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

## August 13, 2012


## Todd S. Brown

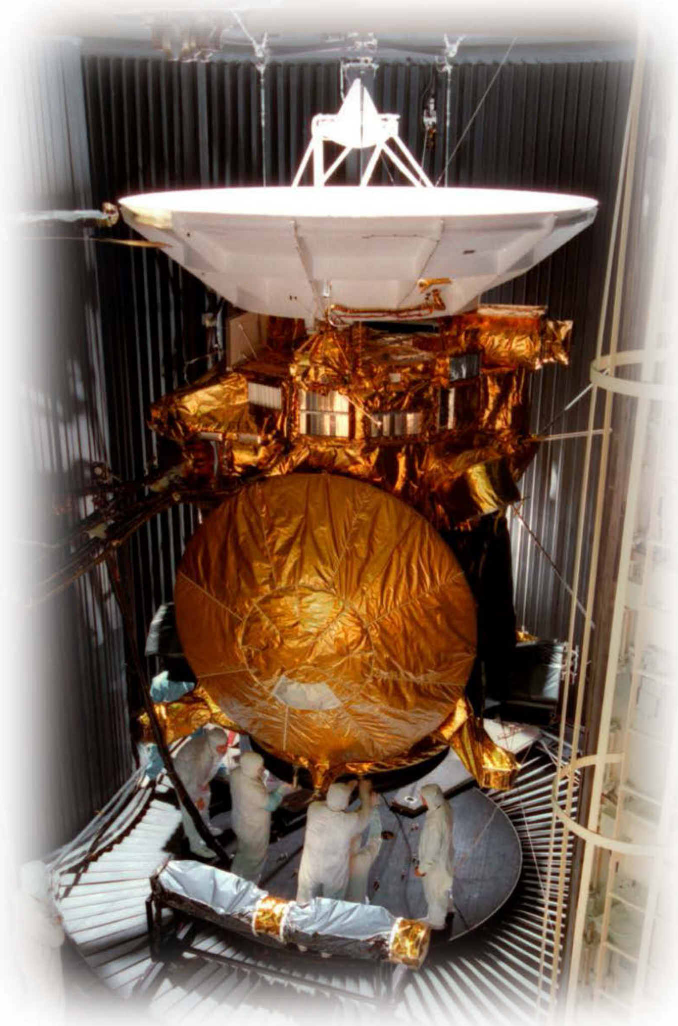
## Jet Propulsion Laboratory, California Institute of Technology

# Overview

- Overview of the Cassini Spacecraft
- RWA4 and the Articulation Motor
- Problem Statement / Purpose
- RCS Controlled Method of RWA4 Position Calibration
- RWA Controlled Method of RWA4 Position Calibration
- Summary/Conclusion

# The Cassini Spacecraft

- Launched in 1997
- Arrived at Saturn in 2004
- 2nd Extended Mission scheduled to last until 2017
- 12 major science instruments
  - Optical remote sensing (cameras)
  - Fields and particles (antennas and spectrometers)
- Must slew to point science instruments
  - No scan platform

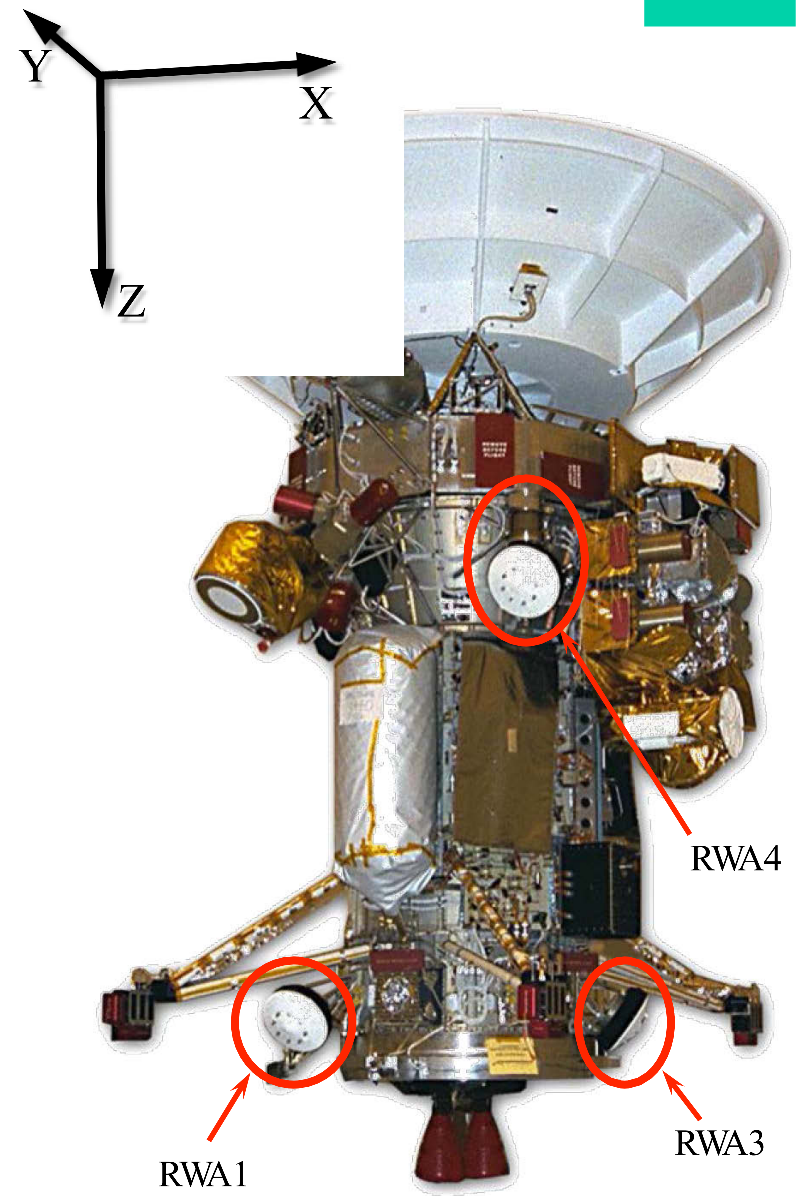


Credits: NASA, JPL

ame

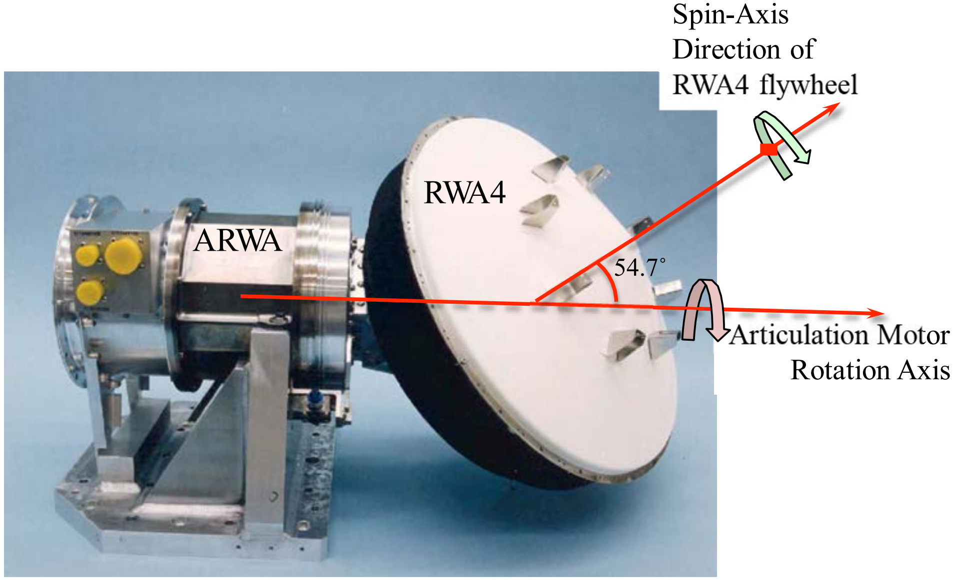
# The Cassini Spacecraft

- 3-Axis stabilized and two sources of attitude control
  - Reaction Control System (RCS) Thrusters
  - Reaction Wheel Assembly (RWA) Control
- RWA Control
  - 3 RWAs used for attitude control
  - 3 RWAs strapped-down (RWA1, RWA2, & RWA3) and 1 backup articulable reaction wheel (RWA4)
  - Current prime set of wheels: RWA1, RWA2, RWA4
    - RWA3 still functional, but with higher level of friction

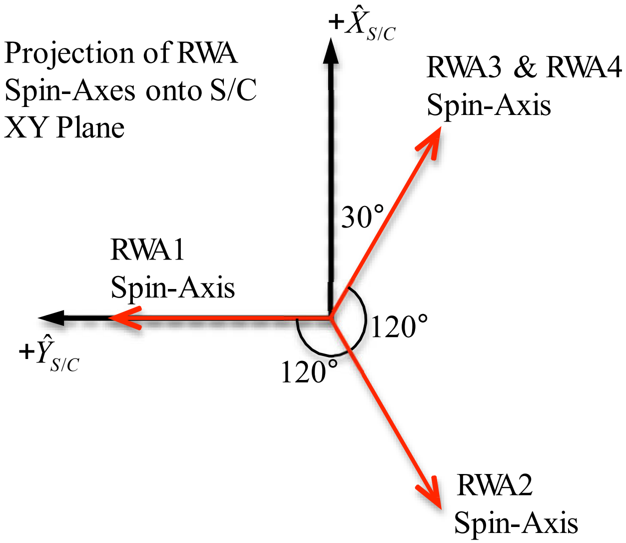



Credits: NASA, JPL

# RWA4 and the Articulation Motor




Credits: NASA, JPL




- The Articulated Reaction Wheel Assembly (ARWA)
  - Motor rotation axis aligned with spacecraft Z-axis
  - ARWA can rotate ±120° so RWA4 precisely matches spin-axis of any of the other RWAs
  - Motor has hard-stops at RWA2 and RWA3 orientations
  - RWA4 aligned with RWA1 at launch
  - Due to RWA3 friction, RWA4 articulated to replace RWA3 in 2003

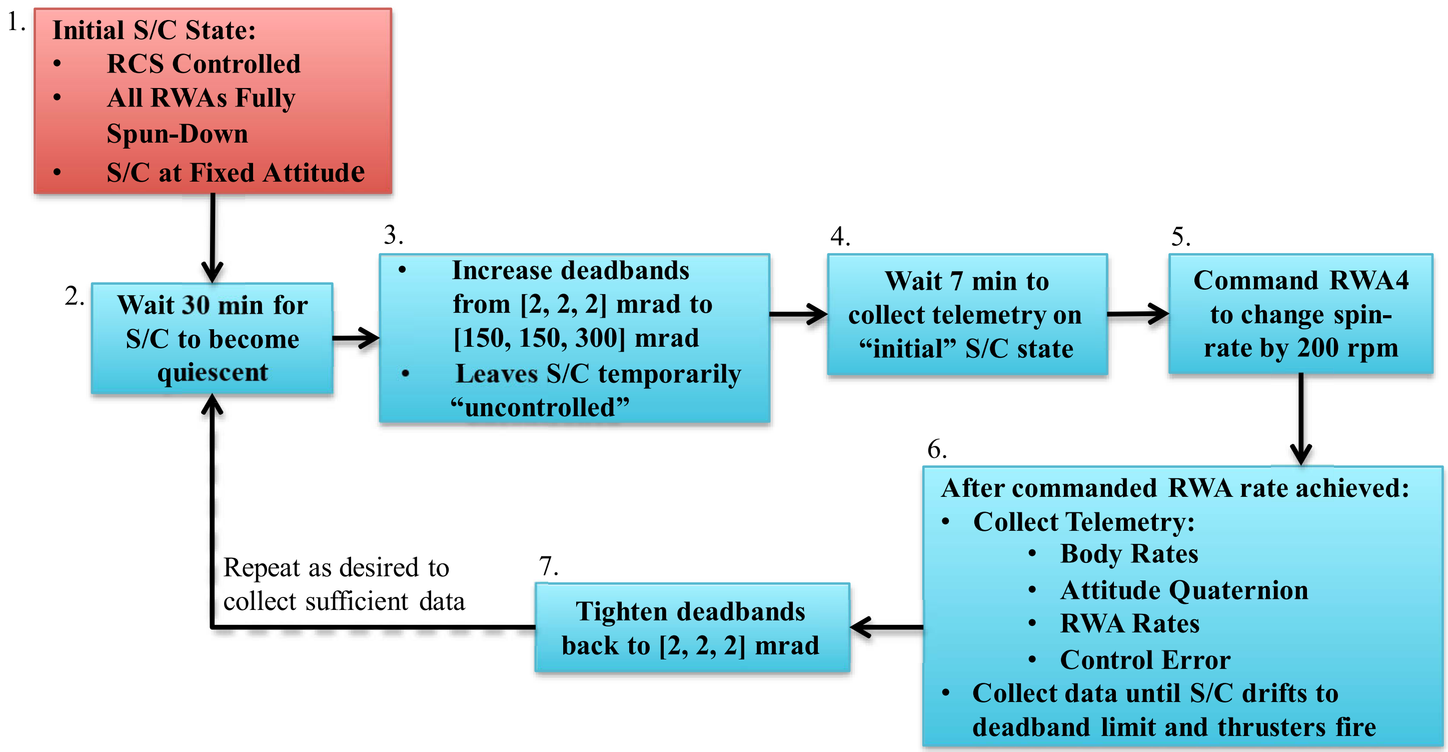
# Problem Statement

- Question: What would happen if RWA1 were to fail in the next 5 years?
- Answer: Articulate RWA4 again replace RWA1 and then use RWA2, RWA3, & RWA4 as the prime set
- Complications:
  - Exact motor orientations cannot be commanded. Motor is simply powered on/off
    - On/Off commands at 1/8 sec resolution or ~1.5° of motion
  - No hard-stop on motor at the orientation of RWA1
  - No accurate telemetry from the motor on the orientation of RWA4
  - Actuation speed of the motor is different in opposite directions and is not accurately known
- **Summary: Although RWA4 must be accurately aligned with RWA1 in order to replace it (±3°), there is no straightforward way to determine what the orientation of RWA4 is after an articulation**

# Purpose

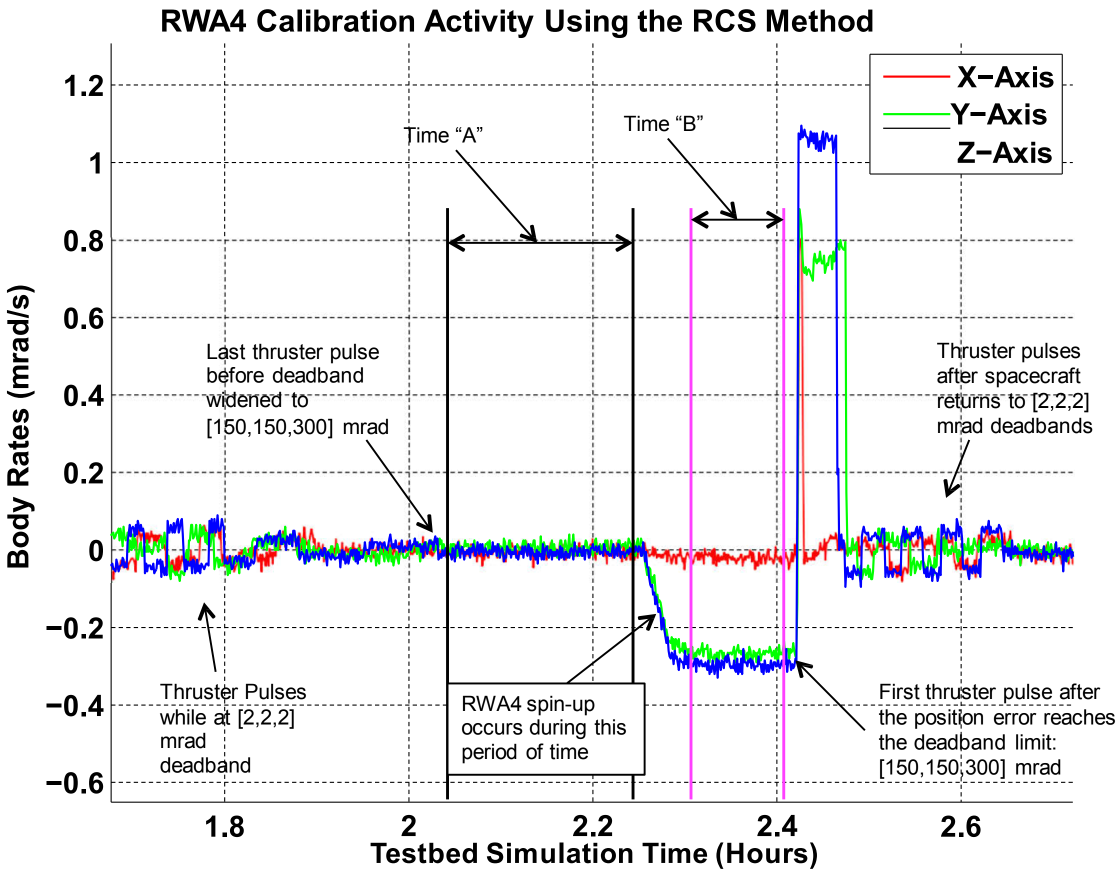
- The purpose of this paper is to present two independent activities that can be performed onboard the spacecraft after an articulation to accurately determine the spin-axis orientation of RWA4.
- Both calibration activities rely on the law of conservation of angular momentum
- Method 1: RCS Controlled Calibration Method
  - Advantage: Can be used with RWA4 in any orientation
  - Disadvantage: Only accurate to ±3° (worst-case)
- Method 2: RWA Controlled Calibration Method
  - Advantage: Believed to be accurate to better than than ±1°
  - Disadvantage: Can only be used if RWA4 is known to be within ~10° of RWA1 orientation

# RCS Controlled Calibration Method




- Widening deadbands leaves spacecraft nearly "uncontrolled" for a short period of time
  - S/C behaves like a "test mass" under the influence of only RWA4

# RCS Controlled Calibration Method




- S/C body rates, attitude, control errors, and RWA rates measured during “Time A” and “Time B” and then averaged
- To find RWA4 spin-axis:
  - First: Equate change in inertial angular momentum of the spacecraft bus to the negative of the change in the angular momentum of RWA4
  - Second: Solve this formula for RWA4 momentum direction

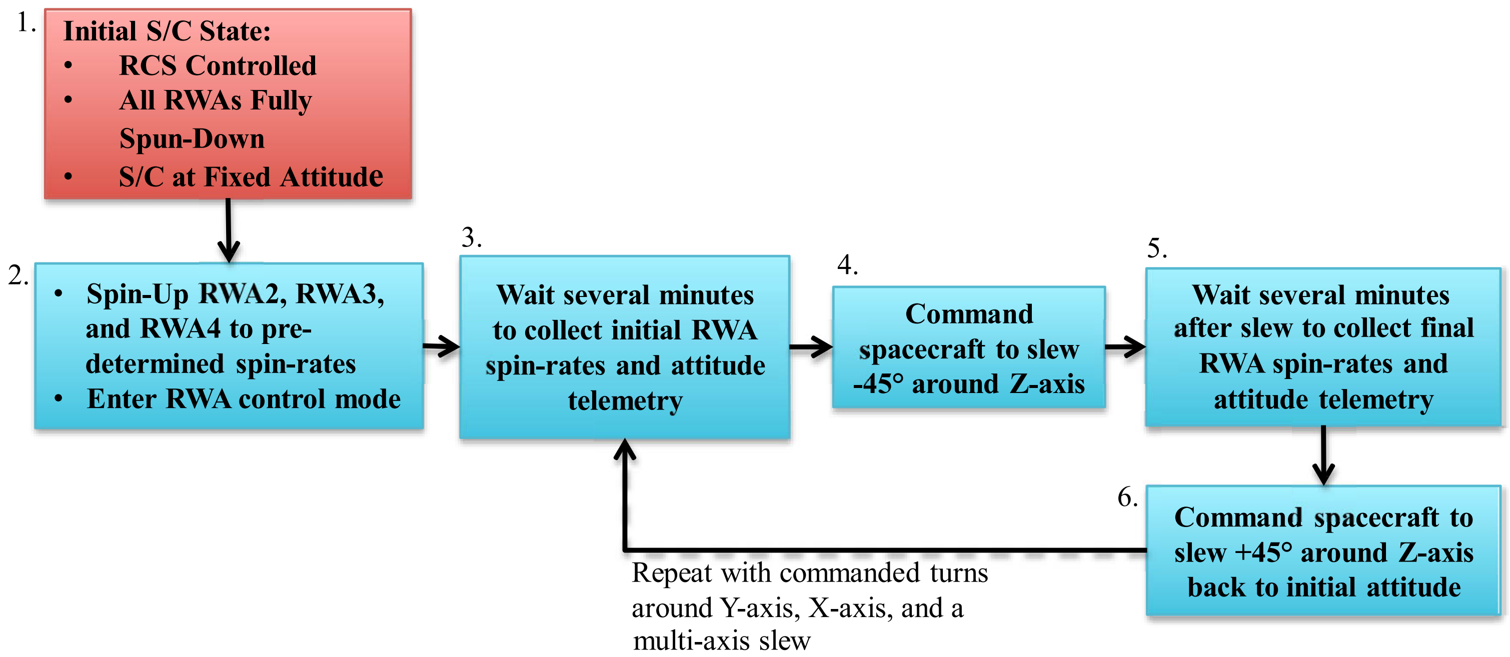
$$\bar{u}_4 = \frac{1}{I_{RWA4}} \left[ \frac{1}{m} \sum_{j=1}^{m} \left( \omega^R_{RWA4}(t_j)\, {}^I C^B_{t_j} \right) - \frac{1}{n} \sum_{i=1}^{n} \left( \omega^R_{RWA4}(t_i)\, {}^I C^B_{t_i} \right) \right]^{-1} \left[ \frac{1}{n} \sum_{i=1}^{n} \left( {}^I C^B_{t_i} [I]^B_{s/c}\, \bar{\omega}^B_{s/c}(t_i) \right) - \frac{1}{m} \sum_{j=1}^{m} \left( {}^I C^B_{t_j} [I]^B_{s/c}\, \bar{\omega}^B_{s/c}(t_j) \right) \right]$$

# RCS Controlled Calibration Method

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

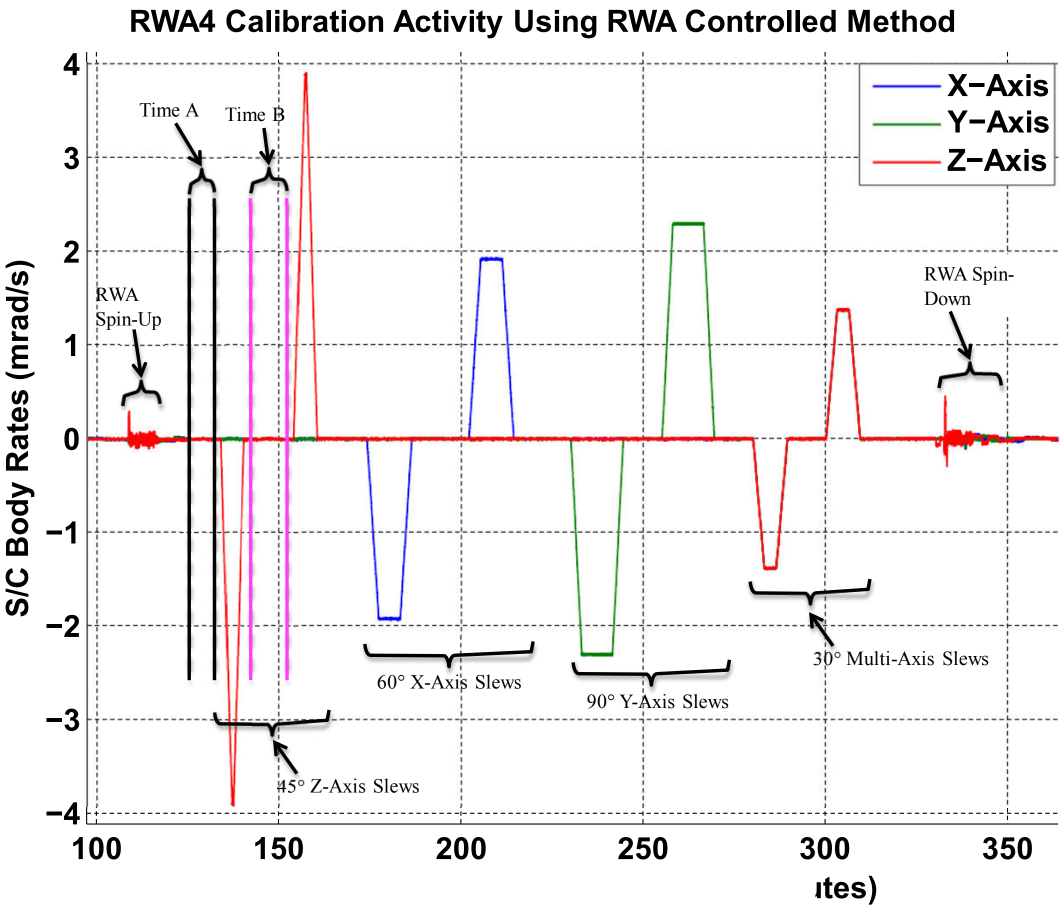
- Following Quantities Known Accurately:
  - S/C body rates and attitude, RWA spin-rates, and RWA4 inertia around spin-axis
- Largest uncertainty associated with S/C moment of inertia tensor
  - Rough Monte Carlo analysis performed with Cassini testbed telemetry indicates mass uncertainty should add no more than ~1.5° error to RWA4 calibrated position
- Calibration method extensively tested in the Cassini Integrated Test Laboratory (ITL) avionics testbed
  - Results indicated that RWA4 position error always measured to better than ±1.4° error
  - Straight-sum of ITL error with mass uncertainty error indicates this calibration method should give RWA4 orientation measurement **with less than ±3° error**
- Currently no plan to test calibration procedure in flight unless RWA1 fails
  - RWA1 currently continues to operate without any performance degradation

# RWA Controlled Calibration Method




- Use RWA4 along with RWA2 and RWA3 to perform several slews to various attitude
  - RWA4 orientation not precisely known, but must be reasonably close to RWA1 (±10°) in order for controller to work
  - Total angular momentum of the 3 RWAs and spacecraft chassis are assumed to be constant

# RWA Controlled Calibration Method




- Use RWA4 to perform various slews to different attitudes
- Record average RWA spin-rates, S/C attitude, & body rates before and after each slew
- To find RWA4 spin-axis:
  - First: Equate total inertial angular momentum of the 3 RWAs before a slew to the same quantity after the slew
  - Second: Solve that formula for the RWA4 momentum direction vector

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

# RWA Controlled Calibration Method

$$\bar{u}_4 = \frac{1}{I_{RWA4}}\left[\frac{1}{n}\sum_{i=1}^{n}\left({}^{I}_{R}C^{B}_{t_i}\omega_{rwa\,4}(t_i)^{B}\right)-\frac{1}{m}\sum_{j=1}^{m}\left({}^{I}_{R}C^{B}_{t_j}\omega_{rwa\,4}(t_j)^{B}\right)\right]^{-1}\left\{\left[\frac{I_{RWA2}}{m}\sum_{j=1}^{m}\left({}^{I}C^{B}_{t_j}\omega^{R}_{rwa\,2}(t_j)^{B}\right)-\frac{I_{RWA2}}{n}\sum_{i=1}^{n}\left({}^{I}C_{t_i}\omega^{R}_{rwa\,2}(t_i)^{B}\right)\right]\bar{u}_2+\left[\frac{I_{RWA3}}{m}\sum_{j=1}^{m}\left({}^{I}C^{B}_{t_j}\omega^{R}_{rwa\,3}(t_j)^{B}\right)-\frac{I_{RWA3}}{n}\sum_{i=1}^{n}\left({}^{I}C_{t_i}\omega^{R}_{rwa\,3}(t_i)^{B}\right)\right]\bar{u}_3\right\}$$

- Telemetry used: attitude quaternion and RWA spin-rates
  - Both quantities known accurately
- Calibration method extensively tested in the Cassini Integrated Test Laboratory (ITL) avionics testbed
  - Simulation telemetry produced RWA4 estimates that were on average just 0.5° from the actual orientation used in the testing. Worst case had just 0.8° degrees error
- The RWA calibration method has been *verified with flight telemetry*
  - Method does not require specific turn sequences, so flight telemetry from an unrelated series of slews was examined
  - Used data from slews with RWA1, RWA2, and RWA3, where RWA1 was assumed to have an unknown orientation (Note: RWA1 cannot move and its orientation is accurately)
  - Flight test produced RWA1 spin-axis measurement just 0.4° from the CBE value used for flight operations
- The RWA calibration method cannot be used unless Ops team is confident (based on results of RCS controlled calibration method) that RWA4 is within ~10° of RWA1

# Summary and Conclusions

- If Cassini's RWA1 were to fail, it would be difficult to verify the orientation of RWA4 after that wheel is articulated to replace RWA1
- AACS team has developed two independent methods to determine orientation of RWA4 from basic flight telemetry
  - RCS Controlled Calibration Method (accurate to ±3°)
  - RWA Controlled Calibration Method (accurate to ±1°)
- Both methods extensively tested in Cassini ITL testbed to verify their accuracy, and RWA method tested on flight telemetry
- Currently no indication that RWA1 will fail in near future. However, the AACS team stands ready should that event occur.

# Backup Slides