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)

- **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

\[ \vec{T} = \vec{b}(t) \times \vec{M} \]
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

\[ T_c = KB\dot{B} \]

- 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: $4.8^\circ$ (3σ)
    - Rates: $0.018^\circ$/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

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

Where $K$ is the controller Gain and

\[
G(t) = \frac{-I^{-1}}{\|B\|} \left[ B \times \left[ B \times \right] \right] = \frac{I^{-1}}{\|B\|} \begin{bmatrix}
B_y^2 + B_z^2 & -B_x B_y & -B_x B_z \\
-B_x B_y & B_x^2 + B_z^2 & -B_y B_z \\
-B_x B_z & -B_y B_z & B_x^2 + B_y^2
\end{bmatrix}
\]
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, $a=350$, $i=51^\circ$
  - 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