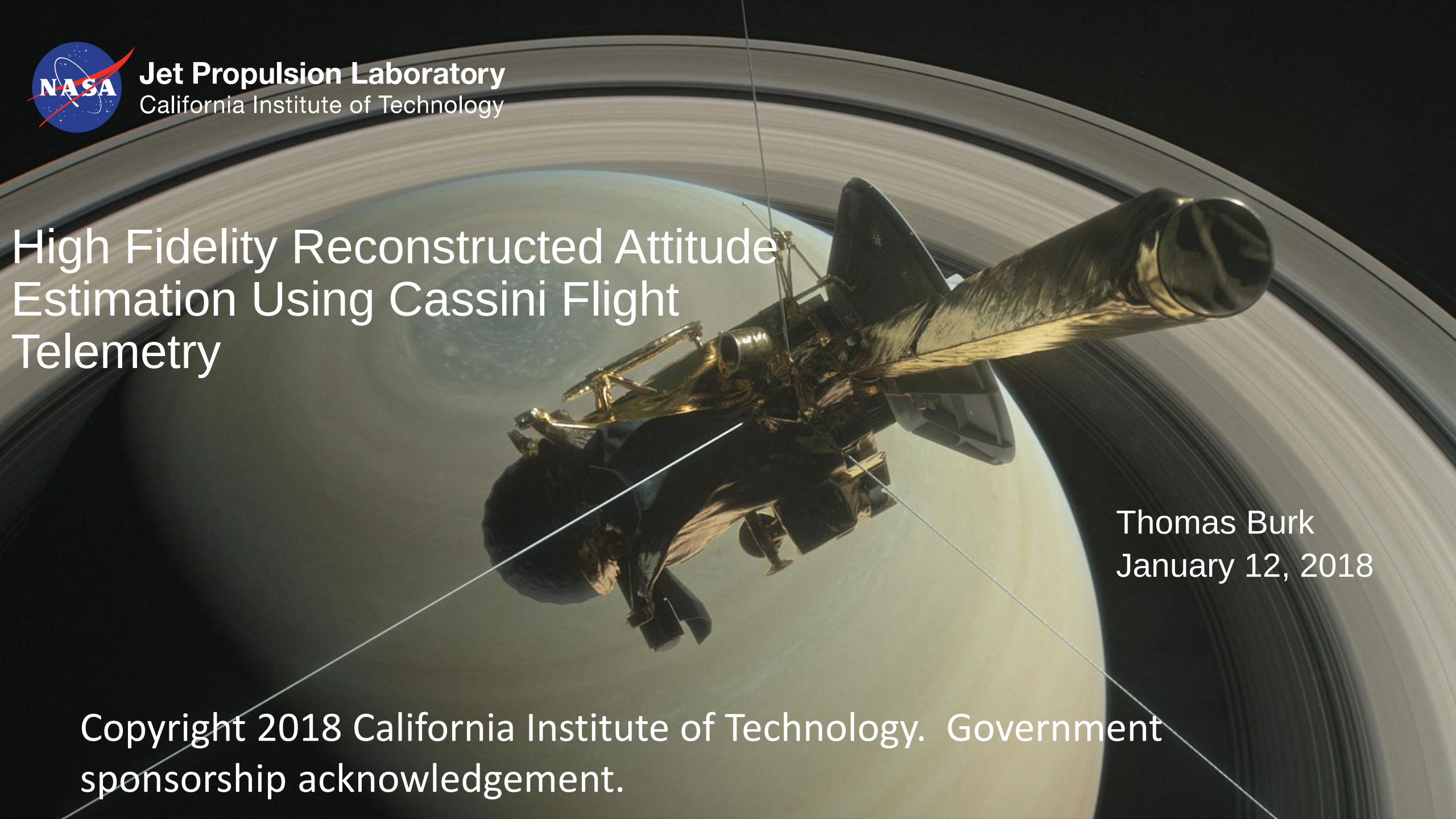

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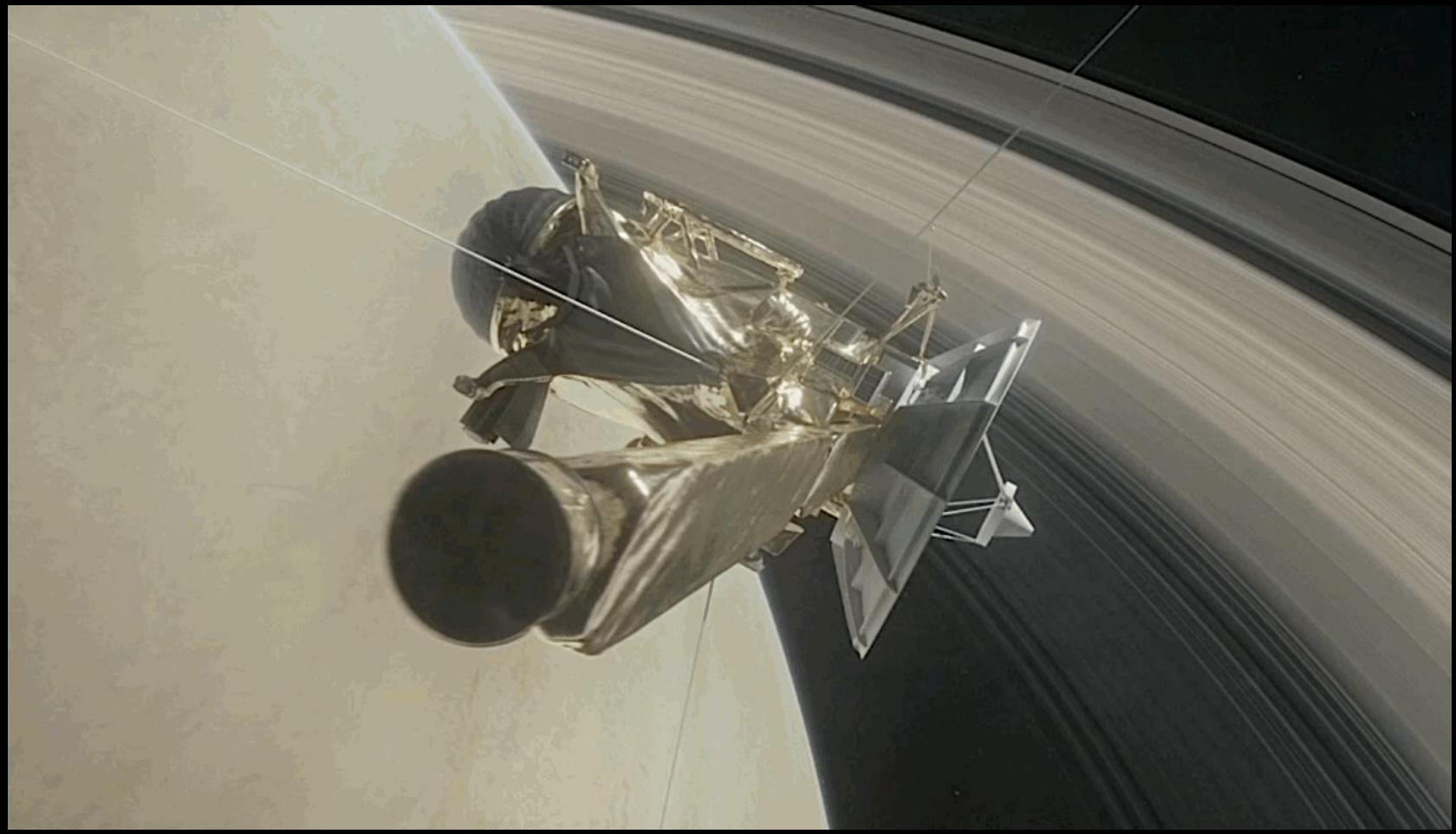
High Fidelity Reconstructed Attitude Estimation Using Cassini Flight Telemetry

Thomas Burk
January 12, 2018

Cassini Crossing Inside the Rings



Suspending Star Identification (SID) will introduce an error in attitude knowledge

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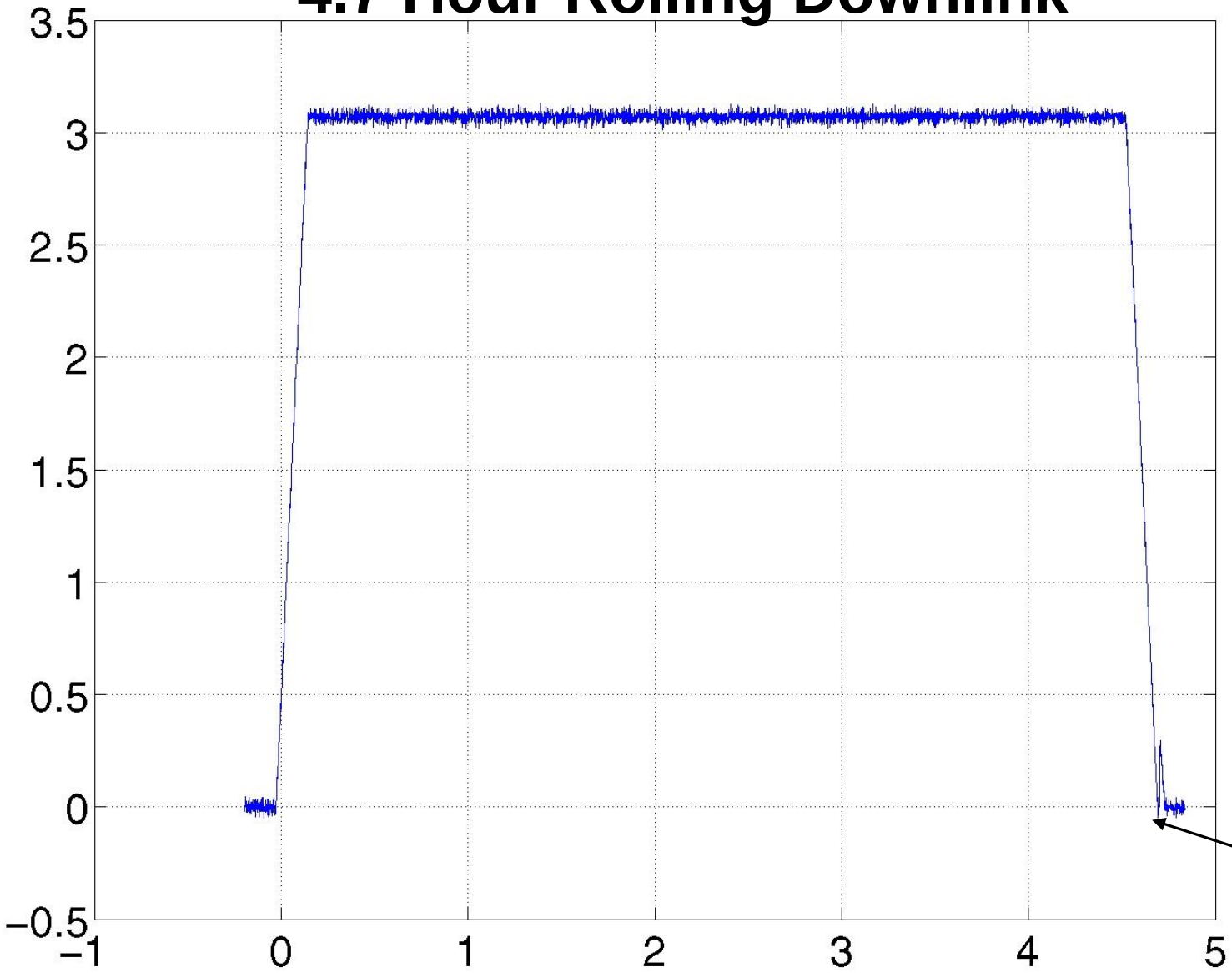
- Cassini attitude estimation was normally accurate to better than 0.5 mrad (0.03°)
  - Requires good star identification (SID) and gyros working together
- Star identification was sometimes suspended from 1 to 5 hours (due to bright bodies in star tracker field of view)
  - Attitude was propagated by “gyros only” during these SID Suspends
  - When SID is re-enabled at the end of the Suspend, the first celestial update causes a “jump” in the estimated attitude
    - Visible via a jump in attitude control error telemetry
  - This re-acquisition correction was typically 1 to 20 mrad (0.06° to 1.1°)
    - Depended on amount of angular rotation during the SID Suspend
    - Large amount of slewing → bigger attitude correction

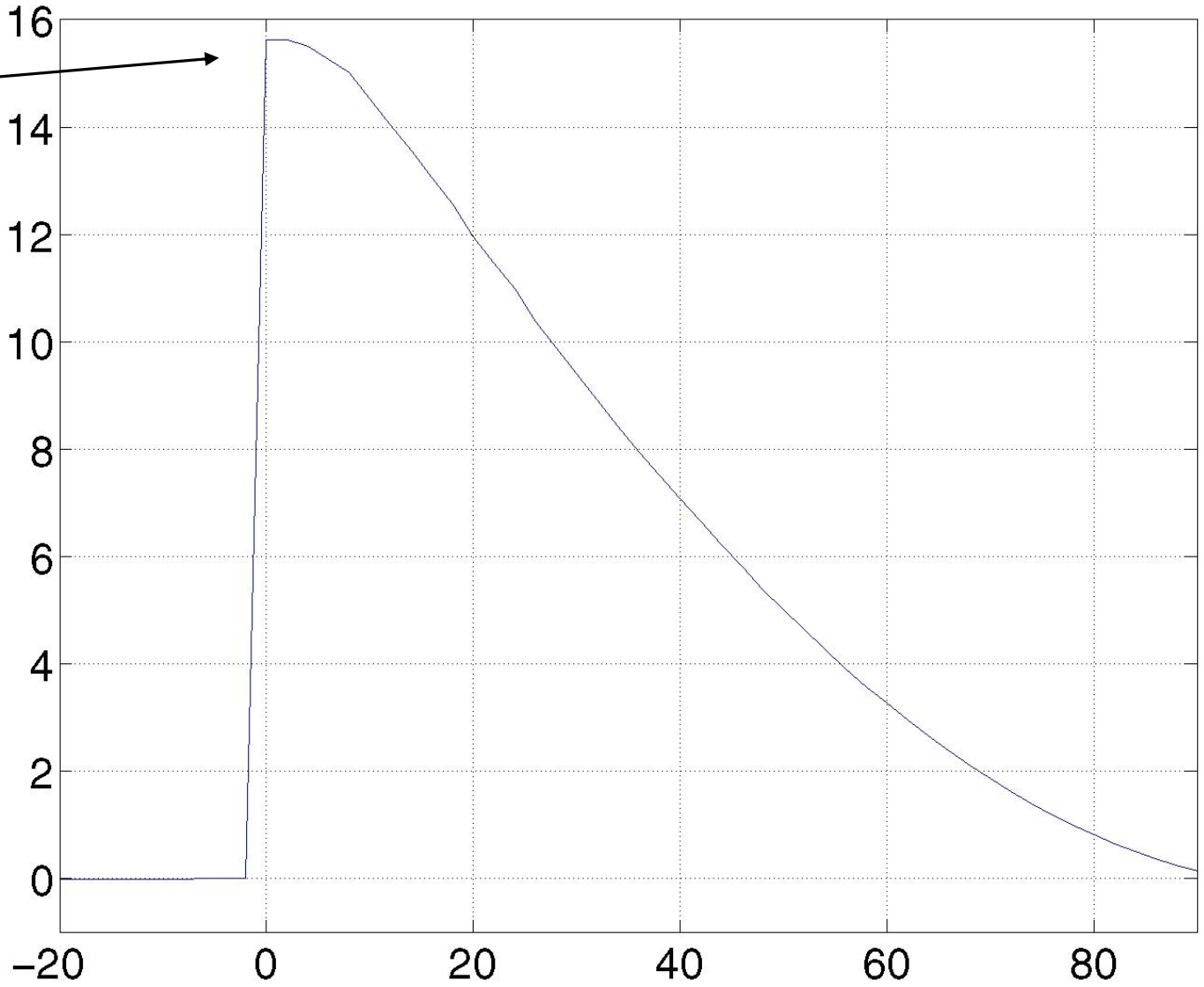
4.7 Hour Rolling Downlink



Example of long SID Suspend during rolling downlink about Z-axis

Example of re-acquisition at end of long SID Suspend

End of SID Suspend



SID Suspends During Grand Finale Orbits

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- Each of the 22 Grand Finale periapses had a long SID Suspend
  - Typically occurred during the ring plane crossing
- This coincided with some of the most important magnetic field measurements of the entire mission
- A 1-2 mrad error in pointing can lead to significant artifacts in Saturn's magnetic field estimates
  - Field oscillations due to Cassini angular rotation
- The Magnetometer team requested we "post-process" the attitude telemetry after playback
  - Produce a "corrected" pointing time-history
  - Try to more closely match the actual spacecraft attitude during these SID Suspends
  - Try to achieve better than 0.5 mrad error if possible

Adjusting S/C reconstructed attitude during SID Suspends

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- Early in a suspend, gyro-only propagation has not introduced much error
  - Later in the Suspend, the growth of the error is significant
- Use the celestial “re-acquisition” correction that occurs at the end of the SID Suspend to better estimate the attitude during the SID Suspend
- Recent trending in gyro calibration results are used
  - Provides good nominal values for gyro scale factor errors

Gyro Angle and Rate Equations

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Gyro scale factor error

Random Walk terms

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

Misalignment term

Gyro bias

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

During slews, gyro scale factor error is typically the biggest contributor to the attitude propagation error

Re-acquisition errors during Grand Finale

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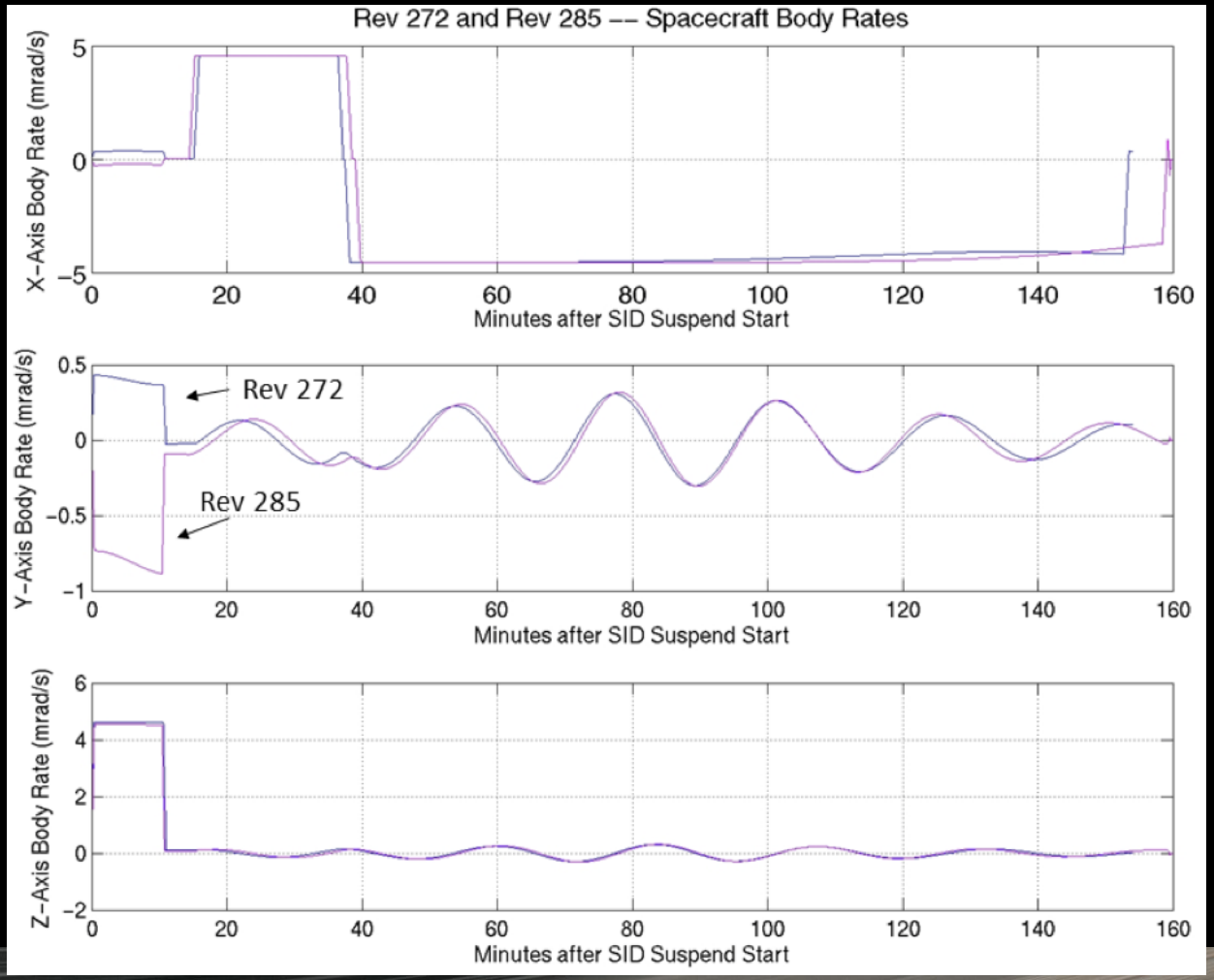
		Reacquisition Correction		
Rev	SID Suspend Duration (H:MM:SS)	X-axis (mrad)	Y-axis (mrad)	Z-axis (mrad)
272	2:33:42	-1.93	0.89	-1.07
285	2:39:56	-0.61	0.06	1.03
273	4:58:02	-0.65	-0.40	19.78
284	4:57:38	-0.14	-0.02	19.53

Rev 272 and 285 rotations are plotted here →

Rev 273 and 284 rotations are purely about Z-Axis



Accumulate attitude errors using gyro scale factor and random walk error inputs

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$$\Delta\vec{\theta}_{error(body)} = \vec{\Omega}_{true} \cdot \varepsilon_i \cdot \Delta t$$

Scale Factor Errors

$$\Delta\vec{\theta}_{error(J2000)} = q^{J2000}_{body} \cdot \Delta\vec{\theta}_{error(body)} \cdot q^{body}_{J2000}$$

$$\vec{\theta}_{error(J2000)} = \sum[\Delta\vec{\theta}_{error(J2000)} + \Delta\vec{\theta}_{Random\_Walk(J2000)}]$$

Random Walk Errors

$$\Delta\vec{\theta}_{Random\_Walk(J2000)} = \vec{\omega}_{Random\_Walk(J2000)} \cdot \Delta t$$

$$\vec{\theta}_{accum\_error(body)} = q^{body}_{J2000} \cdot \vec{\theta}_{error(J2000)} \cdot q^{J2000}_{body}$$

Rev 283 Attitude Error Accumulation – Varying X-Axis Scale Factor Error

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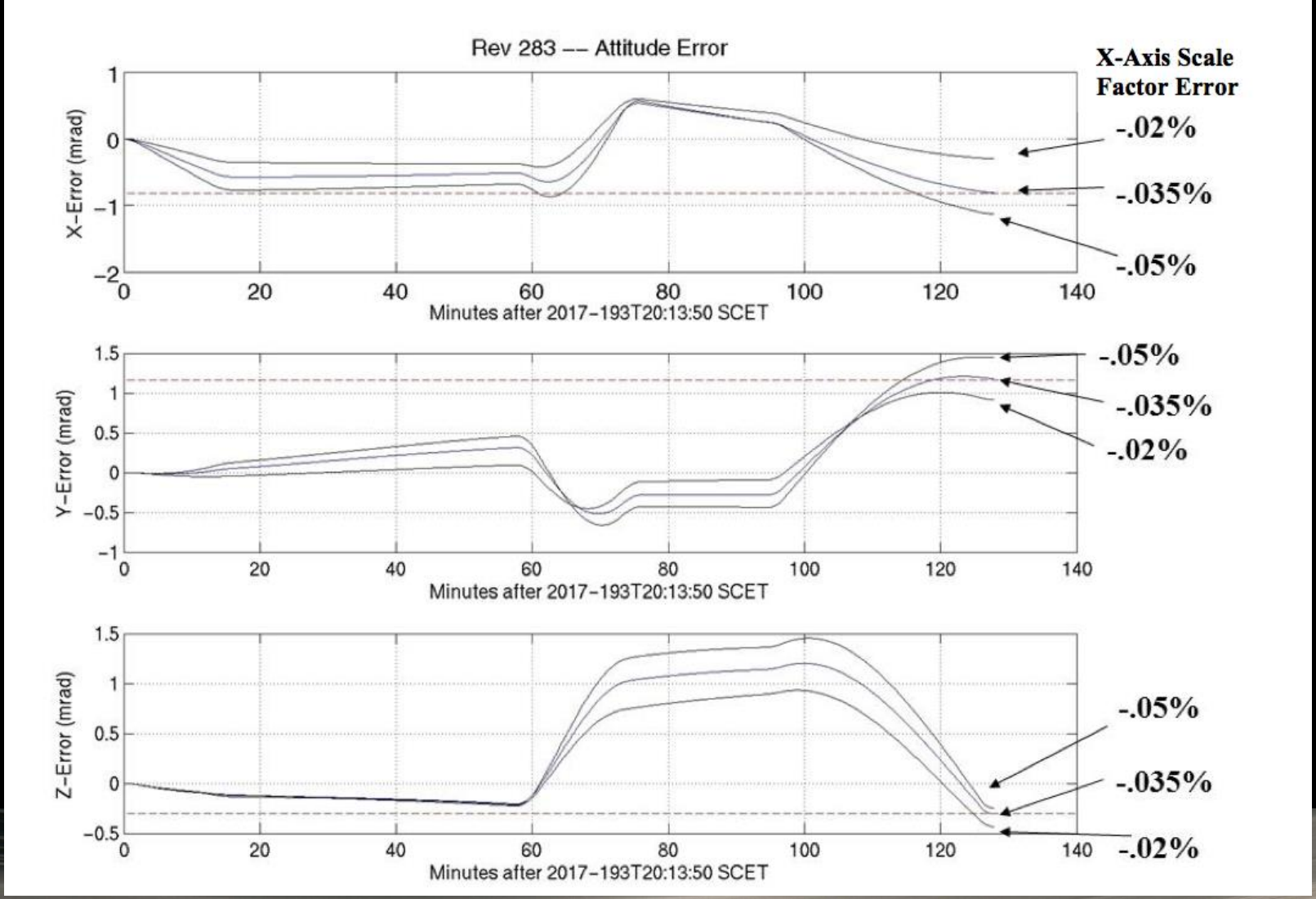

Do summation using actual body rates and adjust gyro estimates to get good fit

- Iterate attitude error accumulation over SID Suspend window by varying:
  - Gyro scale factor errors
    - These are relatively well-known from yearly on-board calibrations
  - Random walk errors
    - Used if scale factor errors cannot reproduce actual re-acquisition errors
- Match the re-acquisition errors at the end of the SID Suspend to within 0.1 to 0.2 mrad in all 3 spacecraft body axes
- There is no unique solution
  - Most Revs produce a good match using most recent gyro scale factor calibration results, with only a small random walk contribution
    - A few require slightly bigger random walk estimates to produce a good match

Attitude Error Accumulation in S/C Body Frame for Similar Revs 272 and 285

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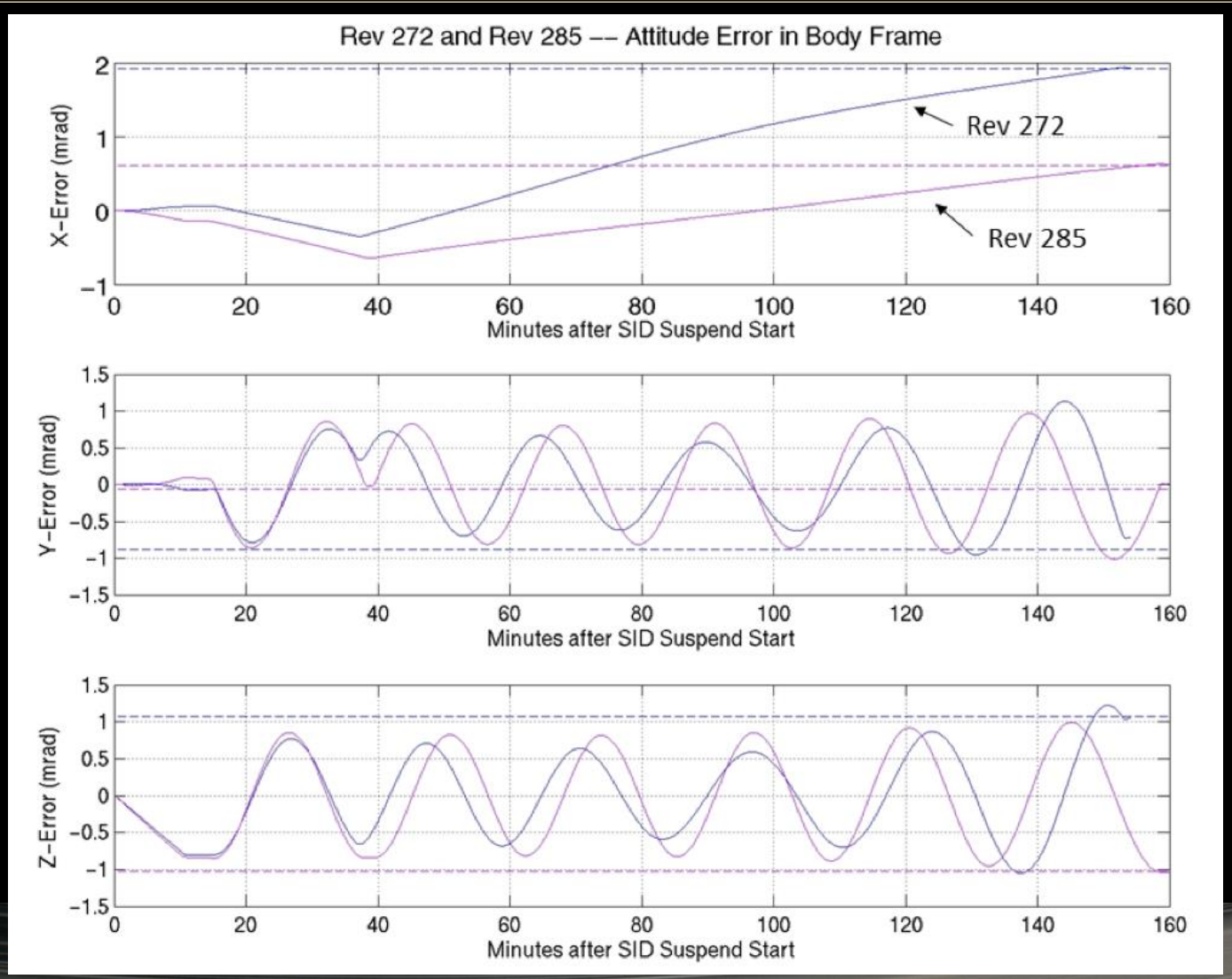
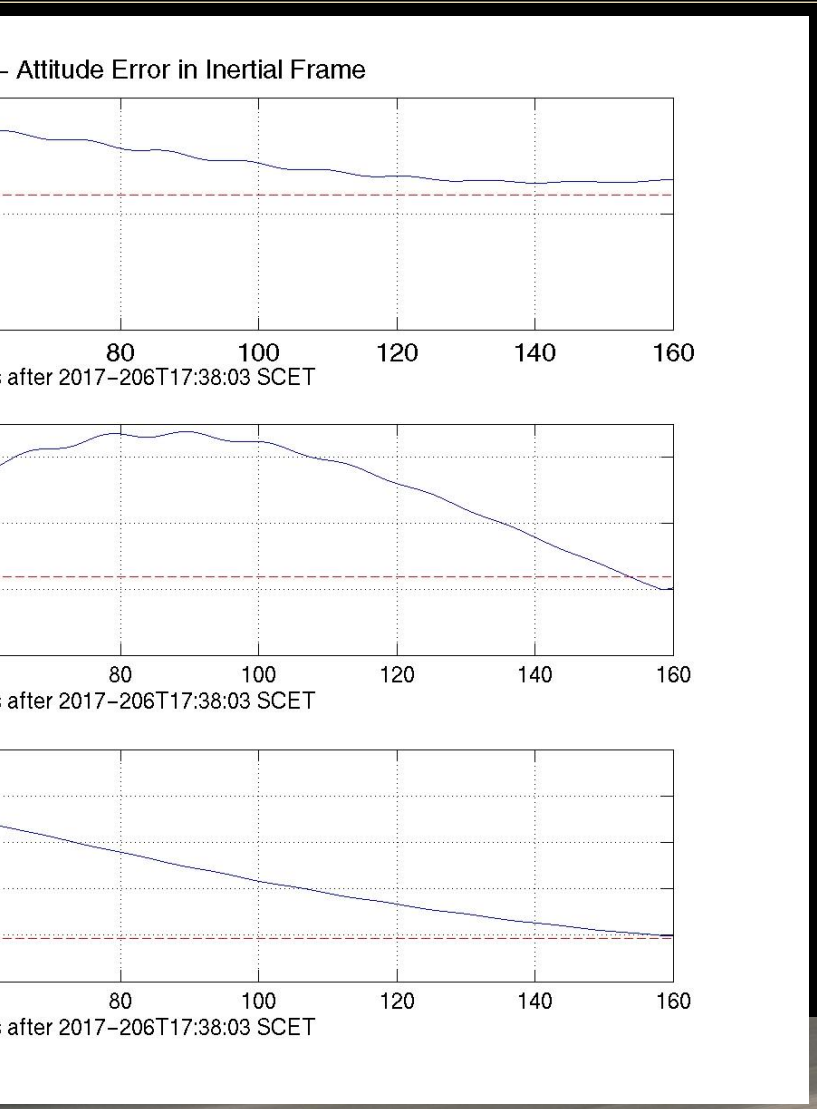


Attitude Error Accumulation Expressed in J2000 Inertial Frame for Rev 285



Rev 272 Magnetometer Data Corrected Using Best-Fit to Match Re-acquisition

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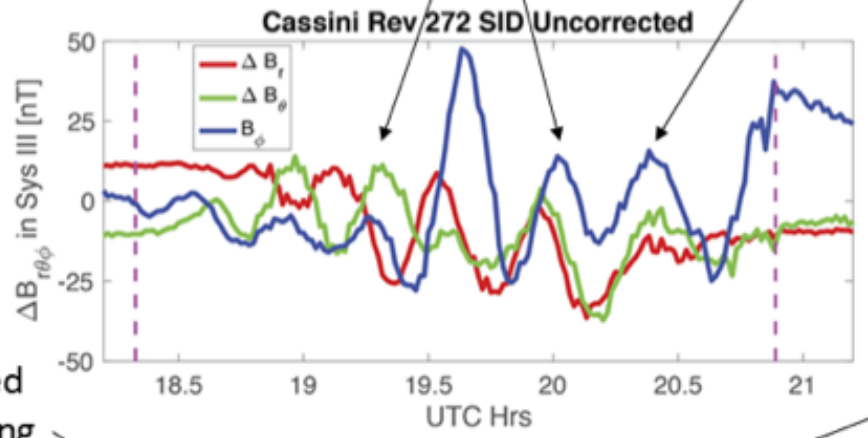
Magnetometer results are greatly improved by correcting for the attitude knowledge error that builds up during SID Suspends

"Spin tones" are artifacts due to uncorrected errors in Cassini rotational motion

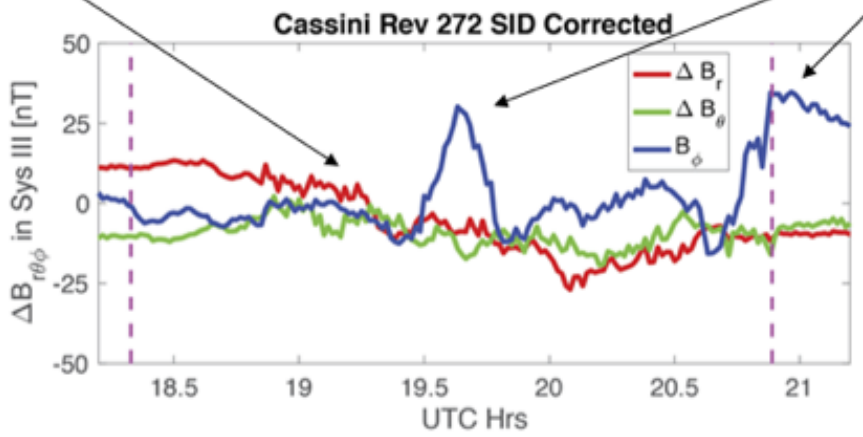


Rev 272 Magnetometer Results

Uncorrected

The artifacts can be greatly reduced by correcting the estimated pointing profile using the best fit method

These peaks are real Saturn magnetic peaks seen in all 22 Grand Finale periapses



Corrected

Science data courtesy of Dr. Hao Cao, Department of Earth and Planetary Sciences, Harvard University

Post-processing can produce improved attitude knowledge during long SID Suspends

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- Use recent calibration results for gyro scale factor errors
- Accumulate attitude error over SID Suspend duration using actual body rates
- Compare end-of-Suspend attitude error accumulation with actual re-acquisition results
  - Make small adjustments to gyro scale factors to improve fit
    - Constrain these errors to be near recent gyro calibration results
  - Include random walk contribution to improve the best fit
- Best-fit results are not only possible solution
  - Produce a few good candidates
- Cassini Magnetometer team has used these results and seen significant improvement in Saturn magnetic field measurements
  - Reduces the artifacts of Cassini angular rotation