Test Readiness Review

Industry Customer:

United Launch Alliance (ULA)

Faculty Advisor:

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02/21/2022

ASEN 4028-011

Presentation Outline

1. Project Overview
2. Schedule
3. Test Readiness
4. Budget

Project Overview

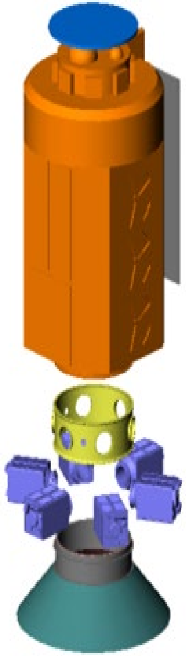
Project Overview

Background:

- The United Launch Alliance (ULA) desires an **optimized** Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Ring.
- How can the design be optimized if it is **not required** to support the primary payload?

Motivation:

- **Mass Reduction:** Without top payload (P/L) requirement, the redesigned ESPA should have a reduced mass compared to the standard ESPA.
- **Shifting Market:** Favoring many smaller payloads rather than a single large payload.



Source: 2018 Moog [1]

Primary Project Objectives

- **Design** a payload carrier that:
  - Maintains ESPA Port Compatibility
  - Maintains ESPA Field of View Compatibility
  - Support six 400 [lb] payloads
- **Reduce mass** compared to legacy ESPA ring
- **Support payloads** through two 8.5 [g] loads radially and axially
  - 12 [g] Root Square Sum (RSS) load
- **Withstand** separation shock environment from a scaled separation system
- **Characterize** shock propagation

Current ESPA Design

SPACEMOD Design

SPACEMOD Design

Unscaled Model Dimensions:

- Mass - 214.6 lbs
    - **27% mass reduction** from traditional ESPA
- Base diameter - 63”
- Height - 19.6”

Scaled Model Dimensions:

- Mass* - 2.97 lbs
- Base diameter - 16.22”
- Height - 5.28”

***Estimated mass**

Quantitative Objectives

Project Element	Level 1 (Threshold)	Level 2 (Objective)	Level 3 (Target)
Launch Loads	**Perform scaled simulation** of 12 [g] RSS acceleration load test **with no simulated plastic strain**	**Perform scaled** 12 [g] RSS acceleration load test **and gathered data**	**Perform scaled** 12 [g] RSS acceleration load test, gathered data, **and scaled model withstood test with no plastic deformation**
Separation	**Simulate shock propagation** of the PSC 2000785G MkII MLB separation system	**Characterize shock propagation** of scaled model of the separation system **through testing and data gathering**	**Characterize shock propagation** of scaled model of the separation system through testing, data gathering, **and the scaled adapter experiences no plastic deformation**
Weight Reduction	Weight is reduced by **15%** compared to Standard ESPA	Weight is reduced by **25%** compared to Standard ESPA	Weight is reduced by **40%** compared to Standard ESPA

Concept of Operations

Manufacturing
6/25 scale at Aero Machine Shop

→

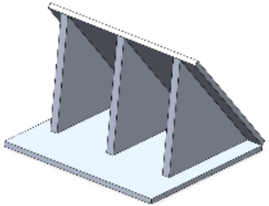
Shock Testing
Scaled PSC 2000785G MkII MLB

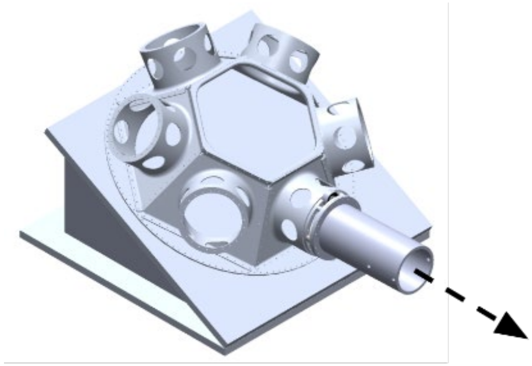
→

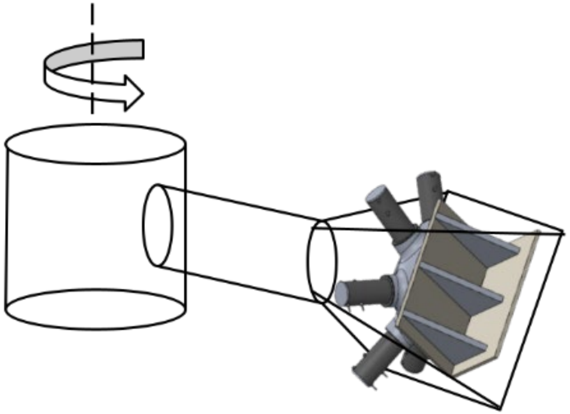
Centrifuge Testing
15.026g RSS load

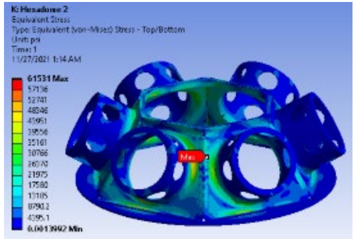
→

Model Validation
Test Data vs ANSYS Model

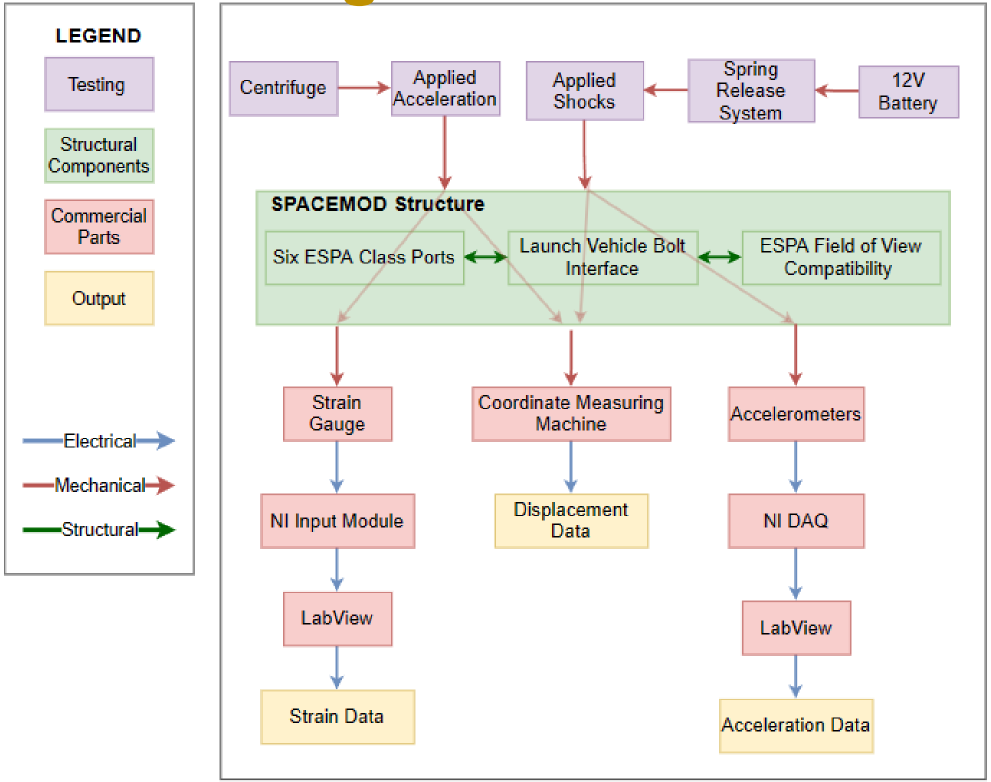








Functional Block Diagram

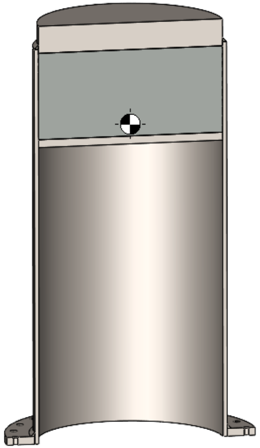


Most Important Critical Project Elements (CPE's)

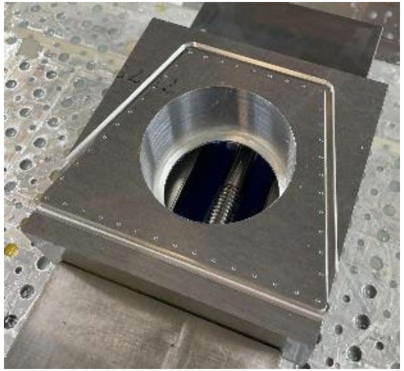
Category	CPE	Reasoning
1. Technical	**1.1** Manufacturing	**1.1** Manufacturability of model is necessary for testing
	1.2 Simulation and Validation	**1.2** Shock propagation must be characterized (DR 3.3)
	1.3 Testing and Analysis	**1.3** Necessary to verify FR 1, 2, 3
	1.4 Mechanical Design	**1.4** Design must withstand required loads and shocks
2. Logistical	**2.2** Data Recording and Presentation	**2.2** Physical product is not delivered; therefore, data and process are vital

Updates Since CDR

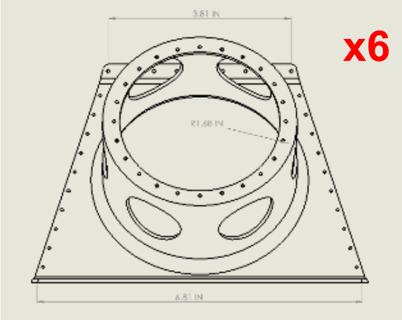
- Changed location of shock testing
  - From IdeaForge to Aerospace Building
  - Ease of testing
  - Access to accelerometers
  - Increased support from staff
- Adapted payload design
  - Provides a higher certainty of center of mass location
  - Lead mass to move CM location to desired spot while keeping design short



Manufacturing Status Update



- Top and Bottom ring have been completed
- Now working on manufacturing the six ports



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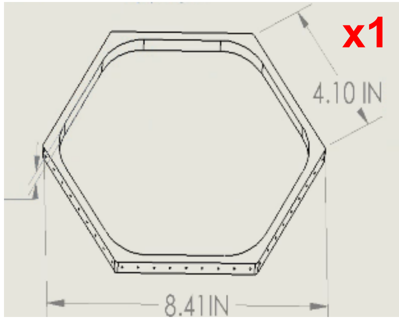

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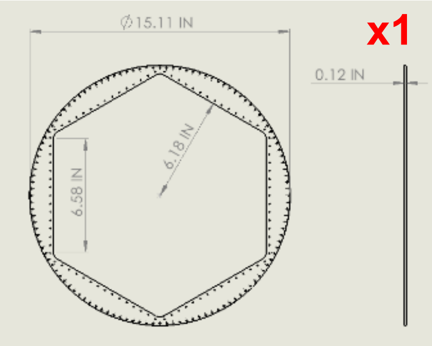

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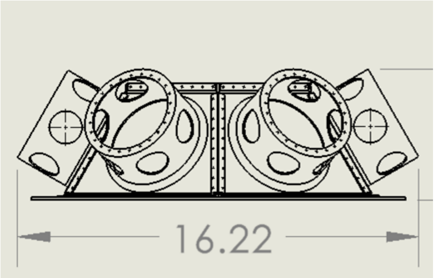
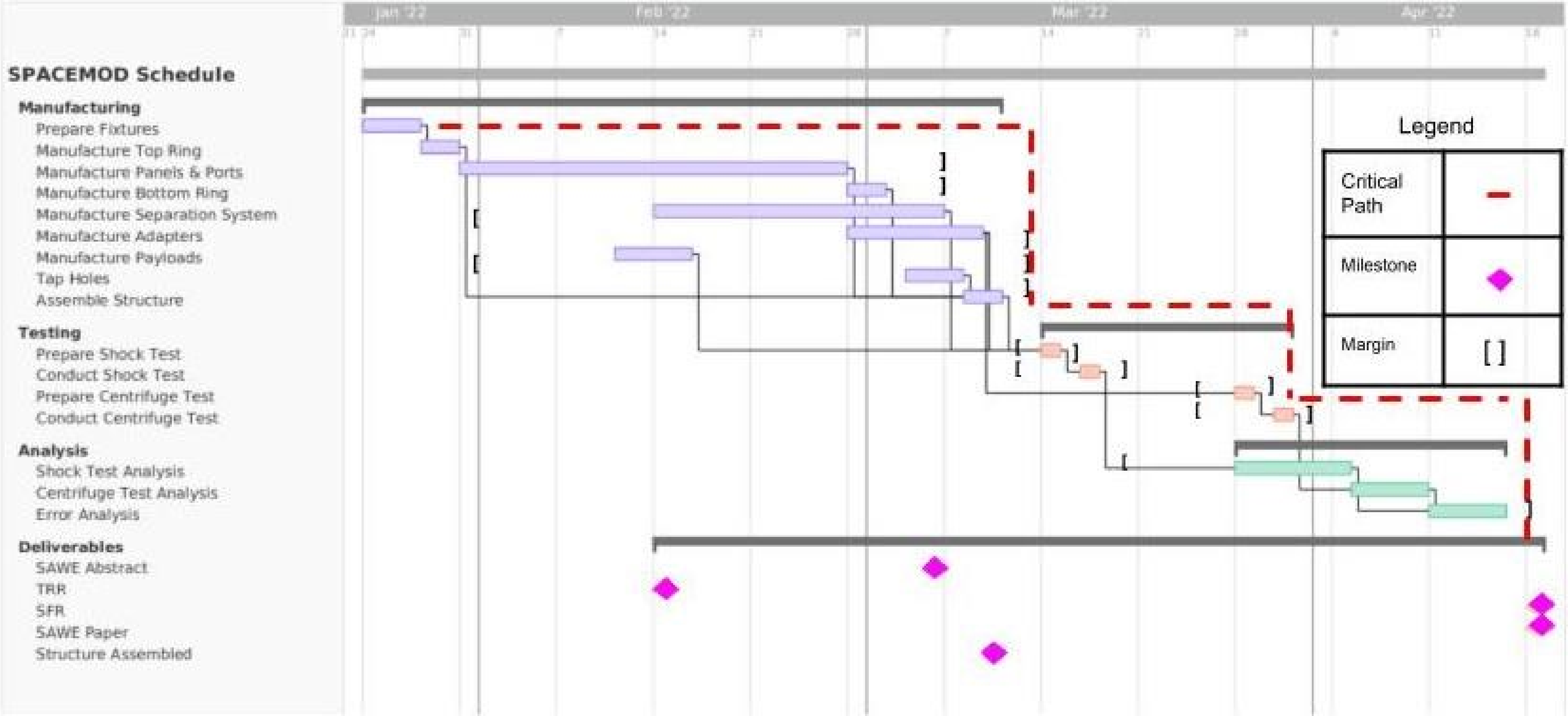


Schedule

Schedule Overview



Project Overview | Schedule | Test Readiness | Budget

Manufacturing and Testing Schedule

Week of 2/14	Begin manufacturing front side of ports Manufacture Payloads
Week of 2/21	Finish manufacturing ports Manufacture Seperation System
Week of 2/28	Transfer Punch and Tap Holes; Manufacture Side Stiffiners Manufacture Testing Adapters
Week of 3/7	Assemble SPACEMOD; Coordinate Measuring Machine
Week of 3/14	Shock Testing
	SPRING BREAK
Week of 3/28	Acceleration Testing

KEY

- Structural Manufacturing
- Testing Manufacturing
- Testing

Test Readiness

Tests To Be Conducted

Acceleration Testing

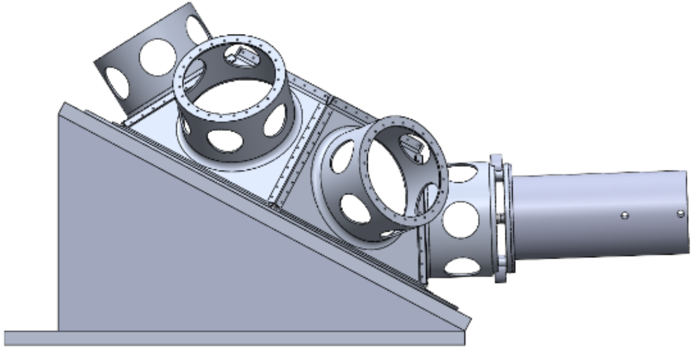
- Validate ANSYS model results
- Verify scaled model experiences no plastic deformation
- Conducted at the Center for Infrastructure, Energy, and Space Testing (CIEST)

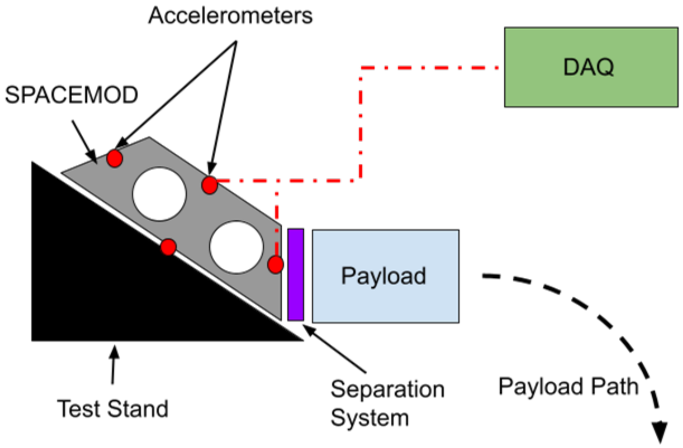
Shock Testing

- Validate shock characterization seen in our ANSYS simulation
- Verify scaled model can withstand typical separation shock environments
- Conducted in Aero Building

Shock Testing

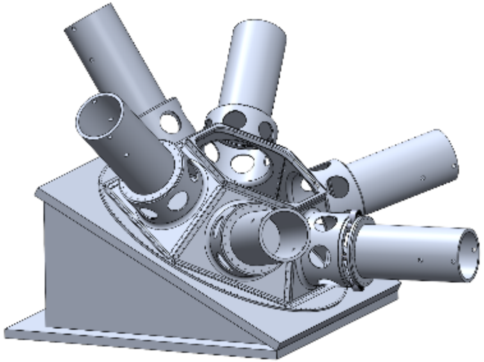
- Characterize shock propagation using sensitive accelerometers placed along surface; acceleration versus time and frequency spectrum plots to be generated.
- Ensure no plastic strain occurs during payload separation.

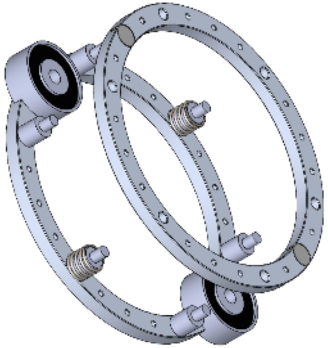


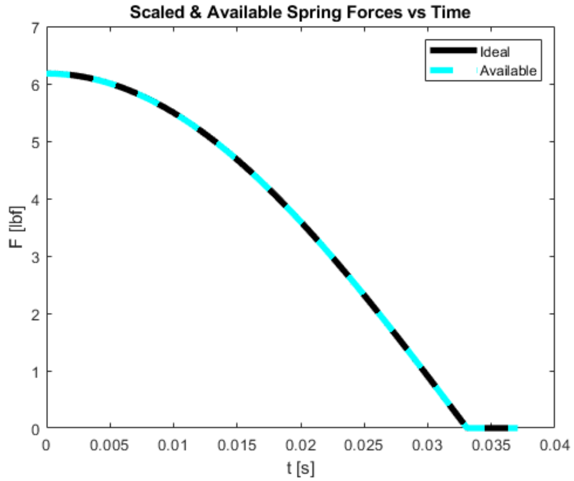


Shock Testing: Separation System Design

- Models Planetary Systems Corp. (PSC) separation system (2000785G MkII MLB)
  - Peak acceleration of ~1.2 [g]
- Dual Spring Electromagnetic release mechanism
  - Follows scaled 2000785G MkII MLB force curve
  - Peak acceleration of ~1.2 [g]

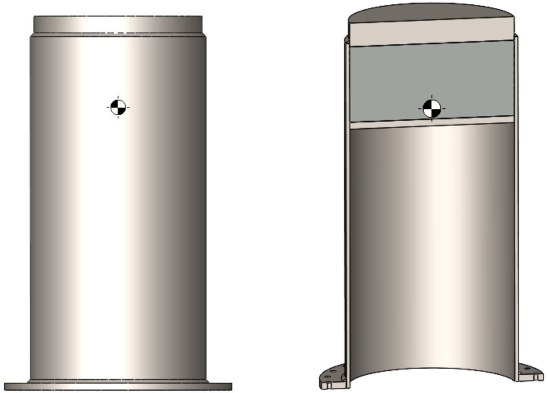


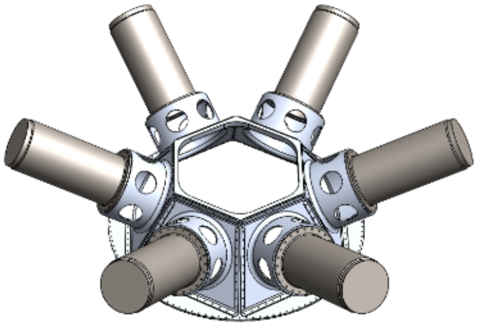




Shock Testing: Payload Design

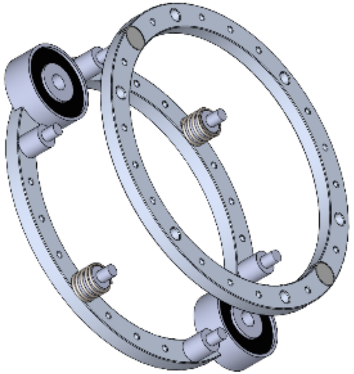
- ESPA class payloads have specific predefined constraints
- Dummy Payloads are designed to replicate the <u>maximum</u> allowed payload weight & CG
- ESPA Class payloads are maximally 400 [lbs] with a CG 20 [in] away from ESPA port
- At scale, these are 5.52 [lb] with a CG 4.74 [in] away from the port





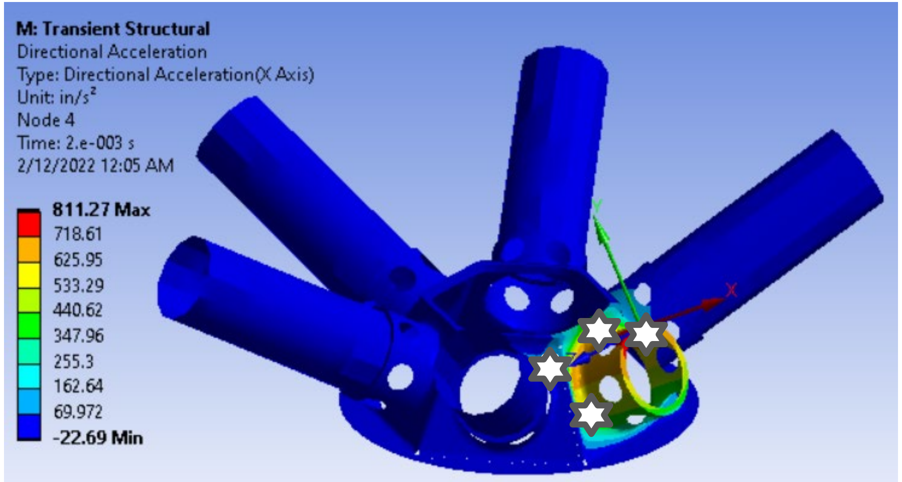
Shock Testing: Equipment and Facility

- Equipment
  - Coordinate Measuring Machine (CMM)
  - Dummy payloads
  - Separation system
  - Accelerometers
  - DAQ & host computer
  - Battery
  - Safety
    - Foam placed on floor to “catch” separated payload.
    - Plexiglass screen will be placed between SPACEMOD and testing members when system is disengaged.
- Facilities
  - Engine Test Cell (Aerospace Building)
  - Advanced Precision Machining

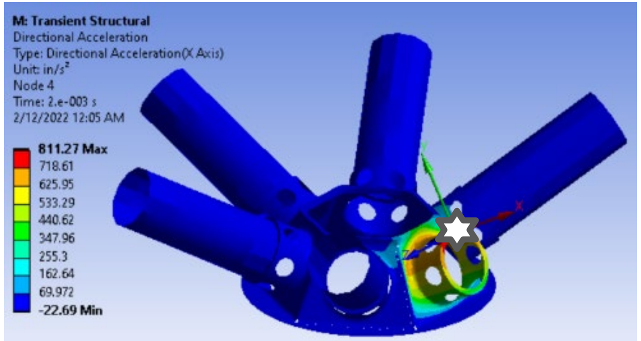


Shock Testing: Placement

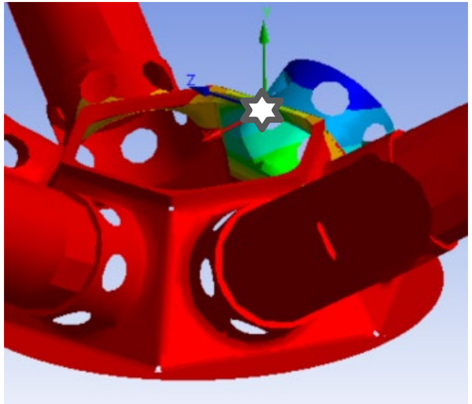
- Placement
    - Three sensors will be placed on the separation panel
    - One sensor will be placed on the panel next to the separation panel
    - These points are predicted to experience the highest accelerations, thus giving us more accurate data, less susceptible to sensor resolution limitations.
- Accelerometers (Piezotronics C22 and C23) have resolutions of (1.57 and 1.18 in/s², respectively).
    - We expect to see 760 in/s² and 46.8 in/s² at our highest and lowest acceleration points



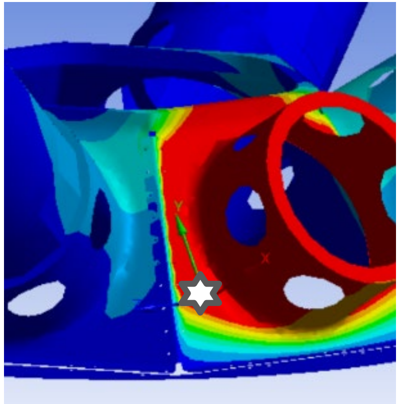
Shock Testing: Placement



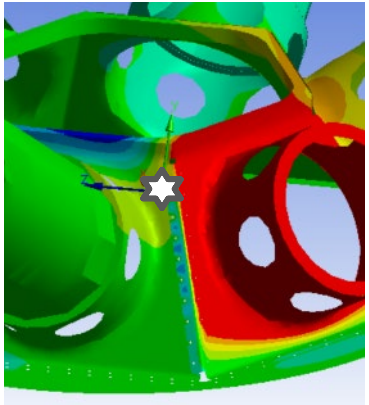
Location of acceleration probe 1



Location of acceleration probe 2



Location of acceleration probe 3



Location of acceleration probe 4

Shock Testing: Procedure

Before Testing:

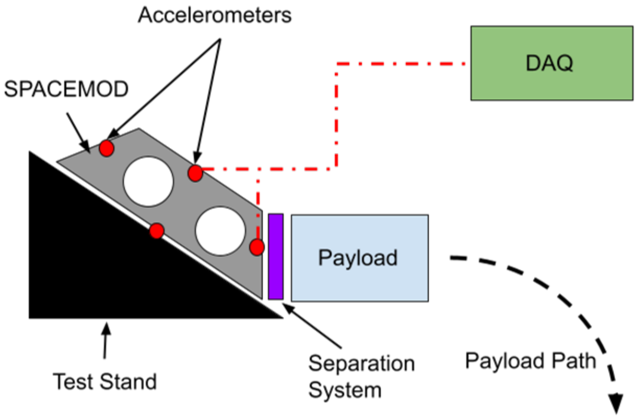
1. Use Coordinate Measuring Machine (CMM) to 3D map SPACEMOD structure
2. Set up structure with payloads, separation system, and accelerometers
3. Wire accelerometers to input module, set up host computer, and power separation system

During Testing:

1. Release separation system
2. Full procedure in [Shock Testing Procedure (STP) document]

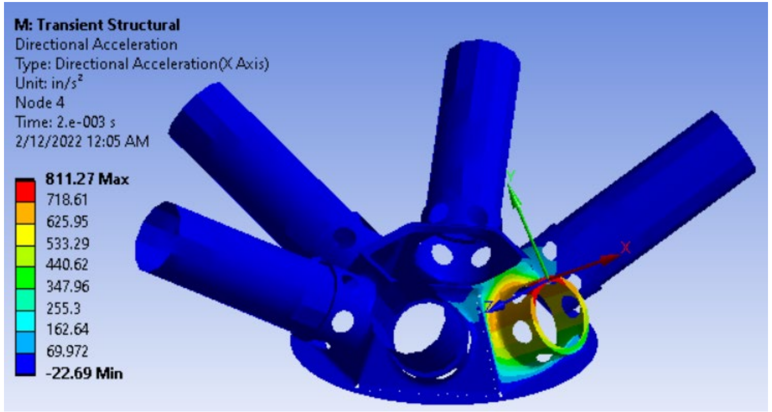
After Testing:

1. Analyze output data to confirm model findings
2. Use Coordinate Measuring Machine to ensure no plastic deformation occurred after shock

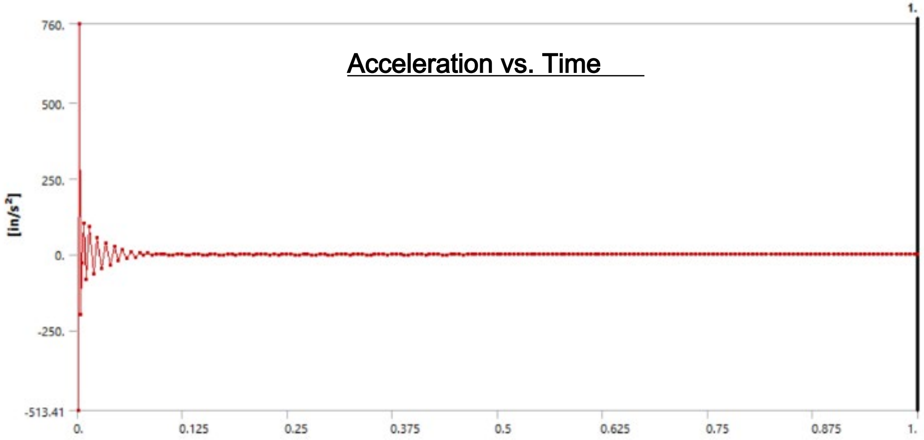


Shock Testing: Expectations

- Models to validate:
  - Spring release mechanism transient structural response in ANSYS Mechanical
  - Same model set-up as shown in CDR with scaled geometry
  - Scaled model acceleration values are used for model comparison



Location of acceleration probe 1



Shock Testing: Limits

- Friction
  - There will be friction losses between guide pins and payload, resulting in a less aggressive deployment shock. (Guide pins will be lubricated to compensate)
- Gravity
  - Payloads won't necessarily follow the same path post-deployment as they would in space.
- Mounting Fixture
  - Some of the shock will also propagate through the mounting structure, resulting in a differing transient response.

Shock Testing: Verification and Validation

FR 3 The SPACEMOD shall maintain structural integrity and additional payload attachment when exposed to a scaled, simulated payload separation shock, which will be characterized.

CPE 1.4 Design must withstand required loads and shocks

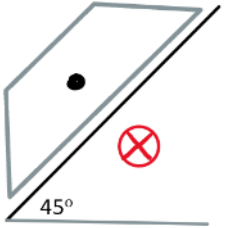
- Test provides a scaled simulated separation shock with our own developed separation system.
- Accelerometers will be placed on the surface of SPACEMOD, and acceleration vs time data generated for various points along structure.
- Coordinate Measuring Machine at Advanced Precision Machining will be used to ensure plastic deformation hasn’t occurred.
- Characterization of shock propagation higher priority than physical performance due to non-physical deliverable of project

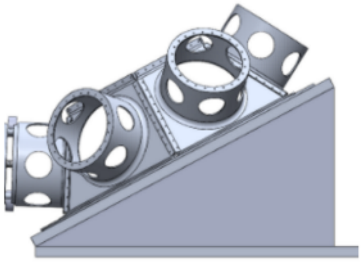
Acceleration Testing

- Ensure that our design can survive launch conditions

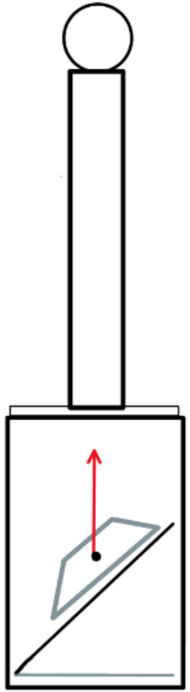
- 8.5g in the axial and radial directions with a FOS of 1.25 (15g RSS load at a 45 degree angle)

Placed into Centrifuge: Side View





Top-Down View as Centrifuge is Spun Up

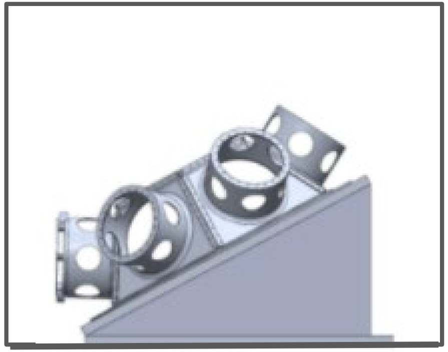


Acceleration Testing: Equipment and Facility

Equipment:

- SCXI-1520 DAQ
- Strain gauges
  - CEA-13-062UB-350
- 15 g/ton Centrifuge
- Host computer
- SPACEMOD structure
- 18x17.5x23 inch dimensions

<-23 inches ->

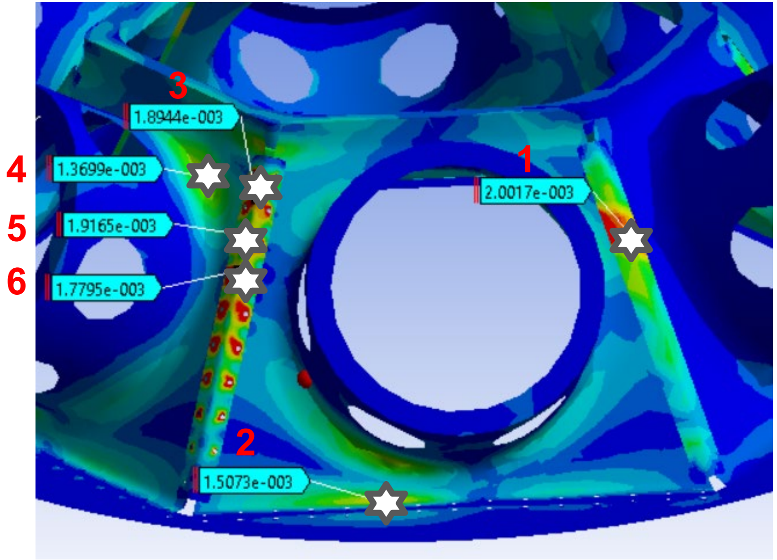


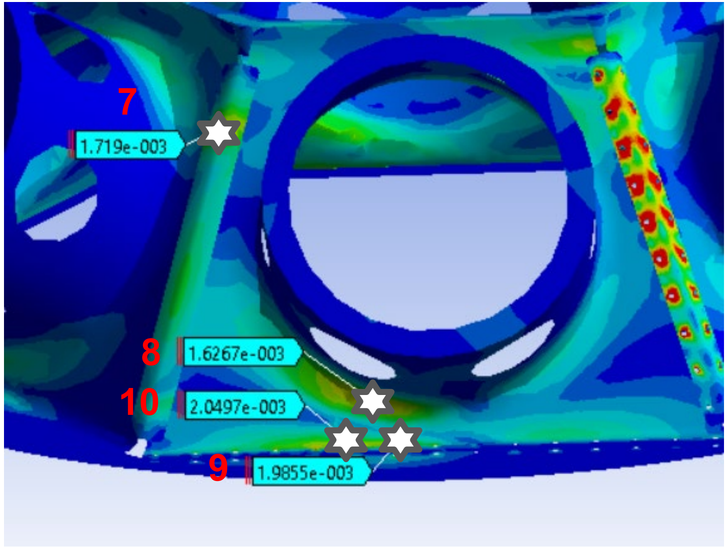
<- 18 inches ->

Facility:

- CIEST Laboratory
- Advanced Precision Machining

Acceleration Testing: Strain Gauge Placement





- Strain Gauges are spread out over the ten places of highest stress/strain on the structure that are most likely to plastically deform.

Acceleration Testing: Strain Gauge Sensitivity

- Strains larger than 1000 με will result in good data and anything under 400 με cannot be differentiated from background noise by SCXI 1520

Strain Gauge	1	2	3	4	5	6	7	8	9	10
Measured Strain (με)	2002	1507	1894	1370	1917	1779	1719	1637	1986	2050
Change in Voltage (mV)	-10.238	-7.710	-9.686	-7.010	-9.804	-9.099	-8.793	-8.374	-10.156	-10.483

Acceleration Testing: Procedure

Before Testing:

1. Use Coordinate Measuring Machine (CMM) to 3D map SPACEMOD structure
2. Strain gauges applied to high stress points
3. Wire strain gauges to input module

During Testing:

1. Centrifuge operated by CIEST staff.
2. Full procedure in Medium Centrifuge Operation Manual

After Testing:

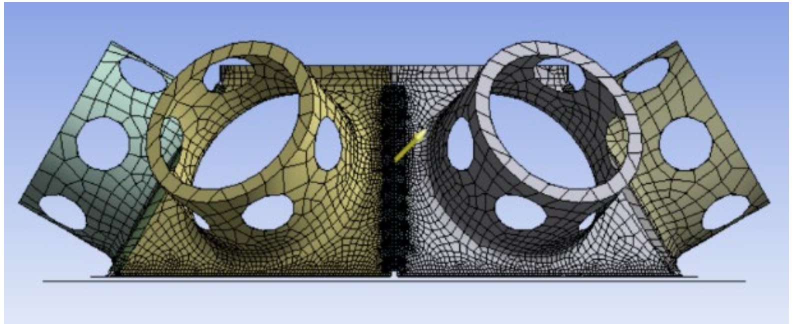
1. Analyze output data to confirm model findings
2. Use Coordinate Measuring Machine to ensure no plastic deformation occurred after loading

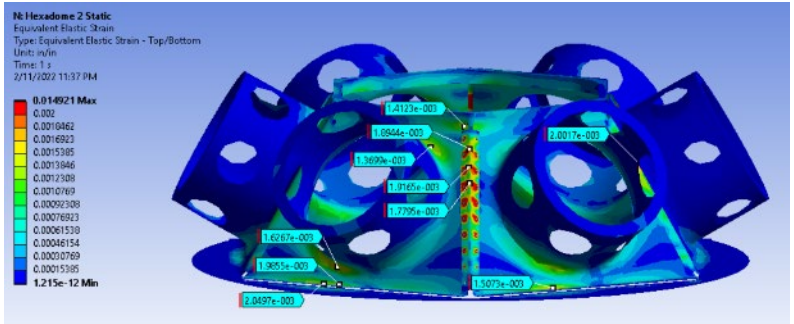
Acceleration Testing: Centrifuge Safety

1. Listen to instructions of centrifuge operator
2. Follow Medium Centrifuge Operation Manual
    a. PPE
    b. Loose wires
    c. Protrusions
    d. Balance
    e. Dry runs
3. Detailed procedure found in Acceleration Testing Procedure (ATP)
    a. Document includes strain gauge preparation, safety, etc.

Acceleration Testing: Expectations

- Models to validate:
  - Static RSS acceleration vector applied to entire structure
  - Same model set-up as shown in CDR with scaled geometry
  - Scaled model acceleration values are used for model comparison
- Validation method:
  - Comparison between static model strain values and test strain values
  - Model error calculated as a function of deviation from reality





Acceleration Testing: Limits

- Due to the centrifuge size being comparable to the SPACEMOD design's height within the centrifuge bucket the entire design will not undergo a 15g acceleration load
  - While this source of error is unavoidable, the changes it will make to the results are calculated to be a +/- 20% in acceleration loading and can therefore be accounted for in the analysis
- We will only be able to compare strain in the design to the simulation at 10 points, limited by the number of strain gauges.
  - This is offset by the use of a Coordinate Measuring Machine before and after testing which will allow us to compare the before and after map of the structure to highlight any plastic deformation not picked up by our 10 strain gauges

Acceleration Testing Verification and Validation

FR 1 The SPACEMOD scaled payload carrier shall maintain structural integrity and payload attachments when exposed to launch-like loads.

CPE 1.4 Design must withstand required loads and shocks

- Strain Gauges are used to verify the stresses and strains seen in the analysis within the structure
- Comparison of the real structure strain gauge data and the analysis simulation allows for unforeseen plastic deformation/high stress concentrations within the structure to be identified by the SPACEMOD team
- Any unforeseen plastic deformation and high stress concentrations can then be measured using a CMM

Budget

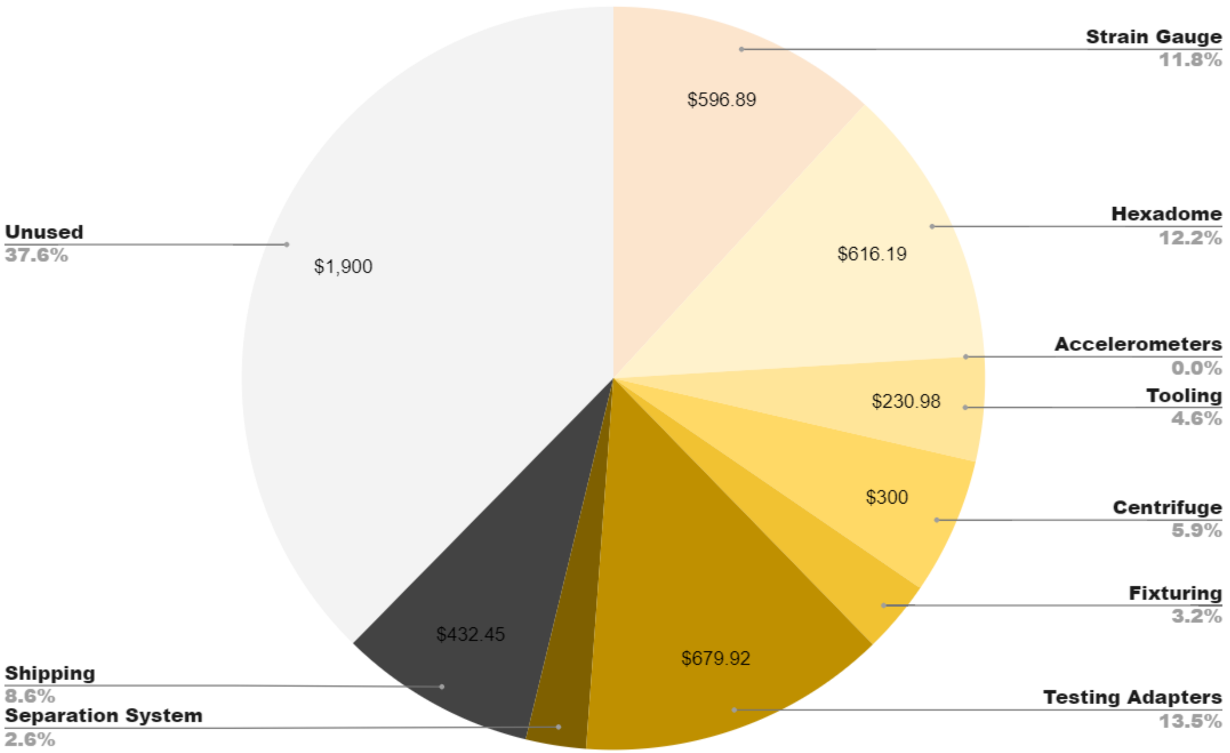
Budget Outline

Month	Parts Ordered	Shipments Received	Total Spent
December	20	5	~$2100
January	8	19	~$550
February	6	9	$650
Future	0	1 **	~$350.00*
TOTAL:	34	33 (So Far)	$3,650.00

*Testing with Centrifuge at CIEST

**Strain Gauges on backorder

Budget Allocation



Budget Overview

High level purchase/receiving overview:

- 34 uniquely ordered shipments
- >106 unique parts w/o screws
- 11 total orders

Project Critical Parts:

- Panel Machining Failure
    - Secondary stock identified and orderable w/in 3 days (<$360)
- Accelerometer and Strain Gauges both large lead time and expensive
    - Contingent strain gauges identified within CU community or identified for purchase with quick turnaround time.
    - Heavy risk mitigation plan to minimize likelihood of “breaking”

Acknowledgements

The ULA team would like to thank Dr. Donna Gerren, Matt Rhode, Nate Coyle, Professor Wingate, and Teaching Fellow Emma Markovich for their contributions in guiding and shaping the content and organization of this presentation.

Thank you to everyone who supported the SPACEMOD team!

References

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Questions?

Backup Slides

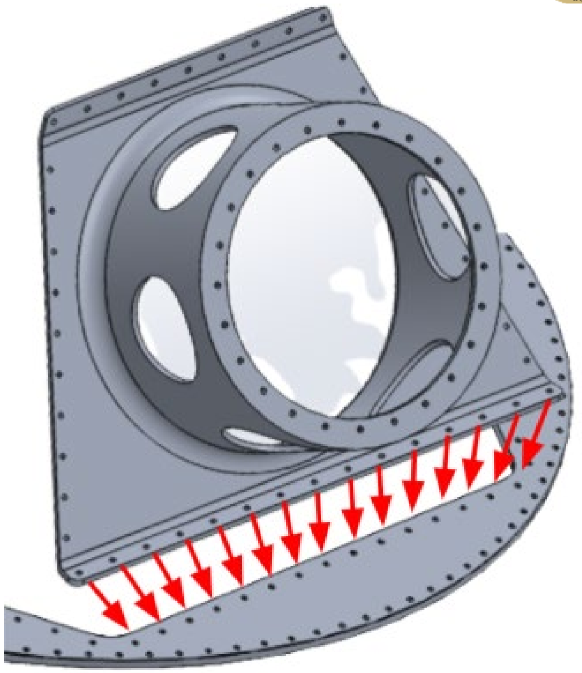
Concept of Operations: A Day in the Life

Sources: 2021 Spaceflight Inc. [4] & 2020 NASA [2]

Manufacturing Tolerances

- Manufacturing tolerance is **+/- .005”**

- In order to ensure the pieces fit together, we will be **transfer punching** the holes
  - All holes on the port itself are being drilled by the CNC
  - Using the holes drilled in the ports, we will transfer punch onto the connecting pieces



Acceleration Testing: Strain Gauge Sensitivity

- Equation's to the right were used to solve for the change in voltage that will be measured by the SCXI 1520 machine.
- Using an input of strain, a gauge factor of 2.05, a lead resistance of 0.05329 Ω (wire resistance of 0.01015 Ω/ft), and an excitation voltage of 10 volts, the change in voltage seen (Vch(strained) - Vch(unstrained)) can be computed.

$$strain\ (\varepsilon) = \frac{-4V_r}{GF(1+2V_r)} \times \left(1 + \frac{R_L}{Rg}\right)$$

$$V_r = \left(\frac{V_{CH}(\text{strained}) - V_{CH}(\text{unstrained})}{V_{EX}}\right)$$

Fig: Equations used to compute change in voltage seen by SCXI 1520

Acceleration Testing: Strain Gauge Sensitivity

- Strains larger than 1000$\mu\epsilon$ results in a good measurement by SCXI 1520
- Voltage output is preferred to be within 5 - 10mV with lowest possible being 2mV corresponding with a strain of 400$\mu\epsilon$
- Therefore minimum strain that can be recorded by SCXI 1520 is 400$\mu\epsilon$

Acceleration Testing: Strain Gauge Sensitivity

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\epsilon}$$

Fig: Equation for change in resistance

$$\textit{quarter bridge} = (\textit{max strain}) \times (\textit{excitation voltage}) \times (0.5\ \mu V/V/\mu\varepsilon)$$

Fig: Equation for maximum voltage that can be measured by SCXI 1520

Strain Gauge	1	2	3	4	5	6	7	8	9	10
Strain Expected (με)	2002	1507	1894	1370	1917	1779	1719	1637	1986	2050
Maximum Voltage that can be Measured (mV)	10.010	7.535	9.470	6.850	9.585	8.895	8.595	8.185	9.930	10.250
Change in resistance for given strain (Ω)	1.436	1.0813	1.359	0.983	1.375	1.276	1.233	1.175	1.425	1.471

Shock Testing: NI 9234 DAQ

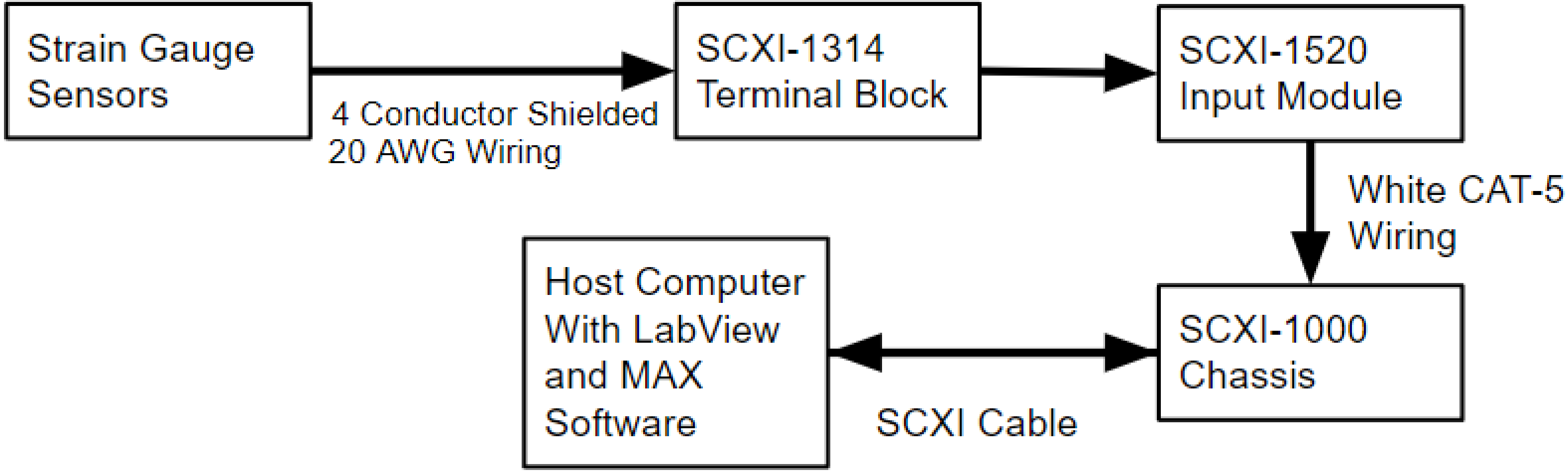
DATASHEET

NI 9234

4 AI, ±5 V, 24 Bit, 51.2 kS/s/ch Simultaneous, AC/DC Coupling, IEPE AC Coupling

- Software-selectable AC/DC coupling (AC coupled at 0.5 Hz)
- Software-selectable IEPE signal conditioning with AC coupling (2 mA)
- -40 °C to 70 °C operating, 5 g vibration, 50 g shock
- 24-bit resolution
- Anti-aliasing filters
- 102 dB dynamic range
- Smart TEDS sensor compatibility

Acceleration Testing DAQ Model



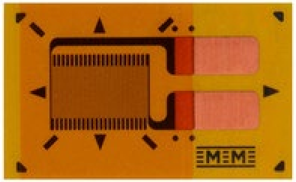
Shock Testing:
Data Acquisition & Software

- NI 9234 DAQ
  - 4 accelerometer inputs
  - Sampling frequency up to 51.2 kHz
  - Built-in anti-aliasing filter that adjusts to sampling rate
- NI cDAQ-9174 Chassis Connected to Laptop via USB

Acceleration Testing: Equipment and Facilities

Equipment:

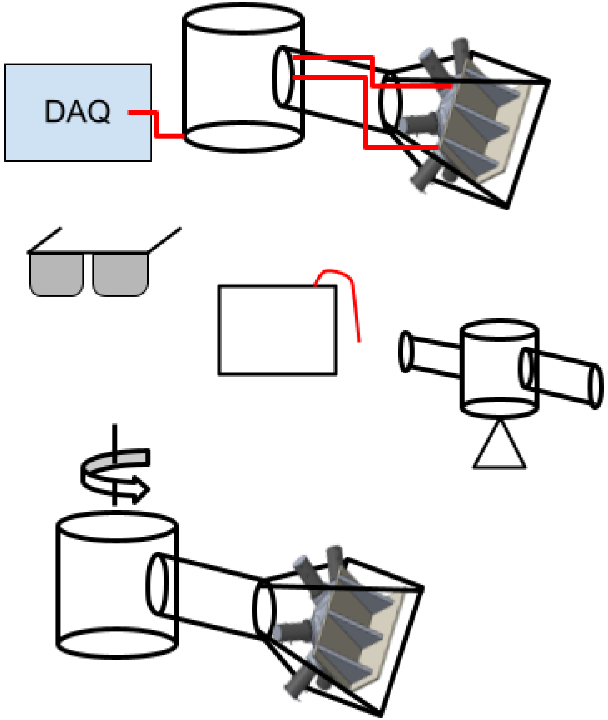
- Strain Gauges Designation:
  CEA-13-062UB-350
- Strain Gauge Wiring:
  4 Conductor Shielded 20 AWG Wiring



Acceleration Testing: Equipment and Facilities

- CIEST Lab Data Acquisition System:
  - NI SCXI-1520 Input Module
    - 10 Strain gauge channels utilized over 2 modules, 8 channels per module
- MAX software is used to configure strain gauge channels
- Customizable Labview software is used to output strain measurements vs time in .csv file

Acceleration Testing: CONOPS



1. Test Setup
   a. Strain Gages
   b. Wiring
2. Safety Check
   a. PPE
   b. Loose Wires
   c. Protrusions
   d. Balance
   e. Dry Runs
3. Test

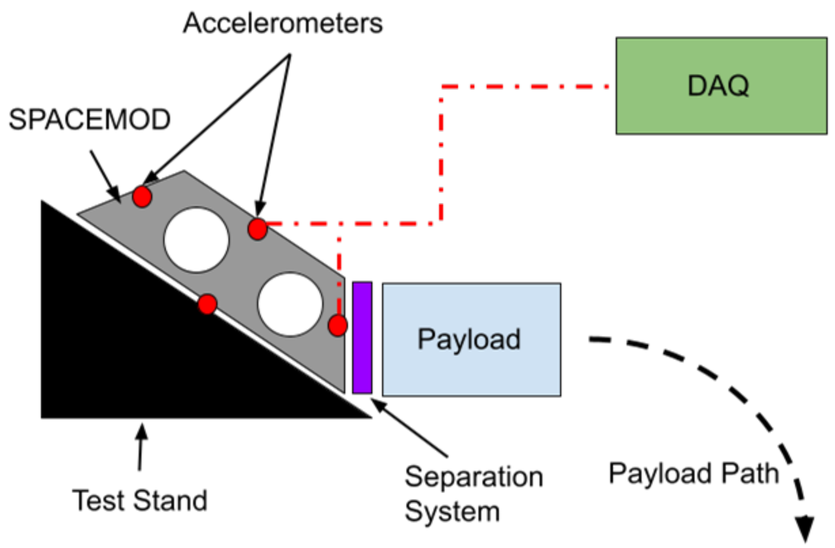
Shock Testing: Status

	Description	Status
Facility	Test will be based in Engine Test Room (Aero)	
Equipment	• PCB Piezotronics Model U35C22 • PCB Piezotronics Model 353B17 • DAQ • Miscellaneous Safety	
Model	ANSYS Transient Analysis	✓
Procedure	Shock Testing Procedure (STP) Document	✓

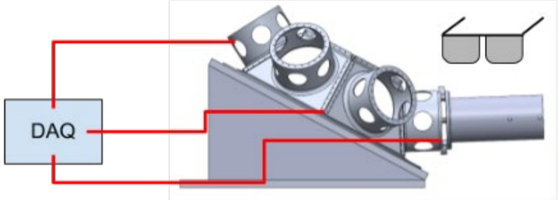
Shock Testing: Procedures

- Outlined in detail in [Shock Testing Procedure (STP) document]

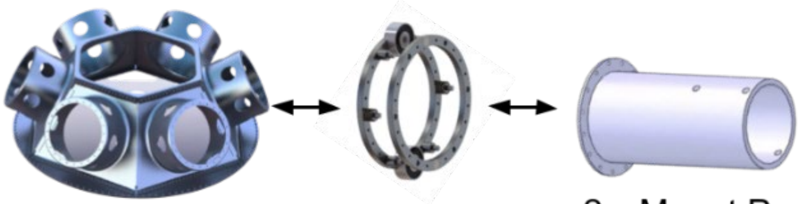
1. PPE
2. Test stand setup
3. Electronics and Software
4. Arm separation system
5. Separate



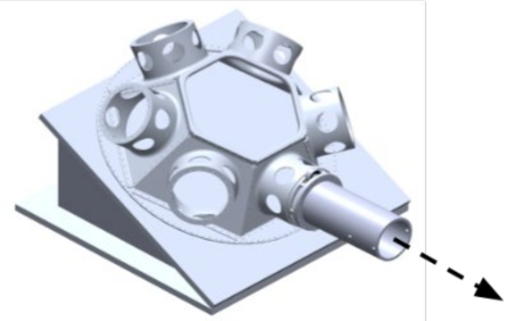
Shock Testing CONOPS



1. Test Setup
    a. PPE
    b. Stand
    c. Accelerometers



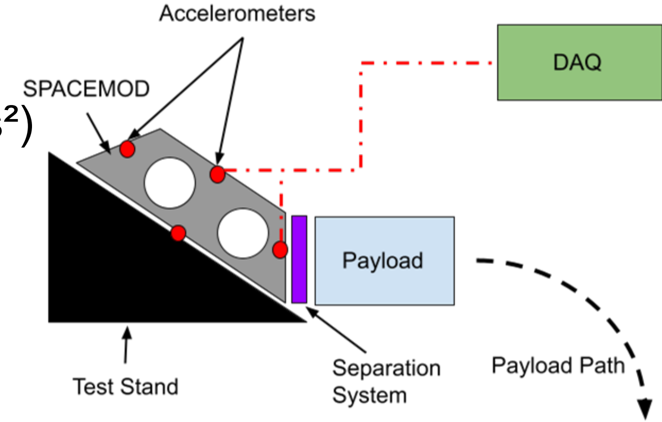
2. Mount Payload



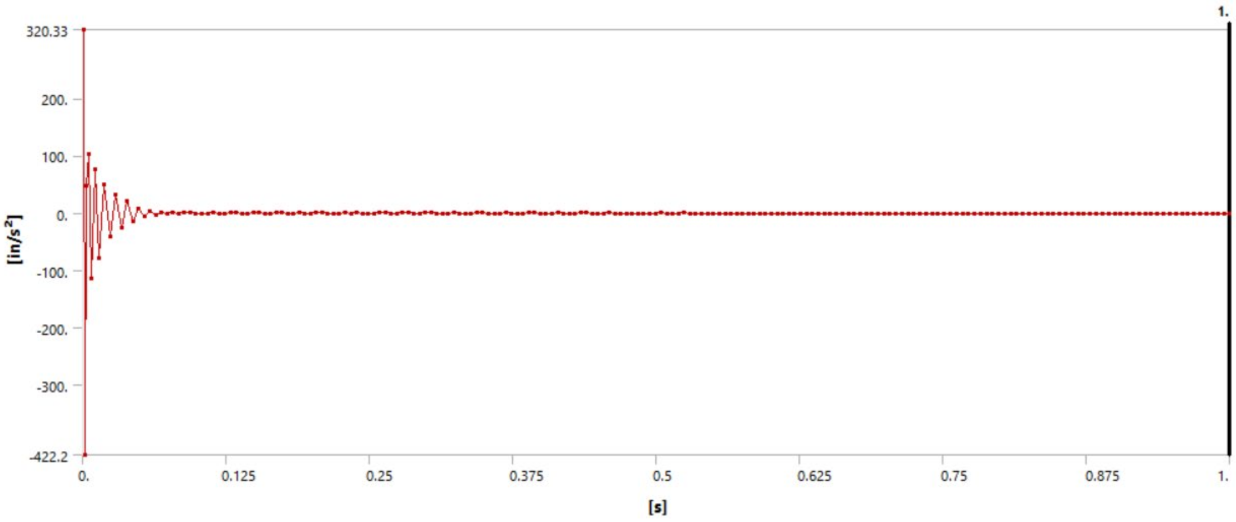
3. Test

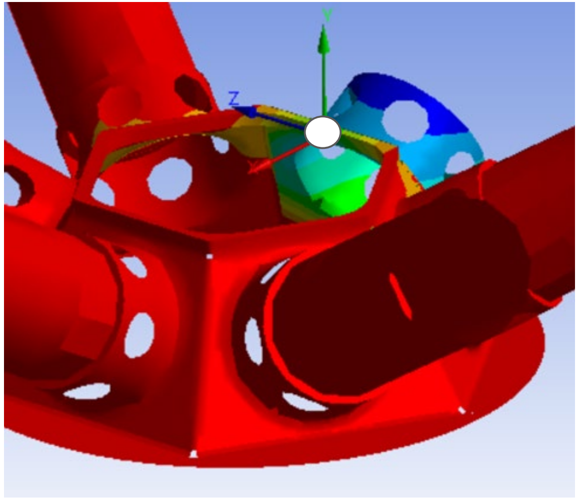
Shock Testing: Accelerometers

- Accelerometers selected:
  - PCB Piezotronics Model 352C22
    - Frequency Range: (±5%) 1-10000 Hz
    - Resolution: 0.004 g rms (0.04 m/s² rms, 1.57 in/s²)
  - PCB Piezotronics Model 352C23
    - Frequency Range: (±5%) 2-10000 Hz
    - Resolution: 0.003 g rms (0.03 m/s² rms, 1.18 in/s²)



Shock Testing: Acceleration Plots

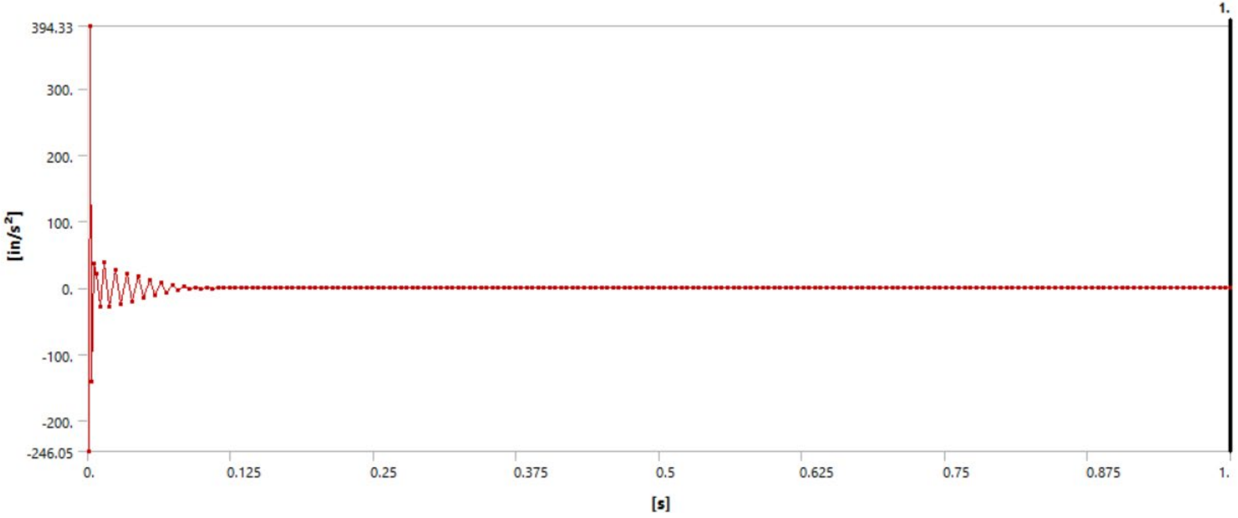


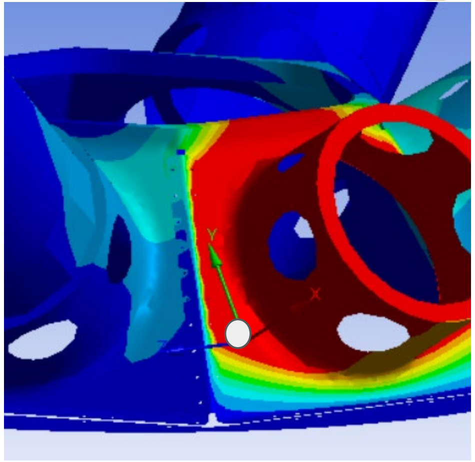


Probe 2 Acceleration vs Time

Estimated Frequency:
120 Hz

Shock Testing: Acceleration Plots

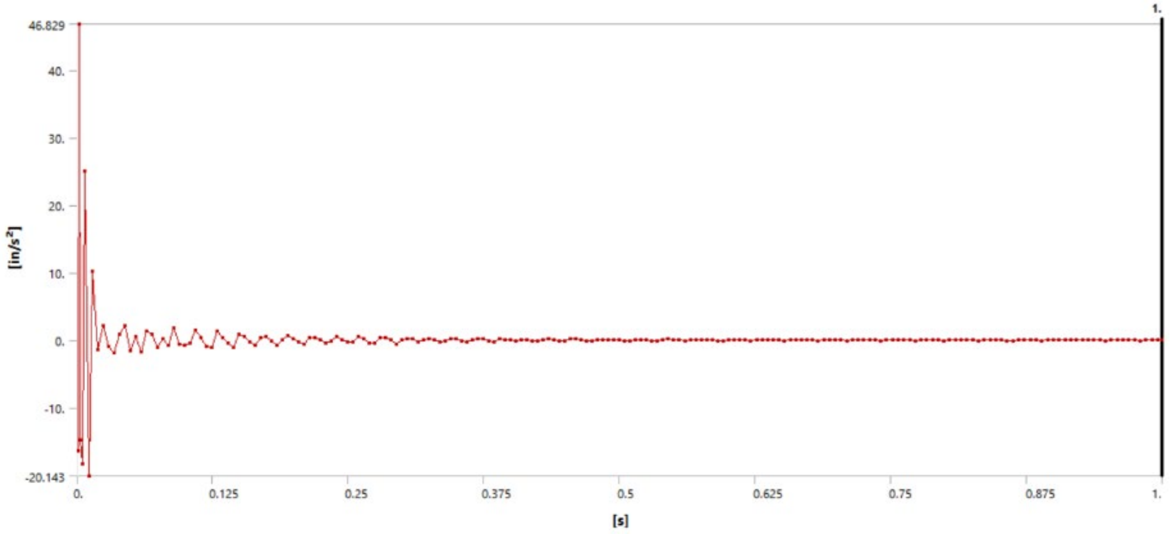




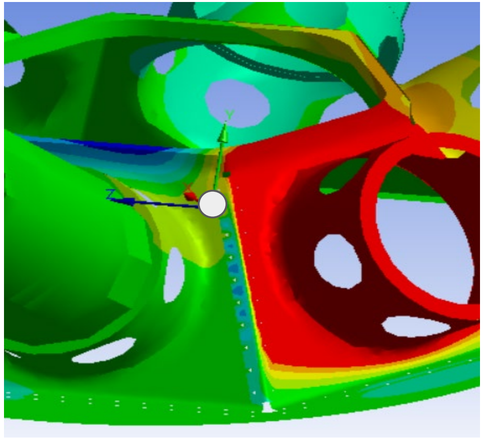
Probe 3 Acceleration vs Time

Estimated Frequency: 100 Hz

Shock Testing: Acceleration Plots



Probe 4 Acceleration vs Time



Estimated Frequency:
110 Hz

Shock Test Safety Checklist

Pre-checklist	1. All members wear closed-toe shoes and pants.
Separation System Priming	1. All members don safety glasses. 2. All members but three stand behind screen (4ft away). 3. No flagging - payload must never be pointed at anything that is not willing to be destroyed. 4. As soon as springs are depressed and magnets are engaged, clamps are applied.
Separation	1. Clamps are removed. 2. All team members stand behind screen. 3. Separation is performed.

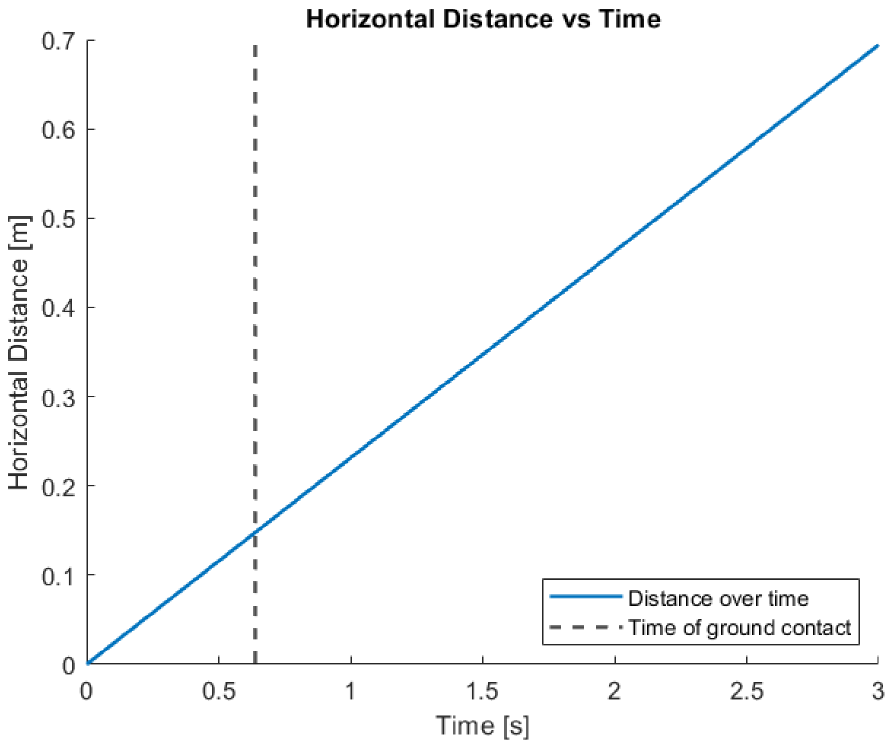
Acceleration Test Safety Checklist

Pre-checklist	1. All members wear closed-toe shoes and pants. 2. All members wear safety glasses and hard hats.
Pre-Spin Up	1. Follow Safety Guidelines in Medium Centrifuge Operation Manual. Summarized: 2. Remain in proximity of emergency stop 3. Make sure all wires are tied down, secured, will not catch, etc. 4. Make sure no objects are on floor of centrifuge. 5. Make sure weight is centered and balanced. 6. Make sure nothing protrudes too far out of bins. 7. Make sure there is enough slack in wires. 8. Manually push through several rotations. 9. Check the motor and slip ring column for impedances. 10. Check that FA-ISOCON wires are secure.

Safety Considerations

- Manufacturing
  - Aero Machine Shop safety regulations
  - Lead Melting Procedure
- Acceleration Testing
  - CIEST Lab Safety Procedures
- Shock Testing
  - Only two team members may prime separation system; all others must be behind a screen and not in the direct line of fire at at distance of at least 4 ft (projected launch distance of 6in yields FOS of 7.9)
  - All team members must wear safety glasses throughout procedure
  - Do not point payload separation system at anything you do not want to be destroyed
  - Push separation system into place, engage electromagnets, and apply clamps
    - One to two team members remove clamps while keeping body parts outside of payload launch direction
    - These team members move behind screen with rest of team
    - Test is immediately conducted thereafter (i.e. electromagnets are disengaged)

Shock Test Launch Distance




```
Final x distance traveled: 0.154202 m
Final x distance traveled: 6.070956 in
```

- Assuming y_0 = 2 meters
  - Extreme over approximation
- All team members must be 4 ft away (FOS = 7.9) and not in direct line of fire

Lead Safety Precautions

Full procedure found in Lead Melting Procedure

1. Travel to outdoor, isolated location
2. PPE
    a. Respirators
    b. Gloves
3. Dust floor with sweeping floor compound
4. Melt lead
5. Wipe down payloads
6. Vacuum with HEPA shop vac
7. Dispose of PPE and lead dross
8. Wash hands, shower, launder clothes