Design and Analysis of the JWST Integrated Science Instrument Module (ISIM) Primary Metering Structure

by
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NASA/GSFC Code 542 & Swales Aerospace

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- Introduction
  - JWST, OTE, & ISIM
  - ISIM Structure Design Status
- ISIM Structural Requirements & Challenges
- Description & Evolution of the Primary Structure
- Finite Element Models
- Baseline Structure Performance Predictions
  - Normal Modes
  - Structural Integrity under Launch Loads
- Further Improvements
- Summary & Conclusion
JWST
James Webb Space Telescope

Optical Telescope Element
OTE

Integrated Science Instrument Module
ISIM

Spacecraft Element
Spacecraft Bus
Sunshield

Courtesy of John Nella, et al. Northrop Grumman Space Technology
ISIM Overview

- ISIM Structure is being designed by GSFC.
- Swales Aerospace substantially contributing to ISIM design and analysis.
- ISIM Instruments are being provided by different agencies.
- ISIM Structure successfully passed PDR (Preliminary Design Review) in January 2005 and meets all design requirements.
- Detailed Design & Analysis of the Structure is in progress.

Total Mass = 1140 kg
ISIM Structure Critical Requirements & Major Challenges

- Scientific Instrument (SI) Accommodations
  - Volumes & Access
- SI & OTE Interfaces
- Total Supported Mass of 1140 kg
- Structure Mass Allocation of 300 kg
- Minimum Fundamental Frequency
  - 25 Hz with margin
- Structural Integrity under Launch
- Thermal Survivability
  - Survival Temp= 22 K
  - Operating Temp= 32 K
- Alignment/Dimensional Performance
  - Launch & Cool-Down to 32 K
  - Operational Stability at 32 K

Design a Structure that satisfies these Constraints and meets the following Challenging Requirements:

**Challenge#1**
Launch Stiffness & Strength

**Challenge#2**

**Challenge#3**
Launch Design Limit Load (DLL) Factors

**ISIM Primary Structure Launch DLL Factors, g’s**

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Thrust (V3)</th>
<th>Lateral (V1,V2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Compression</td>
<td>-6.44</td>
<td>1.5</td>
</tr>
<tr>
<td>Max Tension</td>
<td>+3.25</td>
<td>1.5</td>
</tr>
<tr>
<td>Max Lateral</td>
<td>-3.65</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*a - Lateral loads are swept in the V1-V2 plane*

**Instrument & Instrument Interfaces Launch DLL**

Based on an Enveloping Mass-Acceleration Curve and weight of instrument:

- MIRI: ±13.5 g one axis at a time
- All other SIs: ±12.0 g one axis at a time
Factors of Safety (FS) for Flight Hardware Strength Analysis

<table>
<thead>
<tr>
<th>Type of Structure</th>
<th>Qualification by</th>
<th>FS ultimate</th>
<th>FS yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallic</td>
<td>Analysis &amp; Test</td>
<td>1.40</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>Analysis only</td>
<td>2.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Mechanical Fastener</td>
<td>Analysis &amp; Test</td>
<td>1.40</td>
<td>1.25</td>
</tr>
<tr>
<td>Composite Material</td>
<td>Analysis &amp; Test</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>Adhesive</td>
<td>Analysis &amp; Test</td>
<td>1.50</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Notes:

1 FS listed apply to both mechanically and thermally induced loads. Strength Margin of Safety, MS = Allowable/(FS * Applied) - 1

2 Use of an additional fitting factor (typically 1.15) is at the discretion of the analyst.

3 For tension fasteners, use an FS of 1.0 on torque preload tension. Maintain a minimum gapping FS of 1.25.

4 Localized yielding of adhesive that does not undermine performance is acceptable.
ISIM Baseline Structure Overview

Frame type construction selected
• provides good access to SIs
• structurally more efficient than plate construction for supporting discrete mounting points of SIs. Verified this through early concept studies.

Carbon Fiber Composite Materials used for Primary Structure Members
• Biased Laminate with
  • High specific stiffness
  • Near-zero CTE
• 75 mm square tubes with 4.6 mm wall thickness
• Length~75 m, Mass~130 kg

Kinematic Mounts to OTE
• 2 Bipods (Ti-6Al-4V)
• 2 Monopods (Tubes+Ti-6Al-4V Post Flexures)
• Total Mass~25 kg
Baseline Structure Overview
Metal Joints

- Use of metal minimized due to structure weight limitations
- Metal parts used where absolutely necessary to make joints strong and stiff enough such as Plug Joints and Saddle Mounts (at SI interfaces)
- All metal parts bonded to composite tubes have to be INVAR for thermal survivability
- Adhesive: EA 9309

Total Mass of Metal Plug Joints ~40 kg
Saddles ~45 kg
Baseline Structure Overview
Gusseted & Clipped Joints

- Square Tubes used to make light weight joints possible with gussets and shear clips
- Gussets and clips sized to result in joints with good strength provided that
  - a pair of gussets and a pair of clips are used, and
  - gussets are not notched to undermine the joint load paths
- Gussets: 4.5 mm thick QI (Quasi-Isotropic) Laminate
- Clips: 1.9 mm thick INVAR
- Adhesive: EA 9309

**Joint missing a critical gusset**
Caused by trying to join members in perpendicular planes at the same location.
Not used by the baseline ISIM Structure

**Joints with good load paths**
1) Diagonal Joint, 2) K-Joint

**Total Mass of**
Gussets ~20 kg
Shear Clips ~10 kg
Adhesive~2 kg
An exhaustive study of structure topology has been performed to arrive at an efficient structure lay-out. Selected intermediate results are displayed.

ISIM/OTE interface configuration is also very critical to ISIM frequency & mass.

Started with 3 point Kinematic Mount (KM) interface and considered many options.
Arriving at the Final Structure Topology & OTE Kinematic Mount Configuration

- Found that a lateral (V2) constraint at the +V3 end is very effective
  - if it is at or close to the projected CG of ISIM
  - Because it provides an essential V3 torsional stiffness
  - Finally evolved to a split Bipod (pair of Monopods) as shown below.
- At the –V3 end, two bipods are oriented optimally for maximum stiffness.
- The resulting structure topology is discussed in detail on the next slide.
• Structure lay-out is close to a 3D truss but deviates from it due to need to have open bays for SI integration and stay-out zones

• Open bays are for
  • NIRCam & Light Cones
  • FGS
  • AOS stay-out zone

• Open bays stiffened through adjacent trusses and “wings.”

• No removable members used to stiffen the open bays in view of distortion risk.

• All primary load lines intersect at joints.

• Trusses in different planes are staggered to simplify some joints, for example:
  • with the removal of the dewar, plug fittings at the two lower +V3 corners are also removed and members properly offset and joined through lighter gussets and shear clips.
ISIM Finite Element Models

**ISIM Loads FEM with ideal SI Representations**
used for quick turn around concept and trade studies

**ISIM Loads FEM with full-up SI Representations**
used for final analysis and delivered to project for JWST Integrated Modeling
ISIM Loads FEM with ideal SI Models

- Intentionally kept simple for quick turn around concept and trade studies
- provides good accuracy for normal modes and launch reaction analysis
- Beam, Mass, and Spring elements used with joints assumed rigid
- Total mass adjusted to the allocation of 1140 kg
- SI Representations include mass and mass moments of inertia
  - Mounted with ideally kinematic attachments hence conservative for normal modes and stress analysis
  - tuned to have a fixed base fundamental frequency of ~50 Hz per requirement

Comparison of its fundamental frequency results with those from Distortion FEM demonstrated it to be accurate within 5%, Loads FEM with full-up SIs confirm that it is slightly conservative as expected.
Fundamental frequency is predicted to be 27.7 Hz and meets the requirement of 25 Hz with sufficient margin.

<table>
<thead>
<tr>
<th>fn</th>
<th>Mass Participation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>X</td>
</tr>
<tr>
<td>1</td>
<td>27.7</td>
</tr>
<tr>
<td>2</td>
<td>32.6</td>
</tr>
<tr>
<td>3</td>
<td>33.9</td>
</tr>
<tr>
<td>4</td>
<td>38.4</td>
</tr>
<tr>
<td>5</td>
<td>39.0</td>
</tr>
</tbody>
</table>

Fundamental Frequency Mode Shape dominated by KM and SI support structure flexibilities.
Maximum Deformations & Stresses Under Launch Loads

- Results shown for the envelope of all launch load cases
- Max deformation is under 3.5 mm
- Max tube stress is ~54 MPa which is well under the allowable
Tube Max Reactions & Min MS Under Launch Loads

- Most highly loaded tubes listed and highlighted
- All MS for tube net-section stress are high
  - Away from the joints
  - Calculated in spreadsheet under launch limit reactions recovered from loads model
- All MS for tube column buckling are high

<table>
<thead>
<tr>
<th>Tube Elements</th>
<th>Summary of Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Limit Axial Load, $P_{\text{max}}$</td>
<td>47.9 kN</td>
</tr>
<tr>
<td>Max Tube net-section Stress, $S_{\text{max}}$</td>
<td>54.1 MPa</td>
</tr>
<tr>
<td>min MS for Tube net-section Stress</td>
<td>2.6</td>
</tr>
<tr>
<td>min MS for Tube Column Buckling</td>
<td>3.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Primary Structure Bar Element ENVELOPING Limit Reactions (N, N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>element ID</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>158202</td>
</tr>
<tr>
<td>162306</td>
</tr>
<tr>
<td>106108</td>
</tr>
<tr>
<td>202210</td>
</tr>
<tr>
<td>140148</td>
</tr>
</tbody>
</table>

Moment & Stress
Axial
Buckling
Shear
Joint Reactions & MS under Launch Loads

Gussets

- Joint reactions under launch loads are recovered from loads model. Selected results shown here for gussets.
- Stresses and MS are calculated by hand analysis for:
  - Gusset net-section failure
  - Gusset-tube bonded joint shear failure
- Summarized below and highlighted in the FEM plot

### Summary of Results

- **Gusset Net Section Stress, Smax**: 133.9 MPa
- **MS for Gusset Stress**: 0.94
- **Average Shear Stress, Taum**: 10.5 MPa
- **MS for Joint Shear**: 0.26

### Selected Analysis Data

- **Gusset Thickness, t**: 0.0046 m
- **Gusset bonded width**: 0.050 m
- **Gusset Bonded Length, b**: 0.075 m
- **Safety Factor for Ultimate Failure, SFu**: 1.50
- **Additional Safety Factor, SFa**: 1.15
- **Bond Stress Peaking Factor, SFb**: 2.50
- **Gusset Ultimate Strength, Fcu**: 447.0 MPa
- **I/L Shear Strength, Fi**: 50.0 MPa

### Gusset Codes at ends of member

<table>
<thead>
<tr>
<th>member ID</th>
<th>end A</th>
<th>end B</th>
</tr>
</thead>
<tbody>
<tr>
<td>158202</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>174260</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>206218</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>176264</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>114140</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

### Normal and Shear Stress at Gusset tubes

<table>
<thead>
<tr>
<th>end type</th>
<th>end 1</th>
<th>end 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>gp</td>
<td>133.9</td>
<td>10.5</td>
</tr>
<tr>
<td>gc</td>
<td>129.3</td>
<td>10.1</td>
</tr>
<tr>
<td>gc</td>
<td>98.1</td>
<td>7.9</td>
</tr>
<tr>
<td>gc</td>
<td>88.2</td>
<td>7.1</td>
</tr>
<tr>
<td>gc</td>
<td>82.2</td>
<td>6.6</td>
</tr>
</tbody>
</table>
Summary of All-Up Structure
Reactions & MS under Launch Loads

- ISIM structure meets launch Strength Requirement. All MS under launch loads calculated here as well as in detailed stress analysis (reported elsewhere) are positive.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Failure Mode</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Tubes</td>
<td>Net-Section</td>
<td>+2.6</td>
</tr>
<tr>
<td></td>
<td>Column Buckling</td>
<td>+3.1</td>
</tr>
<tr>
<td>Gussets</td>
<td>Net-Section</td>
<td>+0.94</td>
</tr>
<tr>
<td></td>
<td>Bonded Joint</td>
<td>+0.26</td>
</tr>
</tbody>
</table>

- Following limit reactions predicted by the Loads FEM are used in detailed stress analysis.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Limit Reaction under Launch Loads</th>
<th>kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Tubes</td>
<td>Axial Load</td>
<td>47.9</td>
</tr>
<tr>
<td>Plug Joints</td>
<td>Effective Axial Load</td>
<td>77.7</td>
</tr>
<tr>
<td>Shear Clip Pair</td>
<td>Transverse Shear</td>
<td>6.1</td>
</tr>
<tr>
<td>Diagonal Joint</td>
<td>Axial Load</td>
<td>38.2</td>
</tr>
<tr>
<td>K-Joint</td>
<td>Axial in K</td>
<td>29.3</td>
</tr>
<tr>
<td>Saddle</td>
<td>Normal</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>Shear</td>
<td>8.7</td>
</tr>
</tbody>
</table>
Further Improvements

- Considering improvements in the inspectability and reparability of our joints
- Structure mass margin is low, hence we are looking at ways of reducing structure mass
  - Removal of shear clips that do not carry significant transverse shear loads
  - Tube wall thickness optimization

(one page summary follows)
Sample Tube Wall Thickness Optimization
using 2 different wall thicknesses of 2.9 & 5.8 mm

- NASTRAN optimizer used to assign either 2.9 or 5.8 mm
  thickness to each tube element to minimize structure weight
  while maintaining fundamental frequency at ~27.5 Hz
- As binned results are not practical and cleaned-up to have
  one thickness for every continuous member. Some member
  thicknesses are bumped up to maintain frequency.
- Substantial tube mass reduction (~28 kg) is predicted.

<table>
<thead>
<tr>
<th></th>
<th>optimized &amp; cleaned-up</th>
<th>baseline with uniform wall thk of 4.6 mm</th>
<th>difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1,Hz</td>
<td>27.7</td>
<td>27.7</td>
<td>0.0</td>
</tr>
<tr>
<td>f2,Hz</td>
<td>30.6</td>
<td>32.6</td>
<td>2.0</td>
</tr>
<tr>
<td>f3,Hz</td>
<td>33.9</td>
<td>38.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Tube Mass,kg</td>
<td><strong>104.9</strong></td>
<td><strong>133.1</strong></td>
<td><strong>28.2</strong></td>
</tr>
</tbody>
</table>
Summary & Conclusion

- ISIM primary structure has been designed and sized to meet the challenging requirements of Launch Stiffness & Strength given:
  - Difficult design constraints including:
    - SI integration access,
    - SI and OTE Interfaces,
    - Tight structure weight budget
  - And the other conflicting Structural Requirements namely:
    - Thermal Survivability under cryogenic cool-down cycles to 22 K
    - Alignment Performance under cool-down to and during operation at 32 K
- Simple Loads FEM proved to be very effective & efficient in guiding structure design
  - Concept & Trade Studies
  - Tube wall thickness optimization