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International Space Station Future Correlation Analysis Improvements

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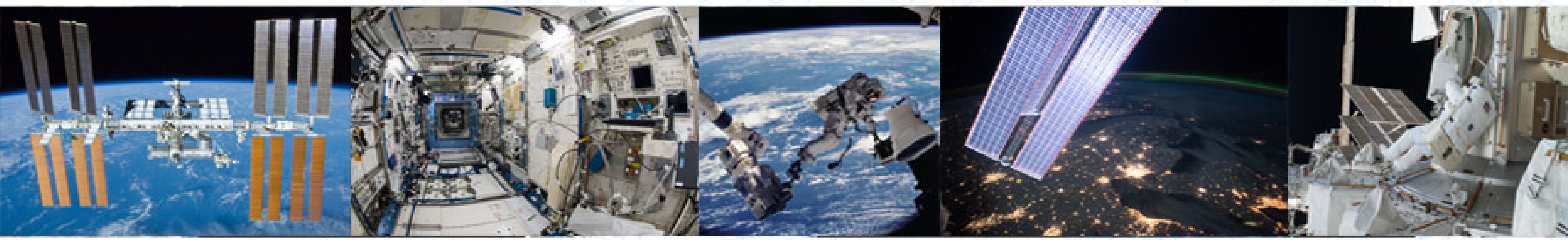
Ongoing modal analyses and model correlation are performed on different configurations of the International Space Station (ISS). These analyses utilize on-orbit dynamic measurements collected using four main ISS instrumentation systems: External Wireless Instrumentation System (EWIS), Internal Wireless Instrumentation System (IWIS), Space Acceleration Measurement System (SAMS), and Structural Dynamic Measurement System (SDMS). Remote Sensor Units (RSUs) are network relay stations that acquire flight data from sensors. Measured data is stored in the Remote Sensor Unit (RSU) until it receives a command to download data via RF to the Network Control Unit (NCU). Since each RSU has its own clock, it is necessary to synchronize measurements before analysis. Imprecise synchronization impacts analysis results. A study was performed to evaluate three different synchronization techniques: (i) measurements visually aligned to analytical time-response data using model comparison, (ii) Frequency Domain Decomposition (FDD), and (iii) lag from cross-correlation to align measurements. This paper presents the results of this study.

Space Exploration | International Space Station

IMAC XXXVI 2018



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Agenda

- **Introduction**
- **F2 Model to Model Correlation and expanded Response Locations**
- **Synchronization Techniques**
  - Graphical using FEM
  - Time Delay from Correlation Lag
  - Frequency Domain Decomposition
- **Summary and Recommendation**

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Introduction

- **The International Space Station (ISS) correlation effort uses four accelerometer groups with distinct clocks and sample rates**
  - All clocks get initial condition from main ISS clock
    - Time sync not consistent
  - Some accelerometer groups are wireless and some are hardwired
- **Not all accelerometers are placed in optimal positions**
  - Repositioning accelerometers entails crew time, which is expensive
  - Owing to its construction over a decade, pre-positioned accelerometers on the ISS are 15+ years old
- **It is cumbersome to time synchronize over 104 DOF graphically.**
- **This investigation seeks an efficient and accurate method to synchronize accelerometer data across the ISS**

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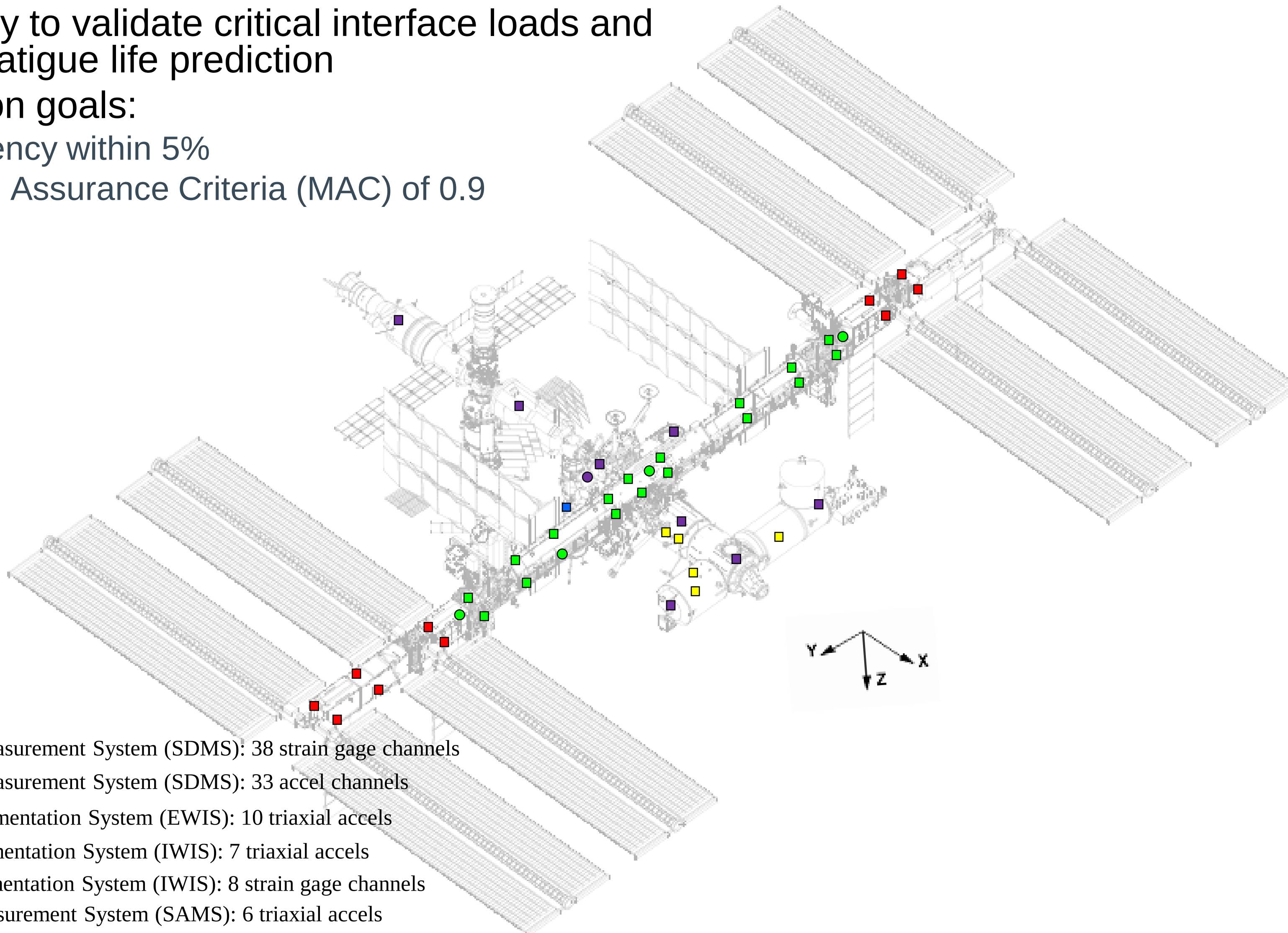
ISS Sensor Location

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



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

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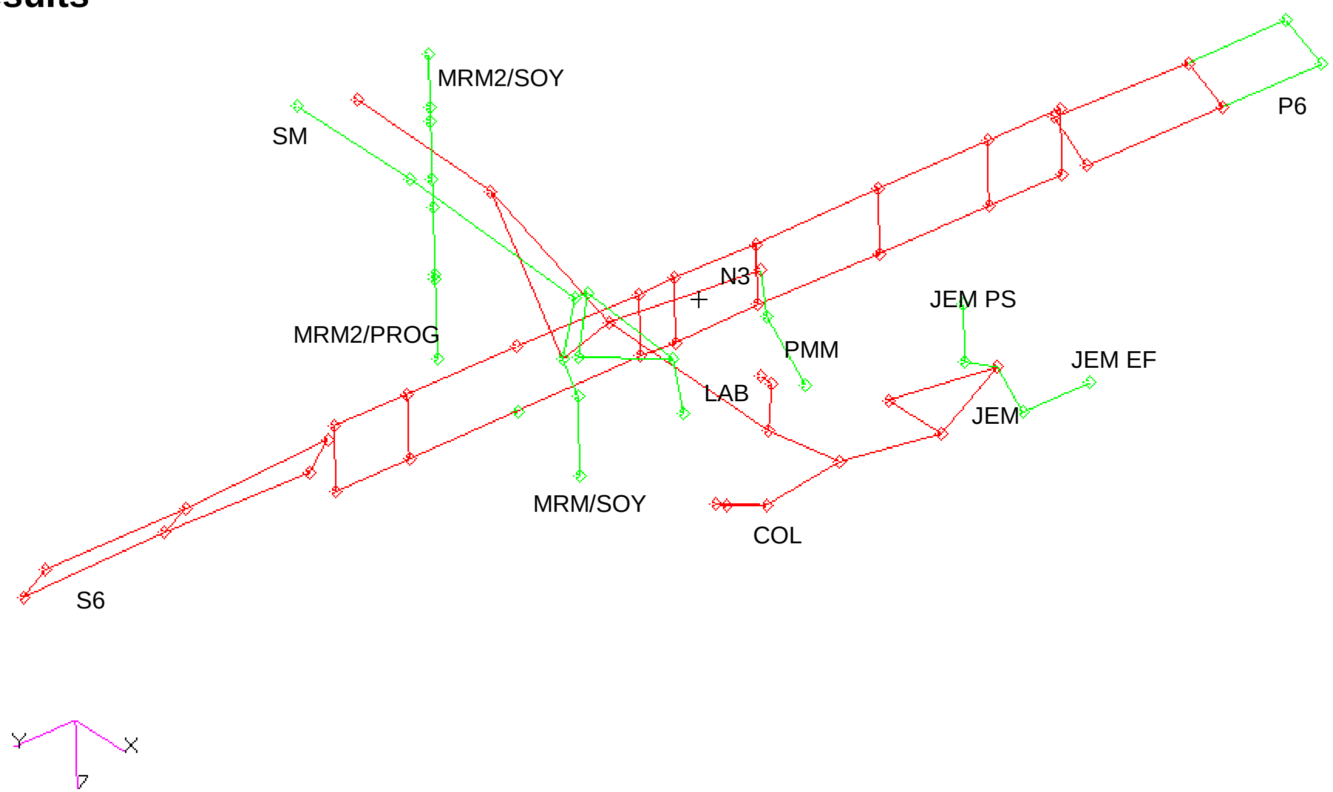
Limitations of Available Sensors for Model Correlation

- **Ascertain what the best MAC that can be expected with perfectly synchronized data and compare to a case where additional accelerometers are included.**
- **Use the analytical system model to compute the time-response to Yaw Firing #2 (F2)**
  - NASTRAN modal transient response
  - F2 Yaw: 6 thrusters, 0.6 seconds duration
- **Two time simulations are performed:**
  - Baseline accelerometers = 104 DOF (Red)
  - Baseline + additional response points = 185 DOF (Red + Green)
- **Extract modes using the Eigensystem Realization Algorithm (ERA) from time histories**
- **Compute MAC between FEM mode shapes and extracted mode shapes.**
- **Compare results**



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Analytical Results Comparison

- **Results show MAC between extracted mode shapes and simulated mode shapes for: 104 DOF & 185 DOF**
- **Modes are down-selected based on high kinetic energy & modal cost**
- **Red boxes highlight newly captured modes using additional response points**
- **The existing number & location of accelerometers, limit modal correlation**

Model Mode# - Freq.	DOF NAME	104 anal	185 anal
220 - 0.394	Freq	0.395	0.395
	MAC	0.952	0.996
223 - 0.409	Freq	0.408	0.408
	MAC	0.982	0.994
256 - 0.46	Freq	0.460	0.464
	MAC	0.959	0.976
257 - 0.465	Freq	0.469	0.470
	MAC	0.704	0.963
287 - 0.542	Freq	-	**0.535**
	MAC	-	**0.884**
289 - 0.557	Freq	0.553	0.557
	MAC	0.838	0.961
304 - 0.598	Freq	0.602	0.598
	MAC	0.945	0.994
315 - 0.641	Freq	-	**0.641**
	MAC	-	**0.941**
352 - 0.774	Freq	-	**0.780**
	MAC	-	**0.867**

Model Mode# - Freq.	DOF NAME	104 anal	185 anal
366 - 0.884	Freq	0.830	0.831
	MAC	0.926	0.955
376 - 0.934	Freq	-	**0.934**
	MAC	-	**0.979**
394 - 1.007	Freq	-	**1.000**
	MAC	-	**0.853**
407 - 1.085	Freq	-	**1.085**
	MAC	-	**0.911**
443 - 1.145	Freq	1.151	1.149
	MAC	0.909	0.812
539 - 1.47	Freq	-	**1.466**
	MAC	-	**0.807**
581 - 1.624	Freq	1.616	1.621
	MAC	0.987	0.991
675 - 1.875	Freq	1.874	1.874
	MAC	0.990	0.991
690 - 1.938	Freq	1.934	1.938
	MAC	0.967	0.973

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Time Domain Synchronization

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Time Synchronization using Graphical Method (Original)

- **Original method to perform time synchronization consisted of co-plotting accelerometer time histories from different locations.**
- **Typically one sensor was chosen as a "reference" to line all others up to.**
  - Service Module (SM), the output response proximal to thrusters were used for synchronization
  - Raw and filtered data used to time shift
- **Since all three axes of a triaxial accelerometer are regulated by a single clock, a single DOF was used for synchronization**
- **Time-shifts varied between 0-.5 seconds**

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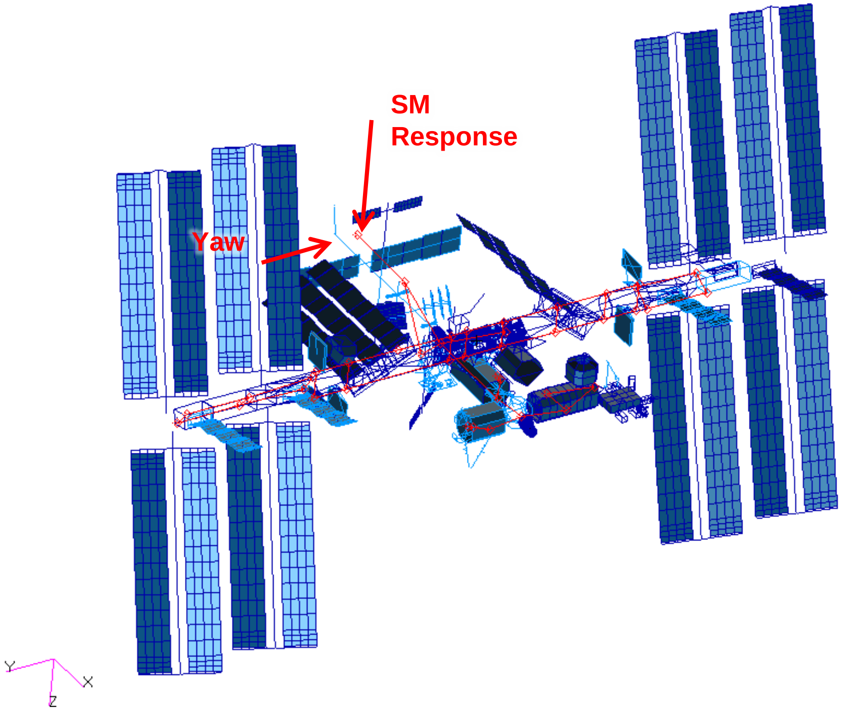
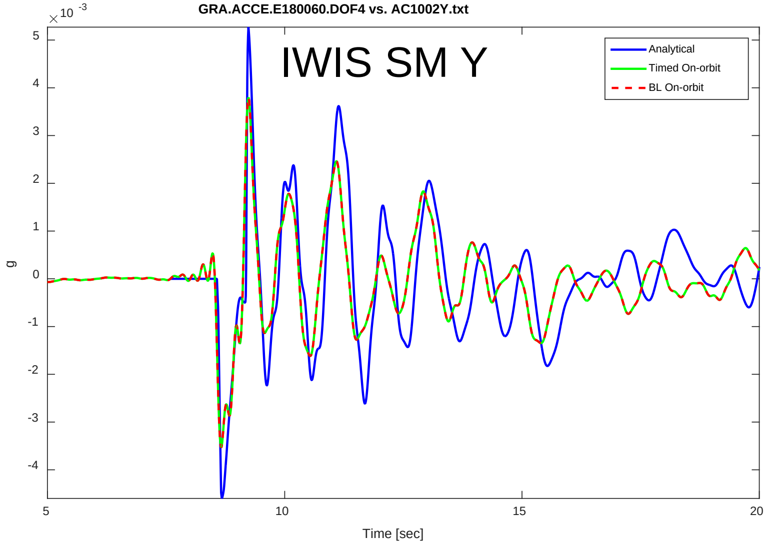
Time Synchronization using Graphical Method with FEM

- **Analytical time-response simulation was used to synchronize accelerometers**
- **Yaw Firing #2 (F2) along ISS-Y (0.35 s to reach 90% thrust) was used to simulate the time-response**
- **Service Module (SM)-Y, the output response proximal to F2 was used for synchronization**
- **Accelerometer data was time-shifted to match the analytical response**
- **Since all three axes of a triaxial accelerometer are regulated by a single clock, a single DOF was used for synchronization**
- **Time-shifts varied between 0.06 – 1.2 seconds**





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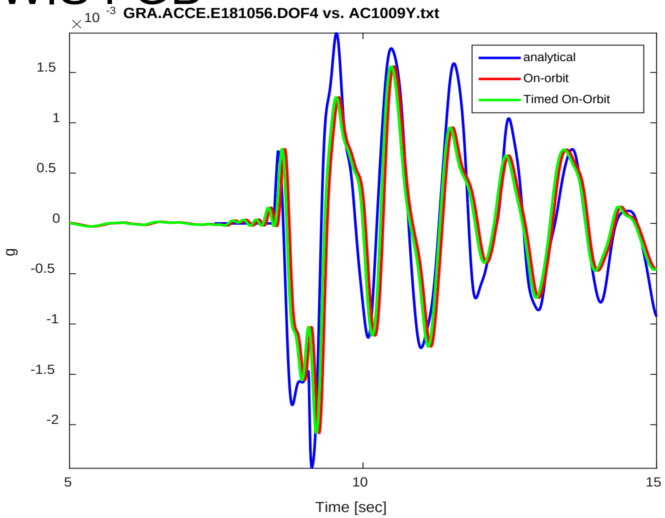
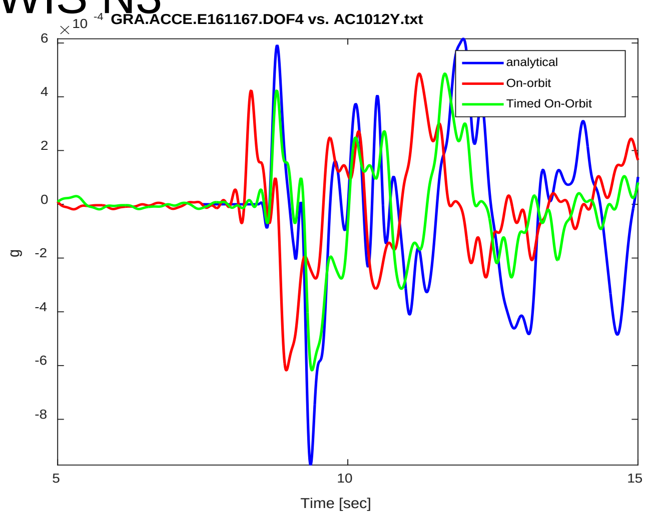
Graphical Method with FEM Results

- **IWIS, SAMS, and EWIS synchronization**

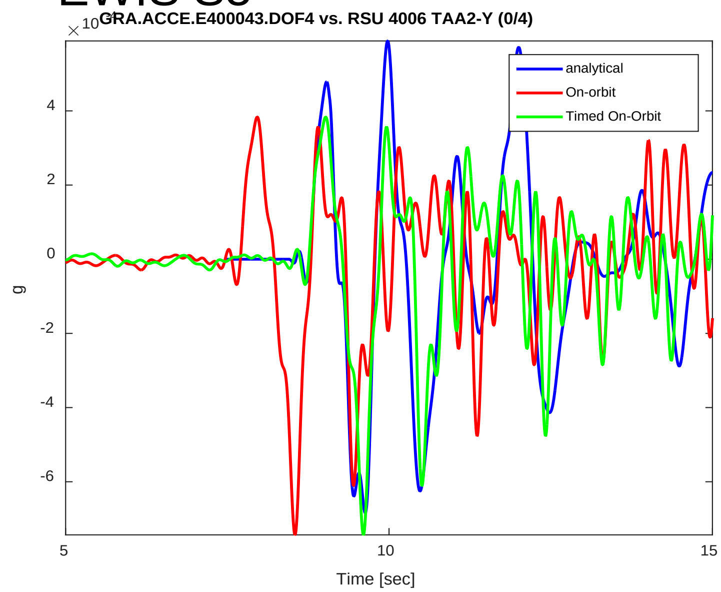
IWIS FGB



IWIS N3



EWIS S5



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Time Synchronization using Correlation Lag Method

- **Let $x(t)$ denote the acceleration time-history obtained from the analytical model**
- **Let $y(t)$ denote, the corresponding accelerometer measurement with time delay τ_0, mixed with statistically independent noise $n(t)$**

$$y(t) = x(t - \tau_0) + n(t)$$

- **The cross-correlation function is given by:**

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T x(t)[x(t + \tau - \tau_0) + n(t + \tau)]\, dt = R_{xx}(\tau - \tau_0)$$

- **The time delay between the analytical response $x(t)$, and the measurement $y(t)$ is given by the correlation lag τ_0**
- **The correlation lag can be computed using the MATLAB functions *xcorr* or *finddelay***
- **The correlation lag can then be used to align the measurements from various accelerometers, prior to model correlation**

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Correlation Lag Method (cont)

- **The time delay obtained from correlation lag is *<u>not</u>* always consistent: e.g. the time delays corresponding to a triaxial accelerometer may vary from one axis to another (despite all three axes of the accelerometer being synchronized to the same clock)**
- **Such inconsistencies are resolved by reasoning/ judgment/ pattern recognition, and sometimes intuition ...**
- **Correlation lag is a good index of time delay, but the method is not readily automated**

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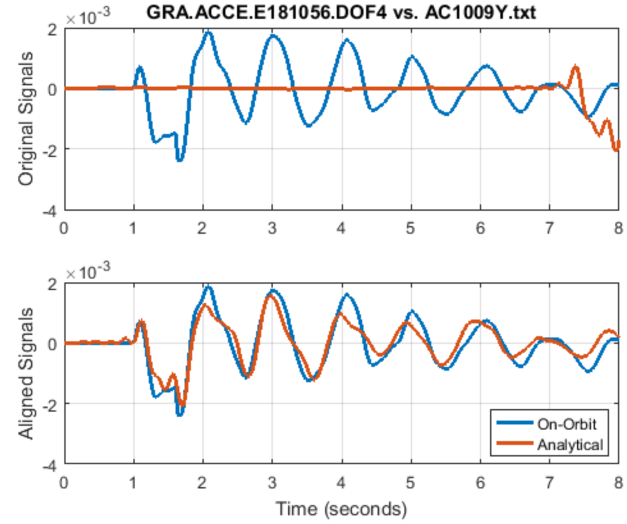
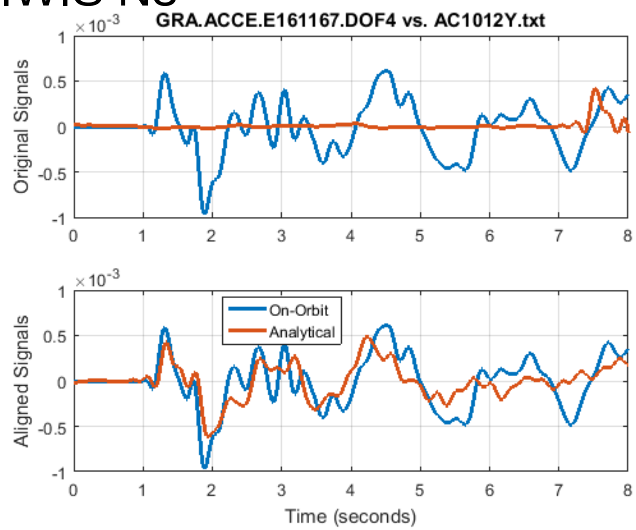
Correlation Lag Method Results

- **EWIS and IWIS synchronization using correlation lag**

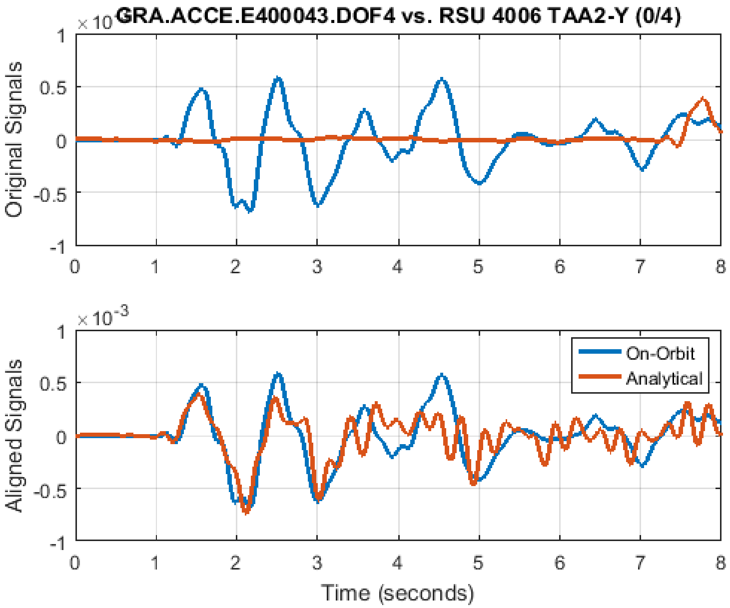
IWIS FGB



IWIS N3



EWIS S5



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Frequency Domain Decomposition Method

- **Objective:**
  - Demonstrate the application of FDD to synchronize ISS accelerometers
- **Background**
  - FDD is the frequency domain analogue of time-delay from correlation lag
  - Here the correlation lag τ_0, appears as the linear phase angle of the cross-spectrum:

$$\theta_{xy}(f) = 2\pi f \tau_0$$

  - Where the cross-spectrum is:

$$G_{xy}(f) = 2\int_{-\infty}^{\infty} R_{xy}(\tau)\, e^{j2\pi f\tau}\, d\tau = \left|G_{xy}(f)\right| e^{-j\theta_{xy}(f)}$$

- **Frequency Domain Decomposition:**
  - Compute the power spectral density (PSD) of accelerometer measurements
  - Perform a singular value decomposition (SVD) of the PSD matrix
  - Plot the first singular value as a function of frequency
  - Modes correspond to those frequencies, where the first singular value peaks
  - Mode shapes correspond to the first singular vector associated with the first singular value, at those peaks
  - The first singular vector is used to compute the phase angle (≡ time-lag)

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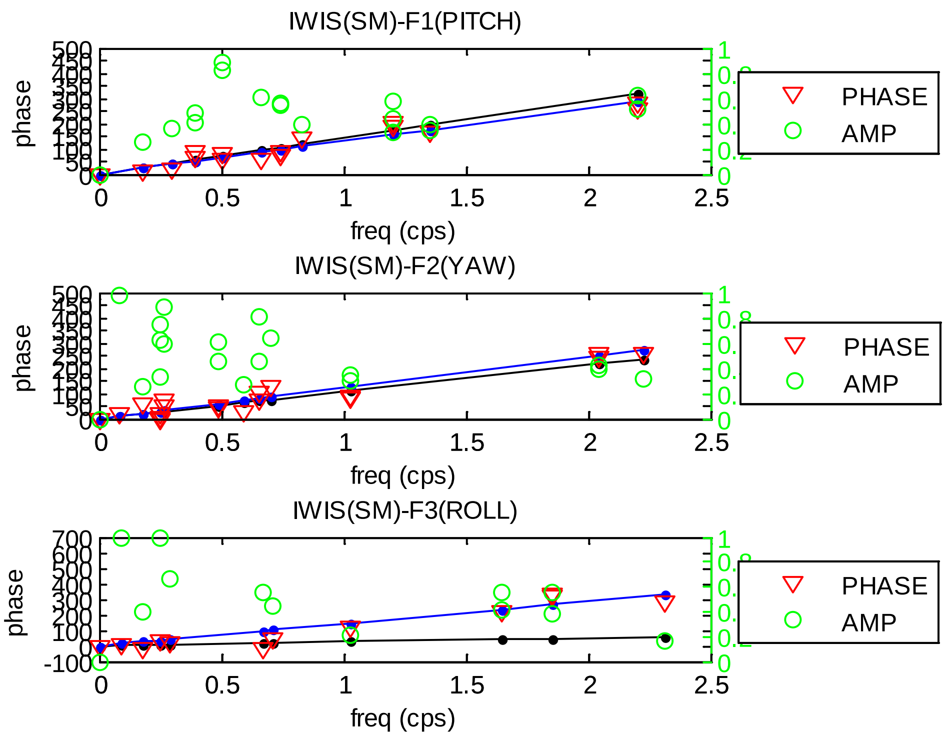
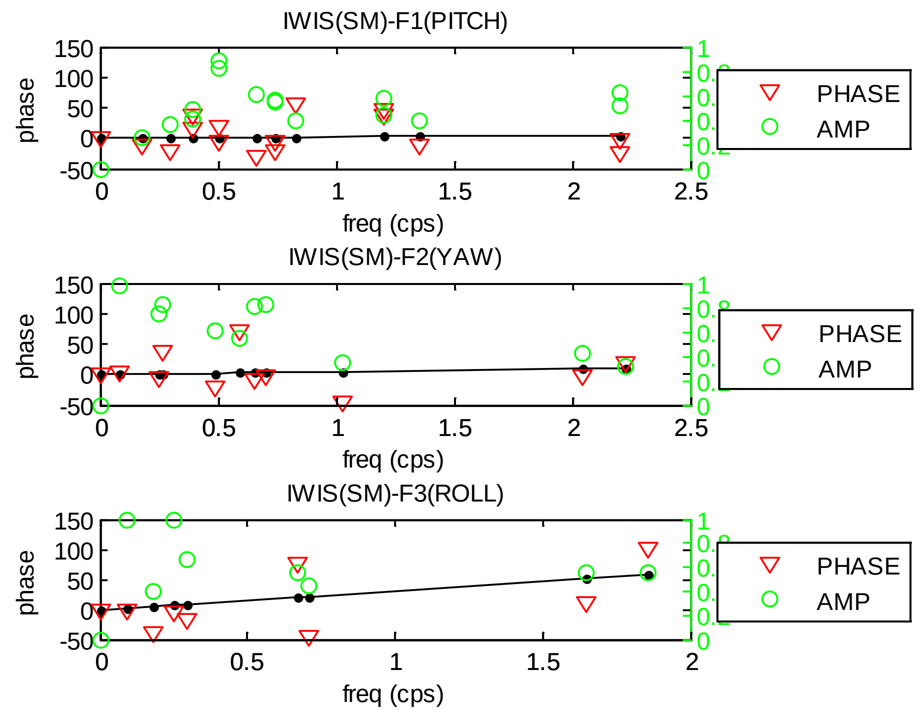
Frequency Domain Decomposition Method

- **Service Module (SM) Module Relative Phase Angles vs. Modal Frequencies**



- **SM Module Relative Phase Angles vs. Modal Frequencies**
  - With time delay estimations included in the measured time histories after two iterations



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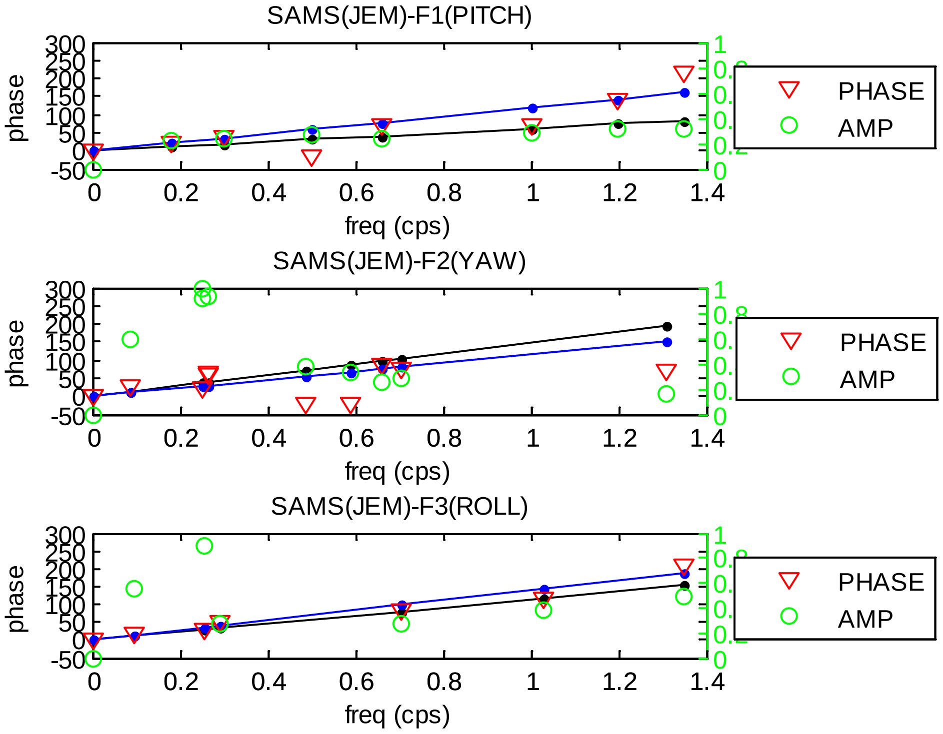
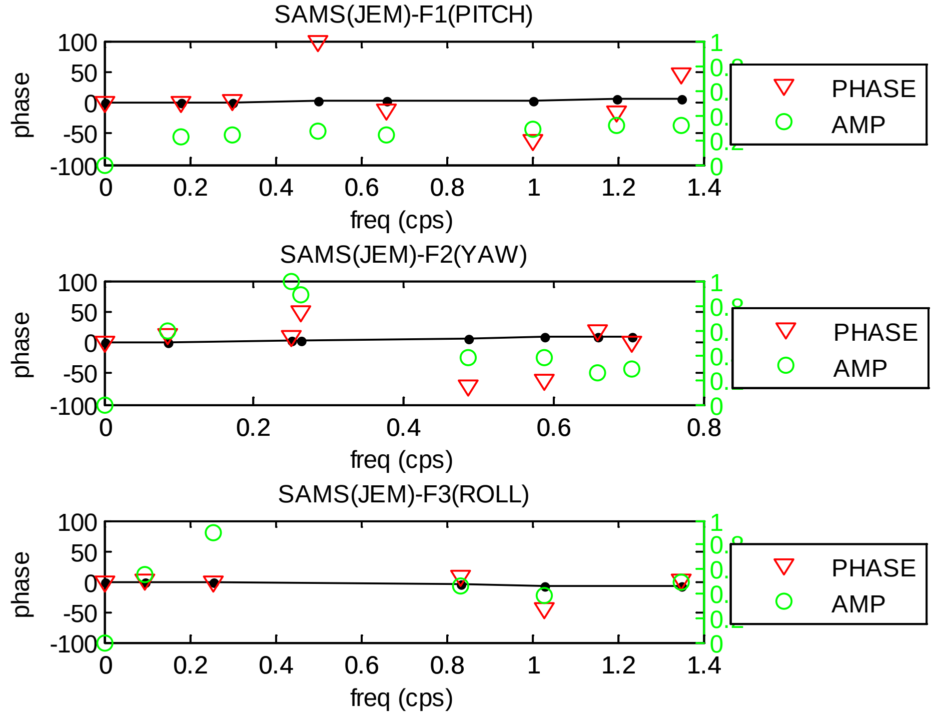
Frequency Domain Decomposition Method

- **JEM Module Relative Phase Angles vs. Modal Frequencies**



- **JEM Module Relative Phase Angles vs. Modal Frequencies**
  - With time delay estimations included in the measured time histories after two iterations



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Results

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Results

Model Mode# - Freq.	DOF NAME	104 Original	104 Graphical	104 FDD	86 Correlation	185 anal
44 - 0.12	Freq	0.084	0.087	0.088	0.088	-
	MAC	0.931	0.938	0.937	0.943	-
44 - 0.12	Freq	0.104	0.102	0.102	0.101	0.120
	MAC	0.943	0.936	0.942	0.932	1.000
83 - 0.176	Freq	0.176	-	0.178	0.172	0.176
	MAC	0.887	-	0.881	0.848	0.995
	Freq	0.182	0.181	0.181	0.181	
	MAC	0.822	0.813	0.805	0.771	
102 - 0.219	Freq	-	-	-	-	0.217
	MAC	-	-	-	-	0.985
128 - 0.264	Freq	0.258	0.261	0.259	0.256	0.267
	MAC	0.892	0.912	0.902	0.897	0.998
	Freq	0.288	0.297	0.290	0.295	
	MAC	0.904	0.898	0.897	0.870	
145 - 0.285	Freq	-	-	-	-	0.285
	MAC	-	-	-	-	0.992
177 - 0.343	Freq	-	-	-	-	0.344
	MAC	-	-	-	-	0.994
215 - 0.375	Freq	-	-	-	-	0.376
	MAC	-	-	-	-	0.967
220 - 0.394	Freq	-	-	-	-	0.395
	MAC	-	-	-	-	0.996
223 - 0.409	Freq	-	-	-	-	0.408
	MAC	-	-	-	-	0.994
256 - 0.46	Freq	-	-	-	-	0.464
	MAC	-	-	-	-	0.976
257 - 0.465	Freq	0.488	0.486	0.488	0.472	0.470
	MAC	0.779	0.881	0.770	0.856	0.963

Model Mode# - Freq.	DOF NAME	104 Original	104 Graphical	104 FDD	86 Correlation	185 anal
289 - 0.557	Freq	-	-	-	-	0.557
	MAC	-	-	-	-	0.961
304 - 0.598	Freq	-	-	-	-	0.598
	MAC	-	-	-	-	0.994
315 - 0.641	Freq	-	-	-	-	0.641
	MAC	-	-	-	-	0.941
318 - 0.668	Freq	-	0.692	-	0.682	-
	MAC	-	0.815	-	0.868	-
352 - 0.774	Freq	-	0.850	-	-	0.780
	MAC	-	0.783	-	-	0.867
366 - 0.884	Freq	-	-	-	-	0.831
	MAC	-	-	-	-	0.955
376 - 0.934	Freq	-	-	-	-	0.934
	MAC	-	-	-	-	0.979
394 - 1.007	Freq	-	1.035	-	1.055	1.000
	MAC	-	0.917	-	0.924	0.853
407 - 1.085	Freq	-	-	-	-	1.085
	MAC	-	-	-	-	0.911
443 - 1.145	Freq	-	1.145		-	1.149
	MAC	-	0.777		-	0.812
539 - 1.47	Freq	-	1.433	-	-	1.466
	MAC	-	0.733	-	-	0.807
581 - 1.624	Freq	-	-	-	-	1.621
	MAC	-	-	-	-	0.991
675 - 1.875	Freq	-	-	-	-	1.874
	MAC	-	-	-	-	0.991
690 - 1.938	Freq	-	-	-	2.005	1.938
	MAC	-	-	-	0.809	0.973

Red text denotes new mode extracted from untimed 104 DOF correlation

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Summary

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Summary

- **The ISS is the largest space structure ever built**
- **It has been constructed over a period of 10 years**
- **Some accelerometers on the ISS were pre-positioned and others added after assembly**
- **The four distinct accelerometer groups have individual clocks, and dedicated data acquisition networks**
- **Current compliment of accelerometers limits the quality of modal correlation and number of modes that can be correlated.**
- **Time synchronizing accelerometer data improves MAC and provides better correlation of higher order modes**
  - Graphical and time-based correlation function methods when used relative to FEM-predicted time histories provided best correlation.
  - More work is planned to improve automation of these techniques.

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