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

by
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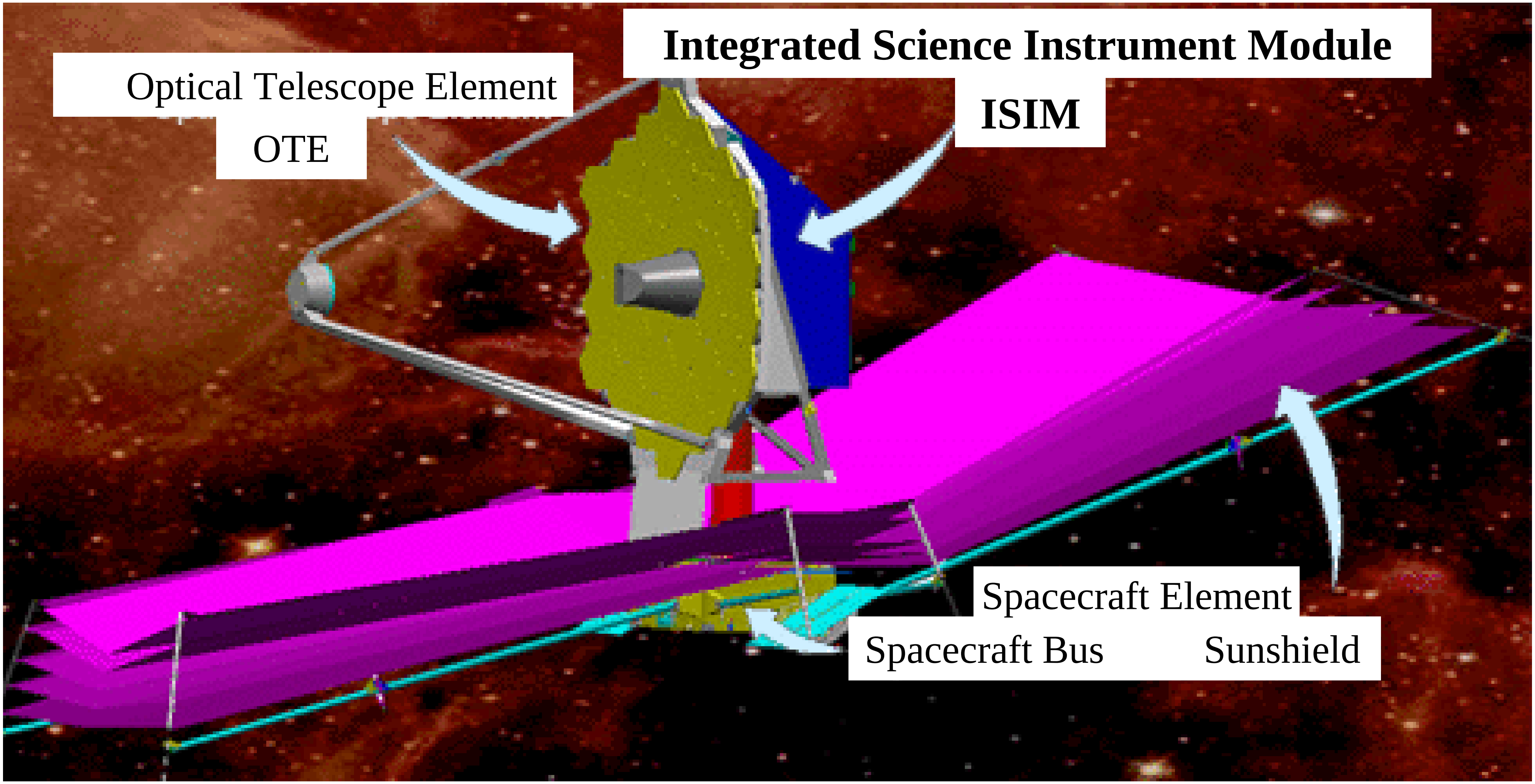
Outline

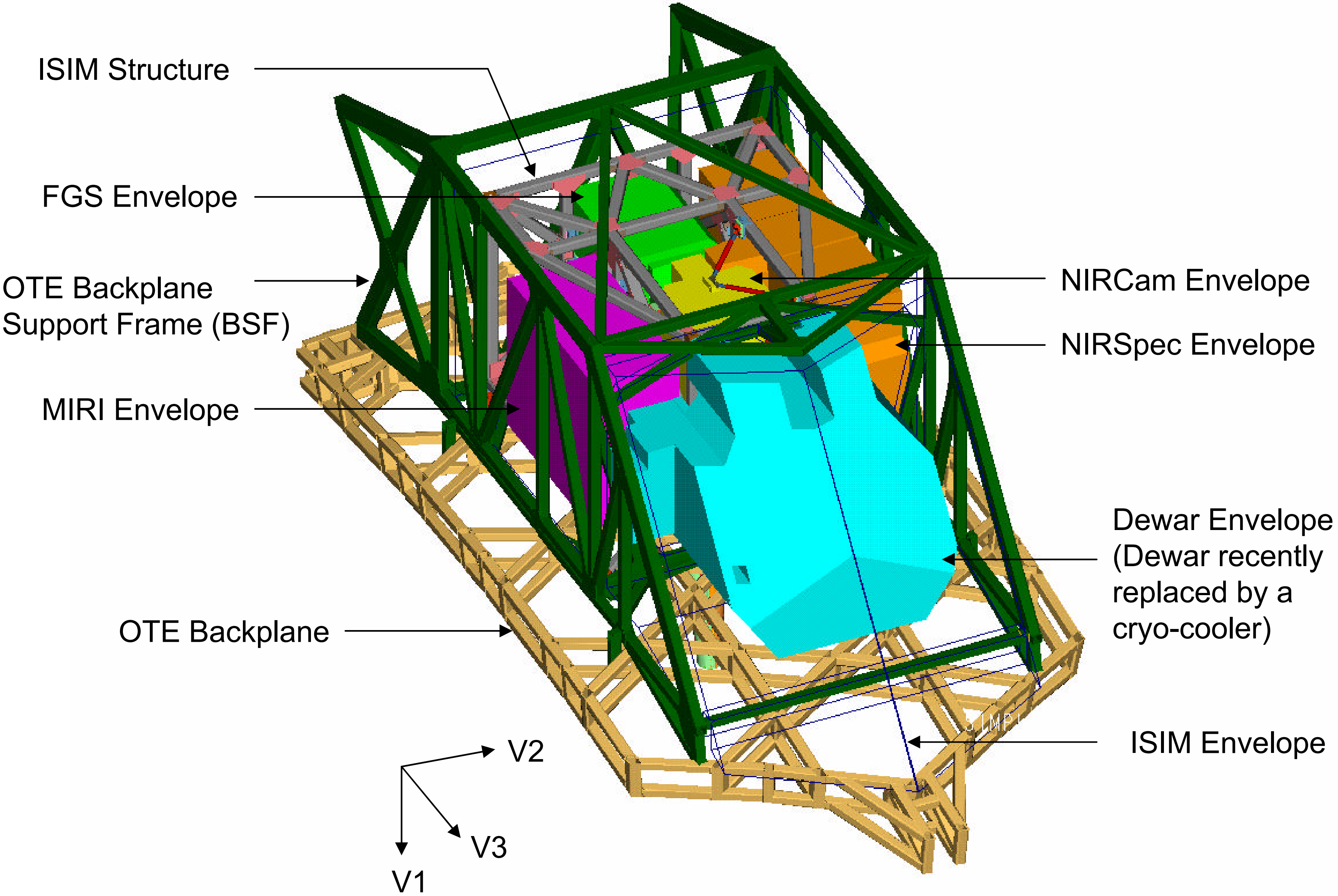
- Introduction
  - JWST, OTE, & ISIM
  - ISIM Structure Design Status
- ISIM Structural Requirements & Challenges
- Description & Evolution of the Primary Structure
- Finite Element Models
- Baseline Structure Performance Predictions
  - Normal Modes
  - Structural Integrity under Launch Loads
- Further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

JWST
James Webb Space Telescope



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

ISIM and OTE Backplane



ISIM Structure

FGS Envelope

OTE Backplane
Support Frame (BSF)

MIRI Envelope

NIRCam Envelope

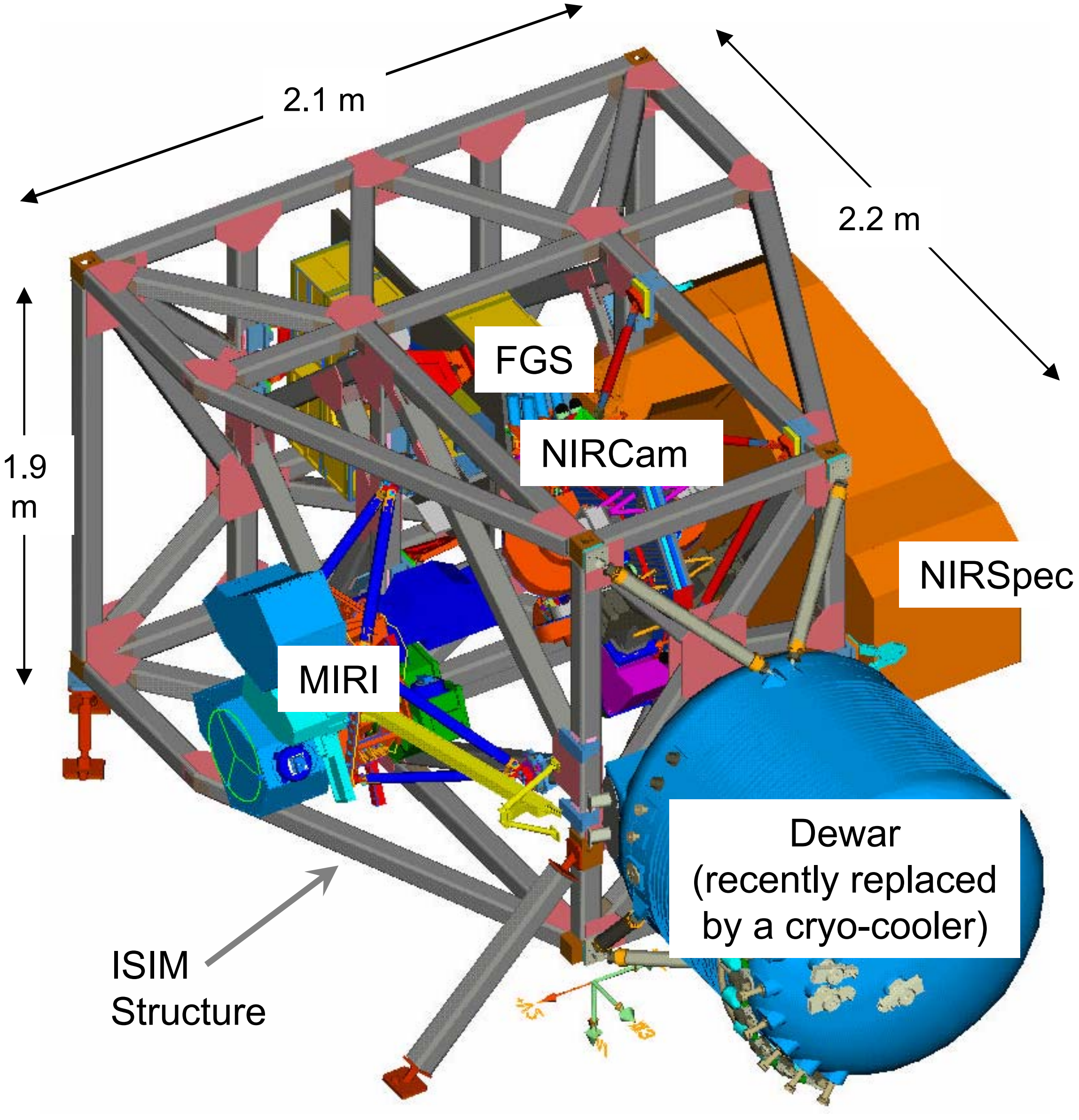
NIRSpec Envelope

Dewar Envelope
(Dewar recently
replaced by a
cryo-cooler)

OTE Backplane

ISIM Envelope

ISIM Overview



Total Mass =1140 kg

- 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.
- Critical Design Review is scheduled for December 2005.

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

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

- Minimum Fundamental Frequency
  - ♦ 25 Hz with margin
- Structural Integrity under Launch

Challenge#1
Launch Stiffness & Strength
Topic of this Presentation

- Thermal Survivability
  - ♦ Survival Temp= 22 K
  - ♦ Operating Temp= 32 K

Challenge#2

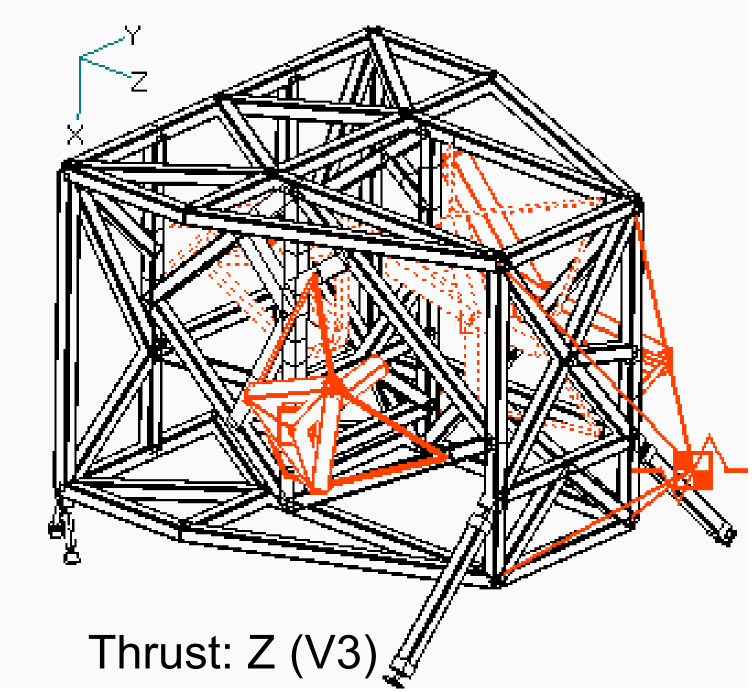
- Alignment/Dimensional Performance
  - ♦ Launch & Cool-Down to 32 K
  - ♦ Operational Stability at 32 K

Challenge#3

Launch Design Limit Load (DLL) Factors

ISIM Primary Structure Launch DLL Factors, g's

Load Case	Thrust (V3)	Lateral (V1,V2)[a]
Max Compression	-6.44	1.5
Max Tension	+3.25	1.5
Max Lateral	-3.65	3.0
a - Lateral loads are swept in the V1-V2 plane		



Thrust: Z (V3)

Lateral: X (V1) and Y(V2)

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

Type of Structure	Qualification by	FS	
		ultimate	yield
Metallic	Analysis & Test	1.40	1.25
	Analysis only	2.6	2.0
Mechanical Fastener	Analysis & Test	1.40	1.25
Composite Material	Analysis & Test	1.50	-
Adhesive	Analysis & Test	1.50	1.25

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.

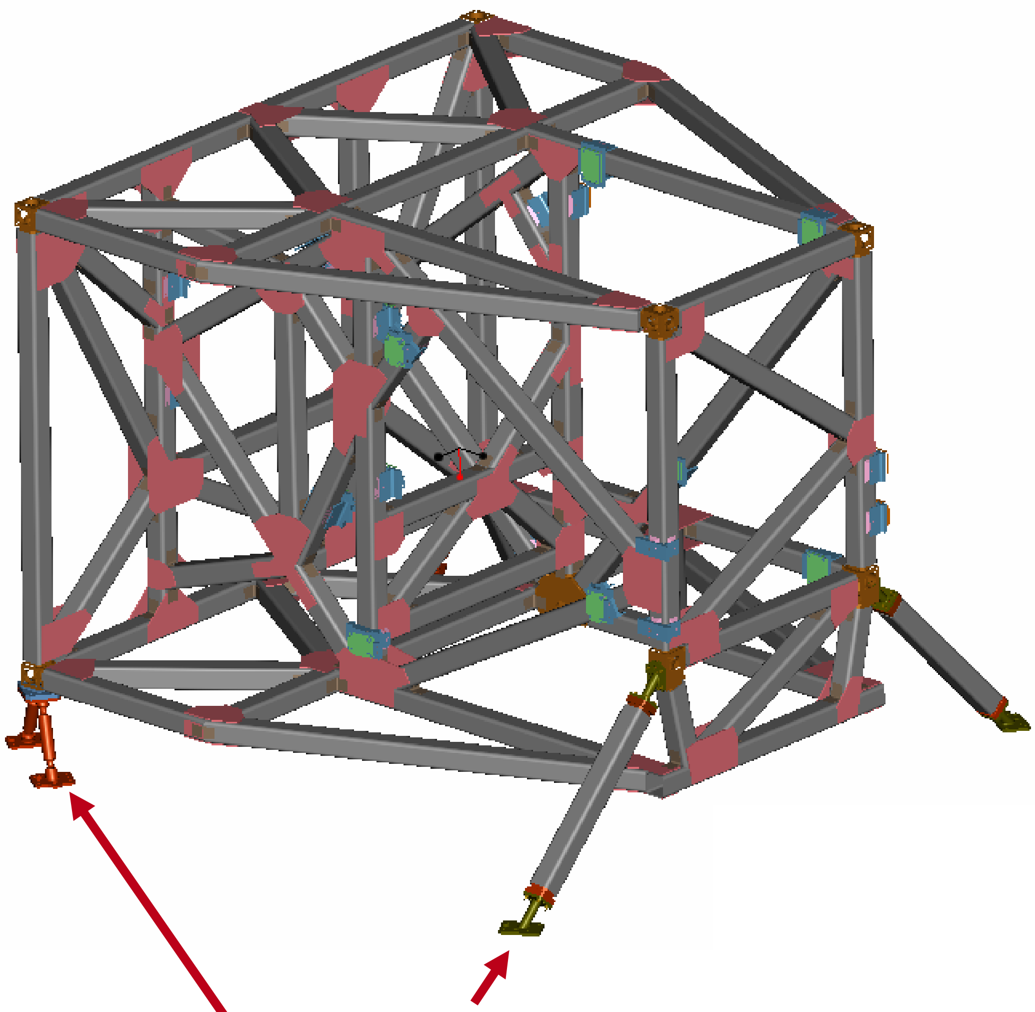
ISIM Baseline Structure Overview

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

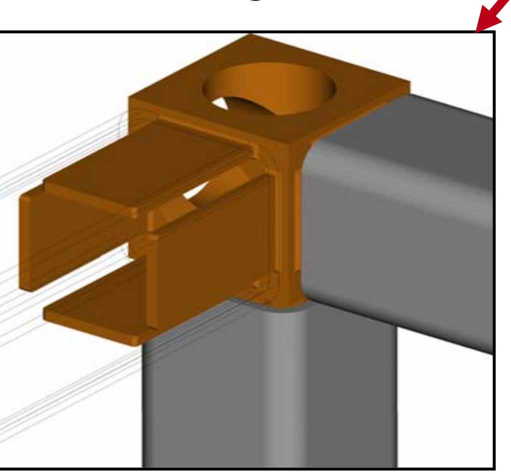
- 2 Bipods (Ti-6Al-4V)
- 2 Monopods (Tubes+Ti-6Al-4V Post Flexures)
- Total Mass~25 kg

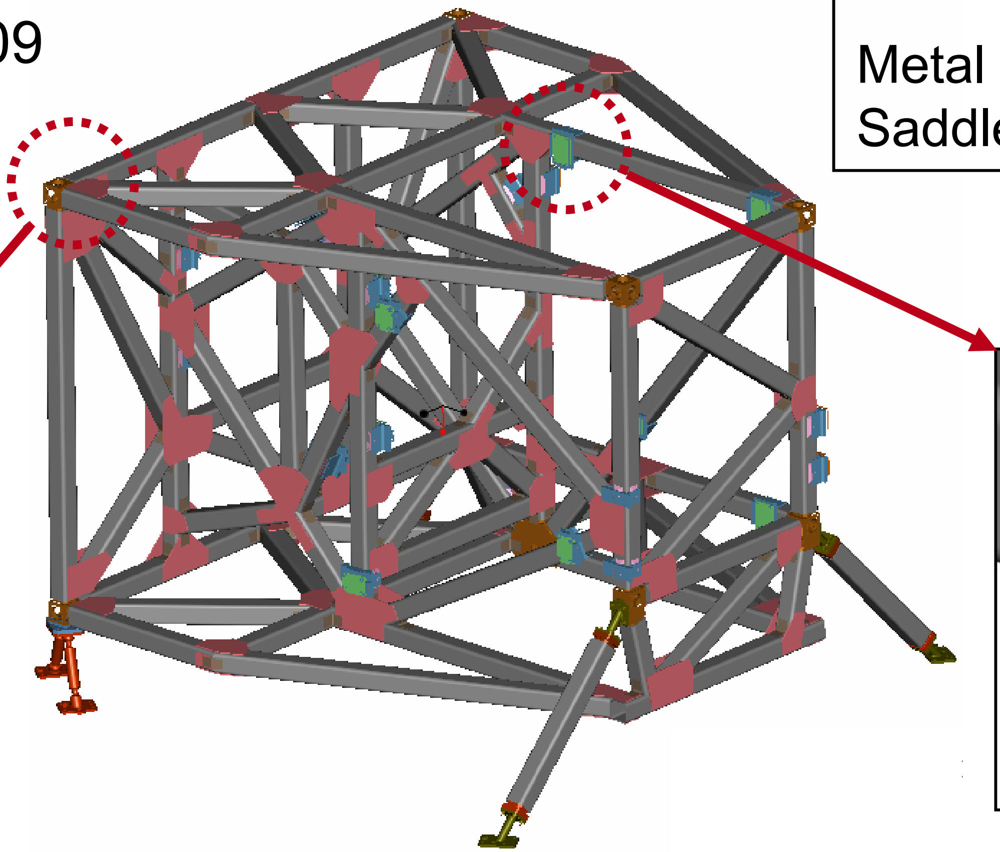
Baseline Structure Overview
Metal Joints

- 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

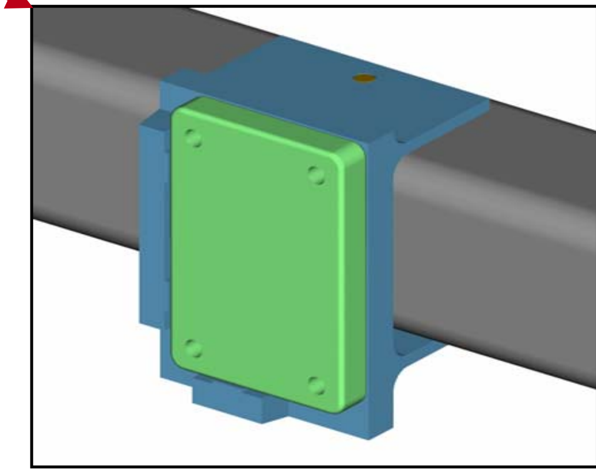
Total Mass of
Metal Plug Joints ~40 kg
Saddles ~45 kg

Plug Joint





Saddle Mount

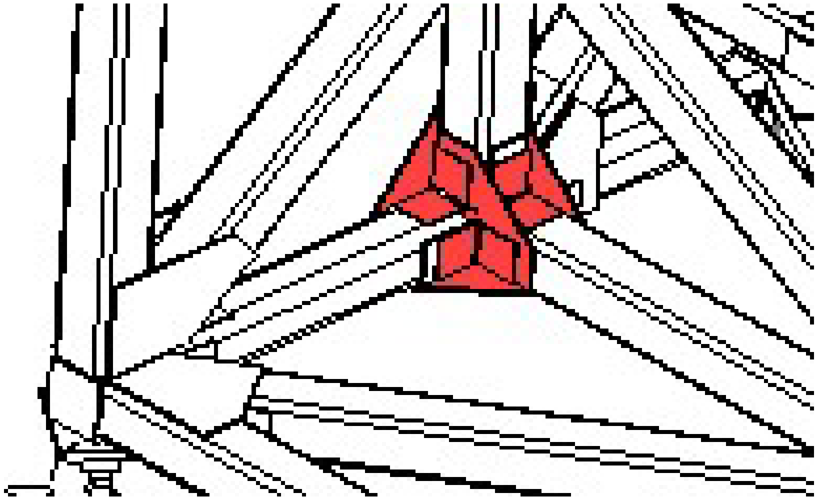


Baseline Structure Overview
Gusseted & Clipped Joints

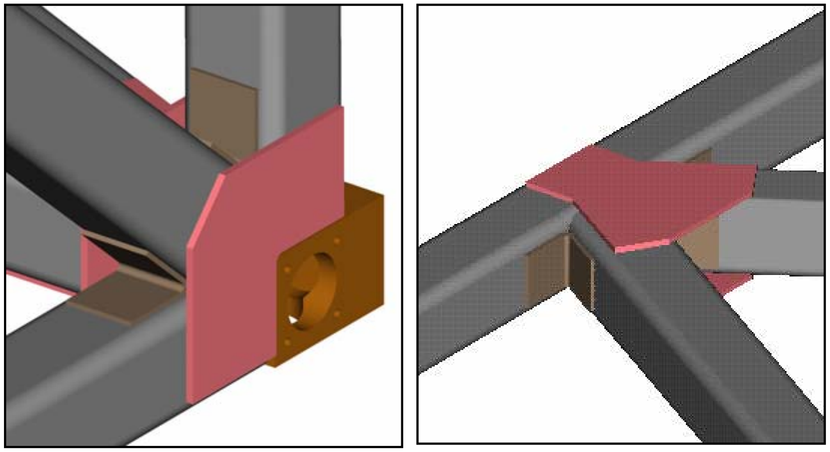
- Square Tubes used to make light weight joints possible with gussets and shear clips
- Gussets and clips sized to result in joints with good strength provided that
  - a pair of gussets and a pair of clips are used, and
  - gussets are not notched to undermine the joint load paths
- Gussets: 4.5 mm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

Total Mass of
Gussets ~20 kg
Shear Clips ~10 kg
Adhesive~2 kg

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

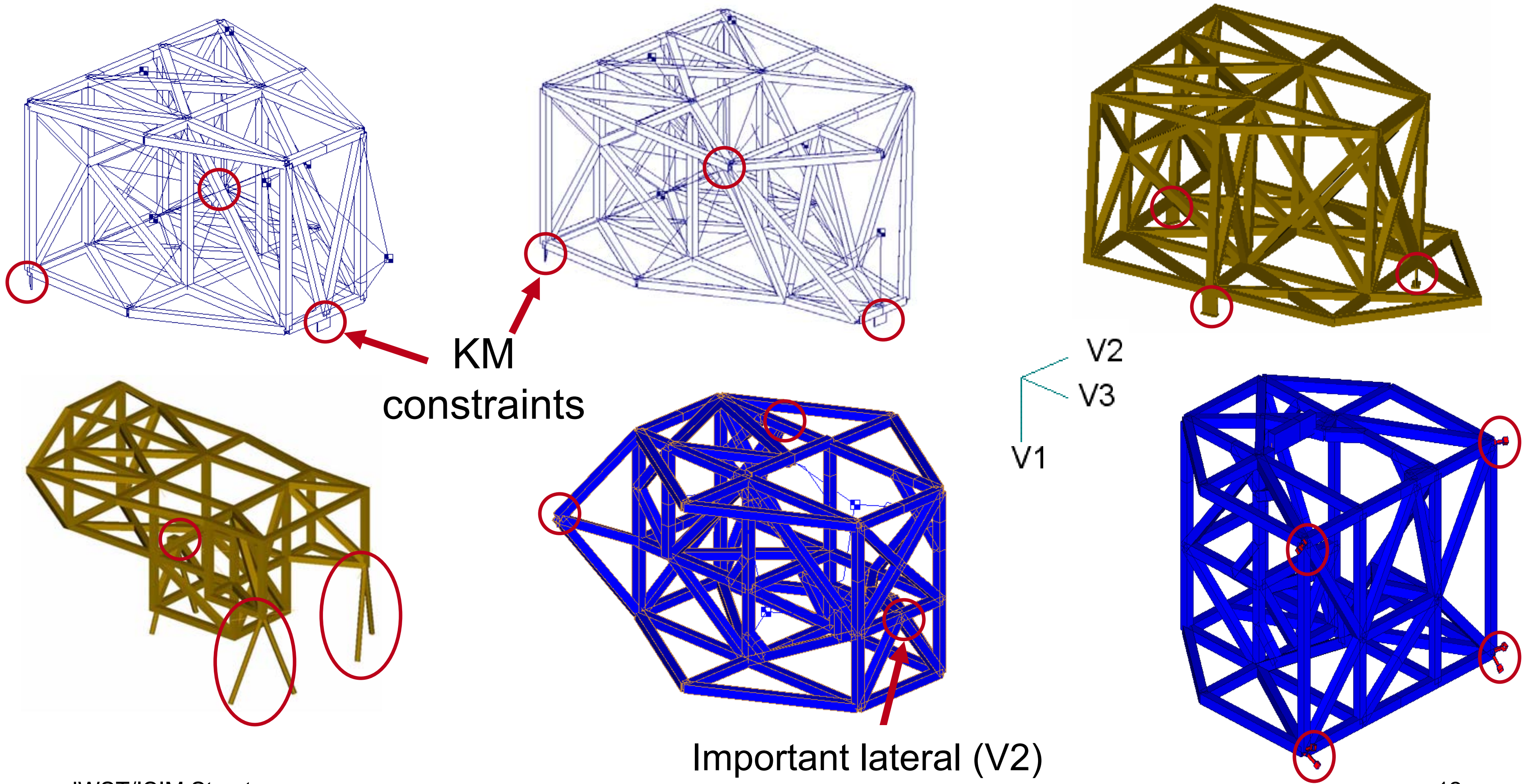


Joints with good load paths
1) Diagonal Joint, 2) K-Joint



Evolution of Structure Topology & OTE Kinematic Mount Configuration

- 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.



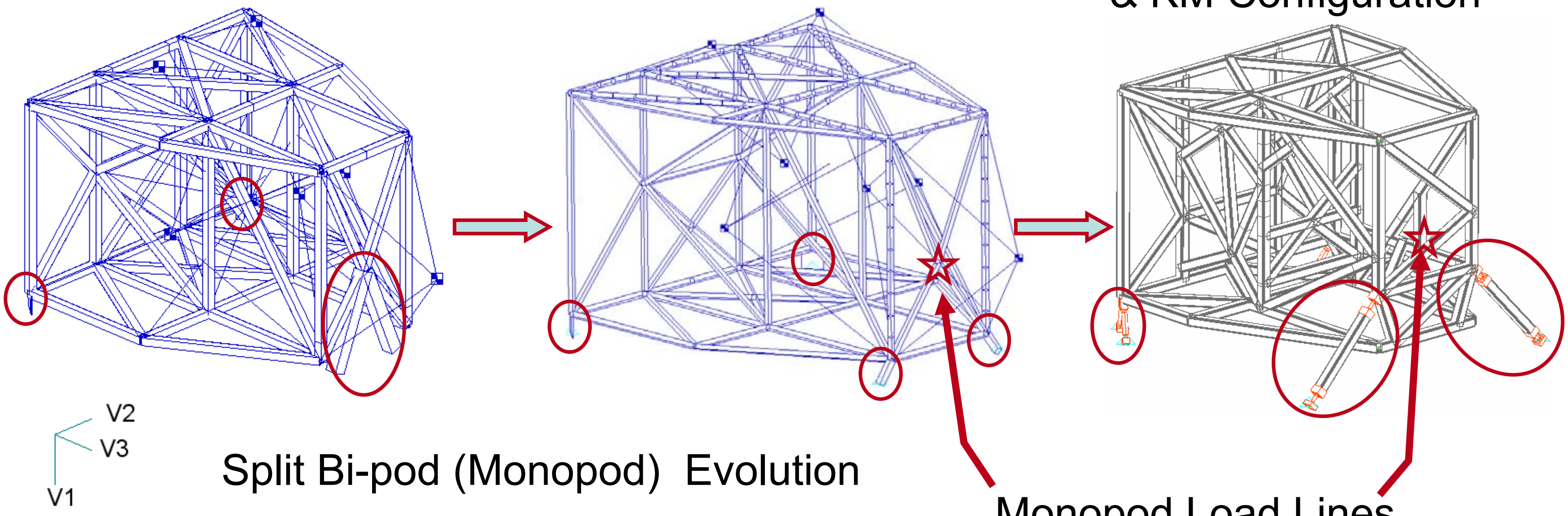
KM constraints

Important lateral (V2) constraint

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.

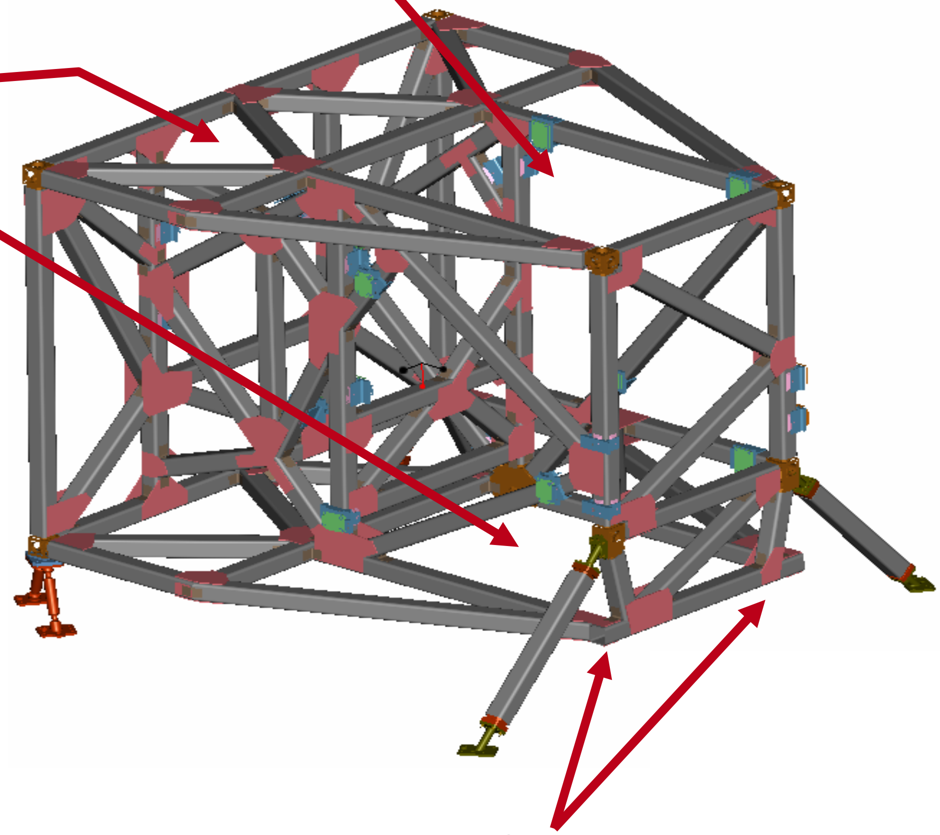
Baseline Structure & KM Configuration



Split Bi-pod (Monopod) Evolution

Monopod Load Lines Intersection Point

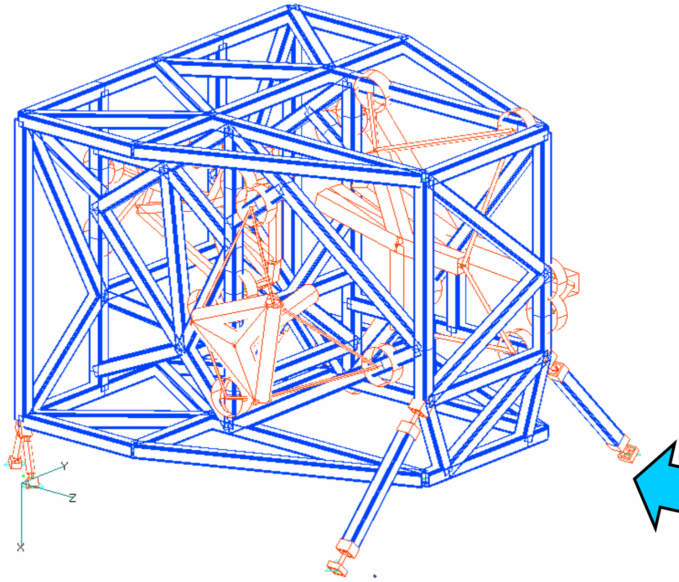
Baseline Structure
Load Paths Discussion



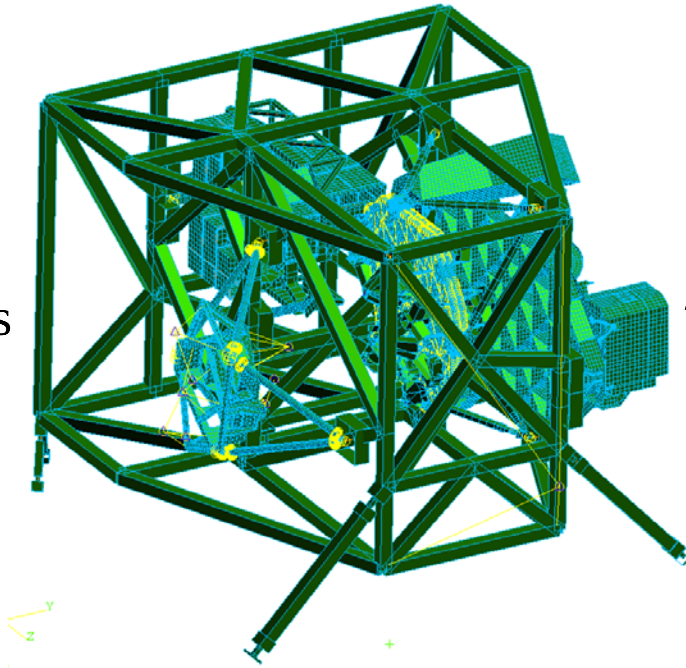
- Structure lay-out is close to a 3D truss but deviates from it due to need to have open bays for SI integration and stay-out zones
- Open bays are for
  - NIRCam & Light Cones
  - FGS
  - AOS stay-out zone
- Open bays stiffened through adjacent trusses and “wings.”
- No removable members used to stiffen 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

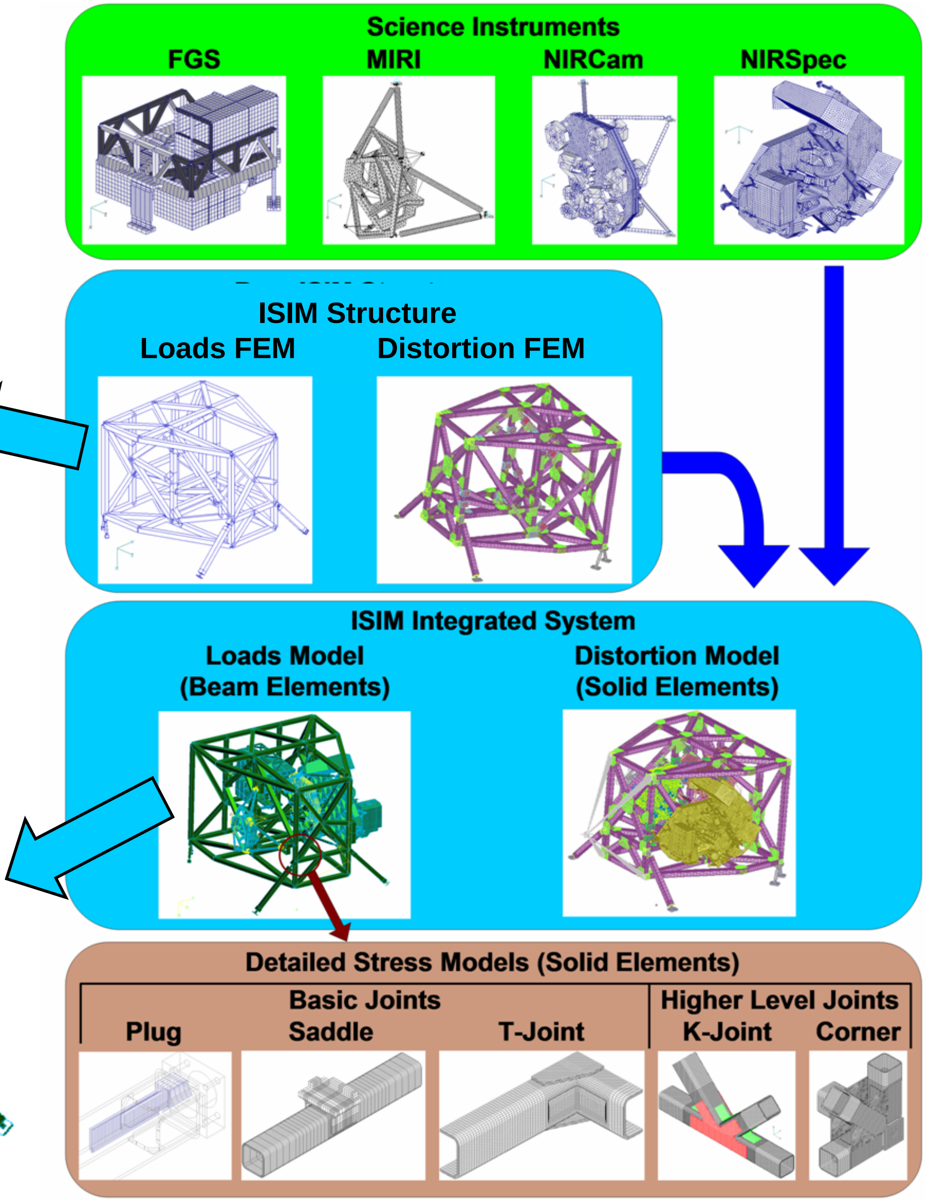
ISIM Loads FEM with ideal SI Representations used for quick turn around concept and trade studies



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



Overview of all ISIM FEMs



Science Instruments

FGS MIRI NIRCam NIRSpec

ISIM Structure

Loads FEM Distortion FEM

ISIM Integrated System

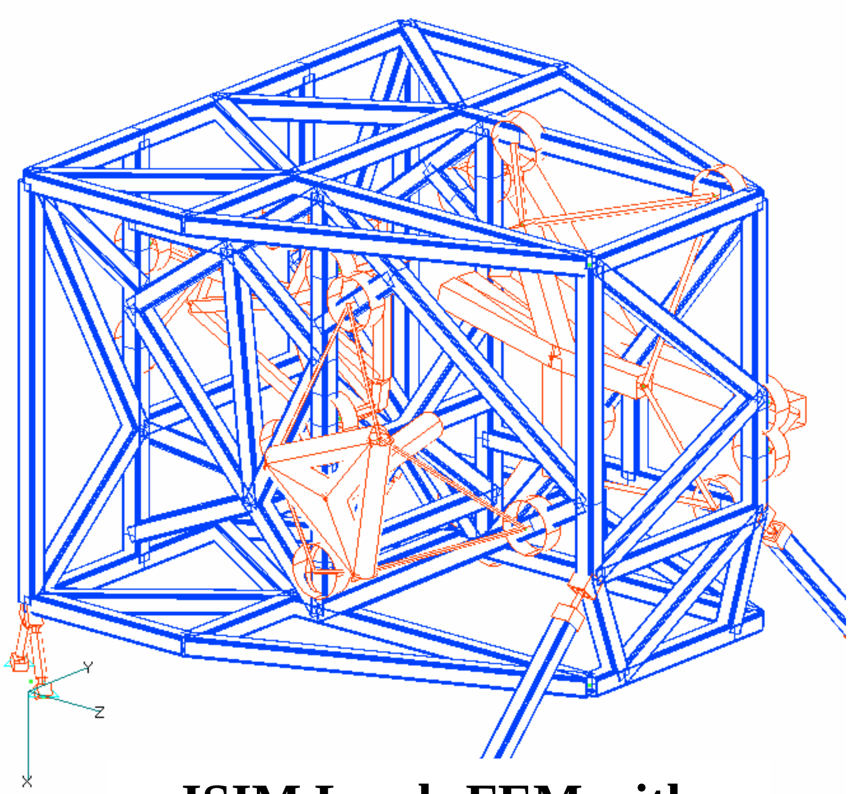
Loads Model (Beam Elements)

Distortion Model (Solid Elements)

Detailed Stress Models (Solid Elements)

	Basic Joints		Higher Level Joints	
Plug	Saddle	T-Joint	K-Joint	Corner

ISIM Loads FEM with ideal SI Models



ISIM Loads FEM with ideal SI Representations

- 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

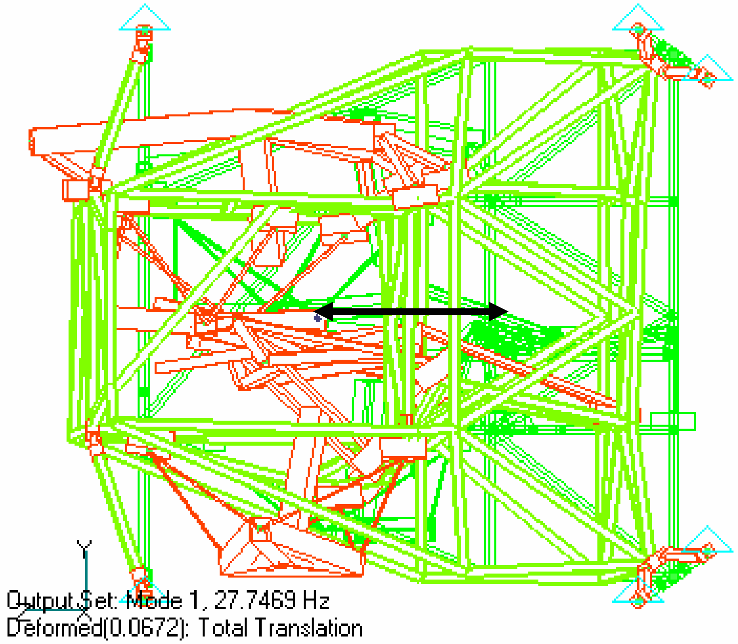
Distortion FEM demonstrated it to be accurate within 5%,

Loads FEM with full-up SIs confirm that it is slightly conservative as expected.

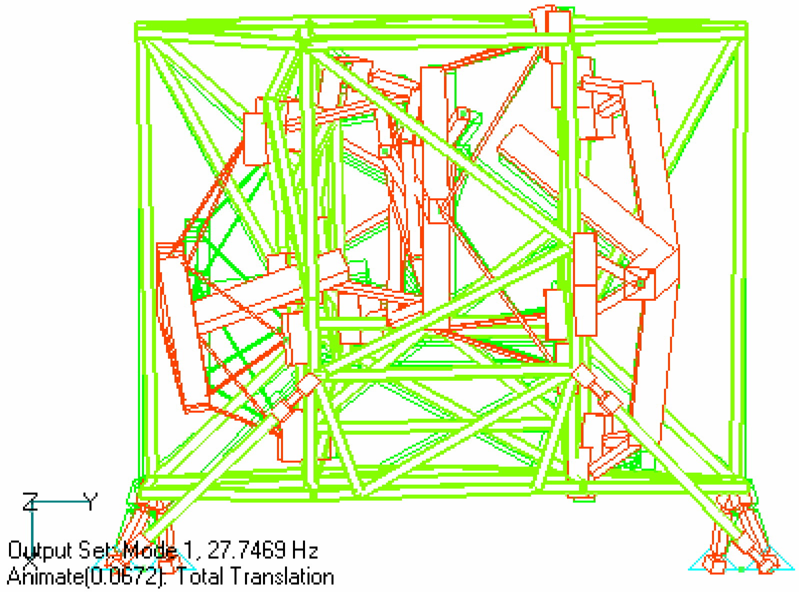
ISIM Normal Modes Summary & Fundamental Mode

Fundamental frequency is predicted to be 27.7 Hz and meets the requirement of 25 Hz with sufficient margin.

	fn	Mass Participation (%)						
n	**(Hz)**	**X**	**Y**	**Z**	**RX**	**RY**	**RZ**	**notes**
1	**27.7**	0.0	0.1	64.3	0.4	58.7	0.3	Major V3
2	**32.6**	0.6	0.1	11.0	10.2	8.6	0.1	Minor V3
3	**33.9**	0.0	74.0	0.1	19.9	0.3	51.9	V2 + V3 Torsional
4	**38.4**	7.2	2.7	0.6	1.8	0.6	21.9	V1 + V3 Torsional
5	**39.0**	22.0	0.4	0.1	0.2	0.0	1.3	V1 due to Local SI



Fundamental Frequency Mode Shape dominated by KM and SI support structure flexibilities



Maximum Deformations & Stresses Under Launch Loads

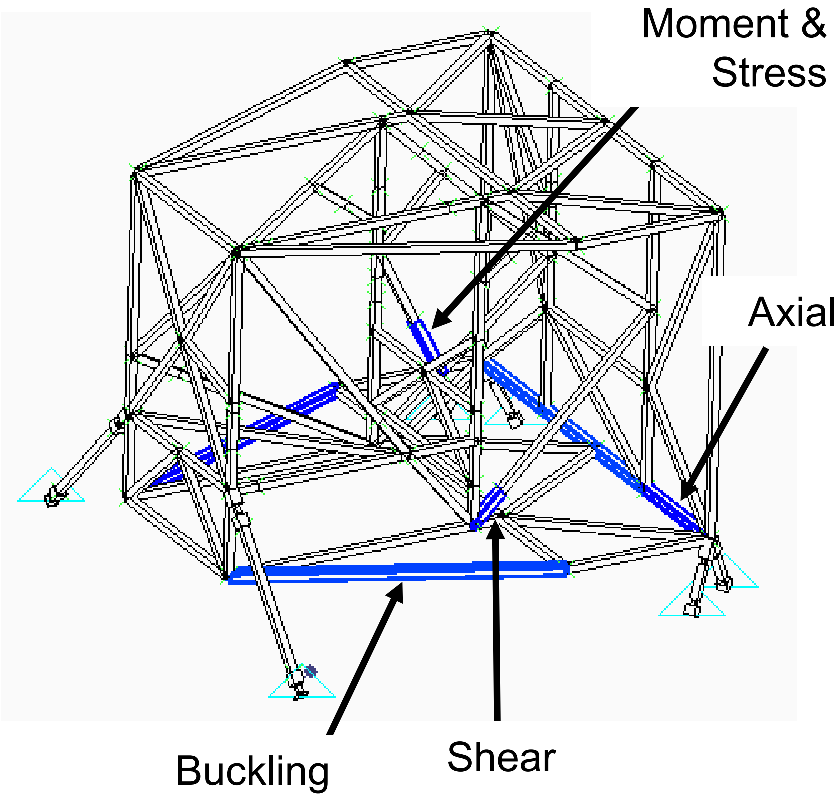
- Results shown for the envelope of all launch load cases
- Max deformation is under 3.5 mm
- Max tube stress is ~54 MPa which is well under the allowable

Primary Tube Stress Contours (Pa) Under Enveloping Load Case

Deformed & Undeformed Shapes Shown

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**



Tube Elements

Summary of Results

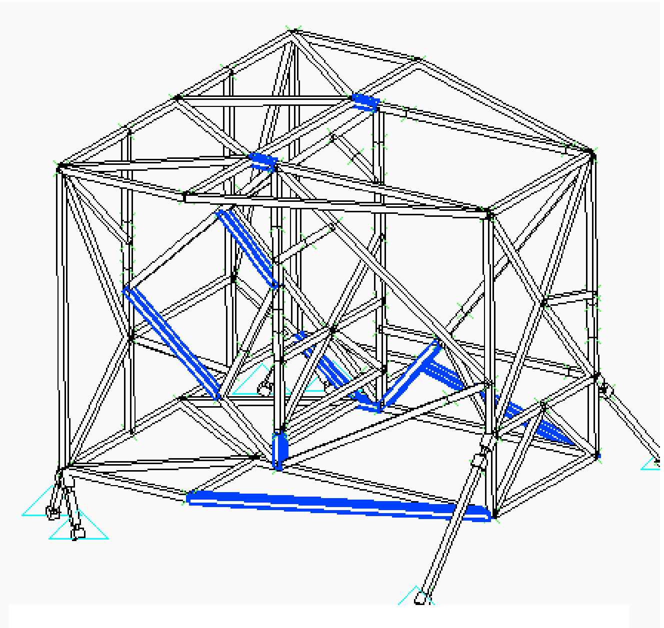
Max Limit Axial Load, Pmax=	**47.9**	**kN**
Max Tube net-section Stress, Smax=	**54.1**	**MPa**
min MS for Tube net-section Stress=	**2.6**	
min MS for Tube Column Buckling=	**3.1**	

Primary Structure Bar Element ENVELOPING Limit Reactions (N, N.m)

element		**MA1**	**MA2**	**MB1**	**MB2**	**V1**	**V2**	**P**	**T**	**stress**	**buckling**	
ID	**worst**	**1021**	**888**	**1197**	**892**	**11898**	**5459**	**47888**	**282**	**MS**	**MS**	
158202	**Stress**	205	834	293	627	731	4538	20568	61	**2.6**	3.7	gp
162306	**Buckling**	70	135	218	88	181	142	25908	8	5.9	**3.1**	gg
106108	**Axial**	198	143	91	130	501	412	**47888**	8	2.8	7.9	cp
202210	**Shear**	752	402	430	275	**11898**	4842	4499	138	3.4	20.4	pc
140148	**Moment**	54	393	**1197**	221	3982	1959	1442	114	10.4	+large	gc

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



Highly loaded gusset-tube joints highlighted

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 1 & 2 are shear directions					**Gusset Normal Stress MPa**	**Bond Shear Stress MPa**
member ID	**end A**		**end B**		**end type**		
	1	**2**	**1**	**2**			
158202	1	0	0	0	gp	133.9	10.5
174260	1	0	0	0	gc	129.3	10.1
206218	1	0	0	0	gc	98.1	7.9
176264	1	0	0	0	gc	88.2	7.1
114140	1	0	0	0	gc	82.2	6.6

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.

Structure	Failure Mode	MS
Primary Tubes	Net-Section	+2.6
	Column Buckling	+3.1
Gussets	Net-Section	+0.94
	Bonded Joint	+0.26

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

Structure	Limit Reaction under Launch Loads	kN
Primary Tubes	Axial Load	47.9
Plug Joints	Effective Axial Load	77.7
Shear Clip Pair	Transverse Shear	6.1
Diagonal Joint	Axial Load	38.2
K-Joint	Axial in K	29.3
Saddle	Normal	15.0
	Shear	8.7

Further Improvements

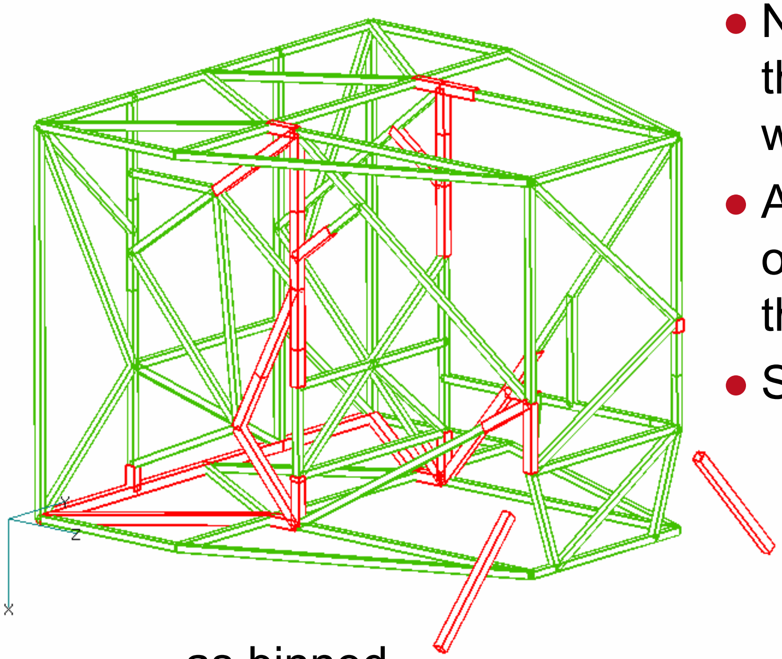
- Considering improvements in the inspectability and reparability of our joints
- Structure mass margin is low, hence we are looking at ways of reducing structure mass
  - Removal of shear clips that do not carry significant transverse shear loads
  - Tube wall thickness optimization

    (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.

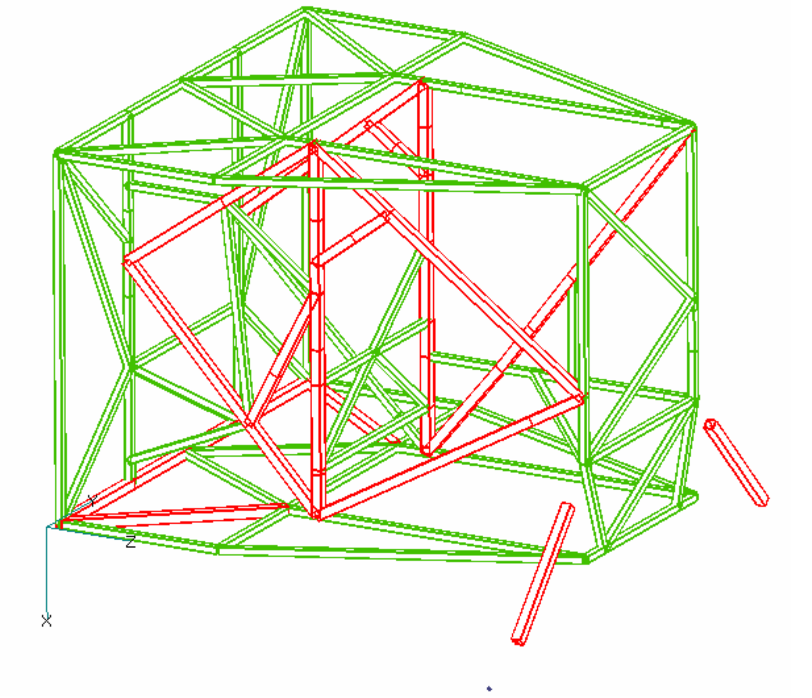


as binned

2.9 mm (green)

5.8 mm (red)

	optimized & cleaned-up	baseline with uniform wall thk of 4.6 mm	difference
f1,Hz	27.7	27.7	0.0
f2,Hz	30.6	32.6	2.0
f3,Hz	33.9	38.4	4.5
Tube Mass,kg	**104.9**	**133.1**	28.2



Cleaned-up after binning

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