Dynamic Stability Finite Element Analysis of Multiple Potential Large Space Telescope Structural Designs

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NASA/MSFC/ES23

October 18, 2023

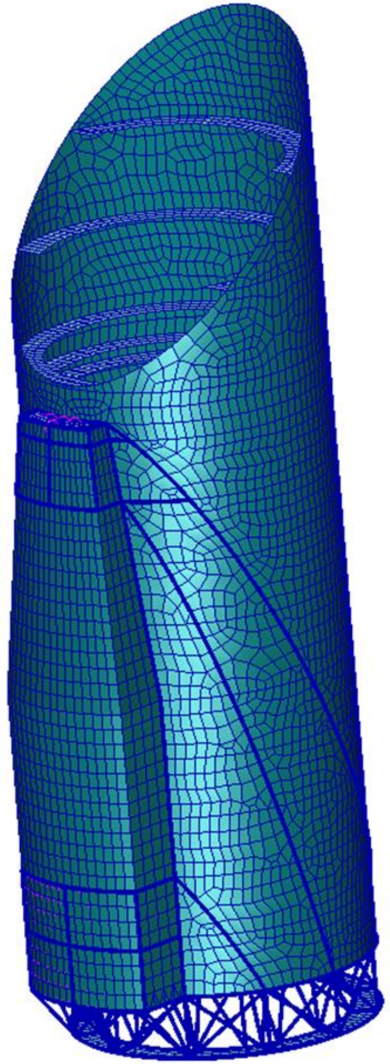
Introduction

- Efforts have been, and are being, exerted to define a next, post JWST, astrophysics flagship mission

- In the area of astrophysics, the NASA 2020 Decadal considered four proposed flagship astrophysics facilities

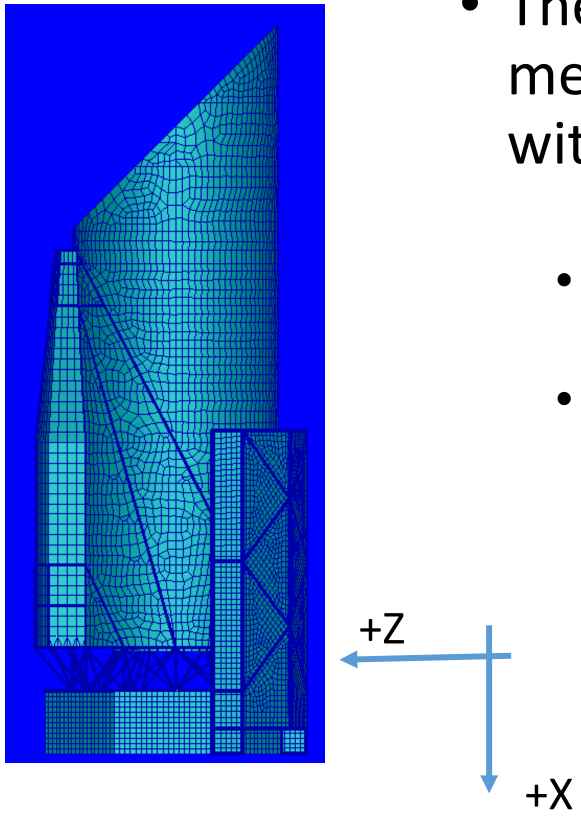
  - One candidate astrophysics facility was the Habitable ExoPlanet Imaging Mission (HabEx)

  - This presentation describes two HabEx structural designs and results from structural dynamic Finite Element Analyses (NASTRAN) performed to predict Primary Mirror (PM) to Secondary Mirror (SM) Line of Site (LOS) stability (jitter) due to Reaction Wheel Assembly (RWA) vibrations



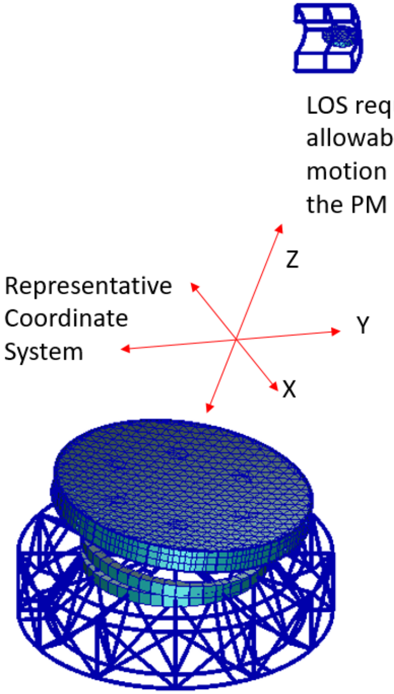
Objective

- The objective of this effort was to determine feasibility of meeting HabEx mechanical stability requirements associated with PM/SM LOS
  - PM/SM LOS alignment is required to be ≤ 5 milliarc-second (mas)
  - LOS stability requirements



FEA global coordinate system

Direction	Allocation
X (m)	2.00E-09
Y(m)	2.00E-09
RSSed - De-Center (m)	2.80E-09
Z - De-Space (m)	5.00E-09
Rx (rad)	1.10E-09
Ry (rad)	1.10E-09
RSSed - Tip/Tilt (rad)	1.60E-09
Rz (rad)	1.50E-09



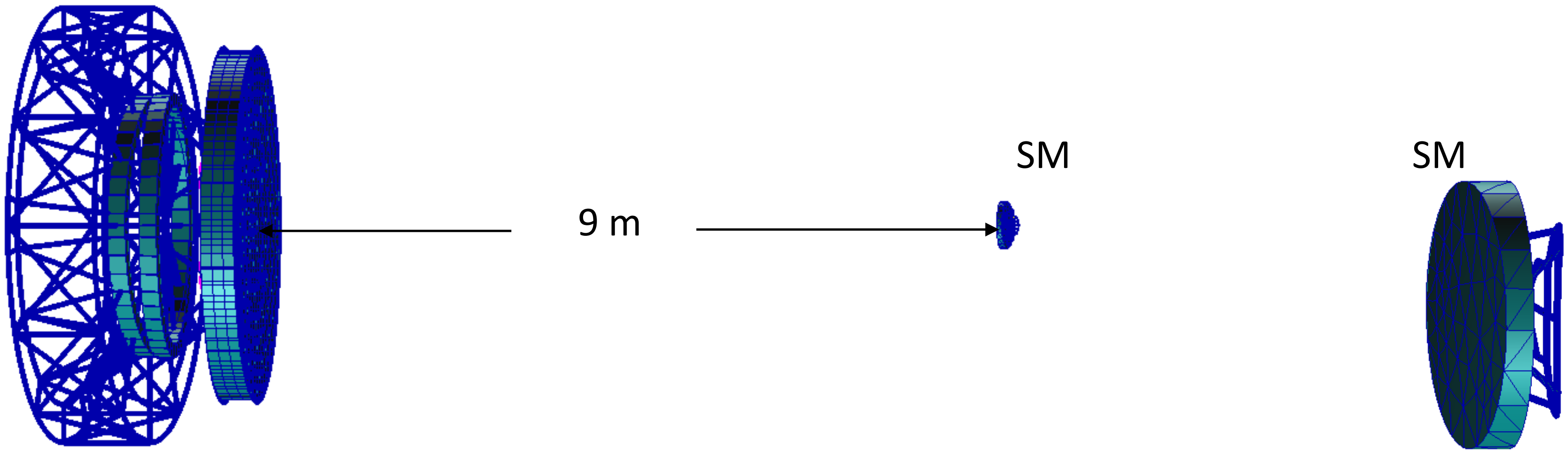
LOS requirements are allowable relative motion between the PM and SM

Representative Coordinate System

Mirror Configuration

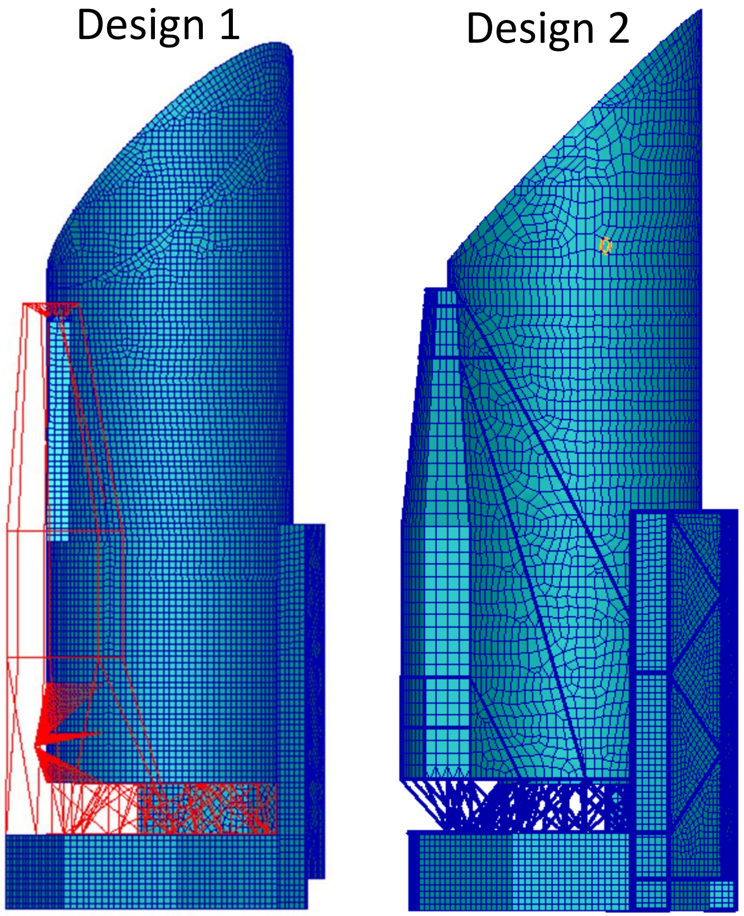
- The two HabEx Designs considered are both off axis optical systems with a 4 m PM and .5 m SM

- The spacing between the PM and the SM is 9 m which adds to the structural design /stability challenge
  - The greater the distance between the PM and the SM the stiffer the structure needs to be



Structural Designs

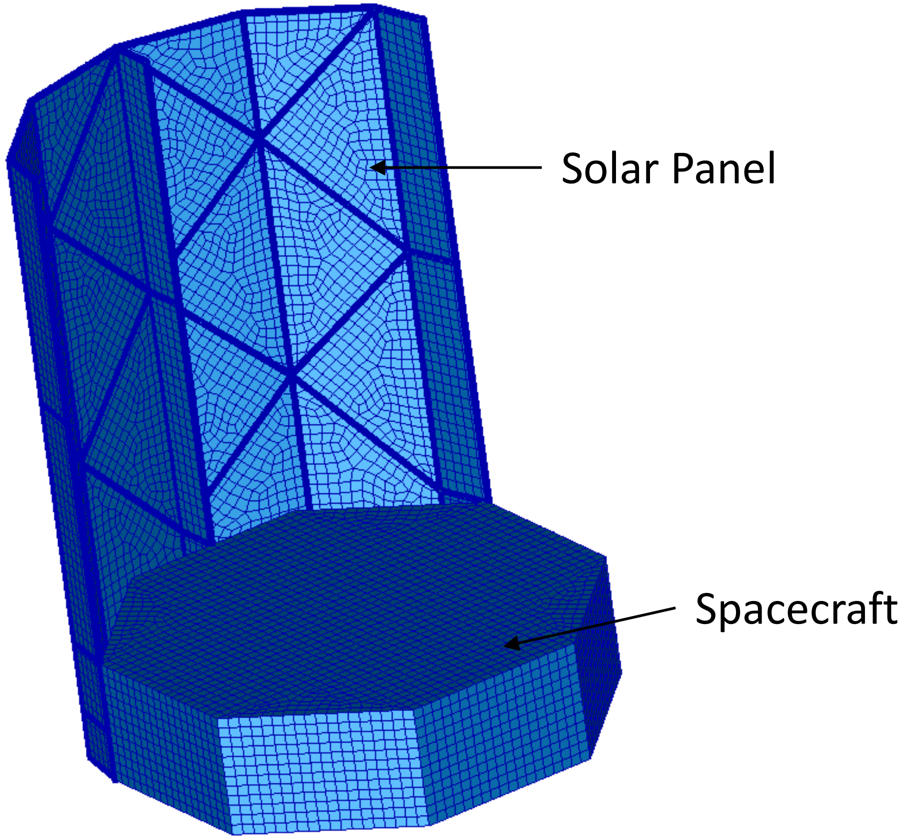
- At the completion of the design 1 jitter analysis, stability requirements were not in hand
  - Performance assessment could not be made
  - Efforts initiated to evolve the initial design
    - Stiffened the path between the PM and SM without creating detrimental modes



Finite Element Models (FEM) of the designs

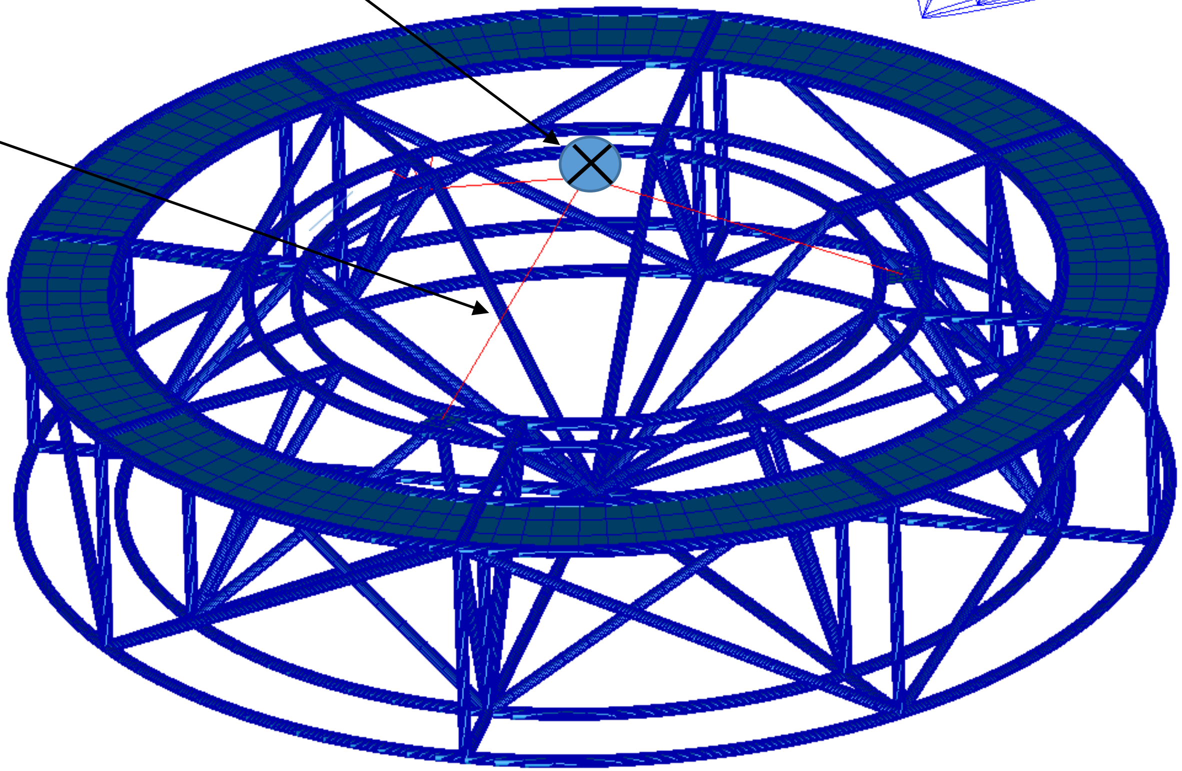
Common Structures

- A simplified Spacecraft (SC) design was implemented in both designs
- It included:
  - Mass properties representing propulsion and avionics
  - RWA load application points
  - Simplified solar panel

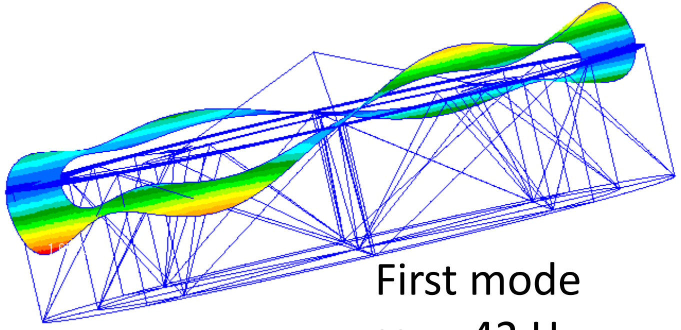


Common Structures

- PM Truss
  - NASTRAN rigid element connecting the PM mass to the Truss
  - Common modeling technique for a first cut
  - Good for capturing conservative global mass effects
  - Not well suited for capturing local effects



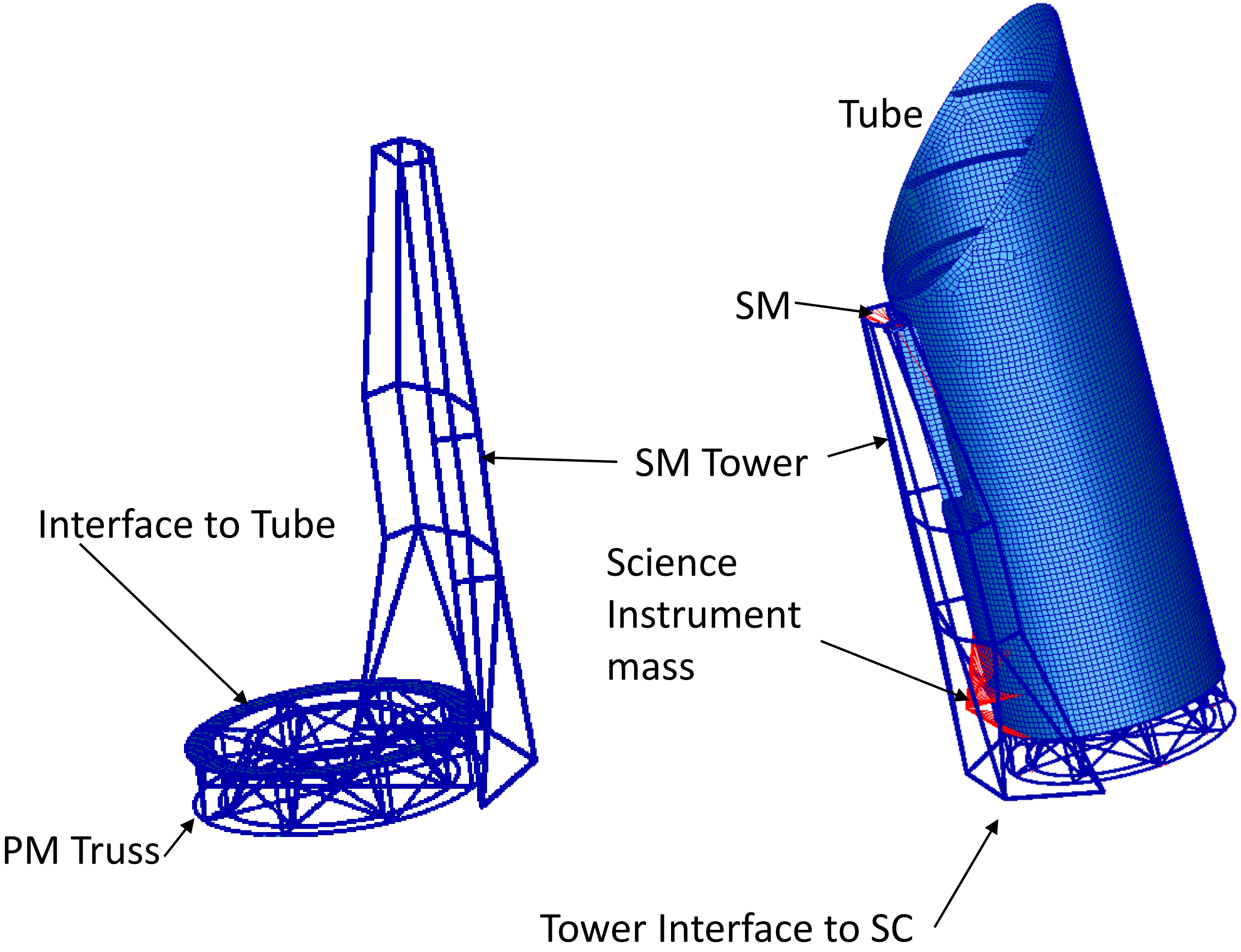
2,000 Kg concentrated mass representing The PM



First mode $\omega_1 = 42$ Hz

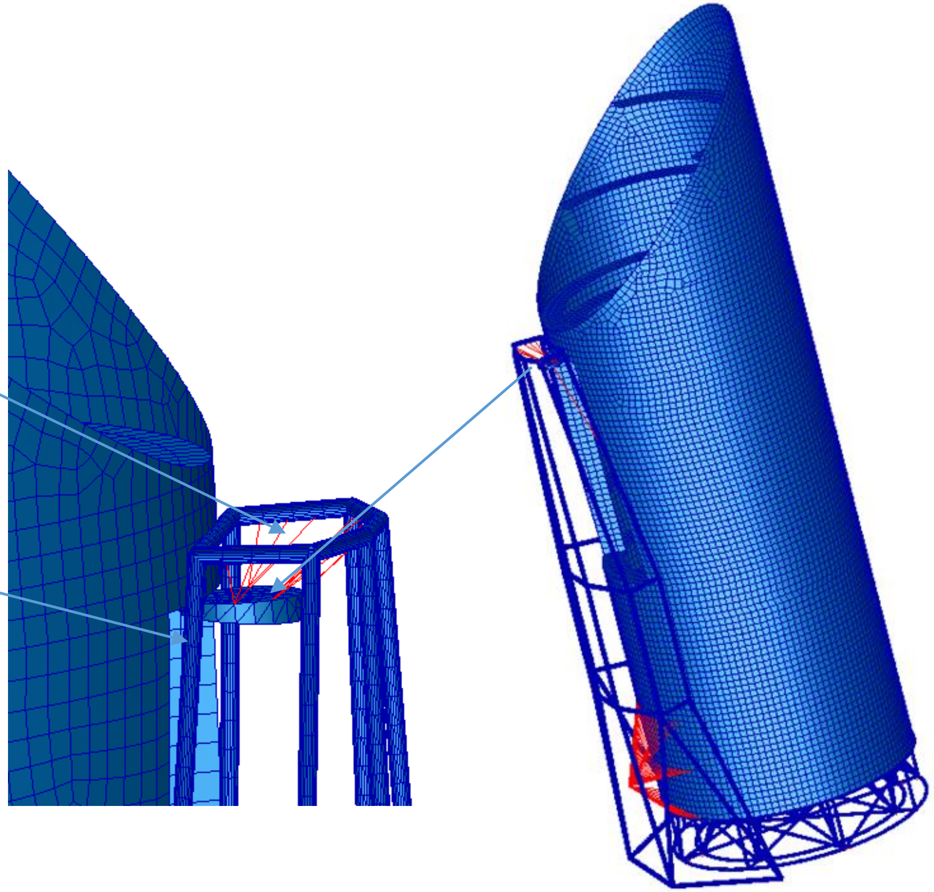
Design 1 Description

- The SM tower is not connected to the Tube
    - Attached only to the SC
- The tower includes non-structural mass (not visible) for the stray light baffle
    - Mass effects present in results, stiffness effects are not



Design 1 Description

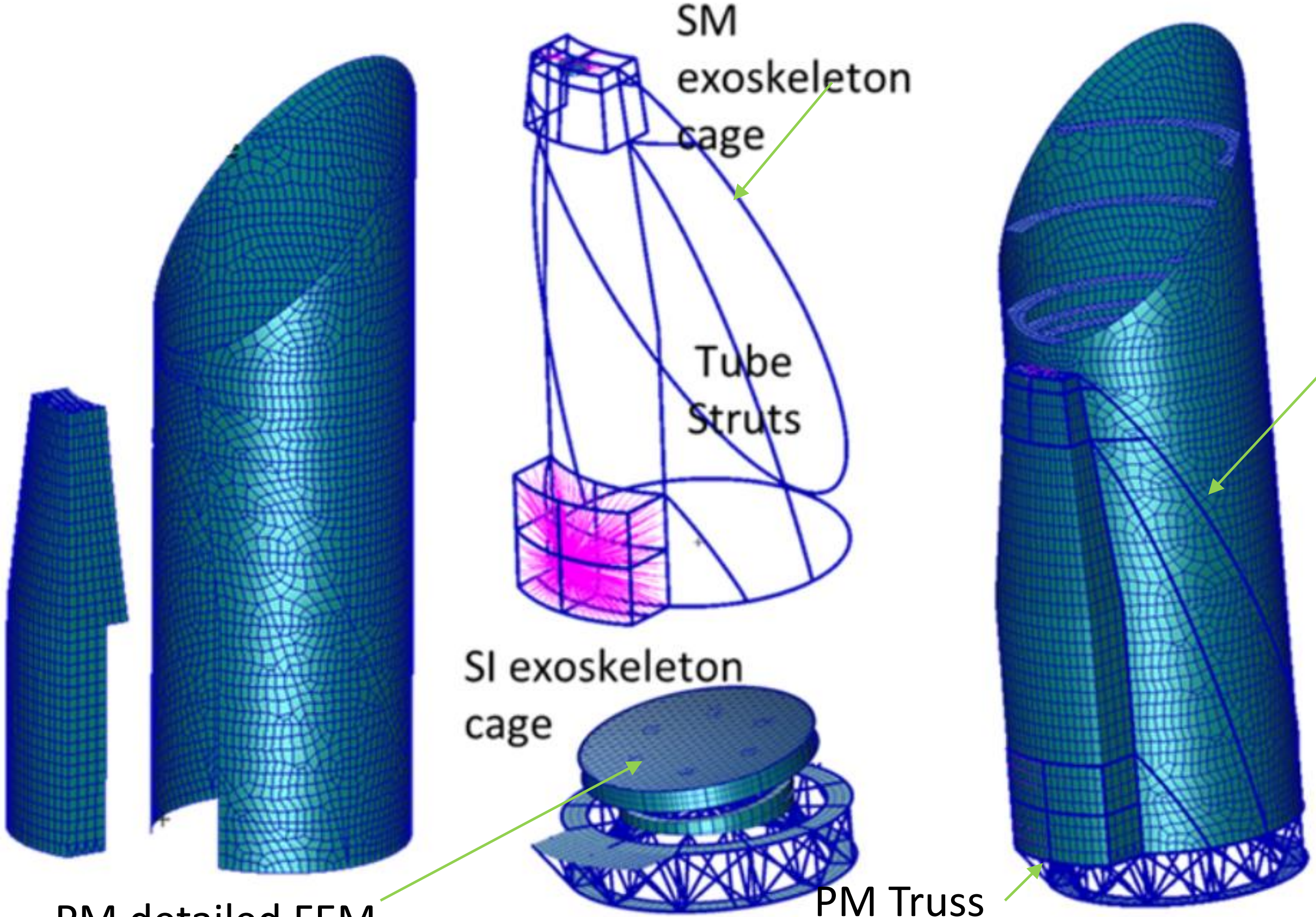
- SM is attached to the Tower via NASTRAN rigid elements
- Tower is not connected to the tube
- It interfaces with the SC deck



Design 2 - Description

- Efforts to better the design included
  - The SM tower was covered with structural material and integrated with the Tube
  - An exoskeleton structure that stiffened the structural path between the PM and the SM was included
  - A detailed Finite Element Model of the PM, created via the Arnold Mirror Modeler (AMM), was included with structural members for the PM support structure (as opposed to a rigid element)
    - The inclusion of supports with stiffness decreased the first mode dramatically
    - The PM truss design was modified to maintain its $\omega_1 \geq 40$ Hz
  - Structural members (as opposed to a rigid element) were included to represent the SM support structure
    - They were scaled based on the PM supports
  - The composite material was changed to be that of JWST, M55J 954-6 at 68°F

Design 2 - Description



Structural SM Tower

SM exoskeleton cage

Tube Struts

SI exoskeleton cage

PM detailed FEM

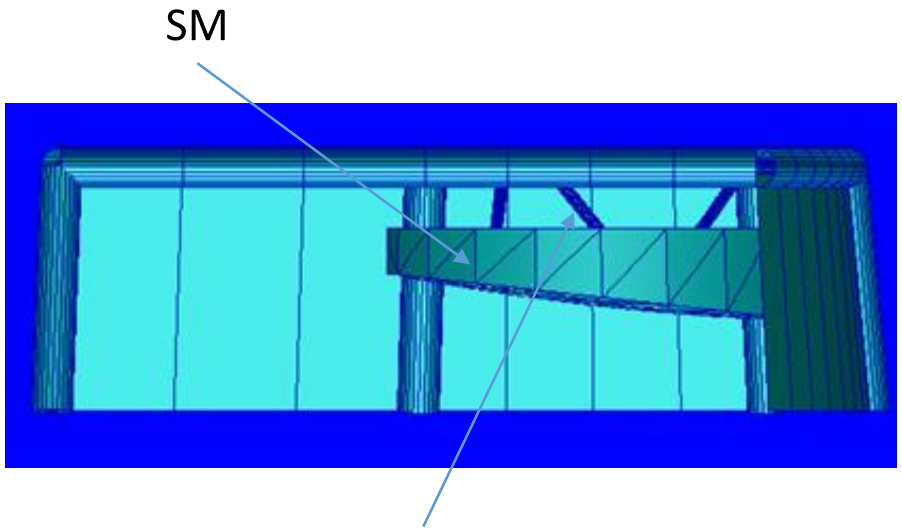
PM Truss

exoskeleton

THE PM and its supports detailed design/FEM was created by the Arnold Mirror Modeler (AMM)

Design 2 - Description

- The SM supports were, in Design 1, NASTRAN rigid elements
    - They were replaced with linear finite elements
    - Their dimensions were scaled from the PM supports provided by the AMM



SM attached to structural tower via structural Members (NASTRAN CBAR elements) as opposed to a rigid element

Dynamic Forcing Function

- LOS jitter errors are due to a vibration source or sources in the system
- Performing structural dynamic analyses to predict performance associated with jitter requires a Dynamic Forcing Function (DFF)
- Guidance Navigation and Control (GN&C) systems are expected to be the only sources of significant vibrations
  - Reaction wheels, thrusters, etc.
  - It was assumed that HabEx will utilize a Reaction Wheel Assembly (RWA) for GN&C
- JWST personnel communicated that their RWA proved to be challenging with respect to meeting requirements
  - ***The allowable vibration specification for the JWST RWA was utilized in these analyses as the DFF***

Dynamic Forcing Function

- Use of the JWST RWA is considered a conservative assumption
  - Between the time the JWST RWA vibration specification was written and the time a potential HabEx mission selects a RWA (assuming it uses RWA's) available RWA's should be more precise (lower emitted vibrations) than that of JW
    - Presumably that technology, like others, will evolve over decades
    - Hence, use of existing JWST RWA data is conservative
  - If HabEx engineers opt to utilize thrusters or some other means to achieve GN&C it is likely that doing so will be done to better performance
    - Hence, use of existing JWST RWA data is conservative

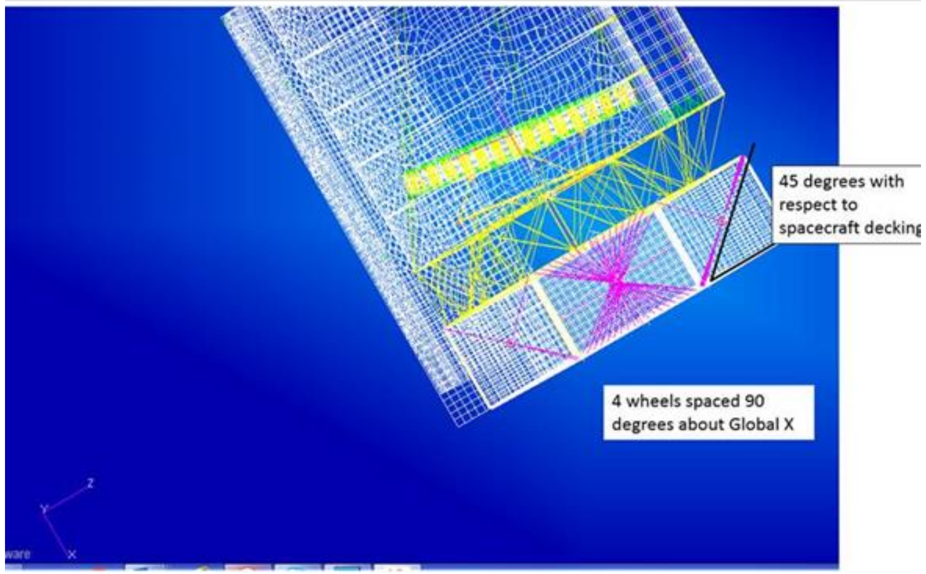
Analysis

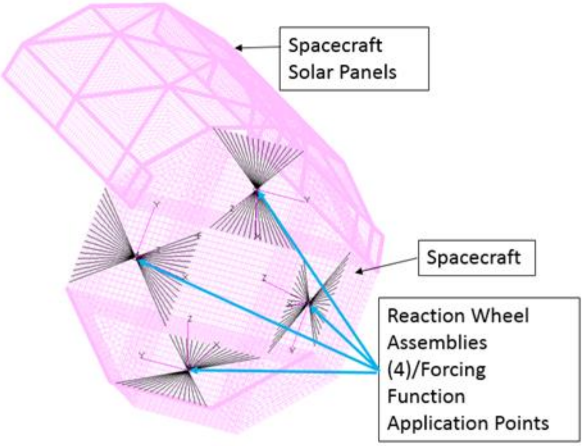
- Frequency Response Analyses (FRA) were performed to predict relative motion between the center of the PM and the center of the SM due to RWA vibrations
  - A sinusoidal input with unit amplitude was input at each frequency assessed
    - $1 \leq \omega \leq 500$ Hz, $\Delta\ \omega = 1$ Hz
  - The displacement of all PM and SM mirror surface degrees of freedom were predicted and the mean displacement response was calculated from that
    - The relative motion between the two was determined from those results
  - Those data were scaled by the DFF
    - An FRA output due to unit input is effectively a transfer function

Analysis

- The FEM was free-free as it would be in service
  - The FEM was not fixed or grounded
- 1% modal damping was assumed
- Results were output at 1 Hz intervals
- 4 DFF Applications Points
  - The locations of the 4 RWAs
  - Loads were applied in numerous directions and results enveloped
- An uncertainty factor of 15% was included
  - Intended to cover uncertainties in material properties WRT making extremely small predictions
- An 80 dB damping was included
  - Based on JWST

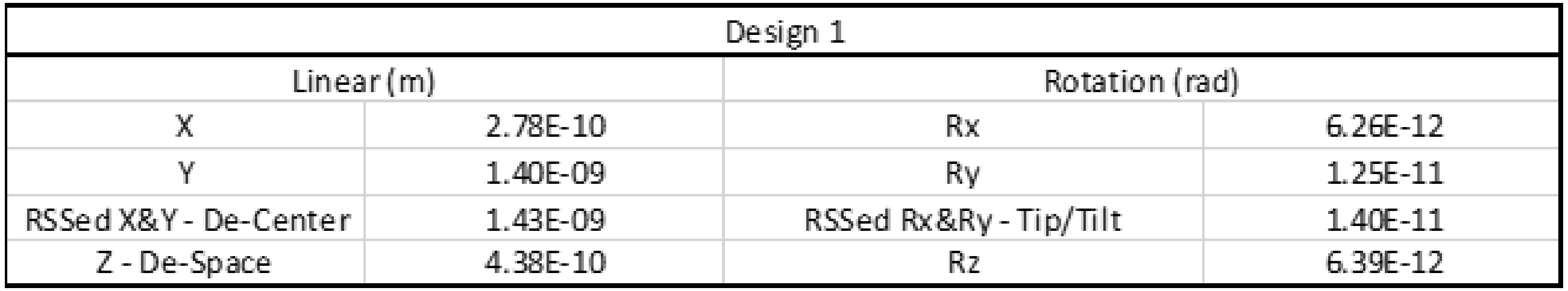
DFF input locations



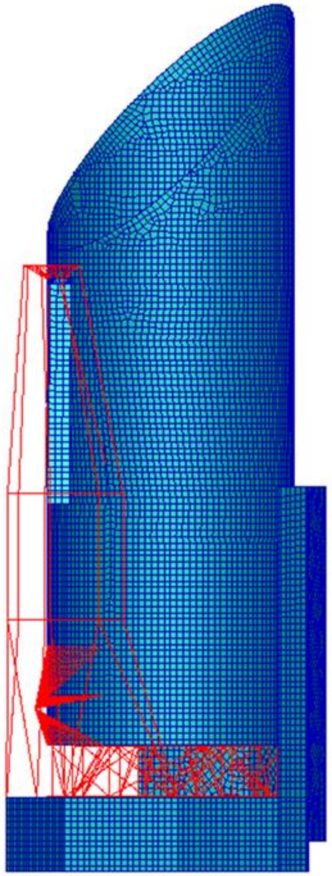


Results

- Design 1 summary
  - SM Tower not tied to tube
  - SM Tower does not include stiffness of cover material
  - Mirror supports are ridged elements

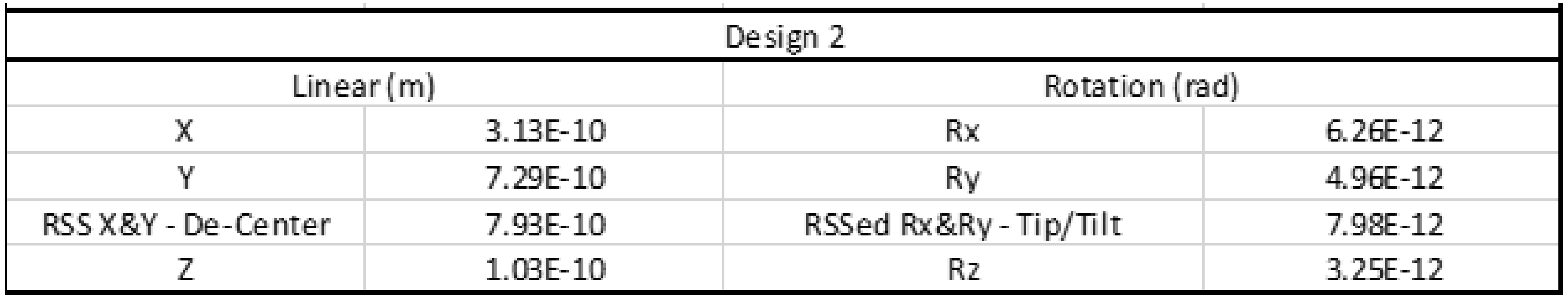


Design 1			
Linear (m)		Rotation (rad)	
X	2.78E-10	Rx	6.26E-12
Y	1.40E-09	Ry	1.25E-11
RSSed X&Y - De-Center	1.43E-09	RSSed Rx&Ry - Tip/Tilt	1.40E-11
Z - De-Space	4.38E-10	Rz	6.39E-12

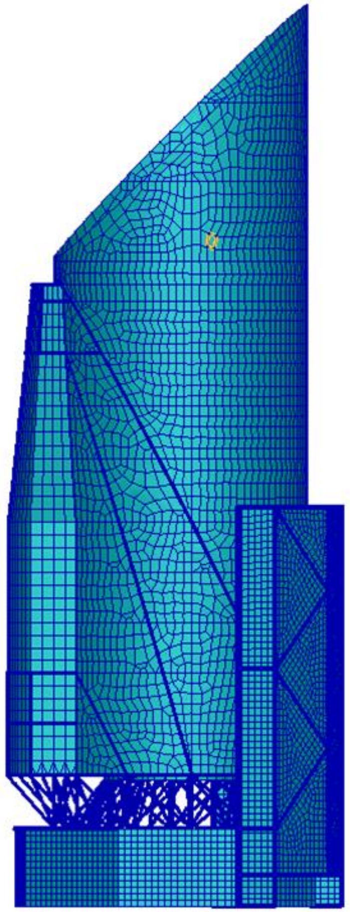


Results

- Design 2 summary
  - Stiffer SM tower
    - Tower/Tube stiffness integrated via FEM of covering
    - Exoskeleton
  - Detailed design of mirror support structures



Design 2			
Linear (m)		Rotation (rad)	
X	3.13E-10	Rx	6.26E-12
Y	7.29E-10	Ry	4.96E-12
RSS X&Y - De-Center	7.93E-10	RSSed Rx&Ry - Tip/Tilt	7.98E-12
Z	1.03E-10	Rz	3.25E-12



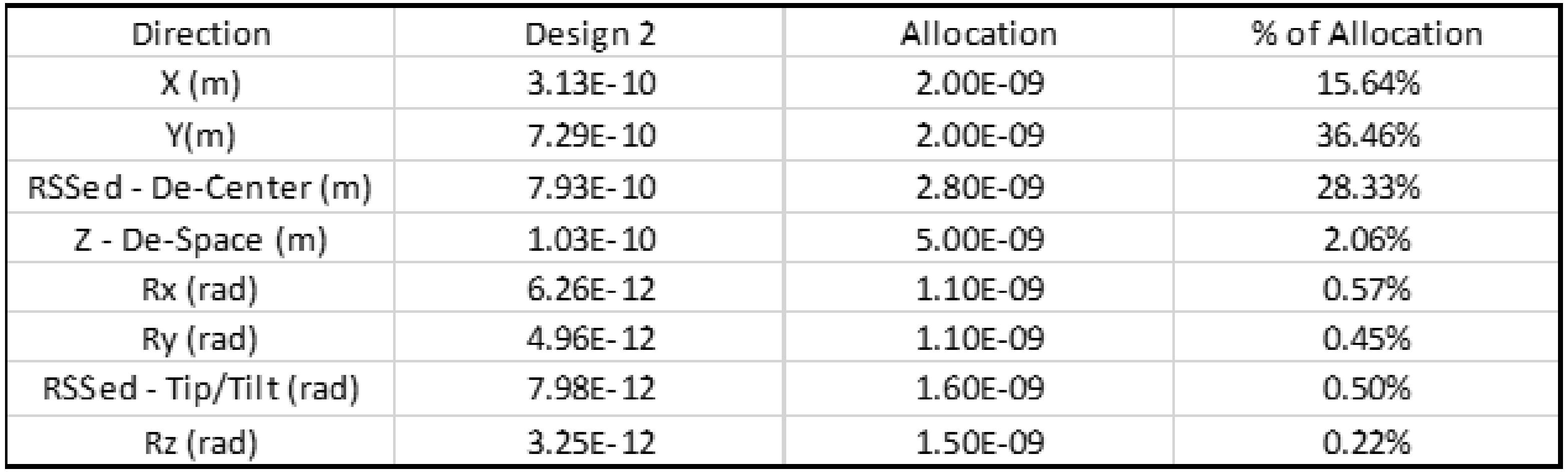
Results

- Comparison
    - Except for Y decenter, Design 2 outperforms Design 1
        - Design 2 RSS^{ed} decenter results outperforms Design 1
            - Design 2, WRT in-plane motion, outperforms Design 1
    - ***Design 2 is more stable than Design 1***

Direction	Design 1	Design 2	Design2/Design1
X (m)	1.40E-09	3.13E-10	2.24E-01
Y (m)	2.78E-10	7.29E-10	2.62E+00
RSS^{ed} - De-Center (m)	1.43E-09	7.93E-10	5.55E-01
Z - De-Space (m)	4.38E-10	1.03E-10	2.35E-01
Rx (rad)	1.25E-11	6.26E-12	5.01E-01
Ry (rad)	6.26E-12	4.96E-12	7.92E-01
RSS^{ed} - Tip/Tilt (rad)	1.40E-11	7.98E-12	5.70E-01
Rz (rad)	6.39E-12	3.25E-12	5.09E-01

Results

- Comparison of Design 2 and requirements



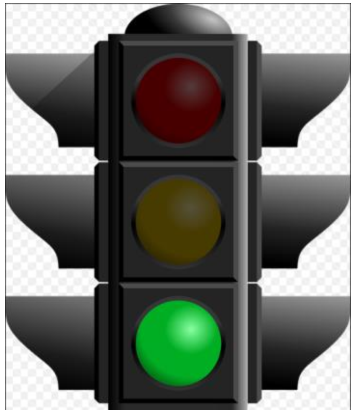
Direction	Design 2	Allocation	% of Allocation
X (m)	3.13E-10	2.00E-09	15.64%
Y(m)	7.29E-10	2.00E-09	36.46%
RSSed - De-Center (m)	7.93E-10	2.80E-09	28.33%
Z - De-Space (m)	1.03E-10	5.00E-09	2.06%
Rx (rad)	6.26E-12	1.10E-09	0.57%
Ry (rad)	4.96E-12	1.10E-09	0.45%
RSSed - Tip/Tilt (rad)	7.98E-12	1.60E-09	0.50%
Rz (rad)	3.25E-12	1.50E-09	0.22%

- Both designs satisfied the LOS stability requirements
- Design 2 outperformed Design1

Discussion of Results

- Conservatisms
  - Material property UF was utilized
  - Input loads (DFF) applied in many combinations and results enveloped
  - JW RWA data is conservative WRT this activity
  - RSS^{ed} maximum vector components that did not necessarily occur at the same frequency
  - 1% damping is thought to be conservative (in general 1-3 % are commonly used)
    - Although this being conservative is questionable WRT the extremely low order of magnitude of inputs and predictions
  - All DFF applied at the same frequency simultaneously
- Non-conservatisms
  - 80 dB reduction based on a simplistic application of that analytically may be over optimistic
- With the conservatisms utilized, margin still exists
  - In the worst case, predictions were only about 1/3 the required maximum limit

Conclusions



- The analyses performed to assess feasibility of the global HabEx structure demonstrated that <u>both designs satisfy PM/SM LOS stability requirements</u>
- Design 2, intuitively, is strategically stiffer than Design 1
  - That which keeps the PM and SM in alignment was stiffened and integrated
    - SM Tower stiffened integrated with the Tube
    - The base of the PM support structure was directly tied to that of the SM via the exoskeleton
    - As anticipated, Design 2 outperformed Design 1

Credits

- Numerous MSFC members contributed to this work:
    - Phil Stahl
    - Mike Baysinger
    - Jay Garcia
    - Melissa Therrell
    - Andy Singleton
    - Ron Hunt
    - Kate Caldwell