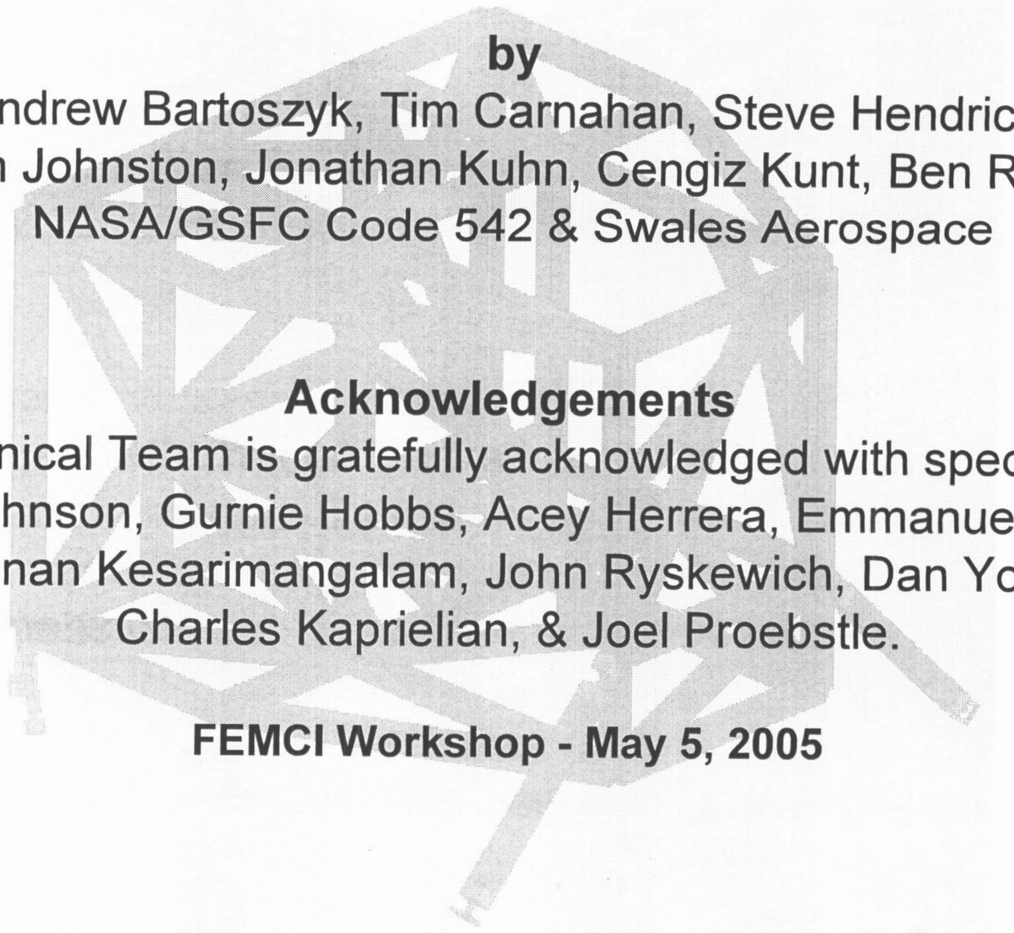
Design and Analysis of the JWST Integrated Science Instrument Module (ISIM) Primary Metering Structure



by
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NASA/GSFC Code 542 & Swales Aerospace

Acknowledgements

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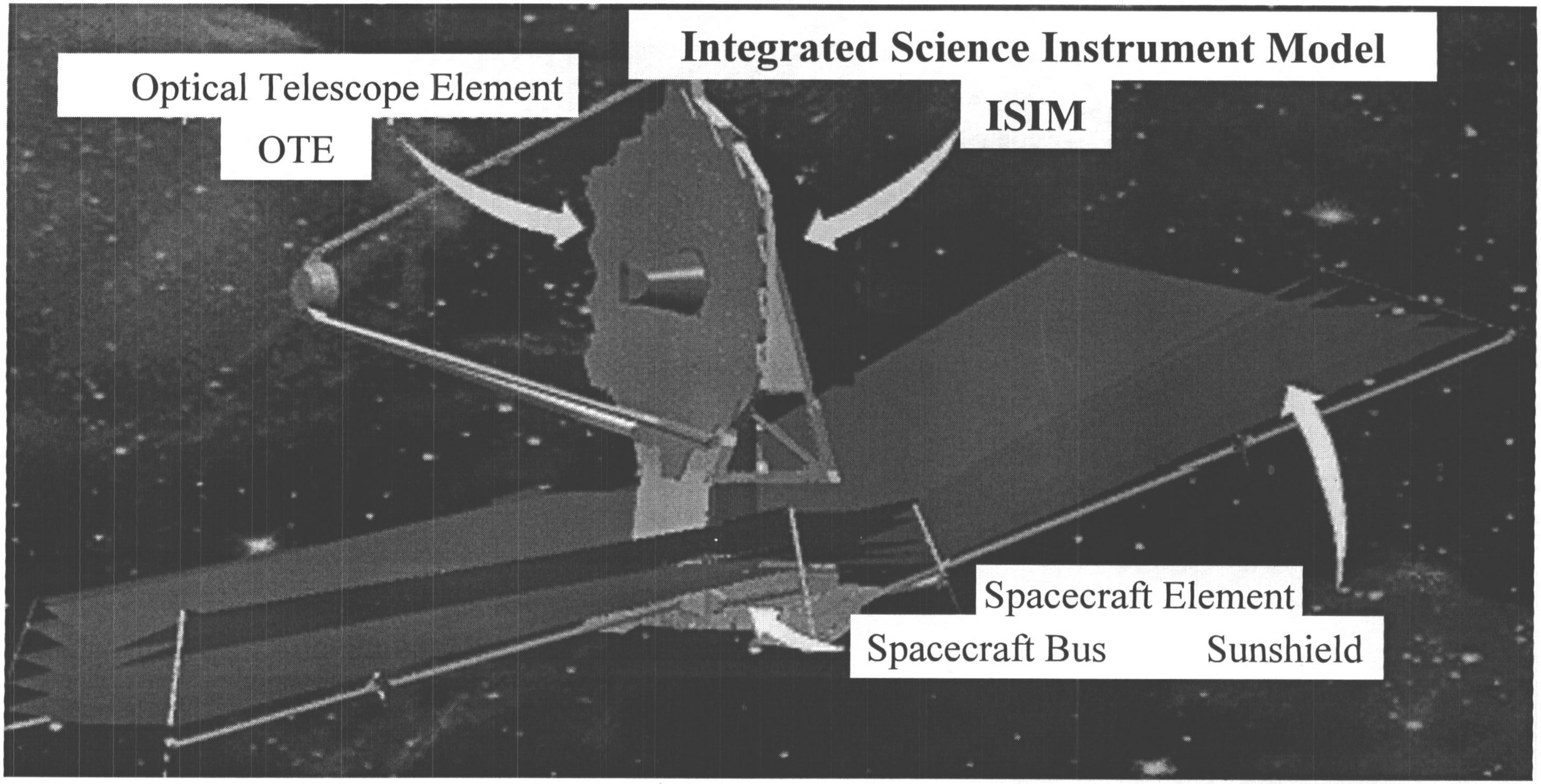
Outline

- Introduction
    - JWST, ISIM, & OTE
    - 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
- Further Improvements
- Summary & Conclusion

JWST
James Webb Space Telescope



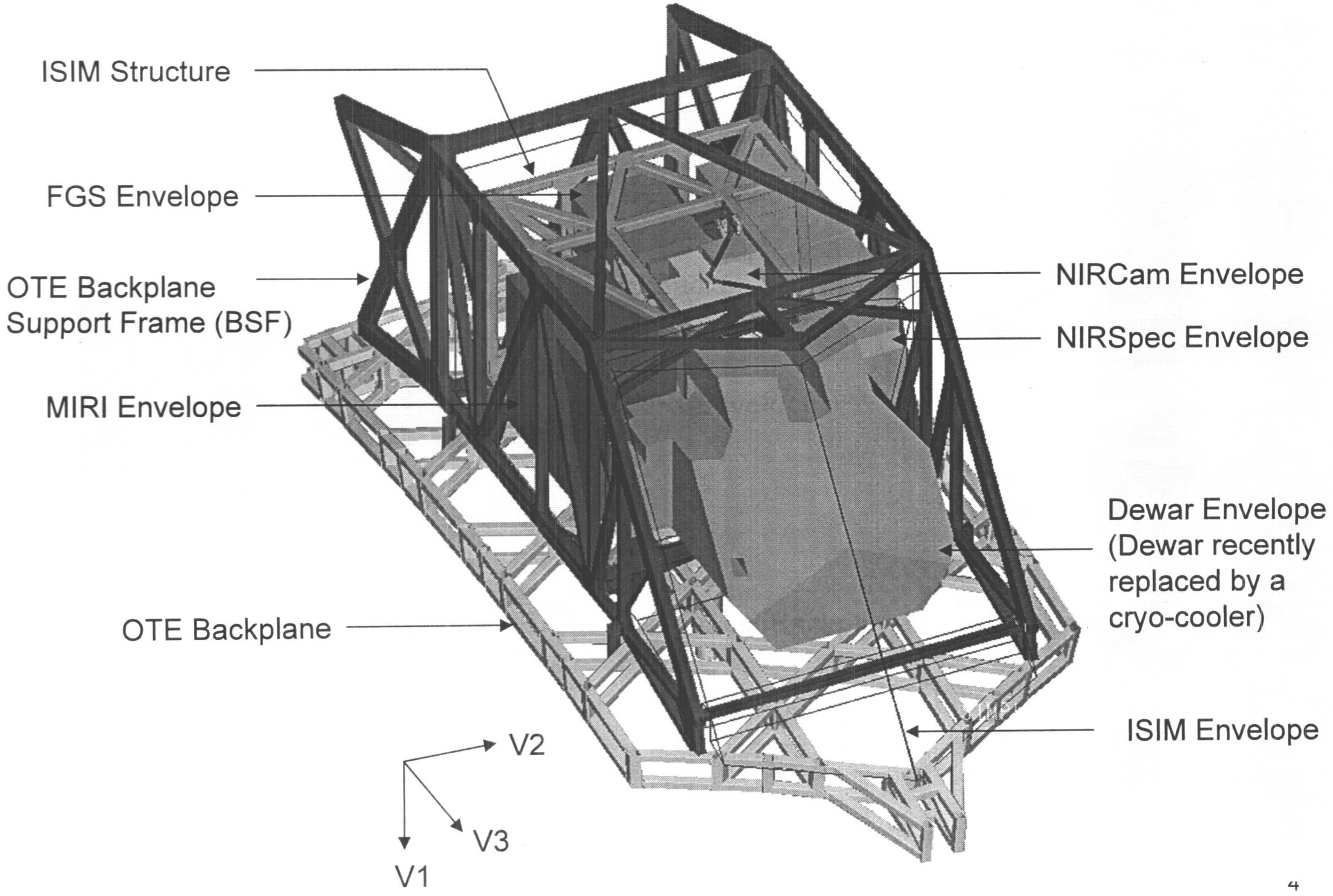
Optical Telescope Element
OTE

Integrated Science Instrument Model
ISIM

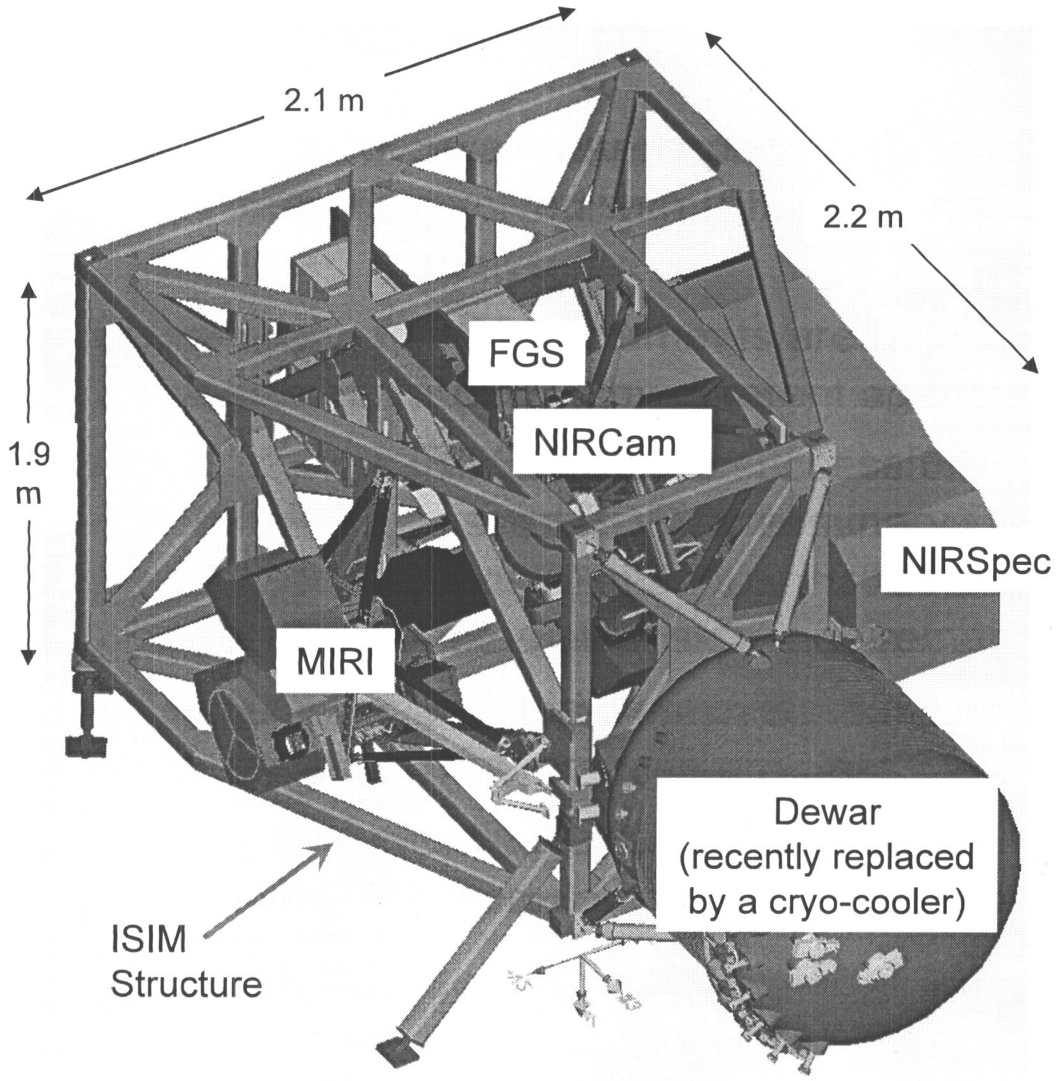
Spacecraft Element
Spacecraft Bus
Sunshield

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

ISIM and OTE Backplane



ISIM Overview



- ISIM Structure is being designed by GSFC.
- Swales Aerospace significantly involved with 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 allocated Mass of 1140 kg
- Structure Mass Budget 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 Strength & Stiffness
Topic of this Presentation

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

Challenge#2

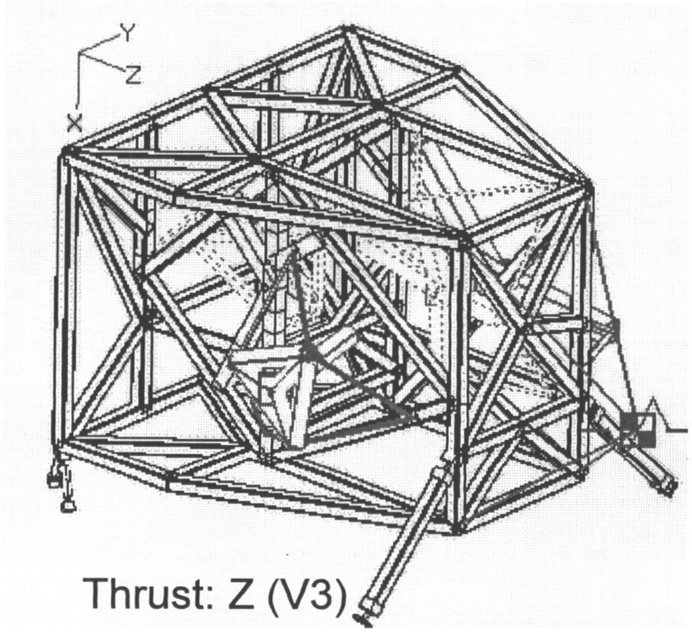
- Alignment/Dimensional Performance
  - Launch & Cool-Down to 32 K
  - Operational Stability at 32 K

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.

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.

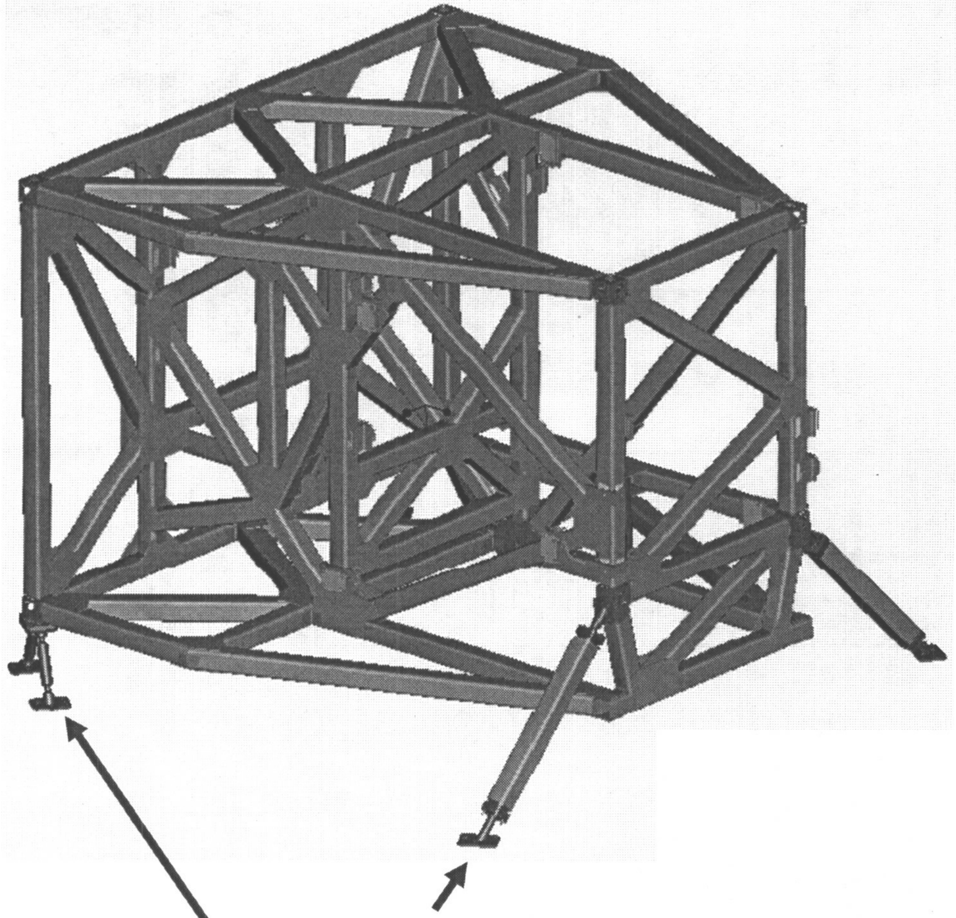
ISIM Baseline Structure Overview

<u>Frame type construction selected</u>

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

<u>Carbon Fiber Composite Materials used for Primary Structure Members</u>

- 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



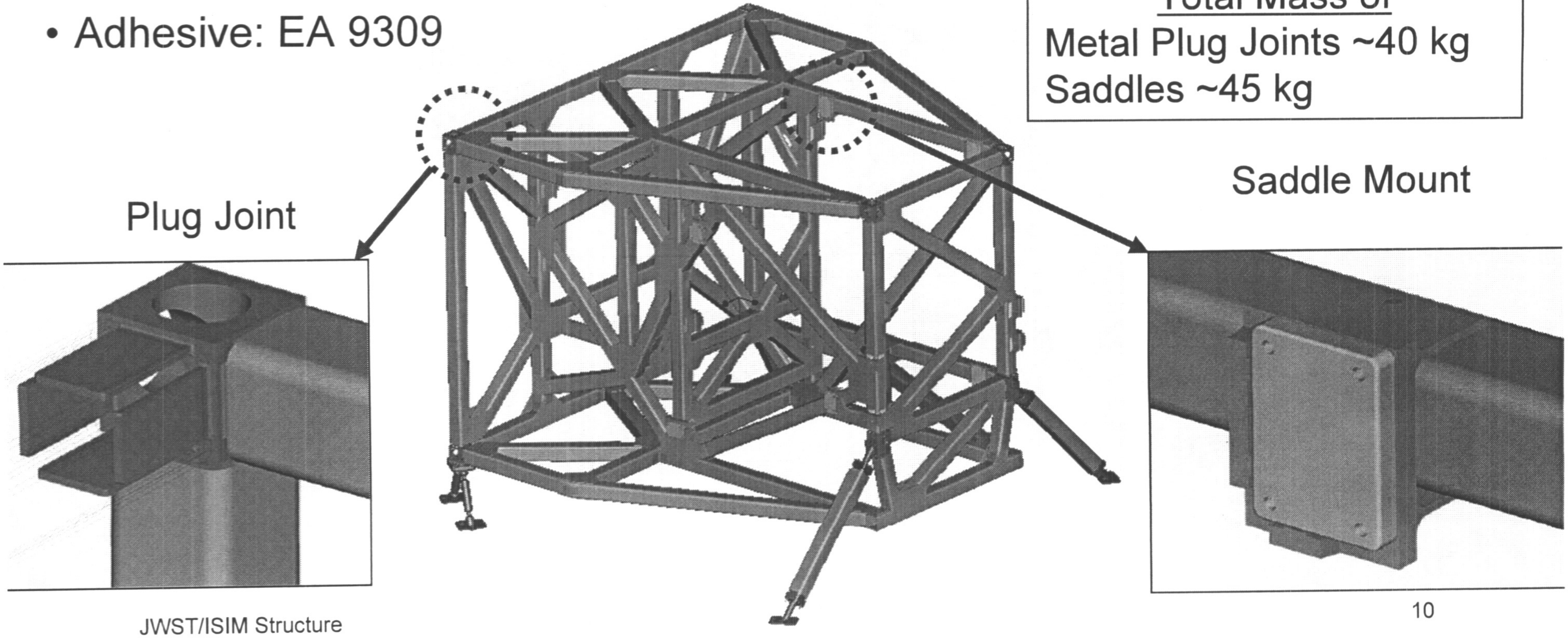
<u>Kinematic Mounts to OTE</u>

- 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

<u>Total Mass of</u>
Metal Plug Joints ~40 kg
Saddles ~45 kg



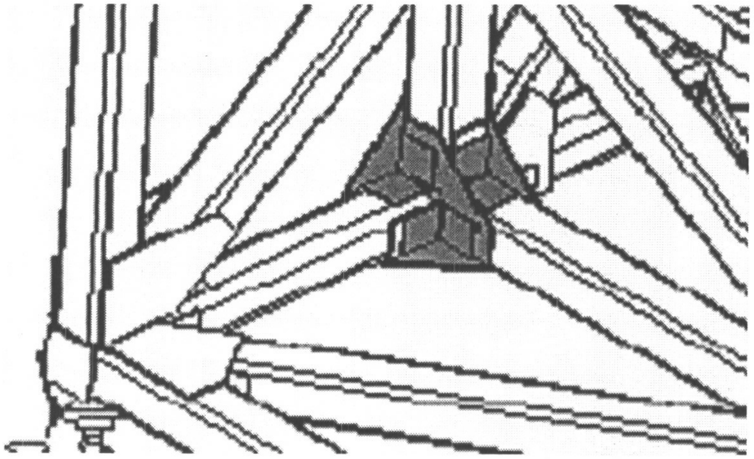
Baseline Structure Overview
Gusseted & Clipped Joints

- 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

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

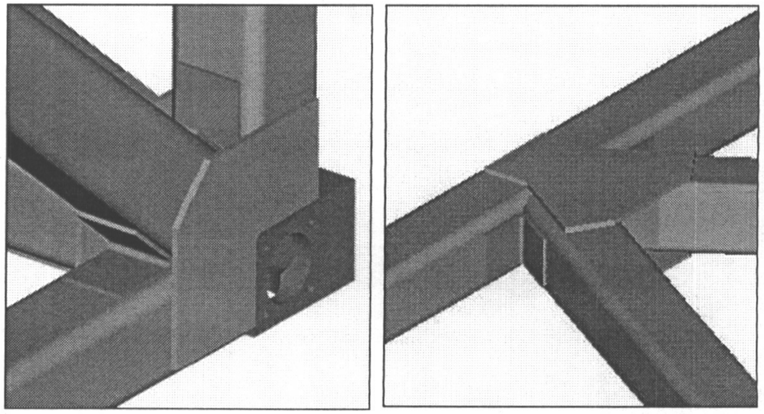
Joint missing a critical gusset

Caused by trying to join members in perpendicular planes at the same location. Not used by the baseline ISIM Structure



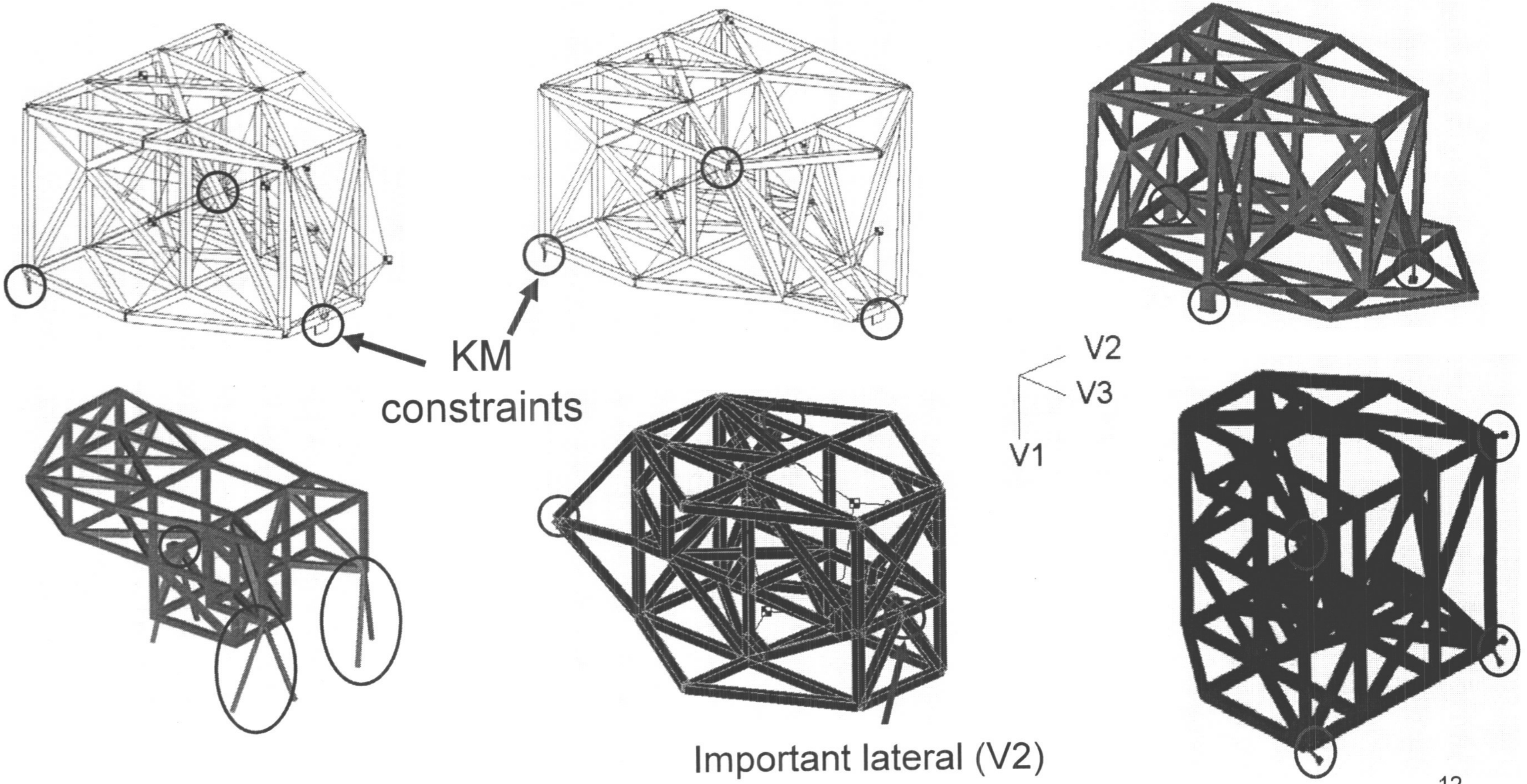
Joints with good load paths

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.

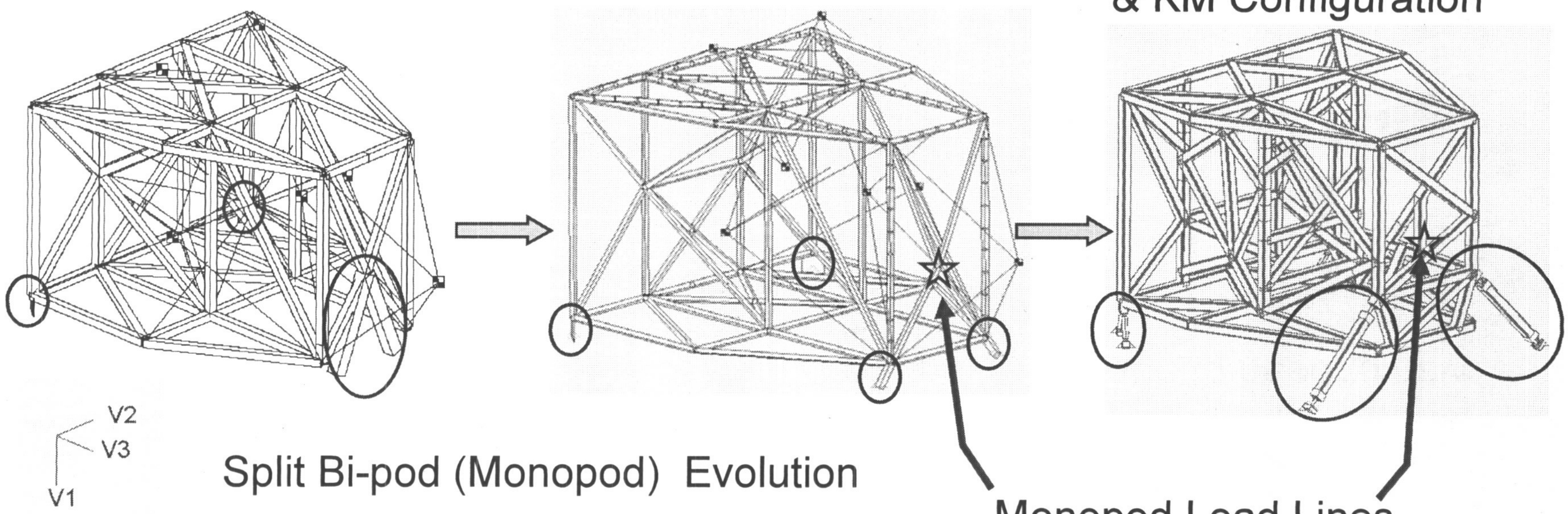


KM constraints

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.



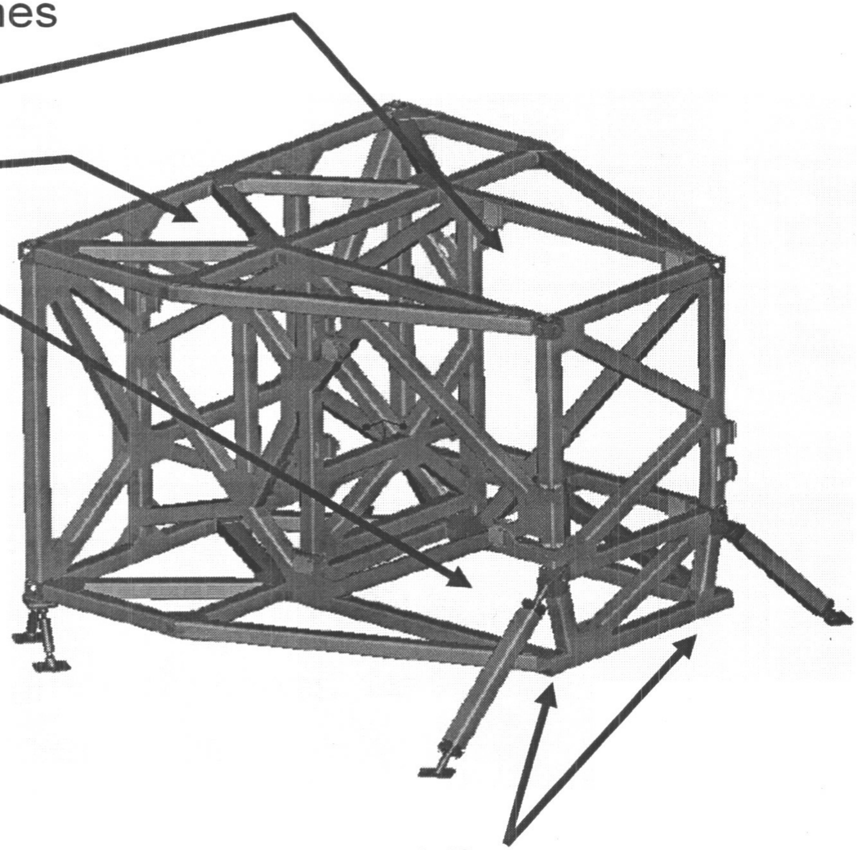
Baseline Structure & KM Configuration

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



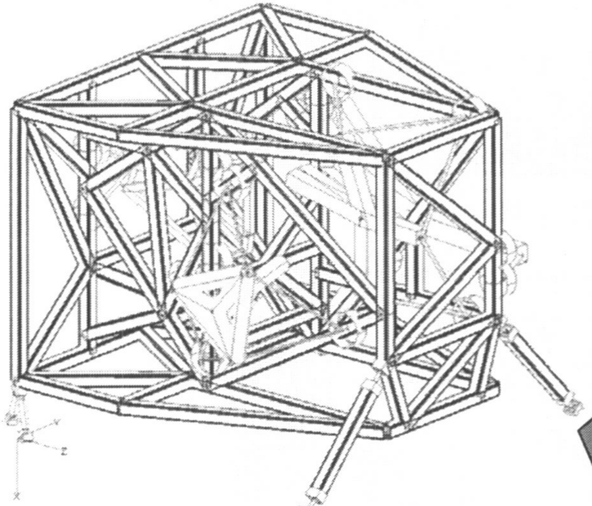
- Open bays stiffened through adjacent trusses and "wings."
- No removable members used to stiffen the open bays in view of distortion risk.
- All primary load lines intersect at joints.
- Trusses in different planes are staggered to simplify some joints, for example:
  - with the removal of the dewar, plug fittings at the two lower +V3 corners are also removed and members properly offset and joined through lighter gussets and shear clips.

Selected Material Properties & Material Property Trades

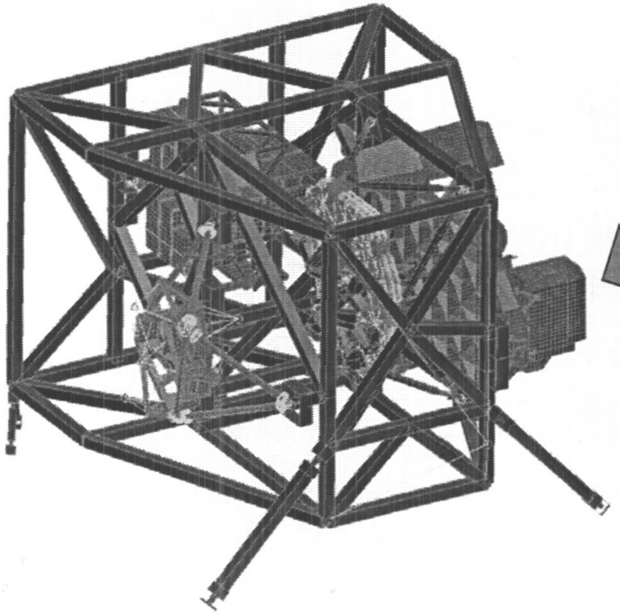
Material - used for	Modulus MPa	Strength MPa	CTE ppm/K
Biased Laminate - Tubes	146,400 axial	439 axial	~0 (axial) 3.5 (hoop)
QI Laminate - Gussets	52,800 in-plane	447 tension	1.9 in-plane
INVAR - Plugs, Clips, Saddles	145,000	248 yield	1.5
EA9309 Adhesive	1490	36.5 shear	51
Ti-6Al-4V - Flexures, Saddles	110,000	828 yield	6.6

- A biased laminate is tailored to keep the tube hoop CTE low for thermal survivability. Axial modulus is reduced as a result.
- A QI laminate is used for the gussets with better overall strength than the tube laminate but not as stiff.
- Shear Clips could not be composite laminate due to low interlaminar strength and high fabrication costs (too many different angles).
- Adhesive is EA9309 instead of the stronger EA9394 in view of its higher elongation and compliance at cryogenic temperatures.
- CTE is secant from Room Temperature to 19 K.

ISIM Finite Element Models

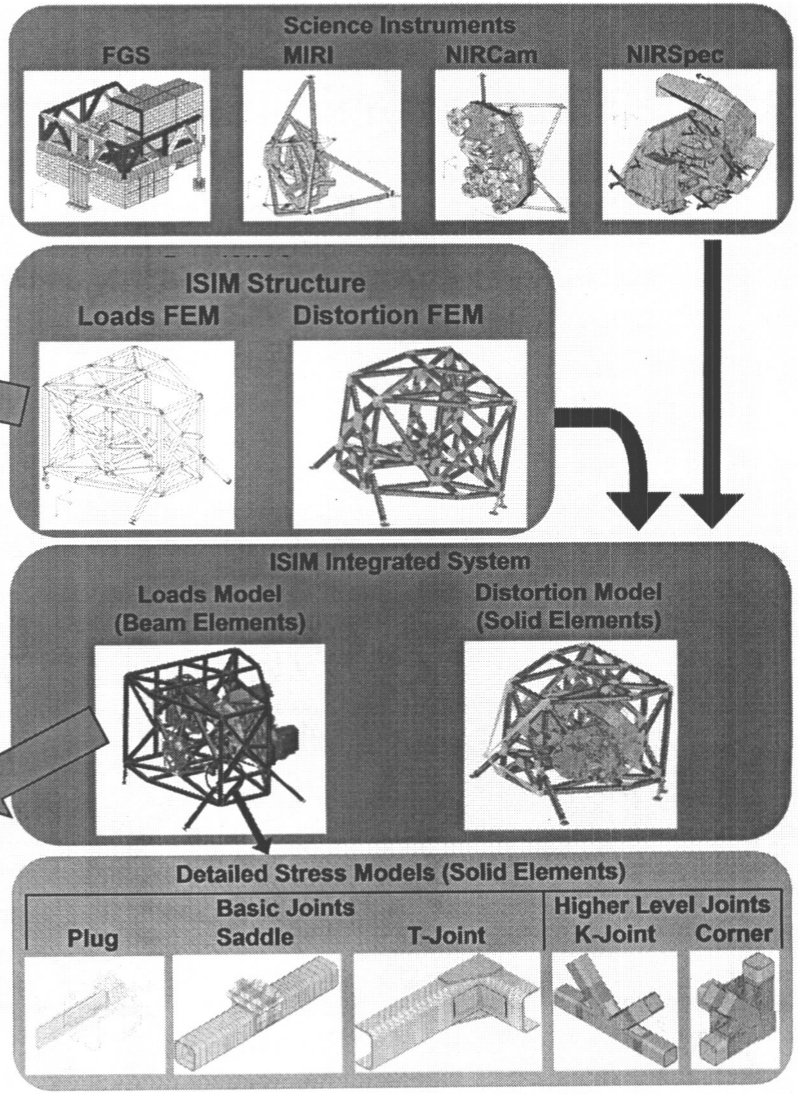


ISIM Loads FEM with ideal SI Representations used for quick turn around concept and trade studies



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

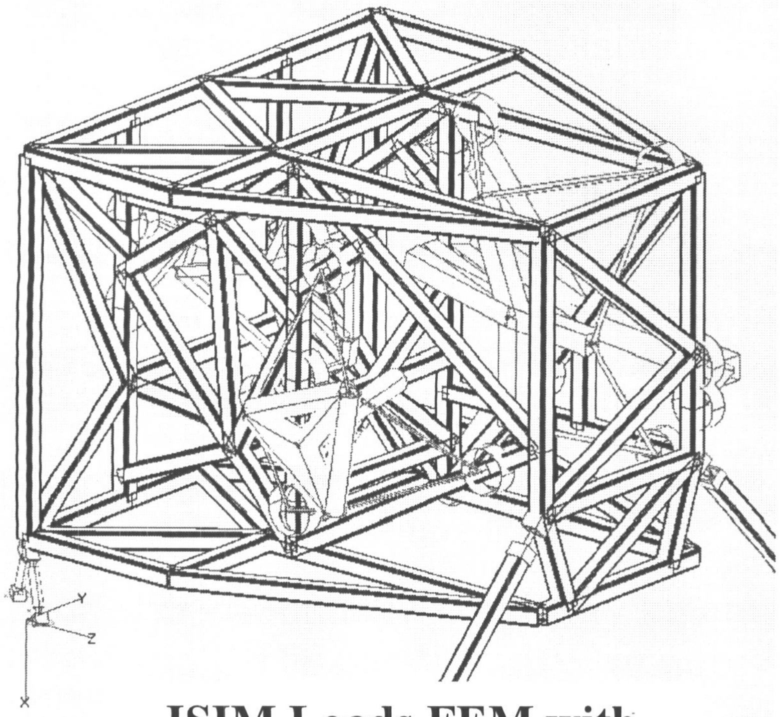
ISIM Integrated System

Loads Model (Beam Elements)
Distortion Model (Solid Elements)

Detailed Stress Models (Solid Elements)

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

ISIM Loads FEM with ideal SI Models



ISIM Loads FEM with ideal SI Representations

- provides sufficient accuracy & quick turn around for normal modes and launch reaction analysis
- proved to be instrumental in conducting many concept, trade, and optimization studies in a very time efficient manner
- Bar and Mass elements 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 frequency results with those from

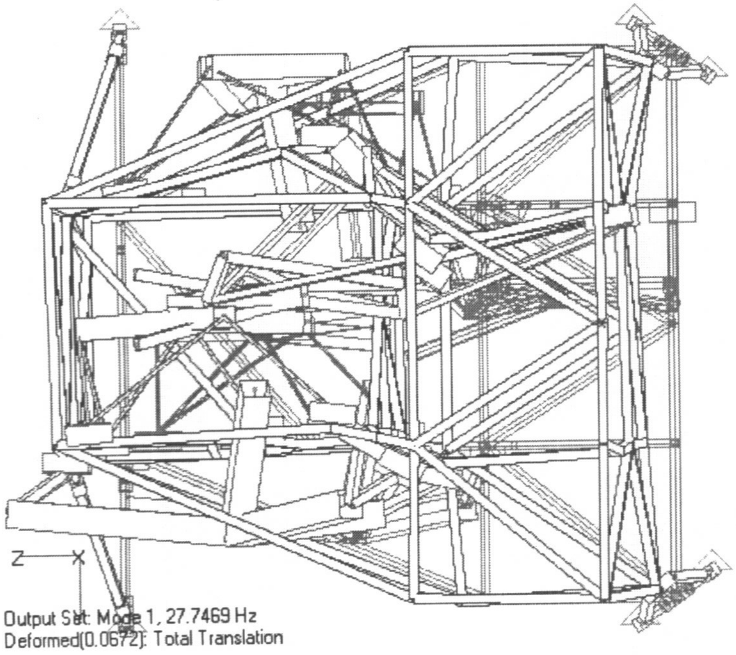
Solid element model demonstrated it to be accurate within 5%

Loads FEM confirm that it is slightly conservative as expected

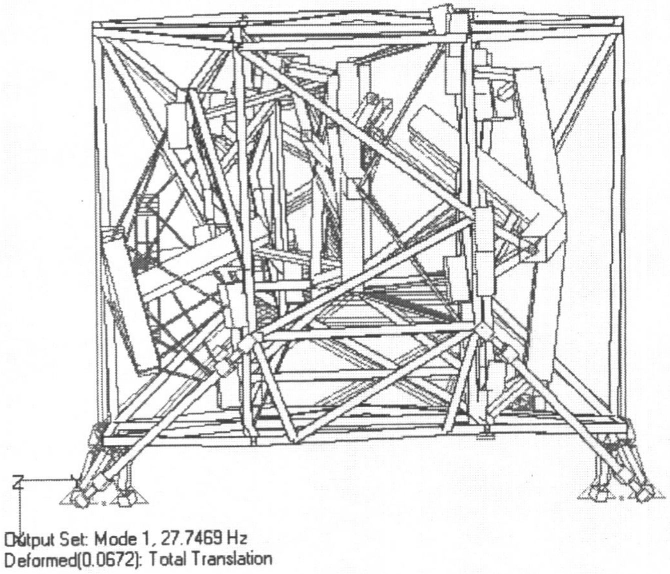
ISIM Normal Modes Summary & Fundamental Mode

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

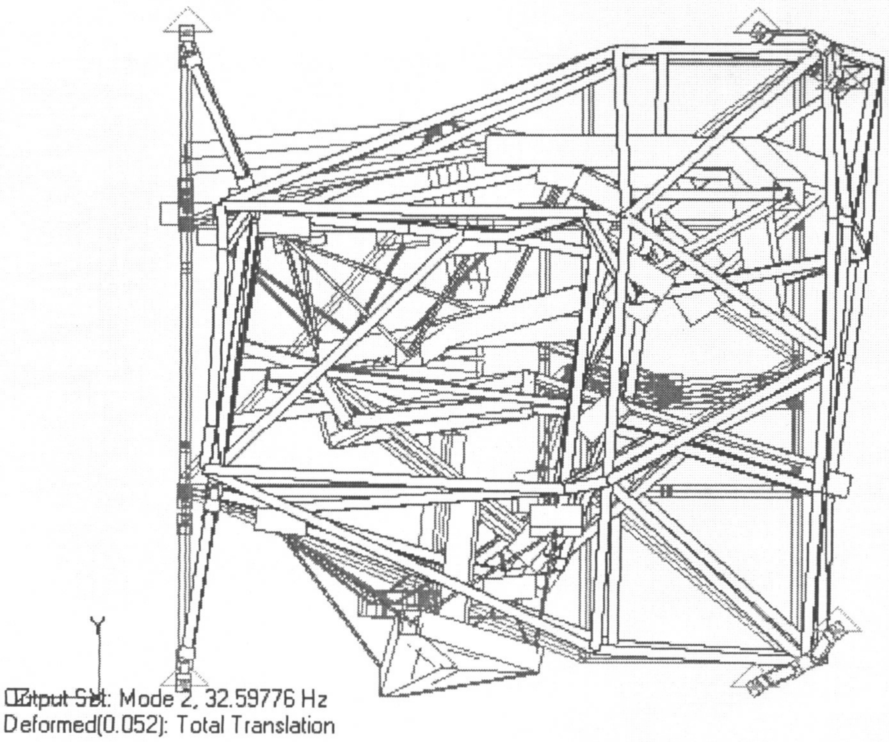


Fundamental Frequency Mode Shape dominated by KM and SI support structure flexibilities

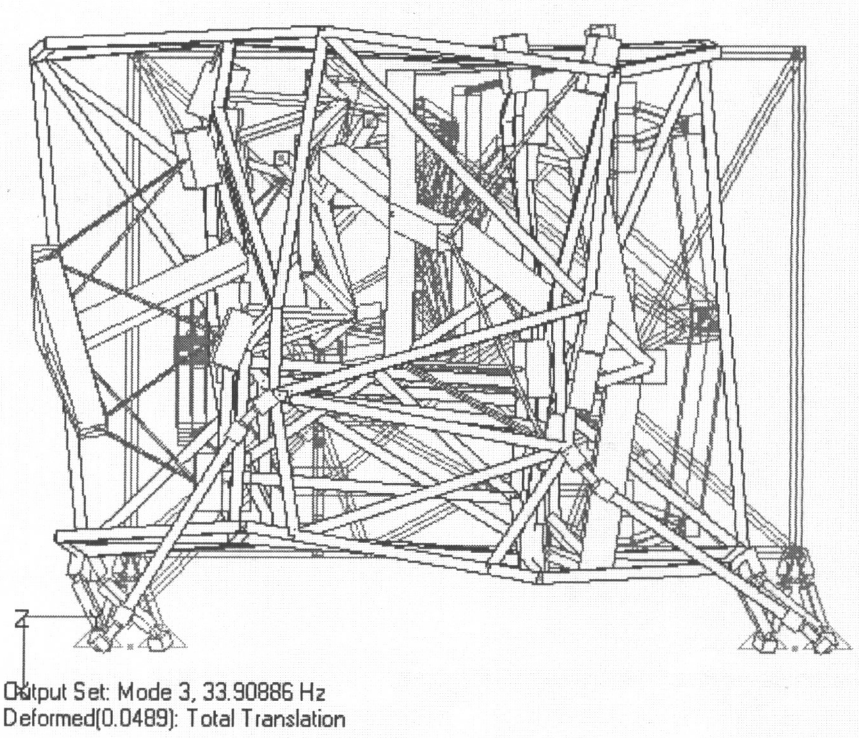


Normal Modes: 2^{nd} & 3^{rd} Modes

	fn		Mass Participation (%)					
n	(Hz)	X	Y	Z	RX	RY	RZ	notes
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



2^{nd} Mode



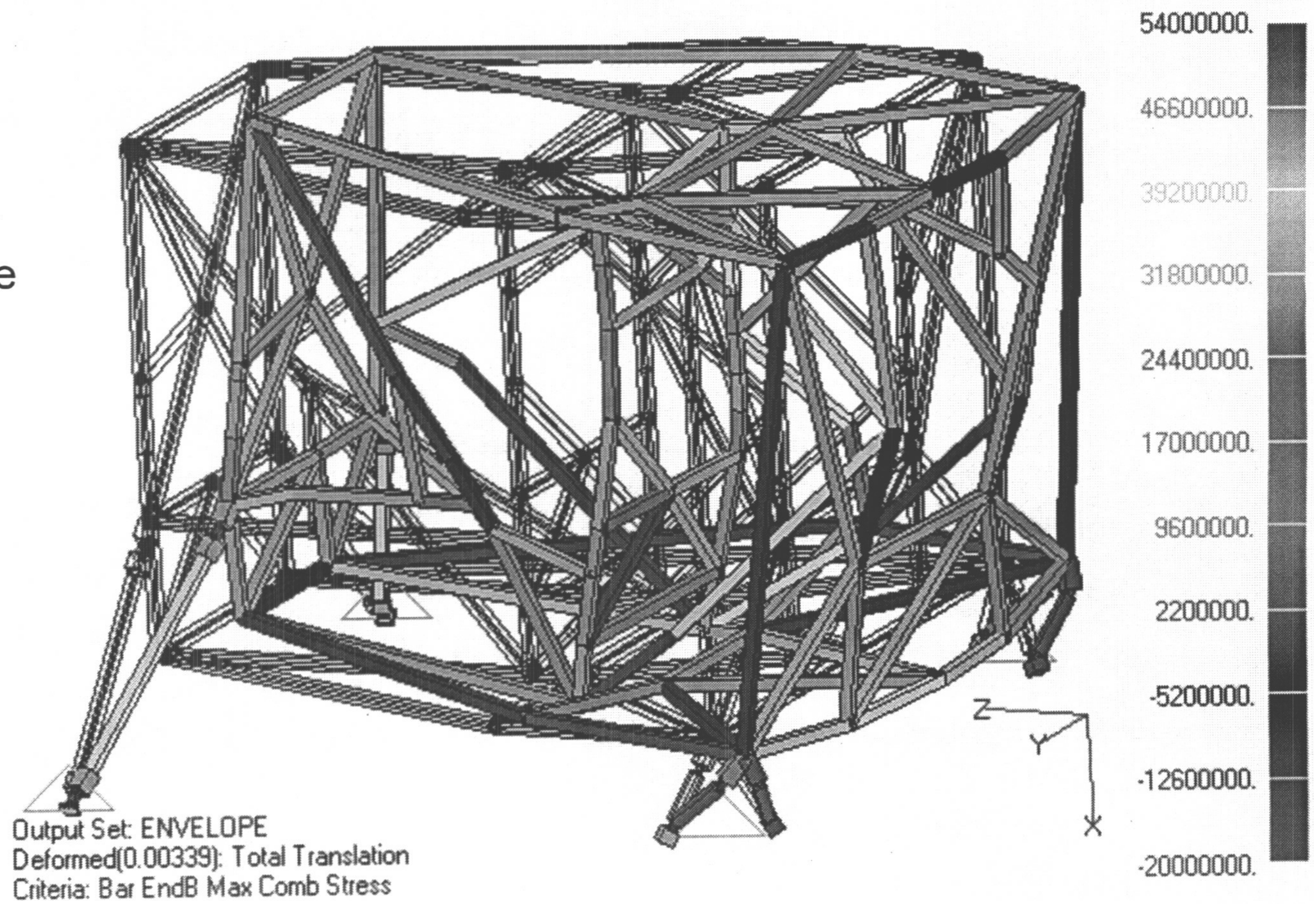
3^{rd} Mode

Deformed Shape & Stress Contours Under Launch Loads

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

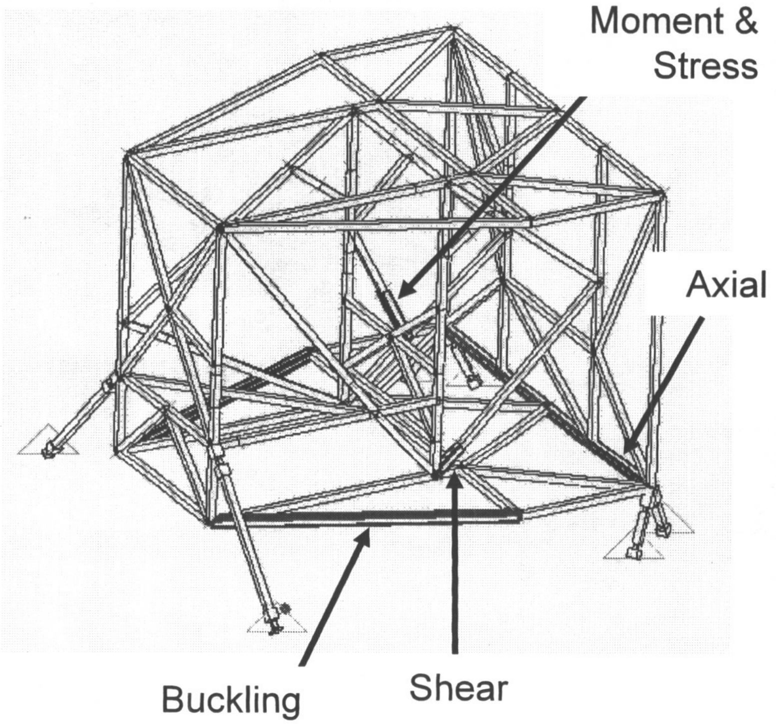
Primary Tube Stress Contours (Pa) Under Enveloping Load Case

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 ID		MA1	MA2	MB1	MB2	V1	V2	P	T	stress MS	buckling MS	
	worst	**1021**	**888**	**1197**	**892**	**11898**	**5459**	**47888**	**282**			
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 Under Launch Loads

- Joint reactions under launch loads are recovered from loads model
- Selected results shown here for plug joints
- Max effective axial reaction is later used in joint detailed stress analysis

Plug Joints

Summary of Results

Max Limit Axial Load, Pmax=	**47.9**	**kN**
Max Eff Axial Limit Load, Pmeff=	**77.7**	**kN**

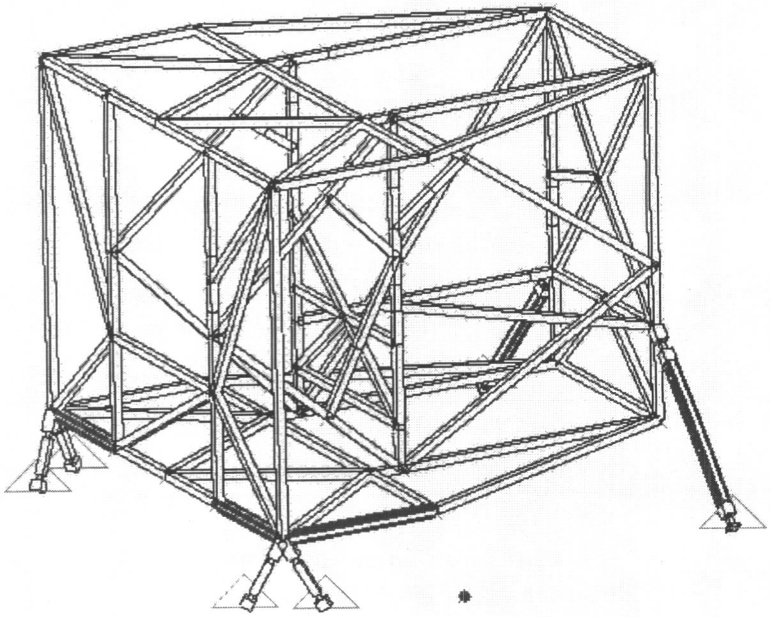
Pmeff includes bending effects.

Plug Max Stress, Smax=	**154.2**	**MPa**
MS for Plug Stress =	**0.43**	

Stress & MS results above are cursory .
See Detailed Stress Analysis for Final Results

Results for selected Plugs with highest Axial Load

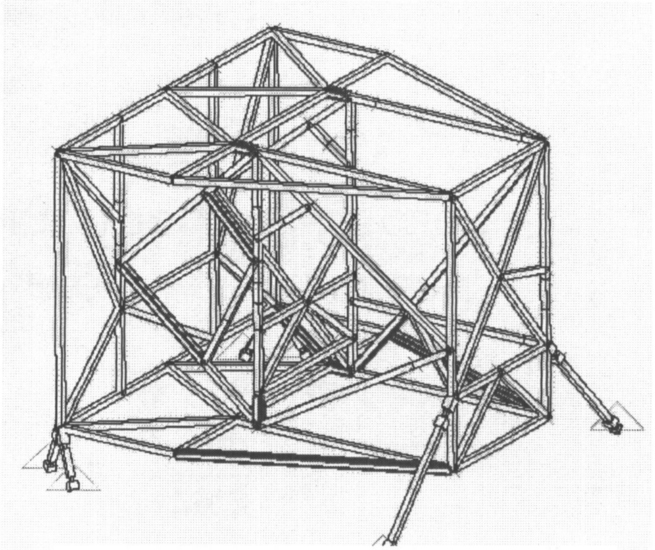
element ID	Plug End Codes A	Plug End Codes B	end types	Axial Load	Plug Stresses, MPa A	Plug Stresses, MPa B
106108	0	1	cp	47.9	0.0	116.5
100102	1	0	pc	44.5	107.3	0.0
308314	1	1	pp	41.7	87.6	90.1
302312	1	1	pp	40.8	86.1	89.4
100162	1	0	pg	25.0	87.5	0.0



Five plug joints with highest axial load highlighted

Gusset MS
Under Launch Loads

- Reactions for all gussets recovered from loads model
- Stresses and MS 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**

member ID	**Gusset Codes at ends of member 1 & 2 are shear directions**				**end type**	**Gusset Normal Stress MPa**	**Bond Shear Stress MPa**
	end A		**end B**				
	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

- Following limit reactions are predicted for use 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

- Preliminary MS under launch loads calculated are all positive and listed below. More under “Detailed Bonded Joint Analysis” Section

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

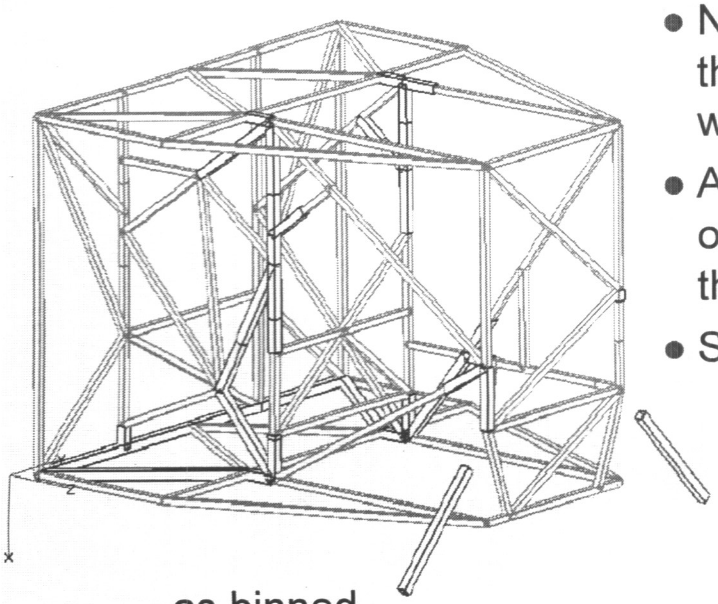
Further Improvements

- Mass margin is low hence we are looking at ways of reducing structure mass
  - Tube wall thickness optimization

    (one page summary follows)
  - Removal of shear clips of members that do not carry significant transverse shear loads
- Also underway is
  - improving launch strength, reliability, inspectability, and reparability of critical joints under SI transverse shear loads

Sample Tube Wall Thickness Optimization
using 2 different wall thicknesses of 2.9 & 5.8 mm

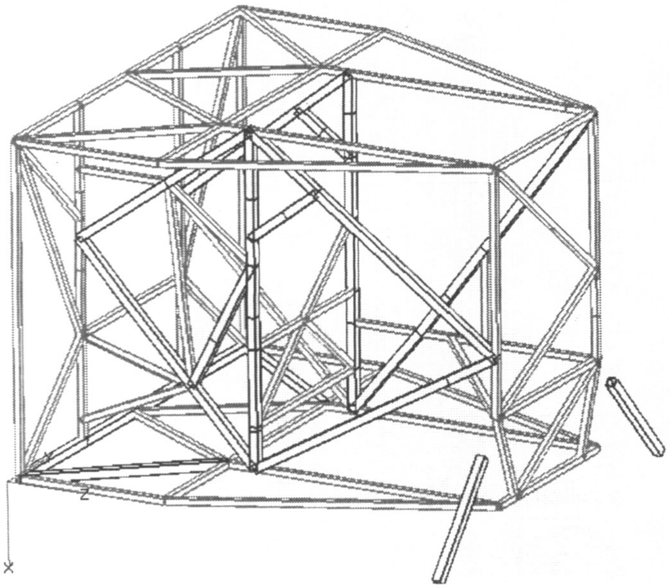
- NASTRAN optimizer used to assign either 2.9 or 5.8 mm thickness to each tube element to minimize structure weight while maintaining fundamental frequency at ~27.5 Hz
- As binned results are not practical and cleaned-up to have one thickness for every continuous member. Some member thicknesses are bumped 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	27.70	27.70	0.0
f2,Hz	30.60	32.60	2.0
f3,Hz	33.90	38.40	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,
    - OTE and SI 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 in guiding structure design
  - Concept & Trade Studies
  - Tube wall thickness optimization