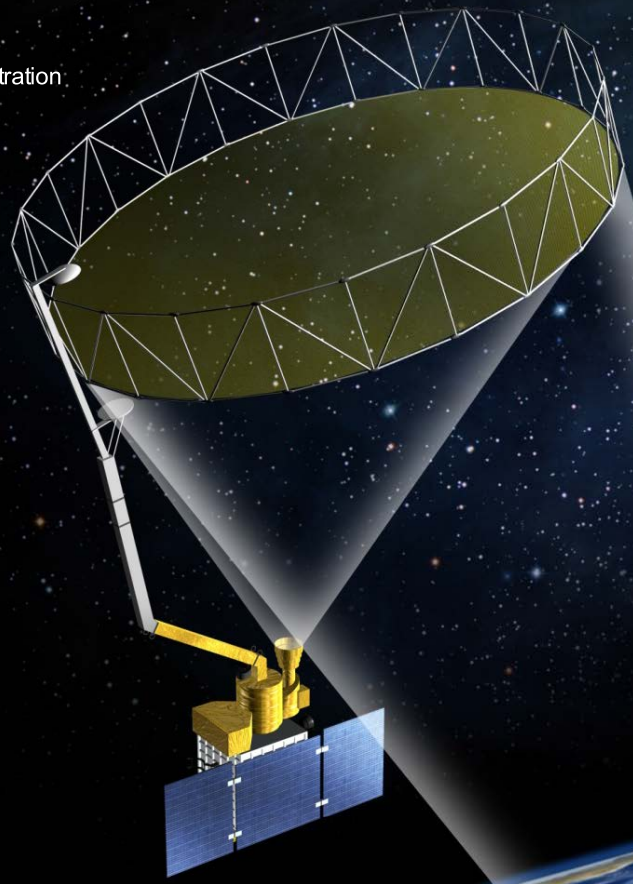
National Aeronautics and Space Administration

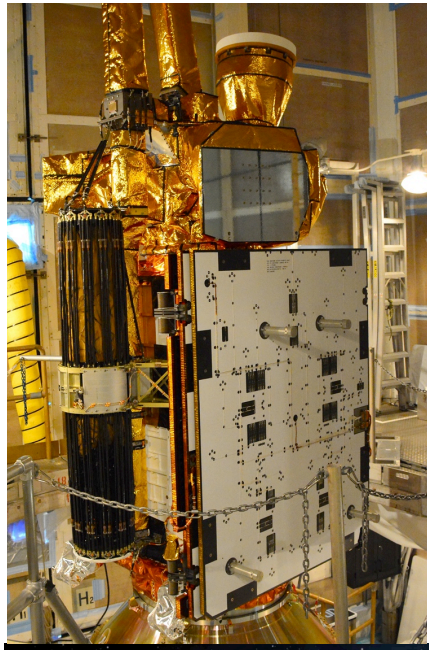


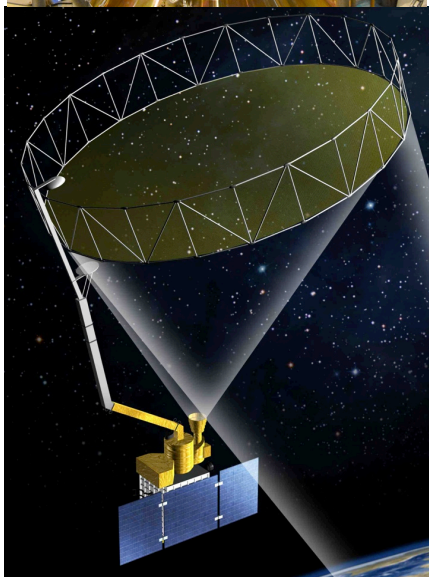
A GNC Perspective of the Launch and Commissioning of NASA's SMAP (Soil Moisture Active Passive) Spacecraft

Todd Brown
GNC Engineer
Jet Propulsion Laboratory
AIAA GNC Conference, San Diego, CA
January 4, 2016

SMAP Mission and Spacecraft Overview

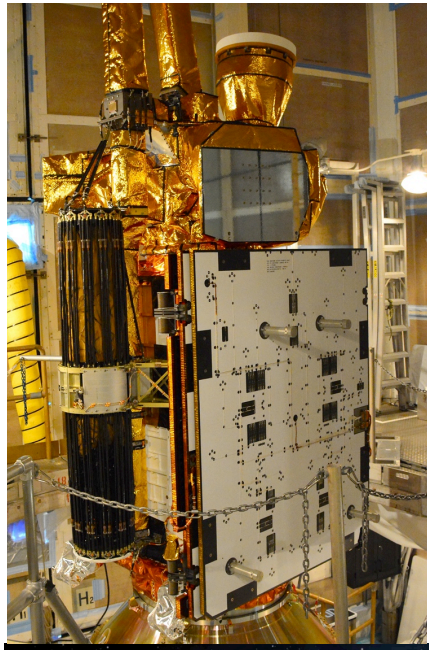
- Mission: Measure global soil moisture levels in top 2 inches of soil every 2-3 days, as well as detect freeze/thaw boundary
- Date Launched: Jan 31, 2015
- Prime Mission Length: 3 years
- 2 Science Instruments:
  1. L-Band 1.41 GHz Radiometer provided by Goddard SFC
  2. L-Band 1.22-1.3 GHz Radar provided by JPL
     - Radar in-flight anomaly on July 7. Instrument no longer functions
- Launch Vehicle: ULA Delta II (Vandenberg Air Force Base)
- Orbit Altitude: ~690 km polar sun synchronous orbit
- 6:00 local mean solar time
  - Continuous sunlight except for <20 minute eclipses in summer season
- Spacecraft Overview
  - Conical-scanning, dual-spinning, 3-axis stabilized
  - Spin rate of Spun Platform Assembly (SPA): 14.6 rpm
  - 6 meter mesh reflector and 5 meter boom on SPA
  - 944 kg
  - Spacecraft designed and assembled at JPL

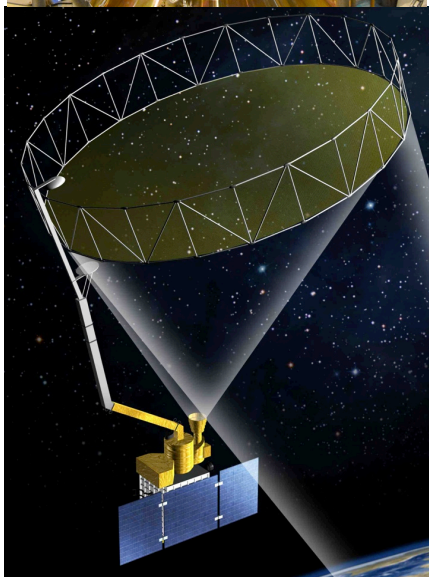




SMAP GNC Overview

- **GNC Hardware**
  - Eight 4.5 N RCS Thrusters
  - Four 250 Nms RWAs
  - 2 analog Coarse Sun Sensor (CSS) pyramids (8 heads total)
  - 1 Stellar Reference Unit (SRU)
  - 2 inertial reference units. IRU-A prime / IRU-B unpowered backup
    - "IRUs" are actually "IMUs" (include accelerometers)
  - One 3-Axis Magnetometer (TAM)
  - 3 Magnetic Torque Rods (MTRs)
  - No GPS. Doppler orbit determination & uplinked ephemeris
- **GNC Controller Description**
  - RCS Control Mode
    - Post launch, for maneuvers, and some extreme fault cases
  - RWA Control Mode
    - Science mode, safe mode, spin-up mode
  - Idle Control Mode (GNC control inactive)
    - Deployment of solar arrays, boom, reflector, and pyro firings
  - Momentum Control Loop
    - SMAP maintains a zero-momentum state
    - Momentum estimated on-board and then TAM data used autonomously to send commands to MTRs to unload momentum

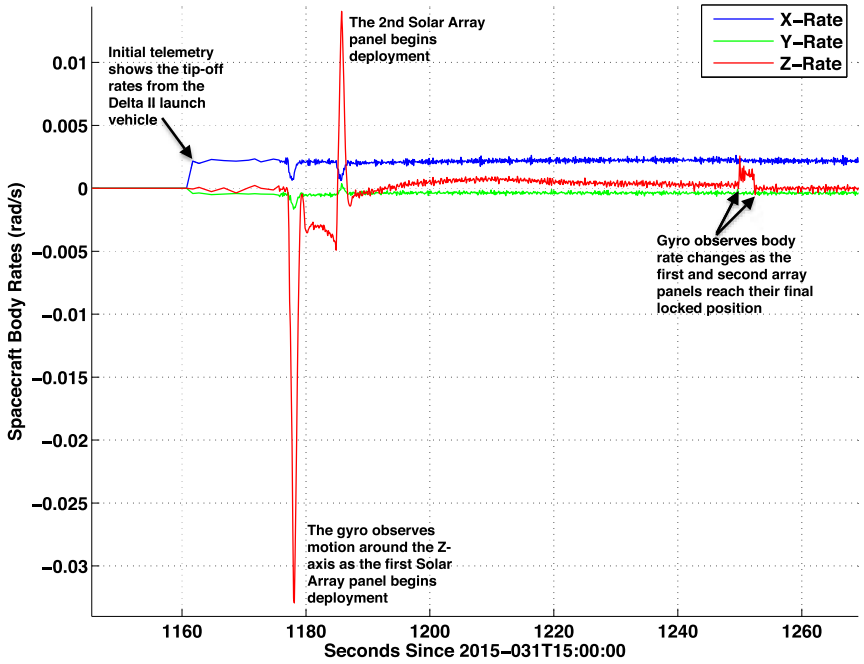




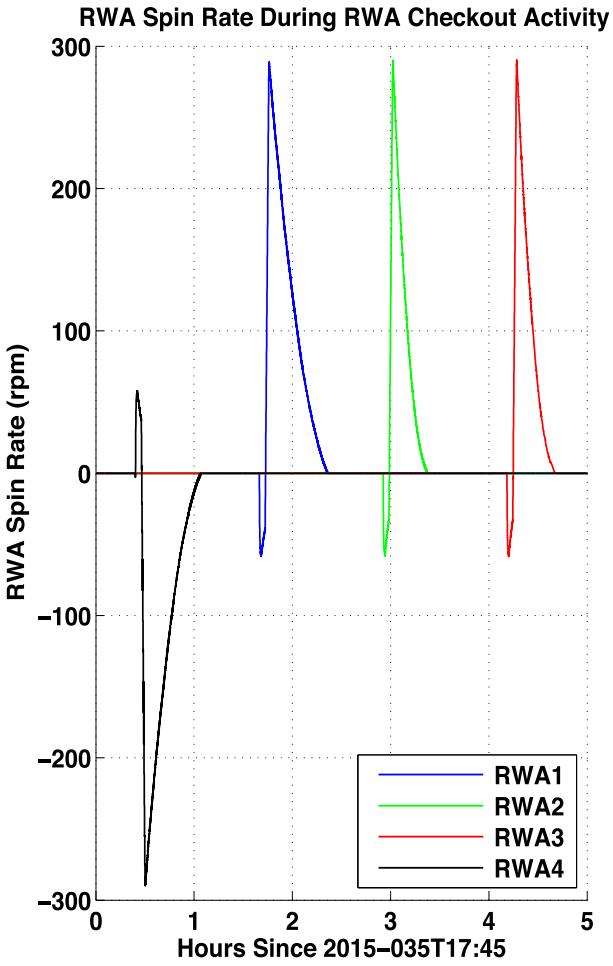
SMAP Launch Day

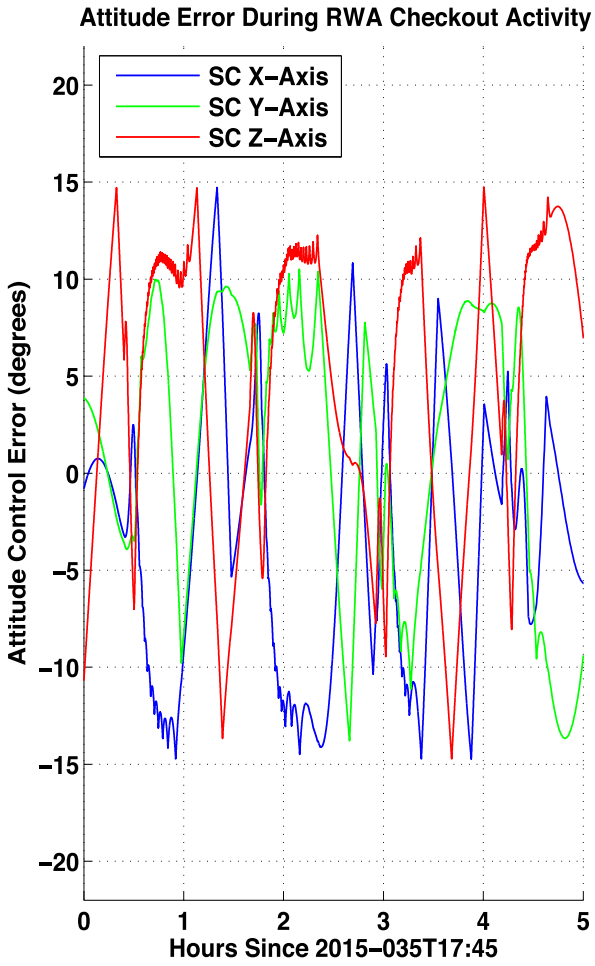
- **GNC Autonomous Responsibilities Post-Launch**
  - "Detumble" the spacecraft (using thrusters)
  - Perform Sun-Search and point +Y axis (i.e. solar arrays) toward the sun
    - Sun search nominally: +180˚Z, +180˚X, +180˚Z, +140˚X
  - Enter "Rotisserie Roll" around Sun direction to ensure periodic low rate communication
  - Critical hardware: RCS, IRU-A, CSS (Phasing confirmed pre-launch)
- **Additional GNC Ops. Tasks on Launch Day**
  - Power On/Check Out SRU and TAM
  - Use TAM/CSS and SRU telemetry to produce ground estimate of inertial J2000 attitude
- **Notes About Launch Day**
  - Ground tool produced real-time J2000 attitude estimate
    - Both TAM/CSS as well as SRU data used
  - No "detumble" occurred (gentle release from LV)
  - No Sun Search occurred (sun already on arrays)
  - CSS thermal anomaly
    - Solar Arrays and Sun Sensor significantly warmer than predicted
    - Due to conservative power generation/consumption estimates
  - SRU anomaly occurred
    - SRU required reset after Earth obstruction

Spacecraft Body Rates During Solar Array Deployment



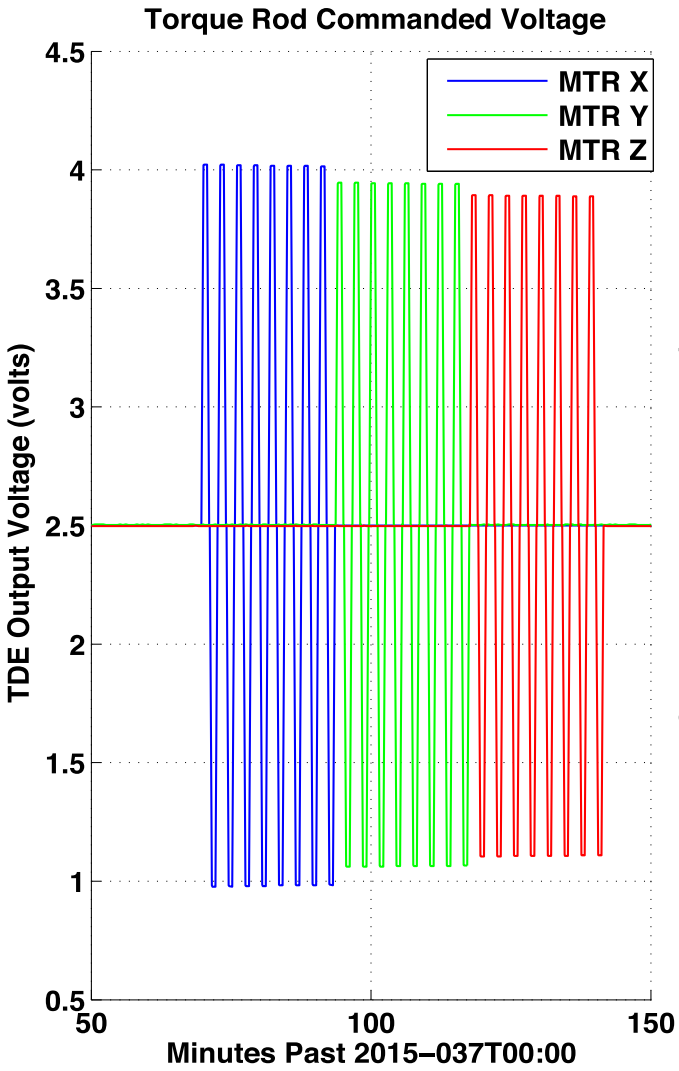
GNC Hardware Checkout

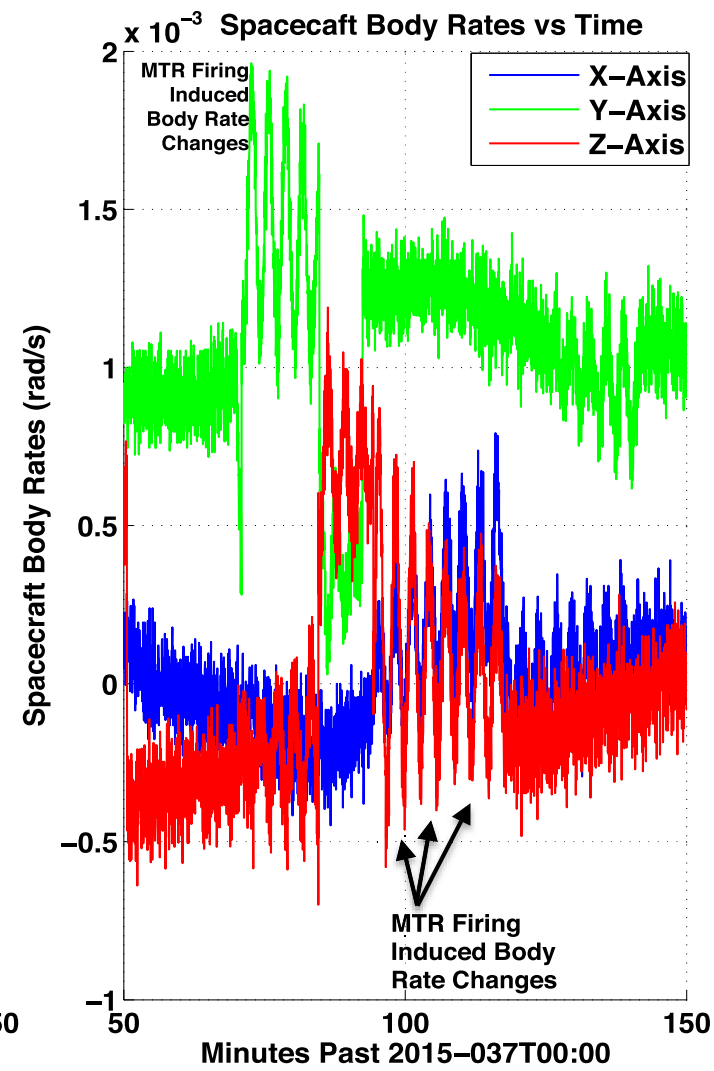




- **Purpose of On-Orbit Checkout of GNC Hardware**
  - Confirms hardware is healthy/responsive to commands following launch stresses
  - Confirms proper hardware phasing
  - Produce baseline measure of hardware performance
- GNC Hardware That Received On-Orbit Checkout Prior to Autonomous Use: RWA, MTR, SRU, TAM
- **RWA Checkout Strategy**: Spin 1 RWA and confirm that spacecraft body rates/attitude error response match predict

MTR Checkout Activity Telemetry



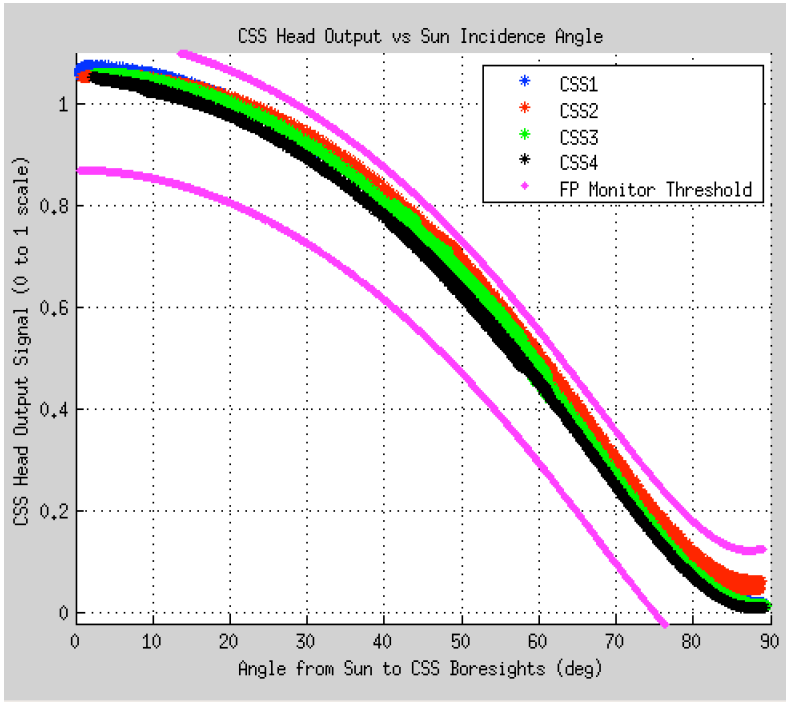


MTR Checkout Strategy:

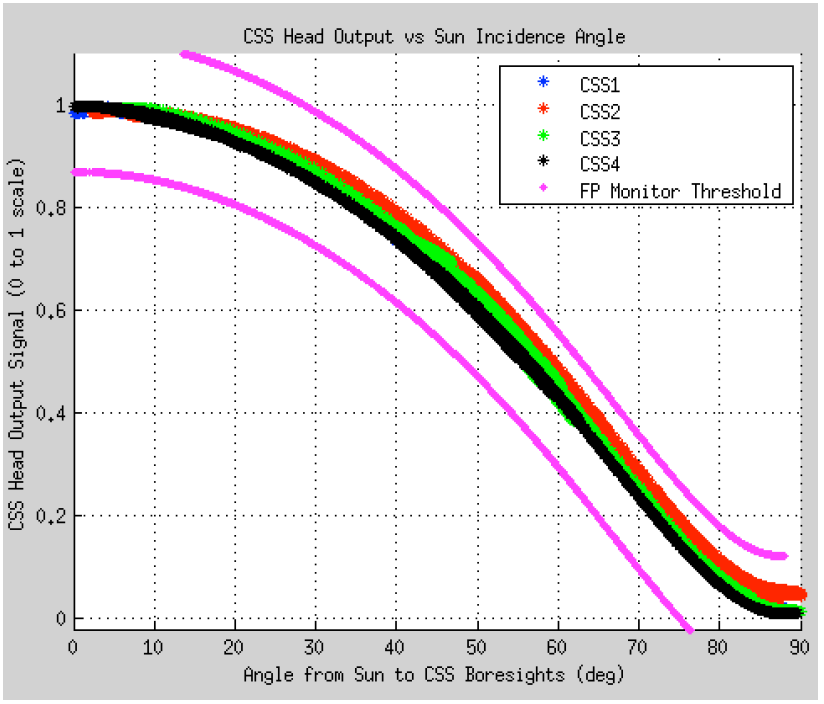
- "Fire" one MTR and confirm that spacecraft body rates/attitude error response match predict
- Each MTR checked out over range of 90 degrees of latitude

Sun Sensor (CSS) Scale Factor Calibration

CSS Output Prior to Scale Factor Update



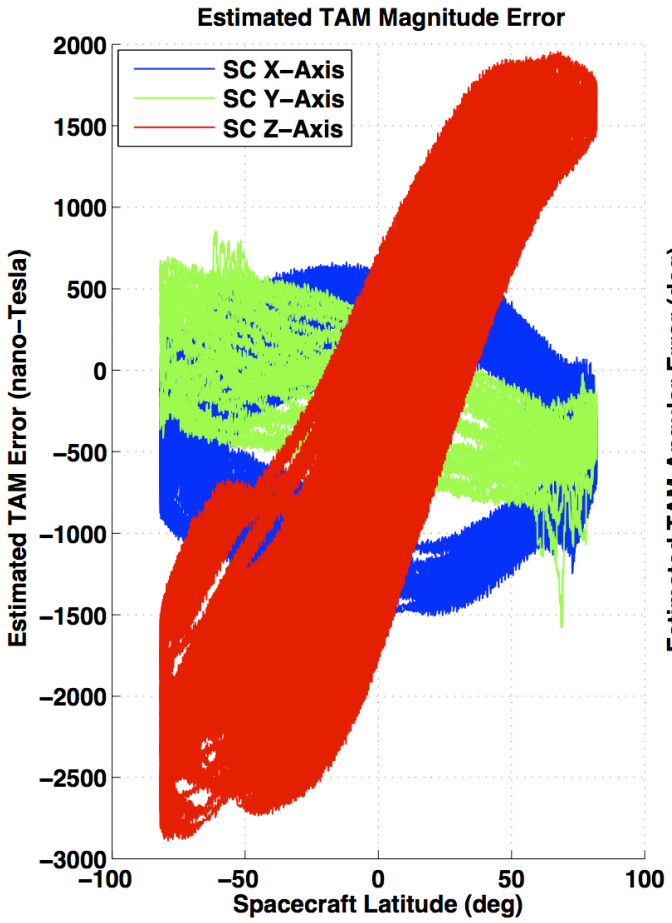
CSS Output After Scale Factor Update

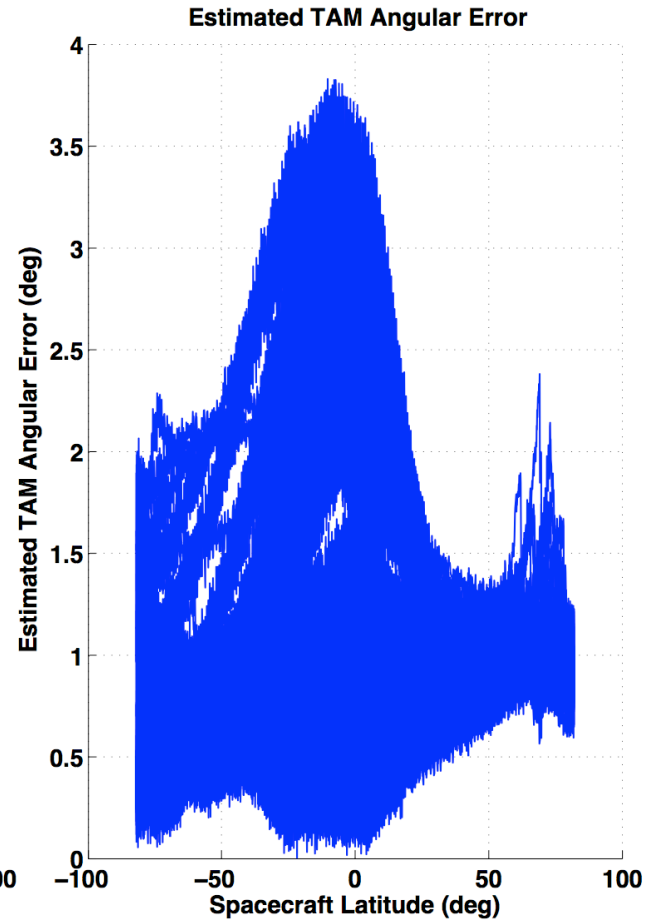


Coarse Sun Sensor Scale Factors:

- Slews performed to sweep sun across full range of each CSS head
- Slews primarily to calibrating spacecraft inertia tensor (i.e. piggyback GNC activities)
- +Y CSS Scale Factor increase required: [CSS1, CSS2, CSS3, CSS4] = [7.1, 6.1, 6.3, 5.1] %
  - Scale factor error primarily due to warmer than expected operating temperature

TAM Bias Estimation

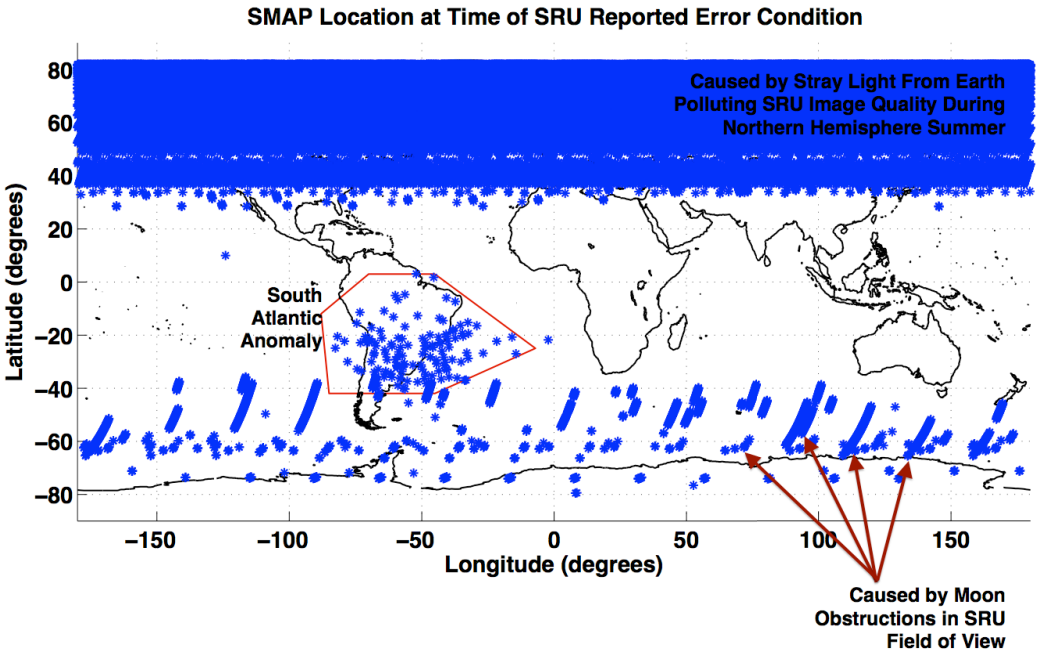




- Three Axis Magnetometer (TAM) Bias Estimation
  - TAM telemetry (vector direction and magnitude) compared to ground model (IGRF) of expected B-Field
  - Estimated TAM bias of [X, Y, Z] = [-443 -160 -402] nT
    - Computed from average measurement error for a specified range of latitude

SMAP Stellar Reference Unit

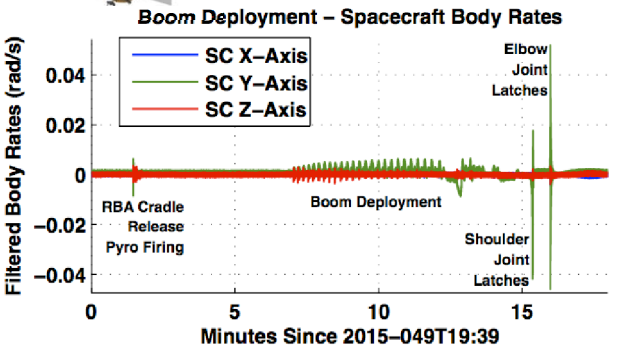
- SMAP SRU has been the most troublesome piece of GNC hardware
- SMAP SRU has exhibited three independent unexpected behaviors
- SRU Issue #1
  - SRU autonomously reports "excessive number of stars" error condition in its telemetry
  - Condition presented itself several 100,000's of times in flight
    - Frequency could mask visibility of other errors
  - Error condition triggered by: **(a)** stray light from Earth albedo reflecting off inside of baffles, **(b)** moon in the SRU field of view, and **(c)** elevated radiation environment of the South Atlantic Anomaly
  - SRU continues to produce attitude estimates even in the presence of the error condition

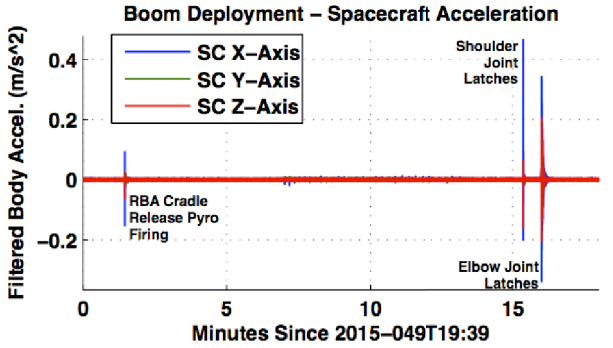


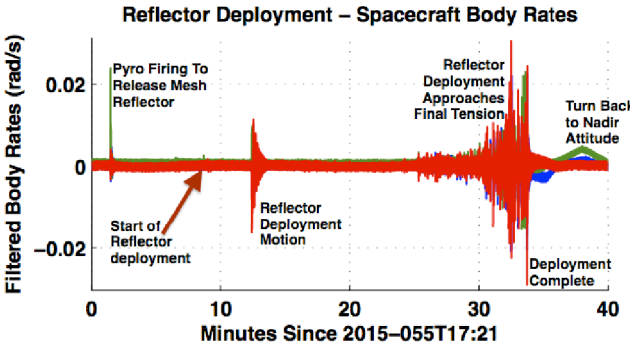
- SRU Issue #2
  - SRU has experienced 4 in-flight unplanned resets
  - Assumed to be due to SEU (sudden event upset) from high energy charged particle
  - SMAP flight software response to resets: safe the vehicle
    - This was changed in later flight software update
  - SRU resets resulted in 2 safing events and nearly a 3rd
- SRU Issue #3
  - Some Earth obstructions caused SRU to cease producing attitude estimates
  - Error condition can only be resolved by resetting the hardware
  - No hardware fix currently available
  - Operational work around: command the SRU to STANDBY before any Earth obstruction

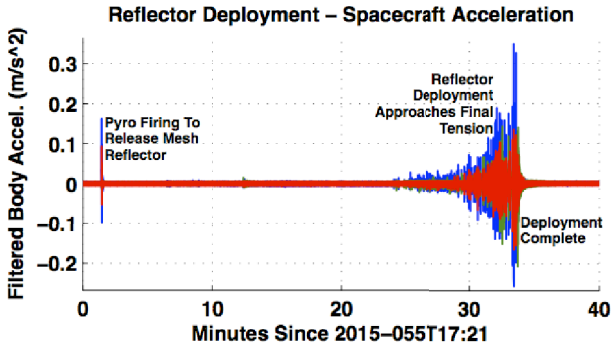
In-flight SRU Checkout:
- SRU attitude estimate compared to TAM/CSS derived attitude estimate with ground tool
- SRU photos downlinked to confirm no optical contamination

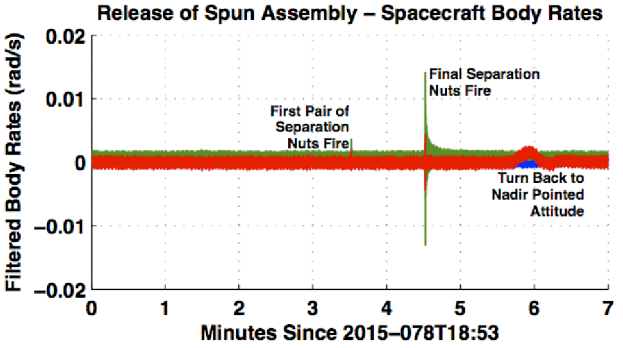
Deployment Events

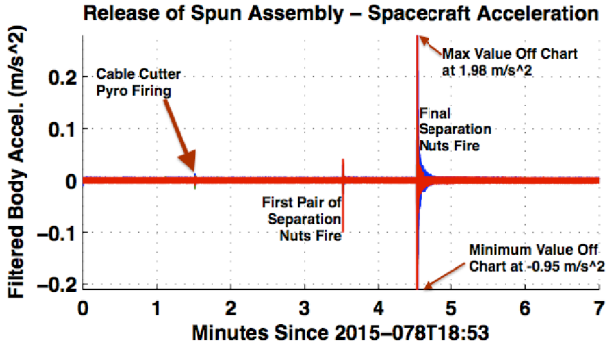






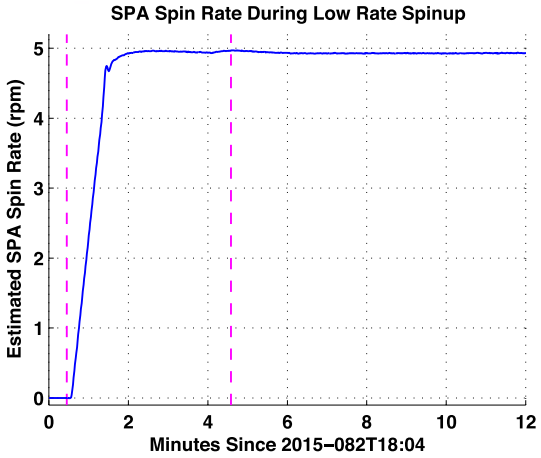


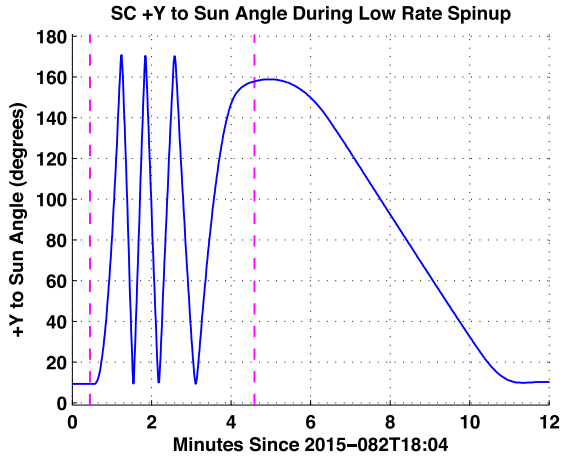


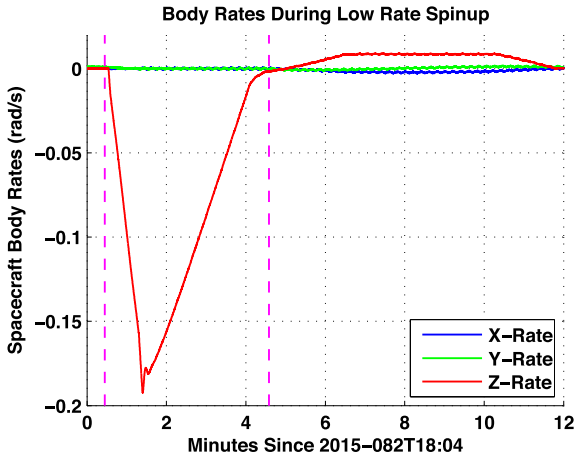


- Commissioning Included 3 Major Deployment Events
  - Boom Deployment
  - Reflector Deployment
  - Release of SPA (Pyro Firing event)
- GNC transitioned to IDLE mode for deployments (attitude control was inactive during activities)
- GNC continued attitude estimation and maintained constant RWA spin-rates
- High-Rate (> 100Hz) IRU telemetry used for 2ndary confirmation of deployment success
- Y-axis momentum bias of +8.25 Nms added for boom and reflector deployments
  - Added for gyroscopic stability to keep solar arrays near the sun
  - Attitude drift during boom deployment: [Y,Z] = [2.9, 14.9] (deg) in 16 minutes
  - Attitude drift during reflector deployment: [Y,Z] = [3.5, 15.8] (deg) in 33 minutes
- IRU easily detected every pyro firing of the mission

Low Rate Spin-Up Activity

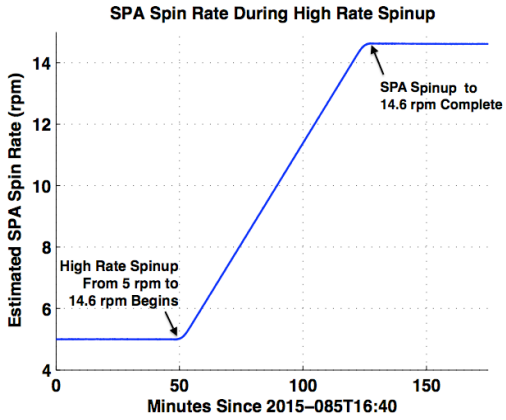


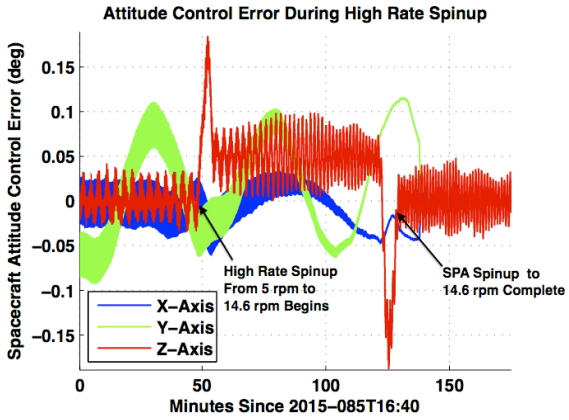


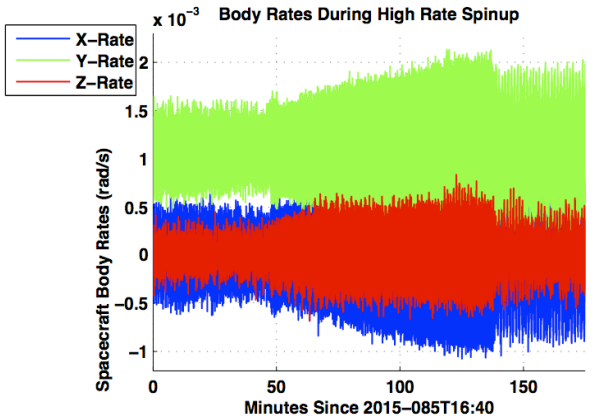


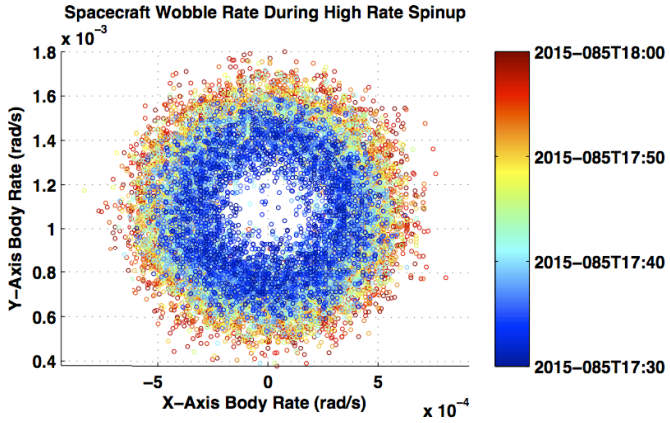
- During Low Rate Spin-Up SPA goes from 0 RPM to 5 RPM in ~80 seconds
- Torque from spin motor overwhelms RWA controller and the spacecraft tumbles (by design)
- Low Rate Spin-Up only performed once (i.e. the spacecraft has never spun down)
- During Spin-Up spacecraft tumbled at 11 deg/s around the Z-axis
  - Highest body rate of mission
- Spacecraft tumbled 3.5 full revolutions before RWA controller regained rate control
- After RWA control regained, 159 deg Z-axis turn to get solar arrays back to the Sun
  - Low Rate Spin-Up was first time Sun reached –Y facing Sun Sensor
- Spin-up telemetry used to calibrate spun inertia
  - Izz Spun: 234.7 kg-m^2
  - This was 4.0 kg-m^2 less than pre-launch estimate

High Rate Spin-Up Activity



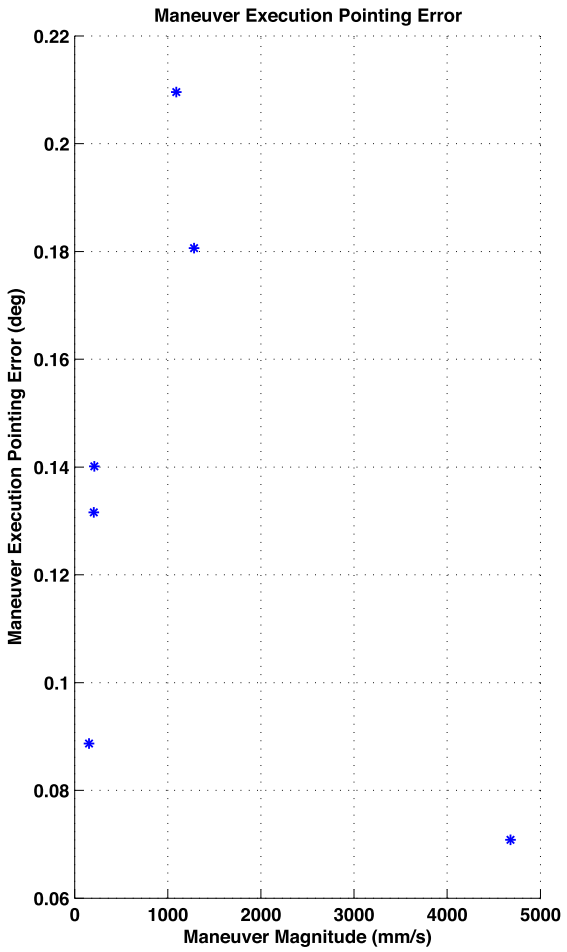


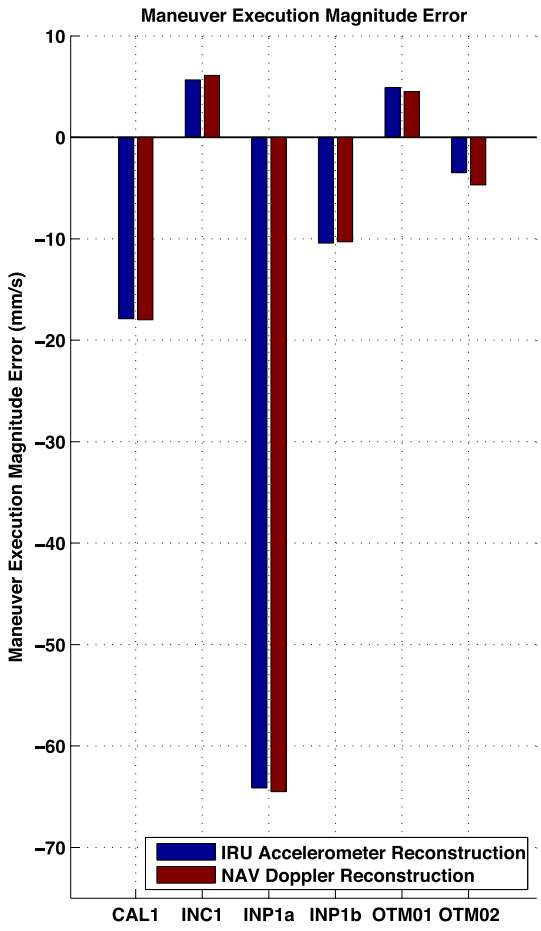




- During High Rate Spin-Up SPA goes from 5 RPM to 14.6 RPM in ~80 **minutes**
- RWA control and nadir pointing maintained through activity
- Controller uses looser gain set when SPA rate is: 0 ≤ (SPA Rate) ≤ 14.6 RPM
  - Notch filter used to mask wobble frequency
  - Notch frequency: 0.243 Hz
- **Attitude control performance while spinning:**
  - Does not include wobble angle, since this is intentionally uncontrolled
  - Attitude error: zero mean
  - Peak Attitude Error
    - **[X, Y, Z] = [2.0, 2.0, 60.0] (milli-deg)**
  - Margin from requirement:
    - [X, Y, Z] = [50x, 50x, 5x]

Maneuvers and RCS Usage

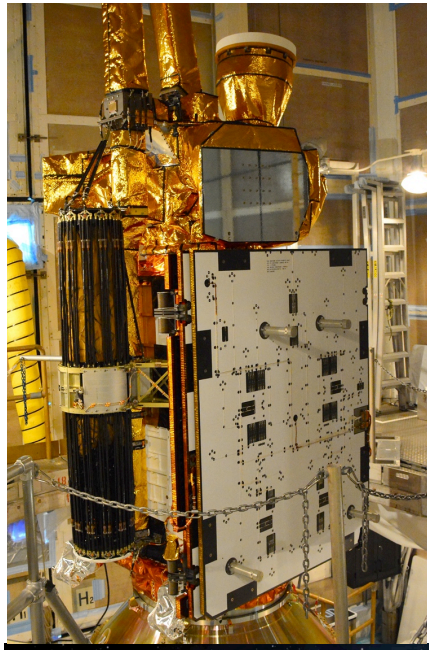


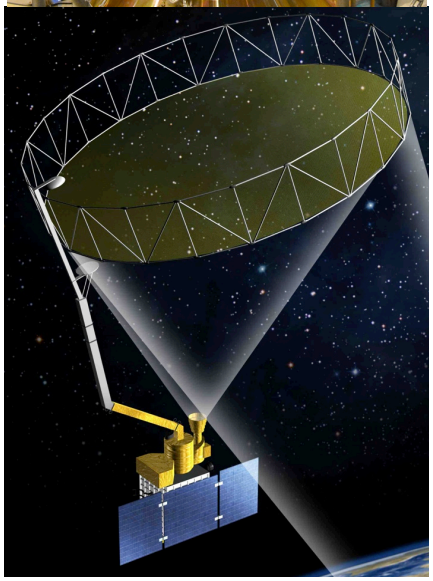


- Executed 5 orbit trim maneuvers as if 12/7/15
- Maneuvers fixed direction in nadir relative "RTN" (Radial-Transverse-Normal) frame
  - INC1 maneuver in the "Orbit Normal" direction to change inclination
  - All other maneuvers in +T or –T direction to adjust orbital altitude
- Maneuvers are "timed burns"
- Maneuvers can occur while the spacecraft is spinning
- IRU-A accelerometers not used by GNC control logic, but used by operations team to reconstruct maneuver performance
  - Accelerometer reconstruction agreed with NAV Doppler reconstruction within 1.2 mm/s
- Maneuver execution magnitude error never larger than 3% of burn magnitude
- Launch load of propellant: 81.025 kg
- **Propellant remaining: 76.7 kg (~95%)**
  - Enough for many decades of orbit maintenance (i.e. mission life not propellant limited)

Summary & Conclusions

- All GNC hardware/software checkout activities successfully completed
  - Commissioning activities proved value of methodical hardware checkout
- SMAP operations team has succeeded in achieving "Lights Out Operations"
- Late Breaking: SMAP project considering orbit change to match orbit of ESA satellite
  - Potentially restores partial radar coverage to SMAP radiometer data
- All GNC hardware is currently healthy and functioning nominally
- **GNC subsystem ready to support potentially many years of operations**





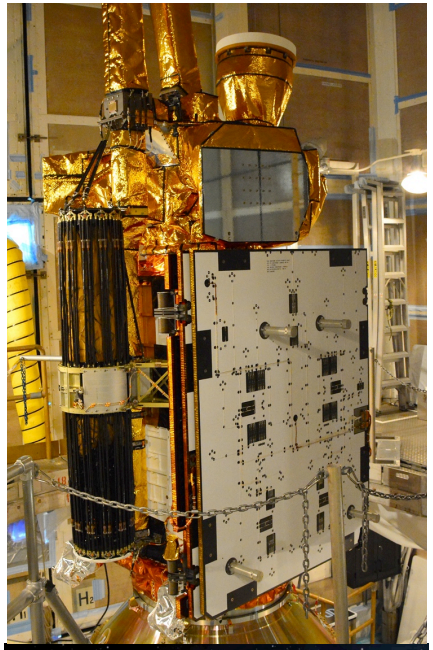
Acknowledgements

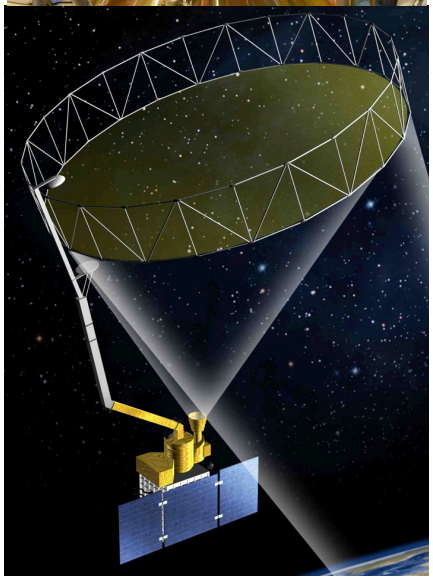
Special Thanks to:

- The SMAP GNC Operations Team: Shawn Johnson, Matt Wette, Dan Eldred, Bryan Kang, and Tina Sung
- SMAP GNC Control Analysis Team
- SMAP GNC Hardware Team
- SMAP Flight Operations Team

Photo Credits and Links:

- SMAP Deployment Animation: https://www.youtube.com/watch?v=-7_YdsNb2w4
- SMAP ATLO Photo: https://www.flickr.com/photos/nasakennedy/15713339273/
- SMAP Science Config.: http://www.jpl.nasa.gov/missions/web/smap.jpg
- SMAP LV Separation: https://www.youtube.com/watch?v=UoIu0z8orC8

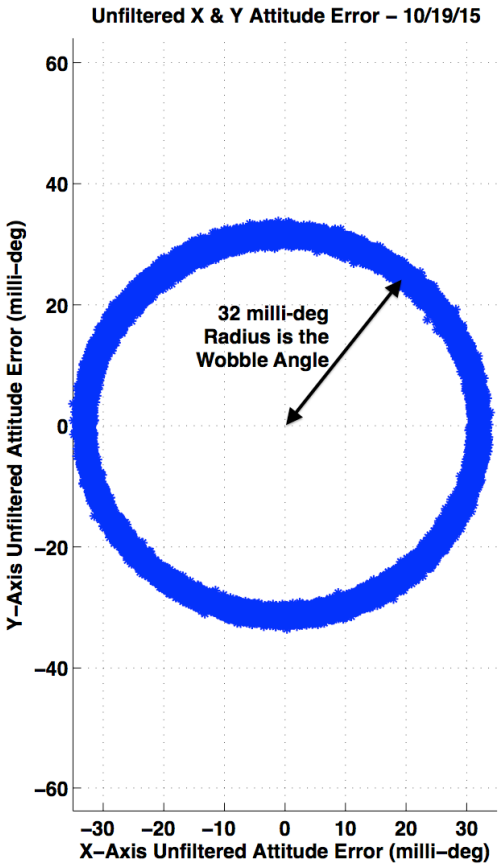


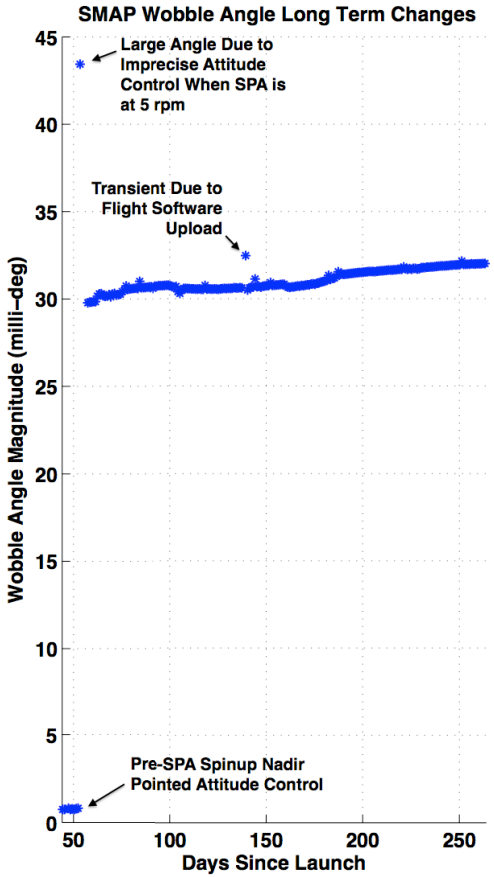


The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Backup Slides

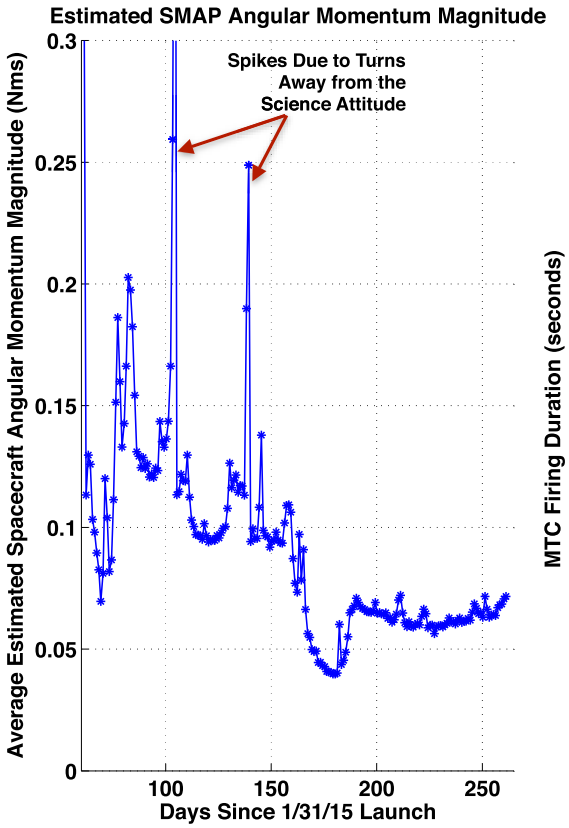
Wobble Angle History

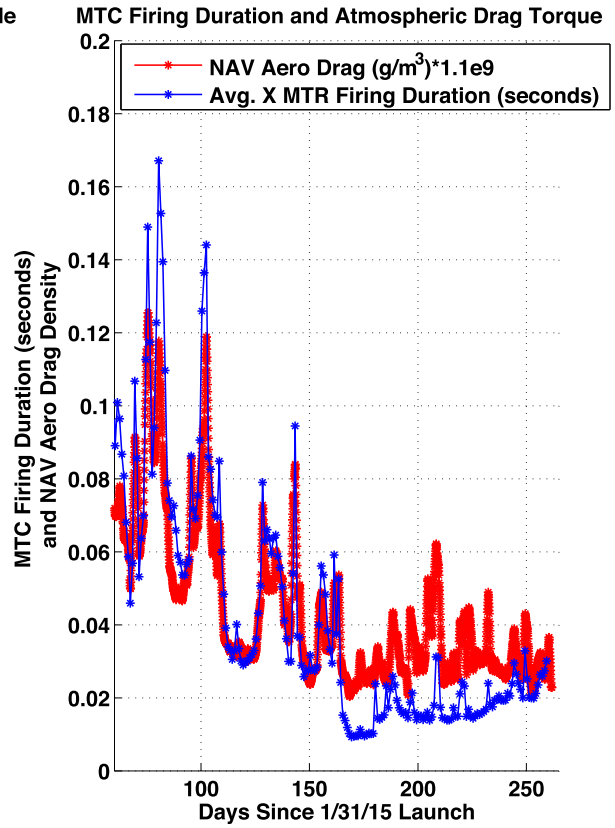




- Wobble present due to offset between SPA center of mass offset and spacecraft spin-axis
- Wobble rate grows as a function of SPA spin rate, wobble angle should be ~constant
- GNC operations team observed that wobble angle has continued to grow slowly over the course of the mission
- Current wobble angle: 32 milli-degree
  - Required to be smaller than 500 milli-deg (17x more than current value)

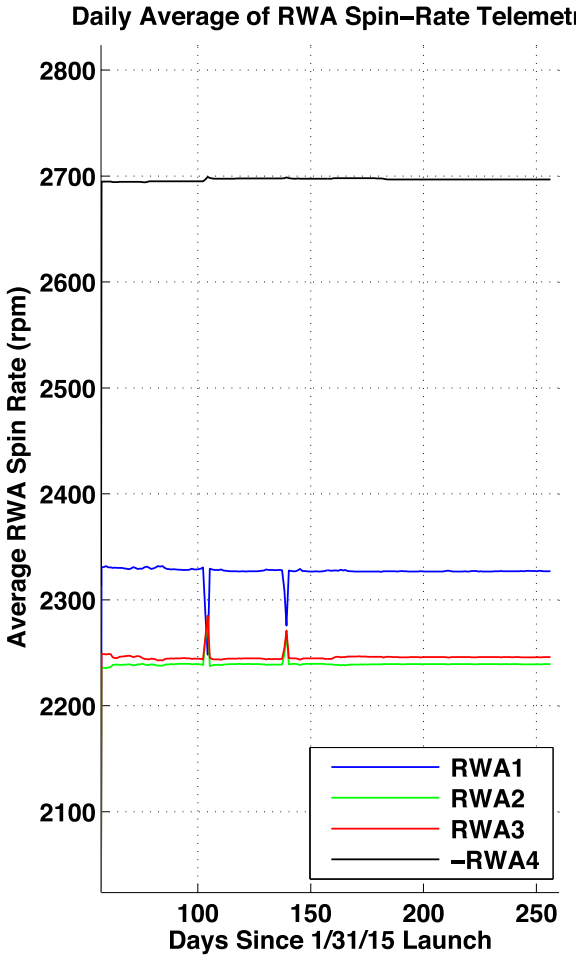
Atmospheric Torque

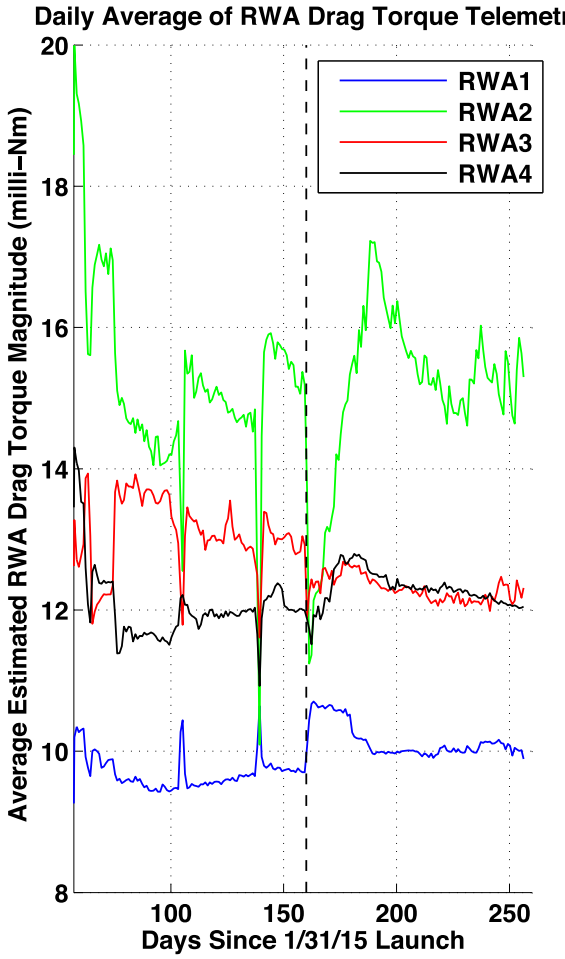




- Operations team has observed strong correlation between Y-axis momentum and Aero Drag
- Navigation estimates Aero Drag based on Doppler Data
- GNC actively estimates momentum error and magnetic torque control commands (MTR on-time) reported in

RWA Drag History





- SMAP RWA spin-rate nearly constant after SPA spin-up complete
- RWA drag torque estimate shows that drag is strongly correlated to RWA temperature gradient
- No significant changes in RWA drag at this point in the mission (~1 year)