In-Flight Position Calibration of the Cassini Articulated Reaction Wheel Assembly

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NASA's long-lived Cassini-Huygens spacecraft is currently in its 14th year of flight and in the midst of its second, and final, extended mission. Cassini is a massive interplanetary spacecraft that is three axis stabilized and can maintain attitude control using either its reaction control system thrusters or using reaction wheel control. Cassini has four identical reaction wheels, of which three are mutually orthogonal and have a fixed orientation. The fourth reaction wheel has an articulation motor that allows this reaction wheel to be aligned with the momentum direction of any of the other three fixed reaction wheels. The articulation motor allows this reaction wheel to be used as a replacement for any of the other three wheels without any performance degradation. However, due to limitations in the design of this backup system, there are few telemetric indications of the orientation of this reaction wheel following an articulation. This investigation serves to outline the procedures that have been developed by the Cassini Attitude and Articulation Control Subsystem to calibrate the position of the articulated reaction wheel assembly in the event that the momentum direction of this reaction wheel must be reoriented.

Acronyms

AACS	=	attitude and articulation control subsystem
ARWA	=	articulated reaction wheel assembly
ATLO	=	assembly, test, and launch operations
CBE	=	current best estimate
ESA	=	European Space Agency
IRU	=	inertial reference unit (gyroscope)
ITL	=	integrated test laboratory (Cassini testbed)
MMH	=	monomethylhydrazine (bi-propellant fuel)
NASA	=	National Aeronautics and Space Administration
NTO	=	dinitrogen tetroxide (bi-propellant oxidizer)
RCS	=	reaction control system
RTG	=	radioisotope thermoelectric generator
RWA	=	reaction wheel assembly
SRU	=	stellar reference unit (star tracker)
XM	=	equinox (extended) mission
XXM	=	solstice (extended-extended) mission

Nomenclature

${}^{I}C^{B}_{t_i}$	=	direction cosines matrix that transforms vectors from the spacecraft body to the inertial frame at time *i*
ΔV	=	change in inertial spacecraft velocity
I_{RWAk}	=	inertia of reaction wheel "*k*" when rotated about its axis of symmetry (spin-axis)
$[I]_{s/c}$	=	inertia tensor of the Cassini spacecraft
$\overline{q}_j$	=	quaternion that transforms vectors from the inertial to the spacecraft body frame at time *j*

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$mrad$ = milli-radian

$\overline{u}_k$ = unit vector of the RWAk spin-axis direction in the S/C body frame

$\omega^{R}_{RWA4}(t_j)$ = magnitude of the angular velocity of RWA4 at time "j" in the RWA frame

$\overline{\omega}^{B}_{s/c}(t_i)$ = angular velocity vector of the spacecraft at time "i" expressed in the spacecraft body frame

$\hat{X}_{S/C}$ = Cartesian X-axis of the spacecraft body frame

$\hat{Y}_{S/C}$ = Cartesian Y-axis of the spacecraft body frame

$\hat{Z}_{S/C}$ = Cartesian Z-axis of the spacecraft body frame

I. Introduction

THE Cassini-Huygens spacecraft is a joint venture between NASA and ESA to fly a massive interplanetary spacecraft to the planet Saturn. Launched in 1997, Cassini made use of gravity assist flybys of Venus, Earth, and Jupiter while en route to Saturn. Upon arriving at Saturn in the summer of 2004, Cassini performed a large ΔV maneuver to enter orbit around the ringed planet. In late 2004, Cassini released the ESA Huygens probe which then successfully parachuted to a soft landing on Saturn's giant haze shrouded moon, Titan, in early 2005.[1] Since 2004, Cassini has performed an ambitious orbital tour of the Saturnian system that includes up-close investigation of Saturn, its rings, many of Saturn's moons, and the fields and particles environment of the entire planetary system. Cassini successfully completed its prime science mission in 2008, and completed its Equinox extended mission (XM) in 2010.[2] Cassini is currently in the midst of its second, and final, extended-extended mission (XXM). The Solstice mission (XXM) is planned to conclude in late 2017 with the dramatic intentional disposal of the Cassini spacecraft by impacting the atmosphere of Saturn.[3]

Cassini is a 3-axis stabilized spacecraft that can be controlled using either its reaction control system (RCS) thrusters, or by reaction wheel control.[4,5] Although the RCS thrusters provide greater control authority than the reaction wheels aboard Cassini, the RCS thrusters are used very sparingly by Cassini to conserve the limited monopropellant hydrazine reserves. Typically Cassini transitions to thruster control only for a handful of types of activities, including: performing ΔV maneuvers[6], controlling the spacecraft during low altitude flybys of Saturnian moons, or to adjust the angular momentum stored in the reaction wheels.[7,8,9] Cassini remains in reaction wheel assembly (RWA) control ~98% of the time. Unlike many Earth-orbiting spacecraft that use reaction wheels to hold a steady nadir attitude, Cassini is a dynamic spacecraft that must slew to perform much of its science collection. Among the 13 major science instruments on Cassini, most are fixed to the spacecraft without any ability to articulate. As a result of this design, the scientific investigations that Cassini performs are heavily dependent upon the use of the reaction wheel controller[10] to frequently reorient the spacecraft.

The Cassini spacecraft has four identical 34 Nms reaction wheels onboard. Of those, three RWAs (RWA1, RWA2, and RWA3) are fixed to the spacecraft bus in an orientation where they are mutually orthogonal and are equidistant from the spacecraft +Z-axis (Fig. 1). The other reaction wheel, RWA4, was originally conceived as an inflight spare wheel that would never be used nominally. RWA4 is attached to an articulation motor called the Articulated Reaction Wheel Assembly (ARWA) that allows the spin-axis of RWA4 to be reoriented to precisely match the orientation of any of the other fixed RWAs (Fig. 2). Prior to the arrival of Cassini at Saturn, telemetry from the spacecraft indicated that one of the fixed RWAs that was being used in the prime set of wheels, RWA3, was experiencing elevated drag. Although RWA3 continues to operate without any performance degradation due to the elevated drag, the decision was made by the project management to articulate RWA4 from its launch configuration, which matched the orientation of RWA1, to instead align RWA4 with RWA3.[4] Following the articulation in the year 2003, RWA4 replaced RWA3 in the prime set of reaction wheels and RWA4 has been used in flight for the last 9 years. RWA3 is currently powered off, though it continues to be exercised periodically and was used briefly in the prime set of reaction wheels in 2011 to assess its health.

As Cassini enters its 15th year of flight, the reaction wheels continue to age and two of the wheels are approaching their 4 billion revolution qualification limit. All four reaction wheels continue to operate without any performance degradation, however, the friction characteristics of each wheel continue to display signs of aging. Although the AACS team has no indication that any of the reaction wheels will fail in the near future, the operations team has nevertheless begun contingency planning to create the procedures that would be required to articulate RWA4 to replace any of the fixed RWAs in the event that a reaction wheel failure occurs. Due to the design of the ARWA used to reorient RWA4, it is more difficult to articulate RWA4 to replace RWA1 than it is to replace either RWA2 or RWA3.

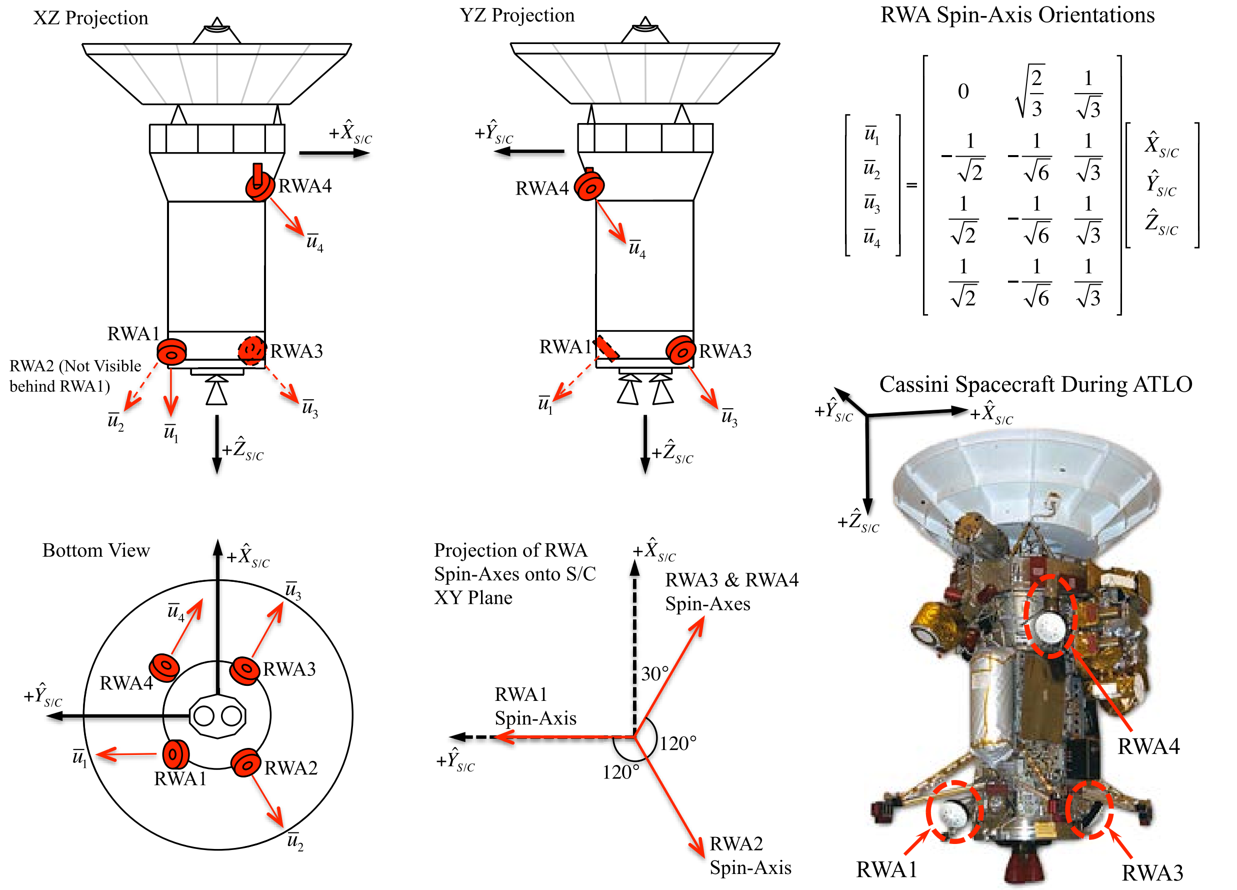

Figure 1. Cassini Reaction Wheel Assembly Mounting. *This schematic depicts the mounting location of the four Cassini reaction wheels (labeled RWA1-RWA4), along with the angular momentum direction of each RWA. RWA4 is currently co-aligned with RWA3, though in the ATLO photo RWA4 was co-aligned with RWA1.*

The RWA4 articulation motor has a rotation axis that is aligned with the spacecraft Z-axis. The spin-axis of the RWA4 flywheel is canted from the articulation motor rotation axis by 54.7° (Fig. 2). This offset angle matches the angle between the spin-axes of the three fixed RWAs and the spacecraft +Z-axis. At launch, the ARWA was locked in an orientation where the RWA4 spin-axis exactly matched the spin-axis orientation of RWA1; this would have allowed RWA4 to replace RWA1 without any articulation. From this orientation, RWA4 could be easily articulated to the orientation of RWA2 or RWA3 by simply rotating the articulation motor by either +120° or -120° around the +Z-axis until the motor encountered a hard stop at either of the two extremes. The hard stops for the articulation motor were chosen such that the spin-axis of RWA4 would precisely match the orientation of either RWA2 or RWA3 at either of the two extremes (Fig. 1). Thus, in the year 2003, when the need arose to articulate RWA4 to replace RWA3, the articulation motor was powered on and driven with the correct polarity until the motor encountered the hard stop at the RWA3 orientation (a -120° articulation of the ARWA around the spacecraft +Z-axis).[4] During the articulation all four reaction wheels were spun-down and powered off and the RCS thrusters were controlling the spacecraft attitude. Since this articulation in 2003, RWA4 has been used almost continuously. Meanwhile, the ARWA motor that was used to articulate RWA4 has not been powered on or used during the last 9 years.

The simple design of the RWA4 articulation motor made it easy for the system to be used once to replace a single malfunctioning RWA. However, the ARWA was only designed to be a single-use motor and there was never any intent for RWA4 to be articulated a second time to replace a different reaction wheel. Despite the intentions of the spacecraft designers, it is possible that in the coming years of the XXM, Cassini could experience a failure of RWA1 or RWA2, and require another articulation (recall that RWA4 and RWA3 are currently co-aligned, so a failure of RWA3 would not require RWA4 to be articulated again).

Should a failure of RWA2 occur, RWA4 could be easily articulated to replace the wheel by simply powering the ARWA motor on until the motor encounters the hard stop at the orientation of RWA2. This process is straightforward and presents little difficulty to the AACS team. However, a failure of RWA1 would greatly

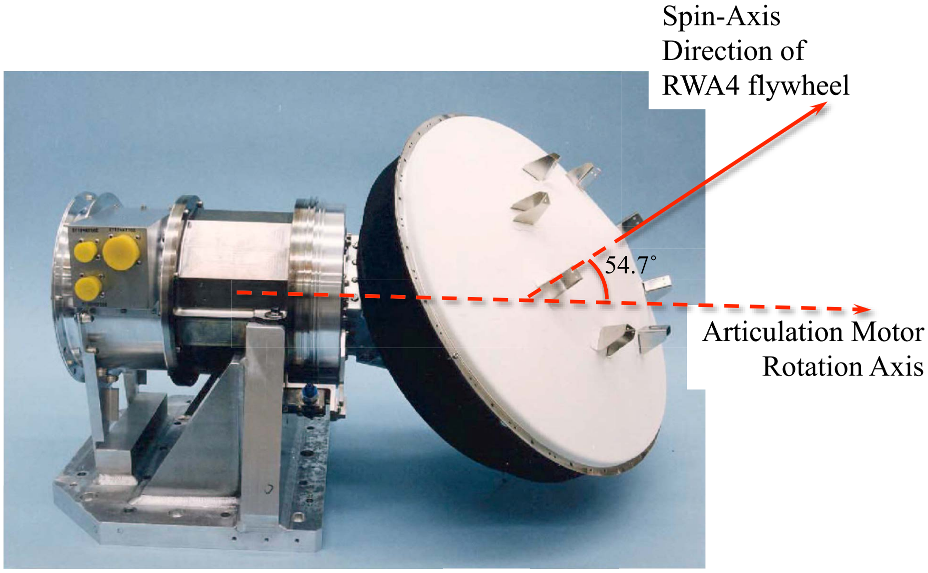

Figure 2. Reaction Wheel 4 (RWA4) and the Articulated Reaction Wheel Assembly. *This photograph, taken during Cassini ATLO, shows RWA4 attached to the articulation motor. The ARWA motor can rotate 120° in either direction from the orientation shown and will encounter a hard stop at either of the two extreme articulation bounds.*

complicate the situation for the Cassini operations team. Should RWA1 fail, the lack of a hard stop on the articulation motor at the orientation of RWA1, would make it very difficult to articulate RWA4 to precisely the same orientation as RWA1. The operations team has determined that in order for RWA4 to permanently replace a failed RWA1 it is necessary that RWA4 be articulated to within ±2° of the RWA1 spin-axis orientation.[4] The Cassini RWA controller would continue to function with minimal performance degradation even if RWA4 were between 2-10° from RWA1 orientation. However, to insure that there is no significant degradation to science pointing, the AACS team will require that the articulation results in positioning RWA4 less than ±2° from the RWA1 orientation.

Since the motion of the ARWA motor is controlled only by powering it on or off (applying power to the motor results in motor motion), any use of the articulation motor will certainly result in either an overshoot or undershoot of the orientation of RWA1. Even the 1/8th of a second resolution of the "on" and "off" commands limit the accuracy of the RWA4 articulation motor to ~1.5° of motion. However, despite the difficulty associated with commanding the RWA4 articulation motor, the most difficult part of reorienting RWA4 would be determining the direction that the spin-axis of RWA4 is pointing following an articulation. This difficulty arises from the fact that there is no direct telemetry from the spacecraft measuring the position angle of the ARWA motor.

II. Purpose

The purpose of this investigation is to describe the procedure that the AACS team has created to accurately determine the orientation of RWA4 following a future articulation. The calibration procedure is broken into two parts: first, a coarse method is used while the spacecraft is in RCS control in order to measure the spin-axis orientation of RWA4 to within ±3°. Second, a more accurate calibration method is performed with Cassini in RWA control to provide a measurement with error of approximately ±1°. Both position calibration techniques leverage the principle of conservation of angular momentum in order to determine the RWA4 spin-axis indirectly from spacecraft telemetry for RWA spin-rates, spacecraft body rates, attitude quaternions, and attitude error. These RWA calibration techniques are described specifically in the context of the Cassini mission, but the methods detailed in this paper are relevant to any spacecraft operations team that is attempting to determine the phasing or orientation of reaction wheels from in-flight telemetry.

III. Calibration of the RWA4 Spin-Axis Orientation

During the course of the 14-year Cassini mission, the AACS team has considered several methods that could be used to calibrate the pointing direction of the RWA4 spin-axis following an articulation. Without exception, these methods have all fundamentally relied on the principle of conservation of angular momentum. One method that was considered, though later rejected, involved changing the momentum of RWA4 while the RCS controller maintained a fixed spacecraft pointing. By summing the impulse bits of each thruster pulse it is theoretically possible to reconstruct the inertial momentum change performed by RWA4 as the RCS controller maintains a fixed attitude. However, in practice this method relies on well-characterized thruster parameters, including: thruster pointing, steady-state thrust magnitude, rise and tail-off decay constants, and pulse-to-pulse variation. The characterization of several of these parameters is currently a topic of investigation by the AACS team, and there remains a great deal of uncertainty. Ultimately the uncertainties associated with these thruster parameters make it infeasible to use RCS controller behavior to accurately calibrate the position of RWA4. The calibration methods that are described below instead rely on telemetry for periods of time where the thrusters are not in use and angular momentum is conserved.

A. Orientation Calibration of RWA4 Using Four Functioning RWAs

As previously noted, this investigation focuses on the case where RWA1 has failed and RWA4 is articulated to replace the failed wheel. However, it should be noted that since Cassini has not yet experienced the failure of any of its reaction wheels, it is currently possible for Cassini to calibrate the orientation of RWA4 using all four of the functioning reaction wheels. Just after the 2003 articulation of RWA4 the orientation of RWA4 was calibrated from flight telemetry with the spacecraft in RWA control and with all four reaction wheels spinning.[4] To accomplish this, the three fixed-orientation RWAs (RWA1, RWA2, and RWA3) were first commanded to a predetermined set of spin-rates while in RCS control. Then, with the fixed reaction wheels maintaining an inertially fixed spacecraft attitude, RWA4 was commanded to increase and decrease its spin-rate to several target wheel speeds. By observing the response of the three controlling reaction wheels to the spin-rate change of RWA4, and by furthermore assuming that the orientation of the three fixed RWAs is perfectly known, it is possible to determine the spin-axis orientation of RWA4 by simply finding the change in the sum of the momentum of the three fixed reaction wheels. This method yielded a measurement of the current orientation of RWA4 spin-axis: [0.713318, -0.402252, 0.573909] (unit vector in the Cassini body-fixed frame), which equates to a misalignment of 0.53° from RWA3.[4] However, since this calibration method requires the use of four functioning reaction wheels, it is not applicable to scenarios where any of the four reaction wheels has failed and this method will not be further discussed.

B. RCS Controlled Method of RWA4 Orientation Calibration

The most robust method that the AACS team has investigated for calibrating the orientation of RWA4 is accomplished while the spacecraft is under RCS thruster control. However, the fundamental goal of the RCS calibration method actually makes no use of the RCS thrusters, instead the controller deadband settings are manipulated in order to put them into a state where the RCS controller is momentarily inactive (no thruster pulses are occurring), and thus the spacecraft behaves like a "test mass" or "test particle" that reacts solely due to the influence of the RWA4. To aid in the understanding of the RCS controlled calibration method, a flow-chart representation of the steps in the calibration activity is included in Figure 3.

To begin the calibration, the AACS team places the spacecraft in a state where Cassini is at an inertially fixed and thermally safe attitude, and there is minimal residual angular momentum on the spacecraft (Fig. 3, Step 1). The spacecraft is left in this state for 30 minutes to ensure that the adaptive pulse width logic of the RCS controller[4,5] has time to achieve the "quietest" initial state possible (Step 2). The RCS control deadband settings are then widened from [2.0, 2.0, 2.0] mrad to [150, 150, 300] mrad, leaving the spacecraft briefly uncontrolled (Step 3). The small initial spacecraft body rates as well as the fact that the position error is much less than the 150 mrad deadband limit insures that no RCS thruster pulses are imminent.

It should be noted that the Cassini GNC flight software does in fact have a COAST mode in which attitude determination is active, but the attitude controller is entirely disabled. This mode has only been entered twice in flight for any sustained period of time: following launch vehicle separation in 1997, and later in 2004 when Cassini deployed the hefty, spring-loaded Huygens probe on its short solo flight into the atmosphere of Titan.[11] However, since Cassini has two sun constraints or "keep-out zones," used to protect sensitive science instruments and radiators from direct sunlight[12], the use of this uncontrolled COAST mode is inherently risky. To mitigate the risk of being fully uncontrolled, the AACS team has elected to perform the RWA4 calibration activities while still under RCS control, albeit a significantly diminished controller.

After the RCS deadbands are widened, there is a pause of ~7 minutes in the calibration activity to allow the AACS team time to collect sufficient telemetry to accurately quantify the residual spacecraft body rates and the attitude quaternions (Fig. 3, Step 4). RWA4 is then commanded to change its spin-rate by a predetermined amount: +200 rpm, or 3.34 Nms (Step 5). The momentum change of RWA4 imparts a torque on the spacecraft, and once the commanded RWA rate change is complete, the spacecraft is left with approximately constant spacecraft body rates. More importantly, the spacecraft body rates will depend on the geometry of the articulation motor connected to RWA4. For several minutes following the completion of the RWA4 momentum change, the spacecraft is allowed to

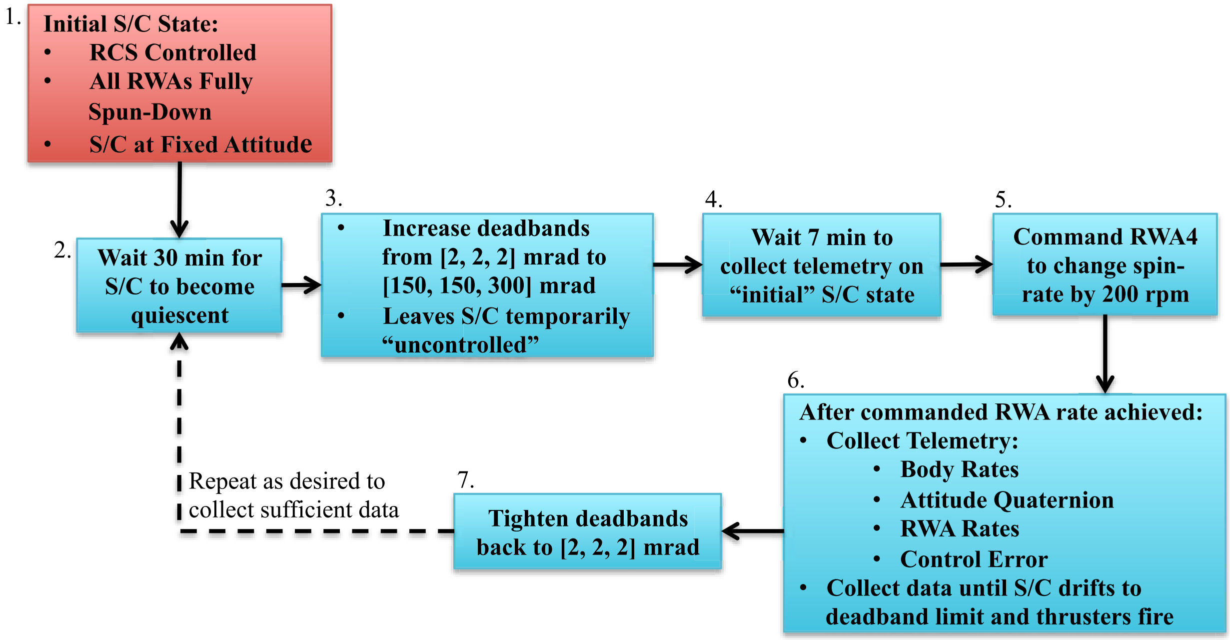

Figure 3. RCS Controlled Method of Calibrating RWA4. *This flow-chart depicts the operational activities needed to gather sufficient data to determine the spin-axis orientation of RWA4 in the spacecraft body frame using the RCS controlled calibration method.*

drift slowly from its initial attitude. During this time AACS is again collecting telemetry to determine the spacecraft body rates, the RWA4 spin-rate, and attitude quaternion (Step 6). After several minutes of slowly drifting the position error of the spacecraft will finally reach the 150 mrad (~8°) deadband limit around X or Y and the RCS controller will pulse the thrusters to decrease the attitude error. It is at this point, once thrusters have fired, that the angular momentum of the spacecraft is no longer conserved and data collection for the calibration ceases. The final step of the calibration activity is to restore the spacecraft deadbands to the normal 2 mrad setting (Fig. 3, Step 7). At the end of the calibration activities Cassini is left with RWA4 spinning at +200 rpm. At this point it is actually possible to rerun the calibration by returning to Step 2 (Fig. 3) and then repeating steps 2-7. However, during Step 5 of the second calibration, RWA4 is commanded to change its momentum by -200 rpm (from +200 rpm to 0 rpm). Re-running the calibration activities produces a second independent measurement of the RWA4 spin-axis location that can be averaged with the result from the first run if desired.

During the calibration activities, approximately 20-30 minutes will pass from the time that the deadbands were widened (Step 3) until the time that the spacecraft finally encounters the widened deadband limits and the thrusters fire (Step 6). It is the AACS telemetry from this 20-30 minute period that provides the dataset used to produce a measurement of the RWA4 spin-axis orientation. Since the inertia properties of both the spacecraft[13] and reaction wheel are known quite accurately (only the orientation of RWA4 is unknown), it is possible to determine from the measured change in the spacecraft body rate, what torque must have been applied by RWA4, and thus it is possible to determine the orientation of RWA4's spin-axis. In effect, the AACS team is leveraging the accuracy of the attitude determination capability of the spacecraft, as well as the relatively well-known inertia properties of the spacecraft to solve for the only unknown: the orientation of the RWA4 spin-axis in the spacecraft body-frame.

Of course, several assumptions are being made when performing this calibration. First, it is assumed that the spacecraft is a rigid body and that motion of the flexible booms on Cassini as well as fuel slosh are insignificant compared to the behavior of the rest of the spacecraft structure. This assumption is valid because the telemetric measurements of the spacecraft body rates and attitude are averaged across several minutes, which should remove the effects of oscillations with periods shorter than a few minutes. Also, of the 3000 kg of NTO and MMH bipropellant that Cassini launched with in 1997[4], only 124 kg remain as of May 2012. Although fuel slosh on Cassini has been previously considered[4,14,15], since these fluids now make up just 5% of the spacecraft mass, fuel slosh is ignored in this analysis.

Also as previously mentioned, it is assumed that the angular momentum of the spacecraft is conserved/constant during the calibration. Telemetry from the eight years Cassini has spent touring Saturn has demonstrated that the only significant external torques altering the momentum of the spacecraft are solar radiation pressure as well as a

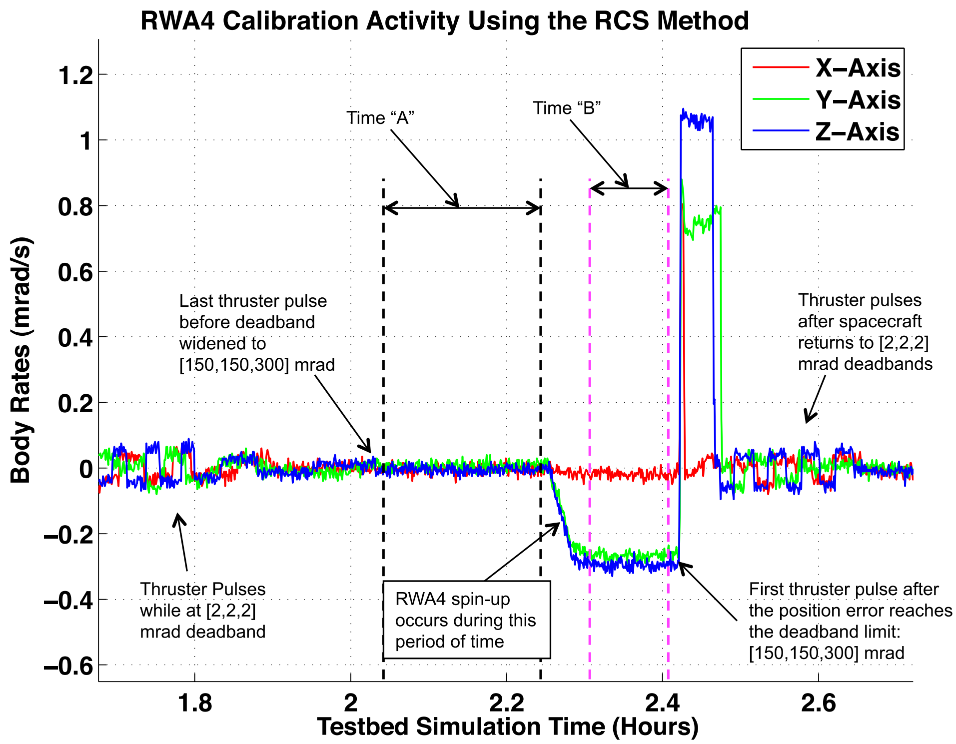

Figure 4. Testbed Simulation Results of the RCS Controlled Method of Calibrating RWA4. *This plot shows the spacecraft body rates during the "uncontrolled" spin-up of RWA4 from 0 rpm to +200 rpm.*

thermal radiation torque on the spacecraft. The latter torque primarily comes from the three blisteringly hot Plutonium filled Radioisotope Thermal Electric Generators (RTGs) onboard Cassini[16], each of which are in excess of 450° F at their external casing. Previous analysis by the AACS team[4,17] has found that at an Earth-pointed attitude, the external torques on Cassini are approximately 3.03e-6 Nm in magnitude. During the ~30 minute RWA4 calibration activity the sum of the external torques is expected to produce a momentum change that is approximately 3 orders of magnitude smaller than the momentum change of RWA4 as it spins-up to +200 rpm. Due to this diminutive size, external torques are assumed to be insignificant.

Besides solar radiation and thermal radiation torques, Cassini does experience measurable gravity gradient torque when it performs a low altitude flyby of one of Saturn's moons and it also experiences a significant atmospheric torque when it performs a low altitude flyby of Titan[4,18,19,20]. Interestingly, Cassini also experiences a measurable torque from flying through the ice plumes beneath Enceladus' south pole[21,22,23]. However, in this analysis it is assumed that the operations team will not choose to perform a calibration of RWA4's orientation during one of these rare and scientifically valuable low altitude flybys of Titan or Enceladus. Therefore any external torque that arises due to Cassini's close proximity to Saturn's moons is also ignored.

The entire procedure used to calibrate the RWA4 spin-axis orientation has been thoroughly tested in the Cassini avionics testbed.[24] Telemetry from a simulation of the calibration activities described is shown in Figure 4. In Fig. 4 the period denoted as "Time A" is the portion of the body rate telemetry that is averaged to produce an accurate estimate of the small initial spacecraft body rates. RWA4 is commanded to spin-up from 0 rpm to 200 rpm between "Time A" and "Time B." The second data collection period, "Time B", begins once RWA4 has reached its commanded 200 rpm spin-rate and ends just before the first thruster firing occurs (once the position errors have reached the deadband limit of 150 mrad). The telemetry gathered during "Time B" is averaged to produce an accurate measurement of the spacecraft body rates induced by the known momentum change of RWA4. Note that there are no thruster firings between the beginning of "Time A" and the end of "Time B." The ~0.3 mrad/s body-rates observed around the spacecraft Y and Z axes are entirely due to the spin-up of RWA4.

The formula used to calculate the spin-axis direction of RWA4 in the body frame, $\overline{u}_4$, is shown in Eq. (1), and variable definition is provided in the nomenclature at the beginning of the paper. This formula was derived by simply equating the change in the average inertial angular momentum of RWA4 to the change in the average inertial angular momentum of the spacecraft.

$$\overline{u}_4 = \frac{1}{I_{RWA4}}\left[\frac{1}{m}\sum_{j=1}^{m}\left(\omega_{RWA4}^{R}(t_j)\,{}^{I}C_{t_j}^{B}\right)-\frac{1}{n}\sum_{i=1}^{n}\left(\omega_{RWA4}^{R}(t_i)\,{}^{I}C_{t_i}^{B}\right)\right]^{-1}\left(\frac{1}{n}\sum_{i=1}^{n}\left({}^{I}C_{t_i}^{B}\left[I\right]_{s/c}^{B}\overline{\omega}_{s/c}^{B}(t_i)\right)-\frac{1}{m}\sum_{j=1}^{m}\left({}^{I}C_{t_j}^{B}\left[I\right]_{s/c}^{B}\overline{\omega}_{s/c}^{B}(t_j)\right)\right) \quad (1)$$

While the magnitude of the momentum change of RWA4 is well known from the spin-rate telemetry, the unknown in the equation is the unit vector pointing in the direction of the RWA4 spin-axis, $\overline{u}_4$. Note that in Eq. (1) there is no requirement that the number of telemetry points gathered before RWA4 is spun-up, *i*, during "Time A" (Fig. 4) matches the number of data points gathered after the RWA4 momentum change, *j*, which are collected during "Time B." In Eq. (1) the computations of the change in the average angular momentum of the spacecraft and change in the average angular momentum magnitude of the reaction wheel are performed in the inertial coordinate frame. The transformation between the inertial and body coordinate frames is accomplished with the direction cosines matrices, ${}^{I}C_{t_i}^{B}$ and ${}^{I}C_{t_j}^{B}$, which are populated using the instantaneous attitude quaternions telemetry as shown in Eq. (2). The attitude quaternions are sampled at the same instant as the spacecraft body rate and the RWA4 spin-rate telemetry and are generated by the onboard attitude determination logic using sensor measurement from the Cassini Stellar Reference Unit (SRU) and Inertial Reference Unit (IRU).

$${}^{I}C_{t_j}^{B} = \begin{bmatrix} \left(q_4^2+q_1^2\right)-\left(q_2^2+q_3^2\right) & 2\left(q_1q_2+q_4q_3\right) & 2\left(q_1q_3-q_4q_2\right) \\ 2\left(q_1q_2-q_4q_3\right) & \left(q_4^2+q_2^2\right)-\left(q_3^2+q_1^2\right) & 2\left(q_2q_3+q_1q_4\right) \\ 2\left(q_1q_3+q_4q_2\right) & 2\left(q_2q_3-q_1q_4\right) & \left(q_4^2+q_3^2\right)-\left(q_1^2+q_2^2\right) \end{bmatrix}^{-1} \quad (2)$$

In all, ten different simulations were performed in the Cassini ITL to test whether the calibration formula in Eq. (1), could provide accurate measurements of the simulated RWA4 spin-axis orientation. In each case the Cassini AACS Cognizant Engineer selected RWA4 orientations that corresponded to arbitrary position angles of the articulation motor connected to RWA4. To add realism to the test, a separate AACS engineer analyzed the telemetry from the testbed simulation but had no prior knowledge of the simulated position of RWA4. In these analyses the RWA4 spin-axis measurement produced by this calibration procedure was on average just 0.4° from the simulated orientation of RWA4. The least accurate of the ten test cases was still just 1.4° from the simulated orientation of RWA4.

It should be noted that the ITL testbed uses simulated spacecraft inertia properties that were effectively identical to the mass properties assumed in the calibration analysis. To quantify the additional error that AACS should expect due to mismatch between the CBE and actual mass properties of the spacecraft a rough error analysis was performed in two different ways. First, the CBE mass properties used in the calibration analysis were varied randomly in a Monte Carlo analysis within the stated uncertainties of each element of the inertia matrix based on the official spacecraft mass properties report that was made during ATLO in January 1997. Second, a separate Monte Carlo analysis was performed where the elements of the inertia matrix were varied by the full range of spacecraft inertia properties that were measured from flight telemetry of slews that were performed to calibrate the Cassini IRUs. The results of these Monte Carlo analyses demonstrated that at worst AACS should expect that mass property uncertainty should contribute no more than an additional 1.5° of error. When summed, the 1.4° worst case measured spin-axis error and the 1.5° error due to mass property uncertainty should result in an ultimate measure of the RWA4 spin-axis orientation that is less than 3° from the actual orientation of the reaction wheel.

Although the RCS calibration method could be executed on board the spacecraft with RWA4 in any orientation, including its current orientation, to more accurately determine the actual error of this calibration method, there are currently no plans to perform this test in-flight due to the time it would take away from science observations and the hydrazine that would be consumed in the process. There are no plans to exercise this procedure in flight unless RWA1 fails and cannot be recovered.

C. RWA Controlled Method of RWA4 Orientation Calibration

The second, and more accurate, procedure that the AACS team has created to determine the orientation of RWA4 is referred to as the RWA controlled method. This calibration method also uses the principle of conservation of angular momentum to determine the spin-axis pointing of RWA4. However, in the RWA controlled method the spacecraft uses RWA4 as one of the three prime reaction wheels that are in control of the spacecraft as several large slews are commanded.

To understand conceptually how the RWA controlled method works, visualize a case where the spacecraft is using three reaction wheels to hold a stationary attitude. If there are (a) no external torques on the spacecraft, (b) Cassini is assumed to behave as a rigid-body, and (c) the spacecraft is at an inertially fixed attitude, then 100% of the angular momentum onboard the spacecraft is held in the three spinning reaction wheels. Suppose that RWA4 has been articulated and the direction that its spin-axis is pointing is unknown. Now, in order for the RWA controller onboard Cassini to function properly it is necessary that RWA4 be reasonably close to the orientation of the reaction wheel it is replacing (in this case RWA4 is replacing a failed RWA1). Let us temporarily assume that RWA4 has been articulated to be within 10 degrees of the orientation of RWA1. The design of the Cassini RWA controller is sufficiently robust that the controller can function even with a grossly misaligned reaction wheel, though performance with a misaligned wheel will be degraded during attitude slews. Importantly, the controller will function without any significant performance degradation while at a stationary attitude.

If the orientation of the RWA4 spin-axis is unknown, then it is not possible for the AACS team to determine what the inertial angular momentum of the spacecraft is at any one attitude. The attitude of the spacecraft is known based on telemetry from the SRU, and the angular momentum contributions from RWA2 and RWA3 are known based on their spin-rate and known pointing direction. The spin-rate of RWA4 is known from telemetry, so it is just the vector direction of the RWA4 momentum contribution that is unknown. Key to this calibration method is the fact that when Cassini is commanded to perform a slew, the spin-rates of the three controlling reaction wheels (RWA2, RWA3, and RWA4) will change. The RWAs pass angular momentum amongst themselves while the spacecraft is slewing. Once the spacecraft completes the turn to the commanded attitude the RWA spin-rates will be different than they were at their initial attitude (this assumes that the initial and final attitudes are unique, that there is a non-zero initial angular momentum, and the momentum vector is not equidistant from the spin-axis of the three reaction wheels). Since the spin-rates of all three reaction wheels are known, as is the orientation of RWA2 and RWA3, and since it is furthermore assumed that the angular momentum of the entire spacecraft is the same at both the initial attitudes and attitude after the slew, it is possible to determine what the RWA4 spin-axis pointing must be in order for the vectorial sum of the momentum contributions of the three reaction wheels to be identical at the two unique attitudes. In short, it is possible from the telemetry for the slews to determine the change in the angular momentum vectors of RWA2 and RWA3 and it is possible to determine the change in the *magnitude* of the angular momentum of RWA4. Although the pointing of RWA4 is unknown, the vector sum of the momentum contribution of the 3 reaction wheels must be the same at both attitudes, and therefore the change in the angular momentum vector of RWA4 must be equal to the sum of the changes in the angular momentum vectors of RWA2 and RWA3. This equality can be used to solve for the pointing direction of RWA4.

A flow-chart depiction of the RWA controlled calibration method is included in Figure 5. When executing the

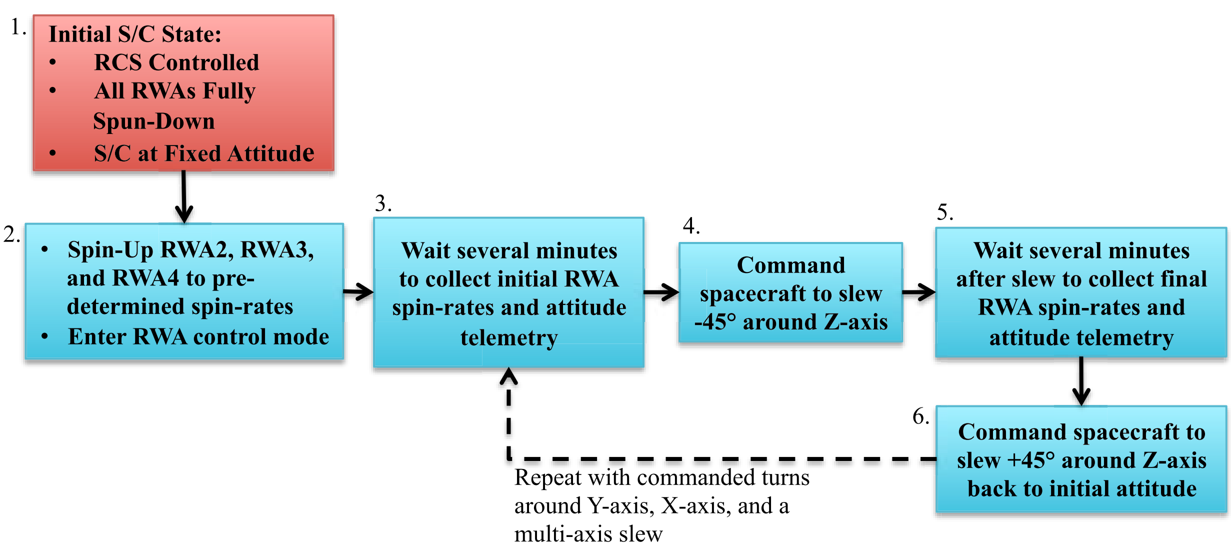

Figure 5. RWA Controlled Method of Calibrating RWA4. *This flow-chart depicts the operational activities needed to gather sufficient data to determine the spin-axis orientation of RWA4 in the spacecraft body frame using three controlling reaction wheels to perform multiple attitude slews. Note that in addition to the 45° Z-axis slews referred to in this diagram, in practice there are also 60° slews commanded about the X-axis, 90° slews commanded about the Y-axis, and a 30° slew that is commanded with equal parts around all three spacecraft axes.*

RWA controlled calibration method the spacecraft begins at an inertially fixed Earth-pointed attitude with the reaction wheels fully spun-down and under RCS control (Fig. 5, Step 1). To begin the calibration, the three prime reaction wheels are spun up to [RWA2, RWA3, RWA4] = [-600, -800, -850] rpm spin-rates while the RCS controller holds the spacecraft attitude fixed. These RWA rates were arbitrarily chosen but have been demonstrated to provide accurate calibration results.

Once the reaction wheels have completed their spin-up, the spacecraft is commanded to enter the RWA control mode (Fig. 5, Step 2). Ten minutes are allowed to pass once the spacecraft has entered RWA control in order for the AACS team to gather stable telemetry for the spacecraft attitude quaternion and RWA spin-rates (Fig. 5, Step 3). With these initial conditions determined, the spacecraft is next commanded to slew around the spacecraft Z-axis by -45° (Step 4). This slew requires several minutes, and during the slew the attitude controller may have position errors as large as 1.5 mrad due to the misalignment of RWA4. The controller believes that RWA4 is perfectly aligned with RWA1, but continues to function even with a considerable misalignment present. Upon the completion of the slew the position errors are easily held by the controller to within tenths of a mrad of the commanded attitude. Once the -45° slew is complete, another 10 minutes are allowed to pass so that sufficient telemetry is again gathered to produce a clean measure of the average spacecraft attitude quaternion and RWA spin-rates (Step 5). Finally, the spacecraft is commanded to slew +45° around the Z-axis back to the initial attitude (Step 6). Upon the completion of these six steps, the AACS team has received sufficient data to produce a measurement of the RWA4 spin-axis pointing. However, in order to improve the accuracy of the estimates, Steps 3-6 (Fig. 5) are repeated three additional times with slews around different spacecraft axes to different unique spacecraft attitudes. Specifically, in addition to the ±45° slews around the Z-axis, the calibration activity also includes ±60° slews around the X-axis, ±90° slews around the Y-axis, and ±30° multi-axis slews that have equal components around the X, Y, and Z axes. After having repeated the calibration activity steps for all 4 pairs of commanded slews, the spacecraft is returned to RCS control and the reaction wheels spun-down until such time as it is determined whether an additional RWA4 articulation is required (to move RWA4 closer to the orientation of RWA1) or whether it is safe with the current RWA4 orientation to reenter RWA control and resume scientific investigations.

The major disadvantage of the RWA controlled calibration method is that it is necessary to assume that RWA4 has been articulated "close enough" to RWA1 in order to use RWA4 to control the spacecraft during the slews used in the calibration activity. So counter-intuitively, RWA4 must be used to control the spacecraft before the calibration analysis has been performed to determine if it is safe to use RWA4 to control the spacecraft. Ordinarily the risk of using RWA4 without any knowledge of its orientation after an articulation would be unacceptable. The reason: if the prime-set of reaction wheels included RWA2, RWA3, and RWA4 but RWA4 was nearly aligned with RWA2 or RWA3 then the spacecraft would have virtually no control authority in the direction of the RWA1 spin-axis (the failed wheel). This would leave Cassini unable to control attitude errors in one direction and any attitude disturbance in that direction would result in an unchecked growth in attitude error. The growing attitude error would ultimately result in system safing and the spacecraft would be returned to RCS control by fault protection commanding. To mitigate the risk associated with using the RWA controlled calibration method, the current plan by the operations team is to use the RCS controlled calibration method (discussed at great length in Section III.B of this paper) to produce a coarse measurement (approximately ±3° error) of the RWA4 spin-axis pointing. Once the RCS controlled calibration method is used to determine that RWA4 has been articulated so that the RWA4 spin-axis pointing is within 10° of the orientation of RWA1, there is no longer any risk associated with using the more accurate RWA controlled calibration method to refine the measurement of the current RWA4 spin-axis pointing.

The RWA controlled calibration method was extensively tested in the Cassini ITL. The ITL testing included 12 end-to-end simulations in the testbed of the calibration procedure. The spacecraft body rate telemetry from one of these testbed simulations is shown in Figure 6. In Fig. 6 the spacecraft body rate data clearly demonstrated the times at which the X, Y, Z, and multi-axis slews begin and end. Also evident in this figure is the fact that each of the slews is performed at a different turn rate and the sizes of each pair of slews varies. Each of the four attitudes that the spacecraft slews to during the test are unique.

Based on the telemetry from the RWA controlled calibration activity, the RWA4 spin-axis vector in the spacecraft body frame can be calculated as in Eq. (3).

$$\bar{u}_4 = \frac{1}{I_{RWA4}}\left[\frac{1}{n}\sum_{i=1}^{n}\left({}^{I}C_{t_i}^{B}\omega_{rwa4}^{R}(t_i)^{B}\right) - \frac{1}{m}\sum_{j=1}^{m}\left({}^{I}C_{t_j}^{B}\omega_{rwa4}^{R}(t_j)^{B}\right)\right]^{-1}\left[\left(\frac{I_{RWA2}}{m}\sum_{j=1}^{m}\left({}^{I}C_{t_j}^{B}\omega_{rwa2}^{R}(t_j)^{B}\right) - \frac{I_{RWA2}}{n}\sum_{i=1}^{n}\left({}^{I}C_{t_i}\omega_{rwa2}^{R}(t_i)^{B}\right)\right)\bar{u}_2 + \left(\frac{I_{RWA3}}{m}\sum_{j=1}^{m}\left({}^{I}C_{t_j}^{B}\omega_{rwa3}^{R}(t_j)^{B}\right) - \frac{I_{RWA3}}{n}\sum_{i=1}^{n}\left({}^{I}C_{t_i}\omega_{rwa3}^{R}(t_i)^{B}\right)\right)\bar{u}_3\right] \quad (3)$$

Although the notation used in Eq. (3) is somewhat long-winded, the formula is effectively stating that the change in the average inertial angular momentum of RWA4 is equal and opposite to the sum of the changes in the average inertial angular momentum of RWA2 and RWA3. Since only the average *magnitude* of RWA4's angular

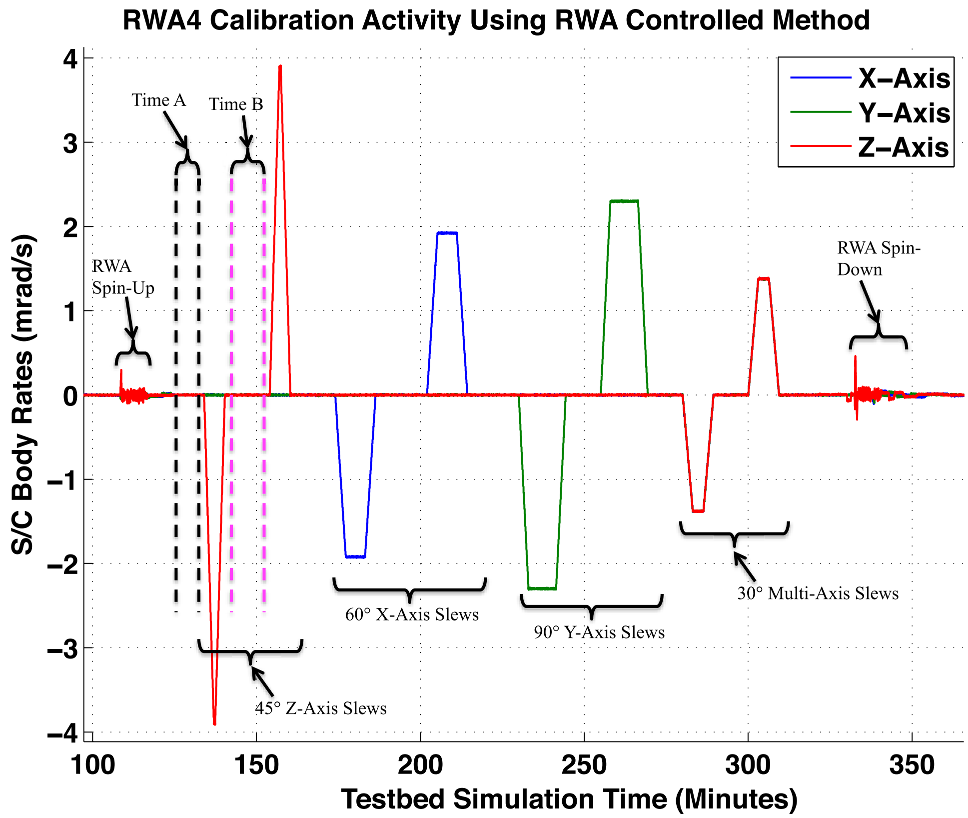

Figure 6. Testbed Simulation Results of the RWA Controlled Method of Calibrating RWA4. *This plot shows the spacecraft body rates during the slews associated with the RWA controlled calibration method. RWA spin-rate and attitude quaternion telemetry would be gathered immediately before the first slew of each pair (Time A) and immediately after the end of the slew (Time B). Four pairs of slews to and from the same initial spacecraft attitude are performed. The telemetry from each pair of turns is used to produce an independent measurement of the RWA4 spin-axis pointing.*

momentum is known from telemetry, the pointing direction of the RWA4 spin-axis, $\overline{u}_4$, is the quantity that the equation is solved for. The direction cosines matrices in Eq. (3), ${}^{I}C^{B}_{t_i}$ and ${}^{I}C^{B}_{t_j}$, are identical to those previously defined in Eq. (2) and the full variable definition for Eq. (3) is supplied in the nomenclature. In Eq. (3) the n data points used to compute the average spacecraft attitude and RWA spin-rates in the summation over variable "i" are gathered during the period of time labeled "Time A" in Fig. 6. "Time A" occurs during the 10 minute pause at the Earth-pointed attitude immediately before the slew to a different attitude is commanded. Similarly, the m data points used to find the average spacecraft attitude and RWA spin-rates during "Time B" are denoted with sub-index "j." The data collected during "Time B" in Fig. 6 occur during the 10 minute pause that occurs after the spacecraft has completed the slew to the non-Earth pointed attitude.

During the testbed trials of the RWA controlled calibration method the AACS team selected various initial articulation positions for RWA4. The primary concern of the AACS team was to determine precisely how far RWA4 could be articulated from the RWA1 orientation without causing the RWA controller to lose attitude control. Astonishingly, the RWA controller[10] proved to be robust to RWA4 misalignments of 40°, and possibly larger since no values greater than this were tested.

In the testbed simulation with RWA4 articulated 40° from RWA1, the attitude control error during the commanded slews never grew larger than 1.5 mrad (0.09°). Although the RWA controller continued to function without any serious performance degradation, the limiting factor became the momentum storage capacity of the reaction wheels. In simulations where RWA4 is used in the controlling set of reaction wheels (along with RWA2, and RWA3) but RWA4 is articulated far from the RWA1 orientation, the spacecraft has reduced control authority in the direction of RWA1's spin-axis. To make up for the lost control authority along that axis, all three of the prime reaction wheels must increase their spin-rates dramatically in order to induce acceleration in the direction of the RWA1 spin-axis. The rapid angular acceleration of the reaction wheels can easily result in the wheels reaching their maximum spin-rate, and this too can lead to system safing. For this reason, although ITL simulations indicate that the Cassini RWA controller can accommodate RWA4 misalignments in the range of 10°-40°, the AACS team has made the operational decision to never use the RWA controlled calibration method unless the results from the *RCS* controlled calibration method (Section III.B) indicate that the articulation angle of RWA4 is within 10° of the orientation of RWA1. This operational rule provides margin against the risk that the reaction wheels might reach their saturation limit, but still provides a 20° wide window (±10° from RWA1) of possible RWA4 articulation angles inside which the RWA controlled calibration method can be used.

During the 12 testbed simulations of the RWA controlled calibration method, the evaluation of Eq. (3) on the testbed telemetry never gave an RWA4 spin-axis error larger than 0.8° from the actual simulated orientation of RWA4. Furthermore, the average spin-axis measurement error from the 12 ITL simulations is less than 0.5°.

Unlike the RCS calibration method (Section III.B), which has never been tested on telemetry from the actual spacecraft, the RWA controlled calibration method has been tested on flight telemetry. Although the slew sequence depicted in Fig. 6 was specifically tailored to give the necessary telemetry to produce a highly accurate measurement of the RWA4 spin-axis, the same procedure can be used for any slews between two unique attitudes. In April 2011, Cassini performed a series of slews that were used to calibrate one of the two IRUs, or gyros. During this gyro calibration the spacecraft was under RWA control, was using RWA1, RWA2, and RWA3 as the three controlling reaction wheels. The series of slews in this gyro calibration provided an excellent dataset to test the RWA controlled calibration method because during this short period of time the spacecraft was not using RWA4 in the prime set of reaction wheels. Recall that Cassini typically uses RWA1, RWA2, and RWA4 as the prime reaction wheel set due to elevated drag in RWA3 (the backup reaction wheel). However, for several weeks in 2011 the AACS team reactivated RWA3 and turned off RWA4 in order to assess the health of the long dormant RWA3. Since RWA4 was articulated to the RWA3 orientation in 2003, there is more uncertainty in the mounting of RWA4 than in any of the other three fixed orientation reaction wheels. Therefore, to test the RWA controlled calibration method on the flight telemetry the AACS team gathered the RWA spin-rate data from RWA1, RWA2, and RWA3 during the gyro calibration slews as well as the attitude quaternions before and after each slew. The AACS team then evaluated a modified version of Eq. (3) where it was temporarily assumed that the orientation of RWA1 was unknown but the orientation of RWA2 and RWA3 was known perfectly. In actuality the orientation of RWA1, RWA2, and RWA3 are all known to within tenths of a degree. When the formula in Eq. (3) was computed to find the spin-axis of RWA1 the resulting spin-axis measurement was just 0.41° from the known orientation of that reaction wheel. This "flight test" of the RWA controlled calibration method has validated the approach used in this method and has provided confidence that the ITL simulations match flight behavior. Based on the results of this analysis, AACS expects that the RWA controlled calibration method to produce spin-axis measurements that are within 1° of the actual RWA4 orientation following an articulation. By using a combination of the RCS controlled calibration method with its expected ±3° error and then using the RWA controlled calibration method with its ±1° error it should be possible for AACS to easily determine whether RWA4 is close enough to the orientation of RWA1 in order to permanently replace that RWA.

IV. Conclusion

As Cassini's exploration of Saturn continues, the spacecraft hardware continues to age. Two of Cassini's reaction wheels, RWA1 and RWA2, are expected to pass their 4 billion revolution qualification limit in late 2012, sometime around the 15 year anniversary of Cassini's 1997 launch. The fact that all four of Cassini's reaction wheel function without any performance degradation is a testament to their quality design and construction. However, all four reaction wheels have exhibited periods of elevated drag that indicate that the wheels are continuing to accumulate wear.[4] Of the RWAs currently in use, RWA1 experiences significantly higher drag than either of the other prime wheels. If RWA1 were to fail at some point in the mission the AACS team must be prepared to articulate RWA4 to replace the failed hardware.

Due to limitations in the design of the articulation motor used to reorient RWA4, there is no indication from the articulation motor (ARWA) telemetry as to the precise orientation of RWA4 following an articulation. Since there is no hard-stop for the articulation motor at the RWA1 orientation or any other sufficiently accurate indication of when RWA4's orientation matches RWA1, the AACS team has developed two independent methods that can be used to determine the spin-axis pointing of RWA4. The first method, referred to as the RCS controlled calibration method, is performed while the spacecraft is in RCS control and uses a period where the spacecraft attitude is allowed to drift in order to use the principle of angular momentum to determine the spin-axis orientation of RWA4. Testbed simulations of the RCS controlled calibration method have demonstrated that the AACS team can expect to produce measurements of the RWA4 spin-axis pointing that are within ±3° of the actual RWA4 orientation. The second calibration method that has been developed by AACS is referred to as the RWA controlled calibration method. In this calibration method RWA4 is used as part of the prime set of controlling reaction wheels, along with RWA2 and RWA3, while performing slews to and from various attitudes. Again, using this method, the principle of conservation of angular momentum is invoked to determine the RWA4 spin-axis orientation. While the RWA controlled method has the serious limitation that it can only be used if RWA4 is known to have been articulated to within 10° of the RWA1 orientation, the method does, however, produce more accurate spin-axis measurements that the AACS team believes will be within ±1° of the actual RWA4 orientation. Both calibration methods have been expanded into full operational procedures and the Cassini AACS team has tested both methods extensively in the Cassini ITL. Although there is currently no reason for the AACS team to believe that RWA1 will fail in the immediate future, the team is nevertheless prepared to respond to such a failure if it were to occur.

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