International Space Station Modal Correlation Analysis

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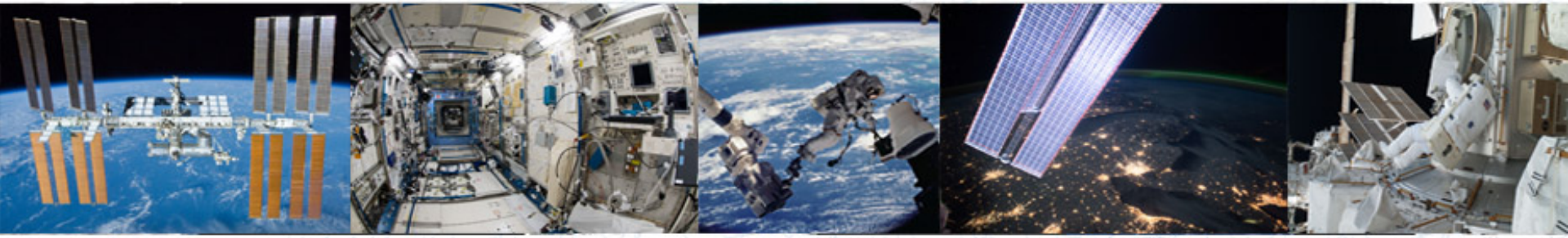
This paper summarizes the on-orbit structural dynamic data and the related modal analysis, model validation and correlation performed for the International Space Station (ISS) configuration ISS Stage ULF7, 2015 Dedicated Thruster Firing (DTF). The objective of this analysis is to validate and correlate the analytical models used to calculate the ISS internal dynamic loads and compare the 2015 DTF with previous tests.

During the ISS configurations under consideration, on-orbit dynamic measurements were collected using the three main ISS instrumentation systems; Internal Wireless Instrumentation System (IWIS), External Wireless Instrumentation System (EWIS) and the Structural Dynamic Measurement System (SDMS). The measurements were recorded during several nominal on-orbit DTF tests on August 18, 2015.

Experimental modal analyses were performed on the measured data to extract modal parameters including frequency, damping, and mode shape information. Correlation and comparisons between test and analytical frequencies and mode shapes were performed to assess the accuracy of the analytical models for the configurations under consideration. These mode shapes were also compared to earlier tests. Based on the frequency comparisons, the accuracy of the mathematical models is assessed and model refinement recommendations are given. In particular, results of the first fundamental mode will be discussed, nonlinear results will be shown, and accelerometer placement will be assessed.

Space Exploration | International Space Station

IMAC XXXVI 2018



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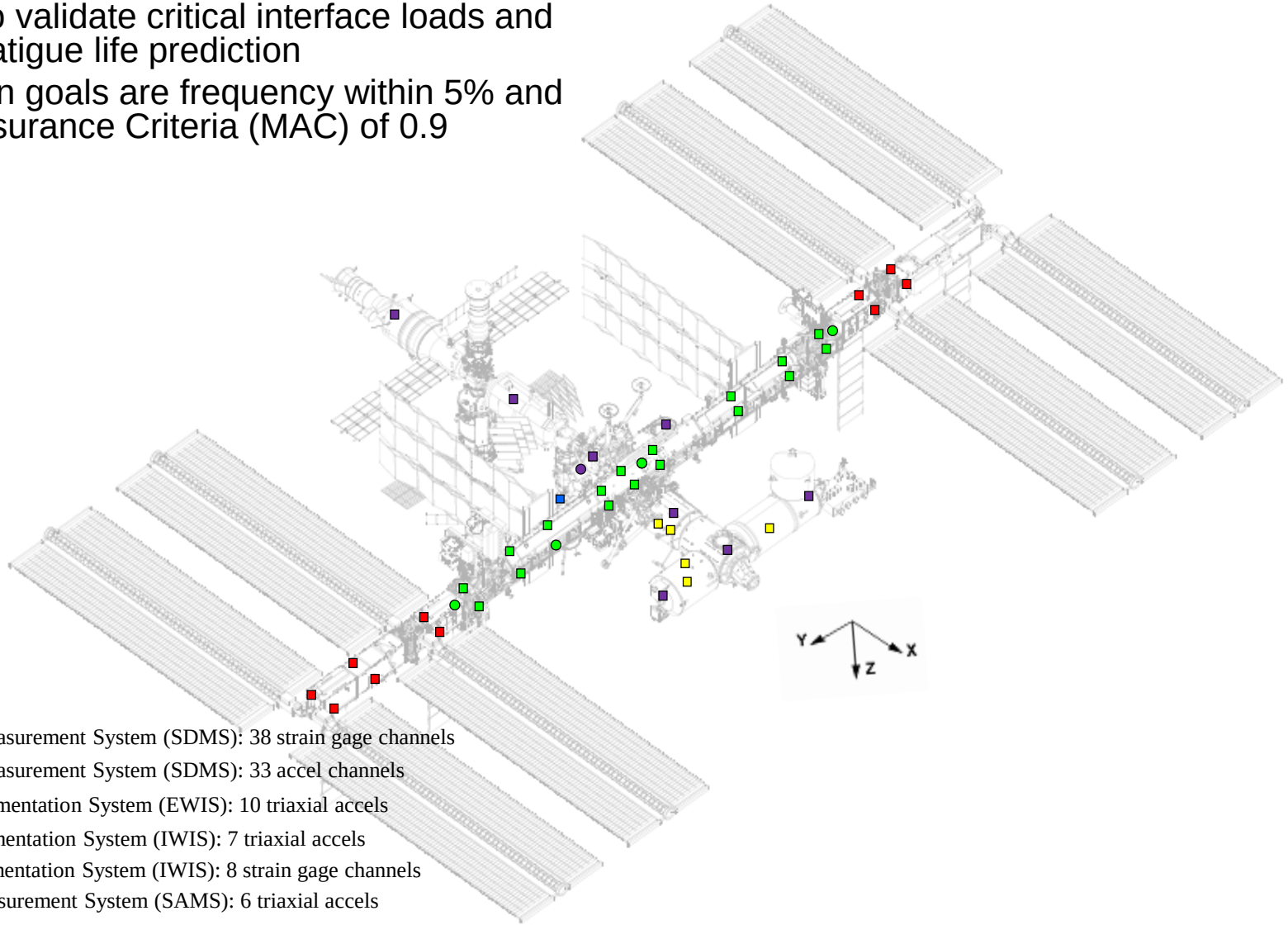
February 2018

Agenda

- **Sensor Locations**
- **Methodology and Configuration**
- **Correlation and NASTRAN Model**
- **Mode Shape Comparison**
- **Comparison to On-orbit Data**
- **First Mode**
- **Summary**

ISS Sensor Location

- **Program verification plan requires model correlation**
  - Needed to validate critical interface loads and improve fatigue life prediction
  - Correlation goals are frequency within 5% and Modal Assurance Criteria (MAC) of 0.9



- Structural Dynamics Measurement System (SDMS): 38 strain gage channels
- Structural Dynamics Measurement System (SDMS): 33 accel channels
- External Wireless Instrumentation System (EWIS): 10 triaxial accels
- Internal Wireless Instrumentation System (IWIS): 7 triaxial accels
- Internal Wireless Instrumentation System (IWIS): 8 strain gage channels
- Space Acceleration Measurement System (SAMS): 6 triaxial accels
- IMU-C: 1 triaxial accel

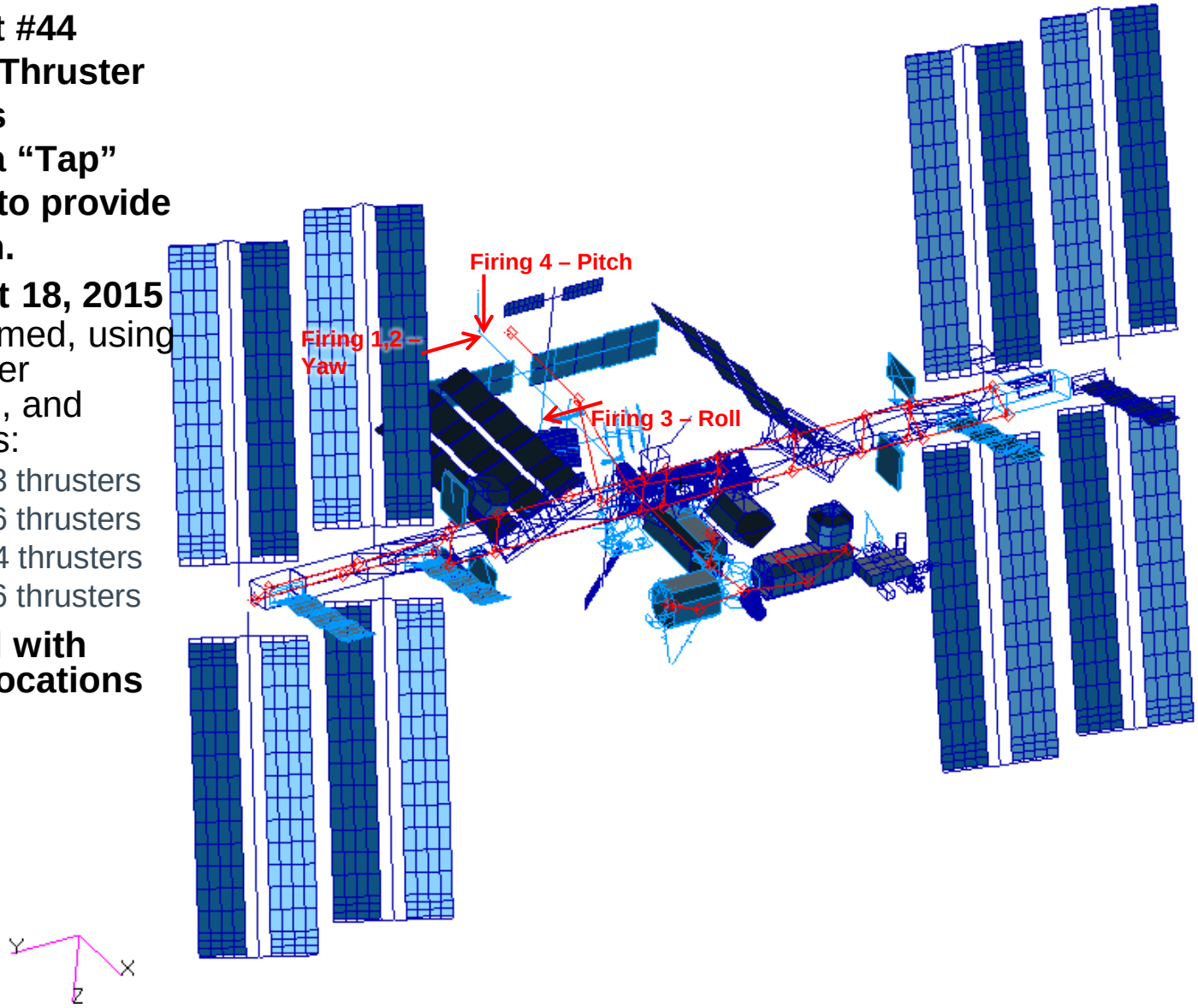
System Model Correlation
Increment (INC) 44 D5 – Aug-18-2015

INC 44 D5 Correlation

- **Synchronize, Partition, and Filter on-orbit data into distinct frequency ranges.**
- **Extract Modal Parameters from on-orbit data using Eigensystem Realization Algorithm (ERA) in time domain.**
- **Use IWIS and SAMS (modules), SDMS and EWIS (truss), accelerometers for correlations analysis**
  - Extract on-orbit mode shapes and compared to corresponding post-flight system model
  - Calculate Modal Assurance Criteria (MAC) between on-orbit and analytical mode shape on each configuration and firing
- **Report modes with MAC's greater than 0.7, within 10-15% frequency difference, and modes with kinetic energy greater than 5% for modules and truss**
  - Compare on-orbit mode shapes for all DTF firings (F1, F2, F3, and F4)
  - Compare to previous DTF results from 2010, 2012, and 2014.

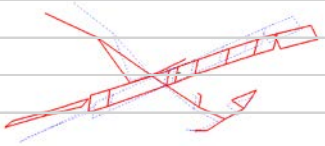
N599D5 PATRAN Model with Accel Grids

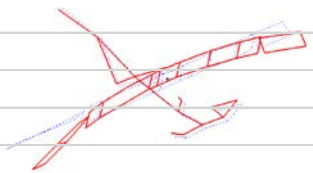
- **During ISS Increment #44 (INC44), a Dedicated Thruster Firing Test (DTF) was performed to mimic a "Tap" test, using thrusters to provide an impulse excitation.**
- **INC44 D5 DTF August 18, 2015**
  - 4 tests were performed, using the following thruster directions, duration, and number of thrusters:
    - F1: Yaw (0.6 sec), 3 thrusters
    - F2: Yaw (0.6 sec), 6 thrusters
    - F3: Roll (0.8 sec), 4 thrusters
    - F4: Pitch (0.8 sec), 6 thrusters
- **Full NASTRAN Model with Accelerometer Grid locations**

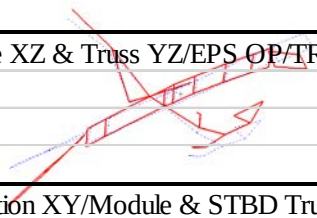


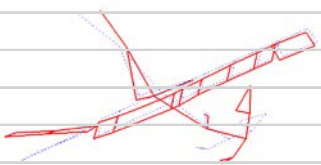
Detailed Correlation Data

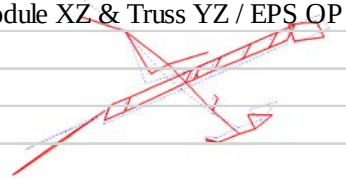
Test Data				Analysis Data					
Mode #	Freq. (Hz)	Damp. Fact. (%)	EMAC CMI	Mode #	Freq. (Hz)	Freq. Diff (%)	Accel Group	MAC	Mode Description
F2-2	0.087	3.1%	97/96	44	0.120	-27.5%	ALL	0.938	Station XY / Module & Truss
F2-3	0.102	3.1%	94/90	44	0.120	-15.0%	ALL	0.936	
F1-2	0.087	4.2%	85/61	44	0.120	-27.6%	ALL	0.933	
F3-1	0.085	2.9%	95/89	44	0.120	-29.2%	ALL	0.873	
F4-2	0.099	2.6%	88/69	44	0.120	-17.5%	ALL	0.855	
F4-4	0.182	2.0%	99/94	83	0.176	3.4%	ALL	0.990	Truss XY Bending / Module XZ
F3-6	0.183	1.5%	79/69	83	0.176	4.0%	ALL	0.895	
F1-4	0.165	1.2%	86/79	83	0.176	-6.2%	ALL	0.823	
F1-5	0.170	1.4%	92/70	83	0.176	-3.4%	ALL	0.821	
F2-5	0.182	1.0%	86/80	83	0.176	3.4%	ALL	0.813	
F2-4	0.160	1.3%	72/28	83	0.176	-9.1%	ALL	0.802	
F1-6	0.181	2.5%	94/85	83	0.176	2.8%	ALL	0.787	
F4-5	0.215	1.0%	90/79	102	0.219	-1.8%	ALL	0.843	Module XZ & Truss YZ/EPS OP/TRRJ IP
F1-7	0.218	2.4%	83/68	102	0.219	-0.5%	ALL	0.835	
F4-6	0.220	1.8%	95/83	102	0.219	0.5%	ALL	0.828	
F3-7	0.218	1.0%	86/67	102	0.219	-0.5%	ALL	0.808	
F2-8	0.261	1.9%	83/64	128	0.264	-1.1%	ALL	0.912	Station XY/Module & STBD Truss
F2-10	0.297	5.2%	95/63	128	0.264	12.5%	ALL	0.898	
F1-9	0.255	2.5%	94/68	128	0.264	-3.4%	ALL	0.888	
F3-3	0.259	9.0%	92/62	128	0.264	-1.9%	ALL	0.876	
F2-11	0.300	4.8%	93/65	128	0.264	13.6%	ALL	0.874	
F1-10	0.260	2.0%	89/46	128	0.264	-1.5%	ALL	0.854	
F3-4	0.250	3.7%	91/62	128	0.264	-5.3%	ALL	0.832	
F4-11	0.302	3.2%	98/79	145	0.285	6.0%	ALL	0.964	Module XZ & Truss YZ / EPS OP
F4-11	0.302	3.2%	98/79	151	0.287	5.2%	ALL	0.953	
F4-12	0.305	2.1%	95/71	145	0.285	7.0%	ALL	0.933	
F1-12	0.311	1.1%	93/73	145	0.285	9.1%	ALL	0.921	
F1-11	0.299	1.2%	91/73	145	0.285	4.9%	ALL	0.890	











Detailed Correlation Data (Cont.)

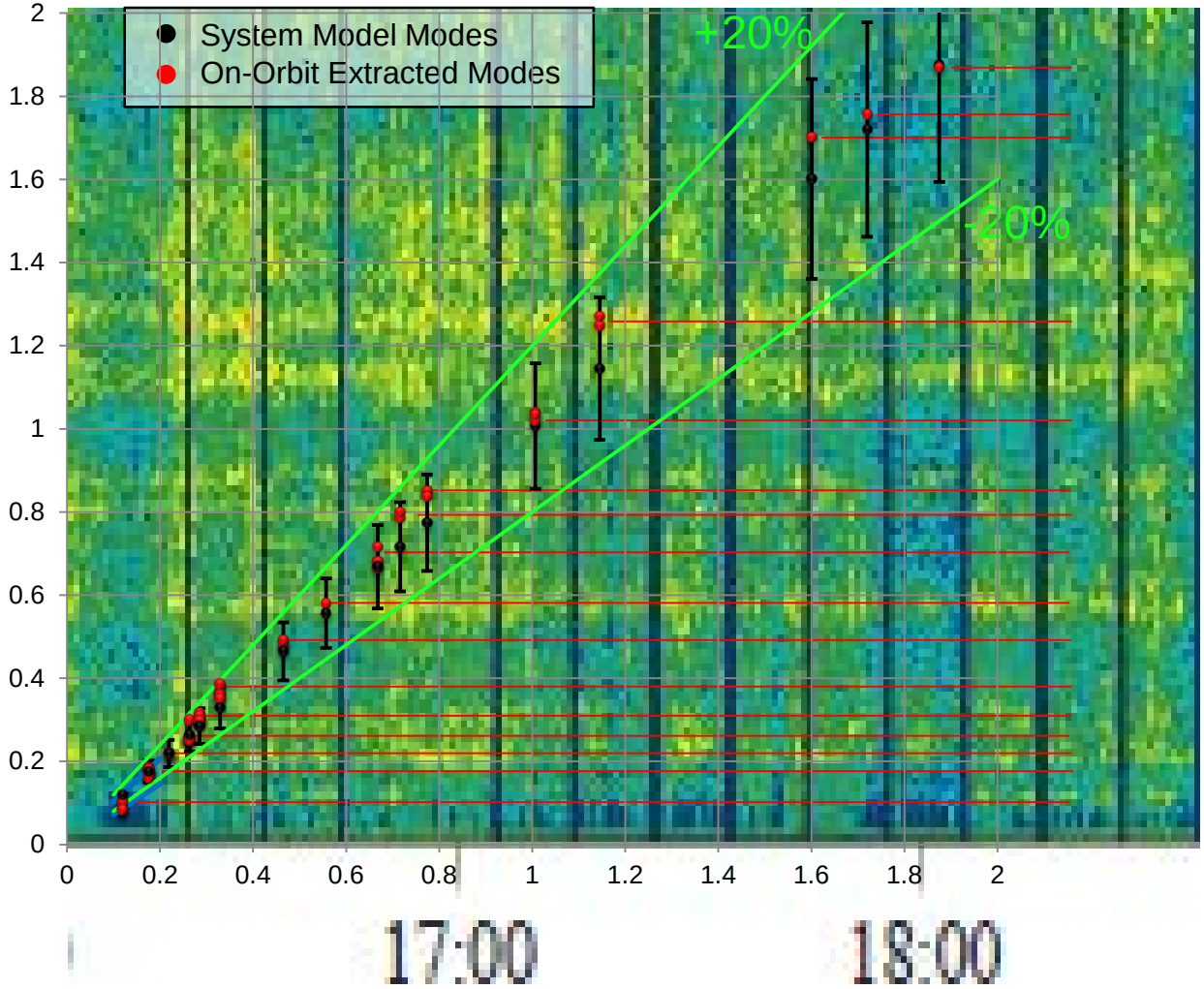
- **Yellow highlights new modes extracted with timed data**

Test Data				Analysis Data					
Mode #	Freq. (Hz)	Damp. Fact. (%)	EMAC CMI	Mode #	Freq. (Hz)	Freq. Diff (%)	Accel Group	MAC	Mode Description
F3-15	0.359	1.2%	86/64	168	0.329	9.1%	MOD	0.904	Torsion Module YZ/ Truss 2nd YZ
F3-18	0.386	0.2%	76/53	168	0.329	17.3%	ALL	0.850	
F3-17	0.352	1.1%	77/58	177	0.343	2.6%	ALL	0.841	
F3-17	0.352	1.1%	77/58	168	0.329	7.0%	ALL	0.739	
F2-16	0.486	3.3%	78/35	257	0.465	4.5%	ALL	0.881	Module and Truss XYZ/ COL-JEM YZ
F2-17	0.492	2.4%	87/37	257	0.465	5.8%	ALL	0.852	
F4-19	0.504	3.3%	75/34	256	0.460	9.6%	ALL	0.734	Module XYZ, Truss XY / COL-JEM YZ
F1-25	0.579	2.9%	98/80	289	0.557	3.9%	ALL	0.728	Module XY Outboard Truss TOR
F2-25	0.681	1.3%	93/72	318	0.668	1.9%	ALL	0.851	Module XZ, Truss YZ
F1-30	0.680	0.9%	85/43	318	0.668	1.8%	ALL	0.838	
F2-24	0.665	1.1%	92/70	318	0.668	-0.4%	ALL	0.740	
F2-28	0.786	2.1%	92/42	327	0.716	9.8%	MOD	0.849	Module XY, MRM1 and RS XZ
F2-29	0.800	1.6%	93/66	327	0.716	11.7%	MOD	0.806	
F2-32	0.850	1.1%	73/27	351	0.773	10.0%	MOD	0.875	Module XY - JEM EF
F2-31	0.837	2.1%	90/18	352	0.774	8.1%	MOD	0.751	Module XY - JEM EF - MRM1
F2-39	1.018	0.9%	88/22	395	1.007	1.1%	MOD	0.801	Module XYZ, Truss XY
F3-37	1.039	3.5%	86/22	394	1.007	3.2%	MOD	0.899	ModuleXY - Truss TOR
F2-40	1.035	3.0%	92/53	394	1.007	2.8%	MOD	0.895	
F2-40	1.035	3.0%	92/53	394	1.007	2.8%	All-EW	0.818	
F1-45	1.139	1.1%	75/22	407	1.085	5.0%	TRUSS	0.797	Module Truss XYZ - JEM XZ
F2-48	1.240	1.8%	88/11	404	1.067	16.2%	MOD	0.817	Module Truss XY Bending
F3-62	1.270	0.8%	84/7	443	1.145	10.9%	MOD	0.871	JEM/COL/RS YZ - Port Truss TOR
F3-85	1.702	1.1%	84/10	575	1.601	6.3%	MOD	0.902	JEM/COL XY - RS YZ
F1-72	1.756	0.9%	81/26	604	1.720	2.1%	TRUSS	0.834	TRUSS YZ - COL/JEM TOR
F1-72	1.756	0.9%	81/26	604	1.720	2.1%	ALL	0.732	
F3-100	1.869	0.2%	85/20	675	1.875	-0.3%	All-EW	0.711	TRUSS and Module XY

NEW WITH TIMED DATA

Extracted Modes vs. On-Orbit Spectrogram

- **Continuous 0-10 Hz spectrograms from SAMS sensors in the Lab produced by the Principal Investigator Microgravity Services (PIMS) group.**
- **High confidence correlated modes match observed modes below 1.2 Hz**
- **Green line +/- 20%, black error bars +/- 15% error, both from system model mode**



First Mode Frequency Difference

First Mode Findings

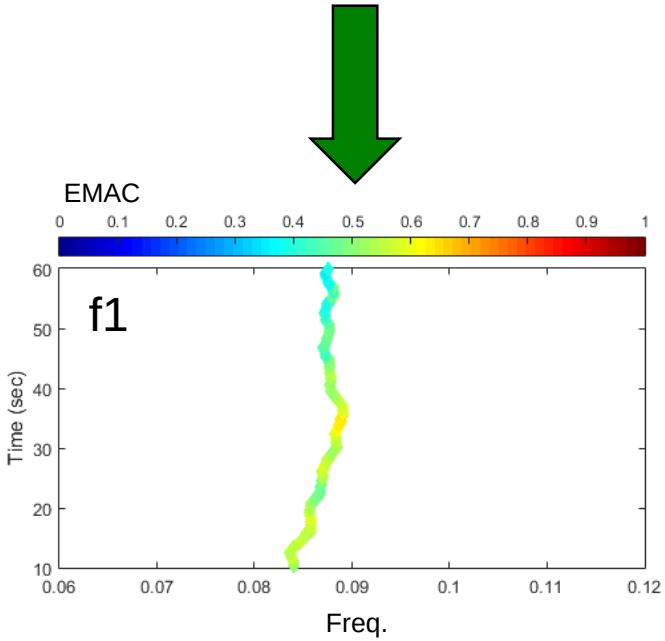
- **D5 DTF was intentionally performed near a Solar Beta where the first global mode exhibits large frequency variability**
  - Observed through long duration spectrograms, 24/7
- **Two yaw firings were employed to investigate the first mode**
  - One - smaller amplitude (F1 = 3 jets) and one - larger amplitude (F2 = 6 jets)
  - Goal: ascertain if the mode is input amplitude dependent
- **The investigation illustrates that disturbance amplitude does affect first mode frequency**
  - Frequency difference between analysis and test is lower with high amplitude excitation

Test Data				Analysis Data					
Mode #	Freq. (Hz)	Damp. Fact. (%)	EMAC CMI	Mode #	Freq. (Hz)	Freq. Diff (%)	Accel Group	MAC	Mode Description
F2-3	0.102	3.1%	94/90	44	0.120	-15.0%	ALL	0.936	Station XY / Module & Truss
F1-2	0.087	4.2%	85/61	44	0.120	-27.6%	ALL	0.933	Station XY / Module & Truss

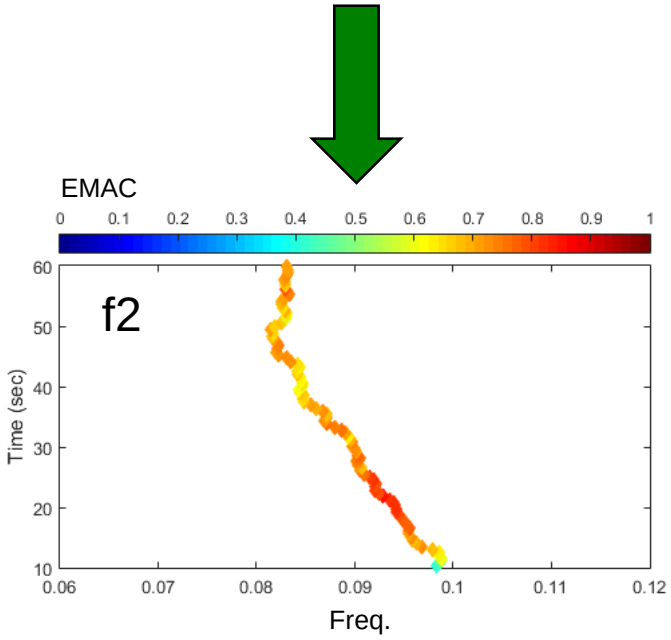
First Mode Findings

- **First mode has the highest frequency (least frequency difference) immediately after the F2 yaw firing (6 jet)**
  - Mode frequency shifts over time as the response damps out
- **Frequency drift over time typical for non-linear mechanism**

LOWEST AMPLITUDE



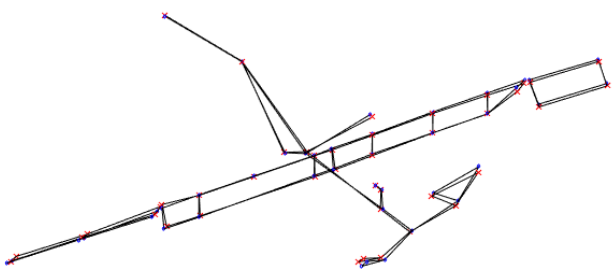
HIGH AMPLITUDE



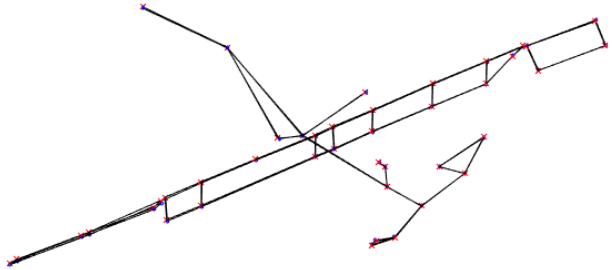
F1 vs. F2

Comparison of low amplitude Yaw firing versus high amplitude Yaw firing

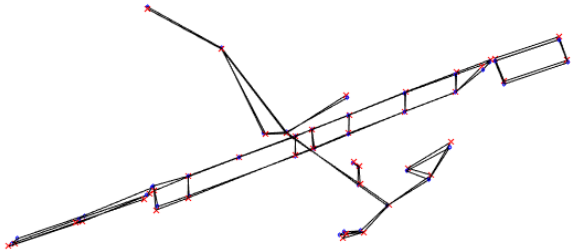
- **[Left] Mode shapes similar but 15% difference in frequency for low amplitude (F1) and high amplitude (F2) firings**
- **[Center] Mode shapes match and 0.5% difference in frequency using F2 decay (low amplitude period) and F1 low amplitude**
- **[Right] Mode shapes similar but 14% difference in frequency using F2 high amplitude and F2 decay**



x N599D5 F1 : 0.0869 Hz
♦ N599D5 F2 : 0.102 Hz
MAC = 0.962 (ALL), Freq Diff = -14.8%



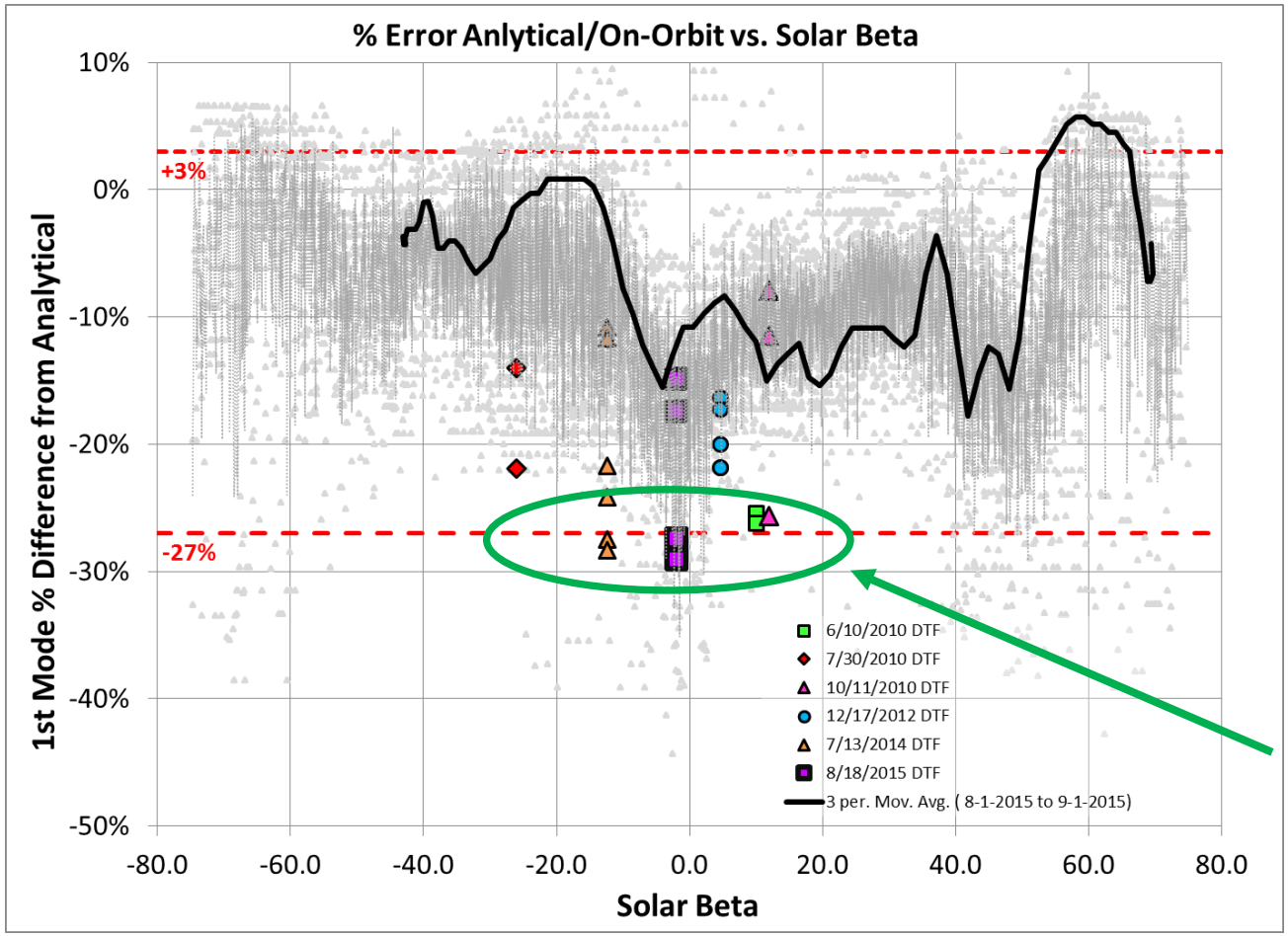
x N599D5 F1 : 0.0869 Hz
♦ N599D5 F2 : 0.0873 Hz
MAC = 0.998 (ALL), Freq Diff = -0.5%



x N599D5 F2 : 0.0873 Hz
♦ N599D5 F2 : 0.102 Hz
MAC = 0.953 (ALL), Freq Diff = -14.4%

First Mode vs Solar Beta Angle

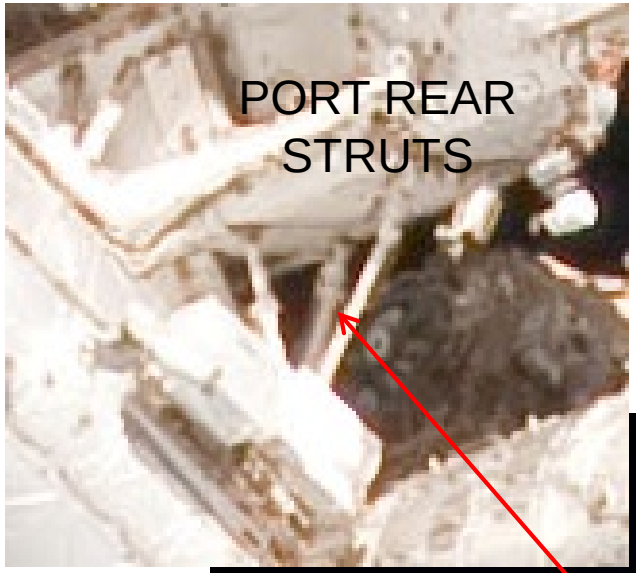
- **Using SAMS data and corresponding system model for first mode, the % error of first mode can be plotted vs. Solar Beta (Sun angle to Orbit Plane)**

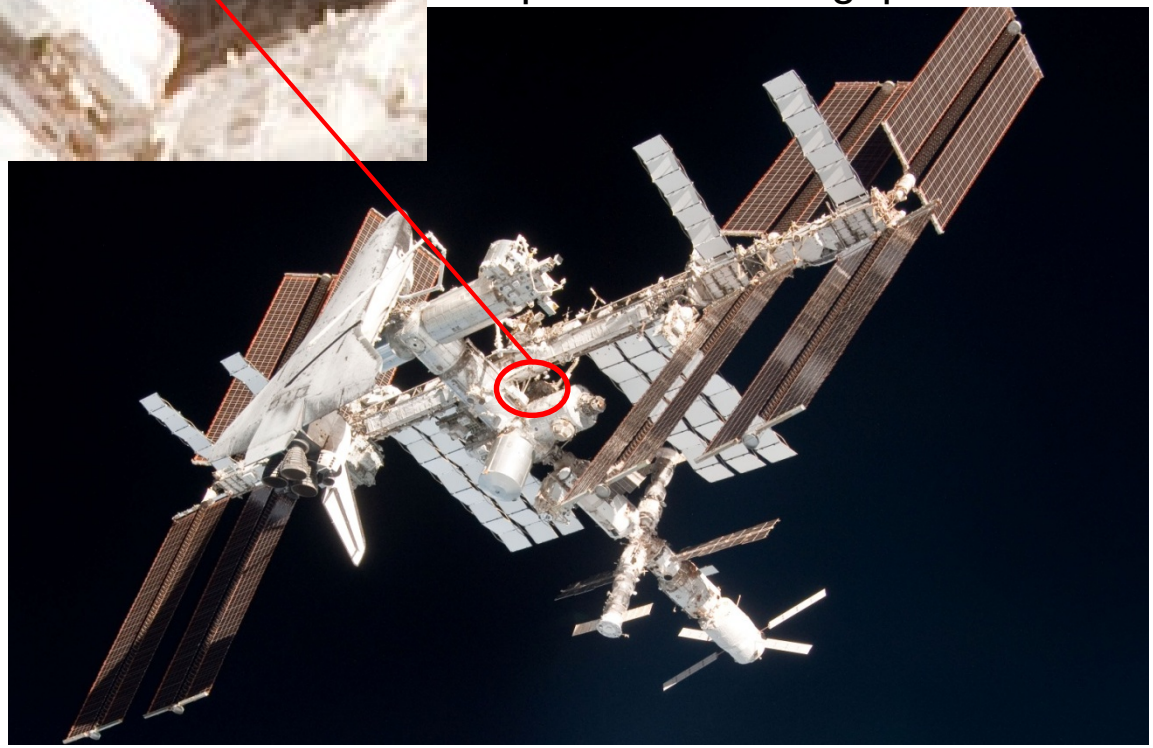


- All first mode % difference shown on graph (grey)
  - SAMS data is collected continuously, so both quiescent and dynamic operations are represented
- First mode DTF extractions shown by plot markers
- Circled data points represent extraction at low amplitude

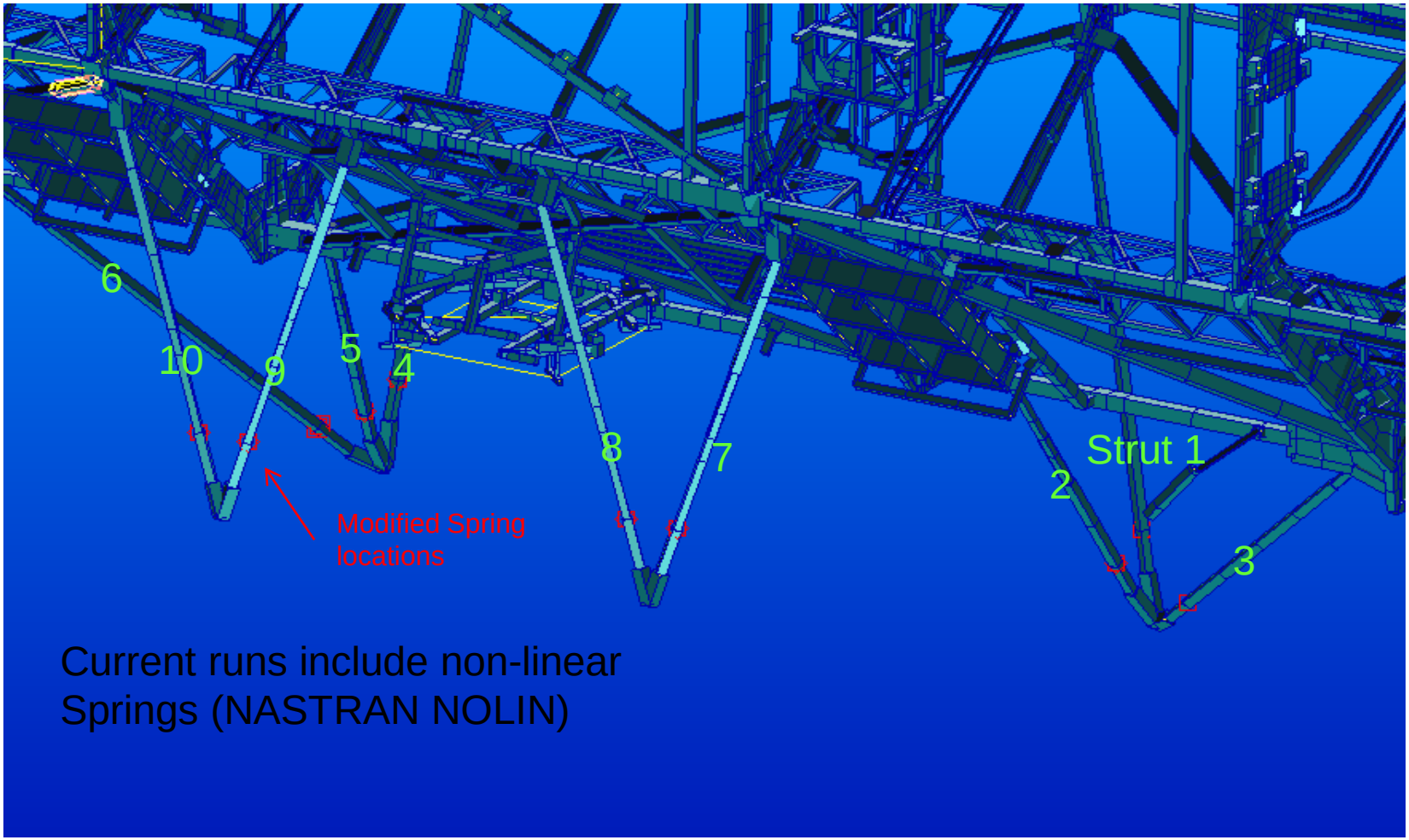
MTS Strut Model Modifications

- Truss and Modules connected with 10 struts called the Module-to-Truss Structure (MTS)
- Struts are sensitive to thermal effects from solar beta changes (some are shadowed)
- Solar Beta near -5 to 0 deg has large effect on first mode
- Added Springs (strut axial) to simulate softening effect of a gap
- First findings are encouraging and will perform thermal preload/friction/gap studies





MTS Strut Modifications



Current runs include non-linear Springs (NASTRAN NOLIN)

First Mode Summary

- **Current work**
  - Developed Craig Bampton models of the module and truss assemblies, connected with MTS struts as detailed bulk data
  - A stiffness curve from ground test will be employed to model strut non-linear stiffness
  - Use NASTRAN NOLIN to perform non-linear time domain runs
  - Perform linear modal extraction on analytical data and compare mode shapes

Analysis Findings

Summary

- **INC44 D5 Global modes under 1.2 Hz extracted with confidence**
  - INC44 D5 modes correspond well to previous test
  - Most modal frequencies within 10-15% of model predictions
  - Modes with KE greater than 5% for modules and truss were correlated
  - Accelerometer time synchronization efforts produced better correlation
- **First XY station global mode continues to show non-linear behavior**
  - Frequency has strong correlation to Solar Beta (thermal environment) and dynamic amplitude
    - Mode is correlated within -27/+3% frequency uncertainty for higher amplitude excitation
    - Current test shows mode is amplitude dependent
  - Additional MTS strut model modification is being explored
    - NASTRAN NOLIN runs
- **High confidence in Loads analysis using integrated ISS models**

Recommendations

- **Continue with new Dedicated Thruster Firing Tests and Tests of Opportunity**
  - **New DTF's will be scheduled before and after configuration changes**
- **Additional accelerometers needed for defining mode shapes of pressurized segment torsion and improved accelerometer phasing**
- **Perform improved accelerometer time synchronization, using MATLAB Sync function, Frequency decomposition and/or other time domain techniques**
- **Model on-orbit MTS strut stiffness and non-linear behavior**
  - Currently exploring thermal pre-load, MTS connection tolerances, and gaps, utilizing NASTRAN NOLIN and GAP elements
- **Continue using current frequency uncertainty and damping for ISS loads and life assessments**
  - Investigate possibility of +-15% up to 1.2 Hz