The Cassini Reaction Wheels: Drag and Spin-Rate Trends from an Aging Interplanetary Spacecraft at Saturn

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January 8, 2016

The Cassini Spacecraft

Spacecraft Description:

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

Mass: 5712 kg at launch, 2243 kg currently

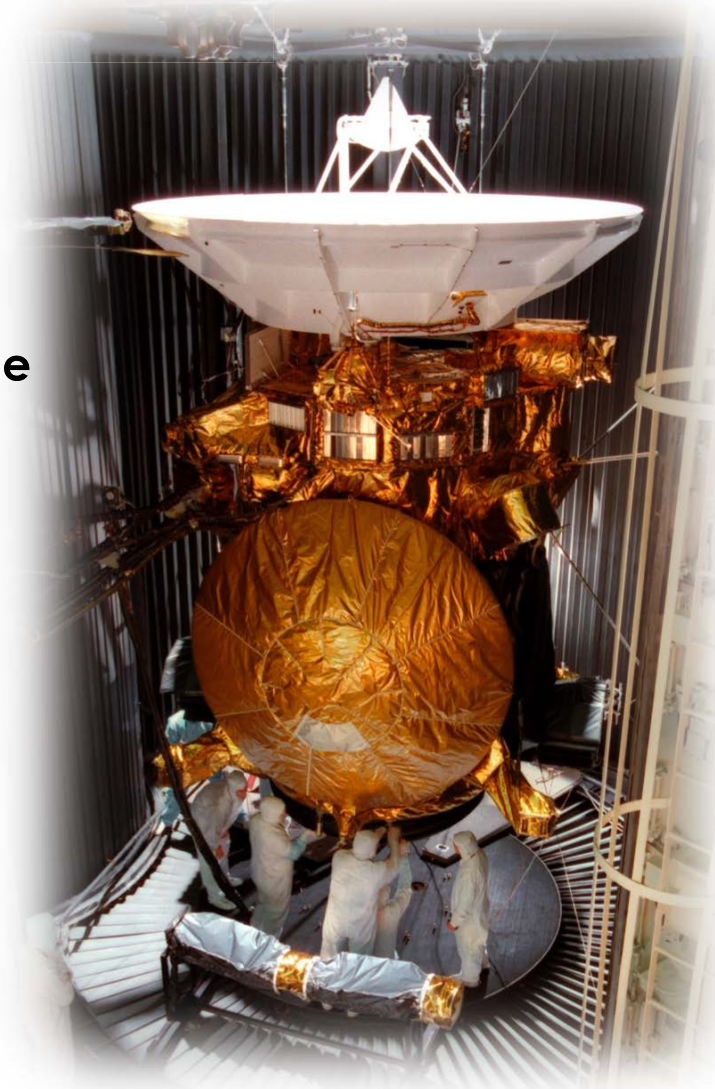
Power: 3 RTGs

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

Attitude Control Subsystem:

3-Axis stabilized using RCS or RWA control

Eight 1 N RCS thrusters (2 redundant branches)

3 orthogonal 36 Nms RWAs (also 1 backup)

2 redundant 450 N main engines

1 Accelerometer (for maneuvers)

2 redundant ACS Flight Computers

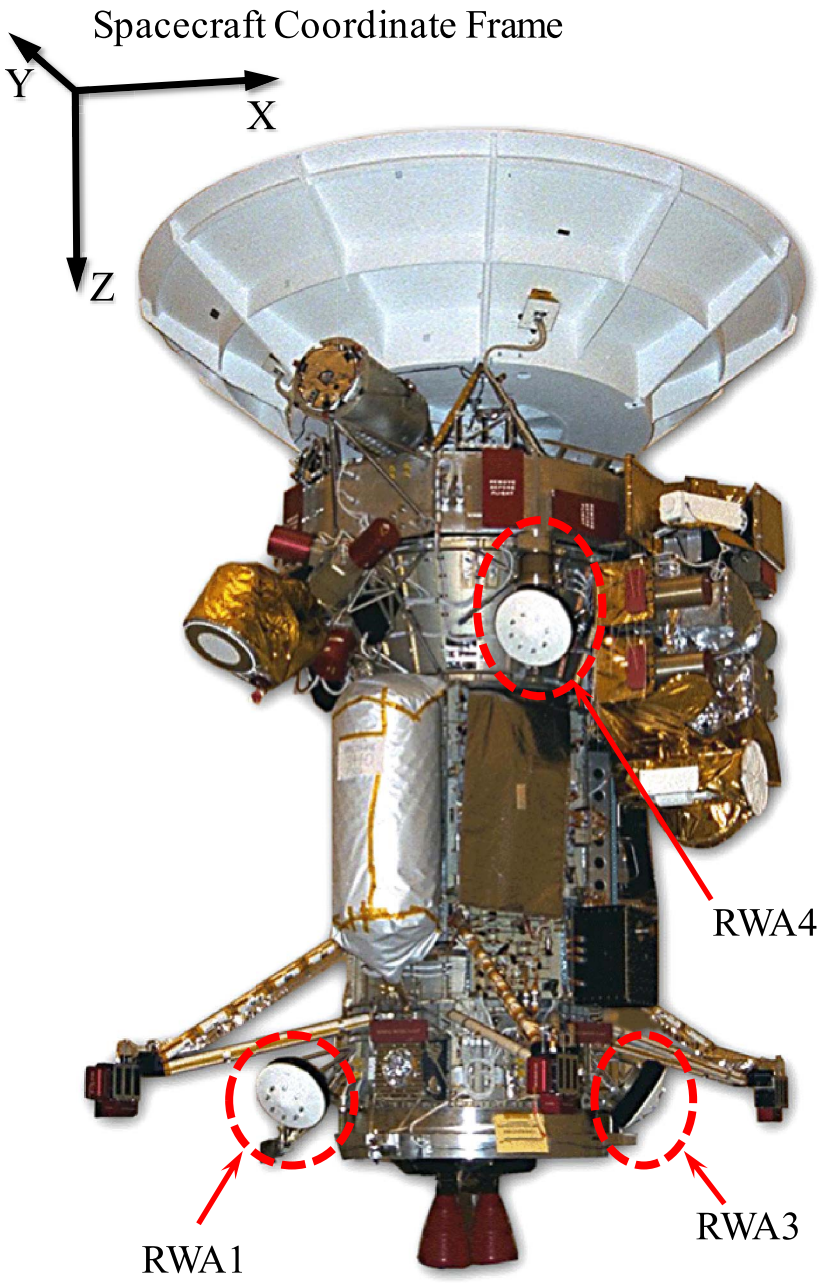
2 redundant Sun Sensors Assemblies on HGA (SSAs)

2 redundant Stellar Reference Units (SRUs)

2 redundant Inertial Reference Units (IRUs)

Cassini's Reaction Wheel Assemblies

- RWA 1-3 are fixed to spacecraft bus
- RWA4 attached to articulation motor
- Only 3 RWAs used in the control loop at once
- Current prime wheels: RWA1, RWA2, RWA4
- RWA3 still functions, but showed early degradation
- Spacecraft flies with biased and varying non-zero momentum states
- RCS thrusters are used to load/unload/modify planned RWA momentum biases



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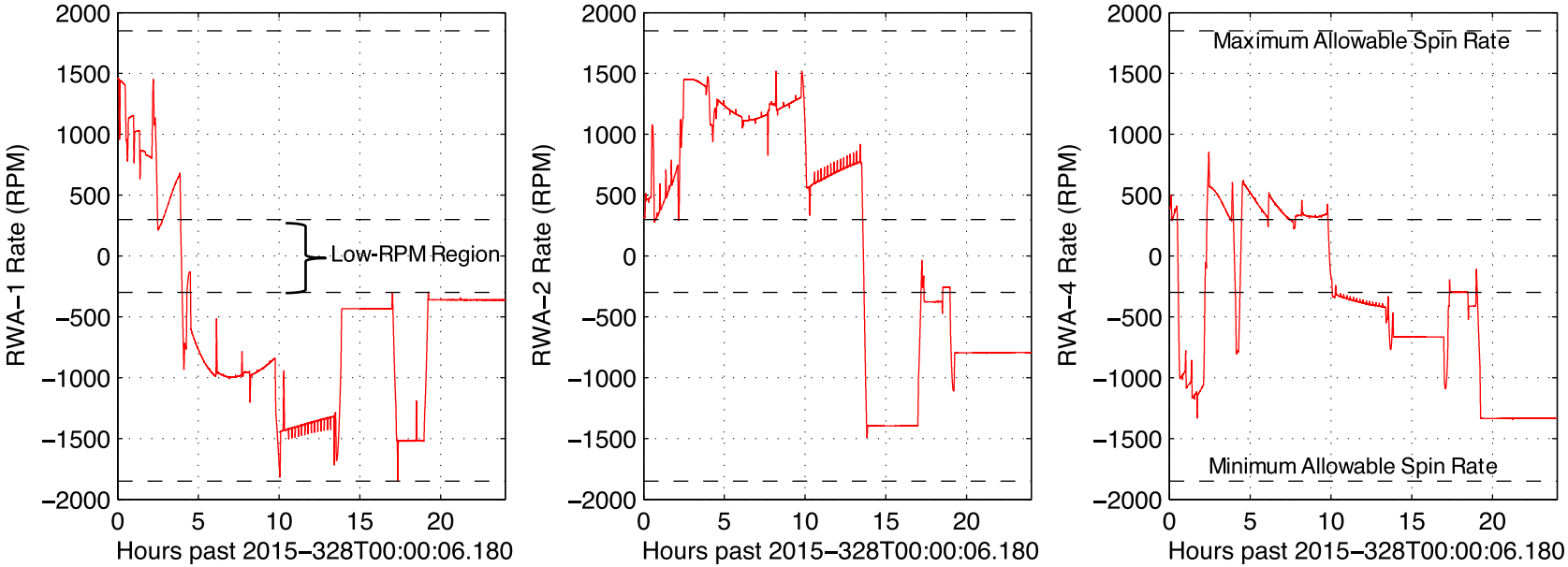
Purpose of This Investigation

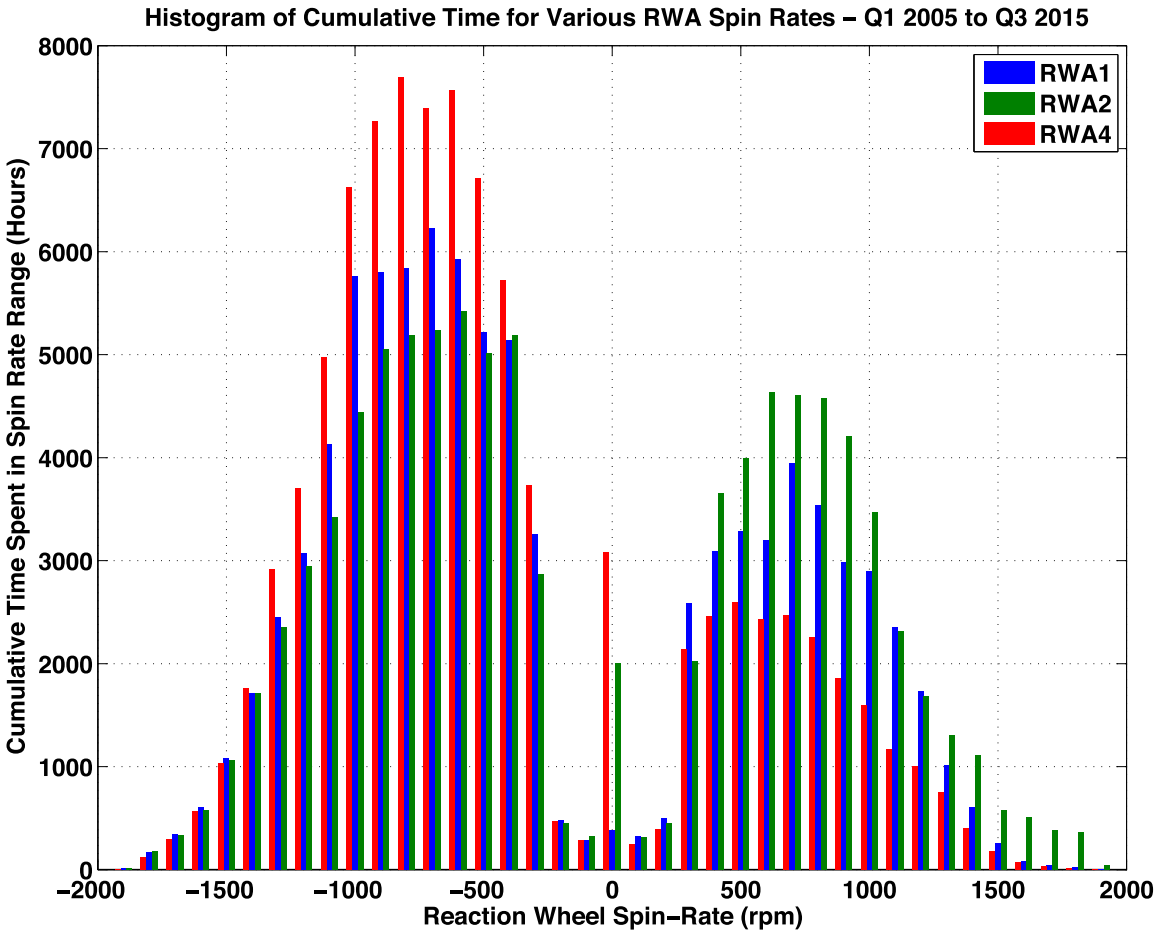
- Describe long-term RWA trending strategy performed by Cassini operations team
- Show 11 years of trending data for:
  1. RWA Spin Rate
  2. RWA Estimated Drag Torque

Typical RWA Usage



- Allowable spin-rate range: -1850 to +1850 rpm (positive right hand rule = CCW)
  - Hardware limit is actually ~2010 rpm, but operations team maintains margin for unplanned disturbances
- Operations in "Low-RPM" region (i.e. -300 to +300) is avoided by using optimization tool (RBOT) to limit planned time in Low-RPM
  - Low-RPM usage may cause bearing wear, due to improperly distributed bearing lubrication
- RWA spin-rates change in plot result from science slews and target tracking
- RWA "zero-crossings" (i.e. spin direction reversals) frequently occur

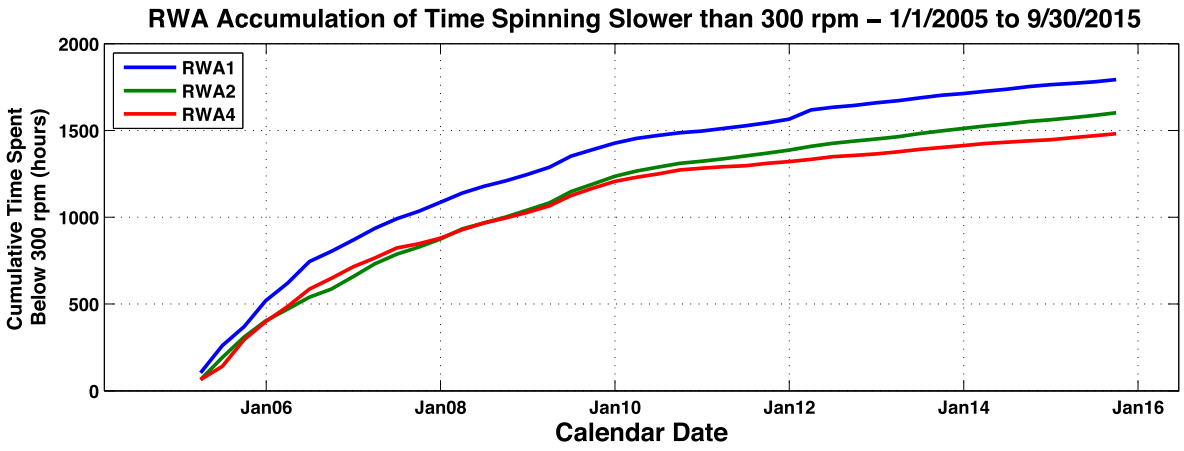
RWA Spin Rate Histogram From 2005-2015

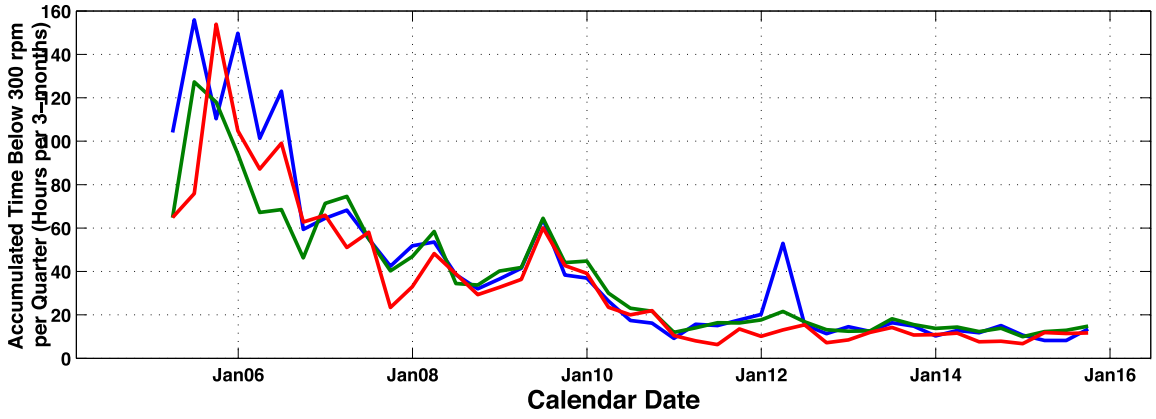


- Plot includes ~11 years of spacecraft flight telemetry
- RWA long-term trends updated quarterly
- Telemetry samples sorted by spin-rate into 100 RPM wide bins and histogramed

- RWA usage is predominantly in the ±300 to ±1200 RPM range
- Very little time spent below 300 rpm or >1500 RPM
- Spike at 0 RPM are artifacts corresponding to periods of RWA inactivity.
- RWA1 and RWA4 spin in the negative (i.e. clockwise) direction significantly more than positive direction
  - Due to unidirectional multi-revolution spacecraft rolls performed for science reasons
- Spin rate data for RWA3 not included because it is rarely powered on
- RWA1 and RWA2 have exceeded 5 *billion* total revolutions since launch, and RWA4 is not far behind

RWA Low-RPM Time Accumulation





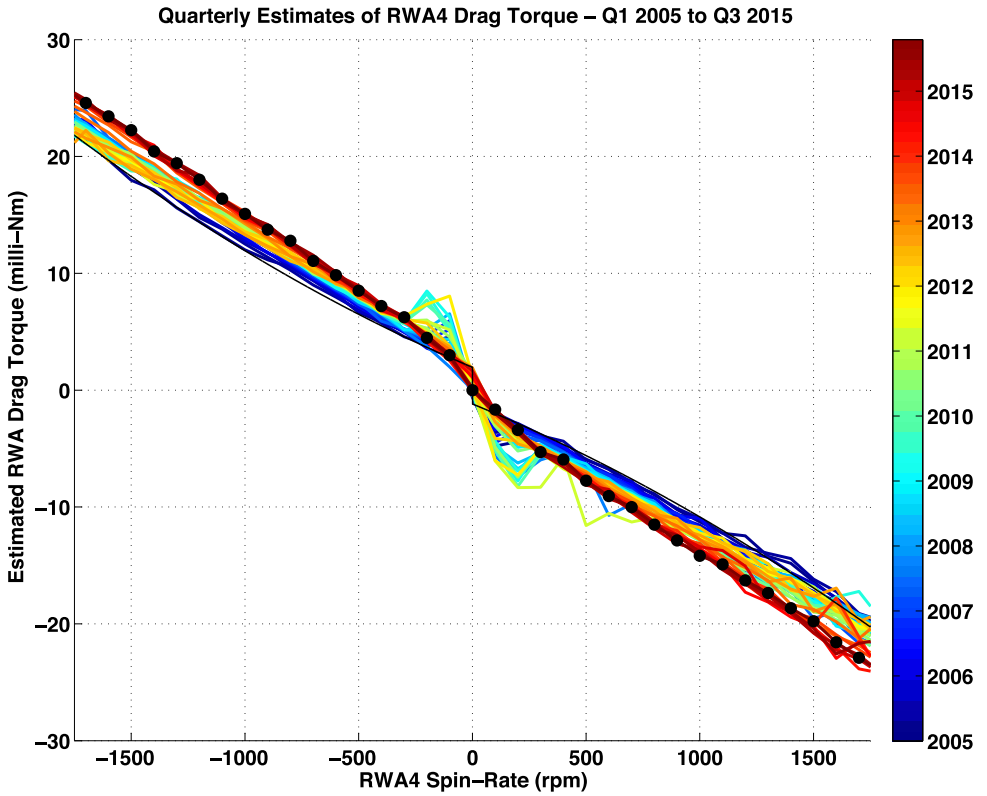
- RWA usage is planned to avoid time spent in the "Low-RPM" region (i.e. -300 to +300 rpm)
- Reaction Wheel Bias Optimization Tool (RBOT) used to select spacecraft momentum that minimizes Low-RPM usage
- Low-RPM usage has been avoided since 2005, but process became more stringent and effective after 2008-2009
- Since 2011, operations team has maintained Low-RPM accumulation to just ~10 hours of accumulation per 3 months (<0.4% of total time)

RWA Drag Torque Description & History

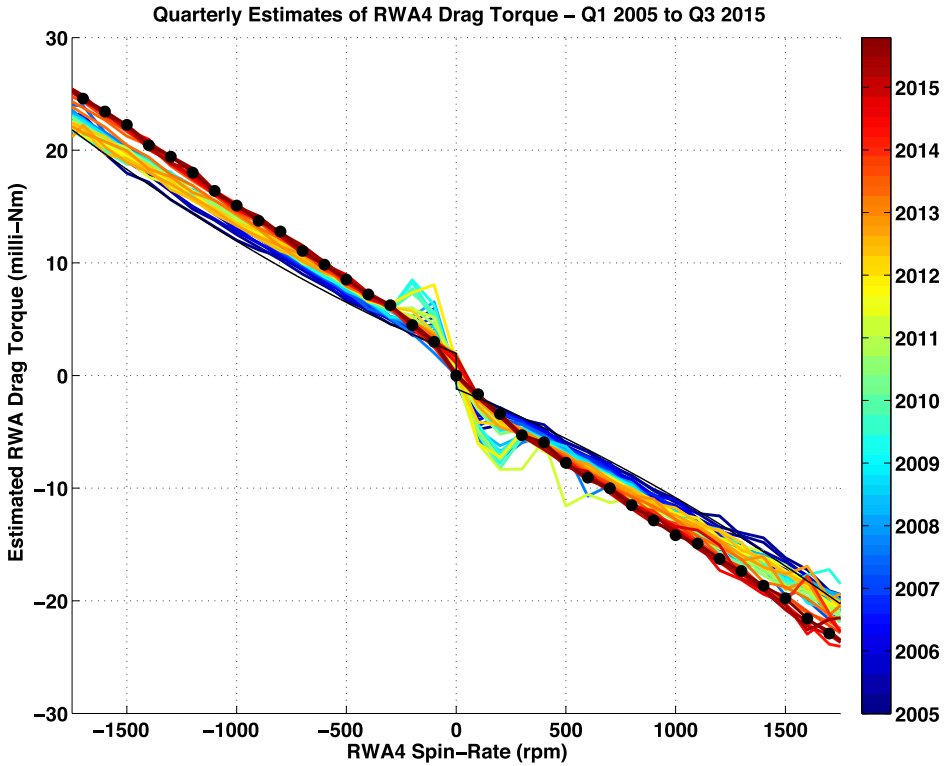
- RWA health gauged by monitoring estimated RWA drag torque
- RWA controller uses PI (proportional-integral) estimator to estimate RWA drag torque for compensation of control output
- RWA drag torque estimate is inaccurate when RWAs are accelerating/decelerating (i.e. during slews or biases)
  - Despite limitations, estimated drag torque telemetry is still the best available information for gauging RWA health
- Across 18 years of flight and 11 years of science operations all 4 RWAs have received considerable wear
- All 4 RWAs have shown instances of rough or elevated drag torque
  - Includes drag torque spikes, oscillations, and roughness
- RWA1 and RWA3 have been the more troublesome wheels
  - RWA3 was demoted to backup role due to bouts of bearing dry cage instability
- RWA2 and RWA4 have generally been better behaved
- 11 years of science operations used to trend drag torque of RWAs 1, 2, and 4

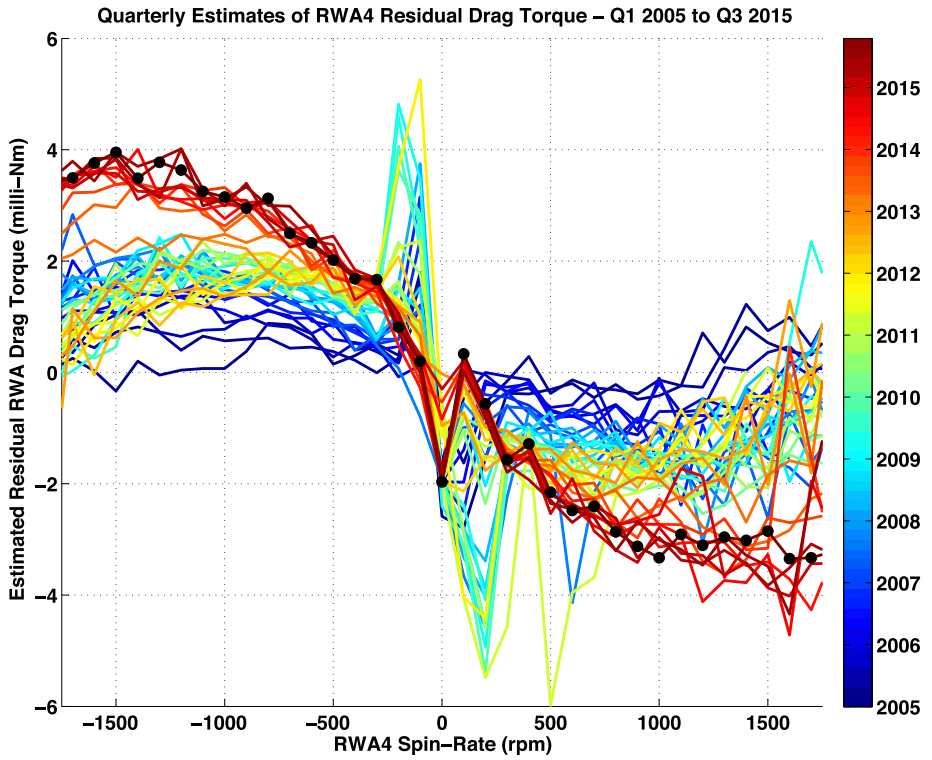
RWA Drag Torque Trending Strategy

- Group telemetry into 3-month long periods of data
- Bin data periods into 100 rpm wide bins based on the RWA spin-rate
  - Data Bins include: [-1850 to -1750], [-1750 to -1650], … , [-50 to +50], … , [+1750 to +1850] (RPM)
- For the telemetry in each spin-rate bin, compute the median RWA drag torque
- Plot the median drag torque for each bin with one color to represent that 3-month long period of time
- Simultaneously plot the curves from every 3-month period for which telemetry is available using color-map as the "time" dimension
- Additionally, find the difference between the observed drag torque and estimated drag torque based on pre-launch calibration curves
- Motor capability 165 milli-Nm



Drag Torque Trends for RWA4

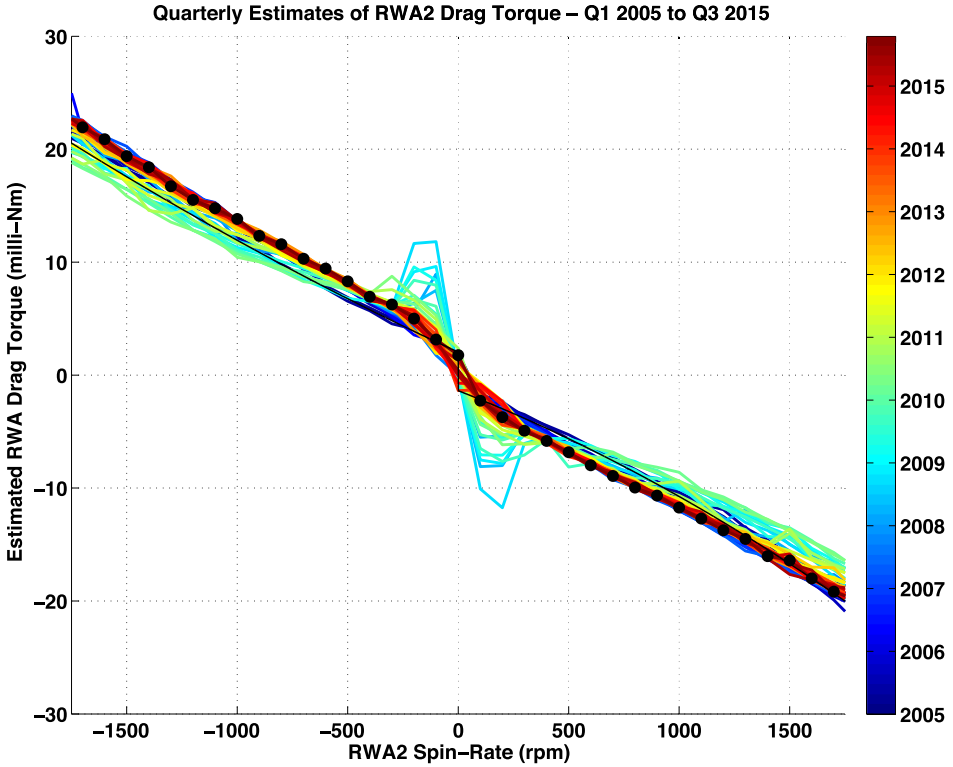


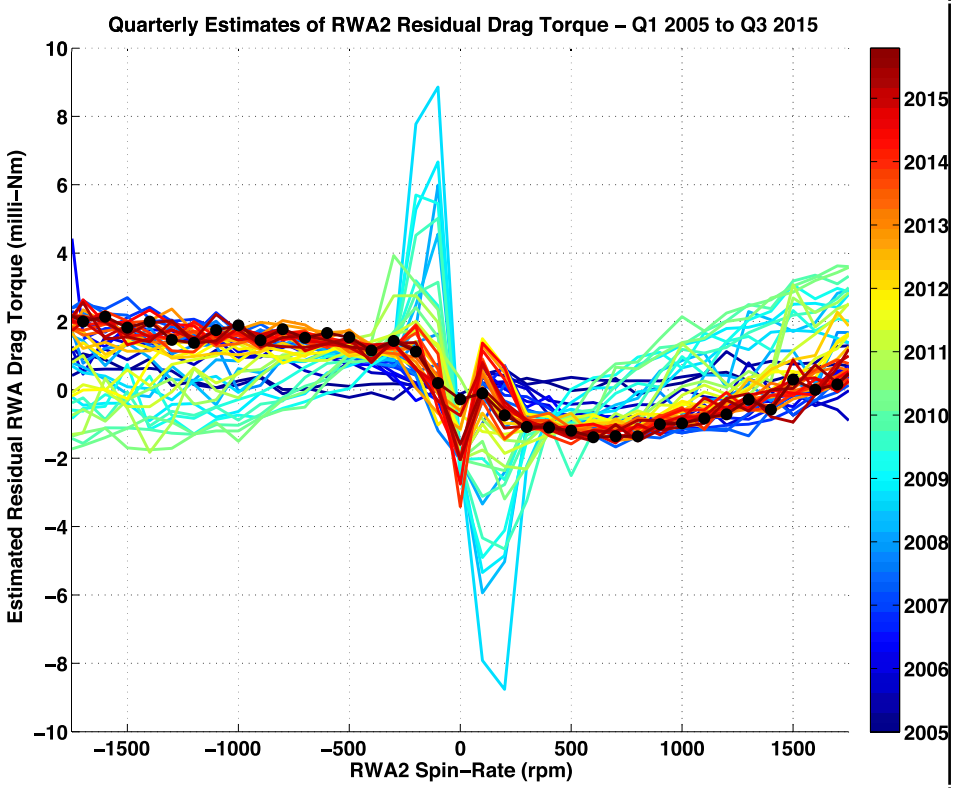


Observations:

- RWA4 shows "expected" aging behavior; drag generally increases over time at all spin rates
- Between 2009-2011 RWA4 had elevated drag upon passing through Low-RPM region. This behavior naturally went away after ~2012
- Note: "Residual RWA Drag Torque" (right-hand plot) is the difference between pre-launch ground measured RWA drag and the observed flight telemetry

Drag Torque Trends for RWA2

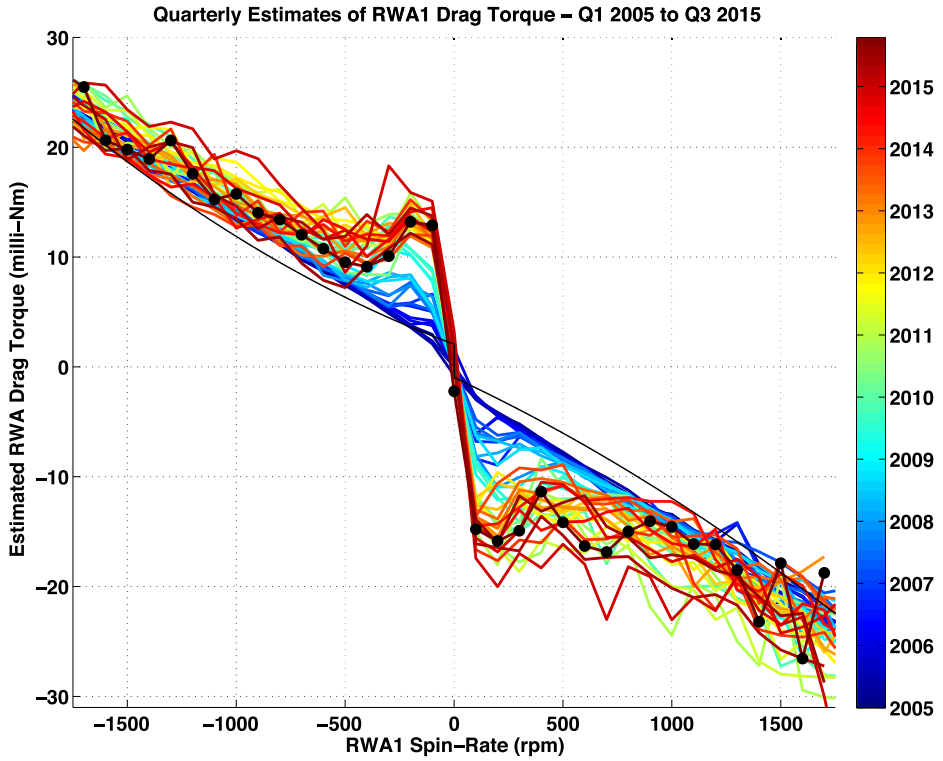


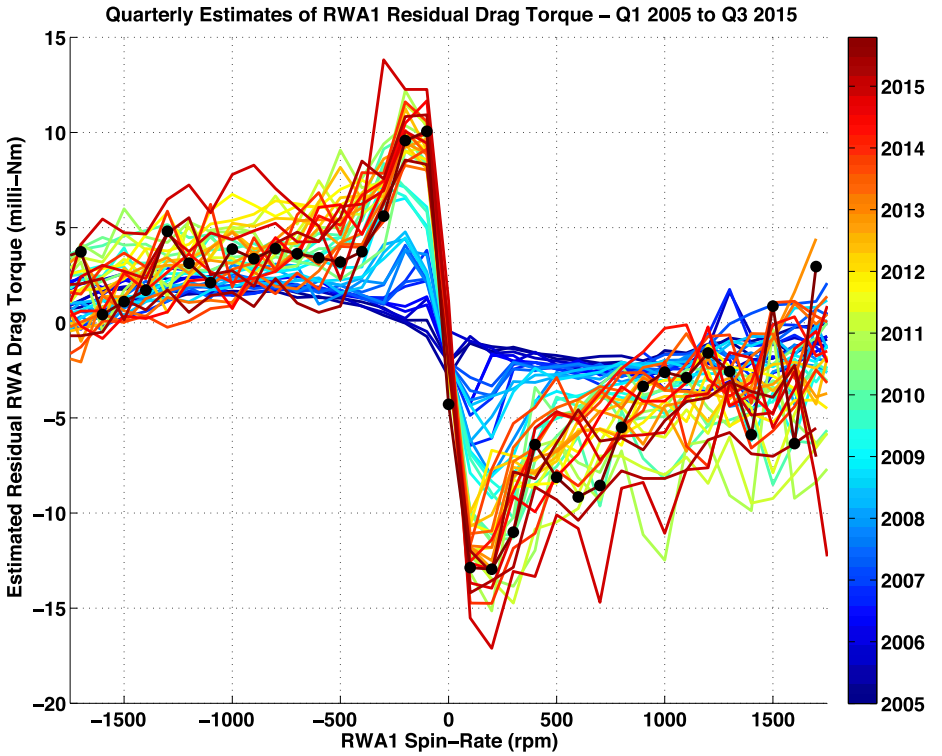


Observations:

- RWA2 shows counterintuitive aging behavior; drag gradually decreased for 5 years and then has slowly increased for 5 years. Drag torque today approximately what it was in 2005-2006. Not bad for 11 year of heavy use on an 18 year old wheel!!
- Like RWA4, between 2009-2010 RWA2 showed elevated drag upon passing through Low-RPM region. This behavior naturally went away after ~2011

Drag Torque Trends for RWA1

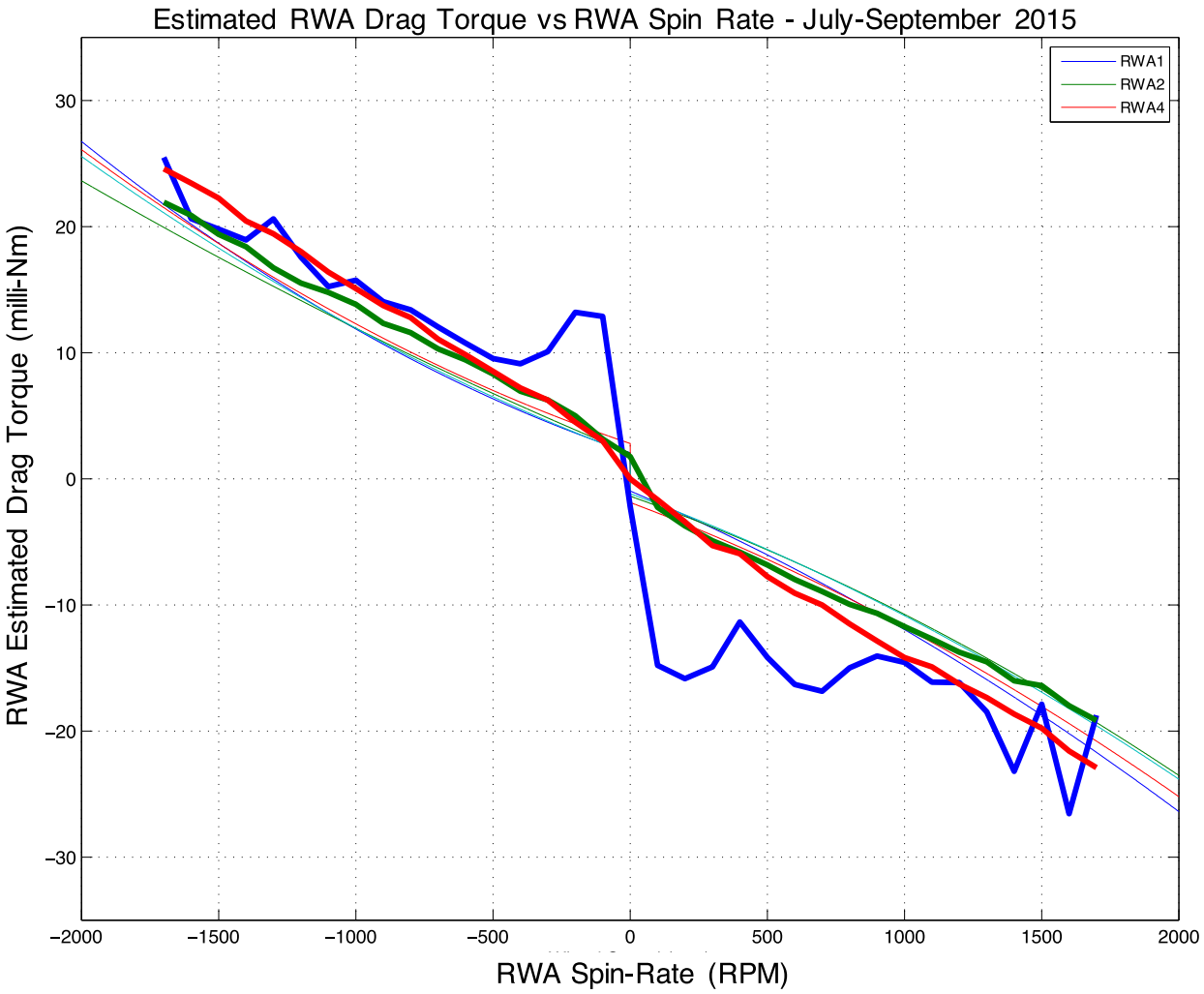




Observations:

- RWA1 experiences frequent drag torque spike events. These spikes result in trending data that is generally higher and "noisier" than RWA2 and RWA4.
  - Drag torque spike events more common below ~1000 RPM.
- RWA1 drag generally increased between 2005-2013. Between 2013-2015 RWA1 has switched between some of the highest and lowest drag levels ever seen. RWA1 is considered the more worrisome of the active RWAs

Comparison of Drag Torque Between RWAs



Observations:

- Thin lines are the pre-launch ground calibrated drag torque predicts for each RWA. Thick lines are based on flight telemetry
- RWA1 generally has the highest average drag torque at each spin-rate range due to frequent drag spikes
- Gradual growth in RWA4 drag torque means that RWA4 sees near the highest drag torque levels for spin-rates >1000 RPM

Conclusions

- The Cassini RWAs have been in flight for 18 years and have performed 11 years of science operations. **All 3 prime RWAs as well as the backup RWA function without any pointing performance degradation**
- RWA drag torque can be periodically grouped, binned based on spin-rate, and averaged to identify long-term variations in drag torque at different spin-rates
- RWA1, RWA2, and RWA4 all show distinct long-term drag torque trend behaviors that can be tracked as a gauge of RWA health
- Although signs of bearing degradation appear to be present in each wheel, **the current pace of RWA bearing degradation appears to be sustainable for the remaining 2 years of the mission**
- The operations team will continue to limit Low-RPM usage. Although it cannot be proven to protect RWA longevity, limiting Low-RPM time remains the only feasible measure available to the operations team