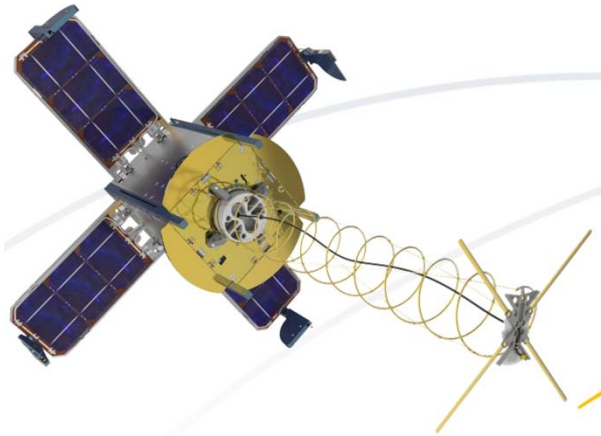

Los Alamos
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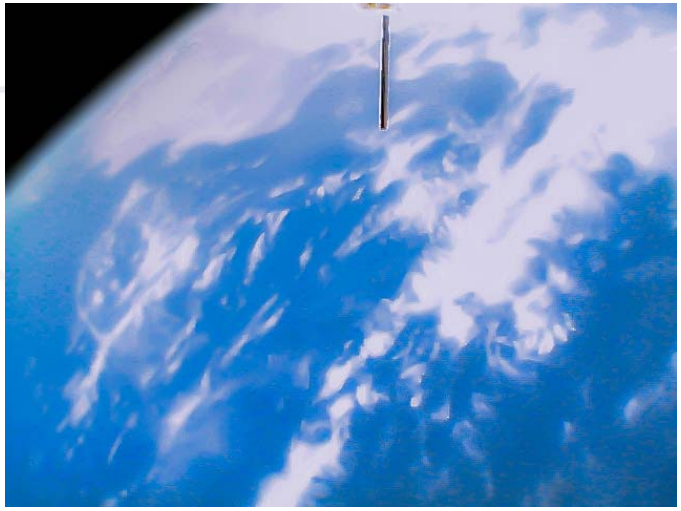
EST. 1943



Compact Attitude Determination and Control System for Small Satellites

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LANL Agile Space Background

- Goal to realize orders of magnitude lower total cost of ownership
  - Regular incorporation of new technologies and improvements to manufacturing
  - Lower development costs (COTS parts, flexible part qualification, common software)
  - Lower launch costs by making satellite small and light weight (high volume efficiency)
  - Lower operational costs through simplicity and automation (tactically controlled)
  - Tailor the risk to the tolerance of the customer, the budget, and the mission
- To date, LANL CubeSats and supporting ground stations have been developed together as systems
  - Designed for specific, operationally relevant, missions
  - Keeping it simple and low cost have been strong drivers
- All development has been done at LANL by its multidisciplinary Agile Space Team

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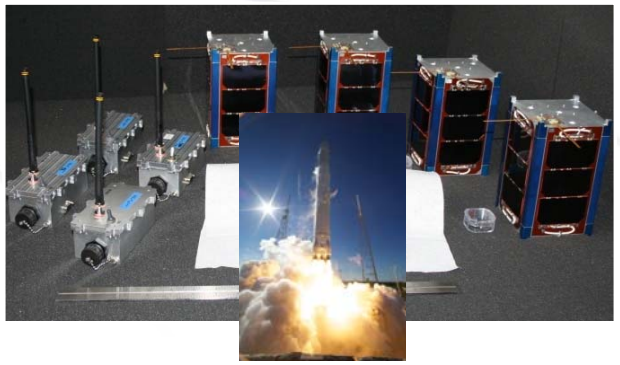
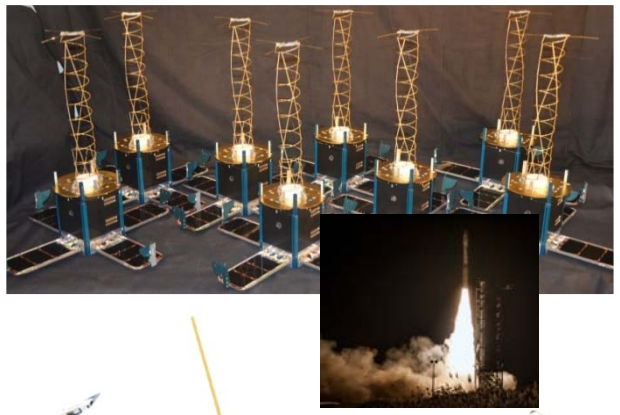
LANL CubeSat Projects

- Perseus Pathfinder:
  - Launched 4 satellites Dec 2010
  - Passive attitude control with permanent magnets and hysteresis rods



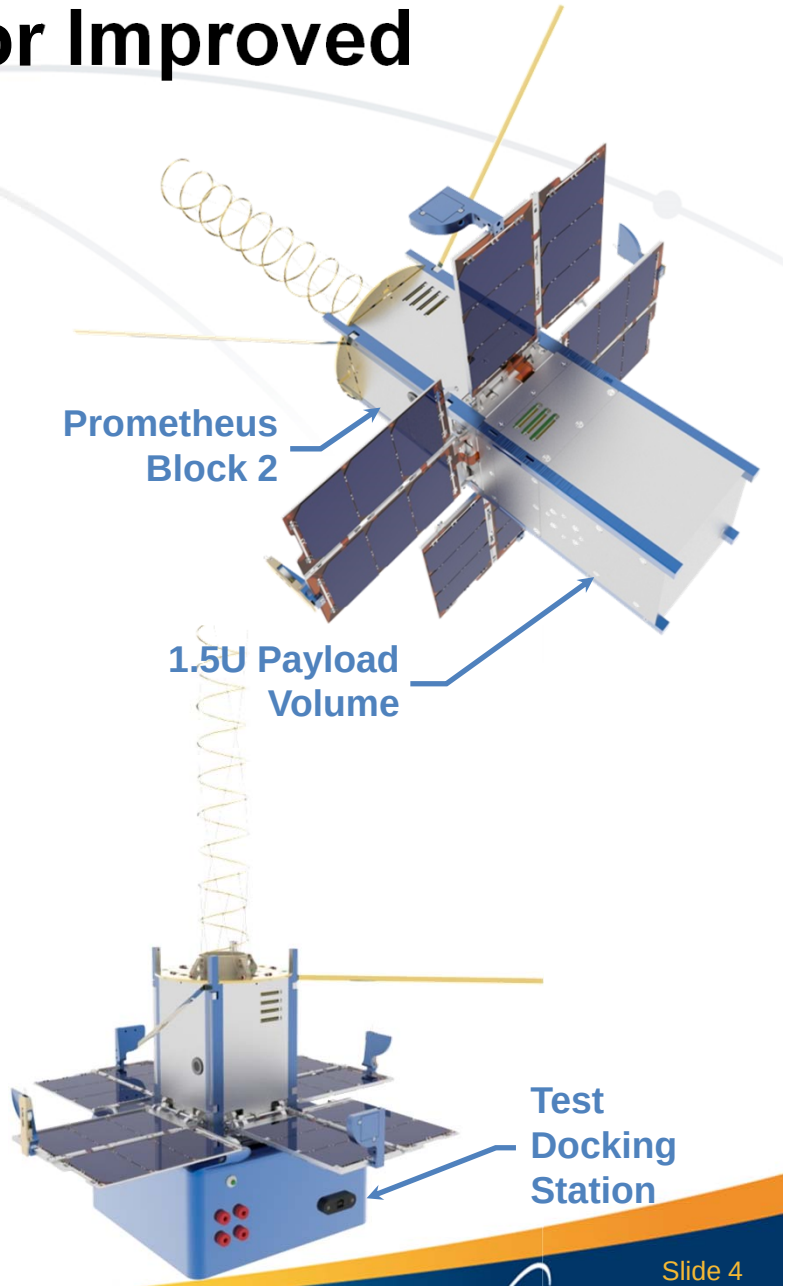
- Prometheus Bock 1:
  - Launched 8 satellites Nov 2013
  - Successfully demonstrated active attitude control with many lessons learned



- Prometheus Block 2:
  - Expecting to launch 10 satellites Summer 2016
  - ADCS design improvements

Hosting Payloads a Driver for Improved ADCS

- Prometheus Block 2 will support payload hosting:
  - Flexible digital / power interface connector
  - Bolt holes
- Prometheus is a 1.5U satellite
- A 1.5U payload volume can be bolted on
- Prometheus will provide
  - Power and power control
  - Communications to/from the ground
  - Pointing
- Hosting connector doubles as a test connector



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On Orbit Operations and Development

- Prometheus is a configured, not scripted system
  - Total cost of ownership, including operations, is a major design driver
  - The satellite is commanded with a list of target locations (for example the ground station at LANL)
  - The satellite propagates its location, the location of the targets, and the access to the Sun on board
  - The satellite automatically determines its orientation and performs the necessary maneuvers
- ADCS is developed and tested on orbit
  - Does not rely solely on ground verification of the software
  - The system is designed so the power and communications systems will function in any orientation
  - The ADCS is completely reprogrammable on orbit (code upload is handled automatically by the ground station)
  - During Block 1, a fully automated capability of uplinking a new configuration, automatically performing an attitude control test, and then downlinking the log files for ground processing.

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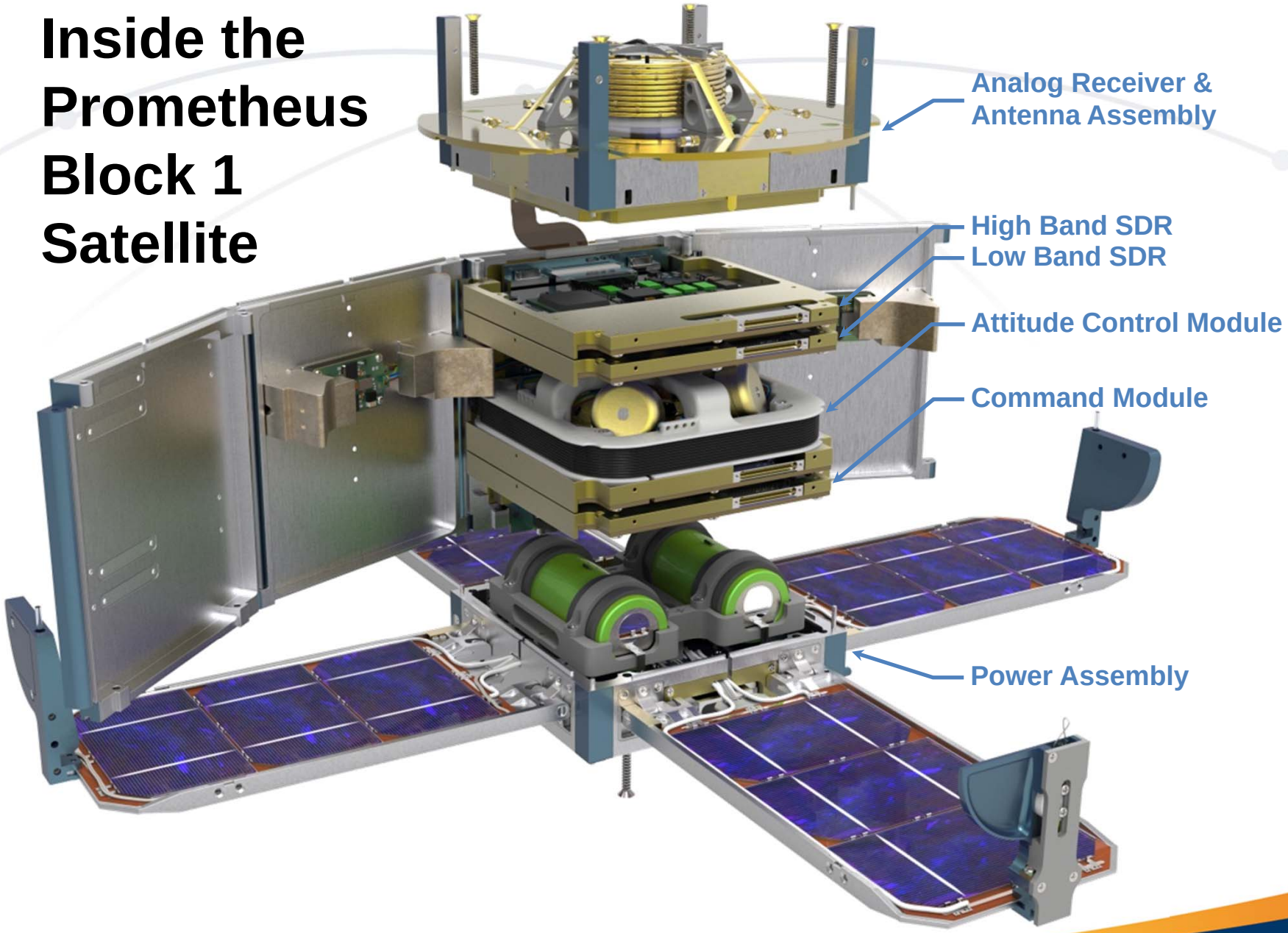
Inside the Prometheus Block 1 Satellite



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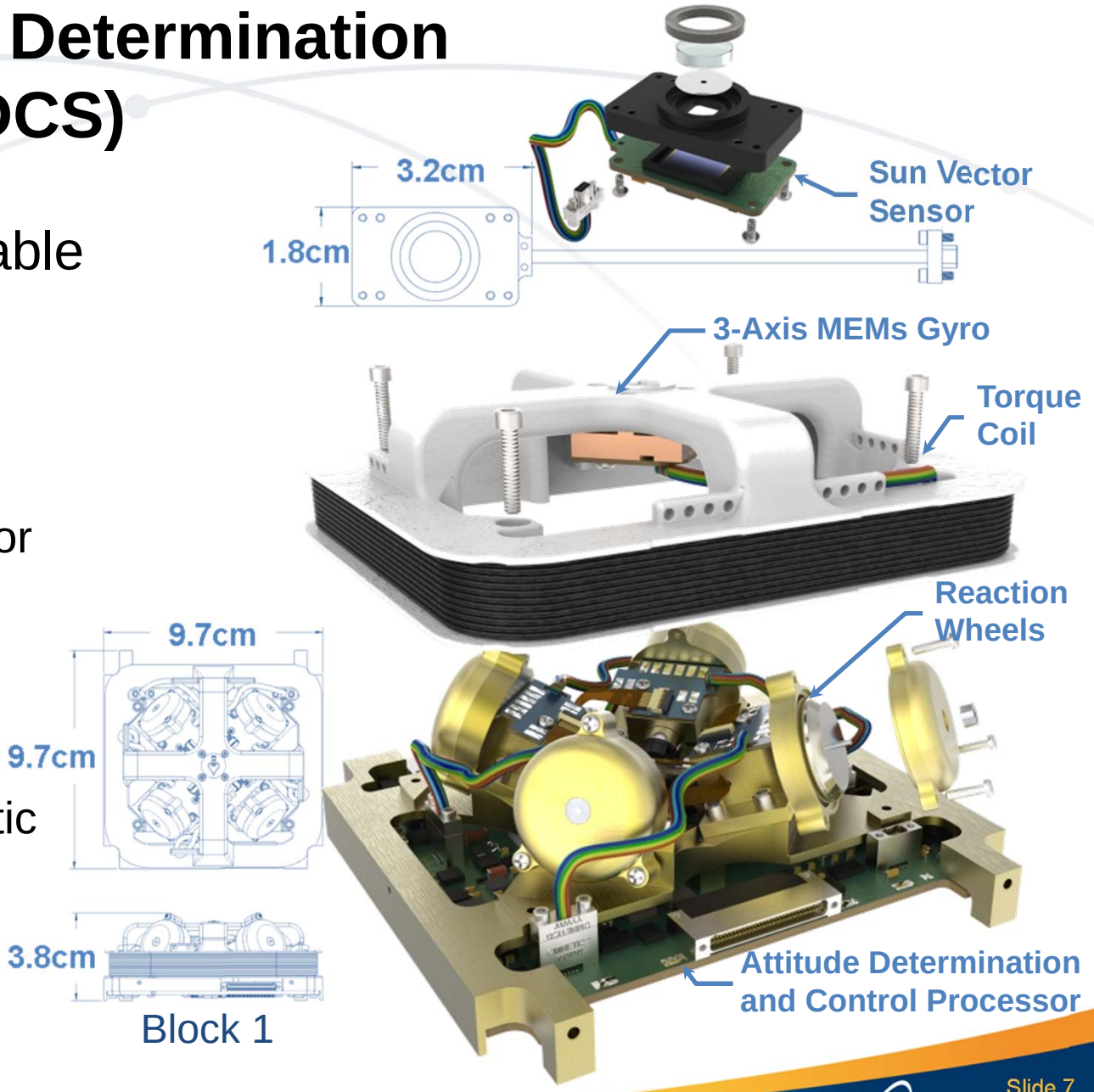
Block 1Attitude Determination and Control (ADCS)

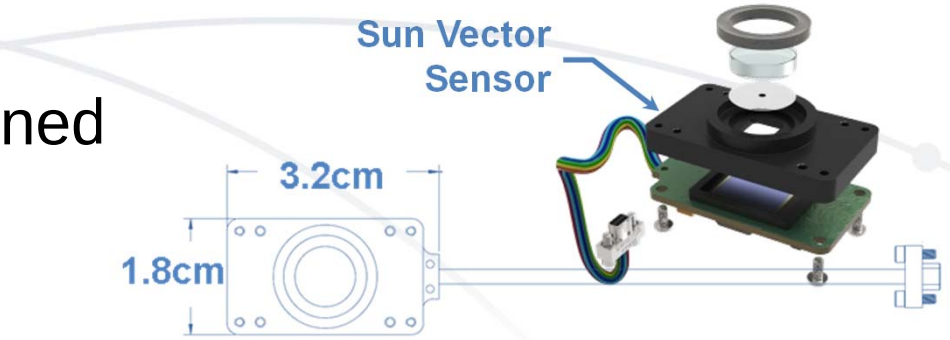
- Fully reprogrammable on orbit
- Sensors:
  - Sun vector
  - Magnetic field vector
  - 3-axis Gyro
- Actuators:
  - Momentum wheels
  - Low torque magnetic torquer coil

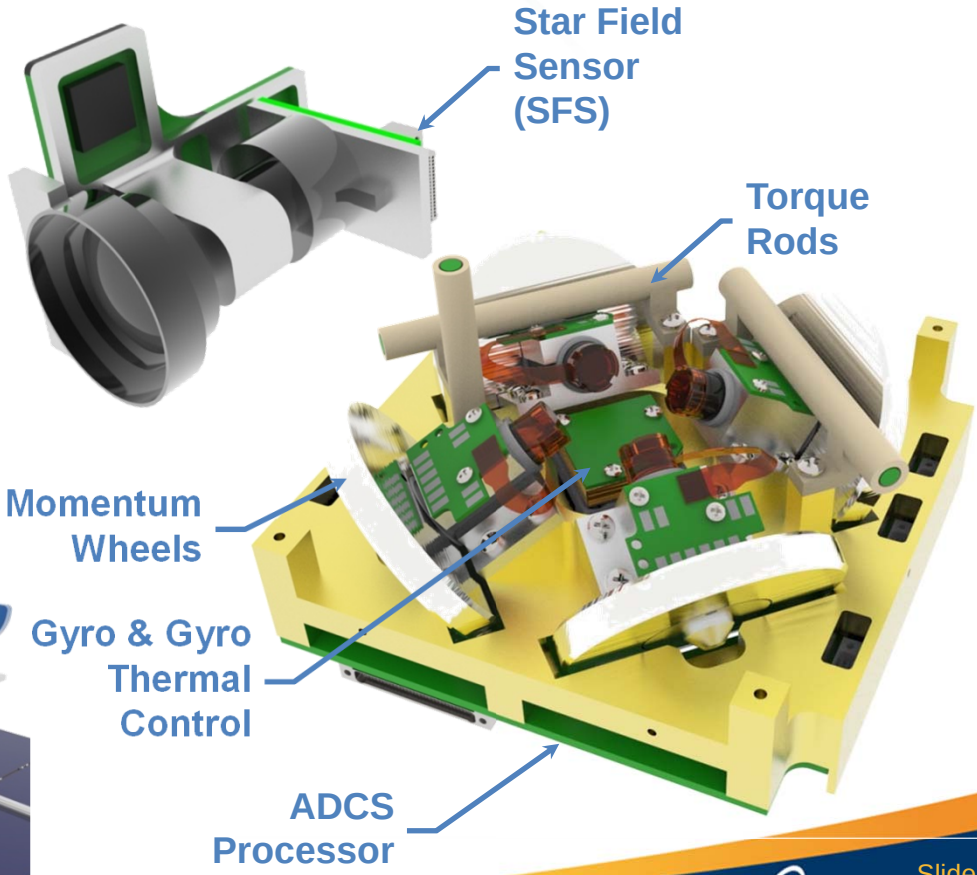


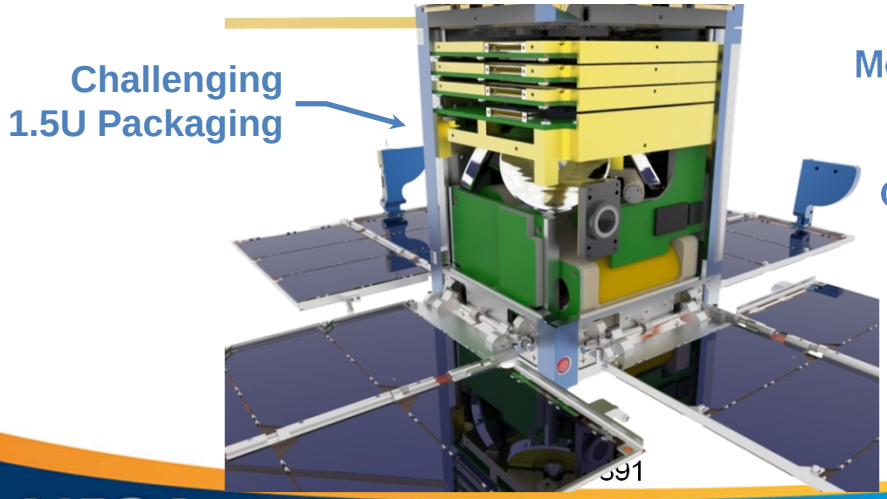
Block 1

Block 2 ADCS

- Improving from lessons learned on Block 1
  - Replacing single coil with 3 orthogonal torque rods
  - Increasing wheel momentum storage
  - Adding star field sensor (SFS)
  - Adding GPS receiver





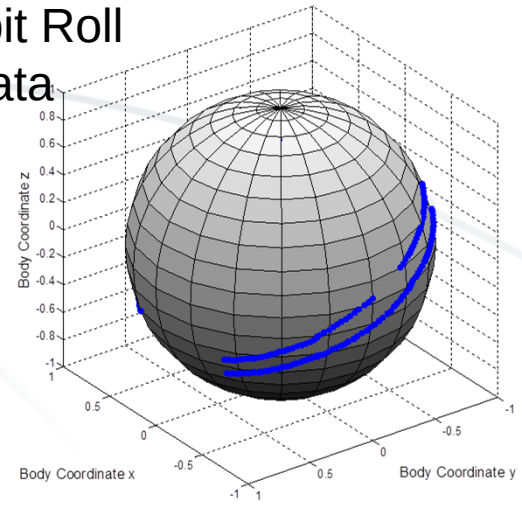


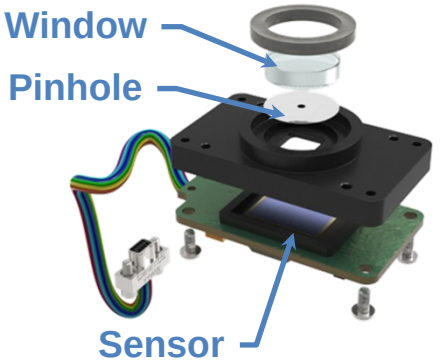
Block 1 Attitude Sensors

- Block 1 relies on magnetometer and a combination of a SVS and gyro to provide attitude knowledge

- Sun Vector Sensor (SVS)
  - Successfully demonstrated on Block 1
  - Adding an automated calibration to each unit for Block 2
- Magnetometer
  - Successfully demonstrated on Block 1
  - Re-using on Block 2 with no changes
- Gyro
  - Successfully demonstrated on Block 1
  - Zero rate bias and sensitivity versus temperature will be calibrated for Block 2

On-Orbit Roll SVS Data





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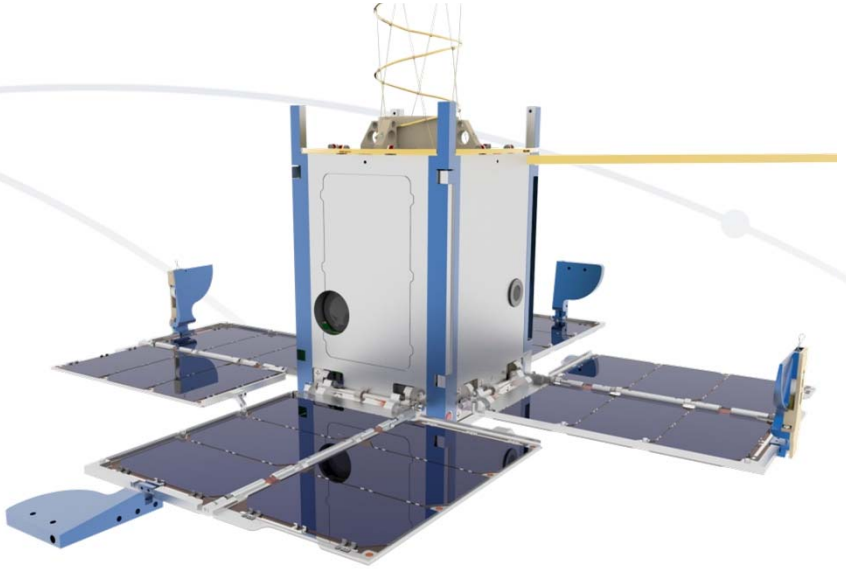
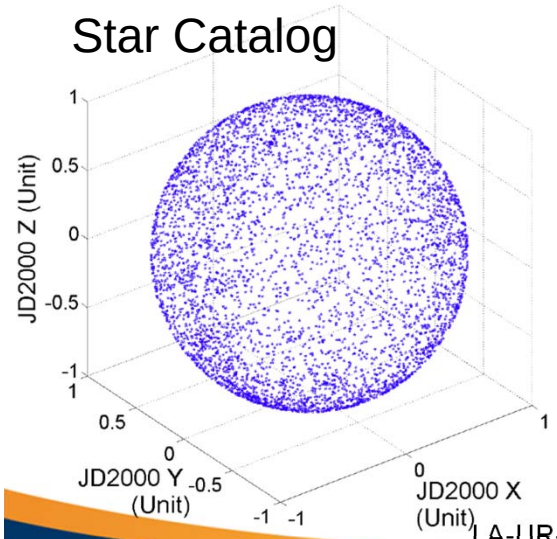
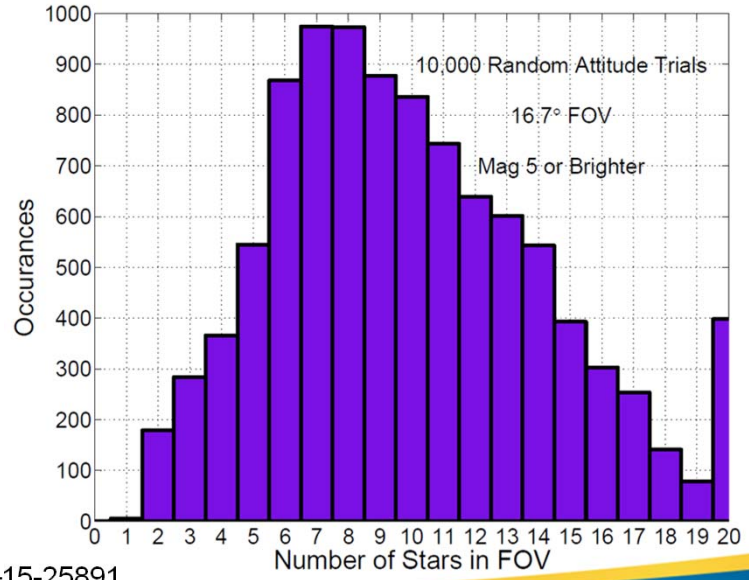
Star Field Sensor (SFS)

- Block 2 will maintain Block 1 sensors with the addition of an SFS
- Improve accuracy of overall attitude knowledge, especially in eclipse
  - Attitude determination of SFS <0.5°







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Momentum Wheels

- 4 kinematically redundant wheels in a pyramid configuration
  - Wheels can be stopped and started for power savings
  - A single wheel failure is tolerable
  - Torque distribution null-space exploited to prevent unnecessary wheel excursions

- Block 1 Momentum Wheels:
  - Conservative design in volume and robustness to launch loads
  - Momentum storage somewhat undersized (complicating the control algorithms)
  - Design not easily scaled to support wheels with higher inertia
- Block 2 Momentum Wheels:
  - Momentum storage has been increased
  - New design is more scalable to support future, larger, platforms

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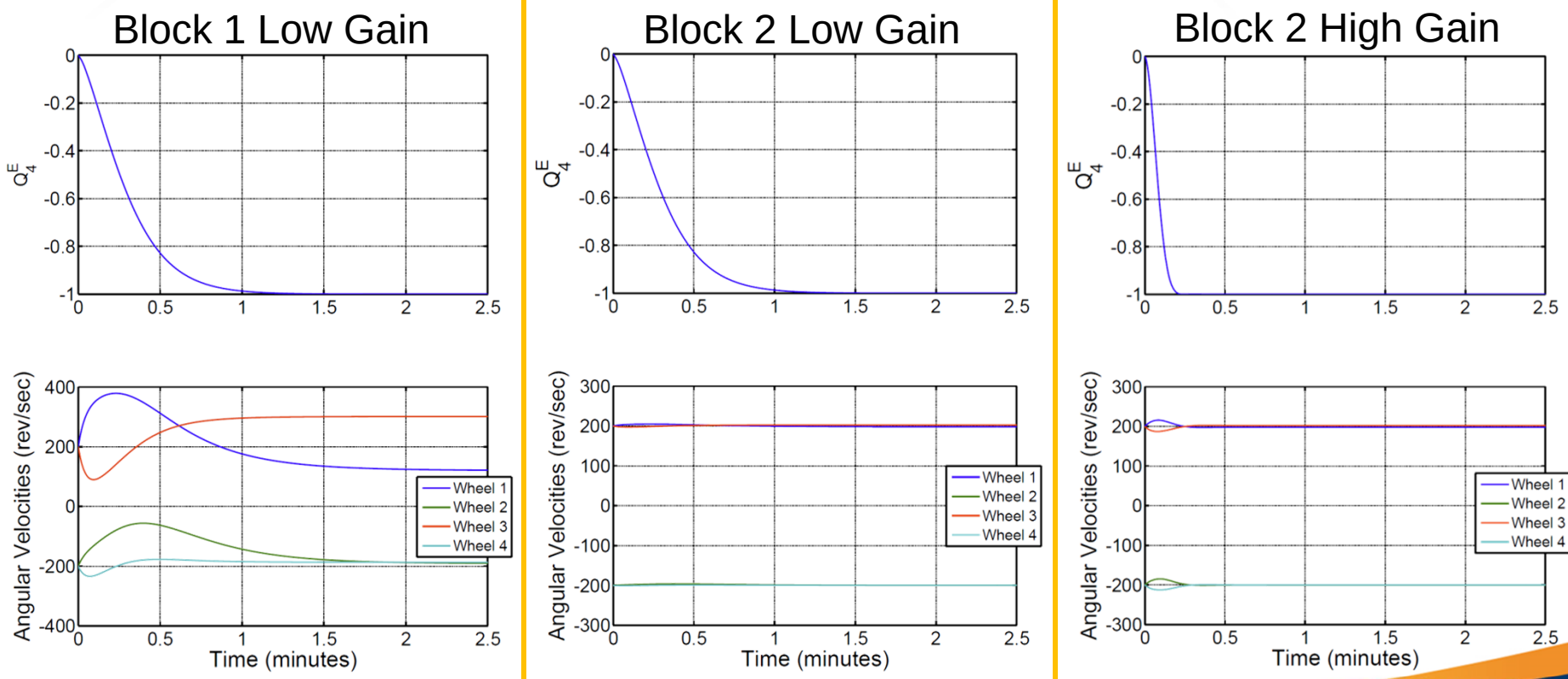
Momentum Wheels Simulations

- 180° Rotation Maneuver with a non-zero initial vehicle angular velocity
- Block 1 wheel assembly completes maneuver but with little margin on wheel angular velocity limits (50 to 380 rps)
- Block 2 completes maneuver easily and can utilize more of the motor torque to complete it 5x quicker



Magnetic Torquers

- Momentum management is performed with magnetic torquers
  - Dissipate angular momentum imparted to the SV during deployment and/or differential drag
- Block 1: Single torque coil
  - Limited torque due to lack of ferrous material
    - Momentum dumping would take significant time and energy
    - Risk to project should large momentum dump be required
  - Single axis limits momentum dumping about that axis
- Block 2: Three orthogonal torque rods
  - New design includes ferrous material enabling significantly greater torque for a given power
  - Better momentum dumping possible with three axis rods
  - A trade study was performed between two common methods of torque rod control

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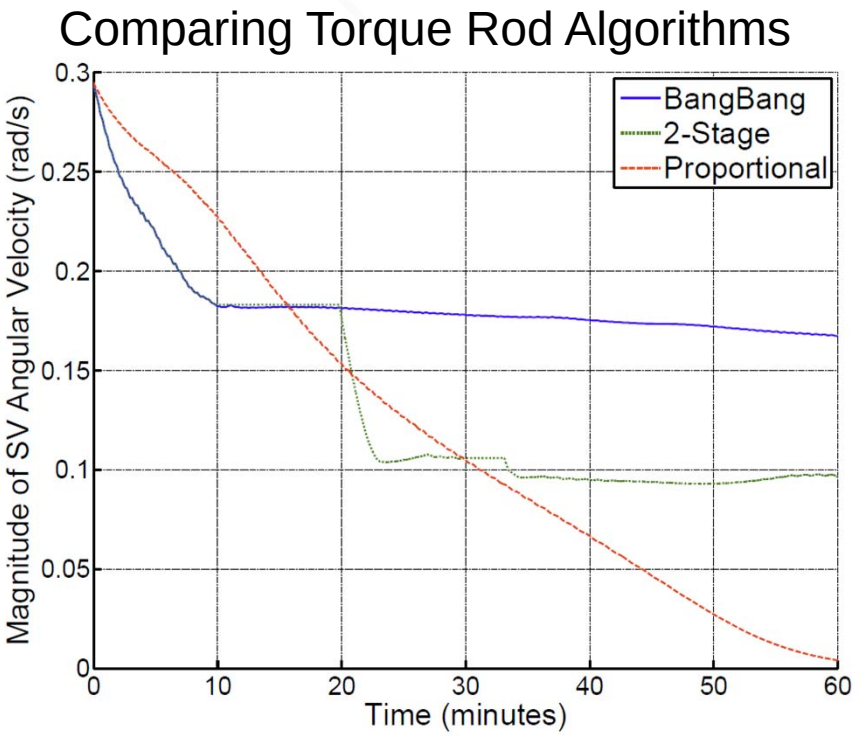
Magnetic Torque Rod Simulation

- B-dot controllers have been compared
- Bang-Bang
  - Residual angular velocity about the Earth's magnetic field vector remains
  - Not energy efficient
- Proportional
  - Significantly lower energy consumption
  - Cancels much more of the total angular velocity
  - Only slightly more complicated to implement
- Both algorithms benefit from being run multiple times with off periods, reducing momentum in stages



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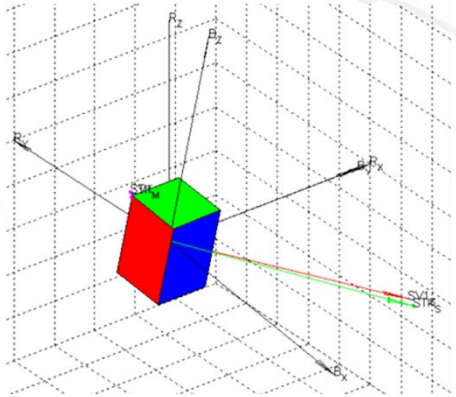
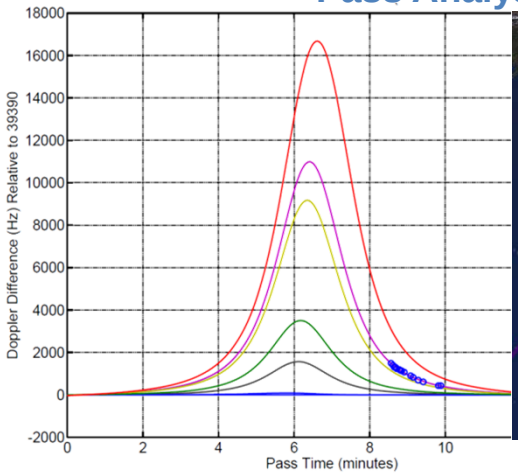
Satellite Navigation Library

- New capability and a new paradigm
  - Single software library for all system navigation needs
  - Library can be compiled for all processors within the system (both in space and on the ground)
  - Developed at LANL for Prometheus (GOTS) available/extensible for other missions
- Library:
  - Orbit propagation (Block 1) and determination (Block 2)
  - Reference vector (Sun & mag field) modeling and star field catalogs
  - Attitude determination and control (targeting)
    - Near-optimal eigenaxis rotation
  - Ground station (Doppler correction, antenna pointing)
- Physics/Mission simulation

Vehicle Attitude



Pass Analysis and Visualization



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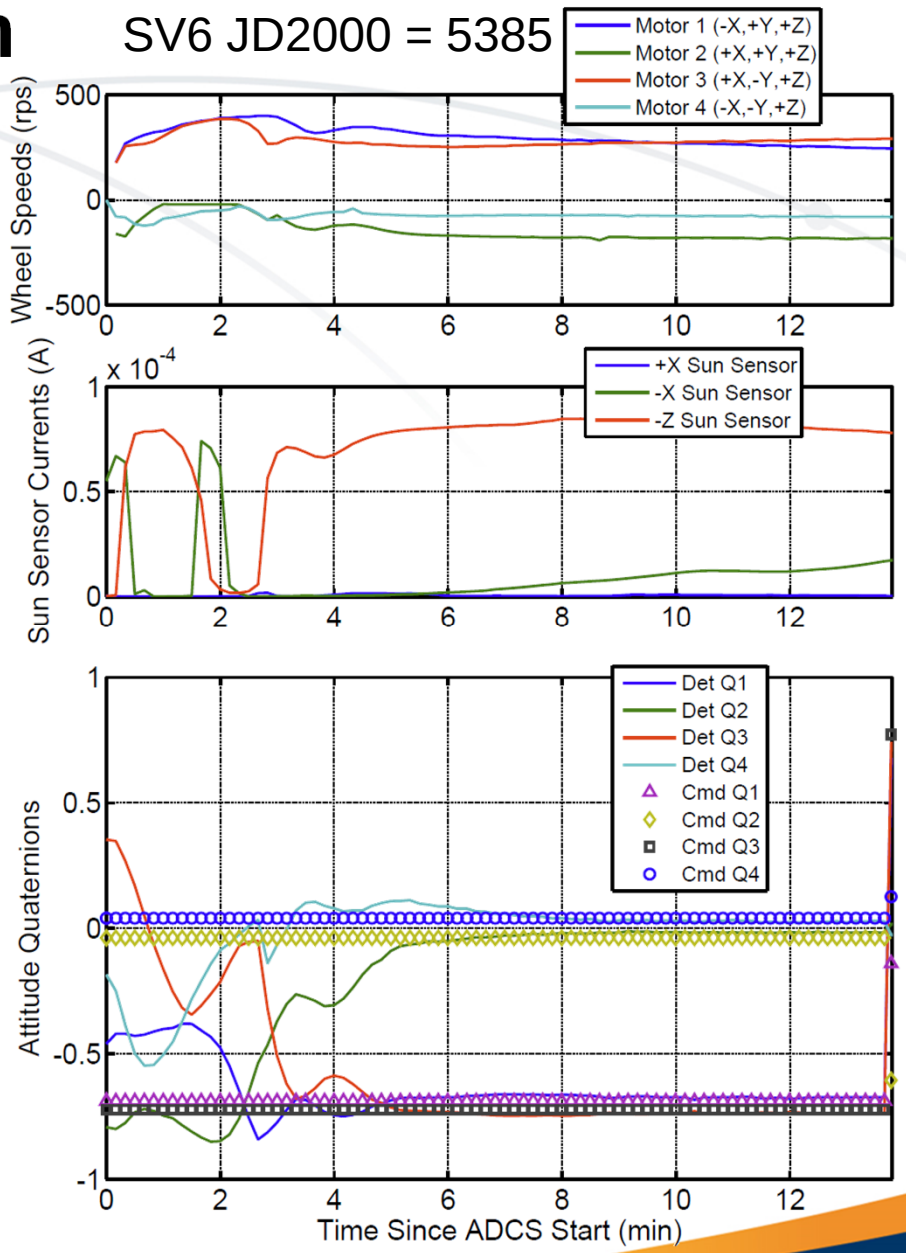
On-Orbit Large Orientation Change Example Test

- ADCS is turned on at time 0 min in plots to the right
- This is a high control loop gain test demonstrating functionality while highlighting areas of improvement moving from Block 1 to Block 2
  - At about 1 min, wheel #2 hits speed limit and torque is redistributed
  - Wheels 1 & 3 are at the high end of their velocity range and cannot supply all of the desired torque
  - The maneuver becomes non-optimal for about 1 min
- Between ~6 and ~14 min, vehicle holds solar panels normal to Sun
  - Only varying a few degrees
  - Note -Z (Sun facing) Sun sensor has high current
- At ~14 min, SV automatically begins a maneuver to a new orientation



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