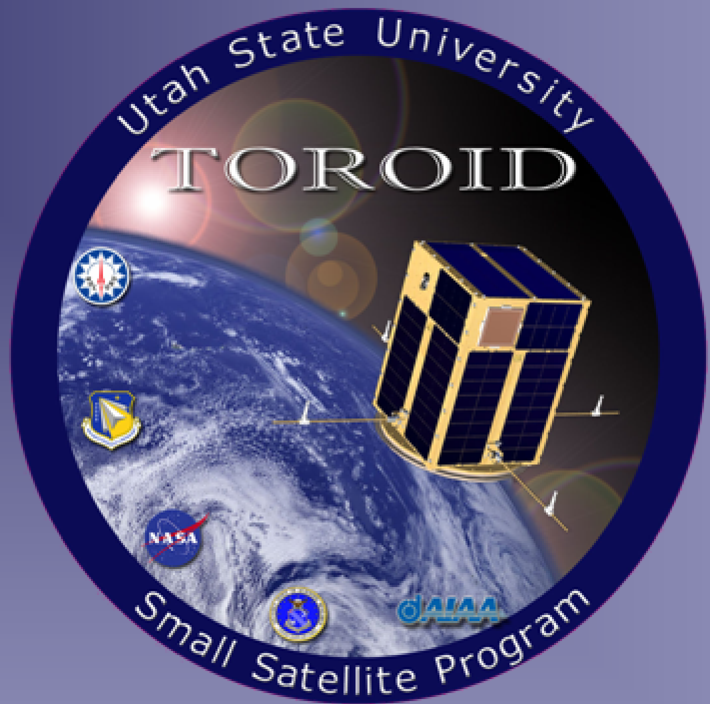
USUSat III - TOROID

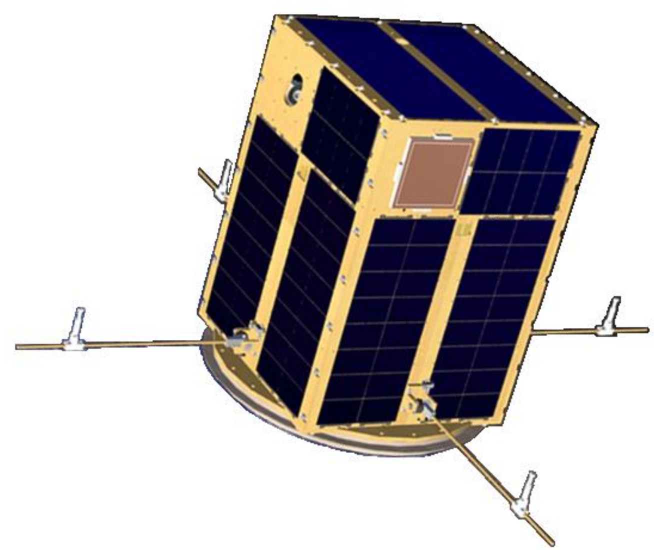
TOmographic Remote Observer of Ionospheric Disturbances



Attitude Determination and Control

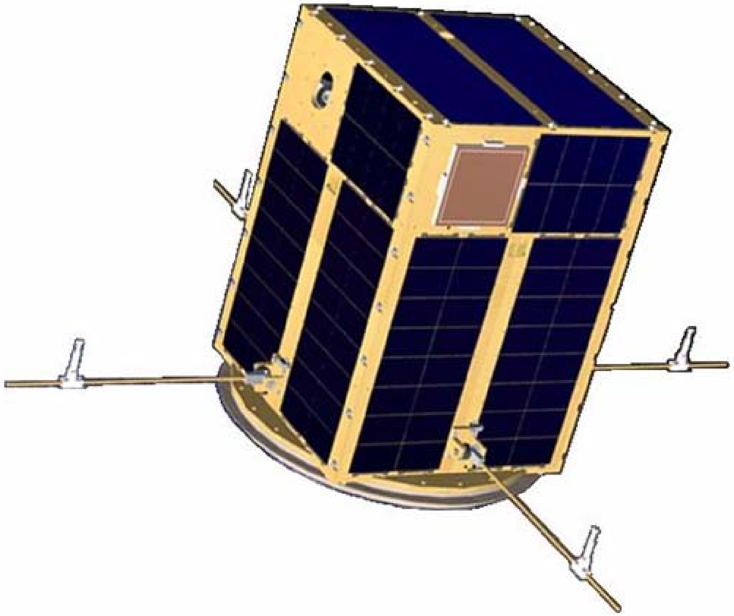
Attitude Determination and Control (ADC)

- Attitude
  - Orientation of the satellite relative to some reference frame (earth, stars, etc)
- Attitude Determination
  - Finding the current orientation of the spacecraft
- Attitude Control
  - Aligning the attitude of the satellite with a desired frame
- TOROID ADC Requirements
  - Without momentum bias: 10°
  - With Momentum bias: 1°



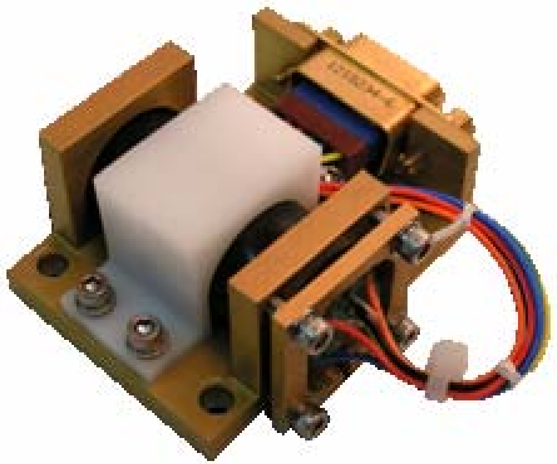
Attitude Determination and Control Overview

- Hardware and Restrictions
  - Attitude determination
    - Three-axis magnetometer
    - CMOS cameras
  - Attitude control
    - Torque coils
- ADC States
  - Detumble (2 phases)
  - Acquire attitude
  - Acquire control (with and without momentum bias)
- Linear Covariance Analysis



Hardware: Attitude Determination Overview

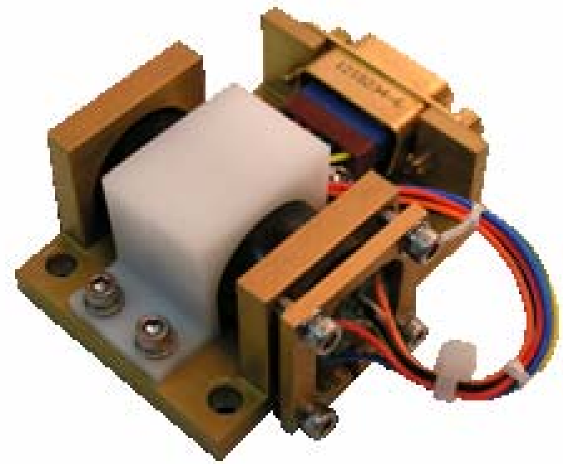
- Three-axis Magnetometer
  – Measures direction and magnitude of the local magnetic field vector
  – Will be the primary attitude determination hardware



- CMOS Cameras
  – Will be used to find the current sun vector and nadir vector
  – Will significantly increase the accuracy of the attitude estimate

Hardware: Attitude Determination Restrictions

- Three-Axis Magnetometer
  - Sensitive to interference from the rest of the satellite
  - Requires accurate estimate of the expected local magnetic field vector



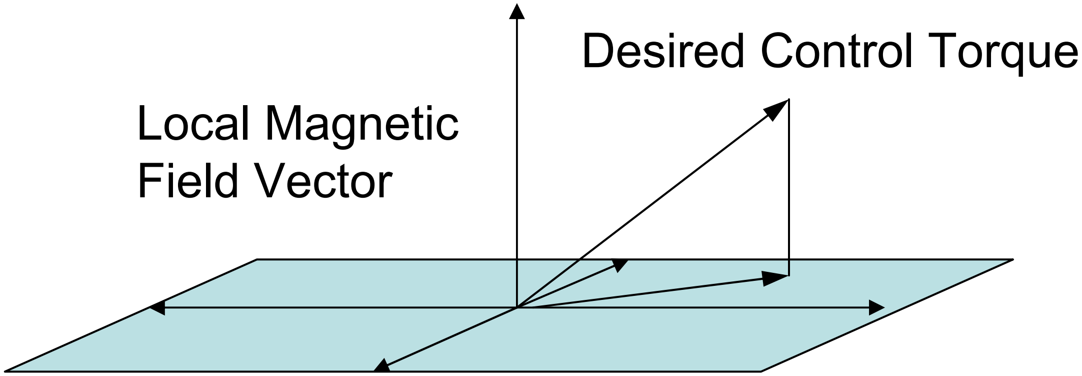
- CMOS Cameras
  - Only useful when the lighting conditions are good
  - Require image processing algorithms

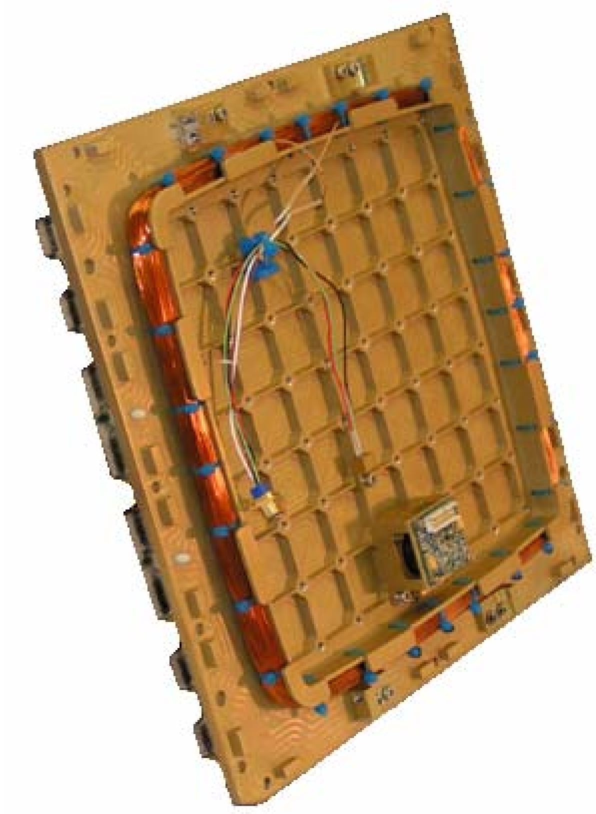
Hardware: Attitude Control Hardware and Restrictions

- Torque Coils
  - Rotate satellite using magnetic moments (like a compass pointing north)

$$\bar{T} = \bar{b}(t) \times \bar{M}$$

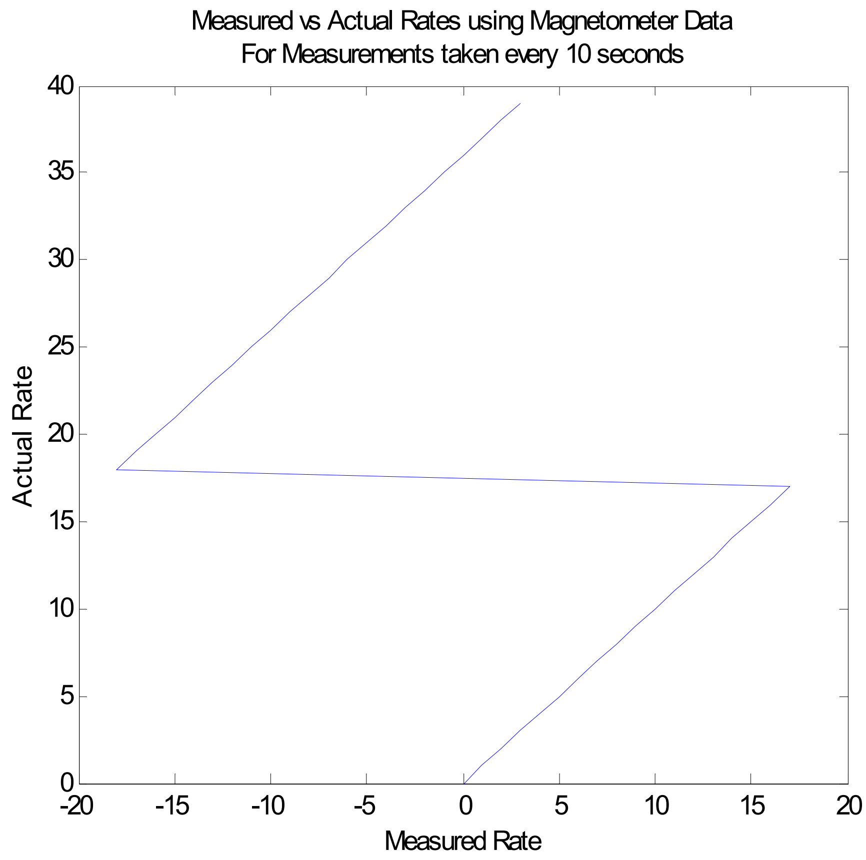
- Restrictions:
  - The torques that can be generated are, by definition, in the plane perpendicular to the local magnetic field vector
  - The desired torque usually is not!
  - System is only controllable over time





ADC States: Detumble-Phase 1

- Spacecraft Initial Rates Reduction
  - Rates over 180°/sec are impossible to estimate (given TAM measurements every 10 seconds)
  - Rate reduction by leaving the torque coils on (has same effect as a boom)
  - Example: Alsat 1



ADC States: Detumble-Phase 2

- Bdot: A Simple Algorithm for Rate Reduction
  - The desired control torque is proportional to rate of change of the magnetic field vector

$$\mathbf{T}_c = \mathbf{K}\dot{\mathbf{B}}$$

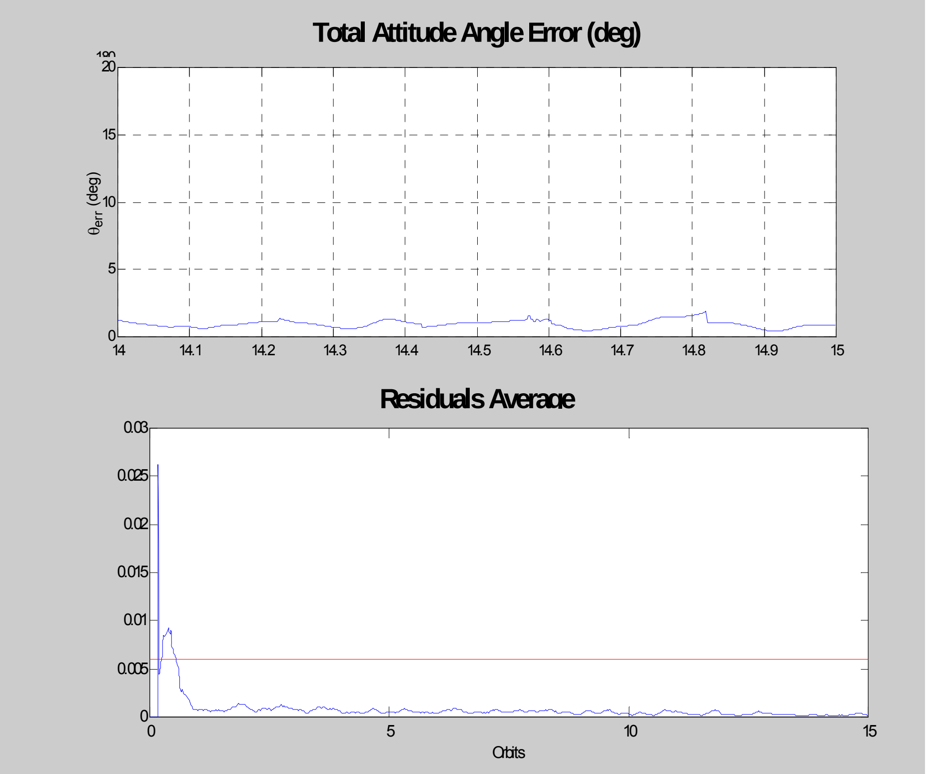
  - Guaranteed to reduce rates if a good estimate of the rate of change of the magnetic field vector is available
  - Does nothing to correct attitude errors

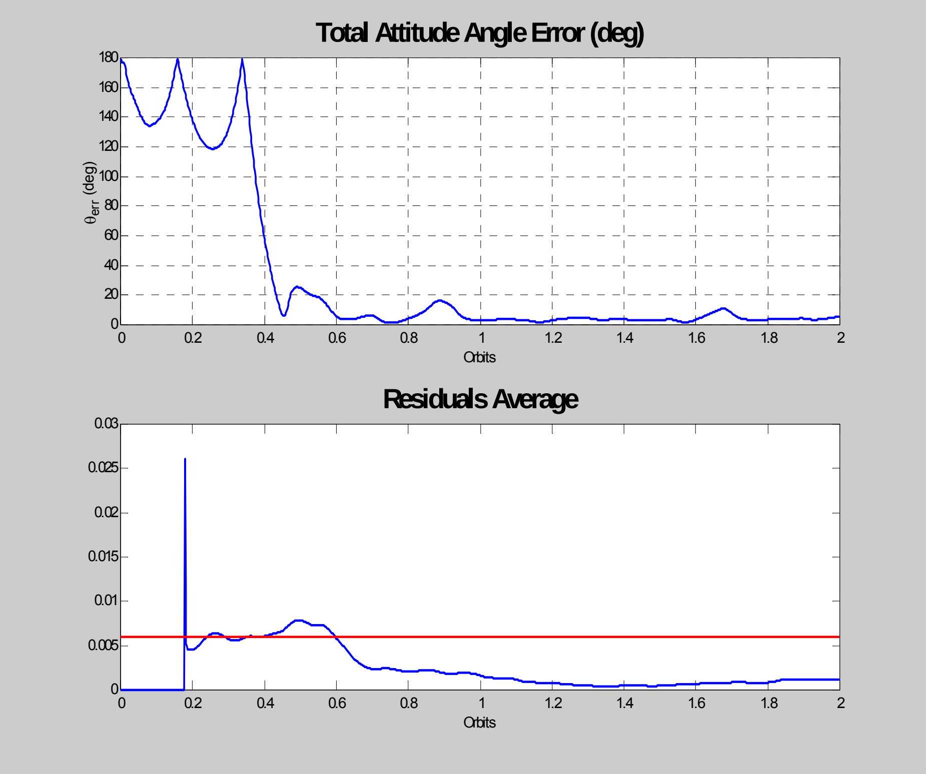
ADC States: Acquire Attitude

- Attitude Estimation: Adapted from ION-F
- State Estimation Kalman Filter
  - Estimates orientation, rates and disturbance torques
  - Expected error (using TAM only)
    - Attitude: 4.8° (3σ)
    - Rates: 0.018°/sec (3σ)
    - When sun and nadir vectors are available, attitude estimation error is less than 0.5°
- Calibration Kalman Filters
  - CF1: Estimates non-orthogonality, bias, and scale factor errors (temperature dependant)
  - CF2: Estimates TAM orientation error
  - CF1 and CF2 can be enable/disabled automatically or using commands from the ground

ADC States: Acquire Attitude

- Some Results: (Best) and (Worst) Case
  - Initial rates: (0 deg/s) and (1 deg/s)
  - Initial orientation: (0 deg) and (180 deg)





ADC States: Acquire Control (Controller Design)

- LQ Regulator (for T_c=control torques and B=measured magnetic field vector)
  - **x**=Euler angles

$$T_c = G(t)K\begin{bmatrix}\int \mathbf{x} \\ \mathbf{x} \\ \dot{\mathbf{x}}\end{bmatrix}$$

Where **K** is the controller Gain and

$$G(t) = \frac{-I^{-1}}{\|B\|}[B\times][B\times] = \frac{I^{-1}}{\|B\|}\begin{bmatrix} B_y^2 + B_z^2 & -B_x B_y & -B_x B_z \\ -B_x B_y & B_x^2 + B_z^2 & -B_y B_z \\ -B_x B_z & -B_y B_z & B_x^2 + B_y^2 \end{bmatrix}$$

ADC States: Acquire Control (Controller Design)

- Gain Selection

$$K = -R^{-1}\overline{G}^{T}P$$

$\overline{G}$ is the time average of G(t) over a single orbit
and P comes from the steady state solution to the Ricatti Equation:

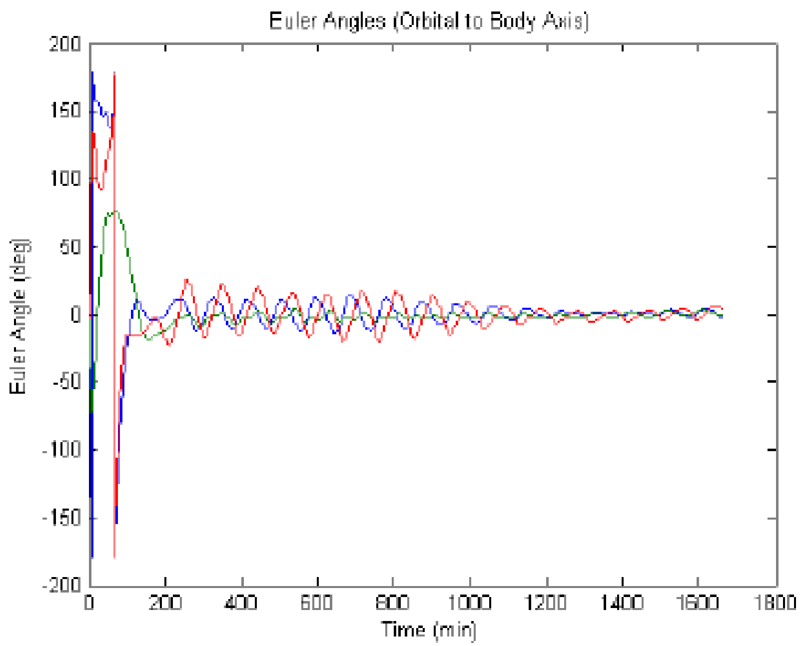
$$\dot{P} + PF + F^{T}P - P\overline{G}R^{-1}\overline{G}^{T}P + Q = 0$$

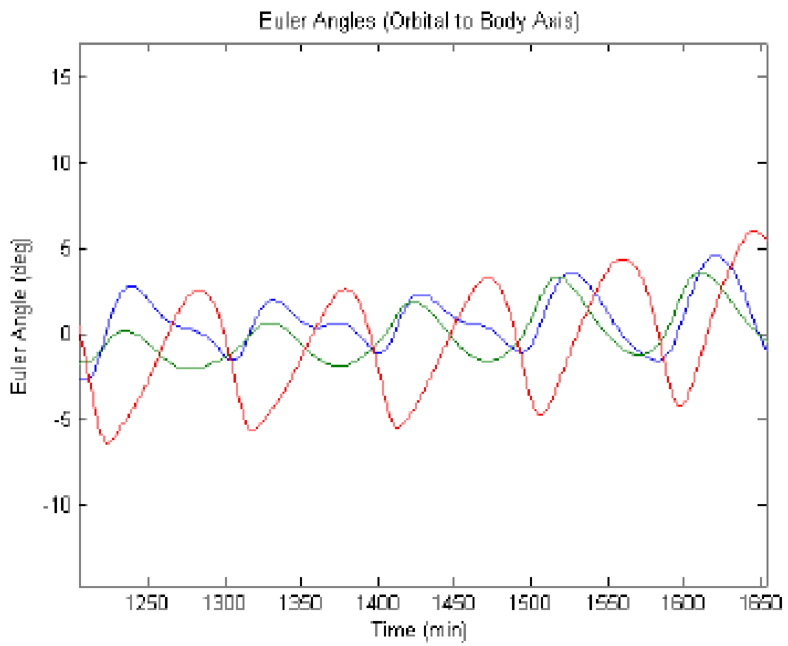
Q and R are chosen according to the desired response of the system.

Note: K is optimal, given Q and R; however, there is no method for finding the optimal Q and R

ADC States: Acquire Control (No Momentum bias)

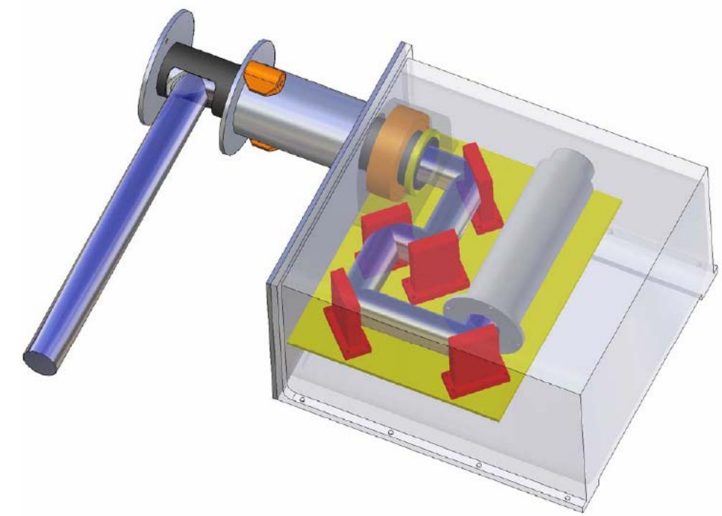
- Sample Results: Altitude=350 km and i=51°
  - Able to meet mission requirements even if the CMOS data (sun and nadir vectors) are not available

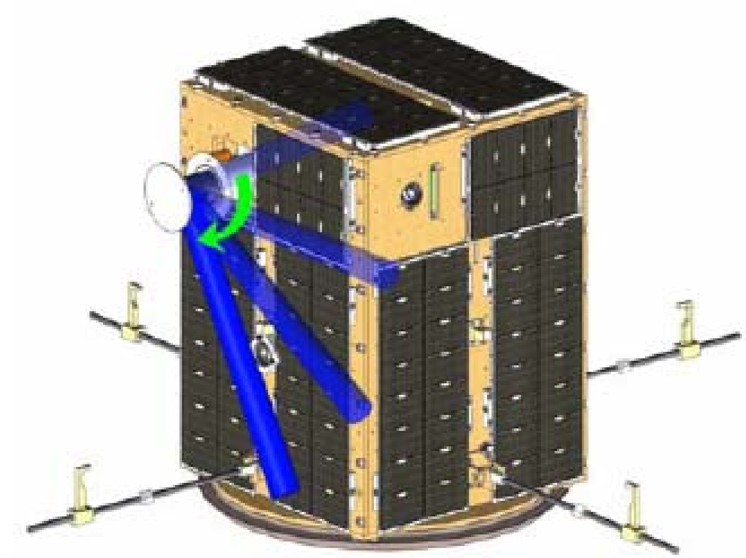




ADC States: Spinup

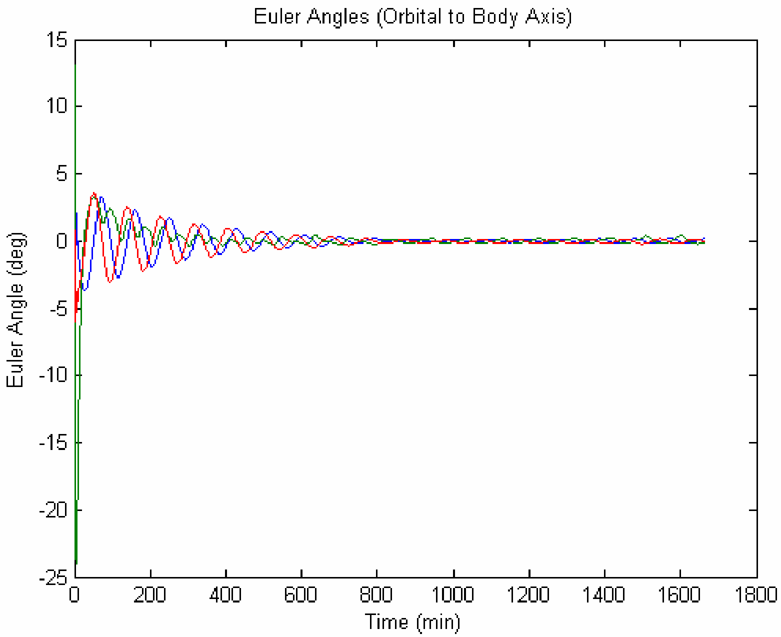
- As the Science Instrument Spins up:
  - The acceleration of the instrument causes the rest of the spacecraft to accelerate in the opposite direction about the y axis
  - The increase in total momentum adds helps stabilize the satellite about the x and z axes

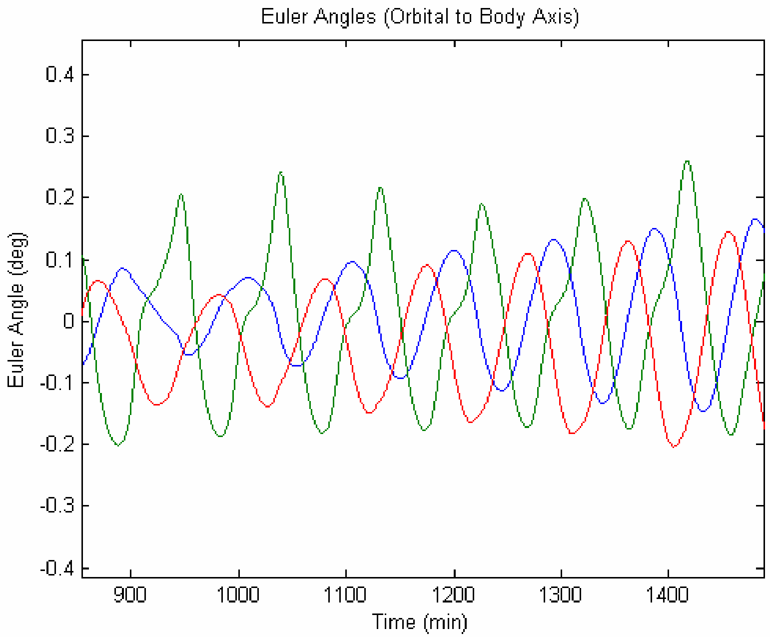




ADC States: Acquire Control (With Momentum bias)

- Sample Results: H_w = 0.05 Nms, a=350, i=51°
  - Meets science mission requirements assuming:
    - CMOS measurements are available
    - sufficient momentum bias.



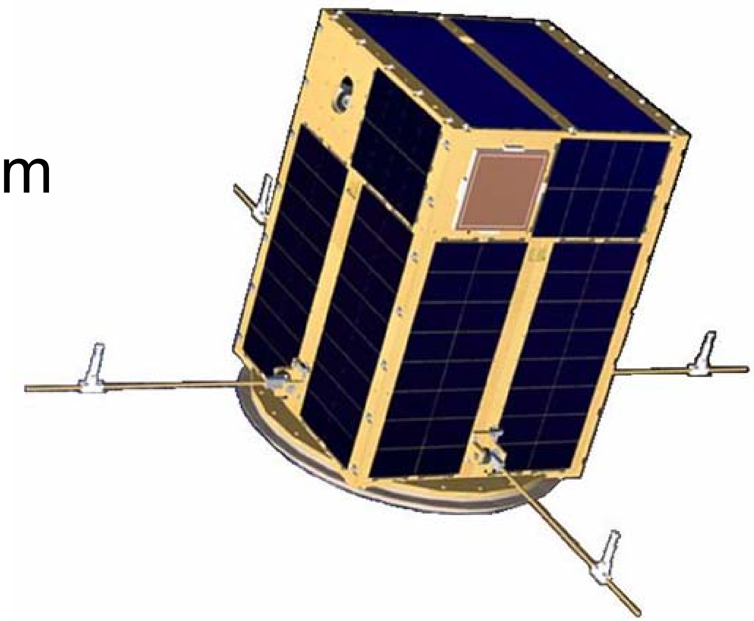


Linear Covariance Analysis

- Linear Covariance (Only for ADC with Momentum bias)
  - Nonlinear system can be described by a set of linear equations written as a stochastic process description (Maybeck 1978)
  - Allows a single simulation run to generate Monte Carlo-type information
  - Possible inputs to vary: science instrument misalignment, sensor biases, sensor noise, orbit parameters, TLE accuracy
  - Desired results: expected error and sensitivity to changes in inputs

ADCS States: General Notes

- Control is Robust:
  - High and low inclination controller gains are saved onboard
  - New gain (optimized for a particular orbit) can be sent from ground station
- Control not Optimal
- Achieving Science Mission Requirements
  - Only possible with CMOS measurements.
  - For the ION-F mission, these measurements are not available when we need them.



ADC: To Do and Future Work

- To Do for TOROID
  - Magnetic interference testing
  - Increase momentum from science instrument (increase speed or add mass)
  - Image processing
  - Final testing and analysis
- Future Work at USU
  - Attitude determination
    - Infrared horizon sensing
    - Star Tracking with CMOS cameras
  - Control
    - Time varying
    - Optimal