Cassini Orbit Trim Maneuvers at Saturn – Overview of Attitude Control Flight Operations

Thomas A. Burk*
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

The Cassini spacecraft has been in orbit around Saturn since July 1, 2004. To remain on the planned trajectory which maximizes science data return, Cassini must perform orbit trim maneuvers using either its main engine or its reaction control system thrusters. Over 200 maneuvers have been executed on the spacecraft since arrival at Saturn. To improve performance and maintain spacecraft health, changes have been made in maneuver design command placement, in accelerometer scale factor, and in the pre-aim vector used to align the engine gimbal actuator prior to main engine burn ignition. These and other changes have improved maneuver performance execution errors significantly since 2004. A strategy has been developed to decide whether a main engine maneuver should be performed, or whether the maneuver can be executed using the reaction control system.

Acronyms

AACS	Attitude and Articulation Control System	LGA	Low-Gain Antenna
ACC	Accelerometer	ME	Main Engine
AU	Astronomical Unit	OTM	Orbit Trim Maneuver
b/g	background	RCS	Reaction Control System (Thrusters)
DSN	Deep Space Network	RPWS	Radio/Plasma Wave Science
FSW	Flight software	RWA	Reaction Wheel Assembly
HGA	High-Gain Antenna	SRU	Stellar Reference Unit
IRU	Inertial Reference Unit	SSR	Solid State Recorder

I. Introduction

THE Cassini spacecraft has been in orbit around Saturn since July 1, 2004. As of May, 2011, Cassini has completed 149 orbits of the planet. Highlights of the orbital tour include 76 encounters with the moon Titan (with 25 of these approaching within 1000 km of the haze-shrouded surface), 14 close encounters with Enceladus (8 coming within 100 km of its icy surface), and one or more close flybys of each of the other larger moons of Saturn. Prior to the era of space exploration, only 9 Saturn moons had been detected from Earth. Since the Pioneer 11 flyby of Saturn in 1979, the Voyager 1 flyby in 1980, Voyager 2 in 1981, and especially since Cassini arrived at Saturn in 2004, more than 62 moons have been discovered, and Cassini's continuing mission allows scientists to not only find more but establish their character; each a unique and distinctive little world. Lakes of hydrocarbons have been discovered near Titan's poles, as well as what could be HC rivers and rain on this alien world. Enceladus has cryovolcanic plumes near its south pole that are continuously venting water that freezes into ice particles that Cassini has sensed as it flies over. Cassini has revealed that both of Saturn's poles possess a monstrous vortex where heat from the interior powers giant thunderstorms. The 12 science instruments on Cassini have allowed study of Saturn's rings in remarkable detail, revealing hundreds of never-before seen spiral density and bending waves, as well as the fine-scale structure of "gravity wakes" in the rings and how they vary with location.

Cassini is a 3-axis stabilized spacecraft with an 11-m magnetometer boom and three 10-m Radio and Plasma Wave Science antennas (see Fig 1).

*Product Delivery Manager, Guidance and Control Section, 4800 Oak Grove Dr., M.S.230-104, Pasadena, CA 91109-8099. AIAA member.

Virtually all the science and engineering instruments on Cassini have fixed orientations on the spacecraft. This includes the science cameras. To point a science instrument at an object of interest, the whole spacecraft must be slewed to achieve the desired pointing[1]. Cassini is powered by 3 RTGs which produced 880W at launch, and are currently producing about 660W of power.

Cassini has a body-fixed 4 meter diameter Cassegrain HGA parabolic reflector dish for telecommunications. Uplink and downlink uses X-band for commanding, telemetry, and radiometry. On Cassini, radiometric data includes two-way Doppler and two-way (turnaround) ranging. Doppler and ranging data are used together for radio navigation of the spacecraft and may also be used as ancillary data for radio science. The HGA has separate feeds for S-band (used during the Huygens Probe tracking in January 2005 as it descended to the surface of the moon Titan), Ka-band, and Ku-band (radar mapping of Titan and other satellites). All these bands are used for radio science as well.

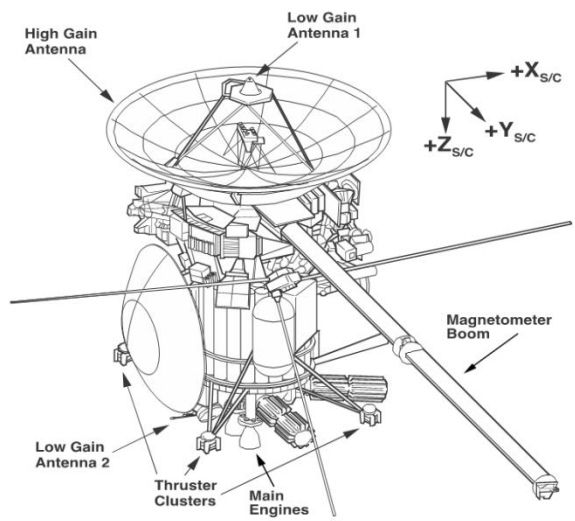

Figure 1. Cassini Configuration at Saturn Arrival

The HGA is mounted on top of the spacecraft stack and points parallel to the spacecraft –Z body axis (Fig. 1). The HGA is used as a Sun shield and also as a shield during hazardous Saturn ring plane crossings. Cassini has dual redundant 2-axis sun sensors mounted on the HGA. Downlink to the NASA Deep Space Network (34m and 70m stations in Goldstone, California; Madrid, Spain; and Canberra, Australia) uses the HGA and X-band telemetry at up to 166 kbps for science data at 9 AU. The engineering allocation of the telemetry is 1896 bps. Cassini has 2 backup Low-Gain Antennas LGAs for emergency commanding.

Cassini has dual redundant Command and Data System 1750A flight computers each with 512 KB of RAM storage. Two 2-Gbit solid state recorders are used for science and engineering data storage as well as storage of copies of engineering flight computer software and science instrument flight software. In the year 2011 these computer storage resources appear primitive, but in the mid-1990s these capabilities on an interplanetary spacecraft were new and considered powerful. Given X-Band telemetry downlink data rate limitations, it sometimes happens that the Cassini SSRs have "carry-over", meaning they cannot be completely emptied during a given downlink.

The Cassini propulsion system[2] includes a mono-propellant thruster-based reaction control system (RCS), and a bi-propellant system supporting main engine ΔV maneuvers. The mono-propellant system consists of a single blowdown hydrazine tank, eight prime and eight backup 0.9 N Voyager-vintage hydrazine thrusters, and a pyro-isolated one-time helium recharge tank. At launch, a single thruster produced approximately 0.98 N which slowly decreased to 0.65 N by April of 2006 when the helium recharge tank was utilized. At that time the thrust jumped back up to about 0.98 N. Since then, the thrust has slowly decreased until, as of June of 2011, it is near 0.7 N.

The prime RCS system has 4 thrusters that fire parallel to the spacecraft –Z body axis (one on each of four thruster clusters. These thrusters are used for Z-axis translational ΔV maneuvers as well as attitude control about the spacecraft ± X and ± Y body axis. Note that attitude control about these axes does impart ΔV to the spacecraft that must be predicted and accounted for in orbit determination and maneuver planning. The prime RCS system has 4 thrusters that fire as couples parallel to the spacecraft Y body axis for attitude control about the spacecraft Z body axis (see Fig. 2). The eight thrusters (4 Y and 4 Z) constitute the prime thruster set. The A branch was prime from launch to March of 2009. At that time, a reduction in thrust in one of the Z-facing thrusters led to a decision to swap to the B branch. The B branch continues to be the prime thruster branch as of 2011. If necessary, Cassini flight software does permit "mixed branch" thruster operation (where some A branch and some B branch thrusters are used at the same time).

The bi-propellant system uses monomethylhydrazine for fuel and nitrogen tetroxide for oxidizer. These hypergolic propellants have also been used on Galileo and the space shuttle orbital maneuvering system and RCS system. Propellant lines feed the bi-propellants to the 445 N prime main engine.

A single helium tank provides high pressure gas to the bi-propellant tanks during pressure-regulated maneuvers.

The largest Cassini ΔV main engine maneuvers have been pressure-regulated, but the vast majority of main engine burns since 2004 only utilize the pressure already in the propellant tanks. Over time, increasing ullage volume in the propellant tanks cause the main engine thrust to slowly decrease with the tank pressure. These "blowdown" burns provide thrust roughly ten percent less than pressure-regulated burns. No further pressure regulated burns are planned.

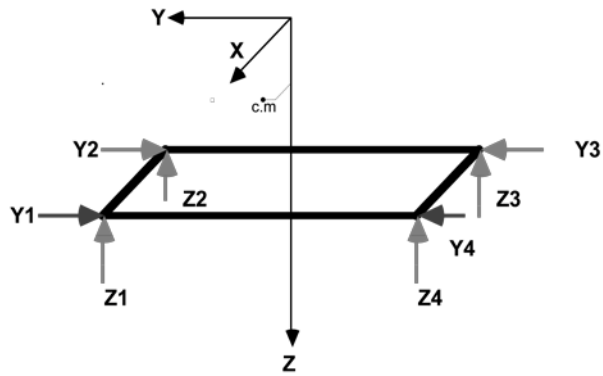

Figure 2. Cassini Thruster Configuration

Control during main engine burns is provided by gimbaling of the main engine. Two linear engine gimbal actuators (called "P" and "Q") provide 2-axis control and the third axis (roll about the thrust vector) is controlled by the Y-facing RCS thrusters. The ΔV imparted on the spacecraft during a main engine burn is measured by an accelerometer that is mounted parallel to the spacecraft's Z-axis. The scale factor of the ACC data was estimated pre-launch to be 2.02033 mm/s per data number[3]. Its bias was estimated to be 2.7 mm/s^2 However, since the ACC's bias changes slightly from burn to burn, a one-minute calibration is always performed before the start of the burn to determine the actual ACC's bias. The flight software then uses the calibrated ACC to accurately determine the magnitude of the ΔV imparted on the spacecraft. The burn is terminated once the commanded ΔV is achieved.

On Cassini, inertial attitude knowledge sensors include a star tracker and gyroscope sensors (a sun sensor is explicitly utilized only when 3-axis attitude knowledge is lost or dropped). Cassini has dual redundant IRUs each containing four HRGs. Three of the four HRGs are used as prime inertial sensors while the fourth gyroscope is used as a "parity checker." Each IRU has a resolution of 0.25 micro-radians (μrad). The prime IRU on Cassini has been powered on continuously since launch, demonstrating outstanding durability. Gyro scale factor errors and misalignments are calibrated onboard every year.

Cassini has dual redundant stellar reference units (star trackers) which are co-aligned with their boresights parallel to the spacecraft +X body axis. Each SRU is capable of full-sky determination of the spacecraft 3-axis attitude. The optical Field of View (FOV) of these trackers is a square: ±7.5° by ±7.5°. The straylight FOV of the SRU is circular with a radius of 30°. Valid star identification (SID) can be suspended up to 5 hours if Saturn, the rings, or other bright bodies enter the straylight FOV. During SID suspends, attitude estimation uses IRU-only attitude propagation. Upon exit of SID suspend, a small attitude correction typically occurs as the star tracker reacquires celestial attitude knowledge and corrects for small IRU scale factor and misalignment errors.

To conserve hydrazine propellant and for precise and stable pointing, the Cassini spacecraft uses 3 strap-down reaction wheel assemblies (RWAs). Each RWA spin axis is fixed in the spacecraft body frame (Fig. 3) but are not coaligned with the spacecraft body axes. Together the RWAs form an orthogonal set and each spin axis is $\cos^{-1}(1/3) = 54.73°$ from the spacecraft +Z body axis. Each RWA has a 34 Nms momentum storage capability and a motor capable of .165 Nm of torque. A fourth RWA is articulatable and can thus be oriented to match any of the other three RWA's spin axis orientation. This RWA was originally the backup RWA but since July of 2003 it has been used as one of the three prime RWAs. Only three RWAs can be used for control simultaneously so one RWA is normally

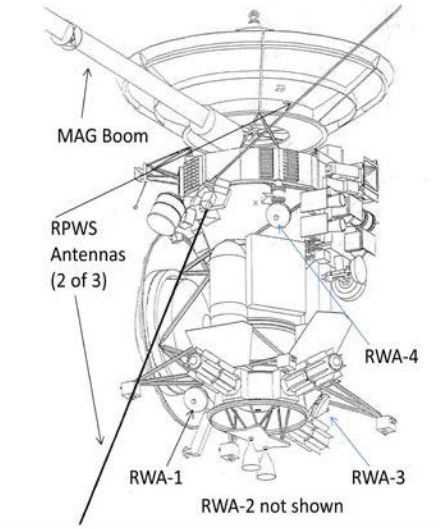

Figure 3. Cassini with RWAs Depicted

powered off. Since arriving at Saturn, Cassini has used RWA control the vast majority of the time. Ground controllers use great care in maintaining the health of the RWA hardware because lack of RWA control would essentially end the bulk of the science mission. The extensive slewing of the spacecraft to track science targets (and the Earth during uplink/downlink periods) would quickly use up the remaining hydrazine propellant if RWA control was no longer available.

Thermal control is achieved via a variety of processes. Waste heat from the RTGs helps heat the central body of the spacecraft. Louvers, heaters, and small Radioisotope Heater Units also assist in thermal control. Sensitive science instrument radiators are oriented parallel to the spacecraft +X body axis. When the HGA is pointed at the Sun, the sensitive science radiators are shaded. The spacecraft can be pointed up to 4.5º away from Sunpoint and the radiators will still be shaded by the HGA from solar heat. But even at 9 astronomical units from the Sun, the +X-to-Sun angle has to be carefully controlled to maintain robust performance of some science instruments. With few exceptions, all science and engineering activities must factor in these thermal constraints. Models for heating and cooldown are used extensively in activity design in order to insure thermal control is maintained.

II. Key Factors in Tour and Maneuver Design

The path that Cassini follows throughout its tour of Saturn is a carefully designed flight path designed to take advantage of the large gravity assist provided by flybys of the moon Titan[4]. For example, a flyby of Titan within 1000 km of the surface at a flyby velocity of roughly 6 km/s provides an equivalent Delta V of about 800 m/s. This amount of Delta V exceeds any single Delta V maneuver ever performed by the Cassini propulsion system (the largest, Saturn Orbit Insertion, imparted 625 m/s). Titan flybys are thus the key to designing the path that Cassini follows in Saturn orbit. During 2007 and 2008, Titan flybys boosted Cassini's orbital inclination from near zero to over 60º so that Saturn and the rings could be observed from high above the ring plane. Similar high-inclination orbital phases are planned for 2012 and 2017. These "Titan-to-Titan" transfers are key to allowing a comprehensive tour of the Saturn system within the constraints of the Cassini propulsion system.

The Cassini mission at Saturn has had three phases. The nominal mission was designed prior to arrival at Saturn in July 2004. This nominal mission tour extended from June 2004 through June of 2008. An extended mission (XM) was funded and spanned two years of exploration through September of 2010. The final phase, called extended-extended-mission (XXM), is currently executing and, if the spacecraft remains healthy, will continue through September of 2017, at which point the trajectory design will cause Cassini to enter the atmosphere of Saturn and burn up.

The design of the Saturn tour involved a complex tradeoff between the time available, the many types of science priorities, and the available spacecraft propellant. Most of the 3,000 kg bi-propellant load was used during three major maneuvers: (1) The Deep Space Maneuver about a year after launch; (2) The Saturn Orbit Insertion burn on July 1, 2004; (3) The periapsis-raise maneuver 2 months after SOI. By the time these were complete, only 22% of Cassini's bi-propellant remained. Thus the entire Saturn tour, XM, and XXM from September 2004 through September 2017 must be designed using only the remaining 22%. Although Titan gravity assists account for the bulk of the trajectory shaping, each encounter requires some deterministic ΔV to stay on the desired or "reference" trajectory, along with providing ΔV margin for uncertainties. Uncertainties include orbit determination inaccuracies, Saturn and moons gravity uncertainties, maneuver execution errors, prediction errors in other activities that impart ΔV on the spacecraft, and drag force uncertainty during flybys that dip into Titan's atmosphere. A typical orbital encounter with Titan involves three maneuvers: a targeting maneuver, an approach maneuver, and a clean-up maneuver (Fig. 4).

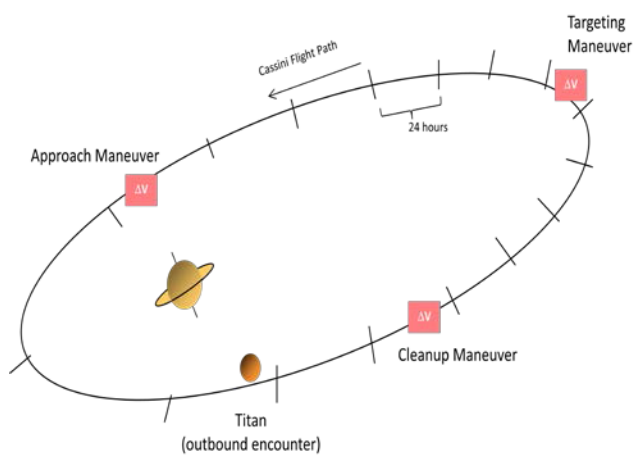

Figure 4. Maneuver Locations in Orbit

Since Saturn insertion in 2004, Cassini has executed over 200 maneuvers to impart ΔV to the spacecraft. About 90 maneuvers have been cancelled, mostly due to small delivery errors although some "clean-up" and "targeting" OTMs are merged into a single maneuver. Omission of planned maneuvers, at certain key times, could cause Cassini to "fall off the reference trajectory". Such an event would mean failure to return to Titan and therefore the spacecraft would become stuck in a single Saturn-relative orbit, invalidating all future plans for science observation. Backup and contingency maneuver plans exist to impart ΔV to avoid such a fate, even at the expense of significant extra propellant usage.

Since targeting to return to Titan is basic to the design of the mission, it does happen that after a flyby the spacecraft can actually be on an "impactor" trajectory. This means that if no additional ΔV is imparted during the next orbit, the spacecraft would collide with Titan during the next flyby. The normal process for ground engineers is to execute a ΔV maneuver, usually 3 days after the prior flyby, to move the spacecraft off the impactor trajectory in as efficient a manner as possible. Again, the essential goal is to keep Cassini near the reference trajectory.

All science and engineering activities onboard Cassini are accomplished via stored sequences of commands. These commands are time-ordered set of commands to accomplish a wide variety of activities. Each command is issued at a planned UTC time. Since science observations, especially their desired "pointing" are designed to occur at an exact UTC time, maneuver design must keep the spacecraft near the reference in both space and time. Most science and engineering activities are merged into a "background sequence". Each b/g sequence is typically 6 to 10 weeks in duration, and is uplinked to the spacecraft about 5 days before it is scheduled to begin execution. A b/g sequence undergoes a series of simulations and ground software checks to insure it will execute seamlessly once onboard[5]. A whole series of flight rule checks are performed by the Cassini attitude control ground operations team. All pointing commands, for example, must meet limitations on maximum slew rates and accelerations, avoiding "keep out" zones, and thermal constraints.

One important keep out zone that must be met, even during ΔV maneuvers, is the limit on RWA wheel speed. Each RWA can spin up to 2020 revolutions per minute, but this hard limit must not be exceeded. If this restriction is not followed, onboard fault protection will autonomously keep the RWA spin rate from exceeding the hard limit, and at the same time it will issue a safe mode command. Safing causes an autonomous transition to RCS control, powers off the RWAs as well as many science instruments, and suspends the execution of any onboard sequence (including ΔV maneuver sequences). Recovery from safe mode is complex and time-consuming for ground operators, so constraints of this type are always high-priority checks during any ΔV maneuver development.

Another constraint important for long-term RWA health and safety is to minimize any dwell at a low RWA wheel speed. Cassini flight experience has shown that large and persistent RWA bearing frictional toruqe spikes can occur if an RWA dwells at a very low spin rate. Excessive dwell time could lead to RWA bearing failure over time. During the approach to Jupiter in late 2000, fault protection autonomously transitioned to RCS control due to large frictional torque when an RWA dwelled near zero rpm for several hours.

A b/g sequence is designed to accommodate ΔV maneuvers, but the commands to perform maneuvers are typically uplinked long after the b/g sequence is already onboard. Orbit determination and maneuver design require very "up to date" radiometric data, especially for any events on the spacecraft that impart ΔV. A typical 'day" for the Cassini spacecraft is to gather science data for 15 hours, and then turn the spacecraft to align the HGA with Earth for 9 hours of playback. It is these standard Earth-pointed time periods that serve as ΔV maneuver "windows". If no maneuver is needed, the window is used for data playback (some science is gathered even during playback). If a ΔV maneuver is required, the maneuver pauses the playback until the maneuver is complete.

A ΔV maneuver is usually uplinked on the same 9-hour DSN uplink/downlink window over which the maneuver is to take place. The nominal strategy is to design burn ignition time to be six hours into the 9 hour OTM window. Thus the maneuver sequence is usually uplinked at the beginning of the track and stored onboard for only a few hours before it begins execution. A standard practice is to always plan for the loss (for example, high winds or rain at the station) of the prime DSN uplink/downlink window and always prepare a backup maneuver that will be uplinked on the next available DSN window. The maneuver team builds and checks this backup maneuver just like the nominal maneuver. Typically, the backup maneuver is slightly less efficient than the prime maneuver, meaning that a slightly bigger ΔV would be required to keep the trajectory close to the reference trajectory.

III. Roll/Yaw Turn Design for Maneuvers

The basic approach to maneuver design was conceived prior to launch[6]. When Cassini was in the inner solar system, it was important to keep the HGA pointed at the Sun and to keep the thermally-sensitive +X side of the spacecraft at least 90º from the Sun. To impart ΔV in the correct inertial direction, the spacecraft must be slewed from the initial attitude to an attitude that aligns the thrust vector with the desired ΔV direction. Rather than a single multi-spacecraft-axis turn to the burn attitude (which could violate the thermal requirements), a two-turn approach called the "roll/yaw" turn strategy was developed. The first turn is a turn about the spacecraft Z-axis (a "roll" turn between -180 degrees and +180 degrees). This turn keeps the Sun 90º away from the +X body axis. The second turn is a turn about the spacecraft Y-axis (a "yaw" turn between 0 degrees and -180 degrees). A yaw turn that has a negative angle insures that the +X-to-Sun angle never drops below 90º during the maneuver. Science camera boresights are coaligned with the spacecraft -Y body axis. This roll/yaw turn strategy also insures that these boresights remain 90º or more away from the Sun.

During the Saturn tour phase of the mission, HGA-to-Earth is used as the initial and final attitude, rather than HGA-to-Sun. The roll/yaw turn strategy is still used, however, and provides adequate thermal protection, even though the +X-to-Sun angle can drop below 90º. At Saturn, from the perspective of the spacecraft, the angle between the Earth and the Sun is always less than 7º. Thus the smallest the +X-to-Sun angle can get (at any time during the maneuver – including during the slews) is: 90º - 7º or 83º. This can cause some heating on the science instruments, but the science teams have accepted this and there is approximately 2-3 hours of "cool down" time after the maneuver before the spacecraft turns towards targets of science interest.

The roll/yaw turn strategy during Saturn tour also tends to minimize the time spent "off-Earth". The spacecraft remains Earth-pointed during the "wind" roll turn and begins to move "off-Earth" at the start of the wind yaw turn. Following the burn, an "unwind" yaw turn in the opposite direction returns the spacecraft to Earth-point. This is followed by the unwind roll turn to return to the initial spacecraft attitude. Propellant slosh settling time is added in between turns and after the burn.

This strategy is followed for all burns, whether ME or RCS. The thrusters used for Delta V during RCS burns are the four thrusters co-aligned with the spacecraft –Z body axis. Thus the effective "thrust vector" for RCS burns can be considered to be the –Z body axis. The main engine is physically mounted about 24 cm away from the Z-axis spacecraft "centerline" (in the +Y-axis direction). Since the Y-component of the spacecraft center-of-mass is very near the "centerline" and the distance from the center-of-mass to the main engine gimbal is about 2.2 meters, the effective "thrust vector" during ME burns makes an angle of about 6 degrees with the -Z-axis. The roll/yaw turn strategy aligns the spacecraft "pre-aim" thrust vector with the desired Delta V vector for the burn. There is a unique closed-form solution for the roll and yaw turn angles for all burn directions. This algorithm has been used for all burns since launch (excepting Saturn Orbit Insertion which had unique requirements).

IV. Main Engine Maneuvers

Science and engineering activities on Cassini require a series of commands that are tailored for each activity long before the activity is uplinked. Unique command arguments are selected as well as the absolute UTC time of the activity. Because most activities follow a standard pattern, ground-expanded blocks are used throughout the Cassini project and are especially useful during maneuvers. The maneuver block is the time-ordered sequence of commands that are always issued during a maneuver.

The Cassini main engine ΔV block has evolved throughout the mission. The block is like the skeleton of commands and inputs to the block include the burn-specific parameters like burn magnitude, minimum and maximum burn timers, burn direction, turn rates and accelerations, mass properties, pre-aim vector, RWA momentum, attitude control deadbands. The ground system "expands" the block input parameters into a time-ordered sequence of commands, ready for uplink. Many automated checks are performed on the maneuver products and any flight rule or other violations are flagged[7]. The specific set of block parameters have evolved over the course of the mission. An important lesson is to avoid "overlays" to the block. Manual overlays introduce increased risk of parameter mistakes or command placement mistakes.

Before reaching Saturn, maneuvers used 50 to 100 grams of hydrazine during the turns to the burn attitude and back. For these maneuvers, the wind and unwind roll and yaw turns were performed in RCS control. To minimize hydrazine usage, the wind roll and unwind roll turns on all ME maneuvers since arrival at Saturn have been

performed in RWA control. The yaw turns for ME burns are done in RCS control, but the turn rate and acceleration are kept small in order to reduce hydrazine usage. The nominal yaw rate is 1.1 mrad/s and nominal yaw acceleration is 0.02 mrad/s^2. The project considered doing ME yaw turns in RWA control, but decided that there would be very small propellant savings given that these turns in RCS control are performed at small turn rates.

A disadvantage of performing ME burn yaw turns in RWA control is that the RWAs would have to either be left spinning during the burn, or spun down at the burn attitude. There were risks associated with leaving the RWAs spinning during the burn. These included a power-related impedance issue when the RWAs were on and the main engine valve was actuated at burn ignition, and the risk to the RWAs themselves (shock and vibration) if spinning at the time of main engine ignition.

If the RWAs were spun down (requiring 15 to 20 minutes) at the burn attitude, then spun back up after the burn (requiring an additional 15 to 20 minutes), this would add significant "off-Earth" time where ground engineers cannot monitor performance real-time and the navigation team loses visibility into the Delta V effects of the RWA spin down and spin up. Vibration effects on the RWA hardware was another factor in favor of performing the unwind yaw turn in RCS control. The spacecraft is jolted by the main engine valve opening and burn ignition. Flight data from OTM-21 is given in Fig. 5. Even when the unwind yaw turn is performed in RCS control, when RWA control was commanded about 30 minutes after the burn, significant RWA torque "roughness" was observed in all 3 axes and took many additional minutes to settle down. In the Z-axis, the torque roughness sometimes reached 60 milli-Nm, peak-to-peak. The cause of this vibration is likely residual oscillations in the MAG boom or the RPWS booms, although propellant sloshing could also contribute. To minimize having the RWAs experience this roughness, the ME OTM block was adjusted to allow a selectable additional settling time after the unwind yaw turn, before returning to RWA control. Fig. 6 shows RWA torque during a later OTM that had this extra settling time. The peak-to-peak torque roughness is now reduced to 20 milli-Nm or less.

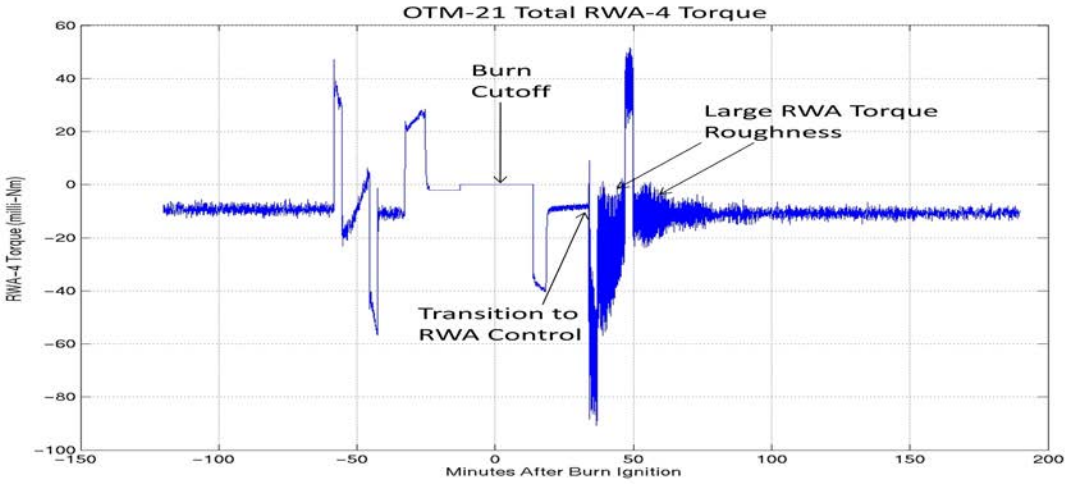

Figure 5. RWA-4 Total Torque During OTM-21. *An early OTM excited RWA torque roughness following transition back to RWA control only 30 minutes after burn cutoff.*

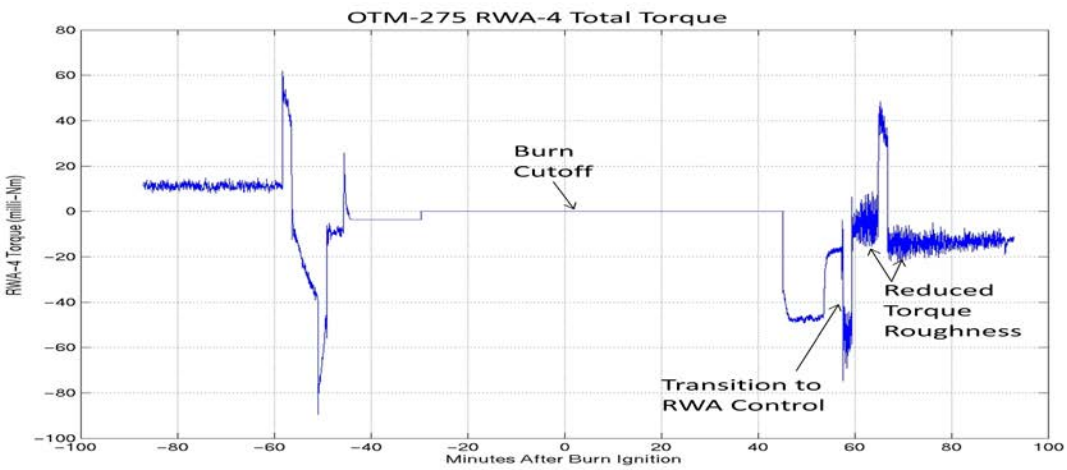

Figure 6. RWA-4 Total Torque During OTM-275. *Torque roughness is minimized by delaying the transition back to RWA control by 20 minutes.*

All main engine OTMs at Saturn have used the hardware accelerometer to sense accumulated ΔV during the burn. Burn cutoff is commanded when the desired ΔV magnitude is achieved. Prior to each main engine burn, a one-minute accelerometer calibration is performed. During the calibration, the ACC output accumulates for 60 seconds in a zero-g condition. The accumulated "counts" of the ACC (N_{ACC}) and the flight software estimate of the ACC scale factor (SF_{ACC}) are used by the flight software to compute a new estimate for the 60-second accelerometer bias calibration: ACC Bias (mm/s^2) = (N_{ACC} x SF_{ACC}) / 60. This measured bias is then used during the burn to estimate burn acceleration. The ACC bias trending has shown very good stability over the course of the mission. The ACC bias varied from a "nominal" value of 2.7 mm/s^2 by up to 10% early in the mission, but since arrival at Saturn the variation has been only about 1% from the nominal value. This reduced variation could be due to the more stable thermal environment at Saturn.

The ACC scale factor is a flight software parameter that is closely related to main engine burn execution error. Burn execution error is a measure of how closely the spacecraft achieves the desired ΔV. The ability to accurately achieve the desired ΔV is a vital aspect of Cassini mission operations and planning. For example, if ME burn ΔV execution was only accurate to 5%, the mission would have used up all of its bi-propellant years ago. If burn execution was perfect, there would be more propellant available and the mission might have lasted beyond 2017. There are a lot of factors that contribute to burn execution error, one of the most important being how accurate the on-board estimation of accumulated ΔV is. Another is the pre-ignition alignment of the engine gimbal to minimize the attitude transient that occurs after ME burn ignition. And of course orienting the spacecraft in the desired inertial direction for the burn and controlling the spacecraft attitude throughout the burn are also key to achieved burn execution.

Since ΔV is a vector quantity, burn execution error has a magnitude and a direction. The magnitude error is referred to as an underburn if the achieved ΔV is less than the desired ΔV. An overburn means the achieved ΔV is greater than the desired ΔV. The achieved magnitude could be precisely correct, but if its direction is significantly different from the desired direction, the resulting pointing error causes the spacecraft to move away from its intended trajectory. For example, a large pointing execution error from one burn might cause the next burn to be bigger than it needs to be, in order to correct for the deviating trajectory. Accurately trending execution error is vital to both planning the rest of the mission and to insuring valuable consumables are available to support it. For example, after about 18 months at Saturn and about 24 ME burns had been performed, execution error trending showed that, on average, the achieved velocity magnitude tended to be about 0.06% bigger than the ideal. To correct for this, a flight software patch was developed to increase the FSW estimate of the ACC scale factor by this amount. As a result, subsequent ME burns were even closer to the targeted burn velocity magnitude. In 2009, after another 50 ME burns, it was decided to slightly reduce the ACC scale factor by 0.02% because execution error trending showed that ME burns were slightly underburning on average.

The Cassini Navigation team is responsible for estimating the achieved ΔV for a burn, in fact for any ΔV event on the spacecraft. They use a sophisticated orbit determination model in conjuction with precise radiometric Doppler and range tracking of the spacecraft to estimate both the spacecraft's flight path and the achieved burn ΔV. Other inputs to the navigation model include optical (camera-based) navigation data from Cassini itself as well as FSW ΔV telemetry which is played back after every maneuver. Decisions are routinely made about upcoming maneuver plans, possible maneuver omission (cancellation), etc. based on the Navigation team's latest orbit determination results. The Navigation team produces a preliminary estimate of the maneuver execution error within hours to days of a maneuver but their final estimate of execution error takes several weeks or more to fully evaluate the effects of the maneuver on the downstream trajectory.

Main engine ΔV burns at Saturn range from 0.3 m/s up to about 40 m/s or more in magnitude. Execution error is expressed as a magnitude error and a pointing error. The magnitude error (V_{MAG}) can be considered a vector parallel to the direction of the desired ΔV direction (V_{CMD}). If the magnitude error points in the same direction as V_{CMD}, this indicates an underburn where the convention is V_{MAG} is considered negative for an underburn. An overburn is depicted as V_{MAG} in the opposite direction of V_{CMD}, where the scalar magnitude of V_{MAG} is a positive quantity.

The pointing error for ME burns can be depicted in two ways. One way is to find the angle between the achieved ΔV vector and the commanded V_{CMD} target. Another way is to construct a pointing error vector V_{PTG} normal to V_{CMD}. The pointing error V_{PTG} has a magnitude that expresses how far away the achieved ΔV vector is from the commanded ΔV direction. Fig. 7 depicts the relationship between these vectors and how V_{MAG} and V_{PTG} can be constructed.

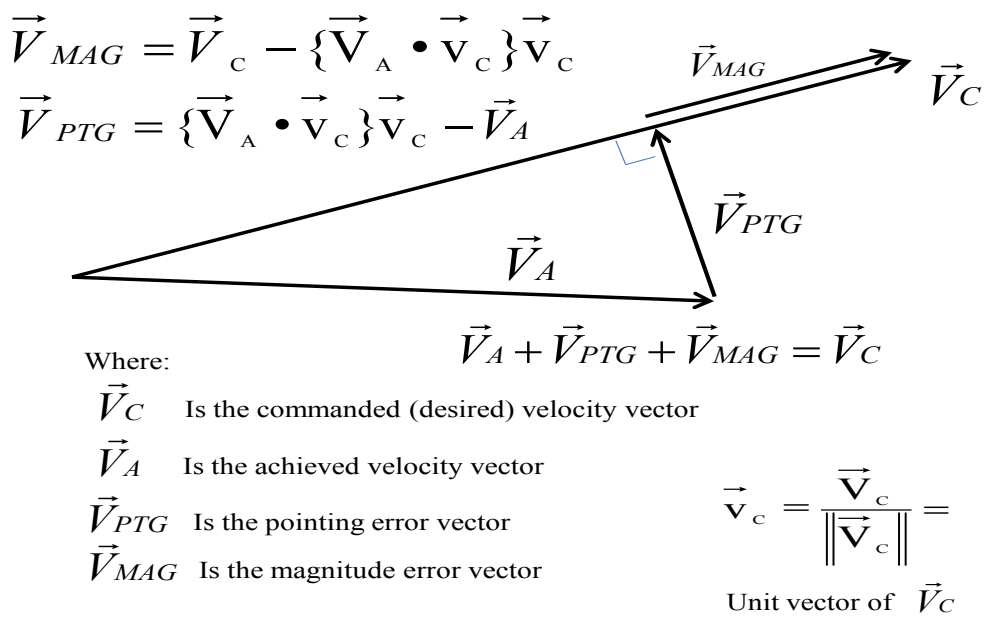

Figure 7. Maneuver Execution Errors. *Magnitude and Pointing execution error vectors are derived from achieved and commanded ΔV vectors.*

Figure 8 depicts magnitude percentage error as a function of burn magnitude ΔV for all ME burns at Saturn. The Y-axis is V_{MAG} / V_{CMD} expressed as a percentage. Very short burns tend to result in larger percentage magnitude errors than longer burns. The uncertainty in ME tailoff impulse tends to be bigger in short burns and the flight software assumes a fixed tailoff impulse. Until 2009, the flight software assumed a tailoff impulse consistent with maximum thrust achieved during pressurized burns. Since virtually all ME burns are now "blow down" burns without pressure regulation in the bi-propellant tanks, the achieved thrust and tailoff impulse tend to be smaller as the ullage pressure slowly decreases. The tailoff impulse parameter in the flight software was updated to a smaller value in 2009. Other reasons for greater magnitude percentage error for short burns include variation in post-cutoff RCS thruster firings for attitude control. Spacecraft body rates at cutoff tend to be larger for short burns because the

thrust vector control system has less time to smooth out any ignition transient. Post-burn thruster firing increases the achieved ΔV magnitude.

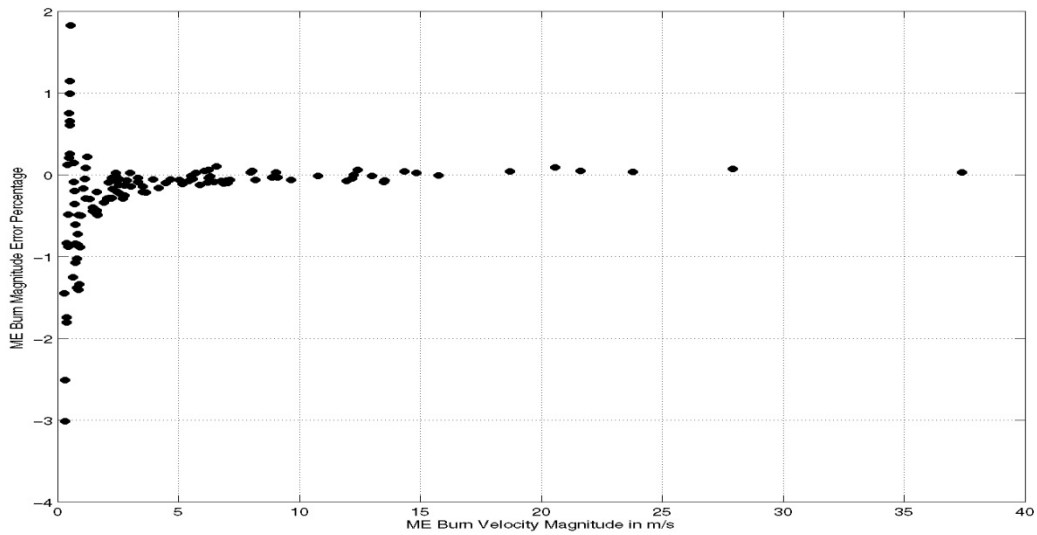

Figure 8. Main Engine Magnitude Execution Error Percentage versus ME ΔV magnitude.

Main engine pointing execution error is depicted in Fig. 9 with pointing error magnitude percentage is plotted against burn magnitude ΔV. Short burns also tend to have greater percentage pointing errors than longer burns.

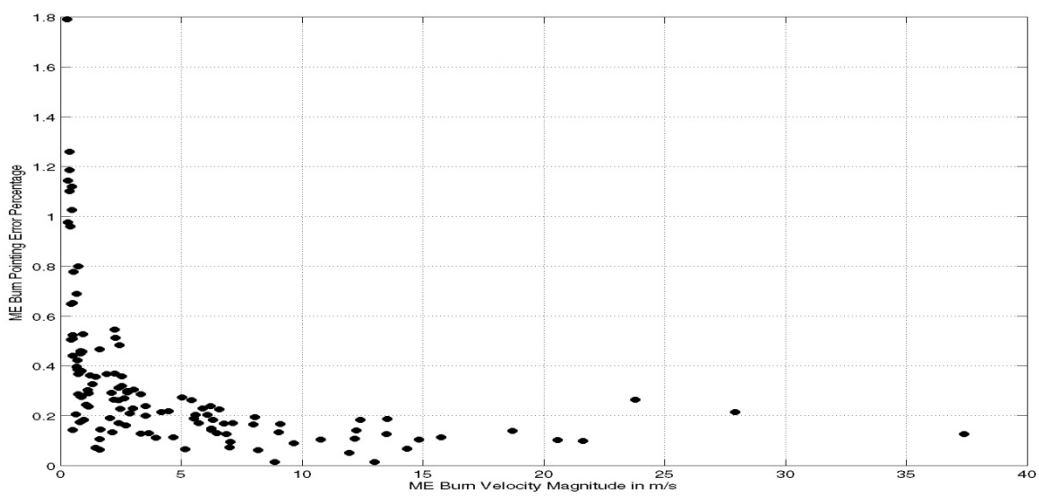

Figure 9. Main Engine Pointing Execution Error Percentage versus ME ΔV magnitude.

All ME burns tend to be more accurate if the main engine pre-aim vector is accurately chosen. The pre-aim vector is used to pre-position the engine gimbal towards the approximate center-of-mass of the spacecraft. It is also used to orient the entire spacecraft at the burn attitude so that the thrust vector points in the desired ΔV direction. AACS analysts use thrust vector telemetry from the most recent ME burn to select the pre-aim vector for the next burn. Non-linear elements in the main engine actuator gimbal assembly cause a .04 Hz limit cycle oscillation in the thrust vector telemetry as seen in Fig. 10. This oscillation is also seen in other telemetry dynamical parameters (for example, Y-axis attitude control error). Trying to construct a pre-aim vector from burn telemetry that does not span at least one complete oscillation will introduce an error. Normally, an average of the last one or two complete

oscillations (spanning roughly 25 or 50 seconds) of thrust vector telemetry of the most recent ME burn is used to estimate the pre-aim vector for the next burn. If the burn duration does not span at least 25 seconds, AACS analysts do not update the pre-aim vector.

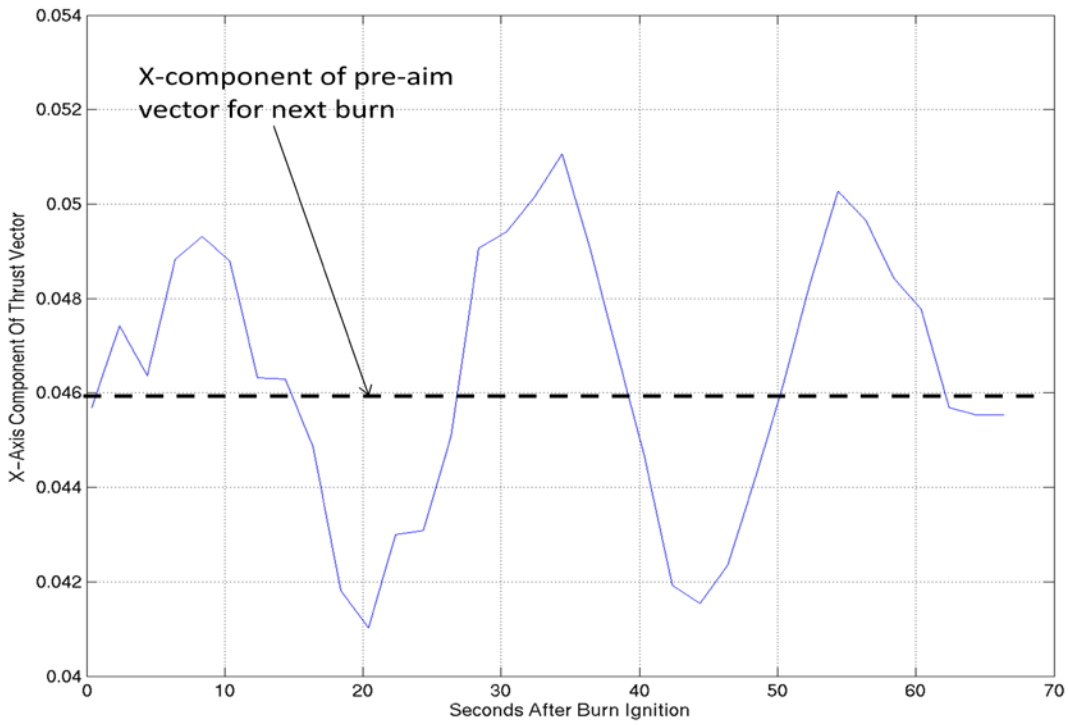

Figure 10. Thrust Vector telemetry (X-axis component) for OTM-249

The trend in the pre-aim vector as bi-propellant is slowly depleted over the years tends to track the changing center of mass of the entire spacecraft. The spacecraft center of mass was not measured pre-launch and is estimated based on a summation of many different "elements" (for example, the magnetometer boom, the main engines, the reaction wheels, etc.) including the amount of bi-propellant and hydrazine remaining. The mass properties of each element was estimated pre-launch in the spacecraft structural frame. A standard product for each OTM is the current estimated total spacecraft mass, center-of-mass, and inertia matrix, based on this analytical summation of elements as a function of propellant remaining.

Figure 11 plots the spacecraft body X-axis and Y-axis components of the pre-aim unit vector history since late 2004 and the equivalent components of a unit vector from the main engine gimbal center to the estimated center-of-mass (computed for that OTM). Although they have similar trends, there is a 11 to 15 mrad difference between the two vectors at any given time. This offset is roughly consistent with a known pointing misalignment of the rocket engine assembly. Review of pre-launch inclinometer test data showed that a misalignment of approximately 0.9 degrees was noted on the ground for the prime flight rocket engine assembly. A pointing error of about 15 mrad was reconstructed after the Cassini Deep Space Maneuver in December of 1998. Rather than attempt a risky update to complicated coordinate frame transformations in the Cassini flight software, it was decided to compensate for this misalignment, for all ME burns after December 1998, by performing a small 0.9 degree turn to adjust the commanded burn attitude a few minutes before each ME burn ignition. This small turn has been performed during all ME burns at Saturn and pointing execution errors through mid-2011 show that this method of handling the pointing bias works well.

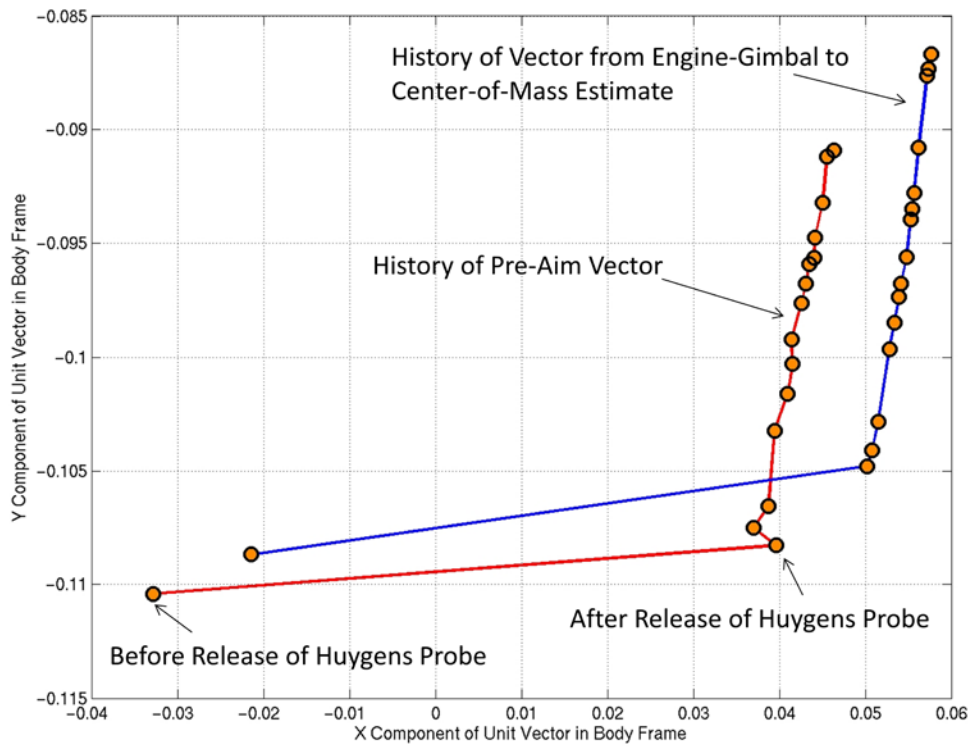

Figure 11. History of Cassini Pre-Aim Vector since 2004. *The X and Y components of the Pre-Aim vector (derived from telemetry) is plotted along with the analytically-derived "engine gimbal-to-center-of-mass" direction.*

V. Modeling Execution Errors

One method of modeling execution error is the Gates[8] method using a fixed term (e_f) and a term (e_p) that is proportional to burn ΔV magnitude. These two terms are independent so a one-sigma magnitude error is found by taking the root-sum-square of the two terms.

Table 1. Main Engine Magnitude Execution error

	2006 to 2009	2009 to Date
Fixed Error	6.5 mm/s	4.5 mm/s
Proportional Error	.04%	0%

Table 1 is based on fits of main engine magnitude execution error using the Gates model. Cassini execution error has improved since 2006 as Table 1 shows for burn magnitude error. The proportional error term has dropped from .04% to zero because in 2009 the accelerometer scale factor was adjusted in the FSW based on observed maneuver execution performance. The fixed error relates to a variety of factors, such as: (1) uncertainty in the main engine tailoff impulse; (2) uncertainty in the time delay between the last time the accelerometer was read and the time the main engine valve actually closes. One additional factor that affects the ΔV magnitude is the fact that after ME shutdown, RCS thrusters must fire to correct for any residual rates on the spacecraft, and keep the attitude control position

errors within a 2 mrad deadband. These post-burn thruster firings can impart up to 10 mm/s of ΔV in the burn direction but can vary considerably from one maneuver to the next. Main engine magnitude and pointing execution error capability has improved significantly since launch.

Figures 12 and 13 show the evolution of ME execution error performance to date.

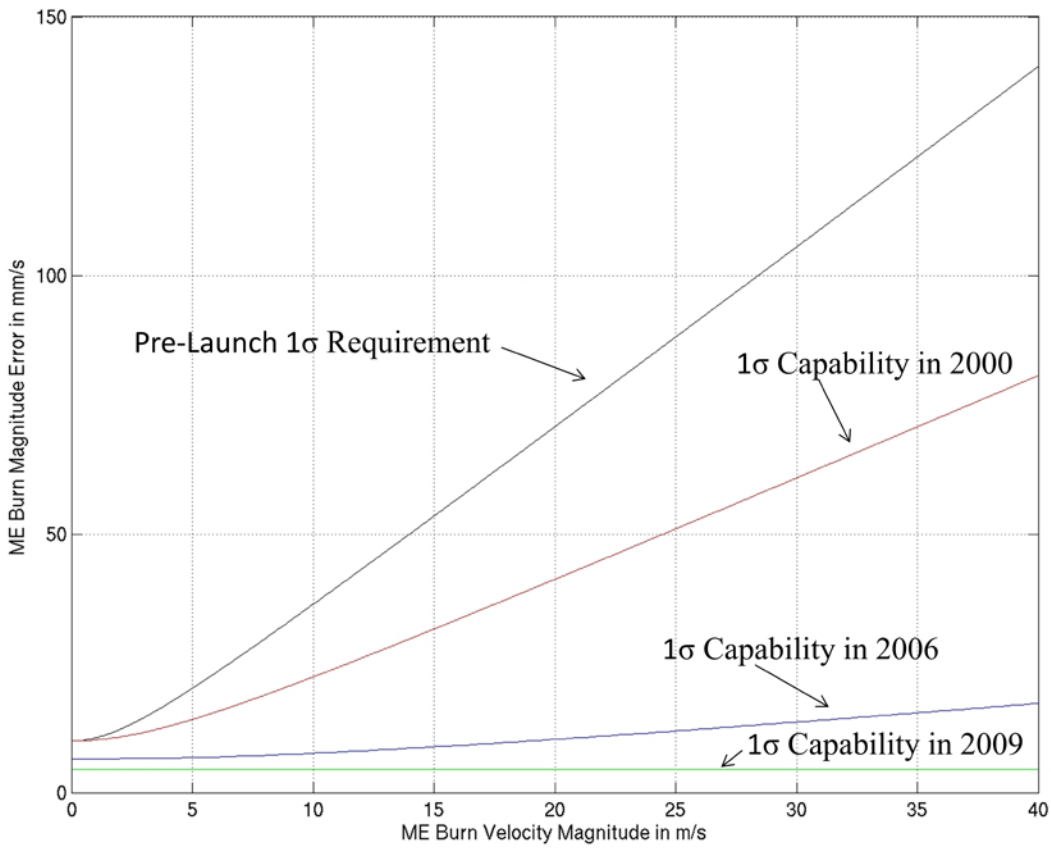

Figure 12. Main Engine Magnitude Execution Error. *Uses the best fit Gates model given flight reconstructions up to that time.*

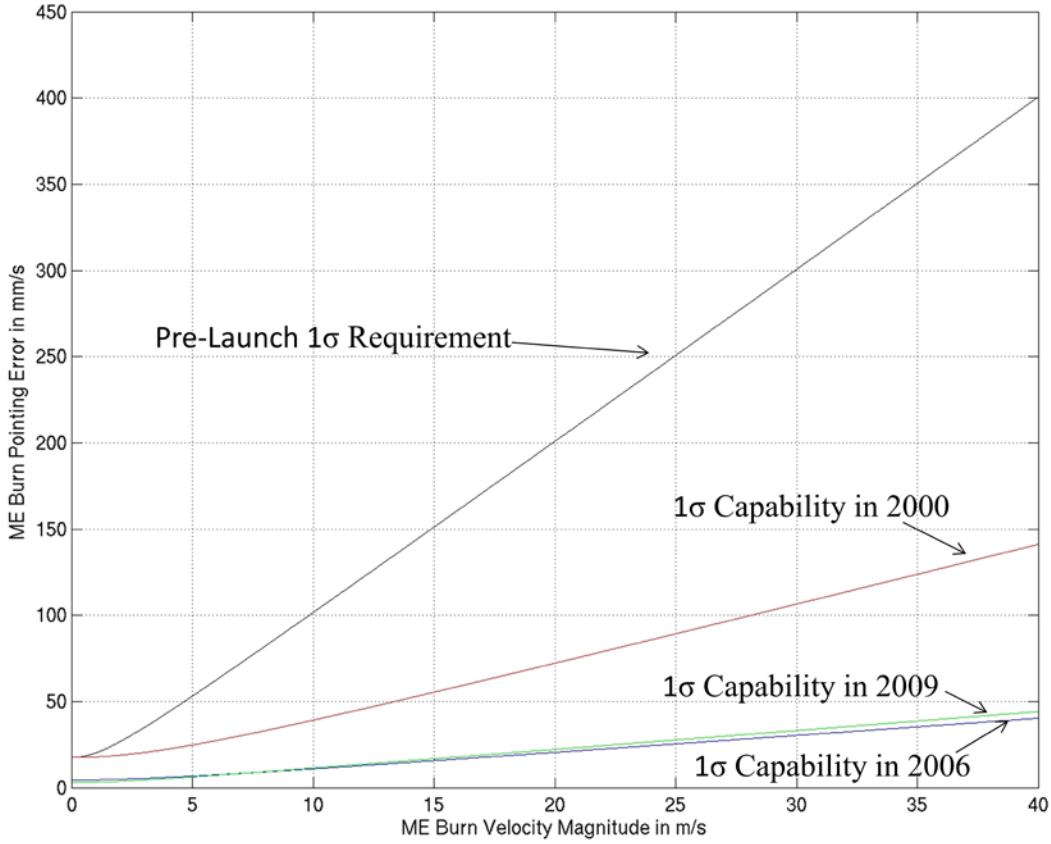

Figure 13. Main Engine Pointing Execution Error. *Uses the best fit Gates model given flight reconstructions up to that time.*

VI. RCS Maneuvers

RCS maneuvers are performed when the desired ΔV is less than what the main engine system can safely perform. The ΔV "cutoff" point, above which an ME burn is used, is discussed in Section VII. RCS maneuvers perform all maneuver roll and yaw turns in RWA control. This allows considerable hydrazine savings. Just before the RCS burn begins, a transition to RCS control is commanded and the RWAs are commanded to hold their current spin rate during the burn. No hardware accelerometer is used during RCS maneuvers (its accuracy is somewhat degraded for these low-acceleration burns). Instead, a "virtual accelerometer" is used which estimates thrust acceleration for each firing Z-thruster based on its on/off status, and on-board estimates (RCS block command parameters) of spacecraft mass and the nominal thrust for each thruster. From these quantities, the FSW computes an estimated acceleration for each firing thruster. In an RCS burn, all four Z-axis-facing thrusters are nominally firing together. Burn cutoff is commanded when the accumulated ΔV magnitude reaches the target. Without an explicit sensor, RCS burns are essentially "timed" burns where total thruster on-time is accumulated.

Attitude control deadbands of 0.5 degrees for the X and Y axes and 1 degree for the Z-axis are used during the RCS burn. When an X or Y deadband is reached, 2 of the 4 Z-thrusters pulse off to provide torque to reduce the attitude control error in that axis (if both deadbands are reached at the same time 1 of the 4 Z-thrusters pulses off).

This "off-pulsing" of the Z-thrusters is used for attitude control during the burn and is accounted for in the Delta V accumulator algorithm. Typically, off-pulsing accounts for about 10% of the burn duration (i.e. the thrusters are on about 90% of the time during the burn). Individual thrusters typically average between 80% and 100% "duty-cycle" on-time during RCS burns. The duty-cycles tend to be smaller the further away the center of mass is from the Z-axis centerline of the spacecraft.

The roll and yaw turn rates in RWA control are changeable depending on the RWA spin rate profiles during the slews. It is possible the OTM slews could cause an RWA to reach a momentum saturation rate of 2020 rpm. In that case, slowing the slew(s) could provide acceptable momentum margin. In other cases, increasing the slew rate(s) can help avoid dwelling for too long at a very low spin rate which could degrade RWA bearing lubricant.

After RCS burn cutoff, the spacecraft remains at the burn attitude for several minutes at the same deadbands as during the burn. Then the deadbands are reduced to 2 mrad about each axis in preparation for the transition back to RWA control. This deadband tightening is important for good RWA controller performance but it does introduce some additional ΔV at the burn attitude. Following transition back to RWA control, the unwind yaw turn is commanded to return the HGA to Earth-point. This is followed by the unwind roll turn to return to the initial attitude.

RCS burn magnitude execution errors at Saturn are plotted in Fig. 14. The figure depicts magnitude percentage error as a function of burn magnitude ΔV for all RCS burns at Saturn.

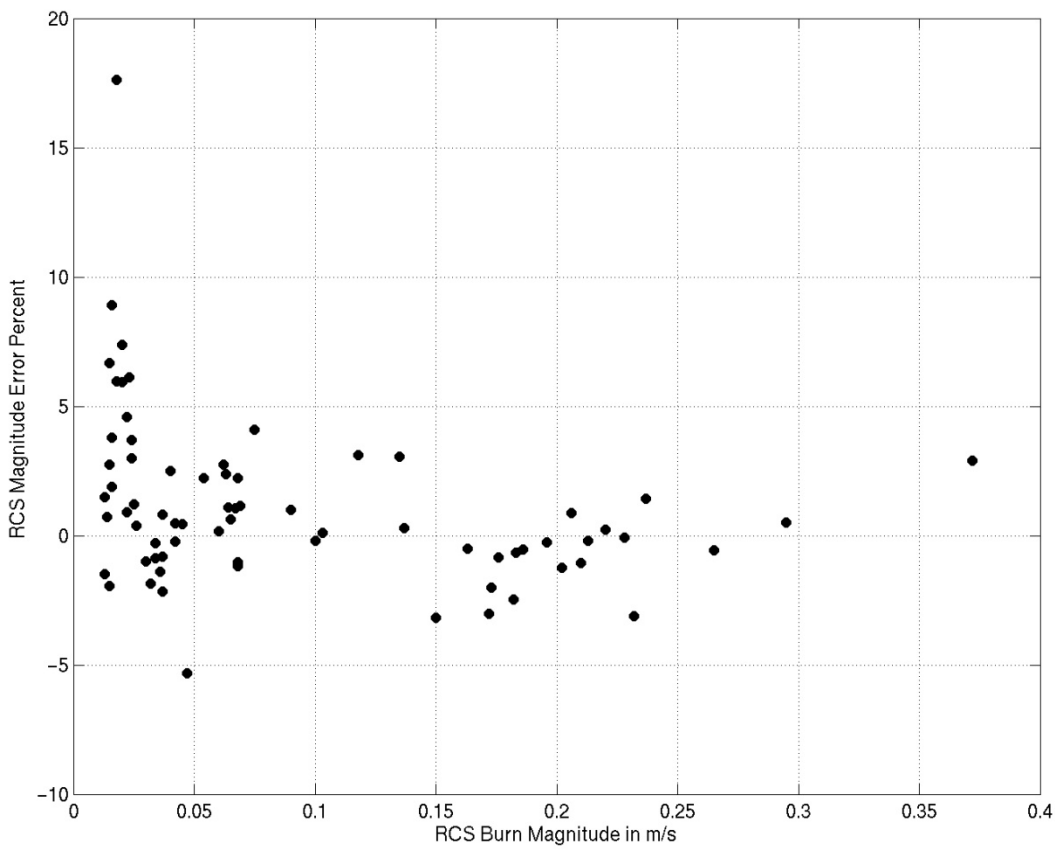

Figure 14. RCS Burn Magnitude Execution Errors at Saturn

The Y-axis is V_{MAG} / V_{CMD} (where V_{MAG} is magnitude execution error) expressed as a percentage. Because the accelerometer is not used for RCS burns, ΔV magnitude execution error is closely tied to a good FSW parameter estimate of RCS thrust force and spacecraft mass. These estimates are always updated prior to each RCS burn. There are several ways Cassini operations engineers track RCS thrust force. The first is reconstruction of the most

recent RCS burn. The Navigation team uses their orbit determination model in conjunction with precise radiometric Doppler and range tracking of the spacecraft to estimate achieved ΔV. Using Thrust = mass × (ΔV / On_Time) where mass is the best ground estimate of the total spacecraft mass, ΔV is reconstructed from Navigation, and On_Time is the total Z-facing thruster on-time from telemetry. There may be small thruster-to-thruster variations, but generally a single Z-thruster force is included in the RCS command block and applies to all thrusters for use by the virtual accelerometer in the RCS burn FSW.

AACS can also estimate thruster forces independently using thruster on-times, the Euler equation, and conservation of angular momentum during slews or RWA biases. One helpful check on thruster performance after an RCS burn is to compare the achieved RCS duty-cycles to recent RCS burns of similar duration. In October of 2008, degradation in an A-branch thruster was observed using three methods: (1) Navigation reconstruction; (2) thruster chamber pressure telemetry; (3) changes in thruster-to-thruster duty-cycles compared to prior burns. This led to the decision to swap to B-branch thrusters in March of 2009. The duty-cycles for the 4 Z-facing thrusters are seen in Fig. 15 (most recent burn is the red line in each plot).

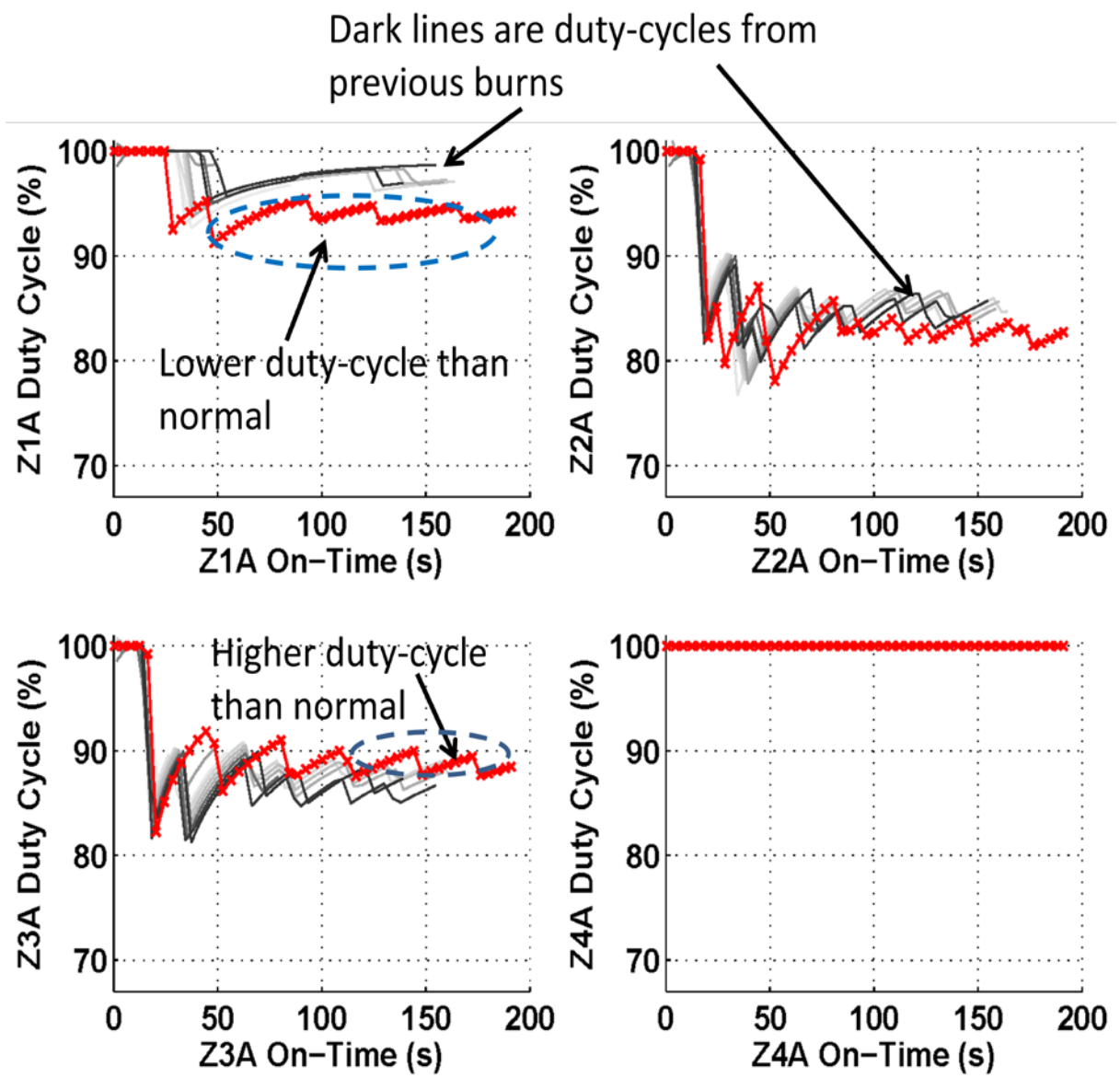

Figure 15. Z-facing thruster duty-cycles during RCS maneuvers in 2008

RCS burn pointing execution error has improved steadily at Saturn, especially compared to burns performed prior to reaching Saturn. After launch, slews to the burn attitude were performed in RCS control to save time and reduce solar heating. But the 2 mrad deadbands used caused the initial attitude to sometimes be as much as 2.8 mrad from the desired thrust direction. Once the slews began being performed in RWA control, the attitude control error at burn ignition dropped essentially to zero. This was especially helpful during very short burns.

One aspect of the RCS ΔV controller FSW that reduces pointing error is the pulse adjuster. For a given spacecraft axis, when the attitude control error reaches the deadband, the pulse adjuster will off-pulse the thrusters longer to drive the attitude control error away from the deadband. The accumulated attitude control error is used as a gain term in the pulse adjuster. The more rapidly the attitude control error reaches a deadband, the longer the off-pulse. The values of these integrators are carried over from one RCS burn to the next. This helps subsequent RCS burn avoid "riding the deadband" during the burn. This results in better pointing, longer off-pulses, and fewer total off-pulses. One RCS burn in November of 2010 had to be performed right after a FSW upload where the prime flight computer had been reset (causing the pulse adjuster attitude error gain to be reset to zero). The effect on burn performance was very noticeable: not only was pointing execution error degraded, but so was the magnitude error. The higher number of off-pulses led to greater errors in the total ΔV because of thruster impulse rise and tailoff uncertainties. Once the attitude control integrators were re-established via ground command, subsequent RCS burns were much more accurate. Attitude control errors during a recent RCS burn are plotted in Fig. 16.

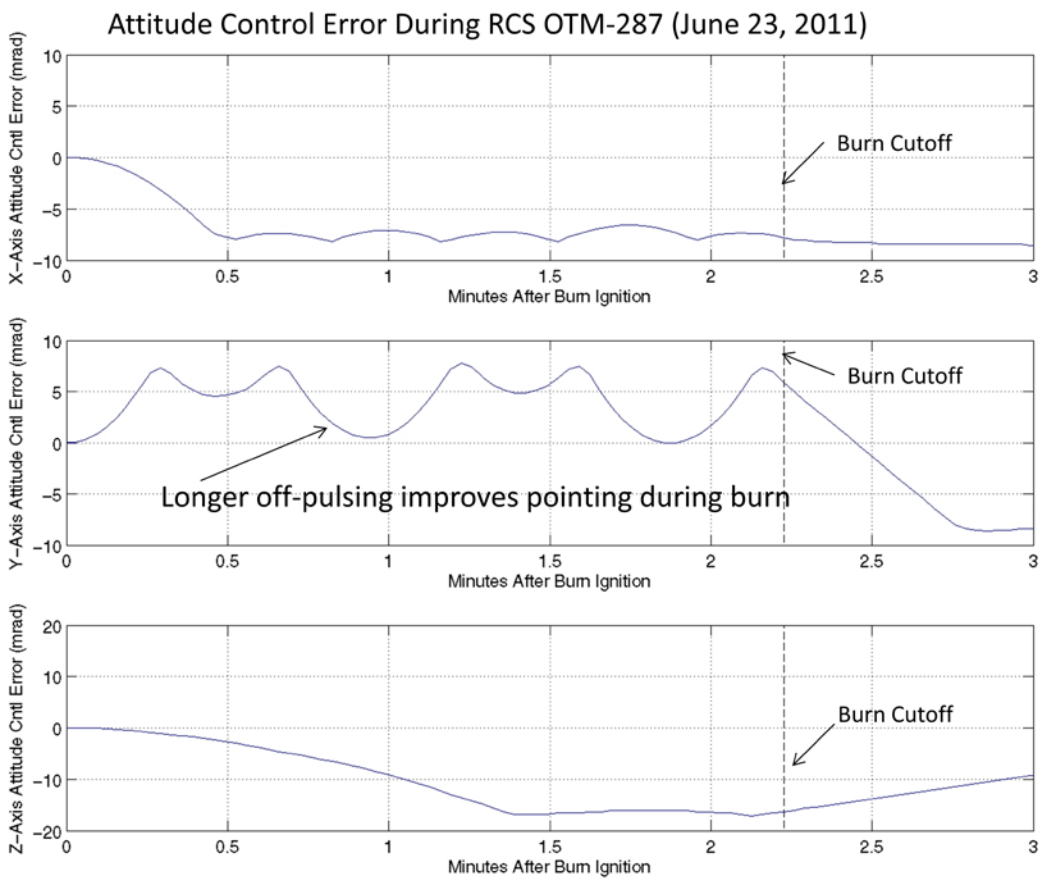

Figure 16. Attitude Control Errors During RCS OTM

VII. RCS versus Main Engine Delta V Cutoff Point

The relative maneuver execution errors of RCS versus ME burns play a role in deciding at what burn ΔV should an ME burn be implemented as opposed to an RCS burn. By co-plotting RCS and ME pointing execution error 1-sigma capabilities using current flight data, the cross-over point in ΔV magnitude above which ME burns are favored is seen in Fig. 17 to be about 0.33 m/s. The Cassini project has chosen 0.3 m/s to be the nominal ΔV magnitude cutoff point. Above 0.3 m/s ΔV magnitude, a main engine burn will be performed. Below 0.3 m/s, an RCS burn will be performed.

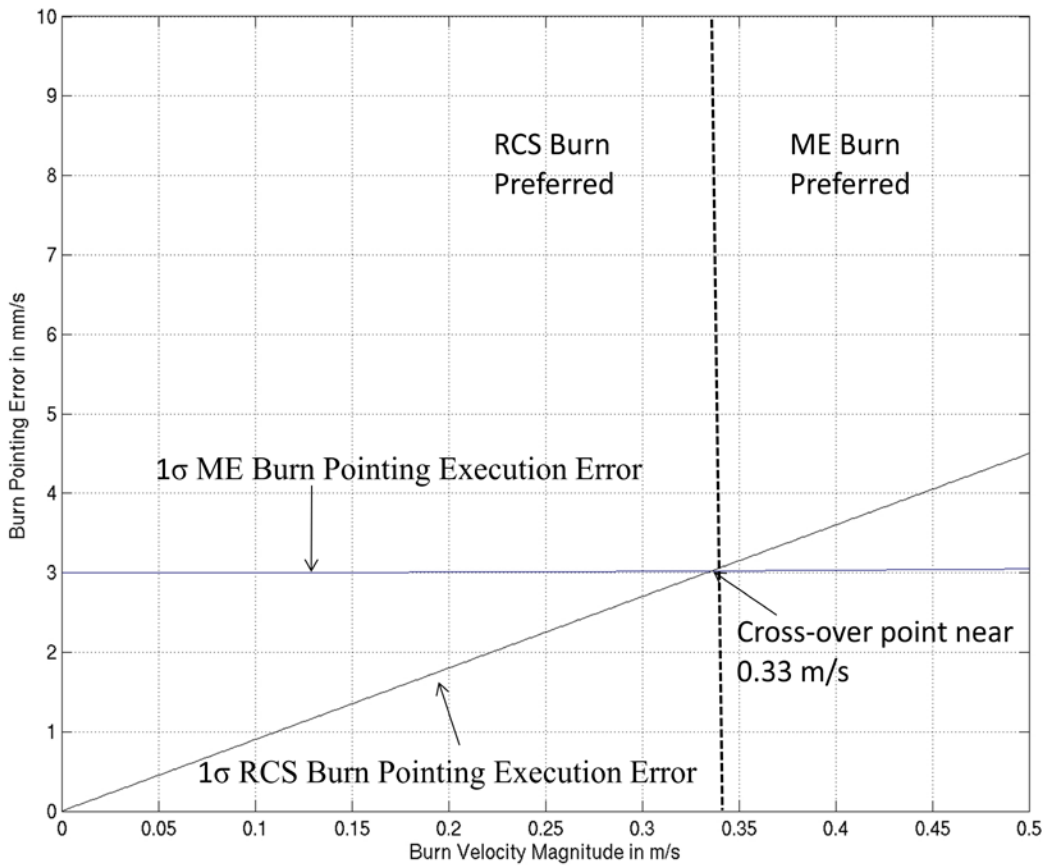

Figure 17. Overlay of Main Engine and RCS Burn Gates Model Execution Errors

VIII. Conclusions

Over 200 Orbit Trim Maneuvers have been performed since arrival at Saturn in 2004. Execution errors have significantly improved between Saturn arrival and today. For main engine burns, small adjustments to the accelerometer scale factor have helped improve magnitude execution error. Main engine pointing error has been improved by careful updating of the main engine pre-aim vector. RCS burn magnitude execution error has been improved by updating the FSW estimate of the RCS thrust force based on reconstruction of the achieved burn ΔV using navigation radiometric data. RCS burn pointing execution error has improved because the flight software uses attitude control error accumulators in the pulse-adjuster logic to keep the thrust vector more closely centered on the desired burn direction. Other enhancements include delaying the post-burn return to RWA control during main

engine ΔV maneuvers to allow dynamical oscillations to damp out (reducing the stress on the RWA hardware). These and other improvements increase the likelihood that the Saturn orbital mission can continue through September of 2017 by careful performance of perhaps 200 more ΔV maneuver.

IX. Acknowledgements

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