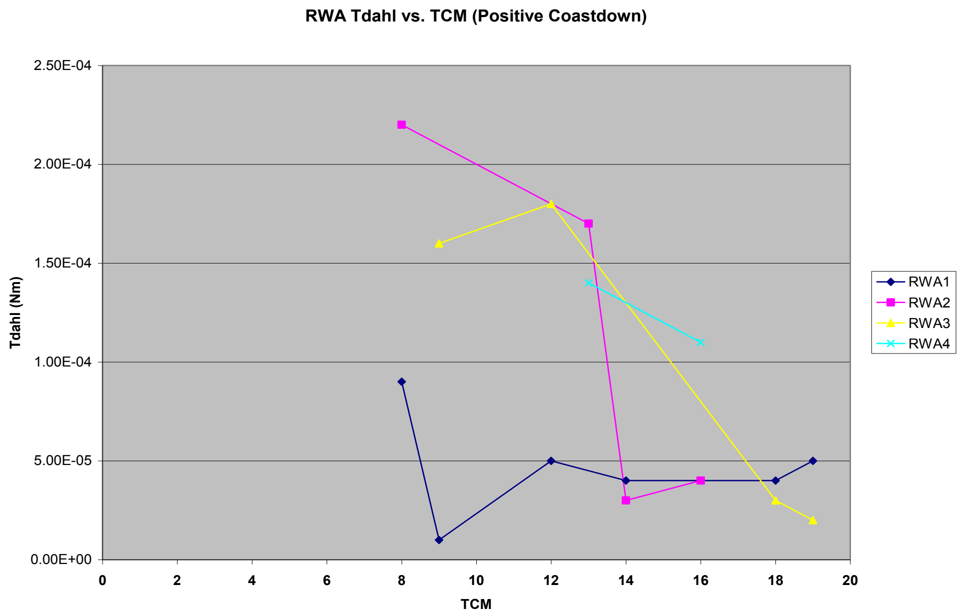

Figure 9. EPOXI Tdahl friction coefficient (Positive Coastdown)

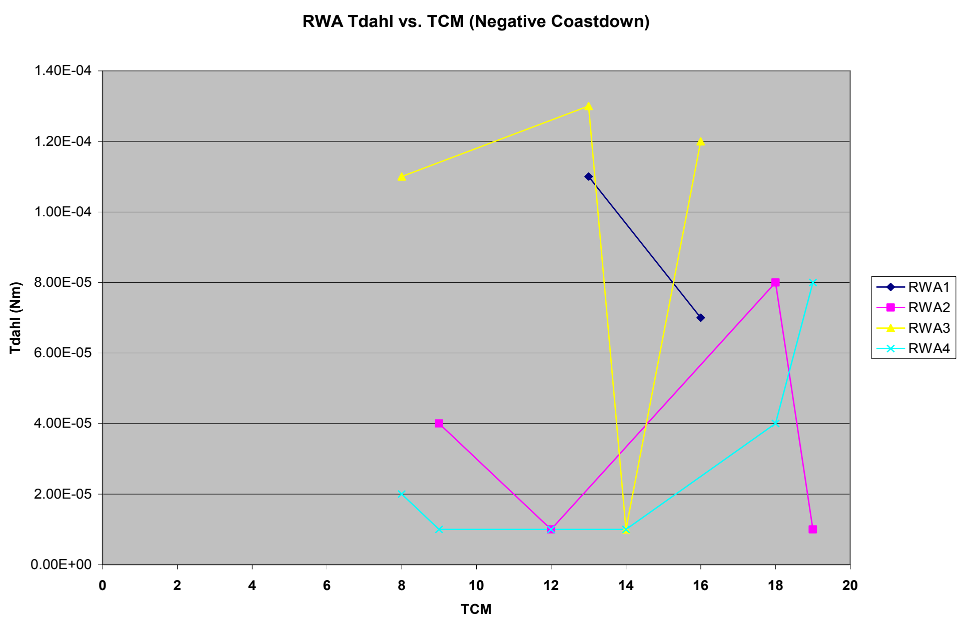

Figure 10. EPOXI Tdahl friction coefficient (Negative Coastdown)

The final step in assessing the overall health of all 4 RWAs was to determine the total low-rpm dwell time (time spent below +- 150 rpm) and the total accumulated revolutions since the Deep Impact mission began in 2005. This was no small feat as it required obtaining a time history of the RWA speed profile since launch and evaluating the integrated revolutions per minute over time. This mission RWA profile was obtained from automated spacecraft telemetry trending plots[7], one of which collected raw RWA speed counts at the end of every downlink pass. Although the raw RWA counts were collected at a rate of once per downlink, the assumption was that the RWA counts would be an acceptable representation of the true RWA speed profile, whose speed telemetry is obtained every 4-sec. The raw RWA wheel profile tachometer counts were converted to RPM values by the following relationship: 54 tachometer counts per revolution at 0.1s sampling. That gives:

$$rpm = N_{counts}\left(\frac{rev}{54\ counts}\right)\left(\frac{sample}{0.1\ sec}\right)\left(\frac{60\ sec}{min}\right)$$

The raw RWA speed telemetry at once per downlink (light blue) was first linearly interpolated with a time step of 1 hr (dark blue). The next step would be to evaluate the RWA wheel speed behavior during the hibernation period, as telemetry was collected only every 6 months during that time.

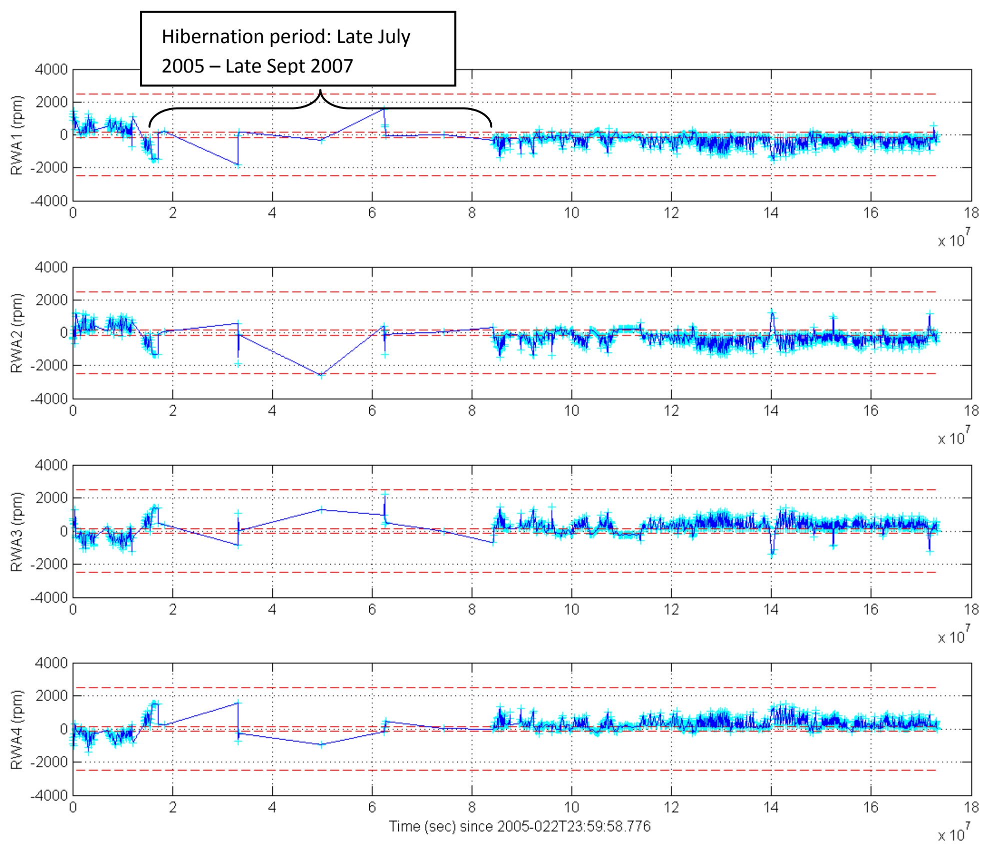

Figure 11. Raw RWA speed profile from start of Deep Impact mission

During the hibernation period sparse telemetry was collected, as can be seen from Figure 11 above. In reality, however, the spacecraft was sun coning—that is, turning about the probe-Sun line to ensure the solar panels would always be illuminated. To accommodate this sun-coning, the RWA speeds

[7] Converted from raw RWA tachometer counts to revolutions per minute.

varied in a complex sinusoidal manner during the entirety of the hibernation. To avoid having to rigorously model these complexities, a simple sinusoidal approximation was used to model the behavior of the RWAs during sun-coning. The amplitudes of each RWA's sinusoid were taken as the average of the actual amplitudes in February 2006 and January 2007. The period of each sinusoid was taken to be 3 hours from peak to peak. The hibernation RWA speeds were computed at a time step of 1hr as well. Then the sinusoidal RWA speed data was inserted into the hibernation period slot, replacing the sparse data, as shown in Figure 12 .

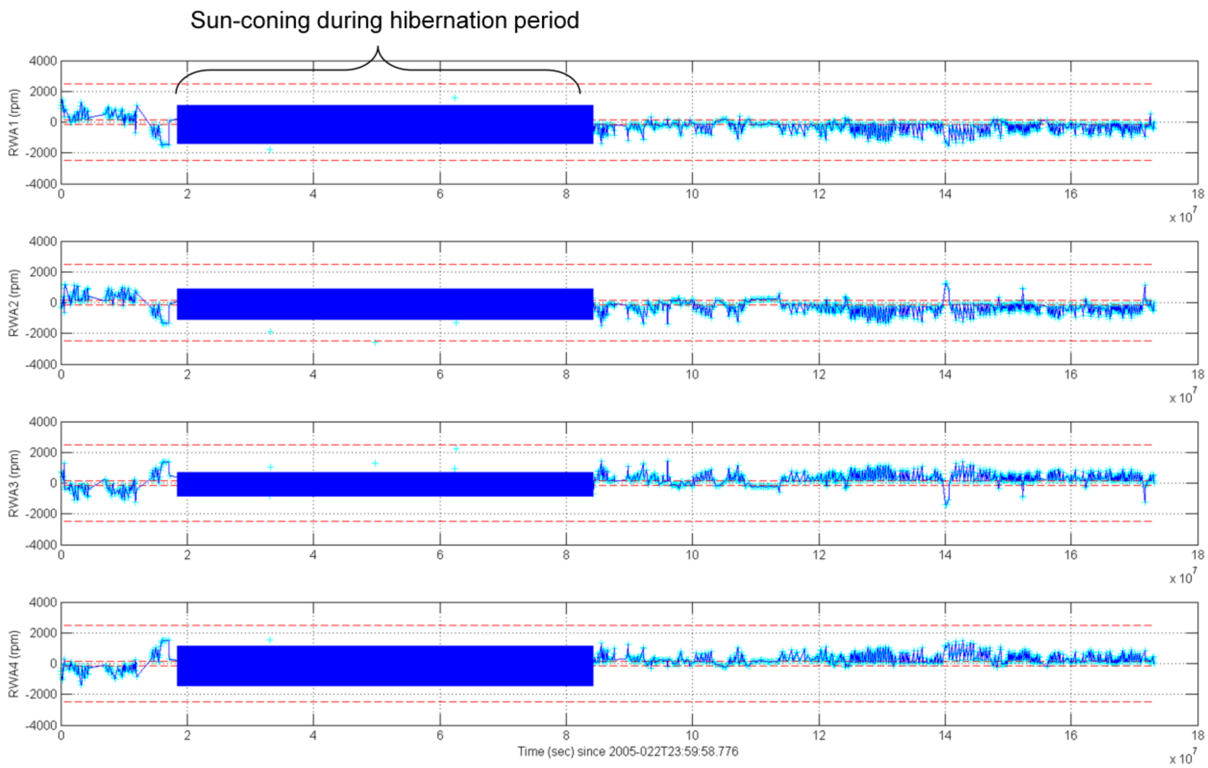

Figure 12. Deep Impact interpolated RWA speed profile since launch

Once this complete RWA speed profile was obtained, the next step was to accumulate the time spent below +-150 rpm, and obtain the integrated number of revolutions from shortly after launch in January 2005 to July 2010. The results of these accumulations are shown in the following two figures. As can be seen in Figure 13, RWA4 has the highest low-rpm dwell time since launch at 7161 hrs. As can be seen in Figure 14, RWA4 also has the highest accumulated revolutions at 1.68 billion revolutions, slightly higher than RWA1. As no lifetime limitations were specified for total accumulated low-rpm dwell time or total accumulated revolutions—given that the prime mission was to be only 6 months—there was no reason to view these as dangerous to the health and safety of the RWAs. Besides, if a wheel failure did occur, ADCS verified that the Flyby spacecraft would be able to perform the intended fast slews for the do-si-do and closest approach comet tracking on three reaction wheels, provided the wheels were biased to pre-selected momentum values as part of a contingency procedure. Fortunately, the comet encounter operated under all four RWAs with no anomalies detected.

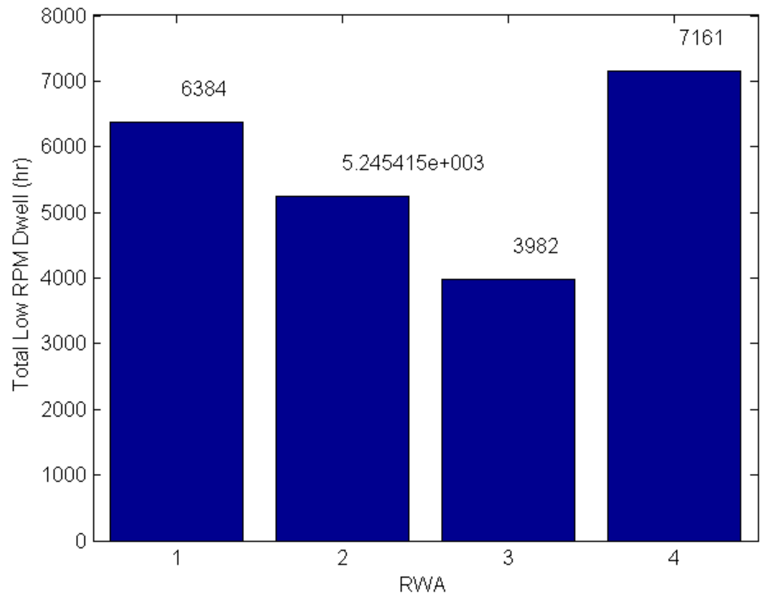

Figure 13. Deep Impact Flyby spacecraft total low-rpm dwell time since launch to TCM19

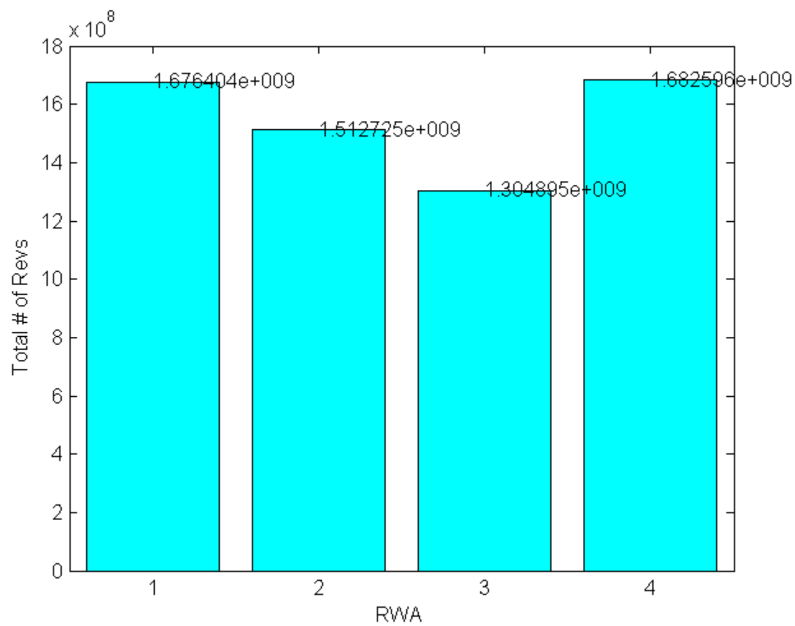

Figure 14. Deep Impact Flyby spacecraft total accumulated revolutions since launch to TCM19

5 Conclusion

In preparing for the close encounter of comet Hartley 2, the ADCS team reviewed several background and integrated sequences (checking the initial conditions vector, sun sensor coefficients, and RWA de-saturation frequency), performed several trajectory correction maneuver designs and monitored the TCMs in real-time, performed special science instrument calibrations, tested the fast-turn rate capability of the reaction wheels in flight, and assessed the health of all four reaction wheel assemblies. These activities helped to ensure that the attitude determination and control subsystem would operate as expected, thereby enabling the spacecraft as a whole to successfully reach comet Hartley 2 and successfully track the comet nucleus during the flyby.

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