Prediction of Lunar Reconnaissance Orbiter Reaction Wheel Assembly Angular Momentum Using Regression Analysis

Russell DeHart

Systems Engineer, NASA Goddard Space Flight Center, Space Science Mission Operations, KBRwyle

Agenda

- Study Motivation & Goal
- Lunar Reconnaissance Orbiter (LRO) Overview
  - Spacecraft
  - Angular momentum control
- Methodology
  - Removing effects of maneuvers
  - Forming piece-wise regression model
- Results
  - Test against 2013 – 2014 telemetry
- Conclusion & Future Work

Introduction

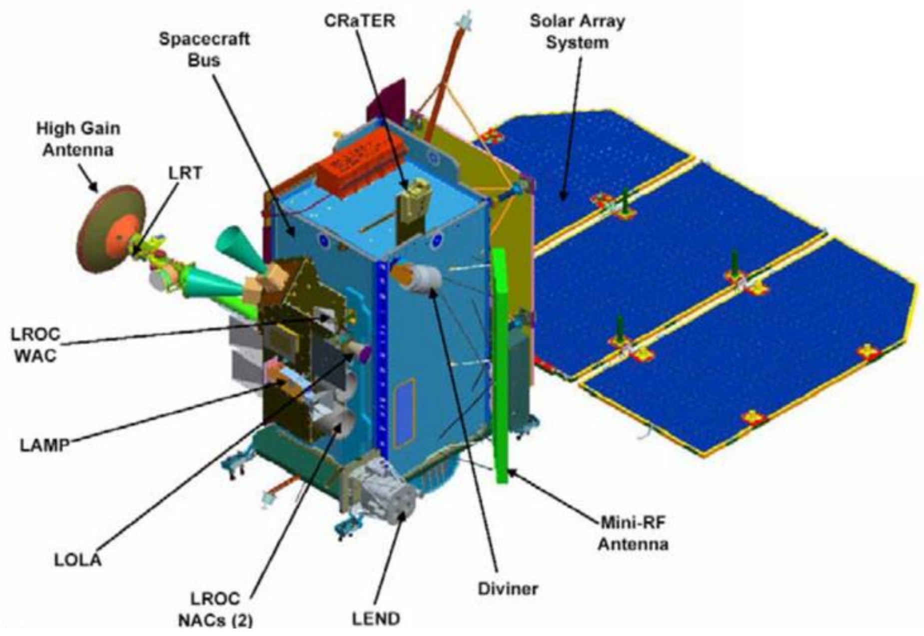
Study Motivation & Goal

LRO Overview

LRO Angular Momentum

Study Motivation & Goal

- Motivation
  - Conserve fuel
    - Fuel remaining at start of 2016: ≈ 34 kg
    - Current fuel usage: ≈ 4 kg/yr
      - Thrusters used for momentum unloads (ΔHs)
      - Includes station keeping & ΔHs, but not orbit changes
  - Increase science collection
    - Three instruments safed during ΔHs: DLRE, LEND, LOLA
    - One also decontaminated for 24 hrs thereafter: LAMP

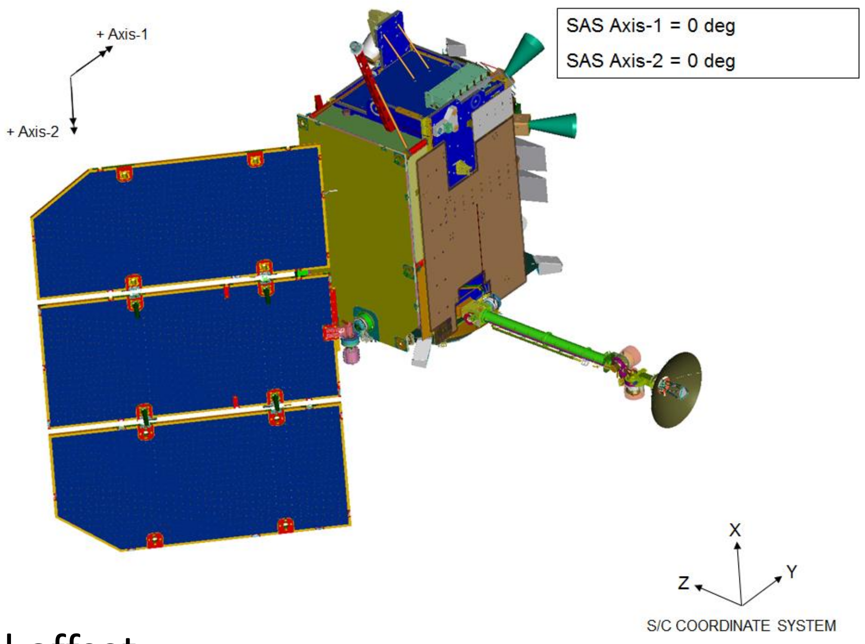


- Legacy planning procedures often resulted in unloads being performed more frequently than needed

GOAL:
Build model to accurately predict growth in LRO angular momentum, enabling optimal scheduling

LRO Spacecraft Overview

- Orbit
  - Changed several times, now 20 km x 150 km
  - Nominally nadir-pointing
- Solar Array (SA)
  - Has inner & outer gimbals
  - Uses tracking and parked configurations
    - Tracking
      - |β| < 30°: Gimbals track sun, but with +30° outer gimbal offset
      - 30° < |β| < 35°: Gimbals track sun, but with -30° outer gimbal offset
    - Parked
      - 35° < |β| < 55°: park inner gimbal at -90°, outer gimbal at +45°
      - |β| > 55°: park inner gimbal at -90°, outer gimbal at +15°
  - Offsets and fixed angles selected to maintain gimbals < 45° C



LRO Attitude & Disturbance Torques

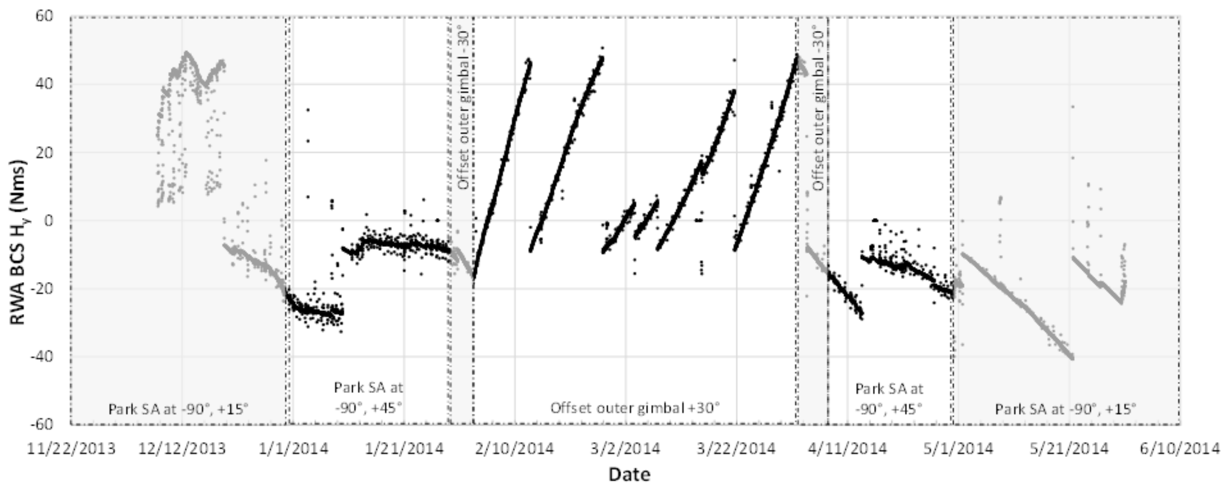
- Attitude control
  - Reaction wheel assembly (RWA) used to:
    - Slew spacecraft
    - Maintain attitude, countering disturbance torques
  - RWA angular momentum capacity
    - 115 Nms at nominal bus voltage
    - 80 Nms at minimum bus voltage

LRO Reaction Wheel Assembly

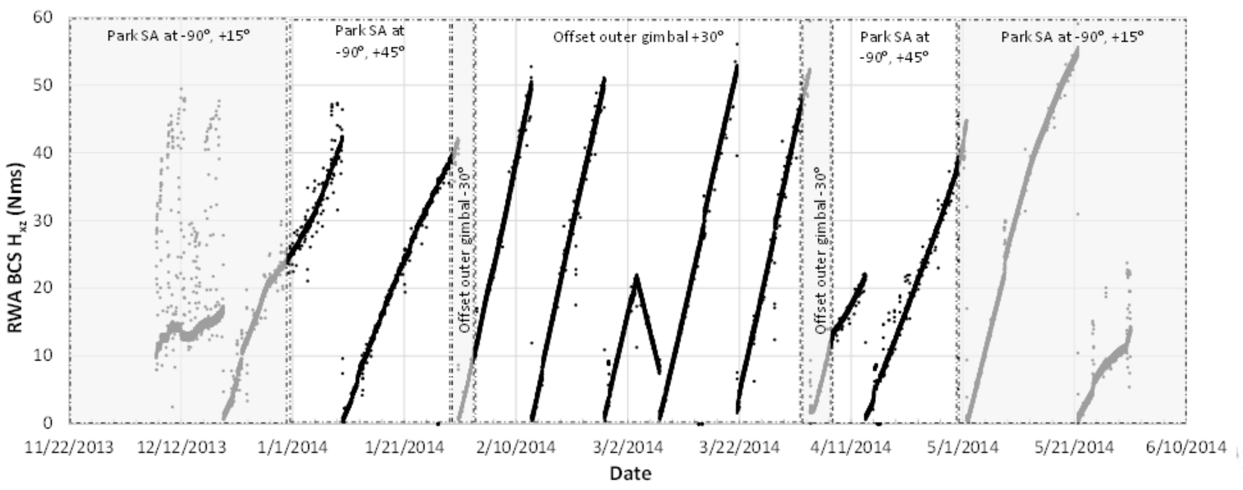
- Since lunar orbit, only 2 significant disturbance torques
  - Gravity gradient torque
    - Movement of solar array dominates changes in LRO inertia matrix
  - Solar radiation pressure (SRP) torque
    - Solar array dominant term due to large moment arm

All disturbance torque orbit-averaged values are simply functions of β

LRO Angular Momentum



LRO RWA BCS H_y, from December 7, 2013 to May 31, 2014.



LRO RWA BCS H_{xz}, from December 7, 2013 to May 31, 2014.

- Body Coordinate System (BCS) H_y very dependent on solar array configuration (and hence β)
- Activities, like pitch & yaw campaigns in Dec 2013 can overwhelm trend

Model must include both regression against β and adjustments for activities

Methodology

Overview

Determining effects of maneuvers

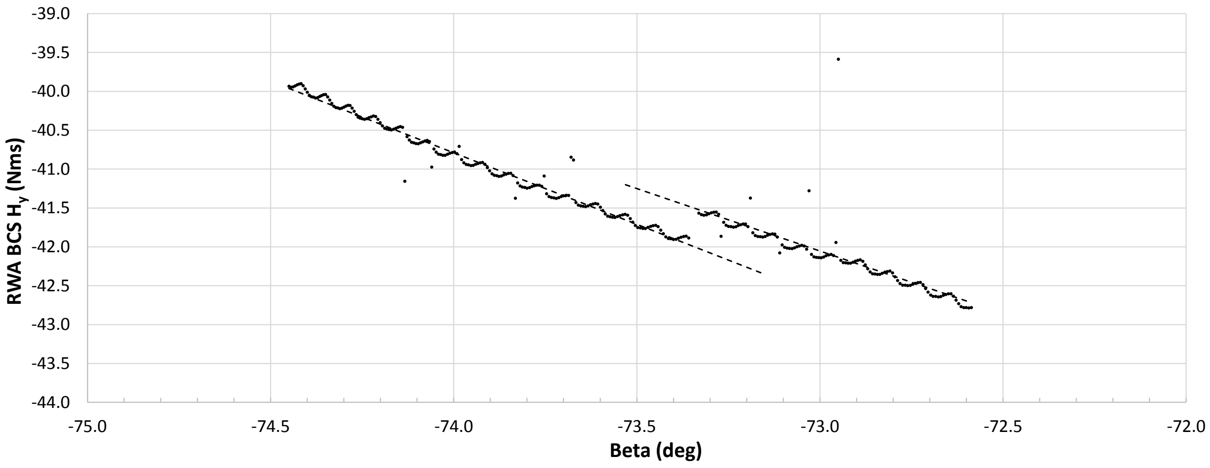
Forming piece-wise regression model

Methodology Overview

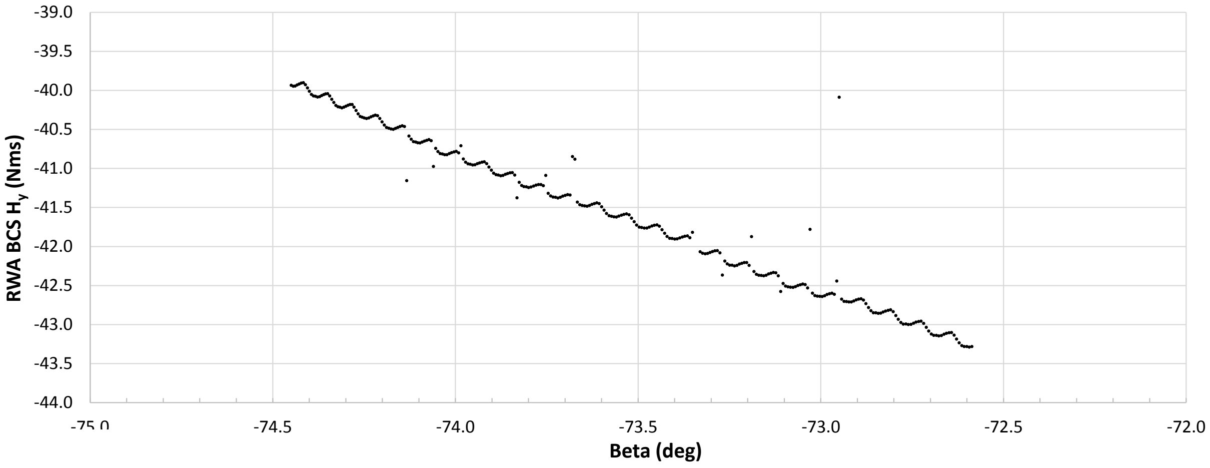
- Piece-wise polynomial least-squares regression
  - One year's worth of data
    - Regress Hy and Hxz against beta separately, with Htot simply being RSS
    - October 2014 – October 2015
    - Covers full cycle of beta values
  - Linear and cubic regressions
  - Define piece boundaries based on SA modes
- First remove effects of slews & unloads to see 'natural' trend
  - Analyze angular momentum in vicinity of each and every activity
  - Collect perturbations induced by activities & make ruleset
  - Perform regression
  - Use regression coefficients—and perturbations—to predict future momentum

Determining Effects of Maneuvers

- Perform linear regressions on either side of activity
  - Perturbance is vertical step change
  - Remove step change to smooth data
  - Repeat several hundred times
  - Example: 0.5-Nms increase in Hy caused by 59° LROC roll
- Make “ruleset”
  - Group slews by type and beta regime at time of slew
  - Define changes in angular momentum due to slew/beta pairs



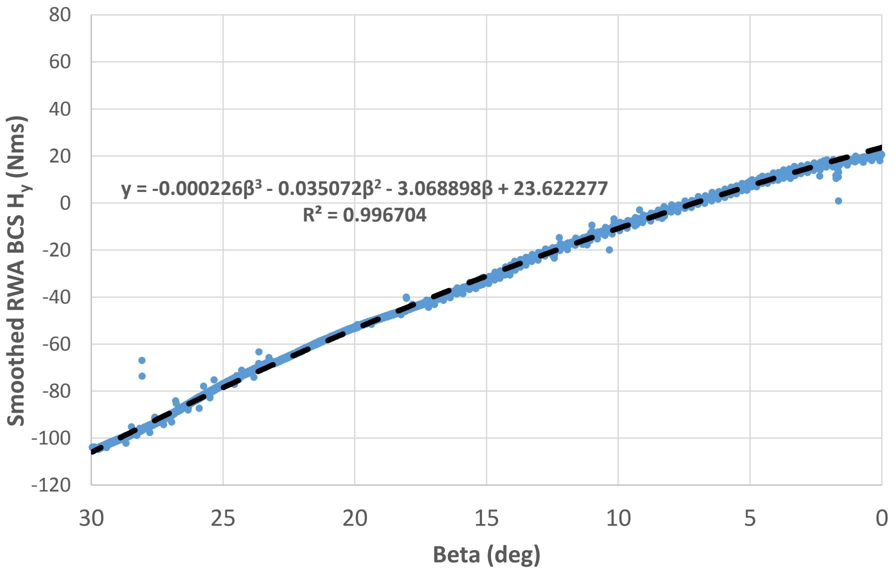
LRO RWA BCS Hy, from June 16, 2014 to June 17, 2014, with linear regressions.



LRO RWA BCS H_y, from June 16, 2014 to June 17, 2014, without effect of roll maneuver.

Forming Piece-Wise Regression Model

- Perform regressions with now smooth data
  - Least squares
  - On Hy & Hxz
  - SA modes guide boundary selection
  - Example at right: beta going from 30° to 0°
- Record six decimal places for coefficients for sufficient precision in angular momentum
- R^2 values > 0.99 typical



Smoothed LRO RWA BCS H_y, for β spanning from 30° to 0°.

Selected linear regression when strongly linear, arbitrarily selected cubic otherwise—it's all about simply achieving a good fit

Results

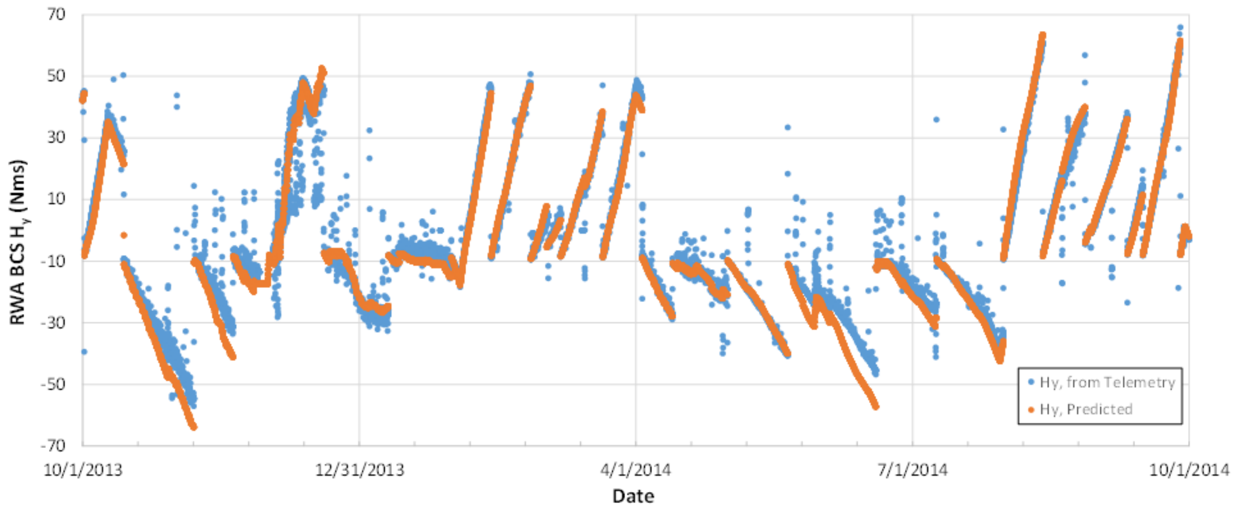
Hy

Hxz

Total H

2013 – 2014 Test: Hy

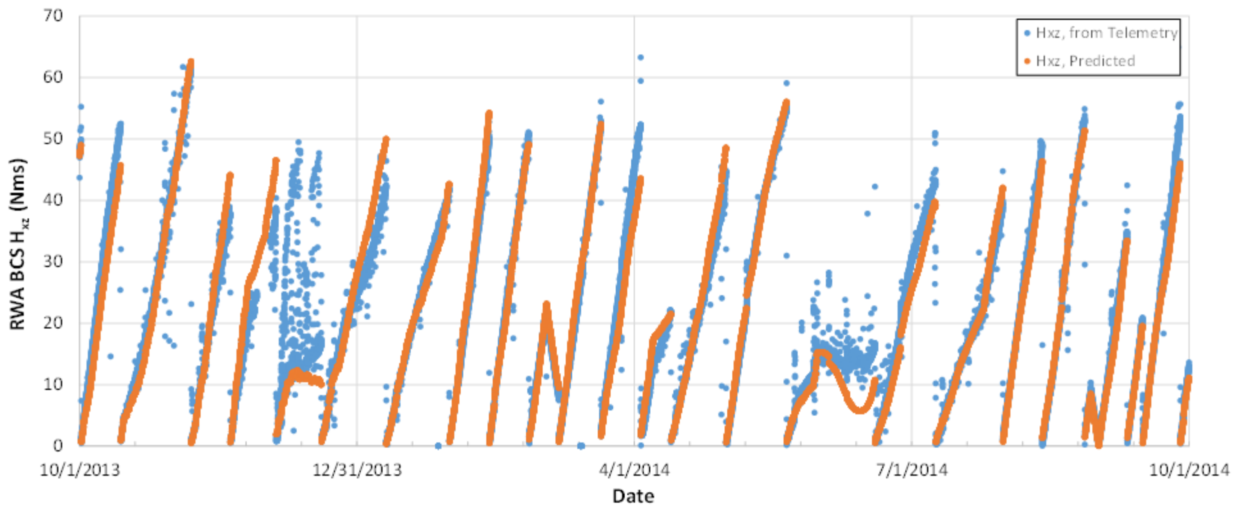
- Use regression from Oct 2014 – Oct 2015 to predict angular momentum in previous year
- Immediately after each unload
  - Initialize model to values from telemetry (Hy≈-9 Nms, Hxz≈0 Nms)
  - Predict angular momentum until next unload
    - 'Baseline' prediction based on:
      - Regression coefficients
      - Beta values predicted at time by FD
    - Add step changes using list of performed slews



Achieved very good fit, even during times when spacecraft activities completely obscured underlying trend

2013 – 2014 Test: Hxz

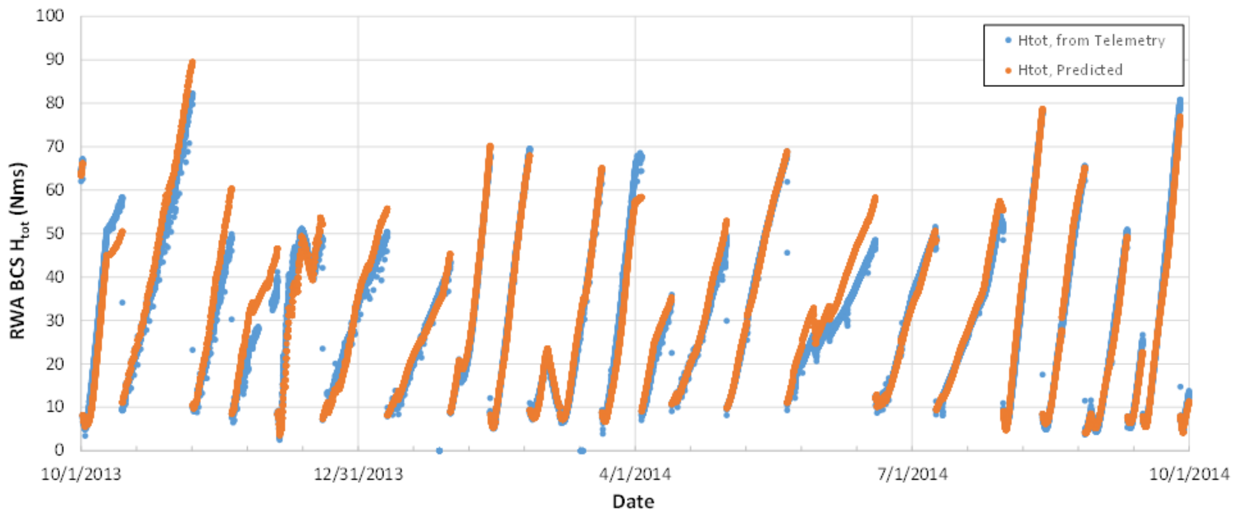
- Largely very good agreement except for Dec 2013 & June 2014
  - Corresponds to when beta has just retreated away from ± 90°
  - Morphology of predicted trend not matching observations
  - Max prediction errors approaching 10 Nms
- Have since formed new regression equations with better, though not perfect fit
- Total H is most important



Achieved good fit, though most challenging period is when beta has just retreated away from ± 90°

2013 – 2014 Test: Total H

- Total H used for unload planning
- Small prediction errors at time of next unload:
  - Mean = 3.7 Nms
  - Median = 2.7 Nms
  - Max = 10.6 Nms
- Operational results would likely be even better than here
  - OPSCON would include using tool intermittently
  - Opportunities for re-synching model against telemetry



Prediction capabilities vastly outperform legacy method employed by mission

Conclusion

Summary

Future Work

Discussion

Summary

- LRO operations now uses these accurate angular momentum predictions
  - Especially accurate if schedule known far in advance
  - Currently schedule 1 – 2 weeks in advance
  - Mission investigating scheduling farther out based on results of study
- Momentum unloads now performed more optimally
  - Momentum target now selected depending on trend experienced after unload
    - For example, don’t select -10 Nms if trend is to become more negative
    - Delays next unload by 3 – 9 days, depending on trend
  - Have waited as much as 42 days between unloads
- Study has enabled other improvements
  - Identified slews that counteract trend in angular momentum
  - Hope to eventually control angular momentum without using propellant

Future Work

- Developing tool to deliver to operations team
- Analyzing angular momentum behavior as beta retreats from ± 90°
- Testing the use of select operational slews to decrease angular momentum
  - Off-nadir attitude providing beneficial gravity-gradient torque
  - SRP smaller factor

LRO Mission Operations Center

Thank you for your attention