VERIFICATION AND VALIDATION METHODS FOR THE PROX-1 MISSION

Christine Gebara
Student Project Manager, Georgia Tech 2017

Dr. David Spencer
Principal Investigator, Georgia Tech

24th Annual Frank J. Redd Student Competition
30th Annual AIAA/USU Conference on Small Satellites
August 10, 2016
PROX-1 MISSION OVERVIEW

- 70 kg
- 22” x 24” x 12” envelope (ESPA-class)
- Launching on STP-2 launch (Falcon Heavy)
- Orbit: 720km circular, 24° inclination
- University Nanosatellite Program 7th Class
**PROX-1: MISSION GOALS**

**Mission Statement**

The Prox-1 mission will demonstrate automated safe trajectory control during proximity operations for on orbit inspection. Passive, image-based observations will be used for the navigation and closed-loop attitude control of Prox-1 relative to LightSail-2.

- Passive Thermal-Infrared Imaging
- Image-Based Relative Navigation
- **Automated** On-board Guidance and Control
- Low-Thrust Propulsion
- Advanced Small Satellite Hardware Demonstration
1. Separation & Detumble
2. Initial Acquisition & Checkout
3. CubeSat Deployment & Orbit Determination
4. Rendezvous & Proximity Operations
5. Sail Deployment & Inspection
**Validation (n.)**
\(\text{va-\textipa{\textsc{i}-d\textipa{\textsc{a}-sh\textipa{\textsc{en}}}}\)\)

Confirmation that the system as a whole can carry out its mission and meet minimum and full mission criteria.

**Verification (n.)**
\(\text{ver-a-f\textipa{\textsc{a}-k\textipa{\textsc{a}-sh\textipa{\textsc{en}}}}\)\)

Confirmation that Prox-1 meets all formal requirements outlined in the requirements matrix created for the mission.
**Requirements Formulation**

### Minimum Mission Success
- Establish 2-way communication
- Verify spacecraft health and status
- Checkout CMG
- Deploy LightSail-2

### Full Mission Success
- Checkout propulsion system
- Checkout visible and IR cameras
- Rendezvous with LightSail-2
- Relative orbit determination
- Automated tracking control
- Station-keeping
- Natural motion circumnavigation
- Solar sail deployment imaging
• 400+ Requirements (including constraints)

• Minimize external references

• Responsibility is assigned to an individual

• Traceable back to mission success criteria

• Living document

• Milestone updates

“Use of glass shall be minimized. Where glass must be used, it shall be non-pressurized and subject only to inertial loading, as required by NASA-STD-5003, Section 4.2.3.6.” (Constraint SS-10)

“The C&DH subsystem shall process satellite telemetry and perform image processing simultaneously.” (Requirement CDH-1)

“MOS shall provide tracking station overflight predictions for scheduling tracking passes throughout the mission.” (Requirement MOS-1)
PRE-INTEGRATION TESTING

Design And Fabrication → Component Confirmation Testing → Subsystem Confirmation Testing → Subsystem Integration → System Level Testing

- Communication
- System Power
- Read Sensor Data

Day In The Life
Simulated Communication
Life Cycle Charge
Command Execution

Design Changes And Fabrication → Component Confirmation Testing → Subsystem Confirmation Testing → Subsystem Integration → System Level Testing

- Communication
- System Power
- Read Sensor Data

Day In The Life
Simulated Communication
Life Cycle Charge
Command Execution

Key:
- Engineering Unit Flat Sat
- Flight Hardware Flat Sat
**Mission Design and Space System Requirement**

“The Prox-1 satellite and all components, including CubeSat, shall be capable of surviving operation in space for the 6 weeks primary mission duration”

**Subsystem Requirement**

“The thermal monitoring system shall monitor all subsystems, using redundancy on critical components, and shall trigger heater activation if minimum temperature is reached.”

**Confirmation Testing**

Testing proves that temperature can be sampled and heaters controlled through subsystem microcontroller.

**System Testing Procedure**

TCS Start-Up sequence
- Enable 5V switch to TCS SMC
- Enable 28V switch to heaters
- Initiate FSW_TCS_WATCHDOG
- FSW request thermistor telemetry
- Begin TCS sampling and storage

**Verification Method**

See TCS data in flight software log.
LESSONS LEARNED

• Anticipate the gap between classroom and clean room knowledge
  – Procedure writing
  – Harnessing
  – Data collection

• Problems are not solved alone
  – Students of various disciplines

• Crawl first, then fly
  – Build up to testing
  – Creative testing
BACK UP SLIDES
COMPONENTS
C&DH
EPS
Instruments
ADCS – Sun Sensors
ADCS – Torque Rods
ADCS - Other
Telecom
Thermistors & Heaters

C/O Prox-1 Structures and EPS team
PASSIVE IMAGE BASED NAVIGATION

• THESIS-IR
  – 640 x 512 thermal imager

• THESIS-VIS
  – 1384 x 1032 visible imager

• Imaging Processing algorithms
  – Developed by GT for relative state estimation
  – Hosted on imaging payload computer
COLD GAS PROPULSION UNIT

- Designed and manufactured by UT Austin’s Texas Spacecraft Lab
- Cold gas thruster
  - R-236fa
    - Non-toxic
  - 50 mN thrust
  - Max pressure of 100 psi at 56°C
  - 15 m/s
- 3D printed
  - Accura Bluestone material
  - Tank and plumbing printed as one contiguous piece
MICRO-SAT CMG’s

- Developed and manufactured by Honeybee Robotics
- Funded through AFRL SBIR
- Provide on-orbit qualification for small satellite CMGs
FLIGHT STRUCTURE
## Connector and Harnessing Index

<table>
<thead>
<tr>
<th>EGSE Procedure Step Number</th>
<th>GTRI Fab?</th>
<th>From Subsystem</th>
<th>Board Connector Type</th>
<th>Board Label</th>
<th>To Subsystem</th>
<th>Board Connector Type</th>
<th>Board Label</th>
<th>Purpose of Harness</th>
<th>AWG (if not 22 AWG)</th>
<th>Harness Length (in)</th>
<th>Margin Length (in)</th>
<th>Total Length</th>
<th>Anchor Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Y</td>
<td>EPS Breakout</td>
<td>DB26 Male</td>
<td>C&amp;DH</td>
<td>CDH Microcontroller and EPS-CDH Interface</td>
<td>DB25 Female</td>
<td>EPS</td>
<td>Power, Comm</td>
<td>18</td>
<td>23</td>
<td>1</td>
<td>24</td>
<td>6 total, 2 on TR long internal plate, 3 on center channel bottom plate, 1 on CMG internal plate</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>CDH ADCS CDH Interface</td>
<td>DB26 Male</td>
<td>ADCS SMC1</td>
<td>SMC 1</td>
<td>DB26 Male</td>
<td>FCE Connector</td>
<td>Power, Comm</td>
<td>23.5</td>
<td>1.5</td>
<td>1.5</td>
<td>25</td>
<td>6 total, 2 on CMG internal plate, 1 on lower bar of CMG internal plate, 2 on CMG internal plate other side, 1 on CMG internal plate shared with SMC 2 db9</td>
</tr>
<tr>
<td>3</td>
<td>Y</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>ADCS SMC2</td>
<td>SMC 2</td>
<td>FCE Connector</td>
<td>Power, Comm</td>
<td>16</td>
<td>2</td>
<td>2</td>
<td>18</td>
<td>4 total, all shared with SMC 1 db9 and SMC 2 db26</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td>ADCS ADCS SMC Interface</td>
<td>DB26 High Density Male</td>
<td>SMC1</td>
<td>SMC 1</td>
<td>DB26 High Density Male</td>
<td>Hardware Connector HDF26 CONEC Female</td>
<td>Power, Comm</td>
<td>6.5</td>
<td>1.5</td>
<td>1.5</td>
<td>8</td>
<td>1 total, 1 on CMG rib underneath second bar</td>
</tr>
<tr>
<td>5</td>
<td>Y</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>SMC2</td>
<td>SMC 2</td>
<td>Hardware Connector HDF26 CONEC Female</td>
<td>Power, Comm</td>
<td>20.5</td>
<td>2</td>
<td>2</td>
<td>22.5</td>
<td>4 total, all shared with SMC 1 db9 and SMC 2 db9</td>
</tr>
<tr>
<td>6</td>
<td>Y</td>
<td>ADCS Sun Sensor Interface</td>
<td>DB26 Male</td>
<td>ELMOS 1</td>
<td>ELMOS 1</td>
<td>DB26 Male</td>
<td>only connector on sun sensor</td>
<td>Power, Comm</td>
<td>10.5</td>
<td>1</td>
<td>1</td>
<td>11.5</td>
<td>1 total, 1 on CMG rib underneath second bar shared 4th SMC 1 db26</td>
</tr>
<tr>
<td>7</td>
<td>Y</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>ELMOS 2</td>
<td>DB26 Male</td>
<td>only connector on sun sensor</td>
<td>Power, Comm</td>
<td>25</td>
<td>1</td>
<td>1</td>
<td>27</td>
<td>4 total, 3 on center channel bottom plate, 1 on battery side middle rib</td>
</tr>
<tr>
<td>8</td>
<td>Y</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>ELMOS 3</td>
<td>DB26 Male</td>
<td>only connector on sun sensor</td>
<td>Power, Comm</td>
<td>16.5</td>
<td>1</td>
<td>1</td>
<td>17.5</td>
<td>2 total, 1 on lower bar of CMG internal plate, 1 on CMG inter plate</td>
</tr>
<tr>
<td>9</td>
<td>Y</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>ELMOS 4</td>
<td>DB26 Male</td>
<td>only connector on sun sensor</td>
<td>Power, Comm</td>
<td>24</td>
<td>2</td>
<td>2</td>
<td>26</td>
<td>5 total, 1 on lower bar of CMG internal plate, 4 on CMG internal plate</td>
</tr>
<tr>
<td>10</td>
<td>Maybe</td>
<td>ADCS High Voltage</td>
<td>DB26 Male</td>
<td>TORC Unit</td>
<td>ELMOS 1</td>
<td>CMG Micro DB15 Male</td>
<td>only connector on CMG</td>
<td>Power, Comm</td>
<td>15.5</td>
<td>1</td>
<td>1</td>
<td>16.5</td>
<td>3 total, 1 on lower bar of CMG internal plate, 2 on CMG internal plate</td>
</tr>
<tr>
<td>11</td>
<td>Y</td>
<td>ADCS High Voltage</td>
<td>DB26 Male</td>
<td>Magnetometer</td>
<td>DB26 Female</td>
<td>Magnetometer</td>
<td>only connector on Magnetometer</td>
<td>Power, Comm</td>
<td>7.5</td>
<td>0.5</td>
<td>0.5</td>
<td>8</td>
<td>4 total, 1 on lower of CMG internal plate, 2 on central channel bottom plate, 1 on battery side middle rib</td>
</tr>
<tr>
<td>12</td>
<td>Y</td>
<td>ADCS High Voltage</td>
<td>DB26 Male</td>
<td>Torque Rod X</td>
<td>DB26 Male</td>
<td>Torque Rod X</td>
<td>only connector on TR X</td>
<td>Power, Comm</td>
<td>24</td>
<td>1</td>
<td>1</td>
<td>25</td>
<td>4 total, 1 on lower of CMG internal plate, 2 on central channel bottom plate, 1 on battery side middle rib</td>
</tr>
<tr>
<td>13</td>
<td>Y</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Torque Rod Y</td>
<td>DB26 Male</td>
<td>only connector on TR Y</td>
<td>Power, Comm</td>
<td>23</td>
<td>1</td>
<td>1</td>
<td>24</td>
<td>1 total, 1 on lower bar of CMG internal plate, 2 on central channel bottom plate, 1 on battery side middle rib</td>
</tr>
</tbody>
</table>
**STEP 2.A.1: TORC CMG**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Fastener Type</th>
<th>Length</th>
<th>Torque Value (in-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>¼ - 20 Socket Head</td>
<td>0.75&quot;</td>
<td>90</td>
</tr>
</tbody>
</table>

**Procedure**
- Record weight in MEL
- The CMG bolts to the bottom plate with the ¼-20 fasteners
- Stake bolts lightly over cap after installation
- Port oriented away from CMG external side. It is closer to the bottom plate

<table>
<thead>
<tr>
<th>Bolt #</th>
<th>Running Torque (in-lbf)</th>
<th>Final Torque (in-lbf)</th>
<th>Tech</th>
<th>QA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bolt #</th>
<th>Running Torque (in-lbf)</th>
<th>Final Torque (in-lbf)</th>
<th>Tech</th>
<th>QA</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Step 2.A.2: Torc CMG

#### Offset and Procedure Table

<table>
<thead>
<tr>
<th>Offset</th>
<th>Procedure</th>
<th>Initial</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Measure and record distances 1A and 1B</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>Measure and record distances 2A and 2B</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>Measure and record distances 3A and 3B</td>
<td></td>
</tr>
</tbody>
</table>

Note: Measurement 2B is the same as 2A but on opposite side. Likewise for 1B and 1A.

** Axes point in positive direction
INTEGRATION OVERVIEW

1) Magnetometer
2) TORC CMGs
3) EPS Stack
4) CDH/ADCS Stack
5) Torque Rod – Y
6) TR Side Internal Plate
7) Torque Rod - X
8) Battery Rib
9) SMC Board #1
10) SMC Board #2
11) CMG Side Internal Plate
12) CMG Rib
13) Torque Rod - Z
14) S-Band Transmitter
15) S-Band Antenna
16) Sun Sensor TR Side
17) UHF Receiver
18) UHF SMA Connector
19) Sun Sensor CMG Plate
20) PPOD Standoffs
21) UT Austin Thruster
22) TCS Stack
23) Heaters/Thermistors
24) Sun Sensor Thruster Plate
25) Visible Camera Assembly
26) IR Structure
27) IRC Rib
28) TR Side External Plate
29) UHF Antenna
30) CMG Side External Plate
31) PPOD Side External Plate
32) PPOD / LS-2
33) Thruster Side External Plate
34) TR Side Solar Panel 1
35) TR Side Solar Panel 2
36) CMG Side Solar Panel 1
37) CMG Side Solar Panel 2
38) Thruster Side Solar Panel 1
39) Thruster Side Solar Panel 2
40) Sun Sensor Top Plate
41) TNC
42) GPS Receiver
43) GPS Antenna
44) Top Plate
45) Top Solar Panel 1
46) Top Solar Panel 2

Bottom Plate
TR Side Plate
CMG Side Plate
P-POD Side Plate
Thruster Side Plate
Top Plate

C/O Swapnil Pujari
INTEGRATION
SCHEDULE HIGHLIGHTS

- 2011: Selected for UNP-7
- 2012: Systems Design
- 2013: Winner of UNP-7
- 2014: Subsystem Development
- 2015: Integration & Testing
- 2016: Launch & Operations
- 2017: Extended Operations
Board Prep

Receive Board
Acceptance Test
Stake Components
Wait 24 hours
Conformal Coat Board
Wait 24 hours
Conformal Coat Board
Wait 48 hours
Touch ups
Wait 72 hours
Acceptance Test

Is it a stack?

Yes
See Stack Prep

No
See Integration

Stack Prep

Prep All Boards
Collect all parts for stack
Integrate Stack
Acceptance Test Stack
Stake Stack
Wait 24 hours
Conformal Coat Stack
Wait 24 hours
Touch Ups
Acceptance Testing

Integration

Collect all parts for integration
Integrate to structure
Acceptance Test with test harnessing
Stake Bolts
Wait 24 hours

Harnessing

Lay Harnessing
Make Harnessing
Conformal Coat Stack
Wait 24 hours
Install harness anchors
Acceptance Testing
Install harnessing
Acceptance Testing
Profit.
TESTING LOCATIONS (DOWNLINK)

Measure distance
Total distance: 2,375.59 ft (724.08 m)
Click on the map to add to your path

Square on Fifth Spacecraft
Van Leer Ground Station
ON-ORBIT HARDWARE VERIFICATION: 1 WEEK

- CMG unit performance test
- Imager payload verification testing
- Thruster alignment and performance test
LightSail Ejection and Orbit Determination: 2 Weeks

- Eject LightSail in cross-track direction (perpendicular to orbital plane)
- Begin imaging until LightSail is no longer in sight

C/O Kevin Oksenuik
• Ground-in-the-loop orbit determination utilized for burn maneuvers
  • LightSail updates available every 24 hours
• Post-rendezvous: Relative orbit determination verification period
PHASE 1 PROXIMITY OPERATIONS: 1 WEEK

- Rest to rest maneuvers (50 - 200m)
  - Sequence Length: 2-3 orbits

- Natural Motion Circumnavigation (within range of 150 m)
  - Sequence length set by ground, dictated primarily by entrance and exit burns, minimal clean up required
  - Goal: Shall maintain stable NMC for at least one Earth orbit

C/O Kevin Oksenuik
LIGHTSAIL DEPLOYMENT AND INSPECTION: 1 WEEK

- Initial stable trailing orbit relative to target
- Target sail deployment
- Tracking and imaging of deployed target possible for one day post deployment without Prox-1 burn required
End-of-Life

- Passivation of spacecraft system
- Automated deployment of Tethers Unlimited Tether Tape
- De-orbit ~ 25 years after launch
LV SEPARATION AND INITIAL CHECKOUT: 1 WEEK