The Cassini Reaction Wheels: Drag and Spin-Rate Trends from an Aging Interplanetary Spacecraft at Saturn

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The purpose of this paper is to provide a summary of the long-term trends of the estimated drag torque and spin-rates of the Cassini reaction wheel assemblies during 11 years of intensive science operations at Saturn. Reaction wheel failure is a common fault for long-lived spacecraft, and in some cases can result in the loss of a mission. For this reason, it is important for spacecraft operators to closely monitor the health and behavior of operational reaction wheels to potentially identify trends or signatures in the reaction wheel telemetry that could portend forthcoming issues. This paper will present the historical trends in the estimated reaction wheel drag torque at various spin-rates over the course of the mission. The objective of this paper is to provide the aerospace community with examples of the types of aging trends that have been observed on Cassini's reaction wheels as an in-flight example of real-world hardware performance. The Cassini reaction wheels usage and drag torque trends are of interest to the larger aerospace community because Cassini's wheels have been operated continuously for over 11 years of science operations, and the Cassini RWA's are frequently run through their full range of possible spin-rates, which gives the Cassini operations team a rich data set to use for health monitoring and trending of real-world reaction wheels.

Acronyms

AACS	=	attitude and articulation control subsystem
ATLO	=	assembly, test, and launch operations
DSN	=	deep space network
ESA	=	European Space Agency
NASA	=	National Aeronautics and Space Administration
HGA	=	high gain antenna
IRU	=	inertial reference unit (gyroscope)
RBOT	=	reaction wheel bias optimization tool
RCS	=	reaction control system
RTG	=	radioisotope thermoelectric generator
RWA	=	reaction wheel assembly
SRU	=	stellar reference unit (star tracker)

I. Introduction

THE Cassini spacecraft launched from Earth in 1997 to begin a multi-decade long mission to explore the planet Saturn and its moons.[1] Cassini-Huygens is a joint NASA and ESA project that consists of the NASA Saturn orbiting Cassini spacecraft and the ESA Huygens probe designed to parachute to a landing on Titan's cloud shrouded surface, which it did successfully in 2005.[2] During its seven-year cruise to Saturn, Cassini performed gravity assist flybys of Venus (twice), Earth, and Jupiter. Cassini ultimately arrived at Saturn and performed an orbit insertion maneuver in 2004 to begin the very successful prime science mission, which lasted 4 years, until 2008.[1] Cassini then successfully completed the Equinox extended mission (2008-2010)[3] and is currently 5 years into the 7-year Solstice extended-extended mission.[4] The Cassini spacecraft has now passed 18 years of flight, with

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just 2 years of planned life remaining before the scheduled dramatic disposal of the spacecraft with an intentional collision with Saturn in September 2017.

The Cassini spacecraft is a large 3-axis stabilized observatory, which has the ability to maintain attitude control either using a set of eight 1 N Reaction Control System (RCS) thrusters, or Cassini can be controlled using the Reaction Wheel controller.[5,6] Although Cassini primarily used the RCS thruster controller for attitude control during the 7 year cruise to Saturn, the spacecraft now spends >99% of the time using reaction wheel control, and the Reaction Wheel Assemblies (RWAs) are spun-down only infrequently and powered off for Main Engine maneuvers[7] and RCS controlled close flybys of Titan[8,9] or other Saturnian moons.[10,11,12] The precise pointing provided by the reaction wheels is vital for many of the science observations performed by Cassini.

Cassini's RWA are not believed to be either the oldest continuously operating RWAs, nor are they the wheels with the most revolutions, but Cassini does have the distinction of being the most distant spacecraft from the Earth to have ever carried reaction wheels (NASA's Pioneer 10 and 11, Voyager 1 and 2, and New Horizon spacecraft all used RCS control or were spin stabilized), and even after 18 years of flight, including 11 years of intensive RWA use at Saturn, all 4 of Cassini's reaction wheels continue to function and can be used to meet science pointing requirements.

Cassini carries 4 identical 36 Nms Reaction Wheel Assemblies (RWAs) as shown in Figure 1; three of those RWAs are used simultaneously by the RWA controller to maintain spacecraft attitude control, while the fourth RWA is generally powered off and kept as an in-flight spare.[13] Three of Cassini's RWAs (RWA1, RWA2, and RWA3) are fixed to the spacecraft bus in an orientation where the wheel spin axes are mutually orthogonal to each other and their spin axes are also equidistant from the spacecraft's Z-axis, which is the High Gain Antenna (HGA) pointing axis. This arrangement gives each of the reaction wheels an equal amount of control authority around the most commonly used spacecraft rotation axis. The fourth RWA (RWA4) is attached to a single-axis articulation motor, which allows that reaction wheel to be reoriented to precisely the same orientation as any of the other

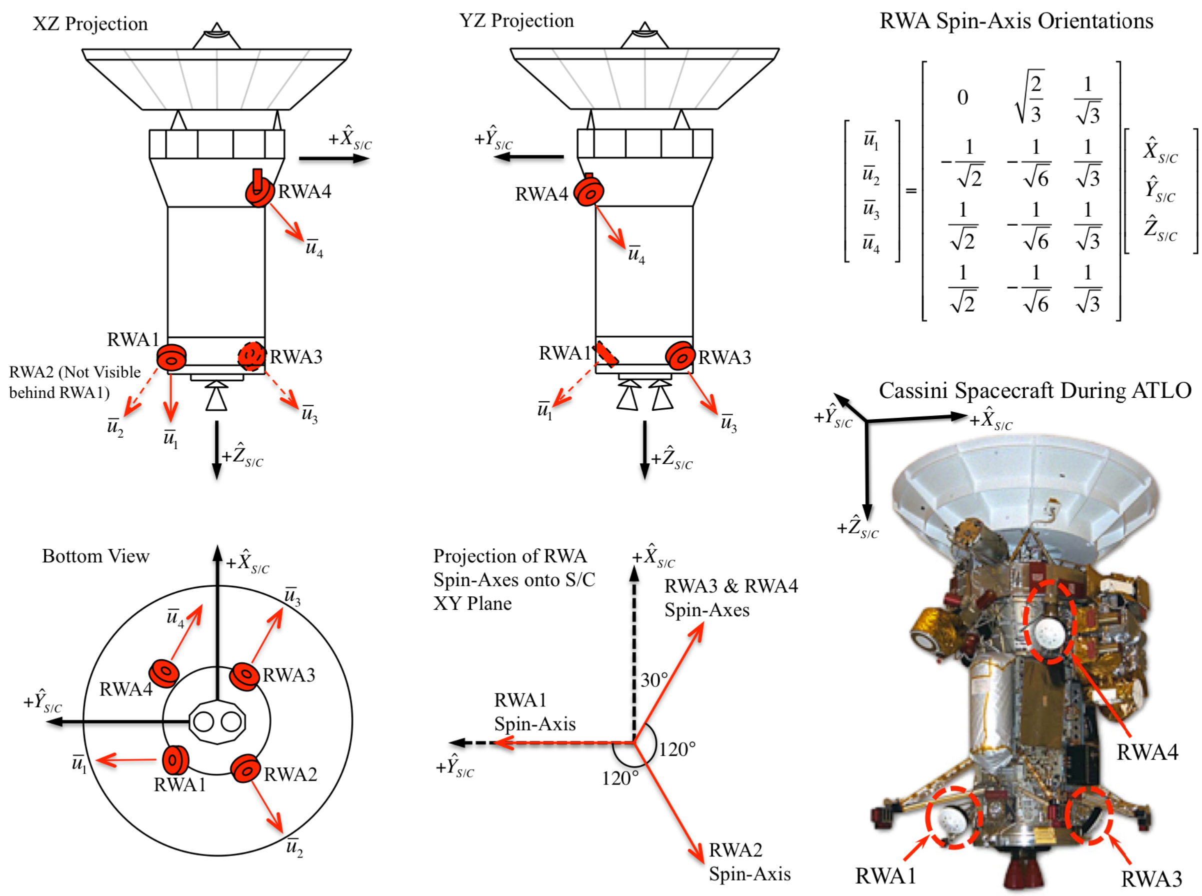

Figure 1. Cassini Reaction Wheel Assembly Mounting. *This schematic depicts the mounting location of the four Cassini reaction wheels (labeled RWA1-RWA4), along with the angular momentum direction of each RWA. RWA4 is currently co-aligned with RWA3, though in the ATLO photo RWA4 was co-aligned with RWA1.*

reaction wheels.[14] With the articulated RWA, Cassini possesses redundancy to protect against the failure of any single reaction wheel, and, given the proper alignment of the articulated RWA, can maintain precise attitude control without any performance degradation using any 3 of the 4 RWAs. The Cassini reaction wheel controller flight software does not allow for more than 3 wheels to be used in the control loop, though the hardware of all four reaction wheels can be spun simultaneously if desired.

Much has been previously written and presented about the Cassini reaction wheels.[6,14,15,16,17,18] The journal article by Lee and Wang[15] should be considered the authoritative text on the specific examples of RWA drag spikes as well as background bearing drag physics, and this investigation is not intended to revisit the same information previously shared. This paper instead focuses on long-term trends in the RWA telemetry. There are trends in the Cassini RWA drag torque telemetry, which do not show up in the telemetry from a single day, but rather unfold slowly over the course over several months or years and these long-term trends have been unreported in previous presentations on Cassini's RWAs. Each of the Cassini RWAs has shown incidents of anomalous RWA drag torque events at some point in their history, but presenting a piecemeal sampling of individual drag spike events provides nothing more than anecdotal evidence of the RWA health. Examining the long-term RWA drag torque trends provides the only method to quantitatively observe whether the RWA drag torque has changed, or is changing, over the course of the mission.

II. Operational Use of the Cassini Reaction Wheels

Cassini carries 12 major science instruments, including remote sensing cameras and spectrometers as well as electric and magnetic field antennas, and dust and charged particle detectors.[1] The majority of the instruments are fixed to the spacecraft and lack the ability to articulate, and as a consequence, the Cassini RWAs are subjected to frequent large changes in spin-rate and frequent spin direction reversals as the Cassini spacecraft slews to point the science instrument at desired science targets. While the RCS controller could be used to reorient the spacecraft, it is only with the RWA controller that the spacecraft is able to achieve the accuracy and stability necessary for many of the science observations.[19] An intense day of science observations, when the spacecraft is close to Saturn or one of its moons, will commonly have hundreds of commanded slews and the RWAs will change spin-rate by >2000 rpm, potentially including multiple spin direction reversals (referred to as "zero crossings").

To avoid dwelling at low wheel spin-rates (which could damage the RWA lubricant and bearings)[15], the RWAs are "biased" frequently to pre-selected non-zero spin-rates. To perform a reaction wheel bias, the spacecraft is transitioned from RWA to RCS control and the wheels are commanded to change their spin rate while the RCS thrusters hold the spacecraft attitude.[20] After the bias, Cassini is returned to RWA control and science operations continue. Cassini executes RWA biases at a frequency of approximately once every 3-4 days. In practice, Cassini experiences negligible external torques due to solar radiation pressure or thermal radiation pressure from the radioisotope thermoelectric generators (RTGs), and the spacecraft is generally too far from Saturn and its moons to experience significant gravity gradient or atmospheric torques. For this reason, when Cassini performs a reaction wheel biasing activity, this should not be though of as "momentum dumping," but rather as the spacecraft changing from one predetermined non-zero momentum state to a different pre-determined non-zero momentum state. Each RWA bias is designed so that, throughout the 3-4 day "segment" in RWA control, low-spin-rate dwell time is minimized and peak spin-rates are kept below a maximum threshold.

The prime set of RWAs used in RWA control mode on Cassini is currently RWA1, RWA2, and RWA4. RWA3 was a member of the prime set from the first use of RWA control (March 2000) until July 2003 (about one year before reaching Saturn). However, RWA3 exhibited several instances of rough and elevated drag torque, which was interpreted to be caused by dry cage instability.[15] Despite the unexpected elevated drag torque shown by RWA3, the RWA controller was still able to meet all pointing accuracy requirements. Nevertheless, as a preemptive protective measure, in 2003 RWA4 (the unpowered backup RWA) was articulated so that its spin-axis was precisely aligned with the spin-axis of RWA3, and RWA3 was demoted to backup hardware status and the prime set of reaction wheels was changed to consist of RWA1, RWA2, and RWA4.[5] Since 2003 RWA3 has been regularly exercised as part of an engineering maintenance activity that spins the wheel to 100 rpm in each direction every 3 months, and RWA3 was used briefly in the prime set of the reaction wheels in 2011 as part of an engineering test. Since RWA3 lacks sufficient telemetry to perform reliable trending, this paper will instead focus on the RWA drag torque trends of RWA1, RWA2, and RWA4.

On Cassini, RWA controlled spacecraft slews are designed by spacecraft operators using ground tools to create commands for science pointing sequences. Spacecraft slews using the reaction wheel controller use profiled turn rate and accelerations that are limited on a per-axis basis relative to the spacecraft body frame (the Cassini body frame is shown in Figure 1). The RWA controlled spacecraft turn rate limits are [X, Y, Z] = [1.92, 2.3, 3.9] (mrad/s)

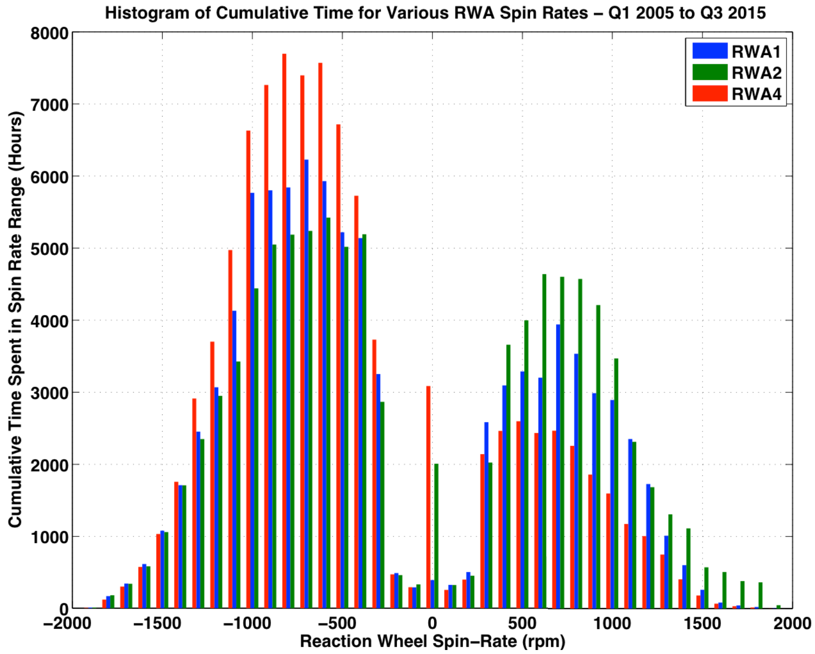

Figure 2. Cassini Reaction Wheel Usage During Mission. *These histograms show the cumulative time that each of the prime RWAs (RWA1, RWA2, and RWA4) have spent spinning in different spin-rate ranges. The RWAs are used across their entire effective range (-1850 to +1850 rpm) but spent the most time in the ±500-1000 rpm range. Wheels are spun counterclockwise (negative) more often than clockwise due to the direction of multi-revolution spacecraft slews performed for science purposes.*

and the spacecraft turn acceleration limits are [X, Y, Z] = [0.01, 0.013, 0.022] (mrad/s^2). Using these turn rates and accelerations the spacecraft can complete a 180 degree slew around the Z-axis in ~16 minutes and ~25-30 minutes for the X and Y axes.

Once a sequence of science slews has been designed, the Attitude and Articulation Control Subsystem (AACS) team uses a ground tool called RBOT (reaction wheel bias optimization tool)[16,15], which runs an optimization algorithm to choose the optimal initial momentum of the RWA's to ensure that RWA spin-rate during the science sequence complies with ground levied constraints. These constraints include: (1) the magnitude of the planned RWA spin-rate is never permitted to exceed 1850 rpm, (2) the time that the RWA's spend spinning slower than 300 rpm shall be minimized, and (3) for RWA spin-rate magnitudes between 300 and 1850 rpm, slower spin-rates shall be given a slight preference. The constraint on time spent below ±300 rpm is imposed partly to avoid the adverse pointing error and controller transient at the moment that an RWA changes its spin-direction, but time spent spinning below 300 rpm is actively avoided primarily because it is believed that below this spin-rate the RWAs experience excessive mechanical bearing wear, which can be avoided if the RWAs are spun sufficiently fast in order to properly distribute bearing lubricant.[15] The AACS team computed the 300 rpm keep-out zone threshold specifically for the Cassini RWAs based on the surface roughness and lubricant properties of the Cassini RWA bearings[5], and as such, this limit does not necessarily apply to RWAs fabricated by other manufacturers.

The RWA spin-rate history for RWA1, RWA2, and RWA4 between January 1, 2005 (which was shortly after Cassini entered Saturn orbit) and September 30, 2015 is shown in Figure 2. In Figure 2, the ~11 years of RWA spin-rate telemetry has been divided into 100 rpm wide bins and the data is histogrammed for each reaction wheel. The Cassini RWA hardware can spin as fast as ±2020 rpm, but the operations team limits the planned spin-rate to ±1850 rpm. The unused spin-rate margin between 1850-2020 rpm allows for attitude control transients when the spacecraft transitions between IRU and SRU based attitude estimation modes, as well as gradual momentum accumulation due to unpredictable external torques. However, due to the RBOT optimization process[16,17,18] used to select planned RWA spin-rate profiles, the RWAs tend to spend the majority of their operating hours between ±300-1200 rpm. As seen in Figure 2, the median spin-rate magnitude for each wheel is between 500 and 800 rpm in both spin directions. RWA spin-rates below 300 rpm or above 1200 rpm tend to be associated with short duration spacecraft slews, when the RWAs are actively accelerating or decelerating the spacecraft. In total, RWA1 and RWA2 have now exceeded 5 *billion* total revolutions, and RWA4 is approaching 5 billion revolutions as well.

One of the most striking features of the RWA spin-rate history shown in Figure 2 is the asymmetry in spin direction. RWA1 (in blue) and RWA4 (in red) have accumulated significantly more hours of operation spinning in the negative (counterclockwise) direction than in the positive (clockwise) spin direction, while RWA2 follows the

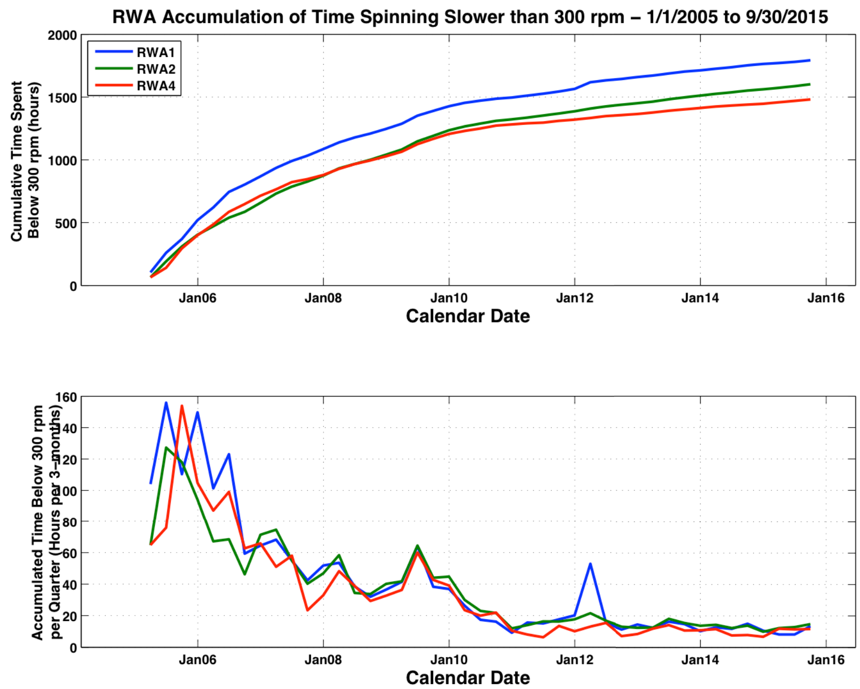

Figure 3. Cassini Reaction Wheel Time Spent at Low Spin-Rates. *The total accumulated time spent spinning at a spin-rate below ±300 rpm for each prime RWA over the course of the mission is shown in the upper plot. The new accumulation of time spent spinning slower than 300 rpm (the slope of the upper plot) is shown in the lower figure. These plots demonstrate the increasing effectiveness of the AACS team in limiting the time the reaction wheels spent in the ±300 "keep-out" zone of spin-rates.*

same trend but to a much lesser extent. The asymmetry in the data is due to a frequent type of science slew that the spacecraft performs. Several of the electric/magnetic fields and particle detecting instruments mounted on Cassini collect superior data when the spacecraft is rolling around a fixed body axis. Although Cassini does not roll continuously, during 9 hour long communication passes with NASA's Deep Space Network (DSN), Cassini will often perform an 8-hour multi-revolution roll around the High Gain Antenna (HGA) pointing direction. These "downlink roll" activities improve science data quality for several instruments without interfering with the data playback, and as such these activities are executed during the majority of telecom downlink sessions. Although the direction of the multi-revolution downlink roll was arbitrarily chosen early in the mission, the same roll turn direction is always used. The direction of the downlink rolls causes all three operating reaction wheels to accelerate in the same direction, and the RBOT optimizer more often finds globally optimal spin-rate solutions with the reaction wheels spinning in the negative direction; thus the asymmetry in Figure 2.

Another observation based on Figure 2 is the large spike visible at 0 rpm for the RWA's. The data bin that is plotted at 0 rpm includes all RWA spin-rate telemetry collected, including data when the RWAs were fully spun down and powered off for periods of RCS control, and as such the data in the 0-rpm bin is dominated by inactivity of the RWAs rather than reflecting real RWA use.

The process of running the RBOT ground tool to limit the amount of time that the RWA's are spinning slower than ±300 rpm[16], along with additional steps that the AACS team performs to hand-modify select science observations to further reduce "low-rpm" dwell has been a complex, time consuming, and continually evolving operations process.[17,18] Over several years of operations the project engineers and scientists have learned several methods that they can use to design observations that are less likely to result in low-rpm time for the RWAs, and the AACS team has become increasingly savvy at finding minimally intrusive changes to the reaction wheel biasing strategy and to the science observations themselves that reduce the total low-rpm time accumulation.[18] The effectiveness of this RBOT process in limiting the total low-rpm time can be empirically gauged by plotting the total number of hours that each of the RWAs has spent spinning slower than ±300 rpm over the course of the science mission (Figure 3). In Figure 3 the accumulation of the low-rpm time between 1/1/2005 and 9/30/2015 is shown in the top half of the plot and the slope (i.e. the derivative) of these curves is shown in the lower half of the plot, where the data is divided into 3 month long periods in order to compute the accumulation rate. Note that between 2005 and 2007, which is the oldest telemetry shown, the RBOT process was already being used to limit low-rpm time accumulation, but in a much less strictly enforced sense than it would later be applied. As a consequence of the operations team improving the RBOT process and more strictly limiting the low-rpm accumulation from science observations, the total quantity of low-rpm time accumulated by RWA1, RWA2, and RWA4 each quarter has fallen from as much as ~120 hours of low-rpm time per wheel to as low as ~10 hours of low-rpm time per wheel per quarter. The pace of low-rpm time accumulation has remained effectively constant since 2011, which demonstrates that the RBOT process, as currently performed, has reached the practical limit of its effectiveness in limiting low-rpm accumulation. The achieved low-rpm time accumulation rate for the Cassini RWAs (10 hours of low-rpm time every 3 months) amounts to the wheels spinning below ±300 rpm during only 0.4% of the time that the wheels are operating. Furthermore, since the RWAs accumulate fewer revolutions per unit of time when they are spinning slowly, the proportion of RWA revolutions that occur while the RWAs are in a regime that is believed to cause excessive bearing wear is fleetingly small. In theory, the substantial effort expended by the operations team in limiting RWA low-rpm time pays dividends in RWA longevity because the rate at which the RWA bearings accumulate mechanical wear is being minimized as much as is practical. The Cassini project sequence development schedule has been tailored to permit science pointing adjustments and in some cases deletion of lower-priority science observations so that low-rpm dwell can be minimied. While it remains impossible to prove empirically that the efforts of the AACS team with the RBOT process unequivocally protects RWA health or prolongs RWA life, the AACS team nevertheless continues to diligently perform the RBOT process knowing that it has the best chance of helping RWA health among any known ground operator actions.

III. Cassini RWA Drag Torque History

As a result of the thousands of spacecraft slews and tens of thousands of hours of precise pointing across 11 years of continuous science operations at Saturn, the Cassini RWAs have received considerable wear. The Cassini Attitude and Articulation Control Subsystem (AACS) continues to monitor the RWA telemetry from Cassini daily and has diligently trended the RWA telemetry across more than one decade of science operations to monitor any disturbing trends or signs of performance degradation. The drag characteristics of the Cassini RWAs have changed appreciably over the course of the mission and all of the wheels have demonstrated at least some periods of elevated or "rough" drag telemetry or drag spikes.[15] Each of the Cassini RWAs has shown its own unique drag torque characteristics and the behavior of each of the wheels has changed over several years, so it is difficult to summarize 11 years worth of RWA quirks in the space of a few sentences.

Speaking generally, the drag torque behavior of the four Cassini RWA's can be described as follows: RWA1 and RWA3 are the two more troublesome wheels[5,15], while RWA2 and RWA4 are better behaved. RWA1 in particular has shown higher levels of drag torque than the other wheels throughout the entire mission at Saturn, and the telemetry from RWA1 is quite frequently punctuated by spikes in the estimated drag torque and is very seldom smooth, even when the RWA is left spinning at a constant spin-rate for an extended period of time.[15]

RWA3 was the reaction wheel that exhibited alarming bouts of what the team believes was dry cage instability[15] within one or both of the reaction wheel bearings during the years preceding the arrival of Cassini at Saturn. Since RWA3 was demoted to a backup role before the science mission at Saturn even commenced, RWA3 has accumulated far fewer hours of operation than any of the other RWAs. Yet although RWA3 is the "youngest" of the Cassini RWAs in terms of accumulated revolutions and hours of operations, RWA3 remains the least trusted of the Cassini RWAs in the minds of the spacecraft operators. This judgement was confirmed when RWA3 was tested for 7 weeks of science observations (it replaced RWA4 in the prime set) during the spring of 2011. Its very rough and large drag torque signature was clearly evident towards the end of the test.

For the prime set of RWAs that has been used during the Cassini science mission at Saturn (RWA1, RWA2, and RWA4), the operations team has an extensive data set of telemetry for RWA spin-rate, RWA total torque applied, as well as the flight software estimated RWA drag torque. The Cassini flight software includes a PI (proportional-integral) estimator which produces an estimate of the RWA drag torque to be used to compensate the commanded torque in the reaction wheel control loop, as well as being a useful quantity to monitor in telemetry and as part of error monitors in the onboard fault protection logic.[13,15] There are known limitations to this flight software drag torque estimate; first, the estimate is smoothed compared to the raw torque data and, as such, general characteristics of the relative noise of the data as well as transient events can be blunted or fully removed as a result of the smoothing.[15] Second, the drag torque estimate tends to produce poor estimates of the actual drag if the RWA is not spinning at a nearly constant spin-rate. That means that the drag torque estimator's data is suspect whenever the reaction wheels are being actively accelerated or decelerated (e.g. while the spacecraft is slewing). Nevertheless, due to the limited bandwidth of the telemetry returned from Cassini 1 billion miles away at Saturn, the drag torque estimate channel is still the best piece of telemetry from the spacecraft that the operations team can monitor in order to search for long-term trends in reaction wheel health.

The long-term trending of the RWA drag torque telemetry is performed on 3-month long segments of telemetry (quarter annum). The RWA spin-rate and RWA drag torque estimate data from the 3-month period is sorted based on the spin-rate, and divided into bins 100 rpm wide (-1850 to -1750 rpm, -1750 to -1650,…,-50 to +50, …, +1750 to +1850 for a total of 37 bins). The corresponding RWA drag torque estimates for times associated with the spin-rate data from each bin is gathered and the average RWA drag torque is computed from all drag torque estimate data that is included in the bin. Averages are used instead of medians because the team wants to retain the effects of drag torque spikes and other transient events in the trending data. Following this strategy the operations team is left with average RWA drag torque estimates for 37 different ranges of RWA spin-rates, and that represents just the data from a single 3-month period of telemetry. The operations team then plots the computed average drag torque values as a function of spin-rate for every single 3-month query period between 2005 and 2015. The resultant plots of average RWA estimated drag torque vs. spin-rate for RWA1, RWA2, and RWA4 will now be examined individually. Since the numbering of the RWA's is arbitrary, and since RWA1 is an outlier, we will begin by examining the trending data from RWA4.

The trending history of the RWA4 estimated drag torque is shown in the left-hand plot of Figure 4, where three variables (spin-rate, RWA drag, and time) are being simultaneously displayed: the average estimated RWA drag torque is shown on the Y-axis as a function of RWA spin-rate (shown on the X-axis) for the 37 bins of RWA spin-rate ranges. The change in the average estimated RWA drag torque over time is shown in Figure 4 using the color map where cooler shades correspond to older data and warmer shades correspond to more recent data. The right hand plot in Figure 4 is simply the difference between the data shown on the left and the analytical prediction of the RWA drag torque for RWA4 based on pre-launch measurements of the RWA drag. The right hand plot of Figure 4 can be thought of as the normalized version or residual of the data in the left-hand plot. The right-hand plot in Figure 4 is useful to trending because changes in drag torque relative to the predicted level are more pronounced. In both plots the data from the most recent data set (July-September 2015) is highlighted with large black dots for additional visibility.

The RWA4 trending data show in Figure 4 demonstrates expected "aging" behavior for the RWA based on the gradual accumulation of wear and tear. The data in Figure 4 shows that RWA4 initially (2005-2007) exhibited lower drag torque levels at nearly all spin-rates and then plateaued and drag torque estimates remained nearly constant for nearly all spin-rate ranges from 2008-2012, and then between 2013-2015 the drag torque estimates began to creep to progressively higher values. The data from the most recent quarter of telemetry stands at or near the highest drag levels seen for RWA4 at any point in the mission for all spin-rate ranges. The behavior of RWA4 matches what one would intuitively expect; there was less drag when the wheel was younger and more drag when the wheel was older. However, some additional words are necessary to explain the "saw tooth" appearance in the RWA4 telemetry between -300 and +300 rpm. Between 2005-2010 RWA4 exhibited a behavior where the wheel would have elevated drag torque in the minutes or hours immediately following a zero crossing (zero-crossings refer

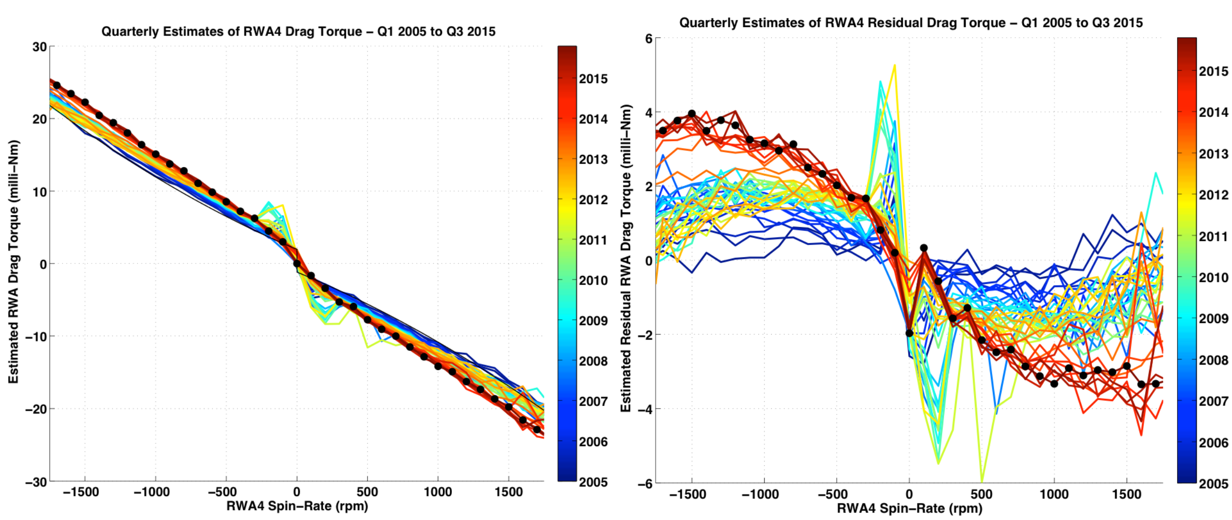

Figure 4. History of the RWA4 Estimated Drag Torque. *The average estimated RWA drag torque over the course of the science mission as a function of reaction wheel spin-rate is shown in the left-hand plot. The difference between the expected RWA drag torque and the observed RWA drag torque (i.e. the residual RWA drag torque) is shown on the right-hand plot. Cooler shades correspond to older telemetry while warmer shades correspond to more recent telemetry. The most recent RWA drag torque data (based on telemetry from July-Sept. 2015) is highlighted with large black dots on both plots for additional visibility.*

to spin direction changes). This is a behavior that was observed for RWA1, RWA2, and RWA4, but in the case of RWA4, the wheel ceased exhibiting the behavior after ~2012. It should also be noted that the drag torque behaviors between -300 and +300 rpm are suspect because RBOT severely limits the amount of time that the wheels dwell in this spin-rate range, which means that the data is predominantly from periods where the RWA's were accelerating and passing through the region without dwelling. As previously noted, the RWA drag torque estimator in the flight software is not accurate when the RWA is changing its rate, which means the trending data for spin-rates below ±300 should not be given too much weight. That said, the limited data for spin-rates below ±300 rpm are still the best data available for trending purposes, despite the limitations.

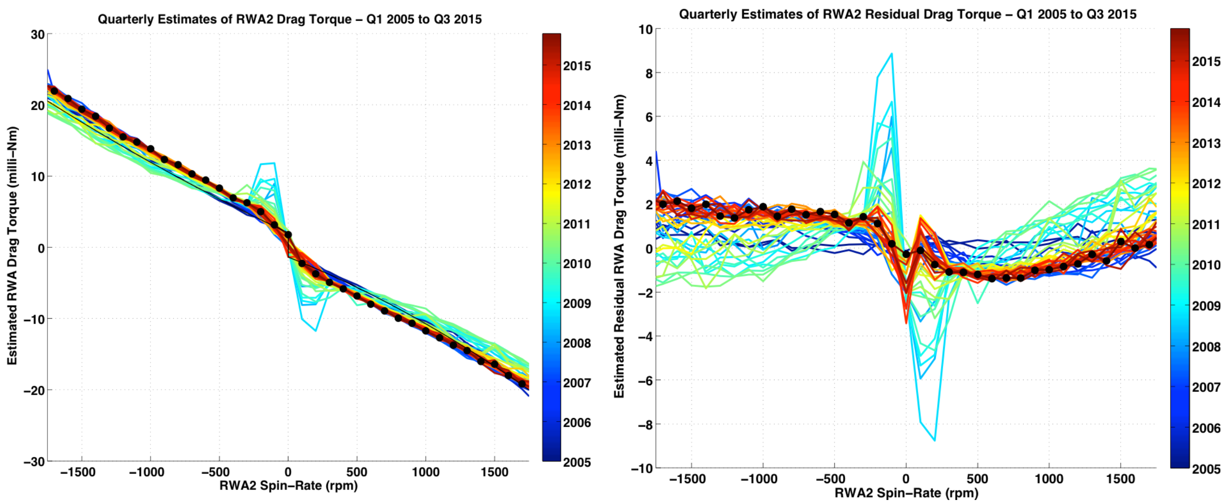

Figure 5. History of the RWA2 Estimated Drag Torque. *The average estimated RWA drag torque over the course of the science mission as a function of reaction wheel spin-rate is shown in the left-hand plot. The difference between the expected RWA drag torque and the observed RWA drag torque (i.e. the residual RWA drag torque) is shown on the right-hand plot. Cooler shades correspond to older telemetry while warmer shades correspond to more recent telemetry. The most recent RWA drag torque data (based on telemetry from July-Sept. 2015) is highlighted with large black dots on both plots for additional visibility.*

From the RWA4 drag torque trending, the AACS team would conclude that RWA4 is showing a slight amount of bearing degradation and increased drag. However, the current pace of drag torque increase, which is at most about 5 milli-Nm of increase in 4 years is so slow that this does not pose a threat to continued use of the RWA between now and the end of the mission in 2017.

The RWA2 estimated drag torque trending data is shown in Figure 5. Similar to the data from RWA4 (Fig. 4), RWA2 also shows pronounced "saw teeth" in the data between -300 rpm to +300 rpm. As previously noted, the data from that spin-rate range is under sampled since the AACS team avoids operating the RWA in that region. However, also similar to RWA4, the "saw teeth" so evident in the data during 2008-2010 were largely absent before that period and after that period. Unlike the data from RWA4, RWA2 showed a counterintuitive aging trend. For most of the spin-rate ranges, RWA2 actually showed a decrease in estimated drag torque between 2005 and 2010. This is evident in that the darker blue shades are actually higher than the light blue and green shades in Figure 5. In fact, RWA2 showed lower drag torque in 2010 than measurements made for that wheel more than 13 years earlier pre-launch. After 2010, the RWA2 drag torque telemetry trend reversed and RWA2 drag increased at nearly all spin-rate ranges and the RWA drag returned to values that were previously seen in ~2005. However, between 2012 and 2015 there has been no appreciable change in the estimated RWA2 drag torque. From this the AACS team would conclude that the RWA2 trending data gives no reason to suspect that the RWA will not be able to support an additional 2 years of operations, and that the RWA2 data from 2015 was nearly identical to the RWA2 data seen in ~2005-2006.

The RWA1 drag torque trending data is shown in Figure 6. As previously noted, RWA1 has long been the "troublesome" reaction wheel. On a general day of operations the estimated drag torque of RWA2 and RWA4 are nearly perfectly smooth, but the drag torque of RWA1 typically shows either roughness or oscillations with a period of 0.5-1 hour between high and low drag torque levels. RWA1 has shown the largest drag spikes and, throughout the mission, has shown drag torque levels significantly higher than the pre-launch measurements. In the RWA1 drag torque trending data in Figure 6 the reader should note that the RWA1 drag torque levels are generally higher than the data from RWA2 and RWA4 at nearly all spin-rate ranges. RWA1 shows particularly large drag torque

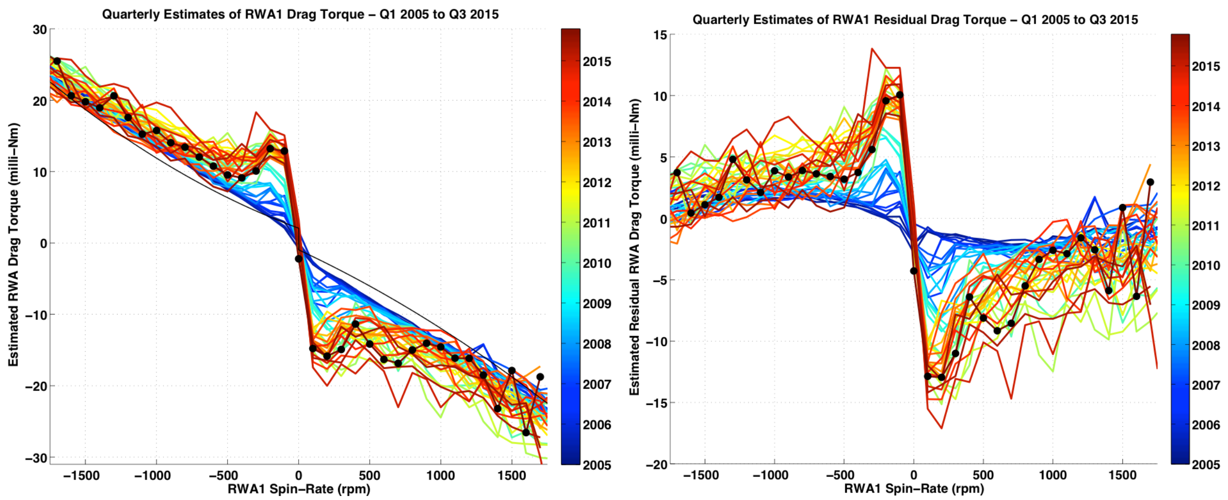

Figure 6. History of the RWA1 Estimated Drag Torque. *The average estimated RWA drag torque over the course of the science mission as a function of reaction wheel spin-rate is shown in the left-hand plot. The difference between the expected RWA drag torque and the observed RWA drag torque (i.e. the residual RWA drag torque) is shown on the right-hand plot. Cooler shades correspond to older telemetry while warmer shades correspond to more recent telemetry. The most recent RWA drag torque data (based on telemetry from July-Sept. 2015) is highlighted with large black dots on both plots for additional visibility.*

levels below ~±800 rpm. The "saw tooth" effect in the -300 to +300 range previously seen in RWA2 and RWA4 is significantly more pronounced in the data from RWA1 and, unlike the other wheels, which eventually stopped showing that behavior, RWA1 continues to show large drag torque spikes immediately after there is a zero-crossing (spin-rate direction reversal) to this day. Drag torque levels on RWA1 tended to grow slowly but continually between 2005 and 2010 to the point where the project had concerns about the longevity of RWA1 (it was concern over the health of RWA1 which prompted the team to perform the test of RWA3 health and functionality in 2011). However, following 2012 RWA1 drag torque actually leveled off and diminished for most spin-rate ranges for several years. Late 2014 brought another reversal of fortune, and RWA1 has shown elevated drag in family with earlier phases of the mission since that time. The elevated drag in late 2014 followed a "rest-period" where all of the RWAs were spun-down and powered off for several days while the Sun passed between Earth and Saturn. In addition, RWA1 has previously shown elevated drag after being powered on and spun-up following RCS controlled Titan flybys and main engine maneuers. Similar RWA "rest-periods" are now avoided where possible. RWA1 longevity was a concern to the AACS team earlier than 2009, when the elevated drag and frequent drag torque spikes seemed to make the prospect of RWA1 lasting until the end of the mission in 2017 seem dubious, though concerns over the wheel's health continue to diminish slightly as the end of mission date approaches. No conclusions can be drawn from the RWA1 drag torque trending data. Although it is heartening that the drag torque levels have not grown substantially since 2009, RWA1 continues to exhibit bouts of elevated drag and large drag spikes and the AACS team continues to closely monitor RWA1 health on a daily basis to make sure that any sudden change in the behavior of the wheel would be immediately noted and responded to. RWA1 also receives preferential treatment from the AACS team when RWA spin-rate profiles for science sequences are chosen as part of the RBOT process. Low-rpm time on RWA1 is further avoided during RCS ΔV maneuvers by sometimes adding RWA biases before and after the maneuver to tailor the RWA spin rate.

IV. Conclusion

The prime set of Cassini reaction wheels have accumulated 11 years of intensive science operations at Saturn and 18 years of spaceflight. The AACS team actively works to minimize the amount of time that each of the RWAs is operated below 300 rpm in order to limit potential bearing damage. Although the AACS team cannot prove definitively that avoiding low-rpm operations protects the longevity of the RWAs, this remains the only feasible measure that the operations team can implement. The health of the RWA hardware is gauged by reviewing long-term RWA drag torque trends. The RWA drag torque trending data between 2005 and 2015 has been gathered and divided into bins based on 3-month periods of time and reaction wheel spin-rate ranges of 100 rpm in order to compute the average RWA drag torque for each reaction wheel and for each bin of data. A review of this trending data reveals that all three of the prime reaction wheels show drag torque trends, which shows signs of gradual degradation. The gradual reversal in the drag torque trends of RWA1 and RWA2 may even be tenuous evidence that limiting low-rpm operations is beneficial to the RWAs. The pace of RWA degradation appears to be sustainable for the remaining two years of the Cassini missing, leading up to the planned intentional impact of the spacecraft into Saturn in 2017.

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