The Design and Development of a Separation System for a Low-Cost Spherical Satellite

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Effects of Satellite Drag:

- 410 km
- 390 km
- 370 km
- 350 km
- 330 km

1999 - ISS drops 10km in several days
2000 - X5 flare 7/14/2000
2001

Fundamental Drag Equation:

\[ \vec{F}_D = \frac{1}{2} \rho \cdot C_D \cdot A \cdot \vec{v}^2 = m \cdot \vec{a} \]

Spherical Spacecraft:

- Characterizes drag coefficient and cross-sectional area
- Several existing spacecraft
  - ANDE Series (recent launch)
  - Starshine Campaign
- These spacecraft have excellent influences on drag models however:
  - Difficulty in maintaining spherical shape when attaching to launch vehicle

The DANDE Mission:

- Proof-of-concept small satellite
- Build a spacecraft that characterizes all variables of the Drag Equation including the drag coefficient and cross-sectional area
- Post in-situ data, “satellite weather station”
- Winner of University Nanosat 5 Competition

Effects of Satellite Drag:

- Proof-of-concept small satellite
- Build a spacecraft that characterizes all variables of the Drag Equation including the drag coefficient and cross-sectional area
- Post in-situ data, “satellite weather station”
- Winner of University Nanosat 5 Competition
### Problems with a Sphere:

- Attachment to launch vehicle
- Primary Structure Layout
- Integration Complexity
- Spherical Smoothness Req
- Power Generation
- Communication Antennas

### First Concept, March 2007

#### Six Architectures

Down-Selected, May 2007

#### Architecture Chosen, June 2007

### Formal Trade Study

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<tr>
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<td>Release Certainty</td>
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<td>2</td>
<td>Abiding by AFRL Requirements</td>
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<tr>
<td>3</td>
<td>Sphere Center-of-Gravity</td>
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<tr>
<td>4</td>
<td>Ease of Bracket Installation</td>
<td>9%</td>
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<td>5</td>
<td>Tip-Off Speed</td>
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<tr>
<td>6</td>
<td>Number of Mechanisms</td>
<td>8%</td>
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<td>7</td>
<td>Accessibility to Bolts / Actuators</td>
<td>8%</td>
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<tr>
<td>8</td>
<td>Obstructed Solar Array Area</td>
<td>8%</td>
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<tr>
<td>9</td>
<td>“Feel Good Factor” (subjective)</td>
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<tr>
<td>10</td>
<td>Ease of Manufacturing</td>
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<td>11</td>
<td>Allowable size of sphere</td>
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<td>3</td>
<td>Three Legs, 1 Mechanism 90°</td>
<td>3.41</td>
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<td>Three Legs, 3 Mechanisms 0°</td>
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<td>Four Legs, 2 Mechanisms 0°</td>
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<td>6</td>
<td>Three Legs, 1 Mechanism 20°</td>
<td>3.19</td>
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The DANDE Baseline Architecture

Launch Vehicle Interface (ESPA)

DANDE Sphere

Interface Bracket

18”
Design of the Separation System

Mechanism Selection:
- Low Shock Release Mechanism of Starsys set as a baseline
- Mechanism design under development, currently at TRL-6
- Starsys to provide mechanism support / advice, meet with students once a month

S/C Launch Requirements
- Design to 20g
  - 2.0 Yield Factor of Safety
  - 1.2 Test Factor of Safety
- Natural Frequency >100 Hz
- Sustain Random Vibration Spectrum (20-2000 Hz)
- Adhere to standard ESPA ring interface / envelope

Constraints Define System Geometry:
- 18-inch sphere diameter
- Use of a 4-point kinematic mount system
- 6x6 inch footprint between bracket & sphere
- Two Mechanisms required (10,000lbs total)

Load Scenario | MOS (Certified Rating) | MOS (Analysis Rating)
--- | --- | ---
20g Design Load: | 0.26 | 1.01
20g Design Test: | 0.05 | 0.68
20g Design Yield: | -0.37 | 0.01

Starsys engineers review designs and give insight to CU student
Kinematic Mount Design

Definition of Kinematic Mount:
• A geometrically constrained interface that allows motion in one direction but not in others
• Compliant to bracket / sphere misalignments or manufacturing miss-tolerances

Mount Types Designed for DANDE:
• Cup/Cone – 3D restriction (1)
• Canoe/Trench – 2D restriction (1)
• Plane/Sphere -1D restriction (2)

Flight and Spare, 2-D Canoe/Trench Mount

Mechanisms (2)
Paraffin Actuator
Kine Mounts
Mechanism Bracket
Interface Bracket
Kinematic Mount Stress Analysis

Analysis Assumptions:

- Hertzian Stress Theory Applied
  - Curved surface under bearing load on a flat plate (typically applied on ball bearings)
- All shear (lateral) loading is taken through the cup/cone mount.
- There are no induced strains from miss-tolerances or thermal expansion
- Female mounts are a harder material than the respective male mounts
- A bearing stress factor of 1.6 was implemented (for materials in compression)

Stress Analysis Results:

<table>
<thead>
<tr>
<th>Mount</th>
<th>Design Sphere Radius</th>
<th>Contact Area</th>
<th>Margin of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-D</td>
<td>13 inches</td>
<td>0.173 in²</td>
<td>0.11</td>
</tr>
<tr>
<td>2-D</td>
<td>10 inches</td>
<td>0.109 in²</td>
<td>0.07</td>
</tr>
<tr>
<td>3-D</td>
<td>0.95 inches</td>
<td>0.180 in²</td>
<td>0.04</td>
</tr>
</tbody>
</table>

1-D Plane/Sphere Analysis Example

\[
C_E = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2}\]

\[
A_{\text{contact sphere}} = 0.520\pi(PdC_E)^{\frac{2}{3}}\]

\[
(\tau_c)_\text{max} = \frac{1}{3}(\sigma_c)_\text{max}\]

\[
(\sigma_c)_\text{max sphere} = 0.918\sqrt{\frac{P}{d^2C_E^2}}\]

Stress, Margin of Safety vs Sphere Radius (for 1-D mount)
Mechanism Preload / Stress Analysis

Preload Calculation (Gapping)

- Determined by closed form analysis
  - Variables: material/geometric stiffnesses, temperature gradients, preload uncertainties, kinematic stiffness
  \[ \delta = \frac{PL^3}{3EI} \rightarrow \frac{3EI}{L^3} = \frac{P}{\delta} \]

- Results: Gapping will not occur
  - In worst loading case scenario, loss of kinematic mount preload is 20.6%

Finite Element Analysis:

- CosmosWorks 2007 Finite Element Tool utilized for static / dynamic stress analysis
- Static Results: MOS: 0.68
  - Within the mechanism bracket, large MOS due to dynamic & geometric constraints
- Dynamic Results, Natural Freq: 110 Hz
**Test Profile:**

- Perform a sine burst test (minimum of 24g’s applied at the base).
- Perform a random vibration test for 120 seconds at specified PSD.
- Perform sine-sweeps between each test run to determine health of the structure.
- Notching applied to prevent over-testing during the random vibration at natural frequencies.

**Success Criteria:**

- Natural frequencies match predicted, and are >100 Hz.
- Shifts in the sine sweeps are below 5% in freq and 15% in amplitude shift on the primary mode.
- Preload torque on primary structural bolts maintained.

**Vibration Assembly:**

- Full primary structure & separation system.
- Contains Starsys™ mechanisms.
- Rigid mass simulators used for internal components.
Sep System Vibe Test Results

**Results:**

- Excellent correlation between tests
- Notching used at fundamental frequency for random

\[
(\dot{x}_{\text{rms}})_{\text{exerted}} = 3\sigma \sqrt{\Delta f_{1/3}} (PSD)
\]

- Primary modes identified with accelerometer placement
- Natural frequency at 84 Hz, ~23% off from analysis

**Design Feedback:**

- Fundamental mode excited in external bracket
  - Flight bracket stiffened with available mass
- Ware patterns created on kinematic mounts
  - Circular pattern size match calculations
- Post vibe separation test successful
  - First separation test at full preload, kinematic mounts did not bind after settling from vibrations
Microgravity Testing

**NASA Facility (C-9 Aircraft):**
- Proposal won in Dec ’07, Flight Apr ’08
- Undergraduate opportunity, new team trained on intricacies of SEP system, follow procedures, create check-lists, interacted with mentors
- Team deliverables: Testing reviews, final report written

**Test Criteria:**
Perform >3 separations showing:
- The two separating parts do not undesirably contact during separation
- The LAB separates from the spacecraft and clears it by at least one foot.
- Ambient factors such as the wall of the aircraft, or human hands do not interfere with the separation system systems during the test.
- Recorded with accelerometers & cameras

**Results:**
- 4 clear field view separations occurred.
- All separations did cleanly separated from system and did not re-contact sphere
- Relative separation velocity within 3% of calculated value.
System Summary:

- Developed innovative separation system which restrains a spherical satellite without impacting spherical requirements
  - Created concept of “interface bracket”
  - Unique kinematic mount concept
  - Established link with an industry partner to use existing mechanisms, establish flight heritage.
- Applications a large variety of spacecraft
- Designed to standards set by the Air Force Research Lab, verified by testing
- Future testing planned:
  - Vacuum / Thermal Separation test planned
  - Qualification plan formulated
- Thanks to industry mentors:
  - Sierra Nevada, (SpaceDev, Starsys), Instar Engineering and Consulting Inc., Laboratory for Atmospheric Space Physics, Ball Aerospace and Planetary Systems

System Outlook:

- Flight integration set for the spring of 2010, will be flown by AFRL
- Industry mentoring has fostered a student design of high fidelity and confidence.
- Team is excited to see successful on-orbit separation
Backup Slides Index

• Comparisons of DANDE Sep system with:
  • ANDE Spacecraft
  • Starshine Spacecraft
• DANDE Science
  • Instruments
  • Effects of SEP hole on DANDE
• Pictures of current spacecraft
  • Kinematic Mounts
  • Separation System
  • Spacecraft Layout
• Kinematic Mounts
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  • Kinematic Mount Design / Restraints
  • More on Analysis Assumptions / Boundary Conditions
  • Analysis for 2D / 3D
• Preload Equations / Variables
  • SpaceDev Mechanism (Low Shock Release)
• Vibration Test
  • Notching practices
  • Test Report Summary
• Microgravity Test
  • Requirement Definitions
  • Test Report Summary
• Space Debris (ejected component)
• Details of Future Testing / Improvements
  • Qualification Testing
  • Thermal Separation Testing at Vacuum

Videos
• CAD Graphic - Integration
• Vibration – Sine Burst
• Separation Video - Post Vibe
• Separation Video - Microgravity
Comparisons of DANDE Sep System with others
DANDE Science

Neutral Mass Spectrometer

Accelometer

Backup Slide
DANDE Science, Effect of Hole in Surface

- Coefficient of Drag discrepancies originate from small ridges that impact multiple surfaces (non-normal contact)
- Total SEP hole measures ~8 inches$^2$
  - Exposed surface contains a flat surface

**Coefficient of Drag Analysis**

- Multiple reflections are prominent inside the concave geometry and at lower incidence angles
- The effect of facets including multiple reflections on $C_D$ is on the order of -2% for DANDE
- Reducing the $\alpha$ proportionally to the reduction of flux of O causes a change in $C_D$ of +7% for Starshine 1 (Simulation not yet run for DANDE)

Locations of multiply reflected particles on a faceted geometry

Figure Credit: Marcin Pilinski
Pictures of Kinematic Mounts
Pictures of SEP System
DANDE Spacecraft Layout

- horizon crossing indicator (x2)
- battery box (x2)
- ball & tube nutation dampener (x2)
- mass trim system (x8)
- Accelerometers (x6)
- 3-axis magnetometer
- patch antenna (x3)
- EMI box (x3)
- wind sensor
- Stiffeners (x4)
- separation mechanisms (x2)
- EGSE connector
- kinematic mounts (x4)
- lightband adapter bracket
Kinematic Mount Definition

Backup Slide
Separation Interface:

- Each mechanism centered about three legs → release timing less critical
- Mechanisms positioned to allow for a single paraffin actuator to trigger both restraining bolts
- Two paraffin actuators will be used, only one necessary to initiate system.
- Kinematic mounts combined with Al shims to prevent rocking created from machining imperfections
- System allows for machining miss-tolerance.
- Springs captured with bracket release
- Ejection speed of: 1 m/s
Kinematic Mount Design / Restraints

3D: A sphere resting inside a cup
- Restricts translational motion in the A, B & C directions at one point.

2D: A sphere resting inside a trench
- Restricts translational motion in two directions at one point.
- When combined with 3D mount, restricts rotational motion in the A & C axis.

1D: A sphere on a flat plane
- Restricts translational motion in the C direction
- When two are combined with the 3D & 2D mounts, restricts rotational motion in the B axis.

Material Selections:
- Male: Al 7050-T745 PER AMS 4050
- Female: S15500 Stainless Steel
- Male material is softer than female, reducing stiction.
- Materials have flight history with kinematic mounts
Kinematic Mount Analysis Assumptions / BC

- The canoe kinematic mount (attached to the mechanism) is allowed to swivel in the C-axis of Figure 2 above to ensure alignment with the trench.
- Male and female components are different materials to avoid cold welding and stiction.
- The male material properties are softer than the female components. This allows movement within the kinematic mounting system after the permanent (but expected) material deformation has occurred.
- All of the lateral loading is taken through the cup/cone mount, (mechanism are not designed to withstand lateral loading).
- Aluminum shims are used to ensure that mounts are level and evenly loaded.
- Each mechanism restraint bolt is centered in between three kinematic mounts. This ensures a clean release when deployed as there is still three-point-contact between the separation systems with only one mechanism preloaded.
- The kinematic mounting system does not induce a forced lateral strain as the mechanisms are preloaded. This is because the system allows unobstructed movement and miss-tolerances between the two components. The same is true for thermal expansion.
- The cup (cup/cone mount) is a sphere to enable free rotation motion inside the cone. Excess material where the mount does not interface to the cone wall is removed to save volume and mass.
- The canoe (canoe/trench) sphere radii do not have to be concentric.
Kinematic Mount analysis for 2D / 3D

\[(\sigma_c)_{max\ cylinder} = 0.789 \sqrt{\frac{P}{d C_E L}}\]

\[A_{contact\ cylinder} = 0.509\pi \sqrt{P L d C_E}\]
Preload Variables

- **Inputs:**
  - Mechanism Preload = 5000 pounds
  - Stiffness of the mechanism bracket / lightband bracket = 1.81e5 pounds / inch
  - Stiffness of the mechanism bolt = 1e6 pounds / inch
  - Stiffness of the kinematic mount interface = 1e7 pounds / inch
  - Coefficient of thermal expansion of the structure = 12.7e-6 inch/inch/degF
  - Coefficient of thermal expansion of the mechanism bolt = 7.1e-6 inch/inch/degF

- **Temperature at preload** = 70 deg F
- **Maximum expected temperature** = 160 deg F
- **Minimum expected temperature** = -65 deg F
- **Bolt preload install tolerance** = 250 pounds
- **Bolt preload uncertainty** = 50 pounds
- **Bolt Grip Length** = 3 inches
- **Input load on system (lateral loading at the spacecraft CG being the worst case).**

Backup Slide
SpaceDev Mechanism (LSRM)

The Low Shock Release Mechanism
- Built by SpaceDev, Starsys™ Series Mechanism
- Max preload of 5000 lbf
- Does not restrain shear load
- Fully electric and mechanical redundancy
- Utilizes a Paraffin actuator
- Has reached a TRL of 6
- Two testing units built and integrated into DANDE engineering Unit
- Independently Passed UN5 Level Specified Vibration Test
- Spec Sheet: UN5-STR802

The Starsys™ Paraffin Actuator:
- Output force of 40 lbf
- Reliability: >0.9999
- Can withstand 30g’s rms for 60sec
- Lifetime: 500 Strokes
- Non-Operating Environment: [-60 to 80°C]
- Spec Sheet: UN5-STR801

Interaction with SpaceDev:
- Have been in close e-mail / telephone contact and have held monthly meetings
- Acting as an advisor
- Have been given access to mechanisms when requested from SpaceDev

Backup Slide
# Vibration Test

<table>
<thead>
<tr>
<th>Req. Number</th>
<th>Pass/Fail</th>
<th>Description of Requirement and results</th>
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<tr>
<td>2.STR.2.8</td>
<td>Fail</td>
<td>DANDE space sector structure shall have a test verified fundamental frequency greater than 100 Hz.</td>
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<tr>
<td>2.STR.2.21</td>
<td>Pass</td>
<td>The DANDE space sector shall withstand the launch vehicle shock environment as indicated in section 8.1.3 of the UN5 users guide</td>
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<tr>
<td>2.STR.4.6</td>
<td>Pass</td>
<td>Sine sweeps shall be conducted from 20 to 2000 Hz at 0.25g to determine the natural frequencies of DANDE before and after structural testing.</td>
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<tr>
<td>2.STR.4.7</td>
<td>Pass</td>
<td>The DANDE space sector shall withstand a sine burst test on the integrated SIP system at a level of 1.2 times the limit loads without failure.</td>
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<td>2.STR.4.8</td>
<td>Pass</td>
<td>The DANDE space sector shall withstand random vibration test levels without failure as displayed in figure 8-2 and table 8-2 of the UN5 Users Guide see 8.1.3.2</td>
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<td>2.STR.4.9</td>
<td>Pass</td>
<td>The DANDE satellite shall withstand the shock testing levels without failure as displayed in Table and Figure 8-3 of the UN5 Users Guide.</td>
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<td>2.STR.4.10</td>
<td>Pass</td>
<td>Shock test will consist of 2 tests in three orthogonal axis, the first given at -6db, the second as seen in the given levels.</td>
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<th>Freq (Hz)</th>
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<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
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<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
<td>495</td>
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To better understand the DANDE separation system, testing will be performed in microgravity to demonstrate the relative environment the system will experience during deployment. Several parameters will be tested for successful adoption of the mechanism which includes velocity achieved upon separation of structure, rotation of LAB, along with surveillance data to identify and treat unforeseen results.

A successful separation is one during which:
- Ambient factors such as the wall of the aircraft, or human hands do not interfere with the separation system systems during the test.
- The two separating parts do not undesirably contact during separation.
- The LAB separates from the spacecraft and clears it by at least one foot.

The data taken from the testing showed that the predicted values of velocity were accurate when compared with the experimental values. The acceleration data was used to find the velocity of the DEUA. The mass of both the DEUA and the LAB were known which allowed the velocity of the LAB to be calculated. The velocity of the DEUA was off from the predicted value of 2.42 m/s by 3%. This means that the energy stored in the springs is converted to kinetic energy (ejection velocity) between the spacecraft and LAB.

<table>
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<th>Relevant Requirements</th>
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<tr>
<td>4.STR3.15</td>
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<tr>
<td>3.STR.3.15</td>
</tr>
</tbody>
</table>

Report Credit: Matt Capron
Space Debris

- The ejected bracket of the DANDE system is contained into one part
- The ballistic coefficient of the ejected bracket is higher than the DANDE sphere
- It is the goal of the DANDE mission to be inserted below 400km, re-entry of the two parts expected in a short time duration

Baseline Configuration

- ESPA Ring
- DANDE Sphere
- Lightband Adapter Bracket (LAB)

Backup Slide
Future Testing & Improvements

Future Planned Testing:
• TVAC Separation Test
  - Three tests: Nominal, Hot & Cold Cases at 1e-6 torr
  - Full flight hardware (electronics, lubricants, sep switches)
• Qualification Testing
  - Perform 8 consecutive separations with full flight hardware
  - Neutrally buoyant release – minimize effects of gravity

Planned Improvements:
• Integration of electrical interface separation connector
• Placement of a strain gage on the release bolts
  - Allows for more accurate preloading knowledge of the bolt
  - Wires will be cut after setting preload for flight
• Thermal / electrical coatings placed on the male kinematic mounts
• Application of a dry lubricant on the kinematic mount surfaces
  - Molybdenum disulfide powder
• Mass margin allows for stiffening of interface bracket
  - Nice to have to raise natural frequency of system.