In-Flight Performance of the Cassini Hemispherical Quartz Resonator Gyro Inertial Reference Units

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The Cassini-Huygens mission is a flagship class NASA/ESA mission to the planet Saturn. Launched in 1997, Cassini is still successfully operating after 16 years of flight and the telemetry from the attitude control hardware on Cassini has produced an immense dataset that allows the Cassini operations team to report on the long-term performance of several commercially available GNC hardware components in the space environment. This investigation summarizes the in-flight performance of the two inertial reference units aboard Cassini. Each of the two Cassini inertial reference units contains four hemispherical quartz resonator gyros. The Cassini operations team previously reported on the performance of the inertial reference units in 2007, and this paper provides an update with an additional 6 years of flight experience at Saturn.

Nomenclature

AACS = attitude and articulation control subsystem
ATLO = assembly, test, and launch operations
ESA = European Space Agency
FOV = field of view
FSW = flight software
GNC = guidance, navigation, and control
HGA = high gain antenna
HRG = hemispherical (quartz) resonator gyro
IRU = inertial reference unit
NASA = National Aeronautics and Space Administration
RCS = reaction control system
RWA = reaction wheel assembly
SID = star identification
SIRU = space inertial reference unit
SOI = Saturn orbit insertion
SRU = stellar reference unit (star tracker)
SSA = sun sensor assembly
XM = equinox (extended) mission
XXM = solstice (extended-extended) mission

I. Introduction

THE Cassini-Huygens mission is a joint NASA and ESA endeavor that has sent a large and sophisticated robotic exploration spacecraft to Saturn. Cassini was launched aboard a Titan IVB rocket in October 1997 from Cape Canaveral and traveled past several planets, including Venus, the Earth, and Jupiter, on its way to Saturn. Upon arriving at Saturn in 2004, Cassini performed a large propulsive maneuver to become the first, and thus far only, spacecraft to enter orbit around Saturn. The original Cassini-Huygens prime mission spanned from 2004 to 2008 and included four years of orbital observations of Saturn as well as numerous close flybys of Saturn's many moons, with special emphasis on Saturn's largest moon, Titan.[1] It is through frequent low-altitude, gravity-assist flybys of Titan that Cassini is able to significantly alter its orbit size, shape, and inclination at regular intervals as part of an

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extended tour of the Saturnian system. Titan was also the landing target of the ESA Huygens probe, which after riding along with Cassini on the 7 year voyage to Saturn, was released by Cassini in late 2004 and parachuted to a successful soft landing on Titan's surface in early 2005.[1,2] After successfully completing its prime science mission, Cassini was tasked with the Equinox (Extended) Mission, which successfully ran from 2008 to 2010,[3] and Cassini is currently in the midst of the Solstice (Extended-Extended) Mission, which is planned to continue until late 2017.[4] The Solstice Mission is designed to end with the intentional destruction of the spacecraft via impact with Saturn's atmosphere. However, in the months prior to the end of the mission, Cassini will first enter orbits that will fly the spacecraft through the narrow gap between the inner-most rings of Saturn and the cloud tops of the planet itself. These orbits through Saturn's rings are referred to as the Proximal Orbits and will present an opportunity for Cassini to produce significant scientific discoveries in the final months of the mission.

The Cassini spacecraft is equipped with 12 major science instruments, including cameras sensitive to visible light, infrared, and ultraviolet wavelengths, as well as instruments designed to study the fields and particles environment at Saturn, gravity science performed in conjunction with the Cassini telecommunication hardware, and a powerful synthetic aperture RADAR science instrument.[1] The majority of these instruments lack the ability to articulate and it is therefore necessary for the entire spacecraft to be frequently slewed between attitudes in order to point instruments at desired science targets. There is no "default" science attitude and the spacecraft performs different types of science observations each day, week, and year. Even during data downlink sessions, where the High Gain Antenna (HGA) is pointed at Earth for 9 hours, it is common for the spacecraft to perform multi-hour multiple revolution rolls around the antenna pointing direction. Since the orientation of the spacecraft is frequently changed, a robust Attitude and Articulation Control Subsystem (AACS) is required in order to collect science, point communication antennas toward Earth, and control spacecraft attitude during propulsive trajectory correction maneuvers.[5] Even after 16 years of flight the spacecraft still executes busy sequences of science observations continuously, just as it has since it arrived at Saturn nine years ago.

The Cassini spacecraft is 3-axis stabilized[6,7] and has the ability to maintain attitude control either with reaction control system (RCS) thrusters[8] or with a set of reaction wheel assemblies (RWAs).[9] Cassini has two redundant sets of eight 1 N thrusters. The reaction wheels include three mutually orthogonal 36 Nms reaction wheel assemblies, as well as an identical redundant backup wheel. The redundant reaction wheel is affixed to an articulation motor that allows the backup wheel to be reoriented to match the orientation of any of the three fixed orientation reaction wheels.[7,10]

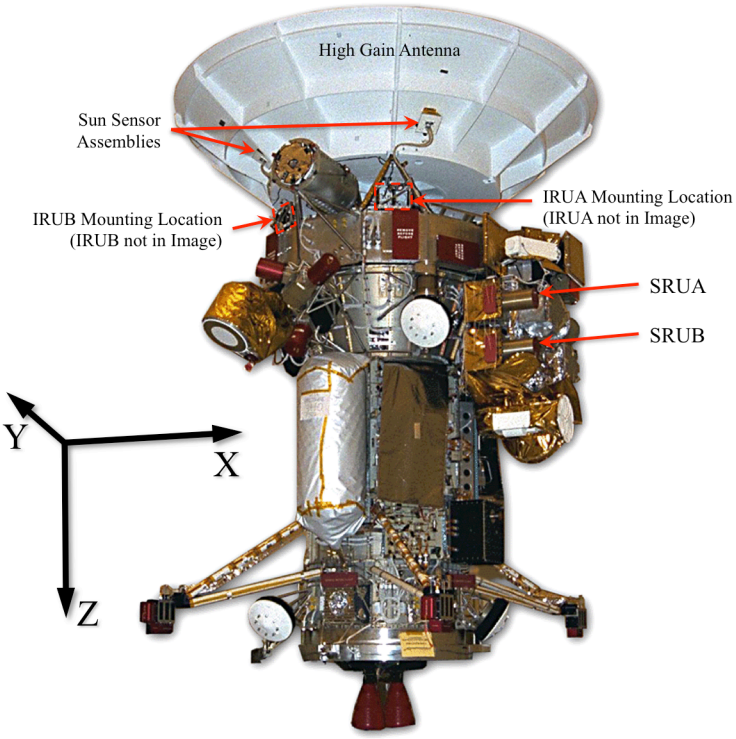

Figure 1. Cassini Spacecraft. *This ATLO image of the Cassini spacecraft shows the spacecraft body coordinate frame and labels several portions of the spacecraft that are mentioned in this analysis, including: IRUs, SRUs, HGA, and the Sun Sensor Assemblies (SSAs).*

II. Attitude Determination Onboard Cassini

The onboard attitude determination of Cassini is performed using data from redundant Sun Sensor Assemblies (SSAs), redundant Stellar Reference Units (SRUs or star trackers), and redundant Inertial Reference Units (IRUs).[6,7] All three of these attitude determination hardware components have identical redundant backups, but nominally only one SSA, one SRU, and one IRU are "prime" and powered on. The backup hardware remains powered-off awaiting activation by ground commands or system fault protection intervention. The two Sun Sensor Assemblies (SSAA and SSAB) are affixed to the High Gain Antenna, pointing along the –Z spacecraft axis, and have a 32°x32° field-of-view (FOV), as is shown in Figure 1. The SRUs (SRUA and SRUB) have a 15°x15° FOV and are co-boresighted along the spacecraft +X axis.

The IRUs (IRUA and IRUB) are mounted on the spacecraft such that they are not aligned with the spacecraft axes and are not aligned with one another (Fig. 1).

The SSAs are only used for attitude determination when the spacecraft must initialize attitude knowledge; for example immediately after launch, or hypothetically, after a spacecraft fault that results in the loss of onboard attitude knowledge. When the spacecraft is commanded to initialize attitude knowledge the spacecraft first performs a "sun search" slew using only IRU rate knowledge, where a single multi-axis spiral turn guarantees that the FOV of the SSAs will find the Sun at any point in the sky.[7,11] Once the SSAs detect the Sun, the spacecraft attitude estimator will have an estimate of the Sun position relative to the spacecraft body frame, and will compute attitude corrections needed to keep the Sun in the center of the SSA FOV, compensating for gyro drift and spacecraft motion as the attitude estimator is receiving updates only from the IRU and SSA.[6] After the attitude estimator gains relative attitude knowledge using the SSA and IRU, the spacecraft will then attempt to use the SRU to initialize *inertial* attitude knowledge. Upon achieving inertial attitude knowledge with data from the star tracker, the onboard attitude estimation no longer uses data from the SSAs, and instead relies entirely upon attitude information from the SRU and IRU.

Inertial attitude knowledge on Cassini is achieved by using one of the Stellar Reference Units (SRUs) to produce an estimate of the spacecraft attitude relative to star patterns in the celestial sky. A pre-filter in the attitude estimator onboard Cassini statistically combines multiple SRU measurements from a 1-5 sec time interval into a 3-axis pseudo measurement with corresponding uncertainties that are fed into the attitude estimator's Kalman-Bucy filter.[6] Since the attitude estimator is running at a significantly faster rate than the 1-5 sec SRU updates, the attitude estimator propagates using rate information from the IRUs collected every 125 msec.[6]

The Kalman-Bucy filter in the Cassini attitude estimator requires onboard propagation of the covariance matrix. Although this is computationally intensive, it has the added benefit of allowing for onboard estimation of several IRU performance parameter values.[6] Despite this capability, during normal operations the estimation of the IRU scale factor and misalignment parameters is turned off, and is only re-enabled during pre-planned gyro calibration engineering activity sequences. The IRU biases are actively estimated onboard the spacecraft during normal operations. However, it should be noted that the biases estimated by the Kalman-Bucy filter are actually pseudo biases because they are measured along the spacecraft X, Y, Z axes rather than the A_1, A_2, A_3 sensing axes of the individual HRGs in the IRU.

III. The Cassini Inertial Reference Units

A. Purpose

Cassini is currently in the midst of its 16th year of flight, and as such, Cassini has produced a great deal of engineering data that can be used to report on the long term flight performance of AACS hardware components, especially that of the IRUs. The purpose of this paper is to report on the long-term trends and performance of the Cassini Inertial Reference Units. The Cassini attitude control team previously reported on the engineering maintenance and performance of the Cassini IRUs in 2007.[12] This paper serves to update the previous data with 6 additional years of data; more than doubling the temporal baseline that was previously presented for IRU parameter trends. In addition, this investigation will also summarize the accuracy of gyro propagated attitude knowledge utilized during periods where star identification with the star trackers is temporarily suspended.

Due to the nature of the Cassini mission, the IRUs selected for use on the mission were required to perform for long durations. The IRUs that were chosen for Cassini were two Space Inertial Reference Units (SIRUs) that were manufactured by Litton Guidance and Control Systems (now part of Northrop Grumman).[13,14] Each of the Cassini inertial reference units (IRUA and IRUB) has a set of four finely machined hemispherical quartz resonating gyros (HRGs).[14,15,16,17] These gyroscopes are well suited to long missions because there are no moving parts and have no known mechanism of "wearing out."[12,15,16] Although SIRU units have flown on several well-known space missions,[13] there is relatively little information in aerospace literature on the flight performance of these IRUs.[19] It is for this reason that the AACS team endeavors to provide updates to the aerospace community on the experiences of operating a complicated spacecraft like Cassini in the space environment and on the performance of the Cassini GNC hardware.[7]

B. Inertial Reference Unit Operating Principle

The operating principle of HRGs is commonly compared to the "singing" of a wine glass when a wet finger is run along the rim of the glass, only in the case of the HRGs the vibrations are produced electromagnetically.[14] The electronics of the IRU sustain a resonant vibration in each of the four quartz gyros, the frequency of which is accurately measured by the digital pulses that are registered by the IRU avionics. Rotations of the IRU assembly

produce changes in the vibration frequency of each of the quartz gyros, and the change in frequency is correlated to the amount of rotation around the axis of symmetry of each of the quartz gyros.[14,15,17,18] Inside each IRU, three of the quartz gyros are aligned mutually orthogonal to each other so as to have independent sensing axes. The fourth gyro in each set is skew and equidistant from the other three gyros and functions as a parity check of the measurements made by the other 3 gyros. The individual quartz gyros inside IRUA are referred to as A_1, A_2, A_3 and A_4, with A_4 being the skew gyro used as a parity check. Similarly, the HRGs inside IRUB are referred to as B_1, B_2, B_3, and B_4. The two IRUs onboard Cassini are not co-aligned (Fig. 1), and it is possible to use either IRUA or IRUB independently. In addition, the Cassini flight software also allows for measurements from individual HRGs inside IRUA to be combined with measurements from IRUB should individual gyroscopes within one or both of the IRUs degrade or fail.[12] For example, the AACS flight software can be configured to make the "prime" IRU use data from A_1, B_2, B_3, and A_4, or any other combination of mixed gyros. However, to date, both IRUs continue to function nominally.

During normal operations Cassini uses IRUA as the prime inertial reference unit and IRUB is kept as backup. IRUA has been powered on continuously since launch, which means that it has operated for a staggering 137,000 hours in the space environment, as of mid 2013. IRUB, on the other hand, has remained powered off for the entire mission except when it is powered on for periodic calibrations, and in the past there were multiple critical spacecraft events where IRUB was powered on as a precaution to act as a "hot backup" in the event that an attitude control safing event were to occur that required a swap to redundant hardware. Thus, since 2004, IRUB has been powered on only eight times for a total of just 173 hours. In addition to its role as a backup, IRUB was used as the prime IRU for science observations for approximately 24 hours on two separate occasions following the completion of IRUB calibration activities, before IRUA was returned to prime status and IRUB was powered off.

IV. In-Flight Calibration of the Cassini Inertial Reference Units

C. Scheduling of the In-Flight Cassini IRU Calibration Activities

Since shortly before arriving at Saturn in 2004, it has been one of the standard engineering/maintenance activities of the AACS team to periodically calibrate both IRUA and IRUB in flight. Although IRUA was used continuously for the 7-year cruise from Earth to Saturn (between 1997-2004), the first calibration of IRUA was not performed until July of 2002, and the first calibration of IRUB was in March of 2003.[12] These calibrations were sufficiently far enough ahead of the 2004 arrival at Saturn to allow for IRU parameter changes to be made in the Flight Software (FSW) version that was loaded on the spacecraft for the Saturn Orbit Insertion (SOI) burn and the rest of the Prime Mission.

Since 2002, IRU calibrations have been regularly scheduled for both IRUA and IRUB, and the schedule of IRU calibrations is shown in Table 1. IRUA, being the prime gyro, has been calibrated annually (in February or March) every year since 2003, and calibrations are scheduled to continue until late 2016. IRUB, being the backup gyro, has been calibrated less frequently. Following the initial calibration of IRUB in 2003, IRUB was not powered on for a calibration again until 2007, but since that time another three calibrations have occurred with another three planned before the end of the mission. Although five calibrations of IRUB in 16 years of flight may seem infrequent, it should be noted that there is always some small risk associated with transitioning from prime to backup hardware and this risk is mitigated by only performing these calibrations at the minimum frequency necessary to establish that the backup is in good working order.

All calibrations of IRUA and IRUB that occurred between 2002 and 2007 were previously reported by Burrough and Lee in a previous publication.[12] This report serves to provide an update on the performance of the IRUs over the last 6 years.

Table 1. History of IRUA and IRUB Calibration Events

	Date of Calibration Activity	Summary of FSW Parameter Changes Resulting from IRU Calibration
IRUA	2002-194	Led to a Scale Factor Error Update and Sensing Axis Correction in A8.6.5 FSW (Feb, 2003)
	2003-058	
	2004-362	
	2005-039	
	2006-042	Led to a Scale Factor Error Update in A8.7.5 FSW (Jan, 2007)
	2007-058	
	2008-065	
	2009-063	
	2010-056	
	2011-042	
	2012-039	
	2013-038	
	~2014-030 (Planned)	
	~2014-350 (Planned)	
	~2015-350 (Planned)	
	~2016-300 (Planned)	
IRUB	2003-065	Led to a Scale Factor Error Update and Sense Axis Correction in A8.7.1 FSW (Oct, 2004)
	2007-188	
	2009-277	
	2011-092	
	2012-118	
	~2013-300 (Planned)	
	~2015-100 (Planned)	
	~2016-250 (Planned)	

D. Purpose of IRU Calibrations

The purpose of the IRU calibration activities is to put the spacecraft into the attitude estimation mode where the Kalman filter is providing 12 state estimation, including providing onboard estimation of the: (a) gyro bias in the direction of the spacecraft X, Y, and Z axes, (b) scale factor errors along the spacecraft X, Y, and Z axes, and (c) misalignment of the actual orientation of the IRU relative to the FSW specified orientation of the IRU.[12] The modeling of the IRU error parameters in the Cassini FSW was previously described by Burrough and Lee[12] and can be expressed as in Equation 1 and 2.

$$\vec{\theta}_{gyro} = \int \left(\vec{\Omega}_{gyro} dt \right) + \vec{\Delta}_{Angle} \tag{1}$$

$$\vec{\Omega}_{gyro} = \begin{bmatrix} 1+\varepsilon_X & 0 & 0 \\ 0 & 1+\varepsilon_Y & 0 \\ 0 & 0 & 1+\varepsilon_Z \end{bmatrix} \vec{\Omega}_{true} + \begin{bmatrix} 0 & \theta_{xy} & \theta_{xz} \\ \theta_{yx} & 0 & \theta_{yz} \\ \theta_{zx} & \theta_{zy} & 0 \end{bmatrix} \vec{\Omega}_{true} + \begin{bmatrix} b_X \\ b_Y \\ b_Z \end{bmatrix} + \vec{\Delta}_{Rate} \tag{2}$$

In Eq. 1, $\vec{\theta}_{gyro}$ is the measured spacecraft attitude vector due to the integrated time history of the IRU derived spacecraft body rates ($\vec{\Omega}_{gyro}$) and the angle random walk of the IRU ($\vec{\Delta}_{Angle}$). Furthermore, the accuracy of the measured spacecraft attitude, $\vec{\theta}_{gyro}$, has a finite resolution limited by the ~0.25μrad quantization of the data, though

this is not refelected in Eq. 1. The measured spacecraft body rates, $\vec{\Omega}_{gyro}$, is a combination of the true spacecraft body rates ($\vec{\Omega}_{true}$) and errors introduced by the per axis scale factor errors (ε_i , $i \in \{X,Y,Z\}$), the sensing axes misalignments (θ_{ij} , $i \in \{X,Y,Z\} \& j \in \{X,Y,Z\}$), the per axis rate bias (b_i , $i \in \{X,Y,Z\}$), and the rate random walk of the IRU, $\vec{\Delta}_{Rate}$. Based on the results of the IRU calibration it is possible to update FSW parameters for the per axis scale factor errors and the sensing axis misalignments. The IRU biases are not updated via a parameter patch because they are estimated by the Kalman filter continuously as part of the normal attitude estimation algorithms.

As a reminder, neither IRUA nor IRUB are aligned with the spacecraft body frame X, Y, and Z axes (Fig. 1), so although the measured gyro parameter errors are specified relative to the spacecraft body frame, these errors are not directly assigned to individual HRGs within each IRU. The Cassini team performs IRU calibrations in this method because the calibrations produce parameter updates that can be implemented in the AACS flight software. So while measuring scale factor errors or biases associated with individual HRGs may have wider academic interest, it would provide less benefit to the AACS team than the current system of measuring these parameters relative to the coordinate frame used by the attitude estimator, attitude commander, and attitude controller in the AACS FSW.

E. IRU Calibration Activity Description

The IRU calibrations themselves are AACS-centric activities that are generally scheduled to immediately follow the end of one of the 9-hour data downlink windows. The IRU calibrations begin with the spacecraft sitting at a quiescent attitude, under RWA control, with the HGA pointed at Earth. The IRU calibration command sequence used by AACS performs the following tasks:

- The standard IRU telemetry schedule is modified to provide visibility of the estimated IRU error channels from the attitude estimator
- (For IRUB calibrations only) IRUB is powered on, allowed to warm to normal operating temperature over the course of multiple hours, and is then commanded to become the prime IRU (IRUA remains powered on).
- The attitude estimator is commanded to enter the "gyro cal" mode of operation where the Kalman filter enters the 12 state mode and estimates IRU scale factor errors and misalignment errors. The attitude estimator is always estimating the IRU bias.
- The spacecraft is commanded to independently execute slews of ~180° around the ±X-axes, the ±Y-axes, and ±Z-axes of the spacecraft body frame. Note that these slews must be carefully designed by an AACS analyst for each IRU calibration to avoid inadvertently pointing the SRU at a bright body (i.e. Saturn, Titan, the Sun, the rings, etc.) that would corrupt the inertial attitude knowledge of the attitude estimator.
- After the slews complete (~4-5 hours), the attitude estimator is commanded to return to the 6 state estimation mode where it estimates only the IRU bias and not the misalignment or scale factor errors
- Finally, the IRU prime-ness and power states are returned to their "pre-cal" settings, and the normal engineering telemetry settings are restored

These IRU calibration activities consume no hydrazine propellant and their only impact to the science teams is the lost observation time, though some science data is still collected by the fields and particles teams during the IRU calibrations.

F. IRU Calibration Results

The results of the IRU calibrations performed in flight are depicted graphically in this section. Figure 2 shows the IRUA bias values measured along the spacecraft X, Y, and Z-axes. As is evident in Figure 2, the IRUA bias values for each axis initially grew at an approximately linear rate between 2002-2008. However, during the last 4 years the calibrated IRUA bias values have remained relatively unchanged. The horizontal red lines in Figure 2 show the Cassini requirement levied on the maximum IRU bias at launch, which was 1 deg/hr, or 4.84 μrad/s (3σ). The X-axis IRUA bias exceeded the required maximum IRU bias for the first time in 2010, which was 2 years after the end of the Prime Mission and after 13 years of flight. However, this is of no concern to the AACS team because the IRU bias values are continuously estimated by the Kalman-Bucy filter in flight. Overall, the performance of IRUA is impressive considering the 16 years of continuous use, and is certainly adequate for continued Cassini operations.

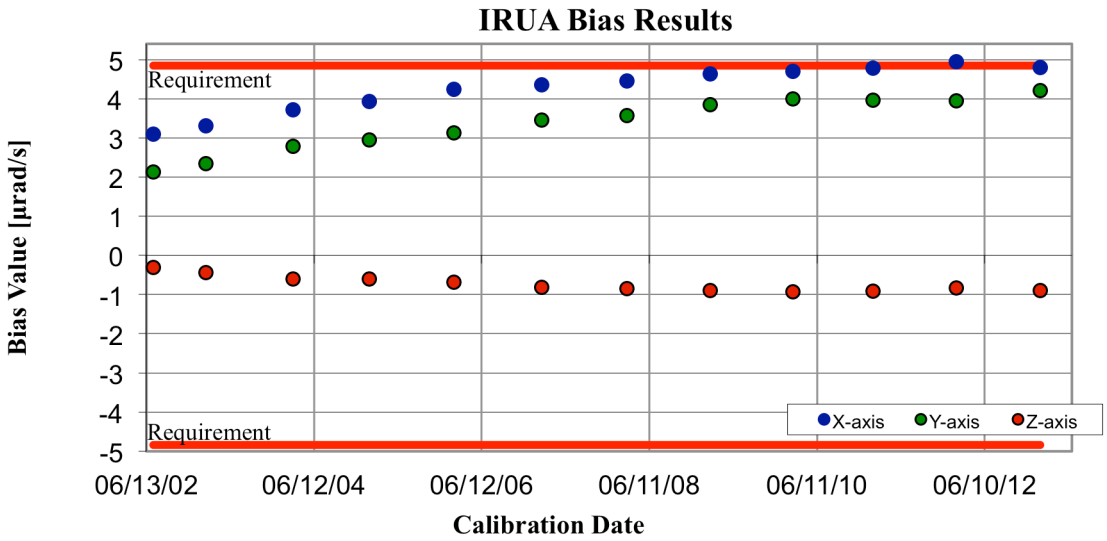

Figure 2. Results of IRUA Bias Calibration. *This figure shows the per axis IRUA bias values that were measured during each of the IRU calibrations performed since 2002. The red line shows the maximum IRU bias value specified by Cassini requirements for launch.*

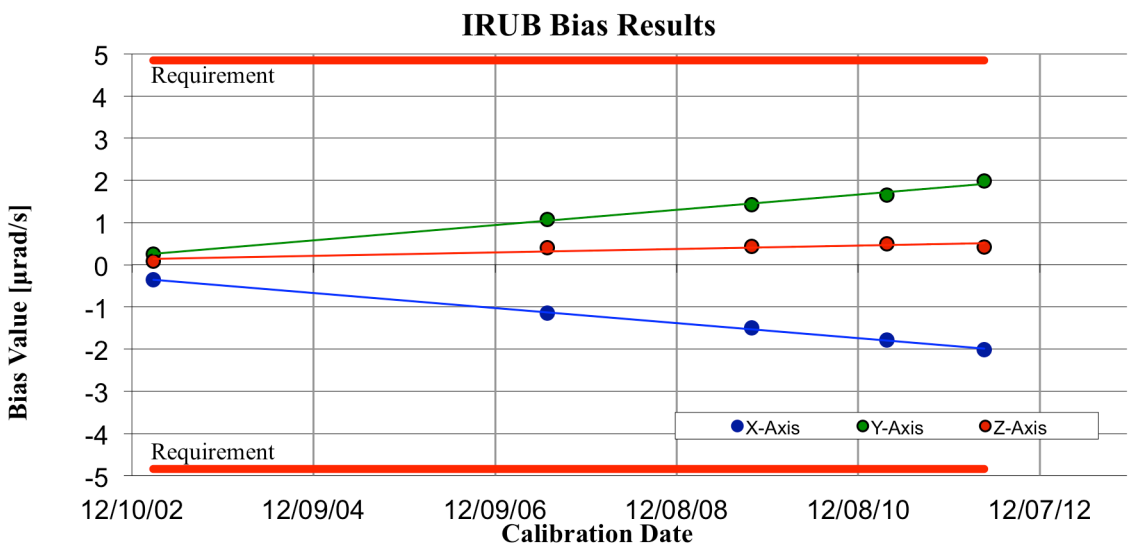

Figure 3. Results of IRUB Bias Calibration. *This figure shows the per axis IRUB bias values that were measured during each of the 5 IRUB calibrations performed since 2003. The red line shows the maximum IRU bias value specified by Cassini requirements for launch.*

Similarly, the calibrated IRUB bias values are shown in Figure 3. When compared to the calibrated results of IRUA two things stand out: first, there are fewer data points for IRUB than for IRUA, and second, the bias values for all three axes of IRUB have been growing at a nearly linear rate since the IRU was first calibrated in 2003. That said, the largest bias values seen on IRUB (~2 µrad/s) are still less than half of what is seen on the X and Y axes of IRUA in the most recent calibration. Although the bias values of IRUB continue to grow, the current growth rate suggests that IRUB remains a healthy and viable backup.

The next pair of Figures, 4 and 5, shows the results of the calibration of the IRUA and IRUB scale factor error parameters. In both Fig. 4 and Fig. 5 the scale factor errors are shown as a percentage of the full-scale factor value. The Cassini requirement on the IRU scale factors limits the maximum scale factor errors to 0.25% (2500 ppm). Figure 4 shows the calibrated scale factors errors for IRUA, and the scale factor errors are currently just 1/5 of the 0.25% limit. Also, it is clear from Figure 4 that the two FSW scale factor parameter updates in 2003 and 2007 did successfully decrease the scale factor errors for the subsequent IRUA calibrations. After the first FSW parameter

update in 2003, the IRUA scale factors began to grow linearly, and this trend continued until the 2007 FSW parameter update. Since the 2007 update, the IRUA scale factor errors have not followed a steady trend and remain small (<500 ppm). There have been no updates to the IRUA scale factor error parameters since 2007, and there are no future updates planned because the current error level easily meets the requirement.

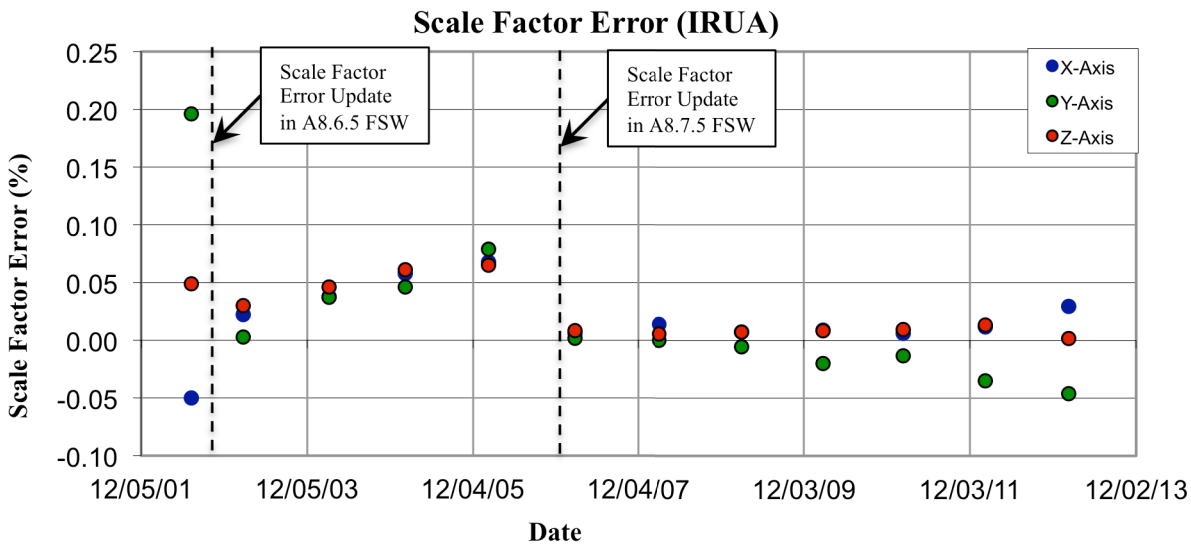

Figure 4. Results of the IRUA Scale Factor Error Calibrations. *This figure shows the per axis IRUA scale factor error values expressed as a percentage of the full scale factor. The Cassini requirement is that the error must be less than 0.25%. The vertical dashed lines demark the two times that the FSW parameter values have been updated in flight to improve the IRUA scale factor errors.*

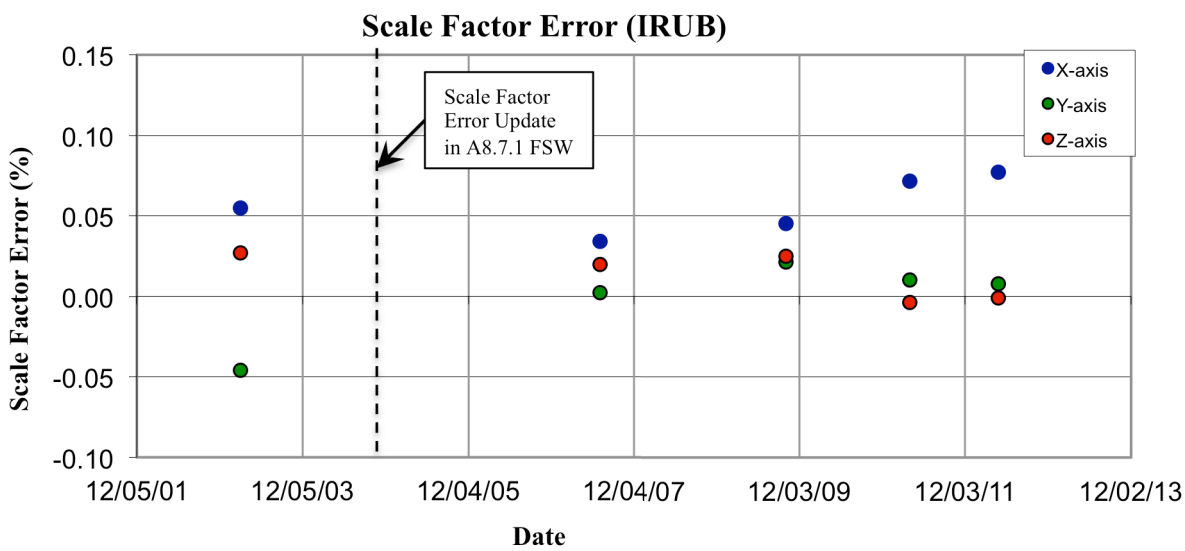

Figure 5. Results of the IRUB Scale Factor Error Calibrations. *This figure shows the per axis IRUB scale factor error values expressed as a percentage of the full scale factor. The Cassini requirement is that the error must be less than 0.25%. The vertical dashed line shows the time that the FSW parameter values were updated in flight to improve the IRUB scale factor errors.*

Figure 5 shows the calibrated scale factor errors for IRUB, and again, the vertical line denotes where the IRUB scale factor errors for each axis were updated with a FSW memory patch. Despite the fact that a parameter update for the IRUB scale factor errors was made in 2004, before this update the scale factor errors of IRUB never approached the 0.25% requirement. Like IRUA, the IRUB scale factor errors are within required performance and do not display any worrisome trends. There are no updates to the IRUB scale factor error parameters.

It should be noted that calibrations of the IRU scale factor parameters are particularly important for Cassini because it is common practice during science operations for use of the star tracker to be suspended for periods of several hours, which forces the attitude estimator to propagate attitude knowledge using only gyro data. During these periods with no SRU data, a mismatch between the FSW scale factor and the actual IRU scale factor can very quickly lead to large attitude errors if the spacecraft performs large slews. These "gyro only" periods are further discussed in Section V. Based on the results of the IRUA and IRUB calibrations the AACS team is confident that the IRU scale factor parameters are accurately defined in the AACS FSW.

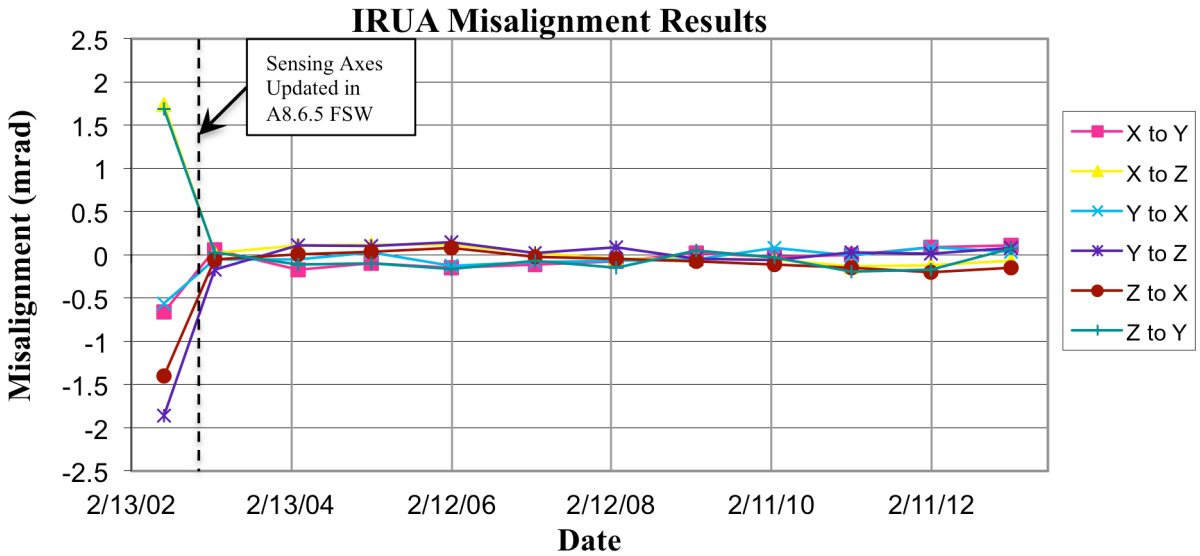

Figure 6. Results of IRUA Misalignment Calibration. *This figure shows the measured misalignments between the actual IRUA sensing axes and the orientation specified in the FSW, measured in milli-radians. The IRUA misalignments were markedly improved by the FSW parameter update performed in 2003 and have remained constant since.*

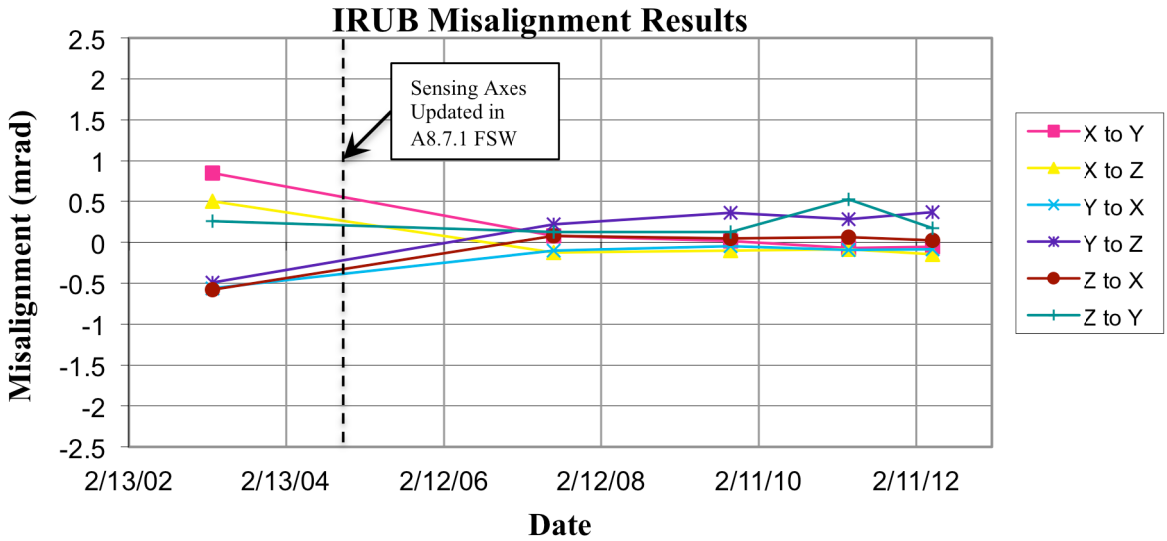

Figure 7. Results of IRUB Misalignment Calibration. *This figure shows measured misalignments between the actual IRUB sensing axes and the orientation specified in the FSW, measured in milli-radians. The IRUB misalignments were improved slightly by a FSW parameter update performed in 2004 and have not changed appreciably since.*

Figure 6 and Figure 7 show the calibrated values of the IRUA and IRUB sensing axes misalignment relative to the alignment of the IRUs parameterized in the FSW. The misalignments are measured as milli-radian deviations from the FSW parameter values. Cassini requirements limit the control of the misalignment to 5 mrad per axis (3σ),

and the alignment knowledge to 2.5 mrad per axis (3σ). Figure 6 shows that the IRUA misalignment in 2002 was easily less than the 5 mrad requirement, and after the IRUA sensing axis parameters were updated in the FSW the misalignment knowledge in all subsequent IRUA calibrations appears to be on the order of just a few tenths of 1 mrad and the current alignment of IRUA appears to be very stable.

Figure 7 shows the calibrated sensing axis errors for IRUB. Based on Figure 7, the misalignment of IRUB after the first calibration was easily within the 5 mrad requirement, and all subsequent calibrated misalignments since the sensing axes were updated in the FSW have been less than approximately 0.6 mrad. The alignment of IRUB also appears to be quite stable. Based on the small and stable calibrated misalignment errors of IRUB, there is currently no plan by the AACS team to perform a FSW parameter update for IRUB in the future.

V. IRU Performance During "Gyro Only" Attitude Propagation

As previously described, the Cassini attitude determination algorithms normally receive inertial attitude updates from the star tracker every 1-5 seconds and integrate the spacecraft attitude between SRU updates with rate information from the IRU, which updates at 8 Hz.[6] However, it is very common during daily operations for science teams to command Cassini to attitudes where the SRU is pointed at bright bodies (Saturn, the rings, Titan, etc.) that interfere with the ability of the SRU to identify celestial patterns, and inertial attitude estimates are therefore not available. During these instances the attitude determination algorithms propagate the spacecraft attitude based solely upon the IRU updates. These "gyro only" propagation periods provide frequent real-world examples of IRU performance.

Long before the science observations are uplinked to the spacecraft the AACS team simulates the expected attitude of the spacecraft during all science observations in order to preemptively identify periods where there will be bright bodies that will fall within the SRU field-of-view. The AACS team issues an "SID-Suspend" command, which puts the star identification (SID) algorithms into an idle state. Normally an SRU fault monitor is used to automatically detect whether the star tracker has ceased functioning due to a hardware fault. The fault protection response if the monitor were to trigger could include swapping to the backup SRU and potentially triggering system safing. However, for periods of time where AACS is expecting the spacecraft to be at attitudes where the SRU will not be able to detect star patterns, the SID algorithms are put into an idle mode and the fault monitor is masked so that the fault monitor cannot be triggered by a "false positive" due to the expected SRU data outage.

During periods where AACS issues an SID-Suspend command the last onboard estimate of the IRU biases for the X, Y, and Z axes are held constant in memory and the spacecraft attitude knowledge is integrated based solely on IRU body rate measurements. Although the IRUs are well calibrated, it is inevitable that attitude errors will begin to slowly grow based on imperfections in the IRU bias, scale factor, and alignment parameters in the FSW. Once the SID-Suspend period ends, the SRU resumes star identification and the spacecraft receives a "truth" measurement of its actual attitude. Instantaneously the spacecraft attitude error grows from ~0 mrad to as large as 50 mrad depending upon the duration of the SID-Suspend period, the stored values of IRU parameters in FSW, and the activities performed by Cassini while star identification was suspended. The attitude controller is typically able to remove the attitude errors within a 1-2 minutes once SRU measurements are resumed.

These SID-Suspend periods can be triggered by either large or small bright bodies in the SRU field of view, or even by spacecraft slews that occur at rates that are too high to allow for the SRU to track stars. Although the SID-Suspends can be triggered in a number of ways, no matter the cause, all SID-Suspend commands are restricted to last no more than 5 hours. This limit is strictly enforced. Although there have been over 500 instances in flight where SID-Suspends longer than 4 hours occurred (with several as large as 04:58:00-04:59:00), there have been no SID-Suspends of 5 hours or greater. Each of these SID-Suspend periods provides a chance to observe the spacecraft attitude control behavior under the influence of only the IRUs. Both the IRU bias and scale factor are "tested" by each of these SID-Suspends due to the science observations that occur during the SRU outage. One very common type of SID-Suspend occurs during the 9-hour data downlink windows. During these downlinks the fields and particles instruments prefer to collect data while the spacecraft performs a multi-revolution roll around the spacecraft Z-axis (which is the pointing direction of the High Gain Antenna). For these downlinks, star identification is often suspended for 4:40 hours, as the spacecraft completes eight complete 360 degree rolls around the Z-axis all while the spacecraft communicates with Earth through the HGA. Any error in the FSW Z-axis scale factor value is accentuated by these long Z-axis slews.

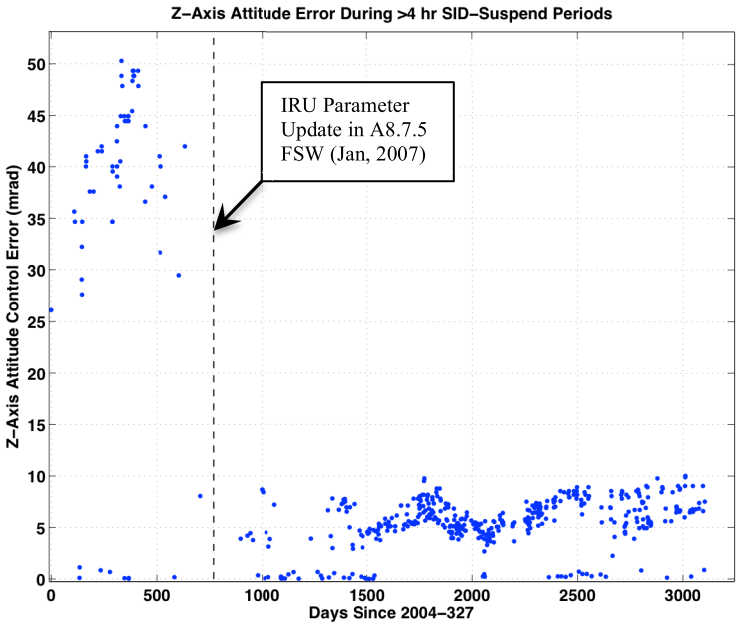

Figure 8. Z-Axis Attitude Error Following >4 hours of Gyro Only Attitude Propagation. *Each point on this graph is the maximum Z-axis attitude error determined by the spacecraft immediately following the end of an SRU outage of more than 4 hours.*

The performance of the IRUs during long SID-Suspend periods is illustrated in Figure 8. In this figure the peak value of the attitude error around the spacecraft Z-axis is shown for 519 instances of SID-Suspends that were more than 4 hours in duration. For each of these data points, the peak error occurred at the very end of the SID-Suspend, when the SRU resumed star identification and the attitude error due to IRU propagation is visible for the first time. Figure 8 shows only the data for the spacecraft Z-axis because the majority of >4 hour SID-Suspends occurred due to multi-revolution rolls around the Z-axis, and thus the attitude error around the Z-axis is typically larger than the X or Y axis error. In Figure 8 the attitude error following the long SID-Suspends were typically >30 mrad between late 2004 and early 2007. However, in January 2007 the IRU scale factor errors were updated in the A8.7.5 FSW version based on the results of an earlier IRU calibration activity (Table 1). Figure 8 shows a dramatic improvement in the behavior of IRUA during the SID-Suspends after January 2007. Since the FSW update in 2007 the Z-axis attitude error from these SID-Suspends has not exceeded ~10 mrad. There are two nuances in the data from Fig. 8 that should be noted. First, there are fewer data points in Figure 8 prior to early 2008 (day 1200 on the plot) because early in the prime mission the spacecraft seldom performed >4 hour downlink rolls, whereas these downlinks rolls became very common later in the mission. Second, there are many data points plotted in Figure 8 that have attitude errors of just 0-2 mrad, despite the fact that the spacecraft propagated the attitude knowledge with only IRUA data for >4 hrs. These points do not indicate that the IRU sporadically improves its performance. Rather, several of the data points plotted in Figure 8 correspond to cases where either the spacecraft remained motionless for several hours, or where the spacecraft rolled around either the spacecraft X or Y axes. In both of those cases the Z-axis error does not grow nearly as large as it does during long Z-axis rolls, and potentially the error in the X or Y axes could be much larger than the Z axis.

To summarize, the Z-axis attitude error points plotted in Figure 8 demonstrate the IRU is currently continuing to perform at a level that is on par with the performance seen in the last seven years. Attitude errors of approximately 10 mrad after 4 hours of gyro propagation is adequate for Cassini and there is no risk that attitude errors of this level from SID-Suspend events would trigger undesired fault protection responses. The data in Fig. 8 provides further evidence that IRUA is displaying no signs of degraded performance due to its age.

VI. Summary and Conclusion

The long mission life of Cassini has produced a plethora of engineering telemetry that is an excellent dataset for the Cassini AACS team to report on the long-term performance of the GNC hardware that was used onboard the spacecraft. Relatively little has been written about the flight performance of the HRGs[19] in IRUA and IRUB, and it is for this reason that the AACS team has provided multiple publications summarizing the flight experience with these two units.[7,12,20] The Cassini AACS team has performed multiple IRU calibration activities onboard the spacecraft and this publication provides a history of the calibrated IRU biases, scale factor errors, and sensing axis misalignments for both IRUA and IRUB. As an independent example of real-world IRU performance, this investigation also provides the observed spacecraft attitude errors associated with periods where the spacecraft was commanded to propagate attitude knowledge without star tracker updates for >4 hours. Based on the results of the IRU calibrations and on the flight telemetry from IRUA, the Cassini AACS team concludes that both IRUA and IRUB continue to perform excellently and there has been no information that gives the AACS team any concern about the further longevity of the IRUs. Although some of the IRU parameters are slowly drifting, none of the IRU

parameter changes have thus far affected IRU performance in any appreciable way. The Cassini IRUs have proven to be very reliable and the choice of the HRG gyros for the Cassini mission has proven to be well conceived.

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