Dynamic/Jitter Assessment of Multiple Potential HabEx Structural Designs

J. Brent Knight*, H. Phillip Stahl*, Andy Singleton*, Ron Hunt*, Melissa Therrell*, Kate Caldwell*, Jay Garcia*, Mike Baysinger*

***NASA Marshall Space Flight Center, AL, USA 35812**

ABSTRACT

One of the driving structural requirements of the Habitable Exo-Planet (HabEx) telescope is to maintain Line Of Sight (LOS) stability between the Primary Mirror (PM) and Secondary Mirror (SM) of ≤ 5 mas. Dynamic analyses of two configurations of a proposed (HabEx) 4 meter off-axis telescope structure were performed to predict effects of jitter on primary/secondary mirror alignment. The dynamic disturbance used as the forcing function was the James Webb Space Telescope reaction wheel assembly vibration emission specification level. The objective of these analyses was to predict "order-of-magnitude" performance for various structural configurations which will roll into efforts to define the HabEx structural design's global architecture. Two variations of the basic architectural design were analyzed. Relative motion between the PM and the SM for each design configuration are reported.

Keywords: HabEx, Space Telescope, Optomechanical Design, Dynamic Stability, Stable Structure, Jitter

ACKNOWLEDGEMENTS

The designs, models, and analyses documented in this paper are the result of the collective efforts of the author and those listed as co-authors. During a time when most MSFC engineering personnel were overwhelmed with Space Launch System (SLS) activities, contributors were willing and able to integrate their respective contributions to this effort into their heavy work load. These efforts were seen as "above and beyond" and are much appreciated.

INTRODUCTION

The next Decadal Survey in Astronomy and Astrophysics will be nominally carried out in the years 2018-2020. Science and Technology Definition Teams (STDT) are established to assess multiple proposals for a next large mission to follow James Webb Space Telescope (JWST) and Wide Field Infrared Survey Telescope (WFIRST). One such proposed mission is the HabEx. The selected next big mission will likely include mechanical stability requirements that are notably more stringent than those of previous missions.

The effects of jitter on alignment in extreme precision instruments is known to be a significant engineering challenge. Therefore, this was selected as a metric to demonstrate general feasibility in structural designs. This paper presents descriptions of two variations of a 4 m off-axis HabEx structural design and results from structural dynamic analyses performed to predict the relative motion between the PM and the SM due to Reaction Wheel Assembly (RWA) jitter. These analyses were performed to demonstrate feasibility of meeting pertinent stability requirements.

At this early date, whether or not the HabEx design will include a RWA is unknown. Other methods of Guidance Navigation and Control (GN&C) have been investigated. Those have been pursued due to the likelihood that they would provide less impact to performance than a RWA. Hence, the selection of a RWA as the analytical disturbance is considered conservative. To analytically include a RWA in response analyses one has to have a vibration spectrum of some sort to represent the vibrations emitted by the RWA. Having no idea what that would be for the real system decades in the future, the JWST RWA specified allowable vibration spectrum was selected as the input to the subject analyses. An underlying assumption is that between the time of these analyses and the actual engineering development, RWAs will improve and facilitate more stable systems. Again, with that assumption, the selection of the JWST RWA as the input disturbance to HabEx feasibility analyses is conservative.

HabEx Structural Designs Considered

Two HabEx structural designs are described in this paper. The overall global dimensions and the optical system design are the same in both cases. The focus of this paper is the telescope structural design and the feasibility of a structure to satisfy mechanical stability requirements.

While stability, extremely low relative motion, between numerous optical elements is required for optical performance, that associated with PM and SM motion was selected as a parameter to assess feasibility. The system's optical design requires PM/SM LOS stability ≤ 5 mas. The 5 mas requirement has been sub-allocated to linear and rotational components of motion and that is presented below. The optical design's 9 m distance between the PM and SM adds to the structural design challenge. Results from structural dynamic analyses utilizing an assumed RWA jitter spectrum performed to predict misalignment (relative motion) between the PM and the SM of those designs are also presented.

Design One

The initial HabEx conceptual structural design, analyzed in the November 2016 timeframe, had the SM tower not integrated with the tube and it utilized IM7-8552 quasi-isotropic composite material properties as an initial starting point. The design included a simplified Space Craft (SC), a concentrated mass representing the Science Instrument (SI), and the SM was modeled with Aluminum properties. Those details were not changed in any analyses reported in this paper. Design 1 is illustrated in Figure 1.. The PM truss with a 2,000 kg concentrated mass representing the PM is depicted in Figure 2.

A first cut PM truss design target was to achieve a first mode frequency > 40 Hz with a 2,000 kg PM integrated with it via a rigid element. The design resulted in a predicted first mode at 42 Hz. Figure 3 illustrates that mode shape.

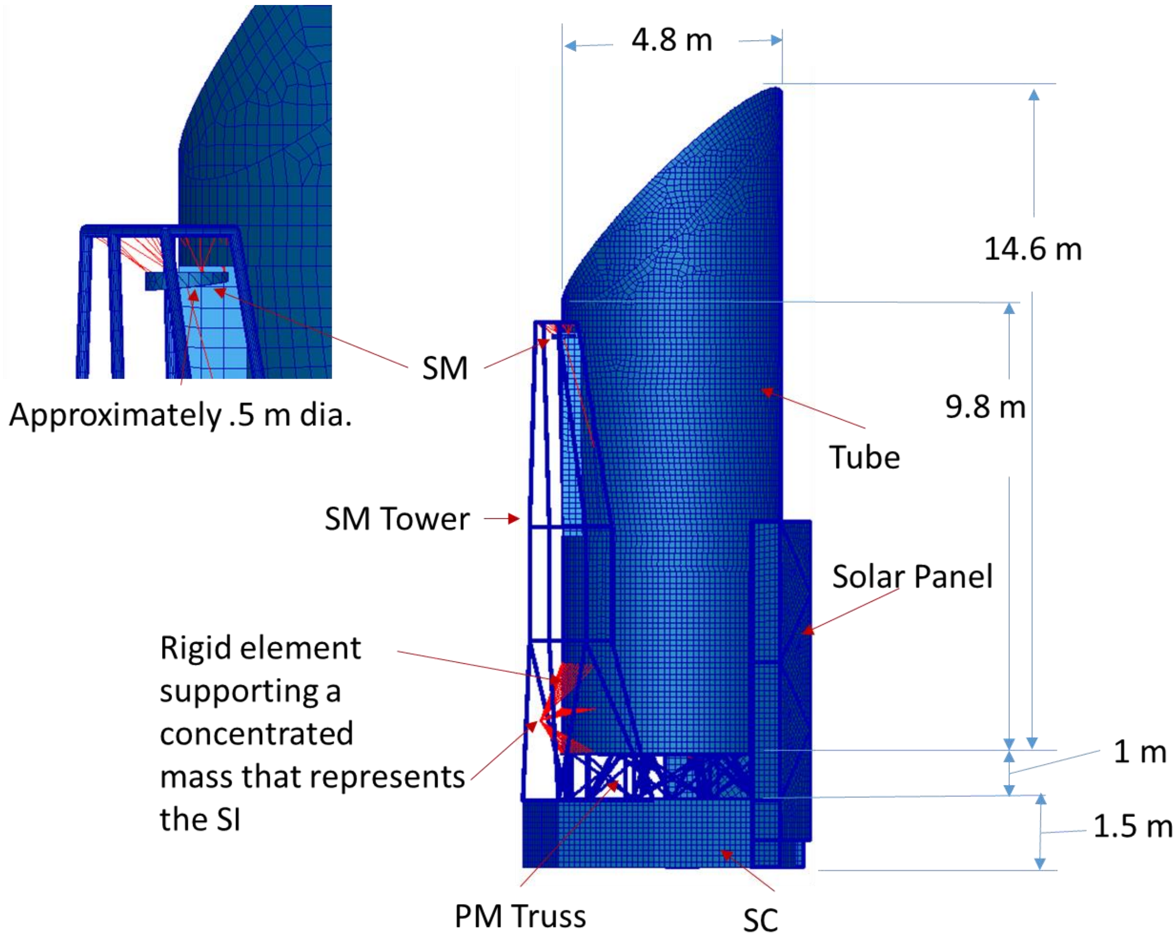

Figure 1. HabEx Structural Design 1 with Approximate Dimensions

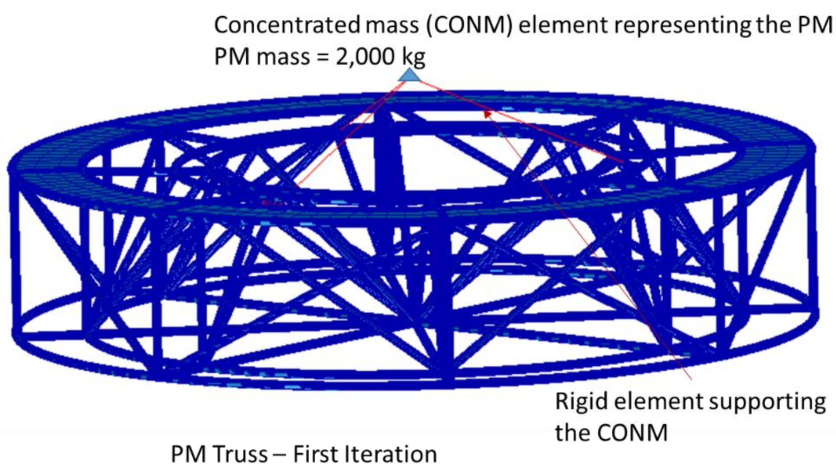

Figure 2. PM Truss

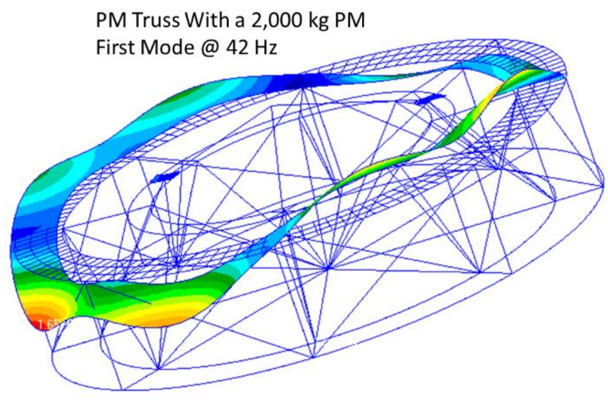

Figure 3: HabEx Design 1 PM Truss First Mode

Design Two

The second design was analyzed in March 2017 timeframe and included numerous modifications of Design One. Those changes include:

1. The SM tower was covered with structural material and integrated to the Tube
2. An exoskeleton structure that further stiffens the structural path between the PM and the SM
3. A detailed Finite Element Model (FEM) of the PM was included with structural members for the PM support struts
4. A further re-designed PM truss
5. Structural members, as opposed to a rigid element, were included to represent the SM support struts
6. The composite material was changed to be that of JWST, M55J 954-6 at 68°F.

Figure 4 depicts the integrated design and each change is described and discussed following.

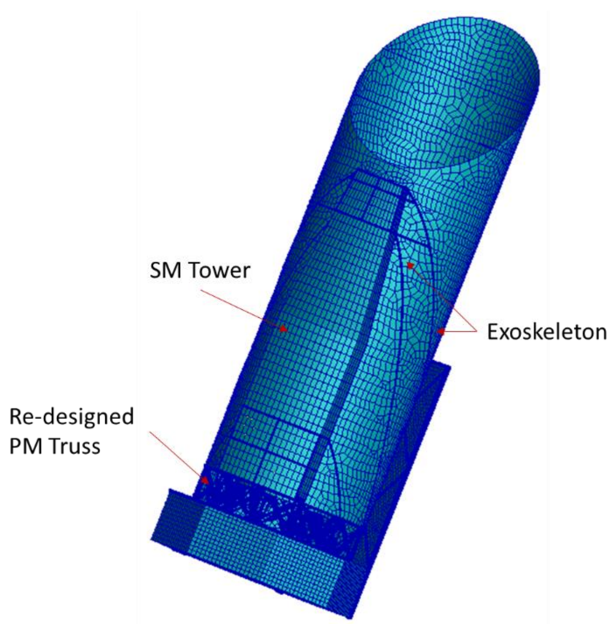

Figure 4: HabEx Structural Design 2

The first listed modification to Design 1 was that the SM tower was covered and that structure was integrated to the tube. Figure 4 clearly shows the covered tower. The tower is structurally integrated with the Tube. Ultimately, extreme stability between the PM and SM are paramount for mission success. By integrating the Tube to the Tower the stiffness between the two increased but the mass did as well. That being the case, the potential for dynamics to manifest that would not have existed in the absence of that integration became possible. Low frequency modes that would impact performance would likely pop up. In addition to that concern, vibrational modes of the Tube would then have a more direct path into the SM support structure.

In an effort to circumvent the anticipated impact to performance the second of the design modifications was implemented. An exoskeleton structure was designed into the system. Figures 5 shows the exoskeleton structure. This structure added notable stiffness along the path of concern and relatively speaking added only little mass. Therefore, any additional modes that resulted would in general be expected to be higher in frequency and less concerning.

The third modification, although not a design change per se, that was implemented was the inclusion of a detailed FEM of the PM with a support structure. That FEM was provided by the Arnold Mirror Modeler (AMM), a Finite Element Modeling tool that is being evolved by MSFC. With the inclusion of a more realistic PM support structure, the modal frequencies of the integrated PM and Truss dropped significantly. Therefore design mod four was incorporated, the PM Truss was again redesigned to increase the first modal frequency. Figure 6 shows the new truss with the detailed PM FEM and Figure 7 shows the first mode shape which occurs at about 46 Hz.

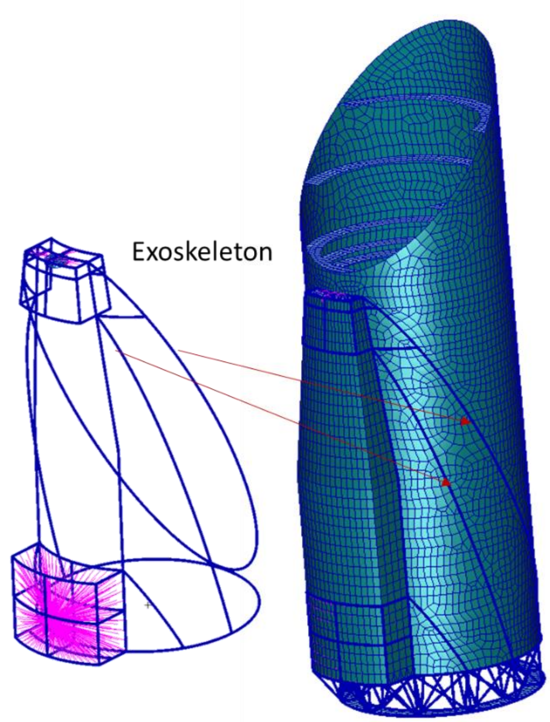

Figure 5: Exoskeleton

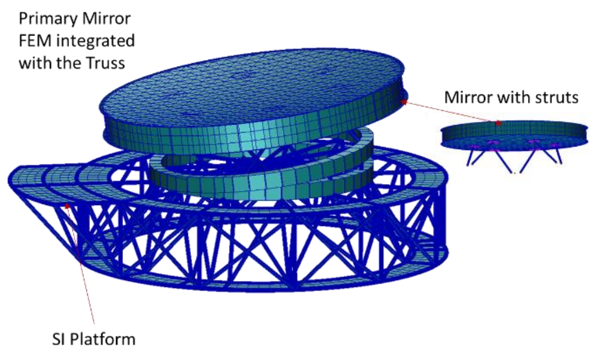

Figure 6: HabEx Design 2 PM Truss and Detailed FEM of the PM

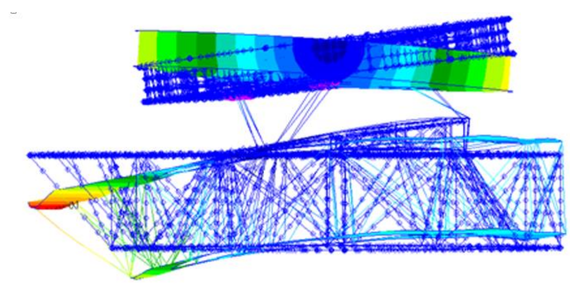

Figure 7: HabEx Design 2 PM Truss First Mode

The fifth design change was included in the same spirit as the fourth. Prior, the SM was attached to the structure via NASTRAN rigid elements which is quite common for a first cut but, nonetheless, fictitious. Therefore linear finite elements were included to represent structural struts. Their dimensions were scaled from those of the PM FEM which was provided by the AMM.

Finally, the sixth change was simply to utilize material properties of a composite with space optical system pedigree. The properties of the JWST composite, M55J 954-6 at 68°F, was utilized.

DYNAMIC FORCING FUNCTION

The objective of this effort was to determine if it was feasible for the proposed, and then modified, HabEx architecture to meet current PM/SM LOS jitter stability requirements. To do so, one has to have Dynamic Forcing Functions (DFF) as input. The primary dynamic disturbance to performance is expected to be the Guidance Navigations and Control (GN&C) system. Depending on the type of GN&C system utilized, those sources could be rotating imbalances or impulses from thrusters or perhaps something else altogether. In any case, with all things in the mix being conceptual in nature and while well suited for feasibility studies, nothing is far enough along to know with certainty what type GN&C system will be utilized. Therefore something erring on the conservative side had to be assumed.

The JWST utilizes a Reaction Wheel Assembly (RWA). JW personnel communicated that the RWA was proving to be challenging WRT to their performance requirements. It seems reasonable to assume that between the time that the JWST RWA allowable vibrations were specified and the time that a HabEx mission gets to a GN&C decision point, more refined RWA's could be evolved so use of those data as an analytical DFF is conservative. Also, in the event that a different GN&C design is utilized it will likely be selected because it is less an impact to performance. In both cases, use of the JWST RWA allowable vibration specification as input to feasibility studies is seen as conservative. Figure 8 shows that data [1].

3.3.1.6 Wheel Unbalance

After exposure to the environments defined in section 3.2.5 of this specification, the unbalance magnitude of the RWA rotating components shall not exceed the following values:

a. Static Unbalance: Less than 1.0 (g-cm) over the operating speed range.

b. Dynamic Unbalance: Less than 14.0 (g.-cm^2) over the operating speed range.

c. The peak radial forces and moments produced by the RWA at any operating speed (including resonant conditions) shall not exceed the values listed in the table below:

Peak Radial Disturbance Limits Including Resonant Conditions

Parameter	Frequency	Max. Limit	Parameter	Frequency	Max. Limit
Force	0-70 Hz	3.5 N	Torque	0-70 Hz	0.5 N-m
(F_X)	70-210 Hz	0.7 N	(M_X)	70-195 Hz	0.3 N-m
	210-270 Hz	10 N		195-225 Hz	1.5 N-m
	270-500 Hz	0.7 N		225-500 Hz	0.3 N-m

3.3.1.7 Axial Induced Vibration

The peak force (amplitude) produced by the RWA in the direction parallel to the its spin axis shall not exceed 0.2 N within the frequency range 2-200 Hz, when measured at constant speeds that are within the operational speed range and that are free of major structural resonances. The peak axial force produced by the RWA at any operating speed (including resonant conditions) shall not exceed the following limit values:

Frequency Range (in Hz):	0-150	150-195	195-225	225-300	300-500
Axial Force (Fz) Limit:	0.7 N	4.5 N	45 N	4.5 N	0.7 N

Figure 8: JWST RWA Allowable Vibrations

The peak radial disturbance limits listed above in Figure 8 were applied simultaneously and in phase at each of the 4 reaction wheels. In an effort to find the worst case combination of radial load vectors of the four wheels, they were applied incrementally about the axis of each wheel initially in 1° increments and the angular direction of the load at each of the four wheels was varied to find the worst combination of load vectors applied to the four wheels. The increment was changed to 10° and the same max condition was determined so from there forward, to save computational time, a 10° increment was utilized. This approach is perceived as notably conservative in that the probability that the worst case combination of the four load vectors occurring is thought to be very low and that it occur continuously even lower. The torque and axial force was applied simultaneously in each case.

Figure 9 shows the load application points on the FEM.

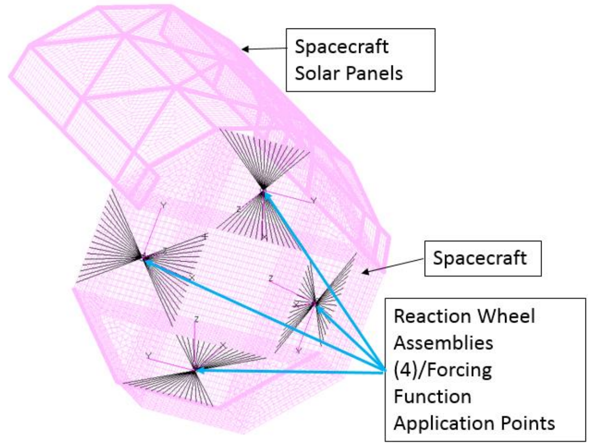

Figure 9: Load Application Points

Each wheel was oriented 45º relative to the SC as shown in Figure 10.

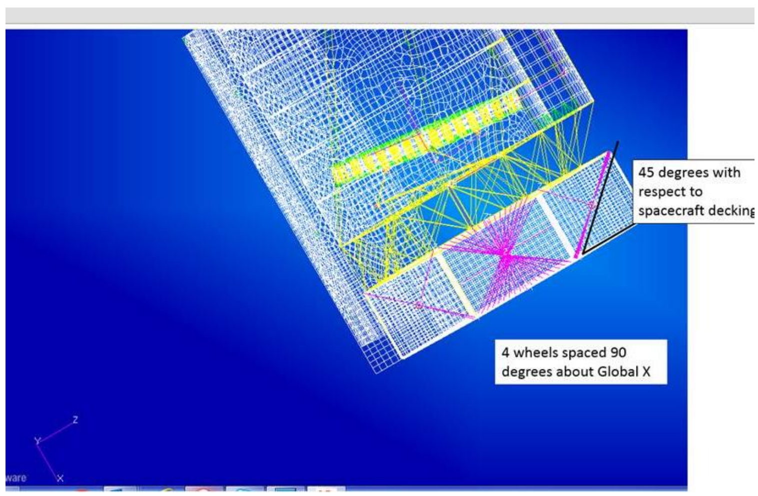

Figure 10: Reaction Wheel Orientation

ANALYSIS

The analysis was performed via Finite Elements. Figure 1 and Figure 4 show the FEM for HabEx Design 1 and 2 respectively. Figure 11 shows the analysis coordinate system.

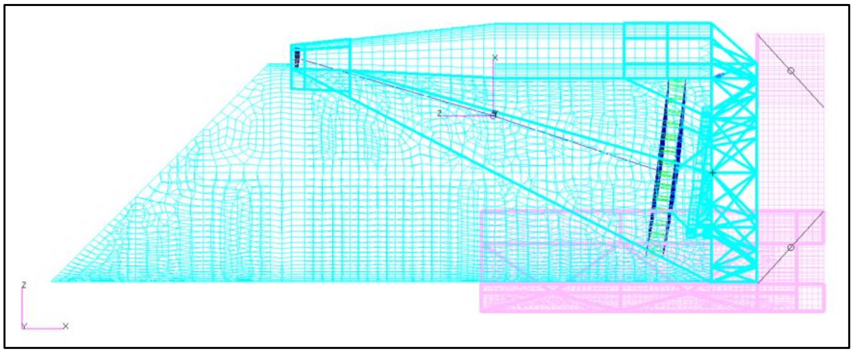

Figure 11: Analysis Coordinate System

The frequency response analysis was performed up to 300 Hz with the FEM in a free-free configuration simulating the in-service condition and with 1% damping. MSC/NASTRAN was utilized as well as MATLAB to analyze the structure. Relative motion between the PM and the SM was calculated by use of a Multi-Point Constrain equation. The normal to the center of the PM and the SM in the undisturbed or un-excited FEM have an angular orientation. The reported predictions are conservative vector components in the analysis coordinate system of the change in that orientation due to the input DFF.

The relative motion was output at each frequency analyzed. The peak results were scaled up to include an Uncertainty Factor of 15% to account for effects of standard material properties being utilized to make extremely small predictions. Also, since JWST has stated that they have achieved passive isolation on the order of 80 dB, results were decreased by 80 dB. The latter, the 80 dB reduction, was applied in the most simple way (-80dB = 20 Log(isolated/predicted)). In reality, the actual damping achieved is a function of the dynamic characteristics of the as built SC and telescope structure, how those two interact, and the actual DFF. This simple analytical approach may err on the side of conservatism or not but at this point in the engineering effort it is a reasonable approach for a feasibility study.

RESULTS

Table 1 presents analysis results and that factored by 1.15 to incorporate the 15 % UF as well as the later then reduced by 80 dB. Allowable mirror motion was provided to MSFC by JPL, the HabEx study lead. Those data were converted into components of PM/SM relative motions. Table 2 presents a comparison of the Design 1 and Design 2 results as well as a comparison of the Design 2 results and the JPL provided requirement allocation (allowable motion).

As seen in Table 2, both designs meet the stability requirement and Design 2, with the exception of Y translation, performs better than Design 1. This being the case, Design 2, the March 2017 design, is considered the baseline structural design. Results reported demonstrate that this baseline meets requirements with notable design space remaining.

Predicted Relative Motion			
Design 1			
Linear (m)		Rotation (rad)	
X	2.42E-06	Rx	5.44E-08
Y	1.22E-05	Ry	1.09E-07
RSSed X&Y - De-Center	1.24E-05	RSSed Rx&Ry - Tip/Tilt	1.22E-07
Z - De-Space	3.81E-06	Rz	5.56E-08
Design 2			
Linear (m)		Rotation (rad)	
X	2.72E-06	Rx	5.44E-08
Y	6.34E-06	Ry	4.31E-08
RSS X&Y - De-Center	6.90E-06	RSSed Rx&Ry - Tip/Tilt	6.94E-08
Z	8.94E-07	Rz	2.83E-08
With 15% UF			
Design 1			
Linear (m)		Rotation (rad)	
X	2.78E-06	Rx	6.26E-08
Y	1.40E-05	Ry	1.25E-07
RSSed X&Y - De-Center	1.43E-05	RSSed Rx&Ry - Tip/Tilt	1.40E-07
Z - De-Space	4.38E-06	Rz	6.39E-08
Design 2			
Linear (m)		Rotation (rad)	
X	3.13E-06	Rx	6.26E-08
Y	7.29E-06	Ry	4.96E-08
RSS X&Y - De-Center	7.93E-06	RSSed Rx&Ry - Tip/Tilt	7.98E-08
Z	1.03E-06	Rz	3.25E-08
with 80 dB Reduction			
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
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

Table 1: Results

Direction	Design 1	Design 2	Design 2 vs. Design 1
X (m)	1.40E-09	3.13E-10	22.30%
Y(m)	2.78E-10	7.29E-10	261.98%
RSSed - De-Center (m)	1.43E-09	7.93E-10	55.47%
Z - De-Space (m)	4.38E-10	1.03E-10	23.46%
Rx (rad)	1.25E-11	6.26E-12	49.91%
Ry (rad)	6.26E-12	4.96E-12	79.23%
RSSed - Tip/Tilt (rad)	1.40E-11	7.98E-12	56.97%
Rz (rad)	6.39E-12	3.25E-12	50.90%
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%

Table 2: Results Comparisons

SUMMARY AND CONCLUSIONS

An initial HabEx conceptual structural design was analyzed in the fall of 2016 timeframe. Numerous design iterations were performed in an effort to better stability associated with PM/SM relative motion. This paper presents and compares results from the initial and the current base line design. It also compares results to the anticipated PM/SM relative motion allowable jitter or “error budget”.

The objective of this design and analysis effort was to determine if it was feasible for the HabEx architectural structural design to satisfy anticipated PM/SM relative motion stability requirements. While significant differences are likely between early predictions such as these and an as built HabEx structure in the distant future, relatively high fidelity models, conservative assumptions, and a comprehensive analysis process have been utilized in this effort. Therefore, it is concluded that predictions herein are as reasonable as can possibly be expected at this date.

While multiple design iterations have been investigated, only the first and the final (to date) were reported in this paper. By and large, the current design is notably better with respect to PM/SM relative motion than the initial design. And in both cases, predictions are well within allocations. Therefore, it is concluded that WRT PM/SM stability, it is feasible that the HabEx structural architecture satisfies performance requirements.

CITATIONS

1. J. Scott Knight, Ball Aerospace Corporation, email dated 3/10/2016