Cassini Attitude Control Operations – Guidelines Levied on Science To Extend Reaction Wheel Life

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The Cassini spacecraft was launched on October 15, 1997 and arrived at Saturn on June 30, 2004. It has performed detailed observations and remote sensing of Saturn, its rings, and its satellites since that time. Cassini deployed the European-built Huygens probe, which descended through the Titan atmosphere (Saturn's largest moon) and landed on its surface on January 14, 2005. The Cassini mission has recently been approved by NASA to continue through September of 2017. This 7-year extension is called the Solstice mission and it presents challenges to the spacecraft operations team and its ability to maintain the health of the spacecraft. To keep the spacecraft healthy for 7 more years, the spacecraft team must carefully manage hydrazine use (about 48% of the 132 kg launch load remains as of January 2011). A vital part of conserving hydrazine is to use the reaction wheel assembly (RWA) control system for precise pointing and slews wherever possible. In any given week, the Cassini spacecraft is commanded to use RWA control about 99% of the time, with about 1% of the time requiring reaction control system (RCS) thruster control (to perform Delta V course corrections or to bias the RWA momentum). Such extensive use of the RWA hardware throughout the mission requires that the RWAs be operated in a way that minimizes degradation in the RWA electronics, DC motor, and spin bearing for each reaction wheel. Three consumables in particular have been identified for the RWAs: (1) Total number of revolutions for each RWA. (2) Time spent at very low wheel speeds. At these low speeds, good elasto-hydrodynamic (EHD) film lubrication may be compromised. (3) Total number of on/off power cycles. The second of these consumables, minimizing the time spent at very low wheel speeds, is especially important to keep the spin bearing healthy and well-lubricated. These consumables are actively managed by the attitude control operations team throughout the mission. One vital management technique is to predict individual RWA momentum (given the pointing and slews that are needed to collect the best science) and to bias the RWA momentum in a way that reduces both the total number of revolutions as well as the time spent below EHD wheel speed. Another strategy to protect RWA health is to alter the planned pointing of the spacecraft (which can affect science collection) so that the RWA consumables are conserved. This paper focuses on why this second technique is needed, and discusses how guidelines have been developed by the attitude control team which affects the planned science pointing, so that science data can be most optimally collected while still minimizing RWA consumable usage.

Nomenclature

CAPS	=	Cassini plasma spectrometer
EGA	=	engine gimbal assembly
EHD	=	elasto-hydrodynamic
EOM	=	end of mission
IRU	=	inertial reference unit
ISS	=	imaging science subsystem
MAG	=	magnetometer
MAPS	=	magnetosphere, atmosphere, and plasma science
ORS	=	optical remote sensing

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RBOT	=	reaction wheel bias optimization tool
RCS	=	reaction control system
RWA	=	reaction wheel assembly
Rs	=	Saturn radii
SP	=	science planning
SPASS	=	science planning attitude spreadsheet
SCO	=	spacecraft operations
SOST	=	satellite orbiter science team
SRU	=	stellar reference unit
SSA	=	sun sensor assembly
XM	=	extended mission
XXM	=	extended-extended mission

I. Introduction

THE Cassini spacecraft began its interplanetary journey to Saturn with its launch on October 15, 1997 from Cape Canaveral, Florida. Its prime mission would not begin until Saturn orbit was achieved on June 30, 2004. During the Earth-to-Saturn "cruise" phase of the mission, four gravity-assist flybys (Venus, Venus again, Earth, and Jupiter) were needed to enable the 5600 kg spacecraft to reach Saturn in 6.5 years. Figure 1 shows the interplanetary trajectory of Cassini during the cruise phase along with the various flyby dates.

A few months after arrival at Saturn, Cassini deployed the 320 kg Huygens probe which successfully entered Titan's atmosphere (Saturn's largest moon) on January 14, 2005, and sent back extraordinary pictures of Titan's surface as well as characterized the thick Titan atmosphere. For the rest of Cassini's life

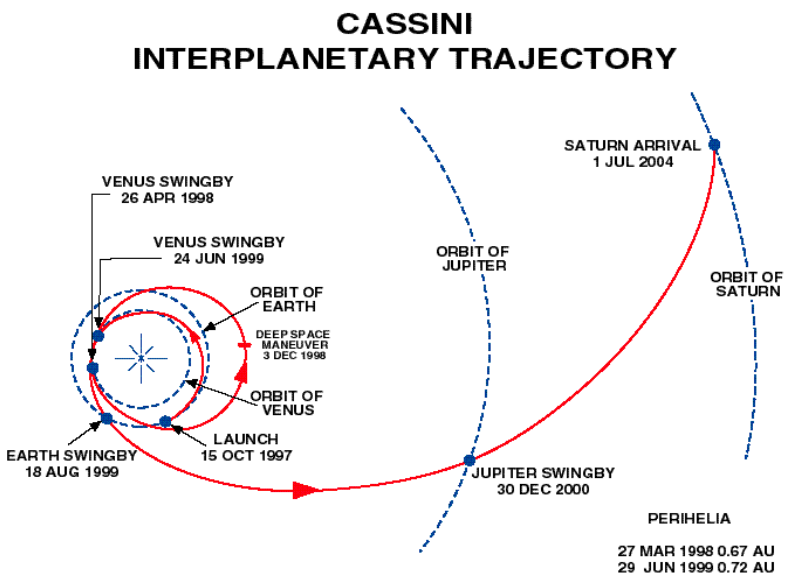

Figure 1. Cassini Spacecraft Mission Timeline

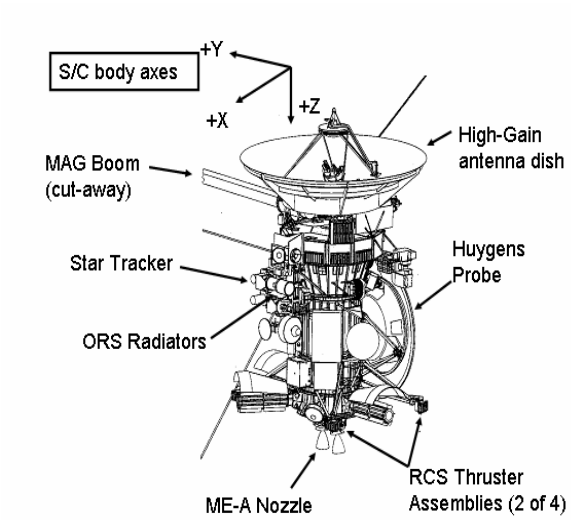

Figure 2. Cassini Spacecraft.

its mission was to orbit Saturn. Major science objectives included the investigation of the dynamics of Saturn's magnetosphere, the structure and composition of Saturn's rings, the characterization of several of Saturn's icy moons, and peering through Titan's atmosphere in order to map its surface.

A typical day in the life of Cassini consists of data-gathering which occupies about 15 hours and the remaining 9 hours are devoted to playing back the data to Earth via a 4-meter High Gain Antenna. Both science and engineering have the ability to store data on two solid-state data recorders which are played back to Earth during the 9 hour playback time. Since Cassini has no independent scan platform for science instruments (science instruments are rigidly connected to the spacecraft body) the whole spacecraft needs to move in order to target objects. Data gathering includes executing many turns to and from scientific targets, tracking these targets, and gathering data from "prime"

as well as "ride along" science instruments. In all there are 12 different science instruments on the Cassini spacecraft. The Cassini Spacecraft is shown in Figure 2.

Cassini ground operations include building "background" sequences as well as "real-time" commands. A typical background sequence is about 5-10 weeks and is usually uplinked to Cassini's stored memory about a week before its execution period begins. Background sequences include all science observation turns as well as various periodic engineering activities for the spacecraft's health and safety. Real-time commands are used for time critical events such as Orbital Trim Maneuvers, which need up-to-date orbit determination.

Cassini is set to end its mission on September 15, 2017 with a farewell plunge into Saturn's atmosphere. The final 4 and a half months of the mission will be dedicated to viewing the Saturnian system from inside the ring plane. Currently all orbits of Saturn are placed outside the rings with a periapsis no closer than 2 Saturn Radii (Rs), approximately 120,000 km. Cassini uses Saturn's largest moon Titan to change its orbital trajectory. The final close flyby of Titan will move the spacecraft's descending node from just outside the F ring (one of Saturn's outer rings) to within a 3000 km wide gap between Saturn's upper atmosphere and the innermost portion of the main rings believed to be a safe environment for spacecraft traversals. The spacecraft will complete 22 proximal orbits (roughly one orbit per week) at a periapsis from 1700 to 4300 km above Saturn's cloud tops. This mitigates any risk associated with the spacecraft's survival in the region by ensuring eventual Saturn impact without the need for any spacecraft maneuvers during the entire proximal orbit period which satisfies potential Cassini Planetary Protection requirements.

II. Spacecraft Status

Cassini has recently entered into an extended-extended mission phase (a.k.a. Solstice mission, XXM) having completed its primary 4-year tour of Saturn and its moons and its 2 year extended mission (Equinox mission, XM). Most of the spacecraft science instruments and engineering components are working nominally. Spacecraft engineering components include: 3 fixed RWAs, 1 backup articulatable RWA, 2 bipropellant Engine Gimbaled Assemblies (EGAs), 8 prime monopropellant thrusters along with 8 backup monopropellant thrusters, 2 Inertial Reference Units (IRUs), 2 Stellar Reference Units (SRUs), 1 single axis accelerometer, and 2 Sun Sensor Assemblies (SSAs). Currently, only the backup monopropellant thrusters and the backup RWA are being used due to degraded performance of the prime units. No primary components have completely failed. Cassini's engineering components can be seen in Figure 3.

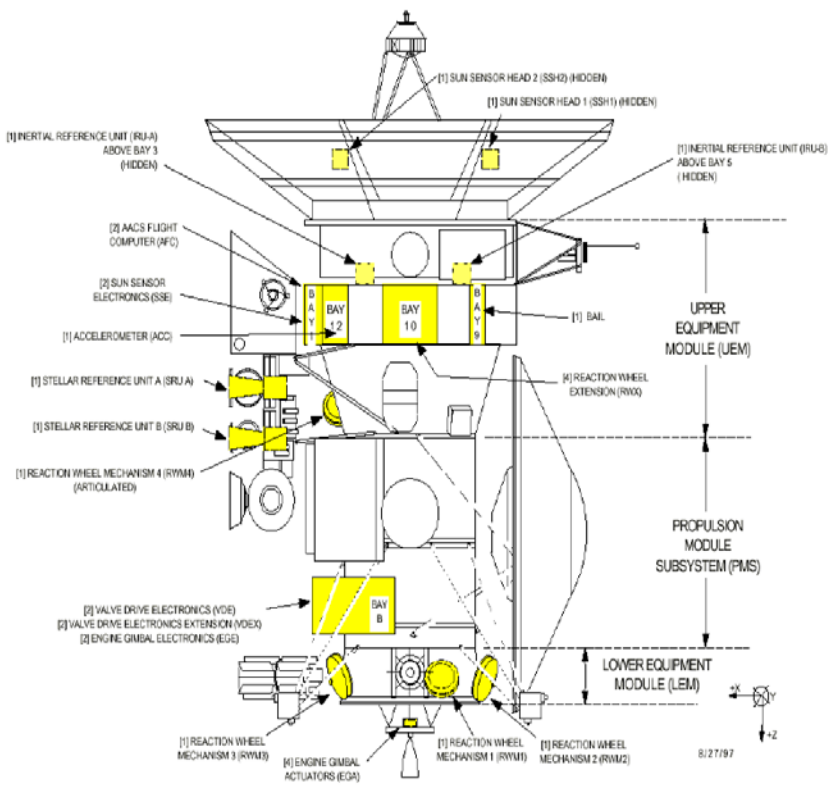

Figure 3. Cassini Engineering Components

Cassini uses two types of propulsion systems: bipropellant Main Engine (ME) propulsion and monopropellant Reaction Control System (RCS). Currently, as of June 27, 2011 Cassini holds about 4.7% of its bipropellant (89.0 kg of Nitrogen Tetroxide and 52.6 kg of Monomethylhydrazine), and about 47% of its monopropellant (61.5 kg of hydrazine) with respect to prelaunch load. Ideally, Cassini should run out of bipropellant fuel and oxidizer at the same time. Maneuvers have two components of change in velocity (delta-V, ΔV): a deterministic (or pre-planned) component and a statistical component required to clean up dispersions to maintain the correct trajectory. Cassini can execute maneuvers using either the main engines or the RCS thrusters.

Generally, ΔVs larger than a crossover point, currently at 0.3 m/s, are done with the ME thruster since it has higher thrust than the RCS thrusters and can impart a higher ΔV in a shorter period of time. RCS thrusters are used for attitude control instead of RWAs during ME maneuvers, low Titan flybys, RWA momentum biases, some radio science experiments, during safeing conditions, and during friction tests of the RWAs.

Cassini has a total of 4 RWAs. The RWA numbers 1-3 are the fixed primary RWAs, RWA-4 is a backup RWA made to articulate to replace any of the other 3 RWAs in case any one of them were to fail. Currently, Cassini is using its articulatable backup RWA-4 to replace RWA-3. The backup RWA-4 has been articulated to align itself with RWA-3 and RWA-3 has been shut off. In 2001-2002 during the early phase of the outer solar cruise, RWA-3 began showing signs of bearing cage instability. Cage (sometimes called a retainer or pocket) instability is an uncontrolled high frequency vibration of the bearing cage that can produce high-impact forces internal to the bearing. In many cases, cage instability causes bearing torque changes and has an adverse effect on the performance of the reaction wheel. As a result, the affected reaction wheel was replaced by the articulated reaction wheel on July 16, 2003. A study conducted by the Cassini Operations Team found that long dwell times in low wheel spin rate regions can create a concern for proper reaction wheel lubrication increasing the chances of cage instability. The bearing spin rate recommended by the manufacturer for the Cassini reaction wheels for achieving the full elasto-hydrodynamic condition is estimated to be 300 to 550 rpm. In addition, the peak wheel spin rate is limited to 2020 rpm. As a result, a Reaction Wheel Bias Optimization Tool (RBOT) was developed for optimization of the reaction wheel management for Cassini mission operations[1]. This tool was designed primarily to minimize low spin rate dwell time as well as reducing high spin rate in order to minimize total wheel revolutions. Currently, RWA numbers 1, 2, and 4 are coming close to reaching life expectancy but are still going strong. RWA-3, having been shut off, is further from life expectancy.

A. RWA Consumables

The Cassini spacecraft operations (SCO) attitude control team must carefully manage total RWA revolutions and time spent at very low wheel speeds. The spacecraft operations team has been tasked, during the Solstice mission, to maintain the spacecraft and its consumables in accordance with a "midlife" spacecraft. Table 1 below shows usage of RWA consumables as of October 2010, predicted usage through the end-of-mission (EOM) in 2017, and the pre-launch specification values.

Table 1. Status of RWA Consumables as of Oct. 2010

Consumables	Current Value	Forecasted 2017 EOM	Specification	Units
RWA Revolutions				
RWA-1	3,230	6,400	4,000	Millions
RWA-2	3,220	6,340	4,000	Of
RWA-3	516	516	4,000	Revolutions
RWA-4	2,740	5,750	4,000	
RWA Low-rpm Time				
RWA-1	7.219	8.258	12.0	Thousands
RWA-2	7.430	8.770	12.0	Of
RWA-3	3.343	3.343	12.0	Hours
RWA-4	3.868	5.317	12.0	

III. RWA Bias Implementation Process

The RWA bias implementation process starts with science teams sending pointing files to the science planning team which integrates the pointing files into one continual sequence. The spacecraft operations team then includes engineering activities such as maintenance activities. The Attitude and Articulation Control Systems team (AACS) process the sequence using RBOT and biases are placed to minimize the RWA cost function and to minimize problem sections (sections in which any one of the RWAs spend over 30 continuous minutes below the sub-EHD wheel speed). RBOT was initiated in early 2002 to insure minimization of sub-EHD operations and lessen metal-to-metal contacts between the bearing balls, races, and cage (see Figure 4). The tool helps AACS uplink engineers determine optimal placement and momentum settings throughout each science sequence.

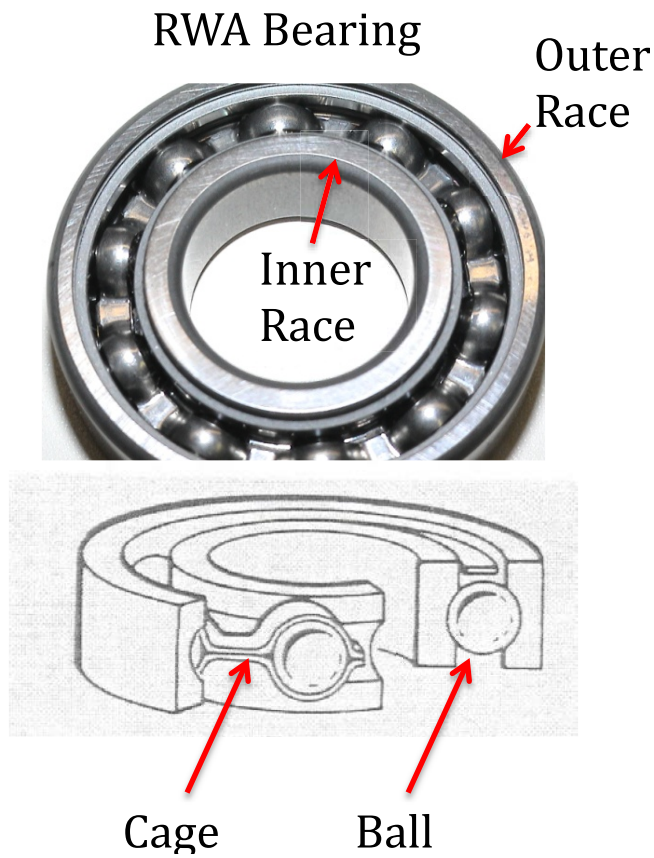

Figure 4. RWA bearing assembly

Unlike most nadir-pointing, earth-orbiting satellites RWA biasing is not mainly driven by momentum desaturation, but instead by the need for the RWAs to stay clear of the low and high rpm avoidance zones. In common earth orbiting satellites external forces due to solar, atmospheric, and gravity gradient torques drive the need for momentum desaturation of the RWAs once the wheels obtain a high enough speed. Often times the momentum build up on the RWAs can regularly be predicted and biasing desaturation times can be scheduled since the magnitude and direction of the external torques is known. Cassini RWA momentum management differs in that the whole spacecraft moves to track one object (such as Saturn) and then may move and track another object (such as Saturn's rings or Cronian moon). This spacecraft motion in inertial space causes a transfer of spacecraft momentum from one RWA to another. Biases performed on Cassini are primarily used to manage the high and low speeds of the RWAs in a segment. Segments are defined as the time between RCS events when the spacecraft is under RWA control. A segment's length can vary depending on the time durations between RCS events such as the time between one ME maneuver and another ME maneuver or the time between a ME maneuver and a low Titan flyby (below 1300 km) in which the spacecraft is forced to go into RCS control to combat the rapid build up of momentum due to external drag torque caused by Titan's atmosphere on the spacecraft.

RCS events such as ME maneuvers and Titan Flybys are known as "hard stops" because the spacecraft is forced to enter into RCS control at these time periods. Hard stops usually allot some time for the AACS Uplink Engineer in charge of each sequence to place a momentum bias to alleviate the problem wheel speeds in the following segment. However, problems associated with high and low wheel speeds may cause an AACS Uplink Engineer to decide that an intermediate bias is needed between the hard stops as is often the case close to periapsis when the science teams need to move the spacecraft over a wider swath of sky (to track objects of science interest) as the spacecraft skirts past Saturn with an increased angular speed. Sometimes multiple intermediate biases are needed between hard stops. The Cassini Project has decided to limit the overall number of biases to 5 per orbit. This was done in order to manage hydrazine usage and insure the mission will have enough hydrazine to last until the September 2017 end of mission. Often times the AACS Uplink Engineer will not need to use the fully allotted biases making the 5 biases per orbit guideline a conservative estimate of total biases and likewise the overall hydrazine usage.

A. The RBOT Design Process

The RBOT process first starts off with the AACS analyst running the RBOT program and coming up with a list of known solutions for the wheel speeds between each segment which initially are bracketed by only hard stops. The tool uses a cost function to penalize undesired spacecraft momentum biases while an optimal solution is found by solving the minimum cost function within the constraints of RWA momentum capability. The cost function is a weighted index as a function of wheel speeds. The objective of the cost function is to heavily penalize sub-EHD wheel speeds while also minimizing the total number of revolutions of the RWAs. The minimum cost RWA speed is dependent on the characteristics of each reaction wheel and may change due to each reaction wheel's behavior but currently this minimum speed is around 550 rpm. A cutoff line at 1850 rpm exists for each RWA so as to not allow

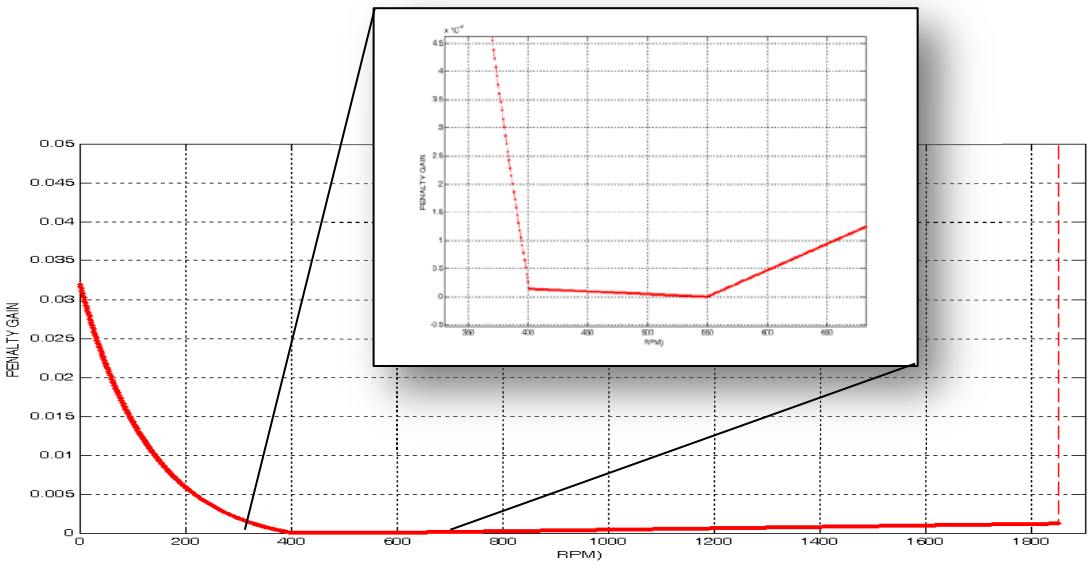

Figure 5. RBOT cost function

any reaction wheel to achieve over 1850 rpm. This includes a built in buffer of 170 rpm as the maximum rated speed of each RWA is 2020 rpm. At 2020 rpm the AACS fault protection flight software will initiate an autonomous reaction-wheel-to-thruster transition when a "high rpm" condition is detected. The 1850 rpm limit provides a margin for the uncertainties not included in the wheel speed modeling equation such as solar torque[1]. Figure 5 shows an example of a cost function which graphs the cost penalty versus the RWA speed.

After the analyst gets back the first set of solutions for each segment there is a process by which the analyst chooses where to place additional biases to help alleviate any areas in which a wheel may spend excessive amounts of time below the sub-EHD region. The additional biases cause another iteration of running the RBOT program and in turn RBOT usually comes out with a better set of solutions that both reduce the overall cost and the continuous time spent in low rpm (sub-EHD region). However, while adding biases helps reduce problem segments it does not eliminate all the problem segments in the sequence. In order to eliminate the problem areas inside each segment some alterations to the planned pointing are needed which may affect science data collection but are necessary to help reduce the time in which the RWAs are in the low rpm region.

B. Altering Science as Part of the RBOT Design Process

While the RBOT program does its best to minimize harm to the reaction wheels sometimes this tool does not adequately reduce all low rpm dwell times. On average one momentum bias is performed every 3-6 days onboard the spacecraft. Every 3-6 day period there are dozens of science observations all of which require pointing in many different directions. The combination of multiple pointing directions along with each RWA's momentum limit results in a major challenge for RBOT in reducing low rpm dwell time. Currently it is up to the AACS uplink engineer to find troubled low rpm regions and change science pointing in order to push the affected RWA through the low rpm region or out of the low rpm region completely. If any RWA's speed is within the ±300 rpm region for more than 30 minutes or within the ±100 rpm region for more than 20 minutes an effort is taken by the AACS team and the affected science team (the science team that is prime during the RWA low rpm dwell time) to come up with

a solution. Many solutions have been devised to solve these low rpm dwell time problems. Some solutions include: offsetting the science instrument's secondary axis, eliminating downlink rolls or reversing the downlink rolls, decreasing the velocity rates of some slews while simultaneously increasing the slew acceleration limits.

Changing the prime science instrument's secondary axis is the second most readily used method for correcting low rpm regions outside of adding additional biases. During sequence development, science instruments determine their boresight pointing attitude as well as a secondary attitude. Most of the time, these secondary attitudes are not critical in retrieving science data. A simple rotation about the boresight usually can bring the problematic reaction wheel or wheels out of the low rpm region (see Figure 5 & 6).

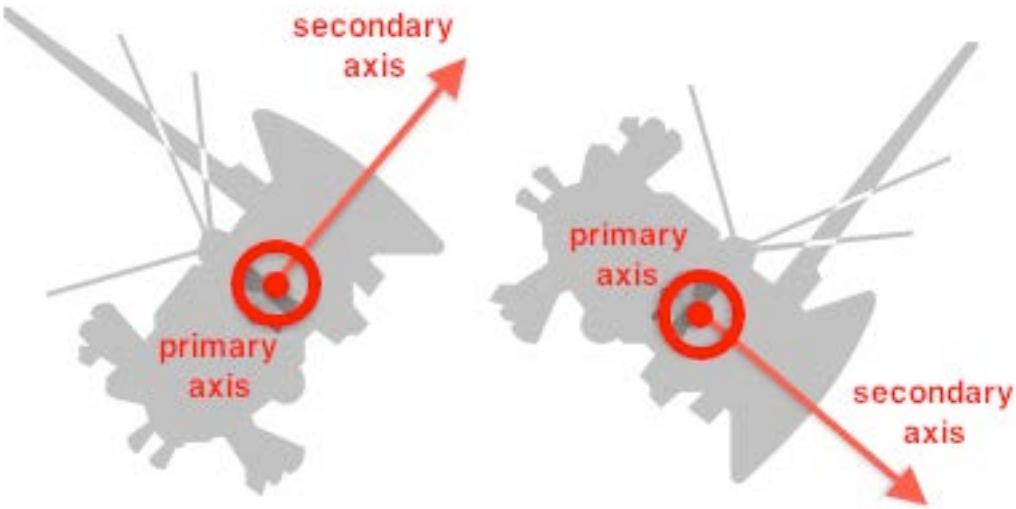

Figure 5. (Left) Cassini spacecraft showing primary and secondary axis. (Right) Cassini spacecraft showing an offset of the secondary axis while maintaining the primary axis (out of the page).

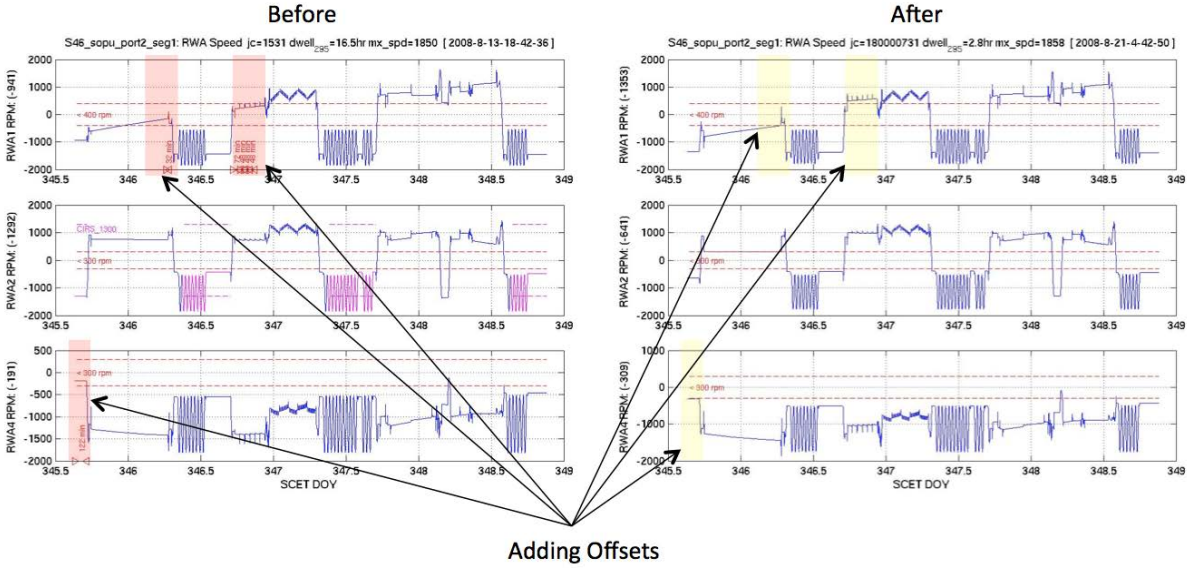

Figure 6. Both Graphs show RWA-1, 2, and 4 wheel speeds throughout a segment duration. (Left) Shows the beforehand RBOT segment with multiple problem areas. (Right) Shows the same RBOT segment but with secondary axis offsets design to push the problem areas out of low rpm.

About 9 hours out of each day Cassini spends downloading data back to Earth via its 4-meter High Gain Antenna. Often times this downlink activity actually involves rolling the spacecraft about the radio frequency boresight allowing Cassini to collect magnetic field science data from its magnetic boom simultaneously. These rolls take the spacecraft through a large angle turn causing more momentum space to be used which sometimes

results in more problematic RWA segments. By eliminating the rolls or reversing the rolls' direction a clearer segment can result (See Figure 7).

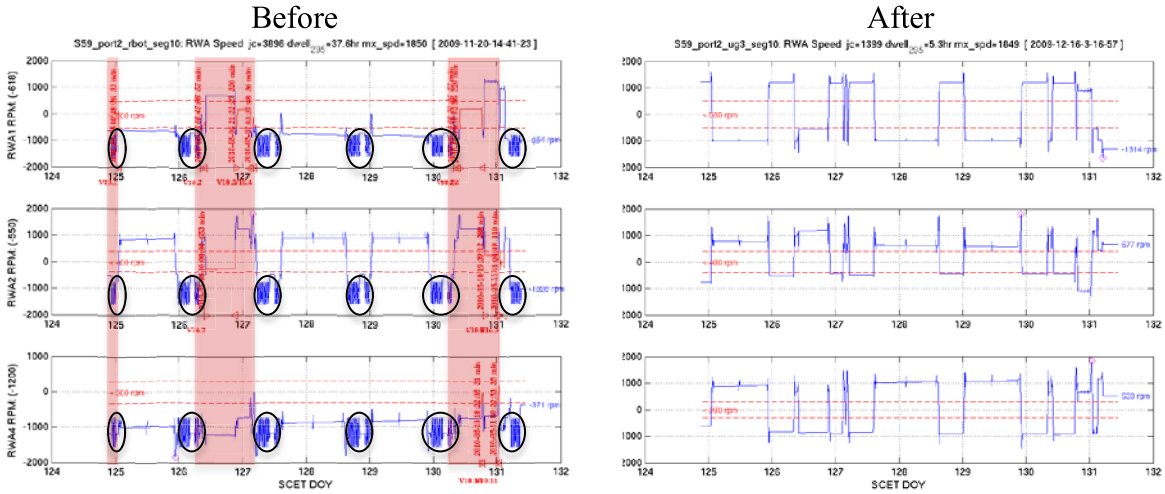

Figure 7. Both Graphs show RWA-1, 2, and 4 wheel speeds throughout a segment duration. The red indicates problem sections while the black ovals indicate where the spacecraft is rolling. (Left) Shows the beforehand RBOT segment with multiple problem areas. (Right) Shows the same RBOT segment but with all the downlink rolls removed. The RBOT program is allowed to reoptimize which results in a solution free of problem areas.

Another method of reducing the low rpm dwell times is by decreasing the velocity rates of some slews while simultaneously increasing the slew acceleration limits. By reducing the spacecraft velocity, a trade off is made between the spacecraft's momentum and the reaction wheels' momentum which can reduce the high RWA speeds. After reducing the high RWA speeds, RBOT can be rerun in order to reoptimize. This in turn can allow problematic low rpm regions to move into higher rpm regions. This method can cause problems when one attitude slew bumps into another attitude slew or runs into science observation time due to the slowing down of the slew. If it is found that the slowing down of the slew causes interference, the slew acceleration can be increased to the maximum acceleration limit, which reduces the time needed to slew. If there is still an interference problem, AACS can work with the science observations to carve out more time in order to complete the slew. This method is used the least, due to the potential interference problems, but sometimes proves useful.

C. Evolution of the RBOT Design Process

Over time the RBOT process has changed and adapted in light of AACS's growing concern over RWA bearing wear as well as the science teams' abilities to address the need to design RWA friendly pointing observations. The RBOT process initially started with the creation of the RBOT program designed only to optimize the wheel speeds of each RWA for each sequence. This program was used by AACS to obtain the best initial bias wheel speeds for each segment. During the beginning of the prime mission (July 2004 until April 2008) the focus was on maximizing science return and there was not a lot of interest in limiting science for the sake of the RWAs. Towards the middle of the prime mission there grew increasing concerns over long continuous time spent in the low rpm (sub-EHD) region despite the fact that the RBOT program was optimizing the wheel speeds to the best of its ability. RWA-1 in particular was showing elevated drag torques at low rpm. At first the approach was to start to add more biases around troubled segments which would alleviate some of the continuous low rpm time regions. Over time these extra biases became a concern because each additional bias consumed hydrazine and plans for an extended mission depended on having enough hydrazine to keep going. It was at this time that the 5 biases per orbit rule went into effect.

The AACS team along with the Cassini project managers decided that more needed to be done to limit each RWA's time spent in low rpm. The AACS team decided to solve this problem with two different solutions. One approach was to change the cost function which RBOT used to calculate how much to penalize low rpm. The cost function initially set by AACS penalized low rpm and high rpm in a way that was intended to consume the RWAs' low rpm dwell time and total revolutions at a rate that was proportional to the specification limits given by the RWA manufacturer (see table 1). Since low rpm was deemed a greater priority than the total revolutions of the wheels, the

RBOT cost function was modified to more heavily penalize low rpm dwell times. The second approach was to focus on continuous low rpm dwell time. Two criteria were used to indicate what would constitute a continuous low rpm dwell problem. First any RWA that dwelled within ±300 rpm for over 30 minutes was deemed to be problematic. Second any RWA that dwelled within ±100 rpm for 20 minutes was deemed to be problematic as well.

Overtime the low rpm region for each RWA has changed. In April 2008 AACS determined a need to increase the keep out region for RWA-1 to ±400 rpm while RWA-2 and RWA-4 would remain at ±300 rpm. The need for this increase was caused by elevated friction of RWA-1 at rpm regions between ±300 and ±400 rpm. This rule only affected the first criteria but left the second criteria alone. In March 2010 AACS decided to raise the keep out regions for RWA-1, 2, and 4 to ±500, ±400, ±300 rpm respectively. This was due in part to more elevated friction seen in RWA-1 and some concern over cage instability in RWA-2. The increase in the keep out region greatly affected how many problem areas there were in any given sequence. The work load created due to the new rule sometimes resulted in an inability for AACS to extensively manage science pointing for all the problematic sections and more science observations needed to be truncated or removed entirely from a segment. In March 2011, after seeing more elevated drag in RWA-1 above the ±500 rpm region AACS sought guidance from tribologists from the Aerospace Corporation. The tribologists indicated that an increased rpm could cause higher energy contact between the bearing ball and race or the bearing ball and cage which may lead to an increase in congealment of the bearing lubricant. For this reason, AACS decided to lower all 3 primary RWA (RWA-1, 2 and 4) low rpm regions back down to the original ±300 rpm. In so doing RWA-1 in particular incurs more elevated friction events but in turn each event is at a relatively lower energy level thereby, AACS hopes, prolonging the lubricant's effectiveness. Also in March 2011 the backup RWA-3 was put back into the prime set of RWAs for the entirety of the sequence #67 (S67, spanned 10 weeks in duration). This was done in order to test the condition of RWA-3 which has not run since the cage instability events back in 2003. The purpose of this test was to determine which RWA seemed to be in better running condition RWA-3 or RWA-1. The test found no significant improvement in RWA-3 behavior thereby clearing the way for RWA-1 to remain in the prime set for the foreseeable future.

In order to limit any continuous low rpm dwell time, AACS needed to alter science pointing. Various methods were used to alter science. At first the focus was on altering the specific science observations that placed any RWA into a continuous low rpm region but other methods such as eliminating downlink rolls and truncating sections of science observations were used if they were deemed useful. A process was devised in order to deal with the back and forth communication that was needed between AACS and the various science instrument pointing designers. A group within the Cassini program who focus on the integrations of science activities called Science Planning (SP) took the lead on devising strategies to cope with the newly formed guidelines. These strategies were also used to bridge the information gap between the AACS engineers and the science community. This process evolved over the years to include regular "RBOT meetings" as well as an effort by SP to force the science community to establish what they deemed as the most high priority science for each sequence. Science teams were also asked whether or not each science observation's pointing could be altered and what types of pointing alterations were deemed acceptable. This type of knowledge helped the AACS team optimize RBOT solutions that minimized alterations to high priority science. In the event that a lower science observation needed to be completely removed to save a higher science observation SP devised a "Triage Meeting" in which the appropriate scientist could be included in the attempt to expedite and resolve any problem in a segment thereby saving the AACS analyst critical time and effort needed to complete safe RBOT solutions. Various other triggers would warranta triage meeting. Those triggers were:

1) Any single observation for which extensive work did not result in wheel safe pointing
2) Any individual segment with a large number of problematic observations
3) A total load of problems that had the potential of taking too long to completely resolve

The triage meeting in these cases would work to alleviate the burden on the AACS analyst from having to deal with splintered communication from various science teams as well as point the AACS analyst to the most important science objectives.

IV. Guidelines and Constraints Levied on Science

Towards the middle of the prime mission AACS realized that there were some basic rules that each science team could use when developing their pointing sequences which could help RBOT minimize the amount of low rpm areas in any given segment. Individual science teams were also concerned with how many alterations and redeliveries were needed for their pointing sequences. So in 2008 AACS together with SP decided to establish a guideline and constraints document for the science teams to follow during integration of the sequences. This document would be

beneficial in helping the RBOT process flow more smoothly. Establishing a general guidelines and constraint document proved to be challenging. First, AACS and the science teams have opposing objectives. When designing a sequence that is best suited for the RWAs in terms of wear on the bearing, it is best for the sequence to be completely devoid of slews thereby maintaining constant RWA speeds similar to the conditions of most nadir-pointing, earth-orbiting satellites. However, generally most science teams would like to have the flexibility of pointing anywhere in the sky at any time in order to remotely observe key phenomenon. Secondly, the various science disciplines have different pointing regiments for the spacecraft. For instance the Satellite Orbiter Science Team (SOST) may want to observe several Cronian moons such as Enceladus, Mimas, and Tethys with the Imaging Science Subsystem (ISS) while in the same sequence the Magnetosphere, Atmosphere, and Plasma Science (MAPS) team may want to study Saturn's Magnetosphere using the Magnetometer (MAG) and will need to spin the spacecraft to obtain their science data. By having 12 different science instruments onboard Cassini the combinations and potential science pointing requirements are numerous. This does not allow for simple RBOT friendly solutions.

AACS along with SP identified 5 constraints along with 9 guidelines for science pointing designers to follow in order to minimize the amount of RBOT problems per sequence. RBOT constraints were designed to limit what types of science pointing would be allowed by SP. RBOT guidelines were not as stringent and were left up to the individual science teams to implement where it was deemed appropriate. The 5 RBOT constraints are as follows:

1) "RBOT-friendly" secondaries shall be used unless science provides justification for why they cannot be used
2) No "AZSCANS" shall be included in any sequence
3) When tracking a body for more than 60 degrees an observation must either be
    a. Less than 3 hours in duration, or
    b. Broken into segments of three hours or less with an inertially fixed quiescent break(~20 minutes at an inertial attitude) between chunks
4) The combination of multiple science activities is restricted during apoapsis segments such that no more than two of the following three items shall be included in any one apoapsis period (outside 20 Rs)
    a. Downlink rolls
    b. MAG calibration/Cassini Plasma Spectrometer (CAPS) rolls
    c. Pointing changes for other science activities that share common pointing
5) All turns greater than 60 degrees shall use slower body rates

A. RBOT Constraint #1: RBOT-Friendly Secondaries

One of the first constraints levied on the science teams was intended to limit the total angular motion of the spacecraft thereby reducing the transfer of momentum from wheel to wheel. This concept is often talked about by the AACS team as reducing the overall momentum space and is known to help RBOT produce more acceptable solutions. For this constraint to be implemented a ground software tool called RBOT_MY_SPASS (SPASS refers to the Science Planning Attitude Spreadsheet) was created to find RBOT friendly secondaries. An RBOT friendly secondary is a secondary vector that maintains a nearly-fixed position in space over the duration of an observation or multiple observations. It is chosen to minimize the relative motion of the secondary axis while the primary axis tracks the target body of interest. The RBOT_MY_SPASS software tool works through defining the spacecraft velocity vector (V) and the prime pointing vector (a.k.a. radius vector, R) and finding the cross product RxV at various times (see Figure 8). The cross product gives a vector normal to the plane of the vectors R and V. This vector is used by the RBOT_MY_SPASS program to provide a decent first guess for a RBOT secondary. The program

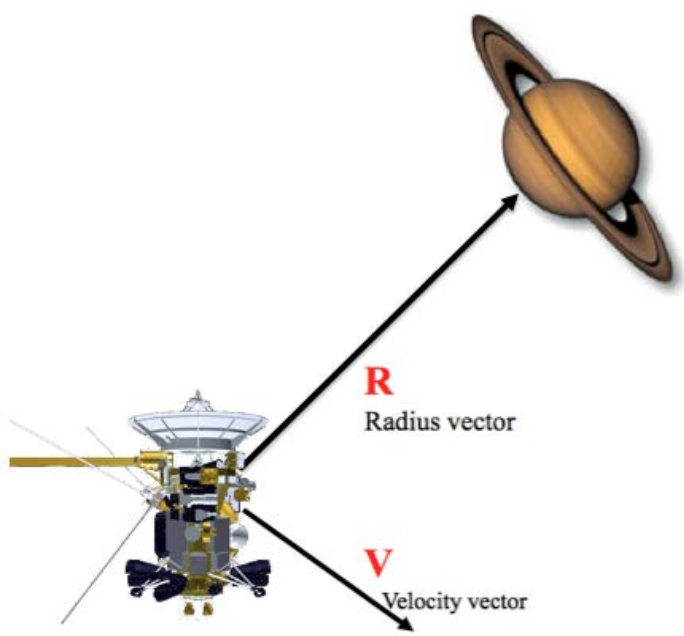

Figure 8. Shows RBOT friendly secondary

then simulates the secondary vector motion while the primary vector tracks the target body. Multiple iterations of the secondary axis render a new secondary that is closest to near-zero motion and therefore the most RBOT friendly.

B. RBOT Constraint #2: No AZSCANS

AACS noticed several types of science observations that became repeat offenders in causing RBOT problems. One of those observations that was used by the ISS instrument was called an "AZSCAN" (Azimuth Scan). The objective of this observation was to follow a portion of Saturn's Ring which was a designated radius from Saturn for one full revolution. One intention of this observation was to find tiny moonlets inside the Cronian ring system. This type of observation often caused RBOT problems in which there was no solution to remedy the continuous dwell time in the low rpm. The problem was significant enough that the science teams redesigned the observation to only view a perpendicular cross section of the rings instead. AZSCANs were then no longer allowed to be integrated into sequences.

C. RBOT Constraint #3: Split Up Long Slow Slews

A common thread of observations that routinely did not have a viable RBOT solution were observations that tracked a body (such as a moon) for more than 3 hours and caused the spacecraft to slew greater than 60 degrees. These types of observations caused the spacecraft to move slowly while also changing the attitude substantially. The combination of the two often resulted in one of or more of the RWA wheel speeds in low rpm for an extended period of time (greater than 30 min). These types of observations were problematic enough that AACS decided to impose another constraint on science. The constraint forced the science pointing designers to break up these types of observations into 3 hour or less segments with a 20 minute quiescent break (20 minutes at an inertial attitude) in between segments. The purpose for the 20 minute quiescent break was to give the AACS analyst enough time to insert a bias or a pointing offset (a rotation of the spacecraft around the primary pointing axis) that could then result in an acceptable solution. This constraint proved useful in alleviating much of the back and forth communication between the science designers and AACS engineers and ended the need for science designers to redesign many of their observations.

D. RBOT Constraint #4: 2 Out of 3 Rule

During XXM the workforce shrank due to a reduction in the funding of the Cassini mission. As a result the program needed to find ways to reduce work load so that RBOT problems would remain manageable. Since higher priority science is usually taken around periapsis and lower priority science around apoapsis, a constraint was implemented only outside of 20 Rs to make the apoapsis segments more manageable while allowing the periapsis segments flexibility. After observing many apoapsis segments AACS was able to heuristically conclude that the combination of downlink rolls along with MAG calibration and CAPS rolls (rolls about the non-z axis) and other types of science such as Optical Remote Sensing (ORS) science would usually result in problematic segments. To reduce the amount of problem areas a constraint was implement to limit science teams to only 2 out of the 3 types of science. The constraint would span a duration of time (about 10 days) and afterwards the science teams could decide to pick another 2 out of 3 types of science observations. An exception to this constraint was made if there happened to be multiple uncharacteristic pointing observations that were considered higher priority. When this occurred SP was advised to bunch the observations towards the beginning or the end of segment boundaries (hard stops and sequence boundaries). The uncharacteristic observations could then be bracketed by biases to give them the best chance of viable RBOT solution. If problems still were present after bracketing these observations then the problematic observations would be removed from the sequence. This constraint has saved AACS, SP, and the various science teams much time and effort in needing to work through RBOT problem areas. Since this constraint has been implemented most apoapsis segments have not had any RBOT problems.

E. RBOT Constraint #5: Slow Body Rates For Long Slews

Long slews with large spacecraft body rates can be problematic for RBOT because so much of the momentum space is used for such an activity. This type of activity often confines the RBOT solution and forces RWAs into low rpm. A constraint was implemented in 2007 which limited any single commanded turn in RWA control where the total turn magnitude (commanded plus target motion compensation) was greater than 60 degrees to lower spacecraft body rates. The lower body rates reduce the overall spacecraft momentum and freed up momentum space so that the RBOT solution set was not as confined. This constraint was deemed important enough to be implemented into the spacecraft flight rules to insure that other ground software tools would alert AACS to any violations.

F. RBOT Guidelines

RBOT guidelines were created to help the science teams understand what types of rules would work towards reducing the overall momentum space and therefore help reduce RBOT problem areas. Science teams were asked to implement these guidelines where it was deemed appropriate. The 9 RBOT guidelines are as follows:

1) Avoid turning the spacecraft unless necessary for accomplishing science
2) Slow down slews
3) Avoid very long slews (> 100 degrees)
4) Be wary of long observation that cover huge swaths of sky
5) Be wary of single observations that point the spacecraft to a unique target
6) Use the same initial secondary for all downlinks within an RBOT segment
7) Put similar science together
8) Exploit the natural motion of the spacecraft body when deciding how to point the spacecraft
9) Do not use a large mosaic (scanning observation) if a small one, or a stare, will suffice

These guidelines were created with one common theme, to limit the overall angular change of the spacecraft and to limit the body rates of the spacecraft (reducing angular momentum). Ideally an inertially quiescent spacecraft will achieve the most optimal RBOT solution. Eliminating any unnecessary slew of the spacecraft as well as reducing the angular velocity of the spacecraft both serve to more closely match the ideal RBOT case. These guidelines have helped to demonstrate to the various science teams ways to minimize momentum space which helps the RBOT solutions. The guidelines have also proven to be a good way to translate AACS concepts into practical examples that the science teams can use.

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