An Optimized Small Satellite Bus and Structure for the THEMIS mission

SSC06-IV-5

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Outline

- THEMIS mission overview
- Probe Bus requirements
- Probe Bus overview
- Probe structure design
- Probe structural analysis
- Structure development testing
- Structure assembly and test
- Structure and bus integration and test (I & T)
- Conclusion
THEMIS Mission Overview

- Mission is a NASA/GSFC MIDEX class with UC Berkeley as the principal investigator.
- The science is to perform electro-magnetic measurements towards understanding the magnetic storms that cause the Northern Lights.
- Mission requires 5 small spacecraft (called Probes) to be placed in different highly elliptical earth orbits. To deploy 5 Probes on one launch vehicle (LV) the Probe Carrier (PC) was developed.
- To achieve the final orbits the probes need to perform ~ 900 m/s of ΔV maneuvers using the on-board propulsion system.
- Probes are spin stabilized.
- THEMIS = Time History and Macroscale Interactions during Substorms
- See 2005 paper SSC05-V-8 for more mission level details.
THEMIS Probe Carrier Assembly

- Standard Delta 10 ft. Fairing
- 3712 PAF
- Star 48 3rd Stage
THEMIS Probe Carrier Assembly
Driving Requirements for Structure design & bus packaging

- Propulsion system (aka RCS) accommodation – integrated with the bus
  - Two propellant tanks
  - One composite overwrap pressure vessel (COPV) pressurant tank
  - Four thrusters
  - Seven valves, two pressure transducers
  - 49 kg of hydrazine.

- Component and Instrument accommodation
  - Extremely tight package
  - Access for I&T and maintenance / rework
  - Clearance for deployable elements
  - Clearance for fields of view (FOV)
  - Launch load sensitivity

- Magnetic and Electrostatic cleanliness
  - Nonmagnetic materials
  - All external surfaces of the probe required to be electrically conductive and have a bleed path to spacecraft ground.

- Mass allocation
  - Minimize structural mass for ΔV
Driving Requirements – con’t for Structure design & bus packaging

- Launch Vehicle (LV) envelope and separation clearance
  - Probe to pairing clearance
  - Probe to probe clearance – PC is spinning at deployment
  - Pad access to certain probe functions

- Spin Balance and Inertia Ratio
  - ratio of spin to transverse inertia is required to be greater than 1.04
  - center of gravity (CG) offset max = 0.18 inches, with respect to the spin axis
  - principal axis alignment, 1.0 degree, with respect to the spin (Z) axis.

- Thermal
  - Probe has to survive any attitude with respect to the sun and a three hour eclipse.
  - Thermal sub-system has small power budget
  - Majority of the available power is dedicated to keeping the propulsion system warm.
The bus is made up of the following components:

- Bus Avionics Unit (BAU)
- Battery
- Auxiliary Electronics Box (AEB)
- Inertia Reference Unit (IRU) assembly
- Antenna and Transponder
- Digital spinning sun sensor
- Body mounted solar arrays
- Separation system
- Harness
- Propulsion system
The bus accommodates the following instruments:

- Quantity 2 Axial Boom (EFI) in center tube
- Quantity 4 Spin Plane Booms (SPB)
- Quantity 2 Solid State Telescope (SST)
- Electrostatic Analyzer (ESA)
- Instrument Data Processing Unit (IDPU)
- Quantity 2 magnetometer booms (FGM/SCM)
Probe Deployed Configuration

- 2X~20 m long radial EFI booms
- 2X~5 m long axial EFI booms
- 2 m long FGM boom
- 1 m long SCM boom
- 2X~25 m long radial EFI booms
Probe bus external view
Probe internal view

- Sun Sensor
- Single Point Ground
- BAU
- Battery
- AEB
- 4X SPB
- 2X Propulsion Tanks
- ESA/IDPU
- Transponder
- Harness Bridge (harness not shown)
- IRU

Dimensions: 34"
Probe Bus Internal View
### Propulsion System Accommodation

<table>
<thead>
<tr>
<th>Propulsion System</th>
<th>Qty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrazine Tanks</td>
<td>2</td>
</tr>
<tr>
<td>Pressurant Tank</td>
<td>1</td>
</tr>
<tr>
<td>Thrusters</td>
<td>4</td>
</tr>
<tr>
<td>Latch Valves</td>
<td>2</td>
</tr>
<tr>
<td>Pyrotechnic valve</td>
<td>1</td>
</tr>
<tr>
<td>Fill/Drain Valves</td>
<td>4</td>
</tr>
<tr>
<td>Pressure Transducer</td>
<td>2</td>
</tr>
<tr>
<td>Lines / fittings</td>
<td>many</td>
</tr>
</tbody>
</table>

Hydrazine tank

Press tank

Thruster bracket

Service bracket
Thruster Plumes

Thruster 60° full angle plume
Structure Design

- Top and bottom decks are sandwich honeycomb panels with graphite composite face sheets.
- Corner panels are solid graphite laminant.
- Side shear panels are also body mounted solar arrays which are sandwich honeycomb panels with graphite composite face sheets.
- The face sheet thickness, core thickness and core density vary from panel to panel to optimize mass.
- Numerous custom panel inserts were used.
  - Some inserts were cured with the panel.
  - The majority of the inserts were installed after panel cure.
  - Aluminum and titanium inserts were used.
  - All inserts were individually grounded to the core.
- Corner panels and side panels are pinned at each corner to carry shear.
- Bottom deck and side panels are thermally isolated using spacers.
Brackets will stay attached to solar arrays.

Thermal spacers between panels & bottom deck.
Mounting Description

- Primary load path is through the bottom deck to the Probe separation ring
- Top spherical pin takes lateral loads only
- Tanks are thermal isolated from top and bottom deck
View showing hidden features, including adhesive
Final, as weighed structure mass was significantly less than the allocation.

<table>
<thead>
<tr>
<th></th>
<th>Allocation (kg)</th>
<th>Final Mass (kg)</th>
<th>% of Probe Dry mass*</th>
<th>% of Probe Wet mass**</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Mechanical</strong></td>
<td>23.8</td>
<td>19.8</td>
<td>24.2%</td>
<td>14.8%</td>
</tr>
<tr>
<td><strong>Structure only</strong></td>
<td>18</td>
<td>14.4</td>
<td>17.6%</td>
<td>10.7%</td>
</tr>
</tbody>
</table>

Notes:
* The not to exceed (NTE) Probe dry mass is 81.8 kg.
** The probe structure design requirement is 134 kg of wet mass. The actual Probe on-orbit mass will be approximately 126 kg.
Structure Analysis

- Major load drivers
  - Thermal induced CTE mismatch stress
  - Launch loads
- Analysis was performed using “test” based factors of safety.

<table>
<thead>
<tr>
<th></th>
<th>Yield</th>
<th>Ultimate</th>
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<tbody>
<tr>
<td>Metallic and machined elements</td>
<td>1.25</td>
<td>1.4</td>
</tr>
<tr>
<td>Composites</td>
<td>-</td>
<td>1.5</td>
</tr>
<tr>
<td>Bonded Joints</td>
<td>-</td>
<td>1.5</td>
</tr>
</tbody>
</table>

- First lateral mode
  Requirement = 35 Hz
  As tested = 40 Hz
Key elements

- Aluminum components mounted to graphite deck.
- Aluminum/titanium fittings lapping graphite face sheets.
- Potting compound embedded in the panels.
- Insert spacing

<table>
<thead>
<tr>
<th></th>
<th>Min °C</th>
<th>Max °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Deck</td>
<td>-100</td>
<td>85</td>
</tr>
<tr>
<td>Bottom Deck</td>
<td>-60</td>
<td>70</td>
</tr>
<tr>
<td>Corner Panels</td>
<td>-105</td>
<td>95</td>
</tr>
<tr>
<td>Top Solar Panels</td>
<td>-125</td>
<td>115</td>
</tr>
<tr>
<td>Side Solar Panels</td>
<td>-120</td>
<td>115</td>
</tr>
<tr>
<td>Bottom Solar Panels</td>
<td>-120</td>
<td>115</td>
</tr>
</tbody>
</table>

Structure Thermal Requirements

Overlap of Inserts and Adhesive in Bottom Deck
Typical FE Model For CTE Mismatch

FEM for ring / bottom deck mismatch

FEM for EFI Axial insert / Bottom Deck

FEM for instruments / bottom deck mismatch
Extensive development testing was performed and led to design changes.
There was no ETU structure so all 5 were protoflight

- Assemble structure
- Match/Template Drill structure
- Configure for Sine Burst
- Ship to GSFC
- Perform sine burst test
- Ship to Swales
- Disassemble & inspect
- Structural components to I&T
- Deliver Top Deck to GSFC for Coatings
- Send solar array substrates to cell vendor
- Send base panel to RCS vendor
- Return AXB to UCB

- Flight AXB with 4 thermal cycles performed at UCB - receive on certlog and inspect
- Flight Bottom Deck 4 thermal cycles with mass mock-ups
- Flight Top, Solar & Corner Panels (4 thermal cycles at bare panel level)

- Template drill 4X solar panels
- Complex thermal cycle test
- Sine Burst test

- Thermal Cycle Testing
- Sine Burst Testing

Mass Mock-ups
Structure had to be completely reassembled to start I&T.

Bottom Deck with Propulsion System
Conclusion

- The THEMIS bus structure and bus packaging design met or exceeded all of the requirements and goals of the THEMIS mission.

- The structure mass is approximately 10% of the design wet mass of the Probe. For a small, one of a kind, satellite, this is a historically small percentage.

- The launch and on-orbit environments were somewhat typical of other missions but the combination of tight requirements and the uniqueness of the Probe Carrier caused the structure design to be tailored for these environments.

- The structural analyses were comprehensive, critical to the success of the design, and in some areas may be unique to this program.

- Five nearly identical bus structures, were fabricated, assembled, tested, disassembled, shipped to vendors, and reassembled in a relatively brief period of time.
Qty 4 Probes in process