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

**Mission Timeline:**
Launch: October 1997
Saturn Arrival: 2004
Huygens Probe Delivery to Titan: 2005
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)**

**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

Credits: NASA, JPL
The Cassini Inertial Reference Units

- **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 4\(^{th}\) 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

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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

\[ \tilde{\theta}_{\text{gyro}} = \int \left( \tilde{\Omega}_{\text{gyro}} dt \right) + \tilde{\Lambda}_{\text{Angle}} \]

\[ \tilde{\Omega}_{\text{gyro}} = \begin{bmatrix} 1 + \varepsilon_x & 0 & 0 & \theta_{xx} & \theta_{xz} & % \\ 0 & 1 + \varepsilon_y & 0 & \theta_{yx} & \theta_{yz} & % \\ 0 & 0 & 1 + \varepsilon_z & \theta_{zx} & \theta_{zy} & \theta_{zz} \end{bmatrix} + \begin{bmatrix} b_x & % \\ b_y & % \\ b_z & % \end{bmatrix} + \tilde{\Lambda}_{\text{Rate}} \]

- 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

<table>
<thead>
<tr>
<th>IRUA</th>
<th>Date of Calibration Activity</th>
<th>Summary of FSW Parameter Changes Resulting from IRU Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2002-194</td>
<td>Led to a Scale Factor Error Update and Sensing Axis Correction in A8.6.5 FSW (Feb, 2003)</td>
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<td>2003-058</td>
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<td>~2014-030 (Planned)</td>
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<td>~2014-350 (Planned)</td>
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<td>~2015-350 (Planned)</td>
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<td></td>
<td>~2016-300 (Planned)</td>
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<td>IRUB</td>
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<td>Led to a Scale Factor Error Update and Sense Axis Correction in A8.7.1 FSW (Oct, 2004)</td>
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<td></td>
<td>~2016-250 (Planned)</td>
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</tbody>
</table>

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 $3\sigma$
- IRU sensing axes are parameterized 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