Trending Main Engine Assembly (MEA) Cover Actuator Performance using Cassini Attitude Control Flight Data

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Objective of Study

- The Cassini S/C has an actuation mechanism that opens/closes an accordion-like cover that protects the MEA from **space/orbital debris**
- Original 20 cycle in-flight life span has now surpassed 80 cycles
- Primary plan is to use MEA cover for dust hazard protection until the end of mission in Sept. 2017 (Proximal Orbits)
- This study is the first to use Cassini **attitude control flight data** in an attempt to trend MEA cover actuator performance
- The goal is to detect any **sudden** change in cover actuation behavior that can be an early sign of oncoming actuator failure

1 cycle = 1 deploy(close) + 1 stow(open)

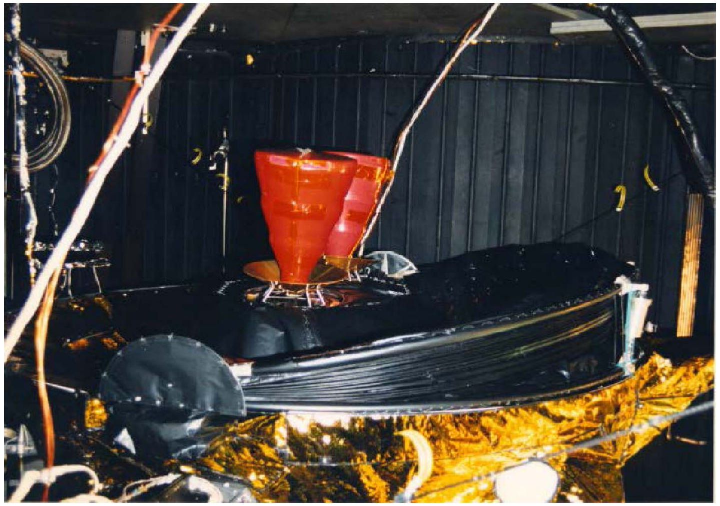


Fig. 1: Flight MEA cover on Cassini before launch[1]

Challenges of Study

- An inability to directly measure actuator torque output
  - Solution: Calculate "disturbance" torque imparted on S/C during cover actuations as an indirect method of trending cover actuator torque
- An unknown "true" disturbance torque profile
  - Solution: Use two different reconstruction methods to estimate disturbance torque
- A sparsity of available flight data
  - Solution: Apply smoothing and interpolating techniques to Attitude Control Subsystem (ACS) flight data

Cassini Spacecraft

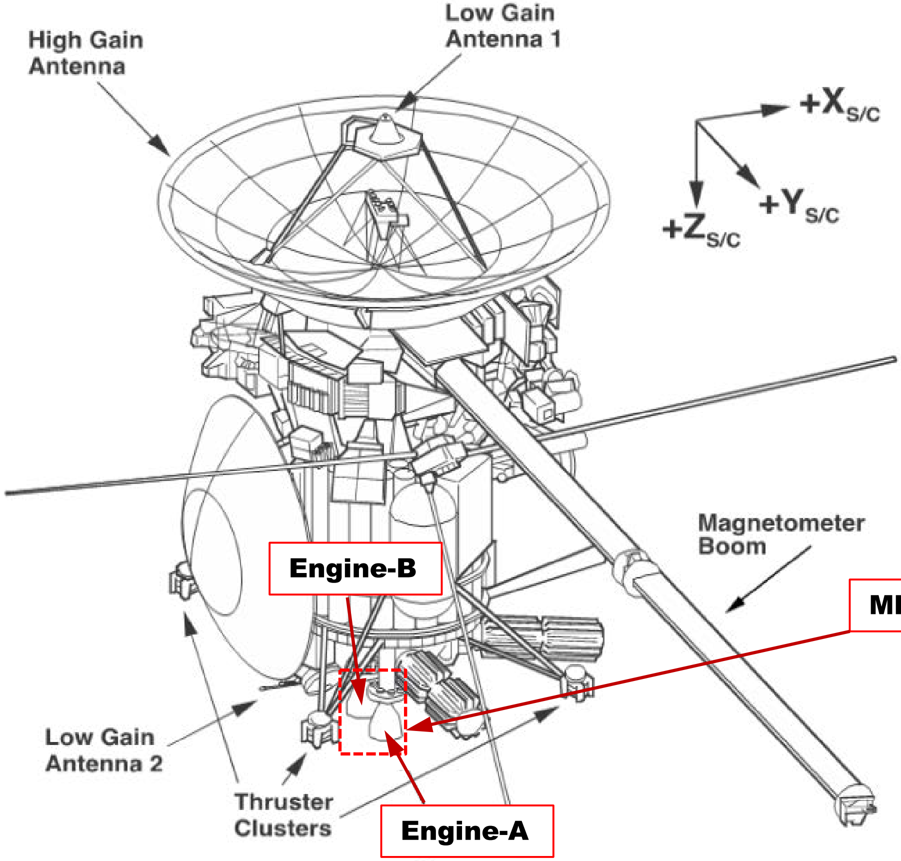


Fig. 2: Overview of Cassini S/C[1]

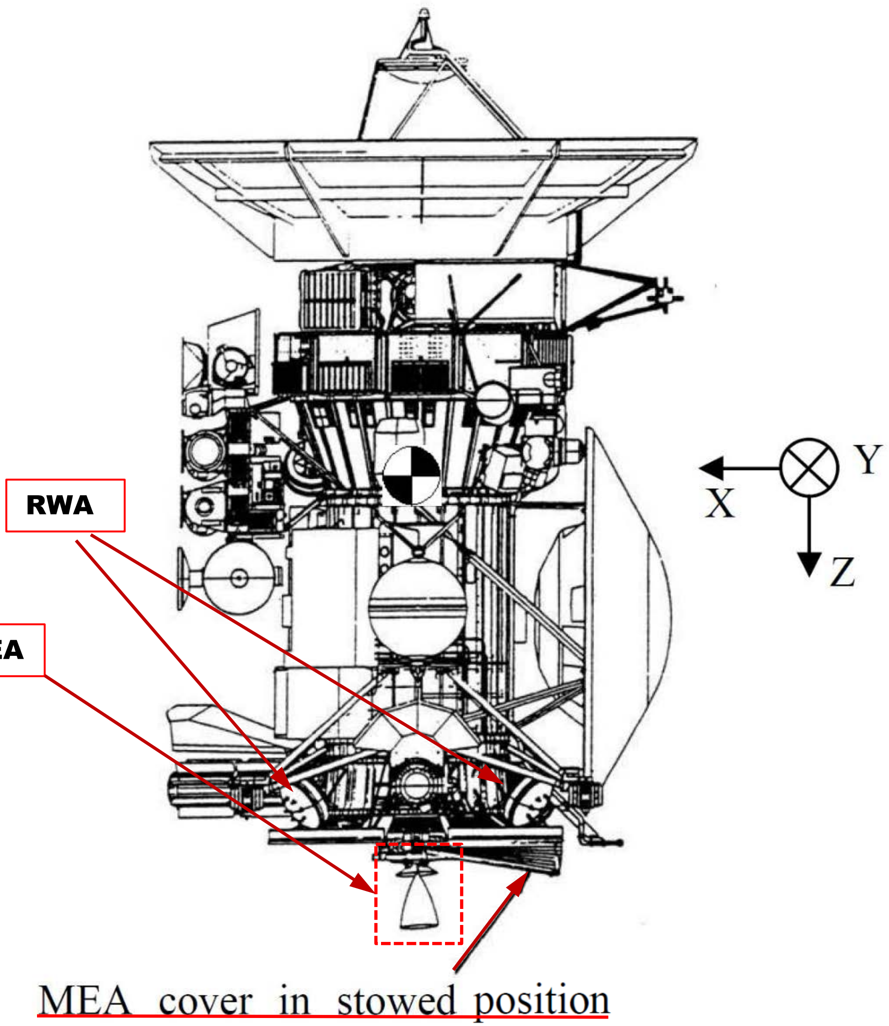


Fig. 3: Location of MEA cover on Cassini[1]

MEA Cover and Actuator System

- Dual drive actuator (DDA) is composed of *two* brushless DC motors, motor-A and motor-B, **but only motor-A has been used for actuations. Only motor-A is trended.**

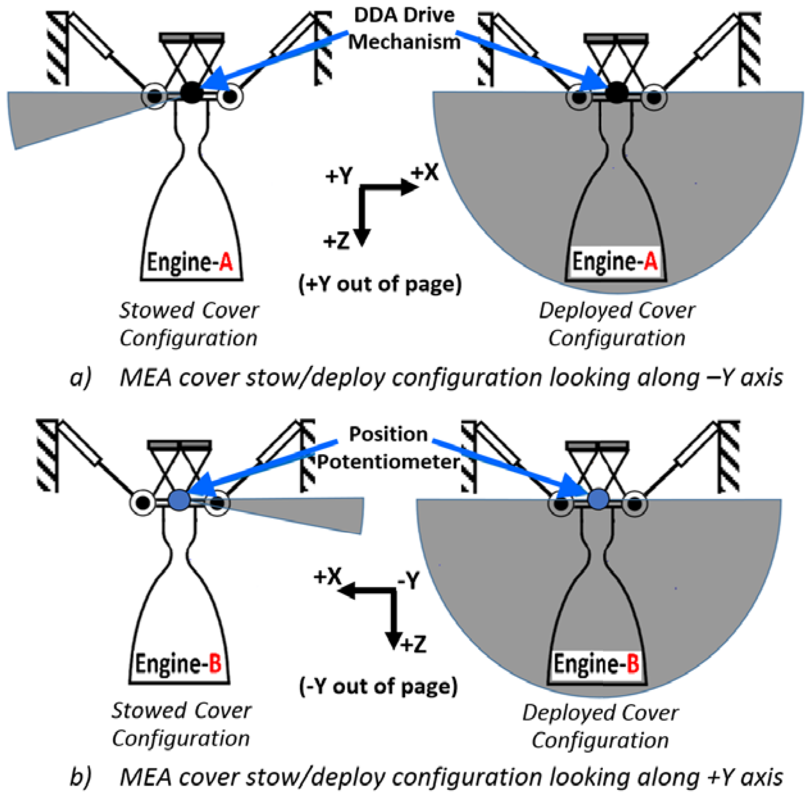


Fig. 4: Cover deploy/stow configuration[1]

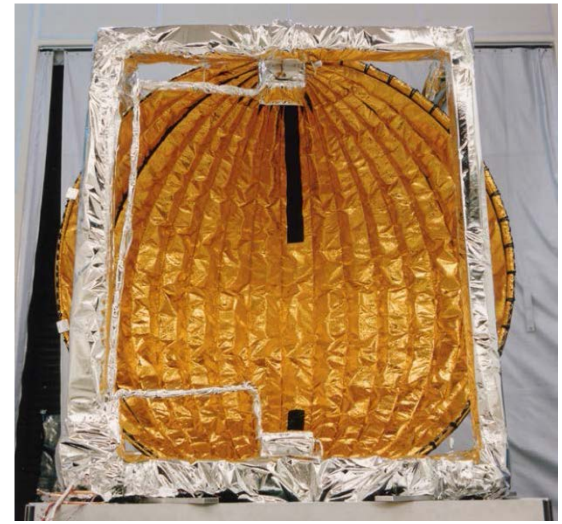


Fig. 5: Engr. model of Cassini MEA cover[1]

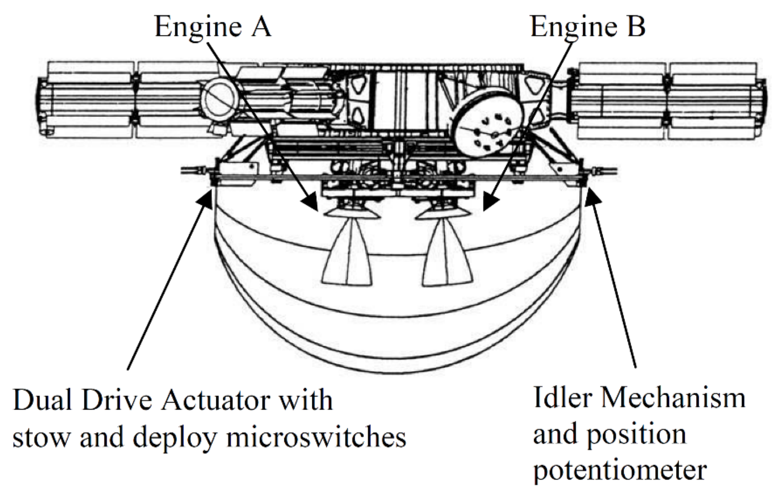


Fig. 6: DDA and potentiometer locations[1]

Two ACS Methods for Estimating Torque

- ACS has two **different** methods of estimating the **disturbance torque** imposed on the S/C by the **motion of the MEA cover**

1. Torque from Conservation of Angular Momentum (RWA rate telemetry)

$$T_{H_{rwa}}(t)$$

2. Torque from Transfer Function (position error telemetry)

$$T_{TF}(t)$$

- Both torque estimation methods should agree with one another in terms of the torque signature each outputs

- Can ground simulations verify results from telemetry?

Torque from Conservation of Angular Momentum

1. Use RWA rate data to construct accumulated angular momentum
2. Smooth accumulated angular momentum
3. Take 1st time derivative of momentum to get torque

- Assume that the accumulation in S/C angular momentum during MEA cover deployments comes *entirely* from the change in RWA rates during MEA cover deployment

- RWA rate at the end of deployment is same as in beginning

Torque from Conservation of Angular Momentum

- Steps in method
  1. Use RWA rate data to construct angular momentum
  2. Smooth angular momentum
  3. Take 1st time derivative of momentum to get torque
- RWA rate is same at the beginning/end of deployment
- S/C angular momentum during MEA cover deployments is ***entirely*** **absorbed** by RWAs during MEA cover deployment

S/C commanded to inertially fixed attitude

$$\vec{H}_{Total} = \vec{H}_{RWA} + \cancelto{0}{\vec{H}_{SC}}$$

$$\vec{H}_{Total} \approx \vec{H}_{RWA}$$

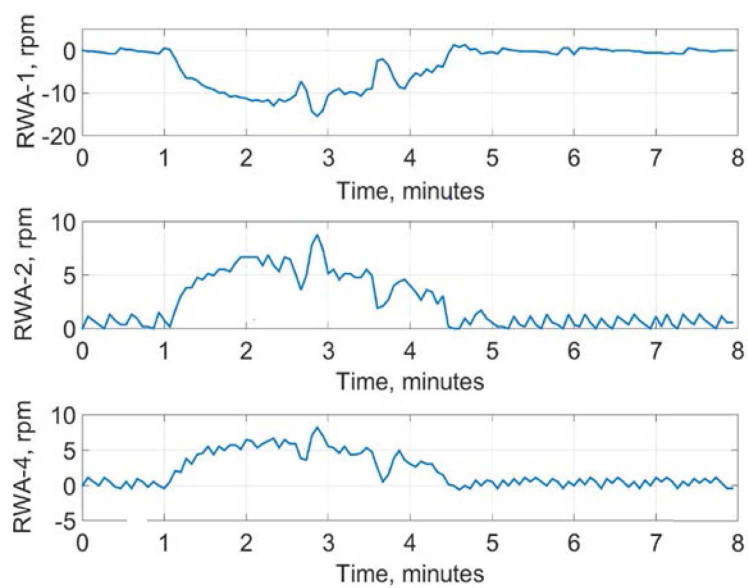


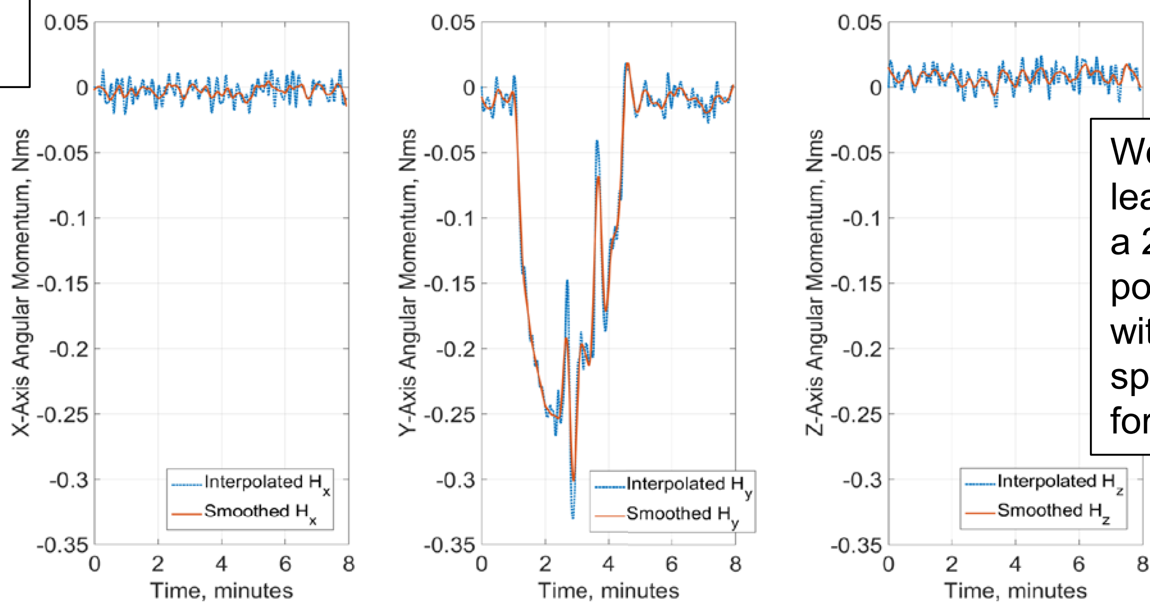
Fig. 7: RWA rate flight data[1]

Torque from Conservation of Angular Momentum

$$\vec{H}_{rwa} = TI_{RWA}\vec{\rho} = \begin{bmatrix} 0 & \frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \sqrt{\frac{2}{3}} & \frac{-1}{\sqrt{6}} & \frac{-1}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} I_{RWA-1} & 0 & 0 \\ 0 & I_{RWA-2} & 0 \\ 0 & 0 & I_{RWA-4} \end{bmatrix} \begin{bmatrix} \rho_{rwa-1} \\ \rho_{rwa-2} \\ \rho_{rwa-4} \end{bmatrix}$$

- This is accumulated angular momentum imparted on S/C by motion of cover
- Angular momentum changes only about Y-Axis as expected

Net accumulated momentum is zero



Weighted linear least squares and a 2nd degree polynomial model with a sample span of 8% used for smoothing

Fig. 8: Smoothed angular momentum[1]

Torque from Conservation of Angular Momentum

- The disturbance torque imparted on the S/C by the motion of the MEA cover is

$$T_{H_{rwa}}(t) = T_{total_y}(t) = \frac{dH_{total_y}}{dt}$$

- This torque signature comes from RWA data during cover deployment

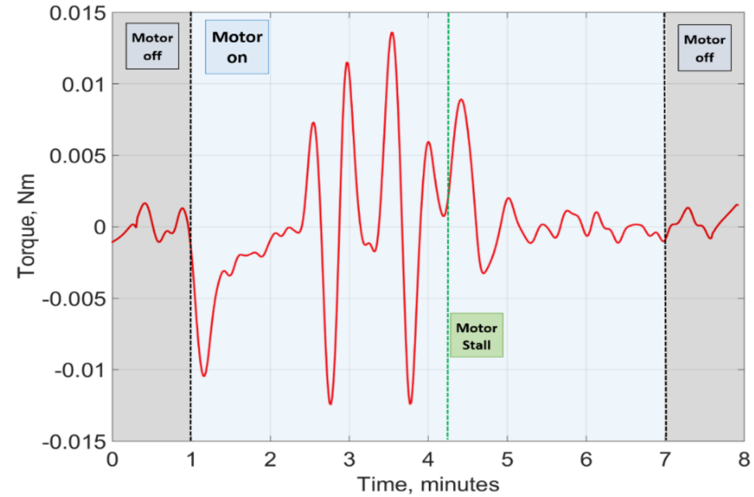


Fig. 9: Disturbance torque during MEA cover deploy[1]

- Potentiometer/current data sheds insight into characteristics of MEA cover actuations
- Data sampled once every 64 seconds

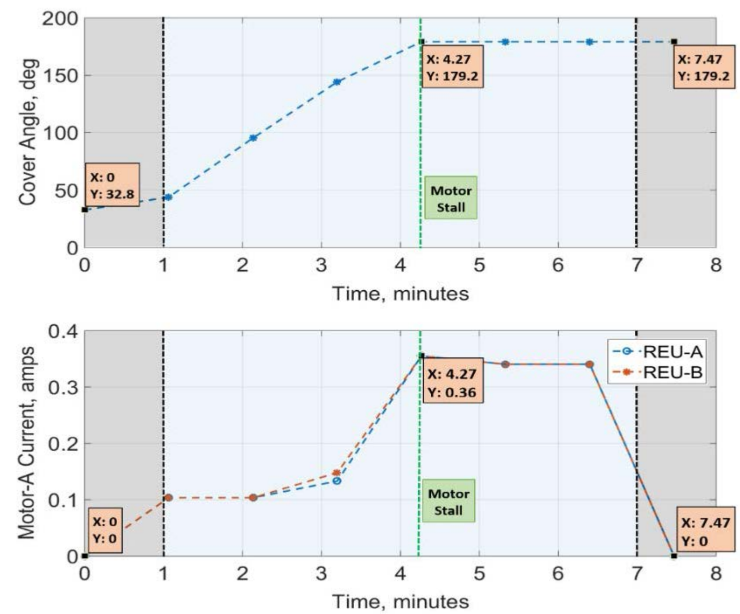


Fig. 10: Motor-A Thermal/Devices data[1]

Torque from Transfer Function

- The Cassini team has previously done work to develop a transfer function of “position error to disturbance torque” for Enceladus plume torque estimates. *See full paper for details and references**
- *Based on a simplified model of the RWA Control System*

$$T_{D_y}(t) \approx -I_{YY}\left\{\ddot{e}_{\theta_y}(t) + 0.15548\dot{e}_{\theta_y}(t) + 0.03529e_{\theta_y}(t)\right\} \text{ Nm}$$

$$T_{TF}(t) = T_{D_y}(t)$$

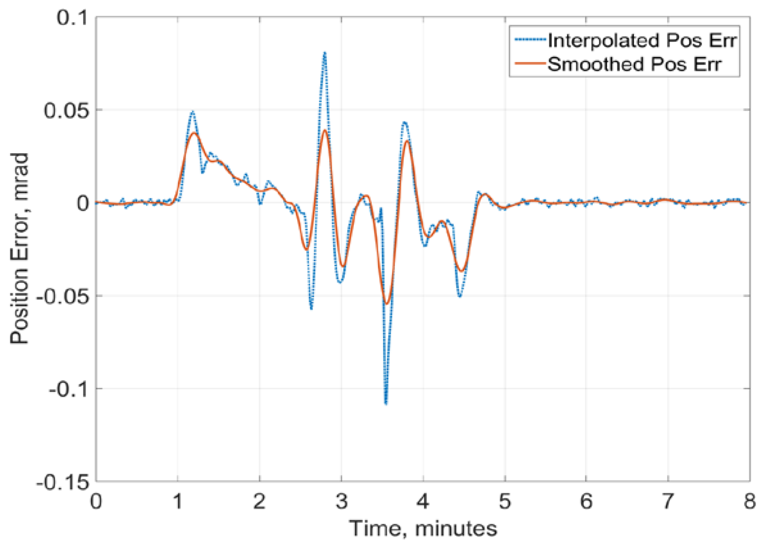
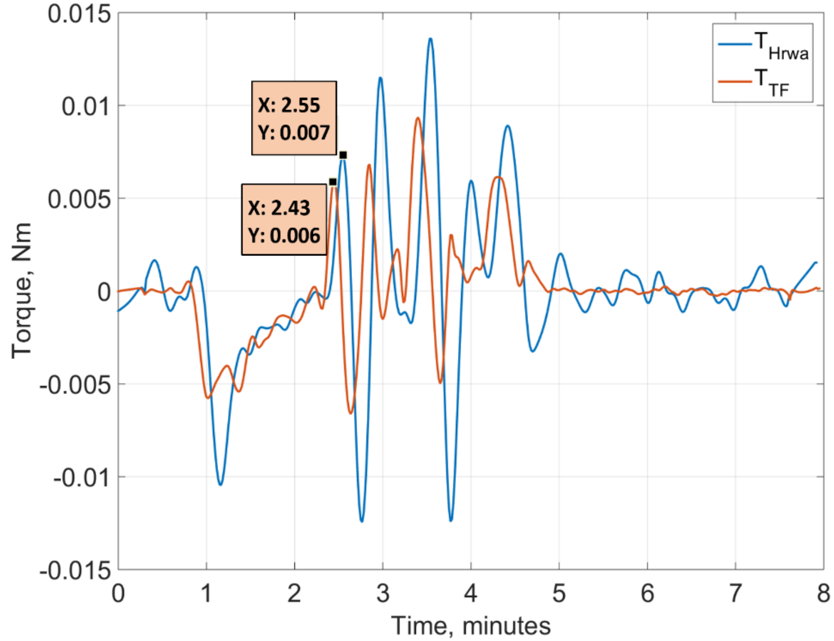


Fig. 11: Smoothed Y-Axis Attitude Control Error[1]

- Where $e_{\theta_y}(t)$ is the attitude control (position) error
- *Same* smoothing technique is applied to *both* ACS reconstruction methods

Torque from Transfer Function

**Applying the same smoothing technique (8% sample span) to both reconstruction methods causes differences in magnitudes*



**RWA controller response lag causes time shift between two reconstructed torques*

Fig. 12: Comparison of motor-A imparted disturbance torque from two reconstruction methods[1]

- Overall, the disturbance torque signature obtained from the "conservation of angular momentum" method, $T_{H_{rwa}}$, agrees with the signature obtained from "transfer function" method, T_{TF}.

Trending Analysis Results (2004-2015)

- The two reconstruction methods were applied to 11 MEA cover deployments, to create trend plots of disturbance torque profiles. *MEA cover deployments listed in paper**

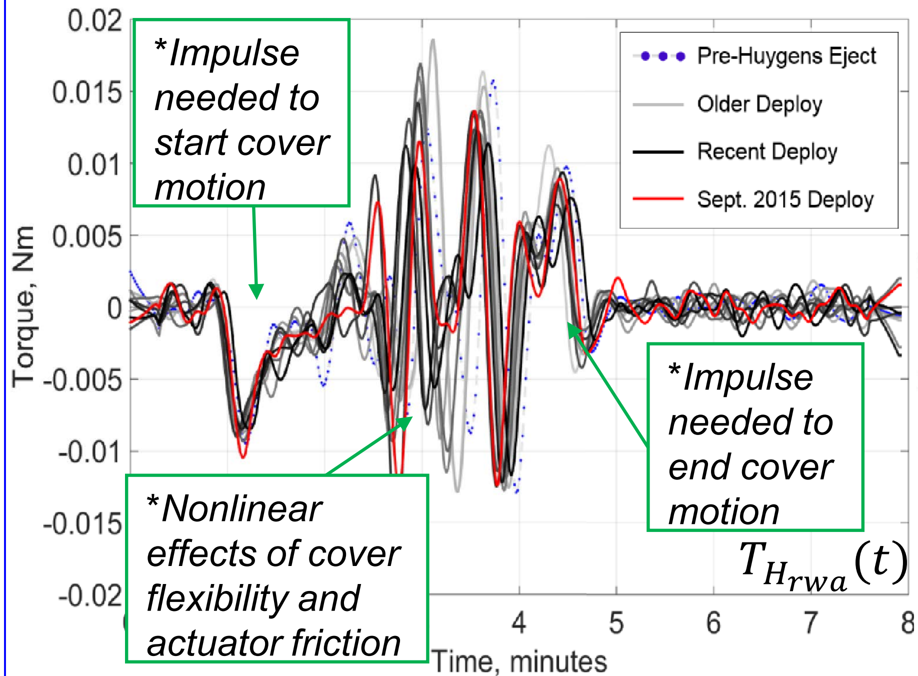


Fig. 13: Trending plot of motor-A disturbance torque derived from Y-Axis RWA momentum[1]

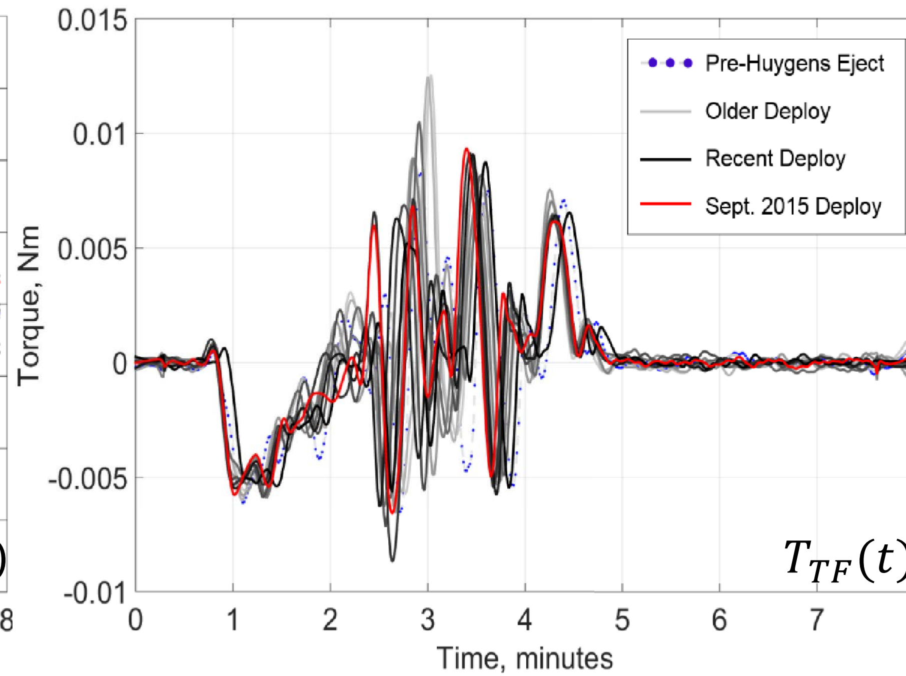


Fig. 14: Trending plot of motor-A disturbance torque derived from Y-Axis position error[1]

Trending Analysis Results (2004-2015)

- Analysis done to quantify gradual change in initial impulse and in magnitudes of peak torque excursions

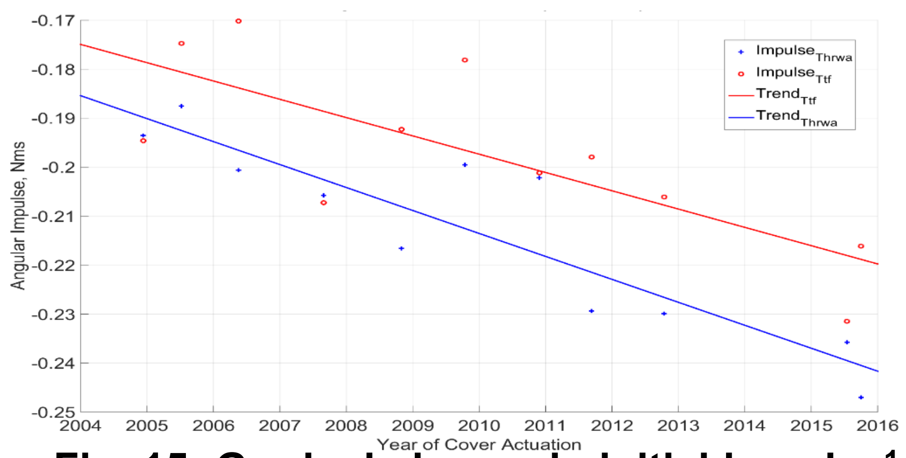


Fig. 15: Gradual change in initial impulse[1]

*Calculating the area under the Torque v. Time plots reveals that impulse magnitude increases by ~30% from 2004-2015

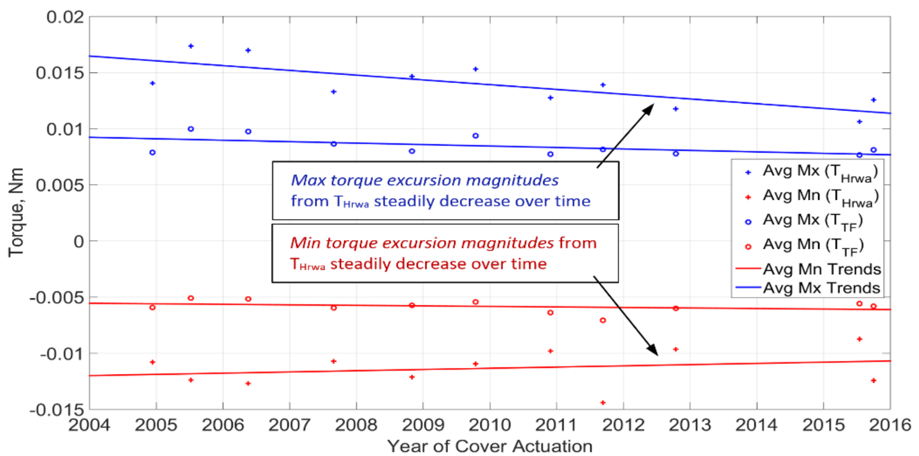


Fig. 16: Gradual change in peak torque excursions[1]

*Calculating the average of the two min and two max torque excursions in the Torque v. Time plots reveals that these spikes are decreasing in magnitude by ~33% from 2004-2015

Two ACS Methods for Estimating Torque

- ACS has two **different** methods of estimating the **disturbance torque** imposed on the S/C by the **motion of the MEA cover**

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$$T_{H_{rwa}}(t)$$

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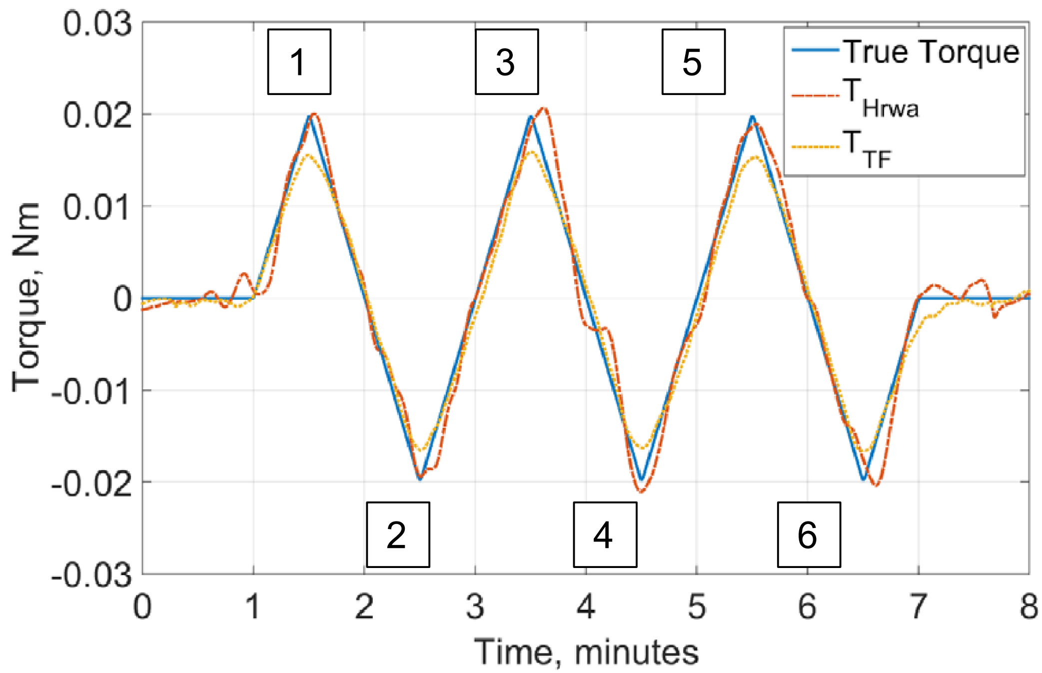
$$T_{TF}(t)$$

- Both torque estimation methods should agree with one another in terms of the torque signature each outputs ✓
- Can ground simulations verify results from telemetry? ?

Ground Simulation Verification

- Flight Software Dynamic Simulation (FSDS) – high fidelity simulation environment with full environmental dynamics and the Cassini flight software (FSW) built in
- Inject a *known* torque profile into FSDS and try to reconstruct it from simulated flight data

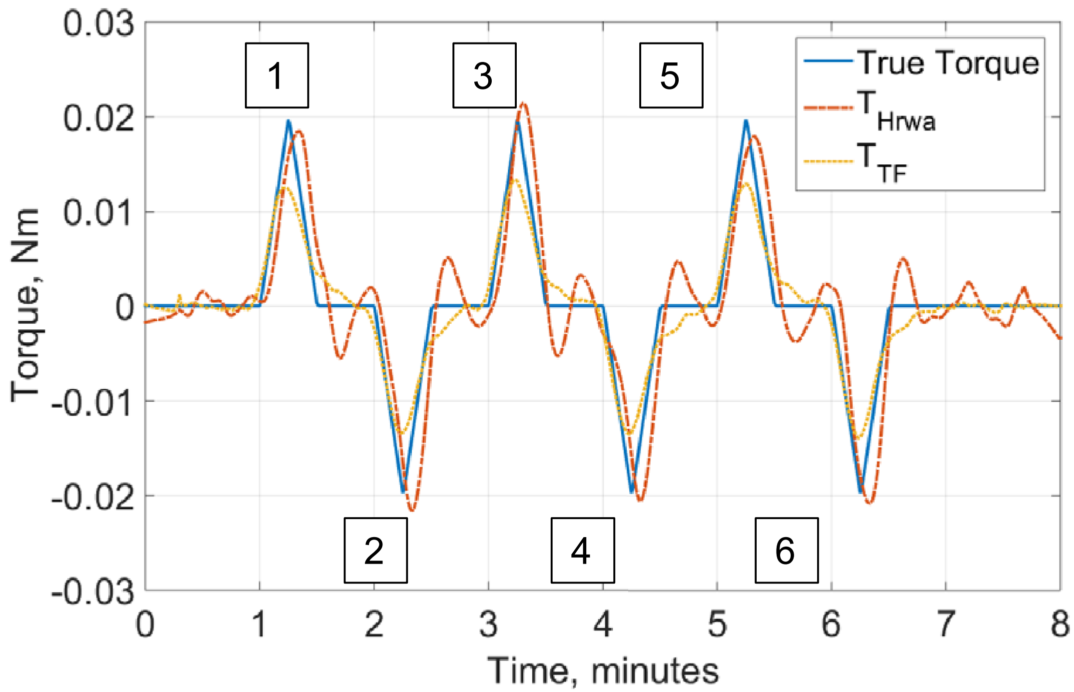


Max Peak Error = 5.97% at peak #4

Fig. 17: Comparison of reconstructed torques to FSDS-injected torque profile #1[1]

Ground Simulation Verification

- Inject a second *known* torque profile into FSDS and try to reconstruct it from simulated flight data



Max Peak Error = 9.91% at peak #2

Fig. 18: Comparison of reconstructed torques to FSDS-injected torque profile #2[1]

Conclusion

- Cassini ACS team used *two different* disturbance torque reconstruction methods to trend MEA cover deployments from **2004 to 2015**, using real flight data
- Qualitative and quantitative trending analysis showed consistent behavior across the years, with **no *sudden* changes in torque signature** that may indicate failure in the MEA cover mechanism before 2017
- FSDS ground simulations were used to verify the torque reconstruction procedures and find an upper bound to the max peak error (~10%)

Reference

- [1]Andrade, L. G. Jr., "Trending Main Engine Assembly (MEA) Cover Actuator Performance using Cassini Attitude Control Flight Data," Paper AIAA SciTech, Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit, San Diego, California, January 4-8, 2016.

Backup

S/C Body Rates During Deployments

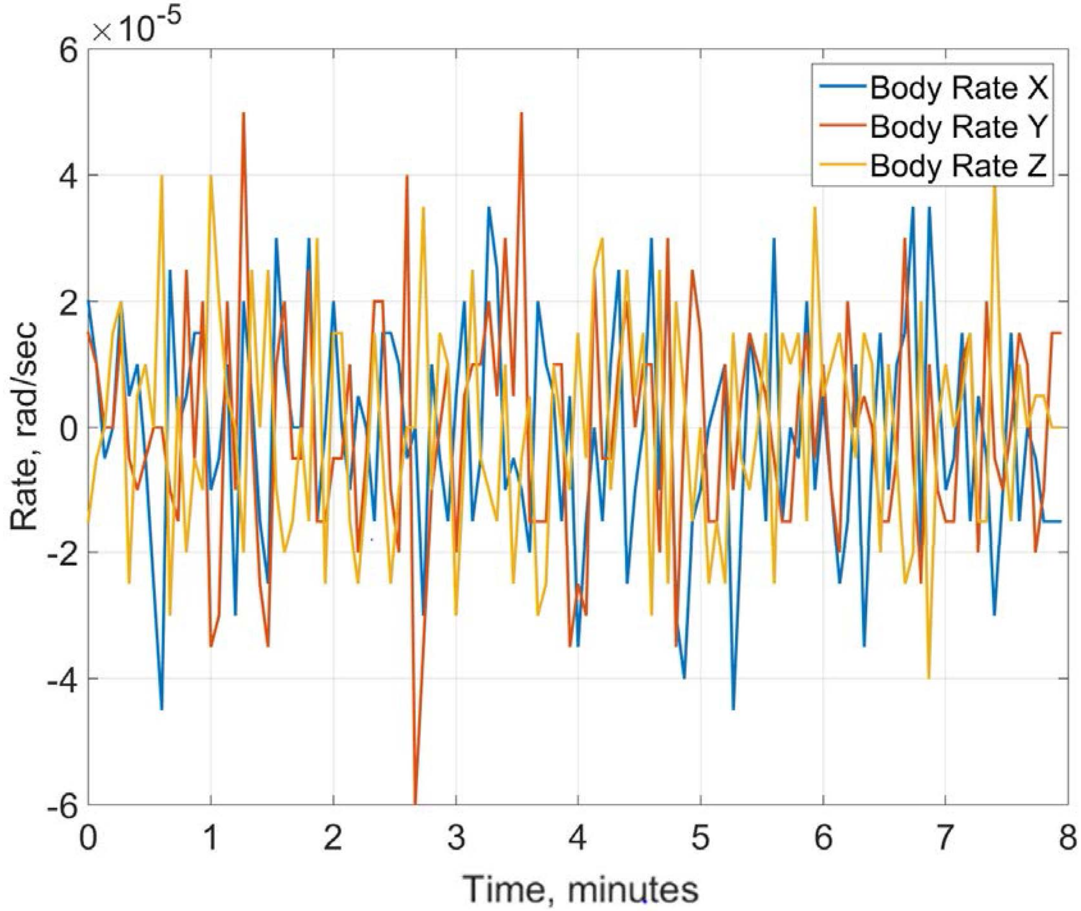


Fig. 19: S/C Body Rates for Deployment on Sept. 29, 2015[1]