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

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Overview

- The Cassini Spacecraft & Mission
- The Inertial Reference Units on Cassini
- In-Flight IRU Calibration Results
- Attitude Propagation with Gyros Only
- Summary & Conclusions

The Cassini Spacecraft

Spacecraft Description:

Size: 6.7 m tall, 4 m wide, 11 m long MAG boom

Mass: 5712 kg at launch, 2273 kg currently

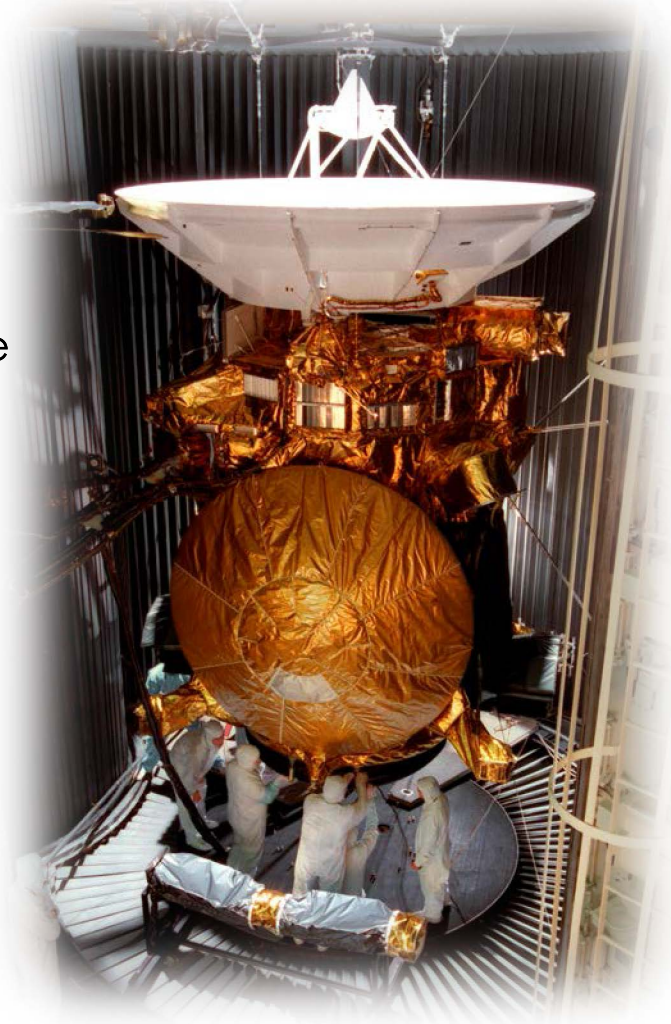
Power: 3 RTGs produce ~650 W (currently)

Payload: 12 science instruments + Huygens Probe

No scan-platform; attitude maneuvers commonplace

Distance from Earth: ~1 Billion miles

Round-Trip Light Time: ~3 Hours



Credits: NASA, JPL

Mission Timeline:

Launch: October 1997

Saturn Arrival: 2004

Huygens Probe Delivery to Titan: 2005

Prime Science Mission: 2004-2008

Extended Mission (XM): 2008-2010

2nd Extended Mission (XXM): 2010-2017

Planned Mission End: Intentional Saturn Impact in September 2017

The Cassini Spacecraft

Attitude Control Subsystem:

3-Axis stabilized using RCS or RWA control

Eight 1 N RCS thrusters

3 orthogonal 36 Nms RWAs (also 1 backup)

2 redundant 400 N main engines

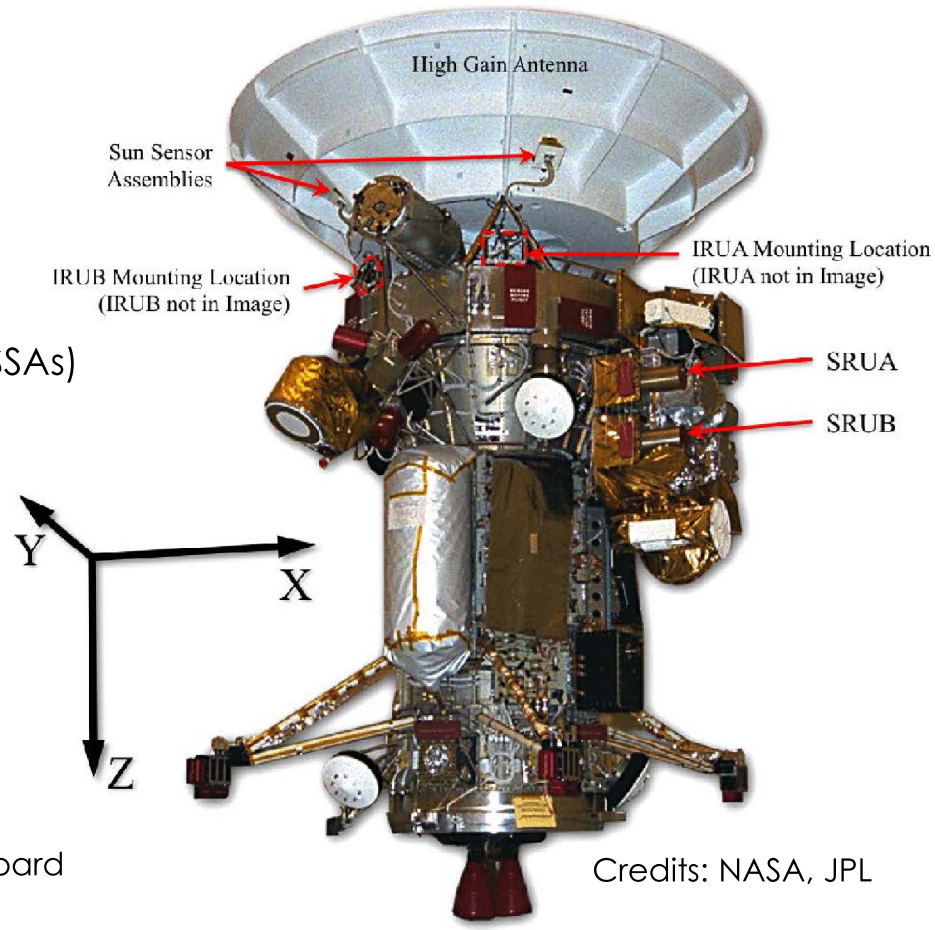
1 Accelerometer (for maneuvers)

2 redundant ACS Flight Computers

2 redundant Sun Sensors Assemblies on HGA (SSAs)

2 redundant Stellar Reference Units (SRUs)

2 redundant Inertial Reference Units (IRUs)



Credits: NASA, JPL

Attitude Determination High-Level Description:

S/C integrates body rate data from IRU(8 Hz)

Attitude updates normally given by SRU (~0.2 Hz)

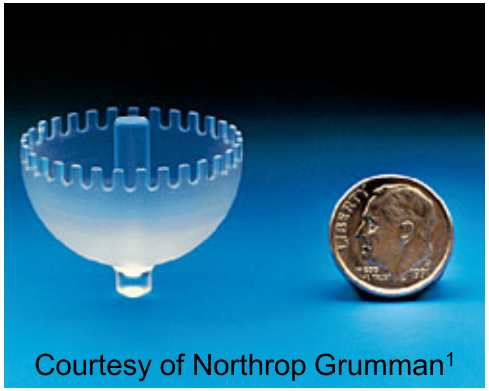
SRU used to produce inertial attitude estimate

IRU rate data combined with SRU data using pre-filter

Kalman-Busy filter propagates covariance matrix onboard

Sun Sensor data used only after safing/detumbling

The Cassini Inertial Reference Units


Courtesy of Northrop Grumman[1]

- **Product Name**: Space Inertial Reference Units (SIRUs) Block I, manufactured by Litton Guidance and Control Systems (now Northrop Grumman)[1]
- **Type:** Hemispherical Quartz Resonator Gyros (HRGs)
- **Pedigree:** Used on NASA missions including Deep Impact, MESSENGER, NEAR, GLAST, Aura, Aqua, Herschel, and TDRS

- **Operating principle:**
  - HRG similar to a 'singing wine glass,' with standing wave pattern maintained electronically
  - Rotations around axis of symmetry causes change in the vibration frequency proportional to rotation rate
  - Each IRU contains 4 HRGs. Three are mutually orthogonal and the 4th is skew and used for parity check
- **Notes about Cassini IRUs**
  - No moving parts and no know "wear-out" mechanism; ideal for long missions like Cassini
  - IRUA powered on continuously since 1997 (>137,000 hours)
  - IRUB powered on just 173 hours in 16 years
  - Neither IRUA nor IRUB aligned with spacecraft body frame, or with one another
  - Cassini AACS FSW allows for combined measurements from HRGs in IRUA and IRUB

[1]Rozelle, D., "The Hemispherical Resonator Gyro: From Wineglass to the Planets," HRG White Paper, Northrop Grumman Corporation Navigations Systems, 2011.
Note: Reference to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

The IRU Calibration

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

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

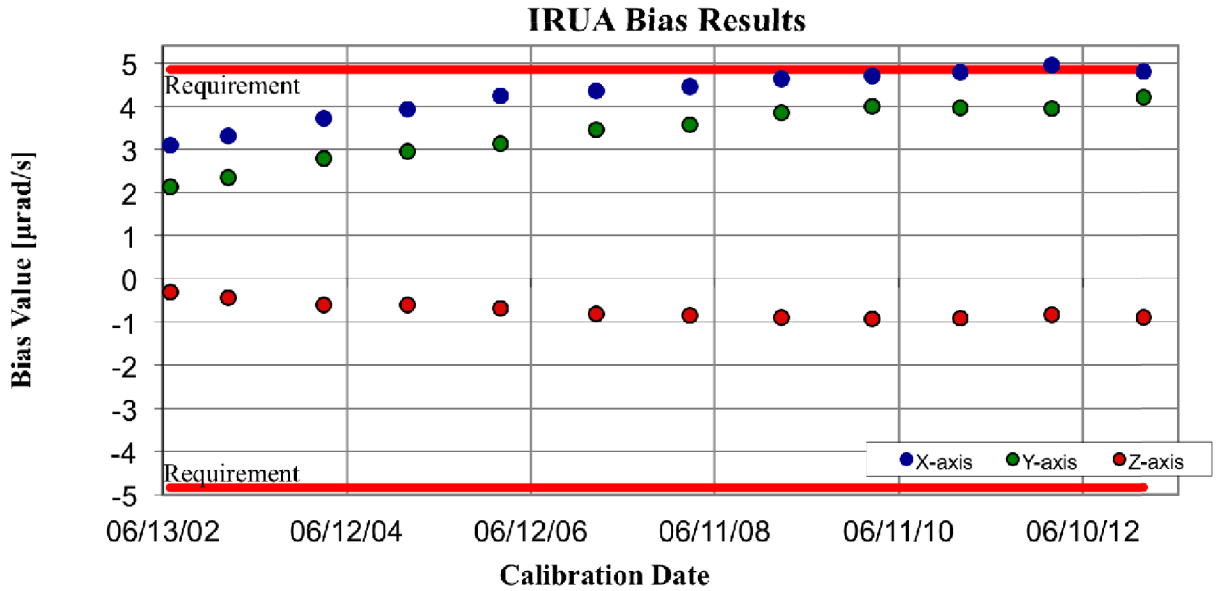
- Attitude determination Kalman Filter can be placed in a 12 state mode for IRU calibrations
- Calibration activity includes S/C slews of approx. +/-180˚ around X, Y, and Z axes
- During calibrations, onboard estimates produced for:
  - Scale Factor Errors
  - Sensing Axes Misalignments
  - Gyro Bias (Note: biases are estimated by Kalman Filter even when not in calibration)
- Cassini team does not estimate Angle/Rate Random Walk
- Purpose of calibrations: AACS FSW allows for parameter updates for scale factor errors and misalignments. Bias is continuously estimated by onboard filter.
- Note: All gyro error terms are measured in the S/C Body Frame, not in the IRUA frame

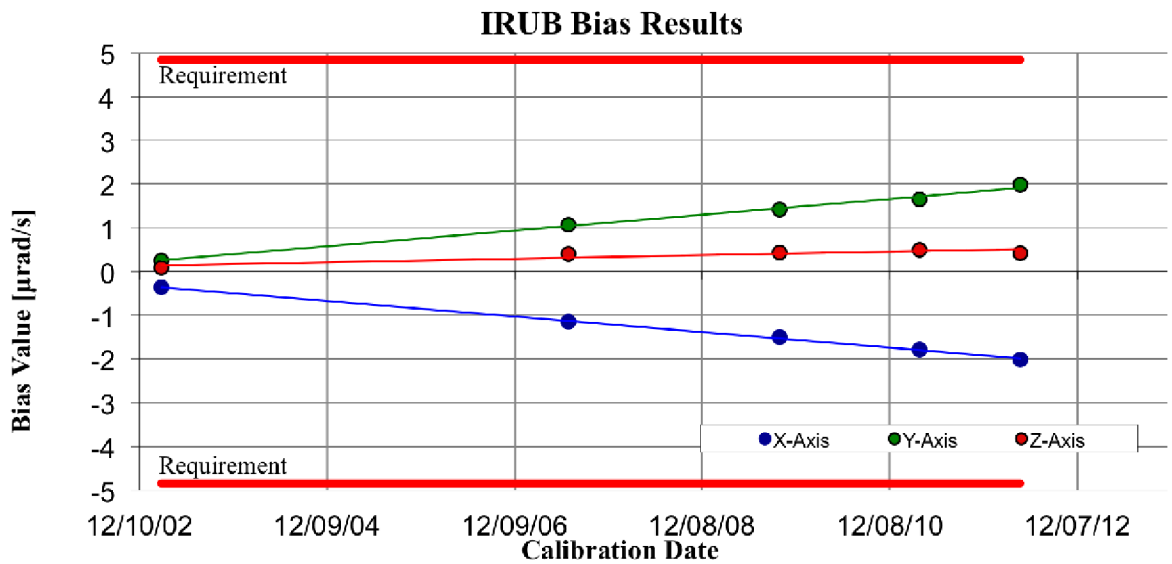
IRU Calibration History

	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)	

Note: IRU Calibration results from 2002-2007 were previously reported by Burrough and Lee (AIAA-2007-6340)

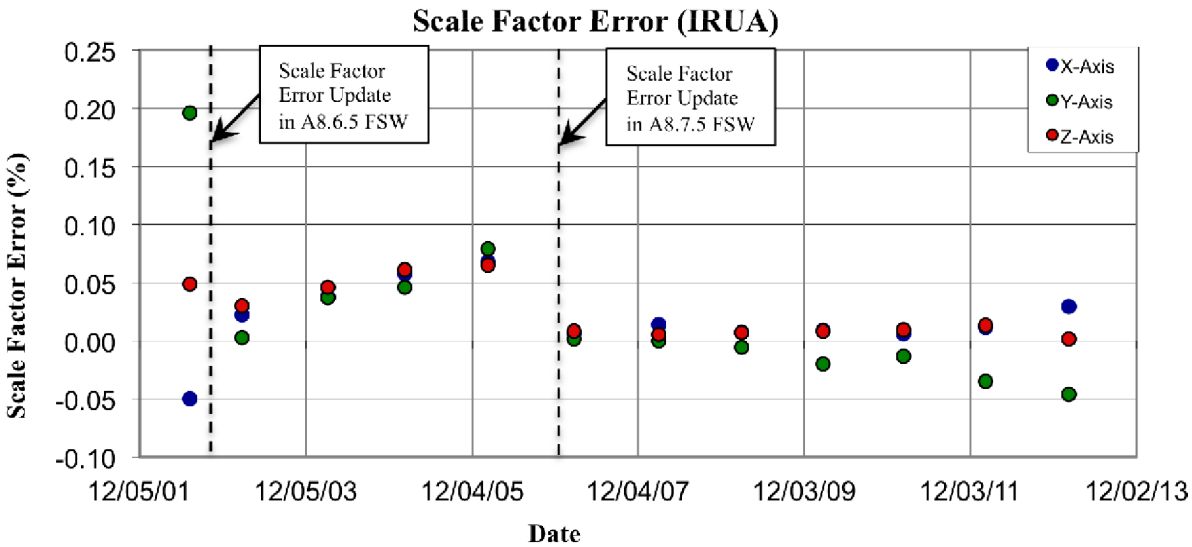
Calibration Results: IRU Bias

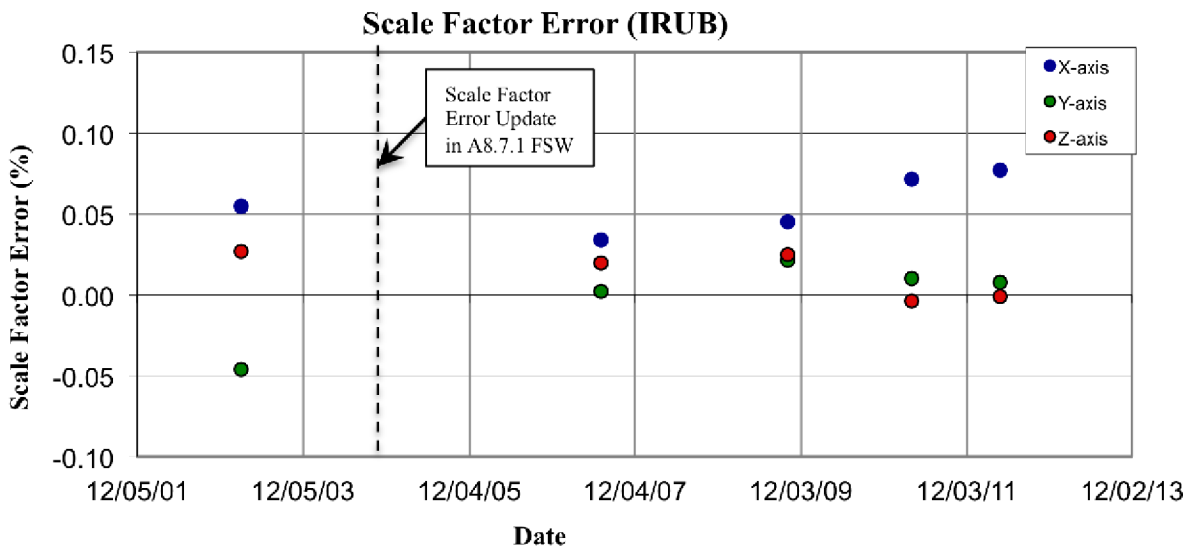




- Pre-launch the required IRU bias was 1 deg/hr (4.84 mrad/s) 3σ
- IRU Bias is estimated onboard and is not updated via FSW patch
- IRUA bias exceeded the pre-launch requirement in 2010, after 13 years of flight. This is not a concern because the bias is estimated onboard
- IRUB bias has grown approx. linearly since it was first calibrated in 2003. Still well within requirements

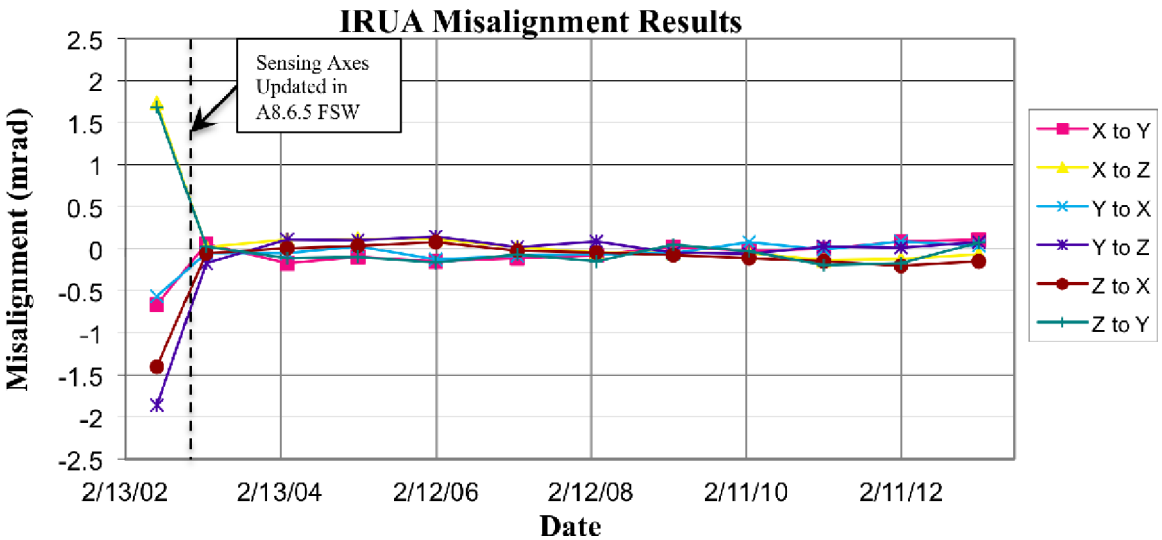
Calibration Results: IRU Scale Factor Errors

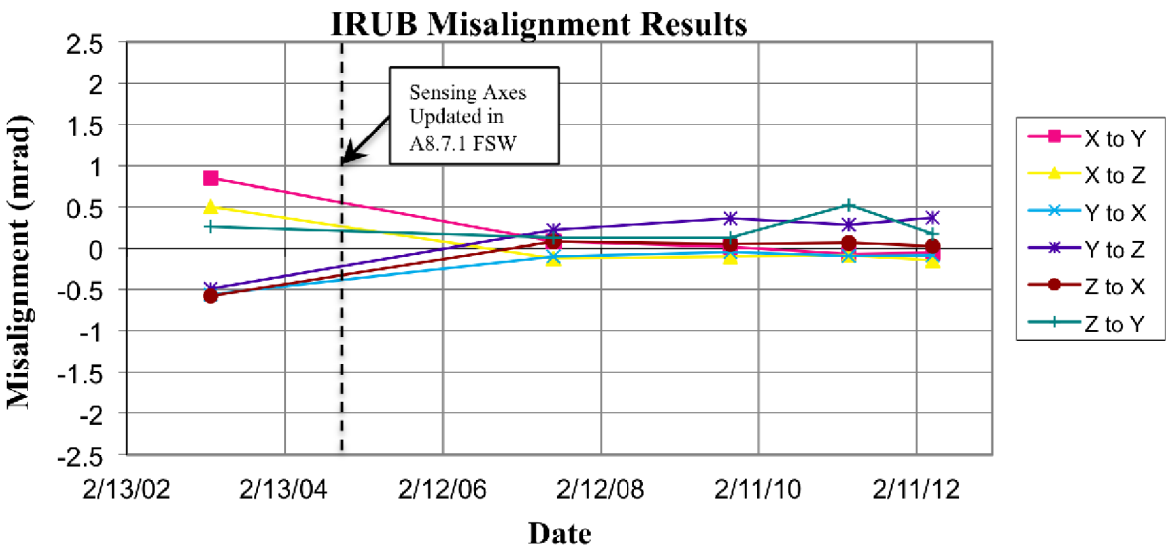




- Pre-launch the scale factor error was required to be less than 2500 ppm (0.25%) 3σ
- IRU Scale Factors can be updated via FSW memory patch
- IRUA & IRUB scale factor errors have never exceeded requirements
- IRUA Scale Factors updated twice in flight. Both updates resulted in lower scale factor errors
- IRUB scale factors were updated once in flight. Update resulted in lower scale factor errors

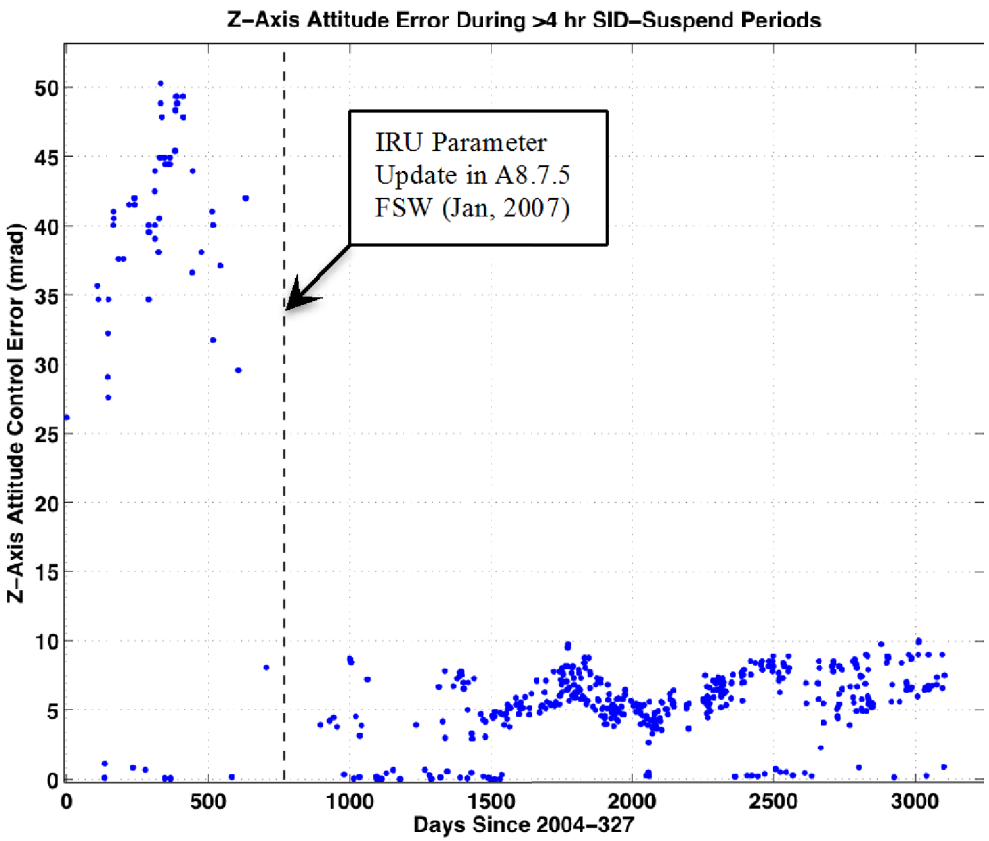
Calibration Results: Sensing Axis Misalignment





- IRU misalignment control required to be less than 5.0 mrad and knowledge less than 2.5 mrad 3σ
- IRU sensing axes are parameterizes in AACS FSW and are updateable
- IRUA & IRUB alignments were each updated once in flight and resulted in reduced alignment errors that have remained small

Gyro Only Attitude Propagation



- Cassini frequently turns to attitudes where a bright body obscures SRU (star tracker) field of view and attitude propagated using gyro data only
- These "SID-Suspend" periods are limited to 5 hours
- Very common for science teams to request a multi-revolution roll around the Z-axis (HGA direction) resulting in >4 hr SID-Suspend periods
- At moment that SRU attitude updates resume (after 4 hours of outage) the attitude error instantaneously grows to a large size indicating gyro propagation error
- Gyro performance can be gauged by monitoring the peak attitude error

Summary & Conclusion

- IRUA & IRUB continue to function and allow attitude control within performance requirements, even after 16 years of flight
  - IRUA has been powered on continuously since 1997
- Results of IRU calibration activities do not show a need for further parameter updates at this time
- Additional IRU calibrations are planned through 2017, though no updates to FSW parameters are expected to occur
- Flight telemetry from "gyro only" propagation periods demonstrate that the IRU performance in flight has not changed appreciably in 7 years