<table>
<thead>
<tr>
<th>Name</th>
<th>Class</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevin Lian</td>
<td>Junior</td>
<td>ADCS Lead</td>
</tr>
<tr>
<td>Spencer Burakowski</td>
<td>Senior</td>
<td>Damping Investigation</td>
</tr>
<tr>
<td>Graham Wing</td>
<td>Sophomore</td>
<td>Control Law (Ops)</td>
</tr>
</tbody>
</table>
Agenda

1. Requirements
2. Overview
3. RFAs
4. Concerns
Requirements

• 12 Requirements
  • 9 Verified
  • 1 Pending
  • 2 Waived
<table>
<thead>
<tr>
<th>ID</th>
<th>Requirement</th>
<th>Verification Method</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADCS-01</td>
<td>The ADC subsystem shall be capable of producing and maintaining a spin rate between 10 and 30 rpm to within ±2 rpm</td>
<td>Spin Test at Aerospace Corporation</td>
<td>Verified</td>
</tr>
<tr>
<td>ADCS-02</td>
<td>The ADC subsystem shall be capable of ±5 degrees of attitude control within target orientation</td>
<td>Matlab/Simulink</td>
<td>Verified</td>
</tr>
<tr>
<td>ADCS-03</td>
<td>The ADC subsystem shall be capable of ±3 degrees of attitude knowledge</td>
<td>Matlab/Simulink/IDL</td>
<td>Verified</td>
</tr>
<tr>
<td>ADCS-05</td>
<td>The integration time of all ADCS sensors shall be sufficiently small so that they are capable of operating while the spacecraft is spinning at rate of up to 30 rpm</td>
<td>Spin Test</td>
<td>Verified</td>
</tr>
<tr>
<td>ADCS-06</td>
<td>The ADC subsystem shall have at least two separate sensors capable of being processed onboard for maneuvers</td>
<td>By design</td>
<td>Waived</td>
</tr>
<tr>
<td>ADCS-10</td>
<td>The ADC subsystem shall not exceed the mass allocated by Systems</td>
<td>Weighed each part</td>
<td>Verified</td>
</tr>
<tr>
<td>ID</td>
<td>Requirement</td>
<td>Verification Method</td>
<td>Verified</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------------------------------------------------------------</td>
<td>--------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>ADCS-11</td>
<td>The ADC subsystem shall not exceed the power allocated in the ELFIN system power budget</td>
<td>Power Budget Documentation</td>
<td>Verified</td>
</tr>
<tr>
<td>ADCS-12</td>
<td>The ADC subsystem shall not exceed the data allocated in the ELFIN system data budget</td>
<td>Data Budget Documentation</td>
<td>Pending</td>
</tr>
<tr>
<td>ADCS-13</td>
<td>The ADC subsystem shall not exceed the pointing error allocated in the ELFIN system pointing error budget</td>
<td>Simulation</td>
<td>Verified</td>
</tr>
<tr>
<td>ADCS-14</td>
<td>The ADC subsystem shall be designed for a 6 month lifetime</td>
<td>Flight Heritage and TVAC tests</td>
<td>Verified</td>
</tr>
<tr>
<td>ADCS-15</td>
<td>The ADC subsystem shall be designed to operate at a dose of 5 krad/yr or greater</td>
<td>Flight heritage</td>
<td>Verified</td>
</tr>
<tr>
<td>ADCS-16</td>
<td>The ADC subsystem shall be SEU tolerant</td>
<td>Flight heritage</td>
<td>Waived</td>
</tr>
</tbody>
</table>
Hardware Overview

- **ACB**
  - Attitude Control Board
  - PIC 24 + PIC 18

- **Torquer Coils**
  - Two orthogonally placed coils
  - Chosen for magnetic cleanliness and power efficiency

- **MRMs (MagnetoResistive Magnetometer)**
  - Honeywell HMC5883L 3-Axis Digital Compass
  - For in-flight attitude control and attitude determination

- **FGM**
  - In house 3 axis fluxgate magnetometer
  - Data is used for science and for ground attitude determination
Flight Magnetorquers

- 28 AWG High Tension Copper Clad Aluminum (HTCCA) enameled with polysol-180 triple layer
- DM Torquer coils have been in 60 degree cycles for 1341 cycles.
- Survived 3 vibe tests at GEVS Qual
- 1 vibe test at Delta II Proto
- 2 vibes, 2 shocks at Delta II Qual

<table>
<thead>
<tr>
<th>Desired</th>
<th>FM A</th>
<th>FM B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y Coil</td>
<td>Z Coil</td>
<td>Y Coil</td>
</tr>
<tr>
<td>Total Mass</td>
<td>77 g</td>
<td>86 g</td>
</tr>
<tr>
<td>Turns</td>
<td>190 turns</td>
<td>246 turns</td>
</tr>
<tr>
<td>Power</td>
<td>0.55 W</td>
<td>0.49 W</td>
</tr>
<tr>
<td>Dipole</td>
<td>0.49 A m$^2$</td>
<td>0.47 A m$^2$</td>
</tr>
<tr>
<td>Torque*</td>
<td>17 µN m</td>
<td>16 µN m</td>
</tr>
</tbody>
</table>

*Assuming 35,000 nT B field
• ADCS Main (PIC24) connects to:
  • ADCS Peripheral Controller
    • UART connection with interrupt capabilities
  • Two sets of flash memory (AT45) via SPI
  • Two torquer coils
    • Via H-Bridges
  • Torquer current sensor
    • Analog connection to ADCS Main
• ADCS Peripheral Controller connects to sensors (I2C)
  • Onboard MRM, off-board MRM, and 4 thermistors

Unchanged since CDR
Software Overview

• ADCS
  • Attitude Determination
    • IDL/MatLab/Simulink
  • Control Law Simulations
    • MatLab/Simulink
  • Maneuver Planning
    • MatLab/Simulink
  • ACB Control Law
    • Microcontroller C
• Work with OPs
  • Orbit Determination
    • STK
  • Scheduling, Command & Control
    • Python, pyQT

Unchanged since CDR
Simulation Overview

- Borrowed from DANDE mission
  - Spin Stabilized
  - Spin vector normal to orbit plane

1. Initial orbit and attitude conditions + rigid body dynamics model
2. Propagating orbit and attitude while modelling Earth B field
3. Calculates controller filtered Bdot that and B-field relative to ELFIN
4. Control law block produces dipole vector
5. Dipole vector is converted into torque
IDL Overview

- Takes in orbital position, magnetic fields reading on ELFIN (Spinning Body Frame), magnetic fields at that location (ECI coordinates), and time.
- Outputs its best estimate at the current attitude vector.

Attitude vector in GEI coordinate: 0.68288516 -0.30198914 -0.66518450
Uncertainty in the attitude elevation angle (deg): 1.8893026
Difference between Attitude Vectors: 1.5627713
Control Laws

• BDot – Torques with a configurable duty cycle between zero crossings of derivative
  • Pros
    • Immune to offsets from torquer coils
    • Gives angular velocity
  • Cons
    • Cannot be used below 5.5 RPM due to limitations from FIR filter

• BAct – Torques when magnetic field in the X direction is greater than the Y and the Z directions.
  • Pros
    • Useful at low RPMs
    • Less vulnerable to noise
    • No phase delay
  • Cons
    • Need to zero out ambient offsets by communicating with the ground
Spin Test at Aerospace Corporation

• Setup
  • Helmholtz Coils to enhance magnetic fields
  • Air-bearing for low friction
  • Interface plate to ensure rotation around center of mass

• Primary Test Objectives
  • Verify that $B_{\text{dot}}$ and $B_{\text{Act}}$ work
  • Verify that ELFIN can calculate its own RPM when there is no torque from coils
  • Determine the faster control algorithm for spinning up ELFIN at given initial RPMs
• The ADC subsystem shall be capable of producing and maintaining a spin rate between 10 and 30 rpm to within ±2 rpm

• Through the Spin Test at Aerospace Corporation, we verified that our Bdot algorithm worked from 5.5 RPM to 35 RPM. BAct is also able to work from 30 RPM to at least 3 RPM. We have also tested to ensure that BAct works at 0 RPM.
The ADC subsystem shall be capable of producing and maintaining a spin rate between 10 and 30 rpm to within ±2 rpm.

Through simulations, we are also confident that we can maintain a spin rate of within ±2 rpm.
• The ADC subsystem shall be capable of ±5 degrees of attitude control within target orientation

• This has been verified through Matlab/Simulink Sims. We ran upwards of 100 sims and they have all resolved to <1 degree difference between attitude vector and target vector.
The ADC subsystem shall be capable of ±3 degrees of attitude knowledge

- Imitated telemetry data from Matlab/Simulink
- IDL algorithm estimates an attitude vector
- Attitude vector changes ~1 degree every orbit
The integration time of all ADCS sensors shall be sufficiently small so that they are capable of operating while the spacecraft is spinning at rate of up to 30 rpm

When in Fast Data Mode, PC dictates timing at 112.5 Hz

- ACB receives short (1 MRM) packets at ½ decimation
  - Uses: spin routines and attitude determination
- Full packets (2 MRMs, 4 TMPs): ¼ decimation
  - Use: low-rate telemetry, comparing both MRMs, reading solar panel temperatures

56.25 Hz nominal collection rate
- Selected in part due to convenience
  - 1/2 * PC timer frequency
- 66% margin from max collection limit (93 Hz)
  - Limiting factor: PC polling
- Can be decimated further on ACB, as needed

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC Timer Frequency</td>
<td>112.5 Hz</td>
</tr>
<tr>
<td>PC Polling Frequency: Small packets, nominal</td>
<td>56.25 Hz</td>
</tr>
<tr>
<td>PC Polling Frequency: Large packets, nominal</td>
<td>28.125 Hz</td>
</tr>
<tr>
<td>PC Polling Frequency: Small packets, maximum</td>
<td>93 Hz</td>
</tr>
<tr>
<td>ACB max storage frequency</td>
<td>≥ 93 Hz</td>
</tr>
</tbody>
</table>

Verification: Spin tests at Aerospace Corporation, benchtop software/spin testing
The ADC subsystem shall not exceed the data allocated in the ELFIN system data budget.

<table>
<thead>
<tr>
<th>Minutes of Data</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>±2.5 Degrees Error</td>
</tr>
<tr>
<td>12</td>
<td>±3 Degrees Error</td>
</tr>
<tr>
<td>10</td>
<td>±4 Degrees Error</td>
</tr>
<tr>
<td>6</td>
<td>±4 Degrees Error</td>
</tr>
</tbody>
</table>
• The ADC subsystem shall not exceed the pointing error allocated in the ELFIN system pointing error budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Estimated Degrees Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRM's</td>
<td>&lt; 1 Degree</td>
</tr>
<tr>
<td>Fluxgate Magnetometer</td>
<td>&lt; 1 Degree</td>
</tr>
<tr>
<td>IDL Software</td>
<td>&lt; 1 Degree</td>
</tr>
</tbody>
</table>

• To compensate for these, we have added 200 nT of noise to the sim to account for the error we will see.
Lessons Learned

• 13 RFAs
  • 0 Closed
  • 12 Resolved
  • 1 In-Progress
  • 0 Rejected
## RFAs from CDR

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1599</td>
<td>Generate a “day in the life” simulation</td>
<td>Resolved</td>
</tr>
<tr>
<td>1545</td>
<td>Define control law topology</td>
<td>Resolved</td>
</tr>
<tr>
<td>1543</td>
<td>Damping</td>
<td>Resolved</td>
</tr>
<tr>
<td>1504</td>
<td>Create an ADCS commissioning plan</td>
<td>In Progress</td>
</tr>
<tr>
<td>175</td>
<td>Attitude Determination</td>
<td>Resolved</td>
</tr>
<tr>
<td>1600</td>
<td>Self-induced noise from coils</td>
<td>Resolved</td>
</tr>
<tr>
<td>1553</td>
<td>In-flight requirement for pointing error</td>
<td>Resolved</td>
</tr>
<tr>
<td>1502</td>
<td>Control Laws should be consistent between ACB and Matlab</td>
<td>Resolved</td>
</tr>
<tr>
<td>1501</td>
<td>Perform day in the life testing</td>
<td>Resolved</td>
</tr>
<tr>
<td>1500</td>
<td>Rephrase attitude requirements to be consistent with a spinner</td>
<td>Resolved</td>
</tr>
<tr>
<td>ID</td>
<td>Description</td>
<td>Status</td>
</tr>
<tr>
<td>-----</td>
<td>-------------------------------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>1499</td>
<td>Refine on board spin phase knowledge requirement</td>
<td>Resolved</td>
</tr>
<tr>
<td>1497</td>
<td>Simulate a variety of orbits</td>
<td>Resolved</td>
</tr>
<tr>
<td>177</td>
<td>Pointing Error Budget</td>
<td>Resolved</td>
</tr>
</tbody>
</table>
RFA #1543: Damping

- From hardware bench test (force on the stacer), oscillatory movement will decay in less than five seconds
  - Heavily damped stacer
- Not worried about nutation

RFA #1600: Self-Induced Noise from coil due to unregulated power

- Measured noise in hardware in a magnetically clean environment
- Saw a noise value of about 100 nT
  - We put in noise values of 150 nT
RFA #1504: Create an ADCS commissioning plan
  • Ensure MRMs and torquer coils are working by collecting data and performing small maneuvers.
  • Will be done incrementally to check for errors along the way

RFA #1502: Simulations should use same control law that is used onboard
  • Simulations match the control law used on board
  • Only difference is the hysteresis limiter we use but that is configurable in flight
    • Due to large noise estimates
Unverified Failures

- The ADC subsystem shall have at least two separate sensors capable of being processed onboard for maneuvers

<table>
<thead>
<tr>
<th>Issue</th>
<th>Description</th>
<th>Possible causes</th>
<th>Risk Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cannot read MRM data from IDPU</td>
<td>FMB After final integration cannot read data from MRM on the IDPU. This issue was first noticed after FMB underwent full vibration testing at Cal Poly.</td>
<td>1) Harnessing. There is a flat flexible cable on the avionics stack that is solely used for the transfer of MRM data from LETC1 to ACB. The individual boards (ACB, LETC1) were checked out, so they could not be the issue. 2) Soldering on MRM. The MRM on IDPU is an ACME installed part, and we have had issues with improper handiwork before</td>
<td>Medium: MRM on IDPU was backup for ACB MRM. We have grown comfortable with just this MRM. However, if the ACB MRM fails, ELFIN can no longer maintain spin.</td>
</tr>
</tbody>
</table>
Differential Drag

- Two ELFINs!
  - Measure temporal data

- Need to get a separation between the two spacecrafts.

<table>
<thead>
<tr>
<th>ELFIN A</th>
<th>ELFIN B</th>
<th>Delta V After 1 month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passively ram points after 21 days</td>
<td>Spinning orbit normal</td>
<td>2.379 m/s</td>
</tr>
<tr>
<td>Passively ram points after 21 days</td>
<td>Spin vector tangent to velocity</td>
<td>4.39 m/s</td>
</tr>
<tr>
<td><strong>Passively ram points after more than 1 month</strong></td>
<td><strong>Spin vector tangent to velocity</strong></td>
<td><strong>2.358 m/s</strong></td>
</tr>
<tr>
<td>Actively ram points after 5 days</td>
<td>Spinning orbit normal</td>
<td>2.7 m/s</td>
</tr>
</tbody>
</table>
Questions?
Backup slides

• Backup slides go here!
Exploded View

- Instruments Stack
- EPD-I
- EPD-E
- PRM
- Stacer
- Batteries
- Avionics
- He-82
- FGM
- UHF
- VHF
• The ADC subsystem shall have at least two separate sensors capable of being processed onboard for maneuvers

• Two magnetometers (HMC 5883L) used for control laws
  • One located on ACB
  • One located on IDPU

• Only one MRM used at a time
  • Two used for redundancy

• FM B cannot read from its IDPU MRM
• The ADC subsystem shall not exceed the mass allocated by Systems

• ADCS is allocated 204 grams.

<table>
<thead>
<tr>
<th></th>
<th>FM A</th>
<th>FM B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z Coil</td>
<td>86 g</td>
<td>84 g</td>
</tr>
<tr>
<td>Y Coil</td>
<td>74.65 g</td>
<td>74.11 g</td>
</tr>
<tr>
<td>ACB</td>
<td>18.7 g</td>
<td>18.7 g</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>179.35 g</td>
<td>176.81 g</td>
</tr>
</tbody>
</table>
• The ADC subsystem shall not exceed the power allocated in the ELFIN system power budget

<table>
<thead>
<tr>
<th>ADCS</th>
<th>$\beta = 0$</th>
<th></th>
<th>$\beta = 15$</th>
<th></th>
<th>$\beta = 30$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time on per Orbit</td>
<td>Estimate W/Orbit</td>
<td>Allocated W/Orbit</td>
<td>Time on per Orbit</td>
<td>Estimate W/Orbit</td>
<td>Allocated W/Orbit</td>
</tr>
<tr>
<td>Board</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active</td>
<td>2.33</td>
<td>0.006</td>
<td>0.007</td>
<td>3.75</td>
<td>0.010</td>
<td>0.001</td>
</tr>
<tr>
<td>Board</td>
<td>94.67</td>
<td>0.188</td>
<td>0.195</td>
<td>93.25</td>
<td>0.185</td>
<td>0.009</td>
</tr>
<tr>
<td>Idle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y Torque</td>
<td>0.70</td>
<td>0.004</td>
<td>0.005</td>
<td>0.52</td>
<td>0.003</td>
<td>0.013</td>
</tr>
<tr>
<td>Z Torque</td>
<td>0.63</td>
<td>0.004</td>
<td>0.004</td>
<td>0.48</td>
<td>0.003</td>
<td>0.011</td>
</tr>
<tr>
<td>Total</td>
<td>0.202</td>
<td>0.211</td>
<td></td>
<td>0.201</td>
<td>0.034</td>
<td></td>
</tr>
</tbody>
</table>
• The ADC subsystem shall be designed for a 6 month lifetime

• Although our HTCCA does not have flight heritage, we have done intensive tests to ensure they will survive for the mission length.

• Torquer coils have been in 60 degree cycles for 1600 cycles. Also survived vibe and shock tests.

• The ACB has flight heritage and will last the 6 month lifetime.
• The ADC subsystem shall be designed to operate at a dose of 5 krad/yr or greater

• The ACB we are using for ADCS maneuvers is a derivative of Aerocube attitude control board.
• The ADC subsystem shall be SEU tolerant

• The ACB we are using for ADCS maneuvers is a derivative of Aerocube attitude control board.
  • Vulnerable to same issue as other Aerocube boards

• Possibly a torquer coil gets turned on from a bit being flipped.
  • Will get fixed after 2 hours when ACB gets reset.
  • Science data during this time would be corrupted.
Spin Test Difficulties

- Leading up to spin test, there were notable changes to the control law due to problems we were noticing with the bench test.
  - $H_{\text{lim}}$ value became split up from a variable value to a value that would triggered at three different instances
  - Needed to become spike tolerant to prevent erroneous zero crossings
  - Implemented a moving average to calculate half periods
Control Law Parameters

• Values that can be changed in-flight
  • Bdot
    • H_Lim
    • Duty Cycle Duration
    • Zero-crossing values
  • Bact
RFAs from CDR

RFA #1: Generate a “day in the life” simulation
- Implemented in terms of precession where we are able to tell ELFIN how long we want to torque for, and it will precess to a target vector.
- Lacking the fidelity in the model to be able to model attitude for more than a few orbits

RFA #2: Define control law topology
- Defined pros and cons of the two control laws in documentation
- Bact should be used until 6 RPM and then should switch to Bdot for ease of use

RFA #4: Create an ADCS commissioning plan
- Need to exercise coils
- Make sure MRMs are working by collecting data

RFA #5: Attitude Determination
- Verified through Matlab/Simulink simulation and IDL.
- Uses Monte Carlo Simulation
**RFAs from CDR**

**RFA #7:** Determine an in-flight requirement for pointing error for each operating mode

- Using a 1,000 nT noise to account for the pointing error.
- Control laws are still functional

**RFA #8:** Simulations should use same control law that is used onboard

- Simulations match the control law used on board
- Only difference is the hysteresis limiter we use but that is configurable in flight
  - Due to large noise estimates

**RFA #9:** Perform day in the life testing

- Took simulated on-orbit data and wrote a script to generate an activity to put in the database
RFA #10: Rephrase attitude requirements to be consistent with a spinner
  • Attitude vector is still defined by the spin vector
  • Resolved

RFA #11: Refine on board spin phase knowledge requirement
  • We have ensured that the spin phase knowledge is none well enough to be able to perform the Bdot algorithm.
  • Rejected because we did not explicitly state this requirement any more
RFAs from CDR

RFA #1497: Simulate a variety of orbits
  • Before our orbit was finalized, we had different estimations of orbits
  • Spin up/down worked in all cases
  • Attitude vector was able to be determined

RFA #177: Pointing Error Budget
  • Allocated 1,000 nT worth of noise
1000 nT of Noise in Sim
Major Changes Since CDR

• Rejected Requirements
  • ADCS – 07: Deperm
  • ADCS – 17: Spin Phase
• The ADC subsystem shall be capable of running a deperm cycle after maneuvers and deployment to ensure the magnetic moment of the spacecraft is compliant with the magnetic cleanliness document.

• This has been descoped. We are unable to deperm our spacecraft with our coils because they are too weak.

• Instead we decided to mitigate the hysteresis dipole during our vibe campaigns.

• Also use non-magnetic materials when possible.
• The spin phase shall be known within TBD degrees onboard

• This requirement was given to ADCS to help science
• Science team now handles this requirement themselves