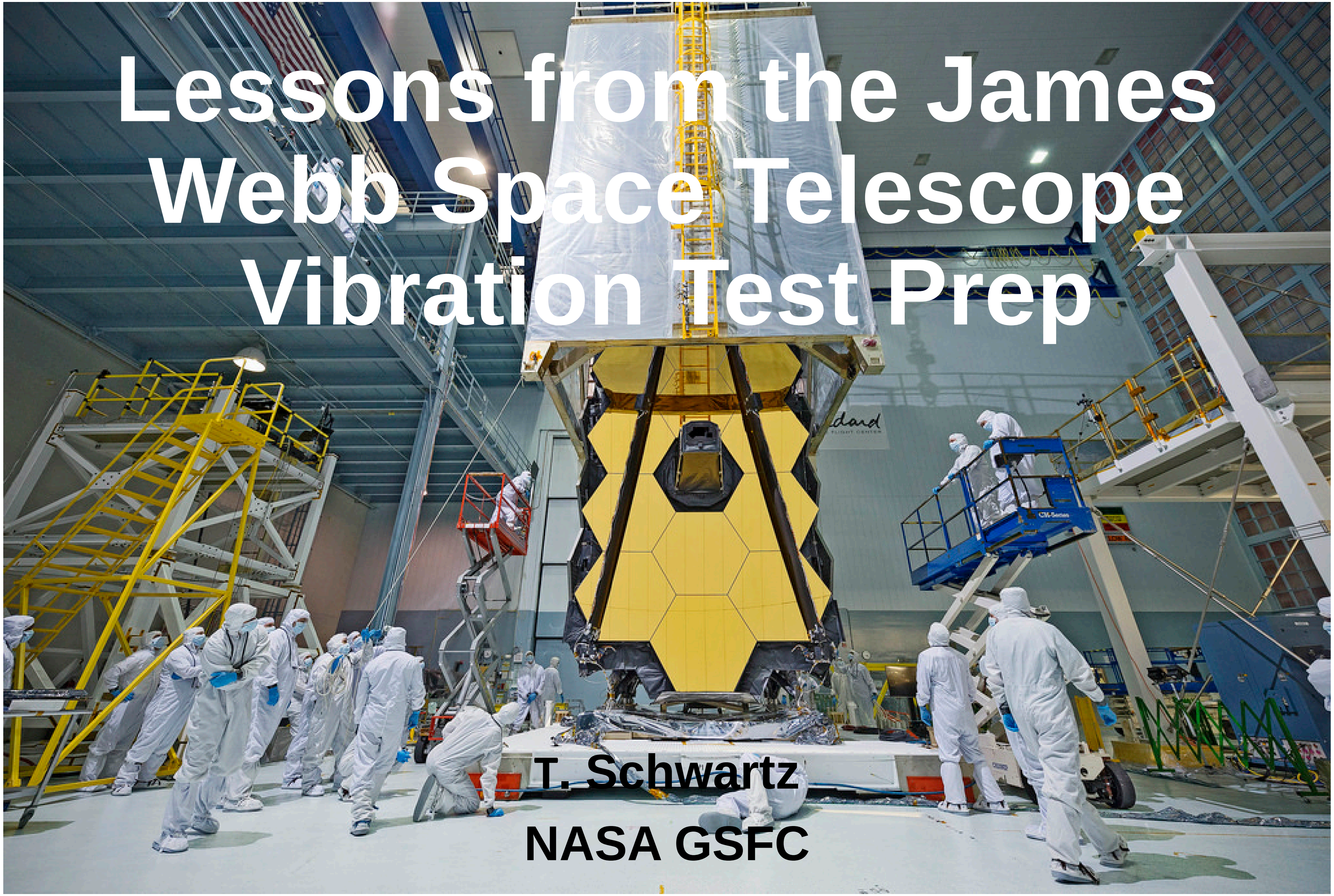
Lessons from the James Webb Space Telescope Vibration Test Prep



T. Schwartz

NASA GSFC

Agenda

JWST/OTIS Overview

Facility Commissioning Challenges

Operational Constraints

Control System

Data Acquisition

Pre/Post Test Signatures

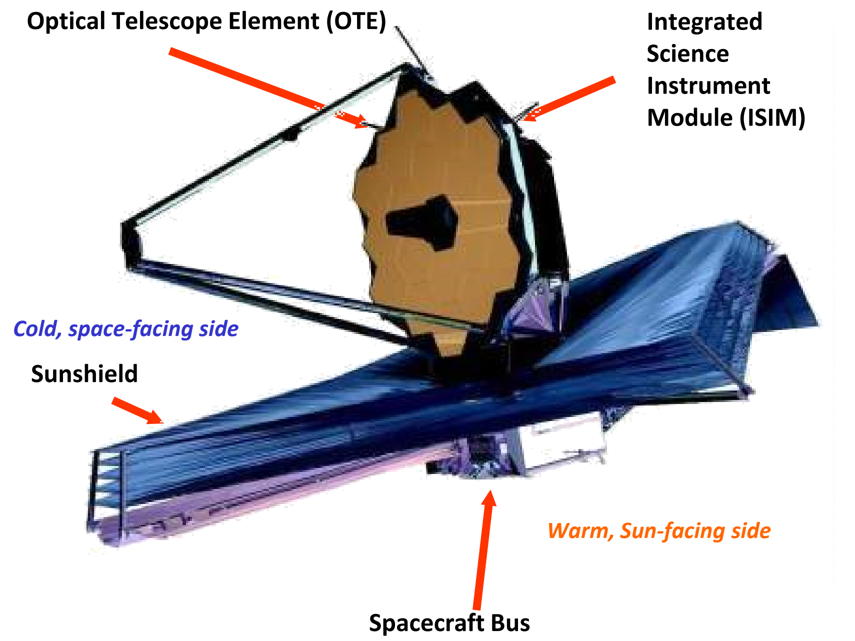
James Webb Space Telescope (JWST)

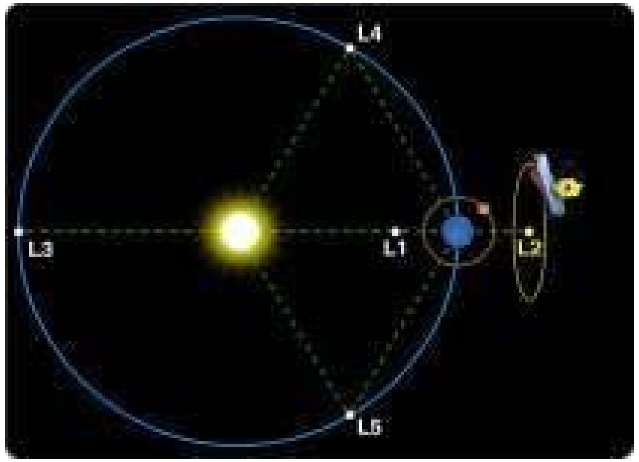
Mission Objective

- Study the origin and history of galaxies, stars and planetary systems
  - *Optimized for infrared observations (0.6 – 28 μm)*

Organization

- Mission Lead: Goddard Space Flight Center
- International collaboration with ESA & CSA
- Prime Contractor: Northrop Grumman Space Technology
- Instruments:
  - Near Infrared Camera (NIRCam) – Univ. of Arizona
  - Near Infrared Spectrograph (NIRSpec) – ESA
  - Mid-Infrared Instrument (MIRI) – JPL/ESA
  - Fine Guidance Sensor (FGS) – CSA





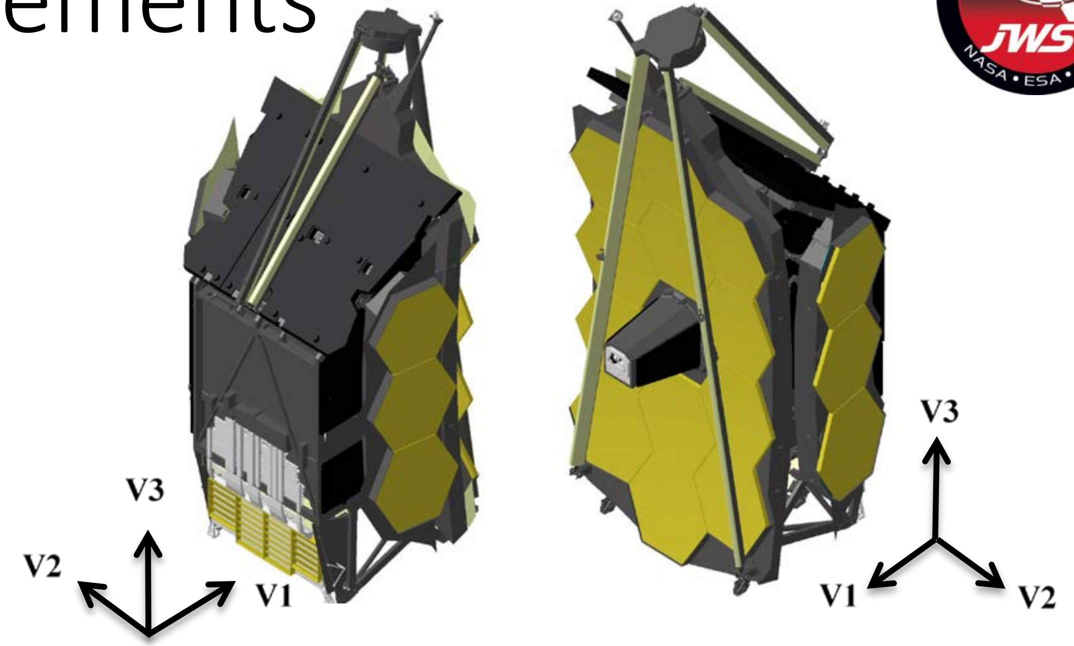
Description

- Deployable telescope w/ 6.5m diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
- Launch on an ESA-supplied Ariane 5 ECA rocket to Sun-Earth L2

Facility Requirements

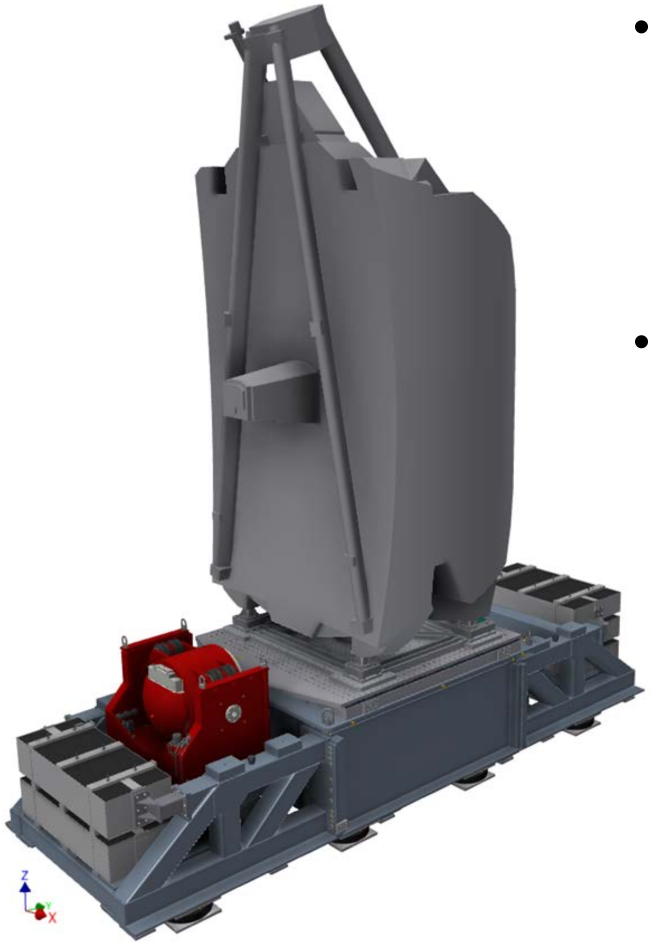
- Test article size
  - OTIS envelope: 8'-5" x 7'-10" x 28'-3"
  - OTIS mass: 8,686 lbs
  - Fixture mass: 6,200 lbs
- Cross-axis motion
  - Bare Table: <10%
  - OTIS Payload: <40%
- Overturning moment capacity
  - Must react moments simultaneously
- No test aborts <400ms

	Horizontal	Vertical
Pitch	3.50e6 in-lbf	1.30e6 in-lbf
Roll	180,000 in-lbf	400,000 in-lbf
Yaw	50,000 in-lbf	300,000 in-lbf



Axis	Frequency (Hz)	Test Level (zero to peak)
V1	5-50	1.00 g
	50-80	1.25 g
	80-100	1.00 g
V2	5-50	1.00 g
	50-60	1.50 g
	60-80	1.00 g
	80-100	1.50 g
V3	5-20	1.50 g
	20-40	0.75 g
	40-60	1.25 g
	60-100	1.00 g

Dual Shaker Systems



- Horizontal system
  - T-film slip table system
  - Single ED shaker
  - Excite V1 & V2 axis

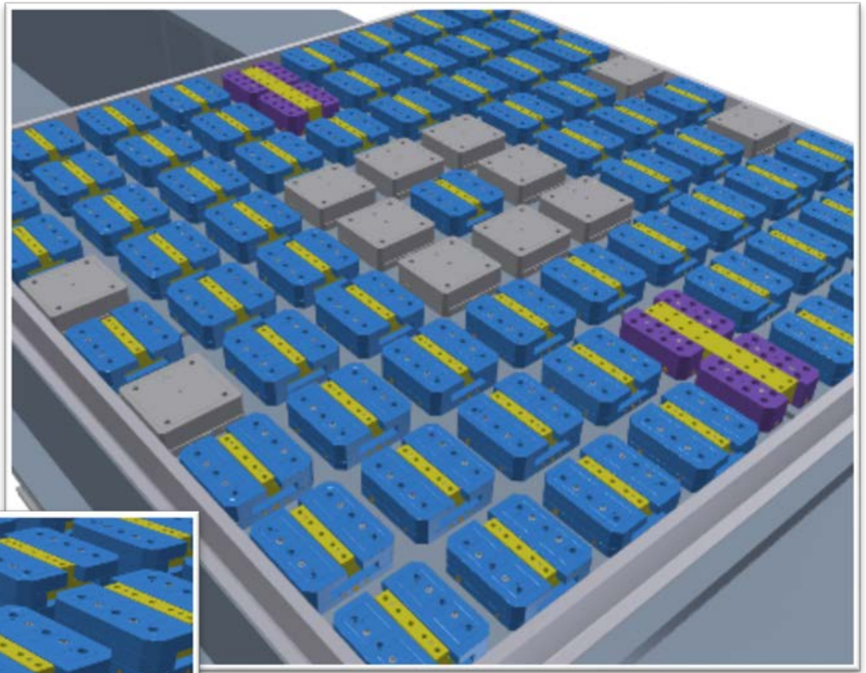
- Vertical System
  - Patented inertial mass guidance
  - Dual ED shakers
  - MIMO control
  - Excite V3

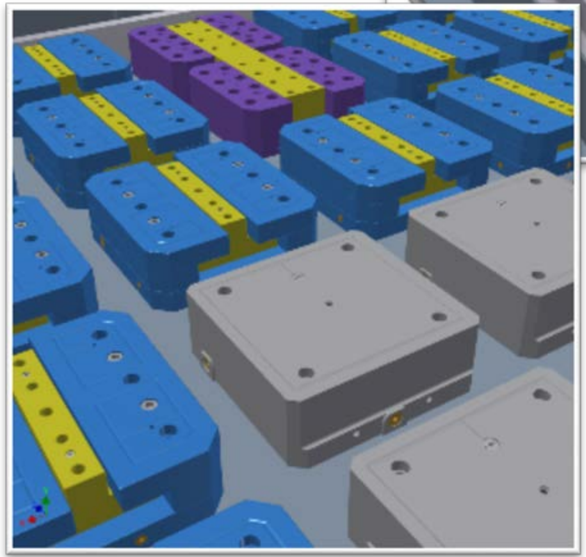
Horizontal System

- Design Concept: T-Film slip table with high rotary inertia reaction base
  - Expansion of standard Team T-Film Table to accommodate extremely large overturning moments
- Design Components:
  - Electrodynamic Shaker
    - Single 50,000 lbf shaker
    - Air isolated trunnion mount
  - T-Film Table
    - Hydrostatic Bearings
    - Couples overturning moments into reaction base
  - Reaction Base
    - High rotary inertia
    - Air isolated
    - High density concrete masses

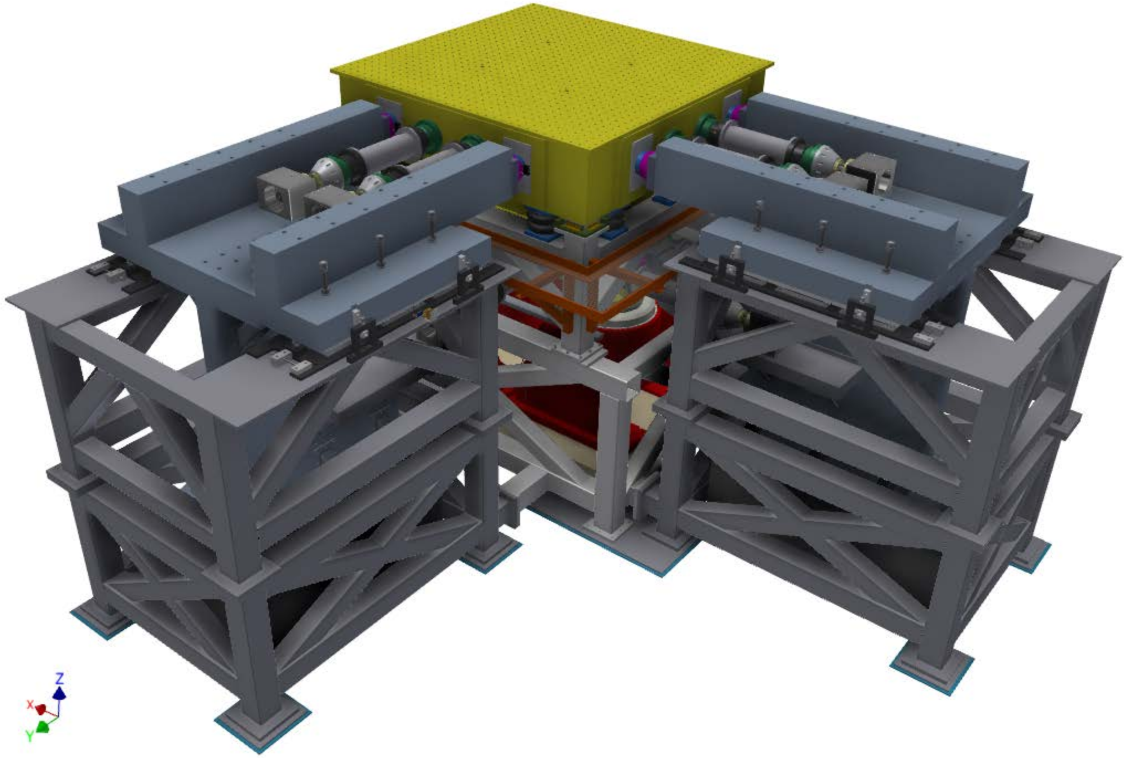
Horizontal System – Hydrostatic Bearings

- T-Film Bearings
  - Fundamental element in Team slip tables
  - Reacts roll and pitch moments
  - Placed in load path from OTIS to reaction base
- Yaw Bearings
  - Reacts yaw moment
  - Guides slip plate in shaker axial direction
- Filler Elements
  - Static load support
  - Do not react moments
- 5-degrees of control



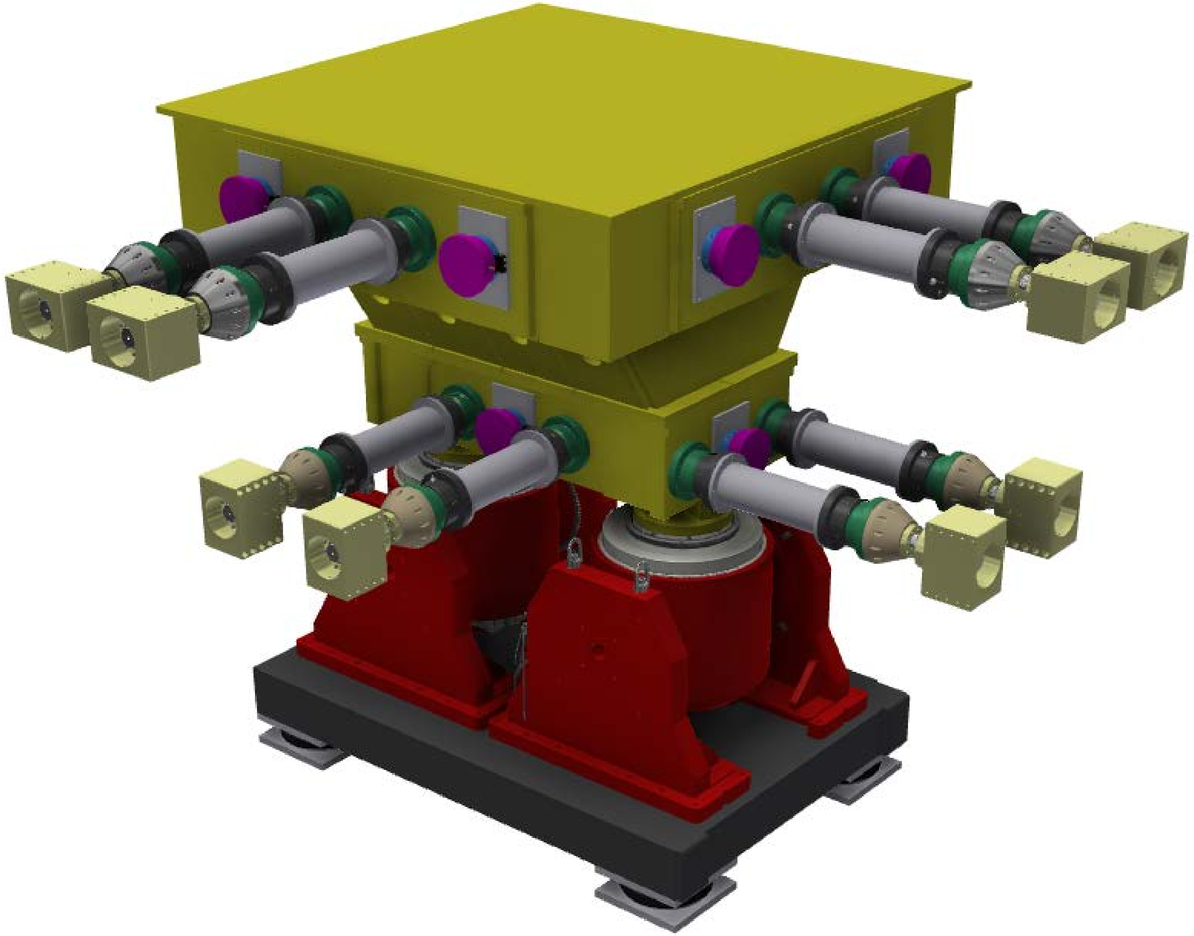


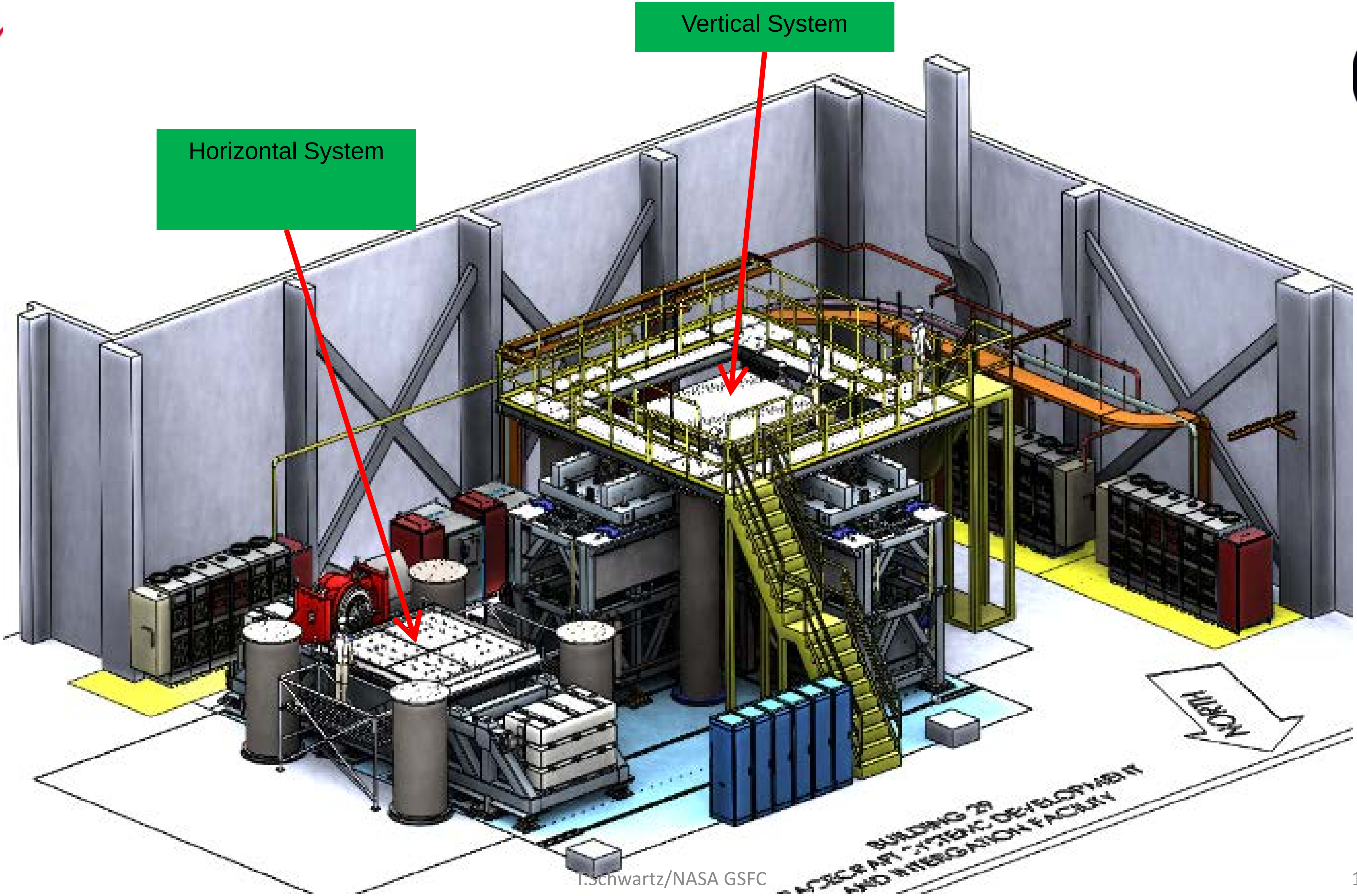
Vertical System



- Design Components:
  - Electrodynamic Excitation
    - Dual 50,000 lb shakers
  - Guided Head Expander
    - Transmits energy from shaker to test article
  - Inertial Masses
    - React moments generated by test article
  - Hydrostatic bearings
    - Provides short, stiff load path into masses
  - Air Isolated Supports
    - Isolates vibration system from building

Vertical System




Vertical System
Horizontal System
BUILDING 29

Soft Shutdown

- The soft shutdown requirement was integral to the system design
- Shutdowns are controlled by the furnished Data Physics control system
  - Abacus hardware
  - SignalStar Vector/Matrix software
- Shutdown time is software programmable
- The Abacus generates an enable signal that is passed to all hardware required to enable test (stop switch, THC, amplifier, TAPS)
- Each piece of equipment must command a relay closed to return the enable signal
- Removal of the enable signal triggers a controlled shutdown

Facility Commissioning Challenges

- Poor Coherence on Shaker#2:
  - Determined to be caused by poor connection between copper current lead and aluminum lead block on shaker
  - The likely root cause of the poor connection is a combination of dimensional discrepancy and galvanic corrosion

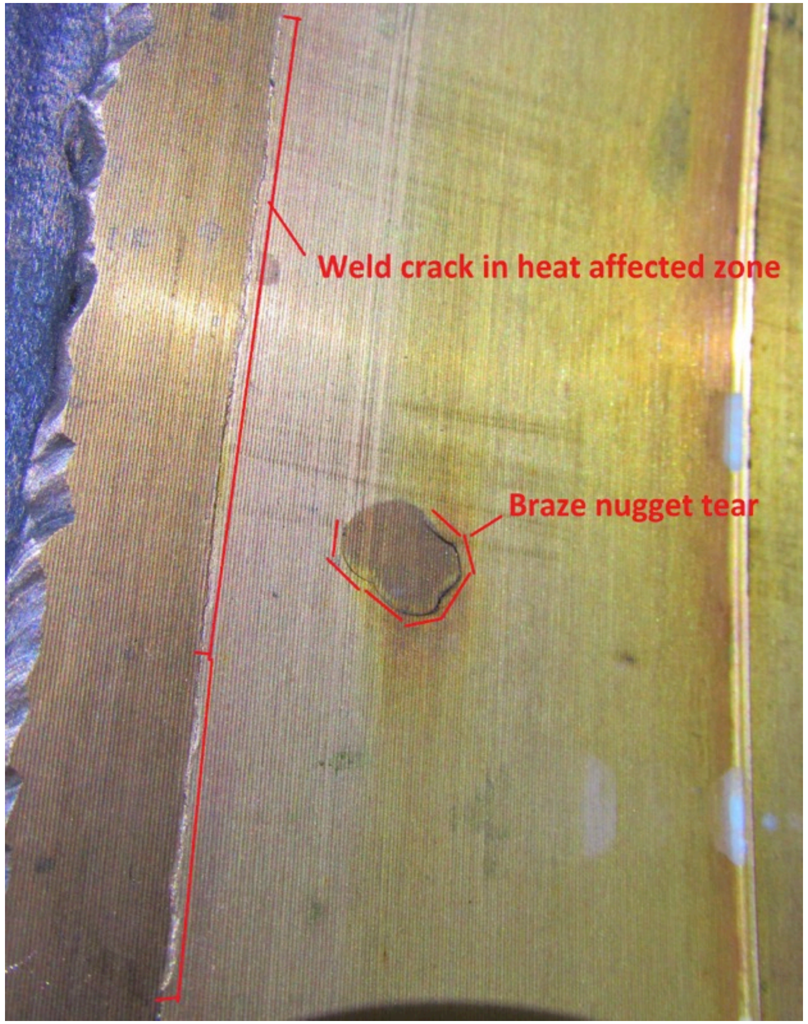
Arcing caused by the poor electrical connection.

A good electrode on the top

The bad electrode on the bottom

Facility Commissioning Challenges

- Opening the shaker up to investigate the coherence problem uncovered cracks in the copper compensating bands
  - Cracks formed in weld areas joining copper plates
  - Cracks formed in the plug welds joining the copper plate to the steel body
- Further investigation showed these cracks in all 3 DP shakers
- DP return the 2 vertical shakers to Corona for repair
- Horizontal shaker remained installed at GSFC



Facility Commissioning Challenges

- The shaker tear down also revealed some possible wear on the upper armature bearing
  - Initially thought the coherence problem could be stiction in bearing or armature rubbing
  - Raised concerns that shaker armature is over constrained
- Possible solutions
  - Redesign shaker driver adapter, adding compliance
  - Increase armature gap in shaker body
  - Compute lateral armature deflections from test data
- DP offers that the copper bands can be removed
  - Acts as a transformer but only at high frequencies (>500Hz)
  - Eliminates troublesome cracked components
  - Increases gap around armature

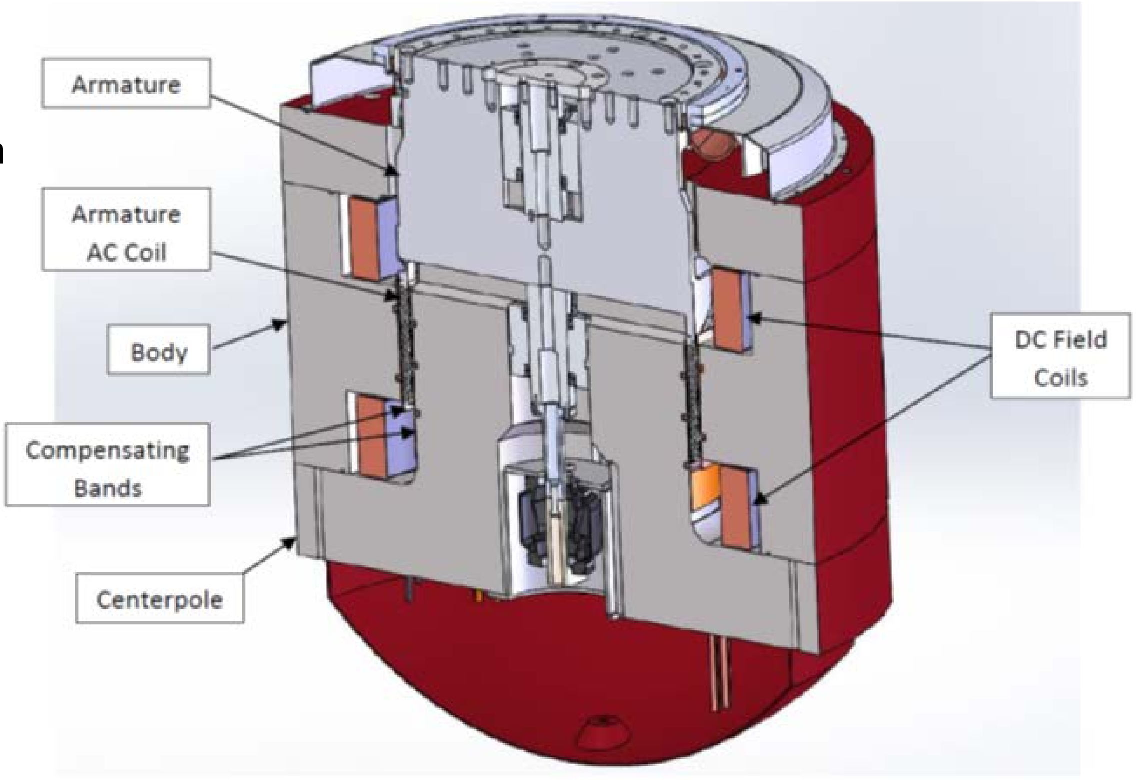


Figure 1: cross section 5022-3 shaker

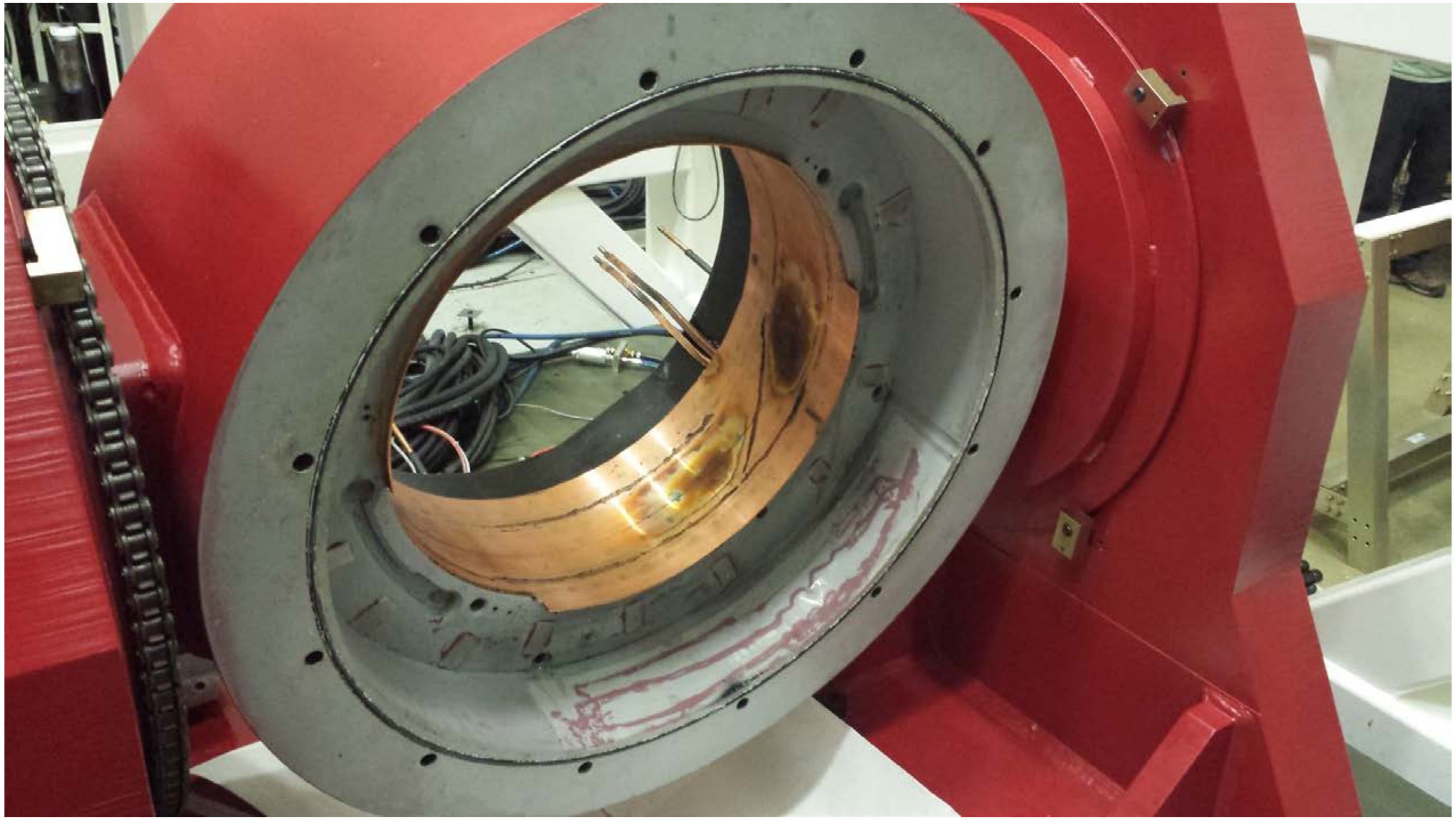
Shaker Rework

- Decision to remove compensating bands
- Factory acceptance test without compensating bands
  - Without cooling integral to the compensating bands, shaker body gets hot and stays hot (250F on body and center pole)
  - Peak force degradation begins at 70Hz
- DP reconsiders and recommends reinstalling compensating bands/cooling, but first turning down the shaker body to retain gap
- JWST agrees and shaker #1 is expedited on the new plan with shaker #2 to follow

Shaker #1 Returns to GSFC

- Shaker #1 completes factory acceptance test and is shipped to GSFC
- During on site acceptance testing, at 27 min into a 30 min random test at 80% force, the amplifier aborted on a peak current fault
- The armature had ruptured and gallons of armature cooling water erupted into the shaker body.

Shaker #1 Compensating Band



Shaker #1 Hot Spots and Rupture

Shaker #1 Failure

- Poor process control resulted in a poor installation of the compensating band
  - Copper was not in sufficiently in contact with the steel
  - Welding process not well controlled, resulted in poor heat conduction
  - The final machining of the band (following welding) resulted in very thin sections of the band
- The armature in shaker #1 was the armature exposed to “no copper” testing
  - Overheating of the fiberglass insulation resulted in compromised mechanical and dielectric properties resulting in catastrophic arcing

Shaker #2

- Following the failure of shaker #1, DP step up efforts to complete shaker #2 rework, perform factory acceptance testing, and deliver to GSFC
- Hot spots on shaker #1 were discovered while shaker #2 was in the midst of factory acceptance test, prompting disassembly of shaker #2 for inspection
- Some hot spots were found on shaker #2, but to a lesser extent than shaker #1

Operational Constraints

- Limit heating of the shaker internals
  - Limit amplifier current to 1750A, ~70% of capability
    - Reduces shaker force to ~35,000 lbf
    - Implemented as limit channel on controller
  - Measure hot spot temp directly with thermocouple
    - Record TC as response channel during test
    - Applied abort limit to TC at 100C
- Monitor voltage coherence for any deviation
- Monitor head expander/slip table/vibe fixture temps
  - Required average temp of 24C +/-3C to perform any test runs

Control System

- Data Physics Abacus/SignalStar
- Integral to satisfying soft shutdown requirement
- During the facility commissioning phase a hard shutdown was experienced while testing on the slip table
  - “Urgency Stop” error message was reported in the software
  - Shaker stopped abruptly
  - DP determined that the software had called for a stop in zero seconds by executing an unexpected code path due to a communication error
- NASA GSFC Flight Software Division was brought in to help

Control System

- Identified that the communication error is a vulnerability when using more than one Abacus chassis (>32 channels)
  - Communication over Ethernet in a ‘realtime’ control system is not robust
  - Ethernet protocol ensures that the data packets with get there eventually
  - Eventually resolved to limit control system to 32 channels
- Hard code 400ms shutdown is such a way that “stop” cannot be called with any other value
- Several other important, but less critical issues were identified
  - Software lockup
  - Lack of a global scale factor for limits
  - Overwrite of test data
  - Improper channel labeling
  - Painfully slow parameter file generation

Control System

- It took several months to get the bugs fixed, properly tested, and the new version delivered
- The fixes implemented seemed to reveal more bugs
  - Faulty start up logic when limits predicted to engaged at start frequency
  - Faulty startup logic when limits predicted to engage as stop frequency.
  - Failure to generate COLA running multiple test runs
- DP went through several iterations and provided several software releases to us
- Settled on a release that was stable and the known risks could be mitigated

Data Acquisition

- Initial requirement ~500 channels
- Existing DSPCon DataFlex 1000 Hardware 320 channels
- Supplemented by purchasing m+p VibRunner

- Final configuration:544 channels of response + 64 channels for facility
  - 288 channels of DataFlex for response
  - 256 channels of VibRunner for response
  - Additional 64 channels of DataFlex backing Abacus and recording facility channels (reaction base accels, amp current, amp voltage, bearing pressures, etc.)

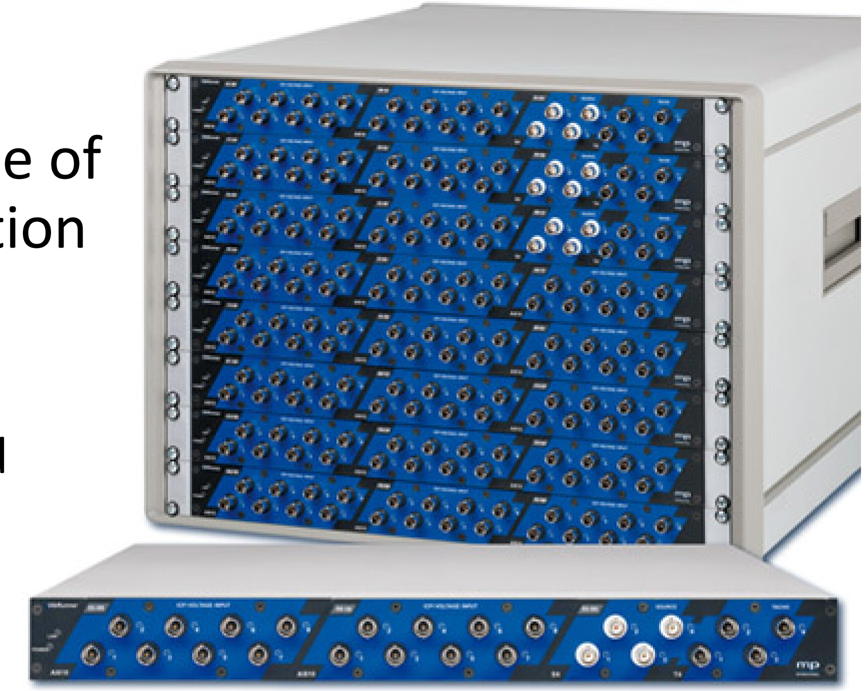
Data Acquisition

- After adding the VibRunner hardware we approached m+p about their ability to interact with our soft shutdown circuit.
- VibRunner is capable of commanding relays with digital I/O to trigger shutdown when abort limits are exceeded
- In our configuration VibRunner controls two relays in series
  - A normally open relay is commanded closed to enable the controller
  - A normally closed relay is commanded open when an abort limit is exceeded

Data Acquisition

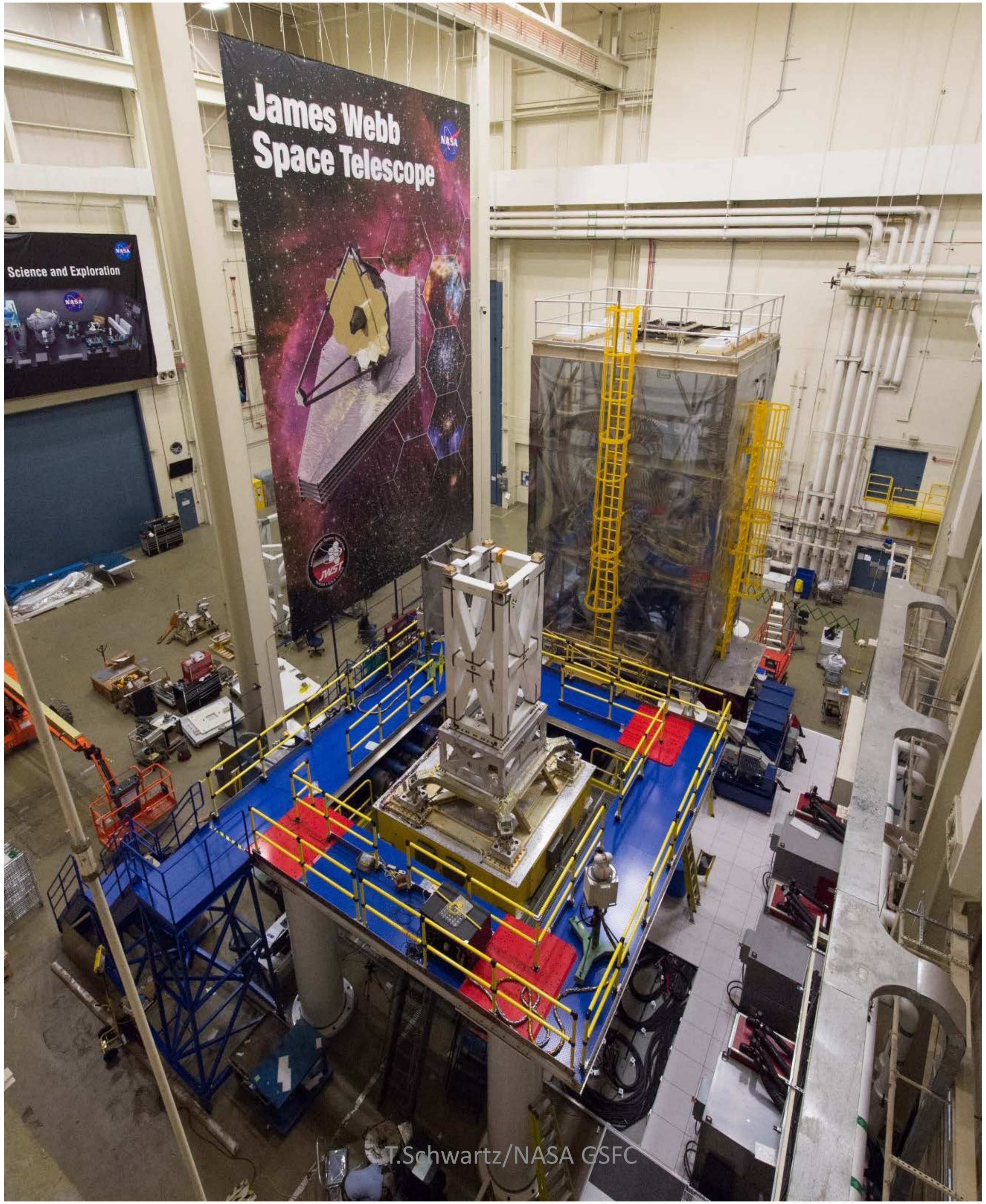
- The resulting system can trigger an abort on any of the 256 channels

- Limitations:
  - COLA must be present to function, due to our use of the sine reduction package to drive data acquisition
  - Only configured to abort on time domain peak acceleration
    - Other options should be possible, but have not tested them yet



Completion of Facility Commissioning

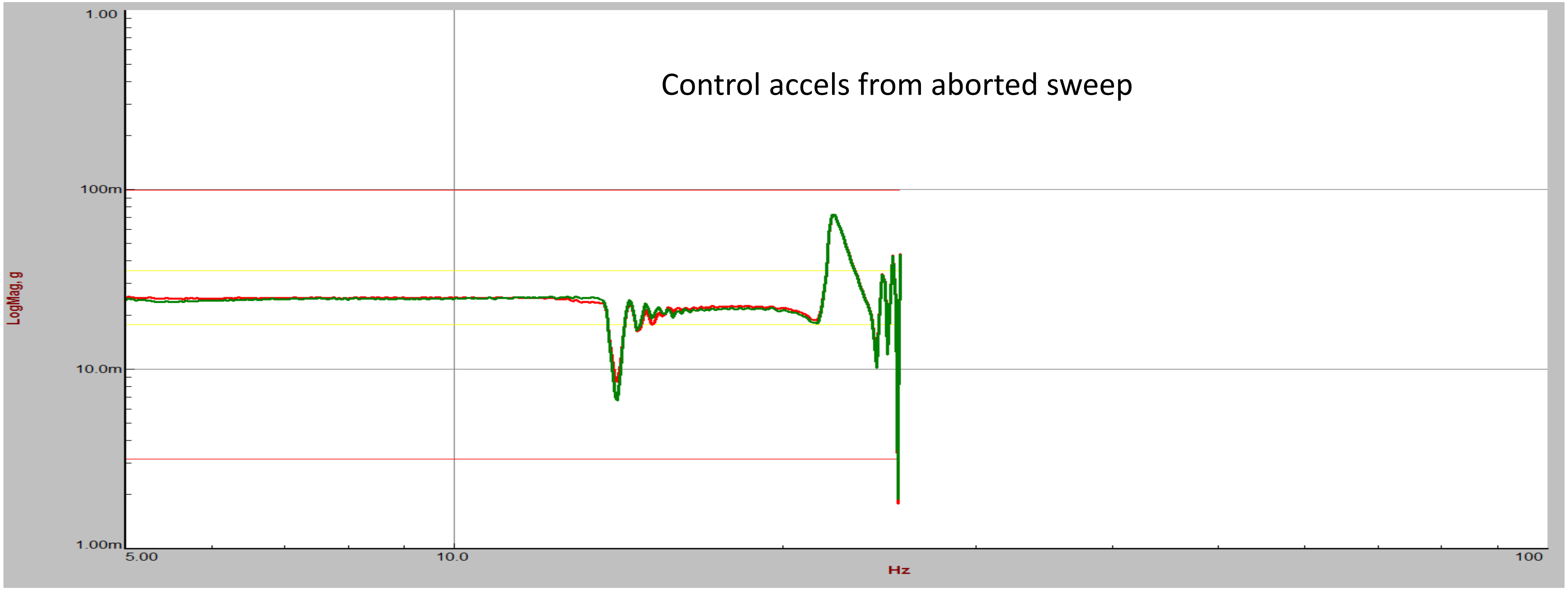
- Dynamic test mass
- Final software
- Enforcing operational constrains
- Performing OTIS test specification



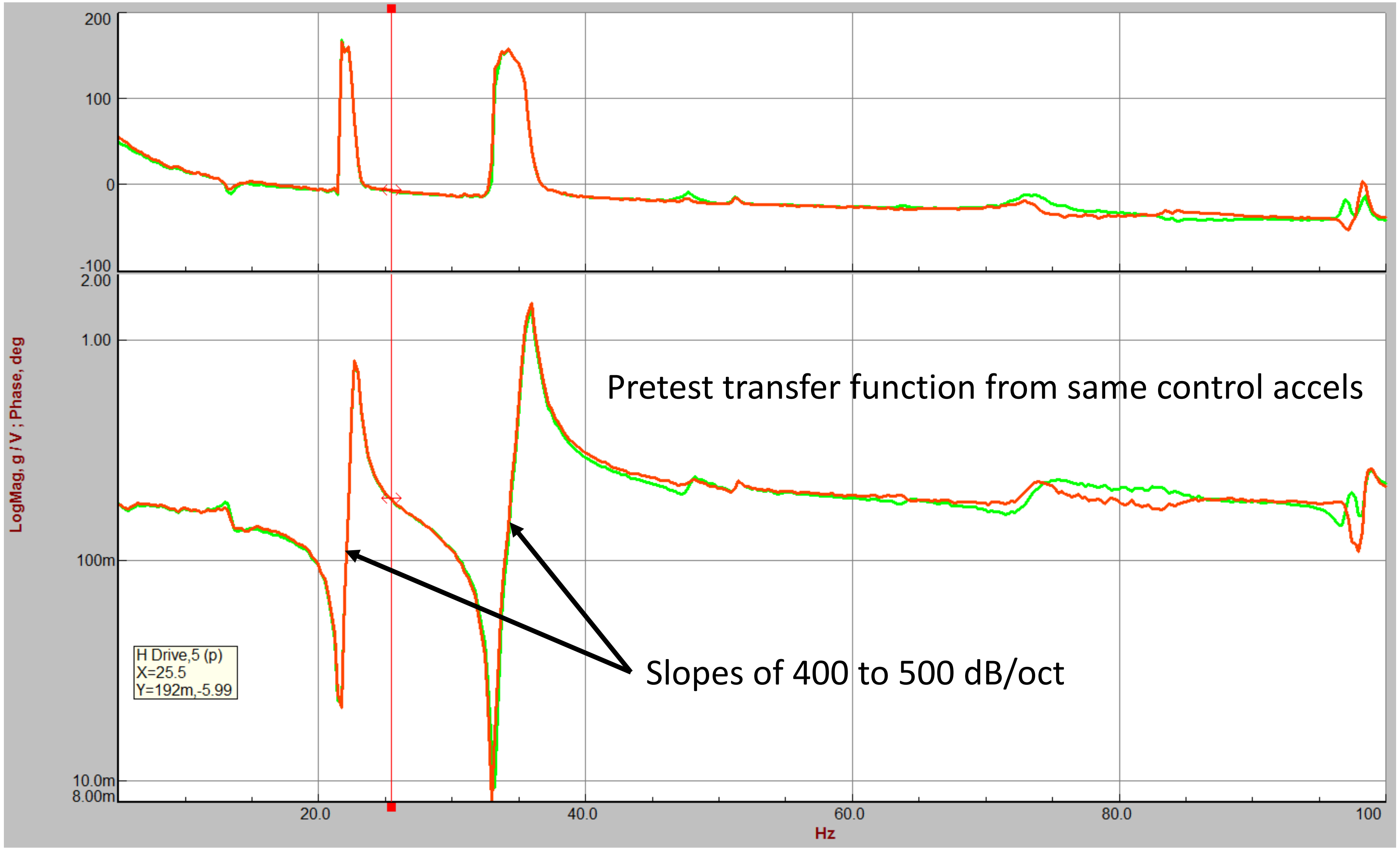
T.Schwartz/NASA GSFC

Pre/Post Signature

- Sine control at requested levels (0.025 to 0.05g) difficult to control with lightly damped test article



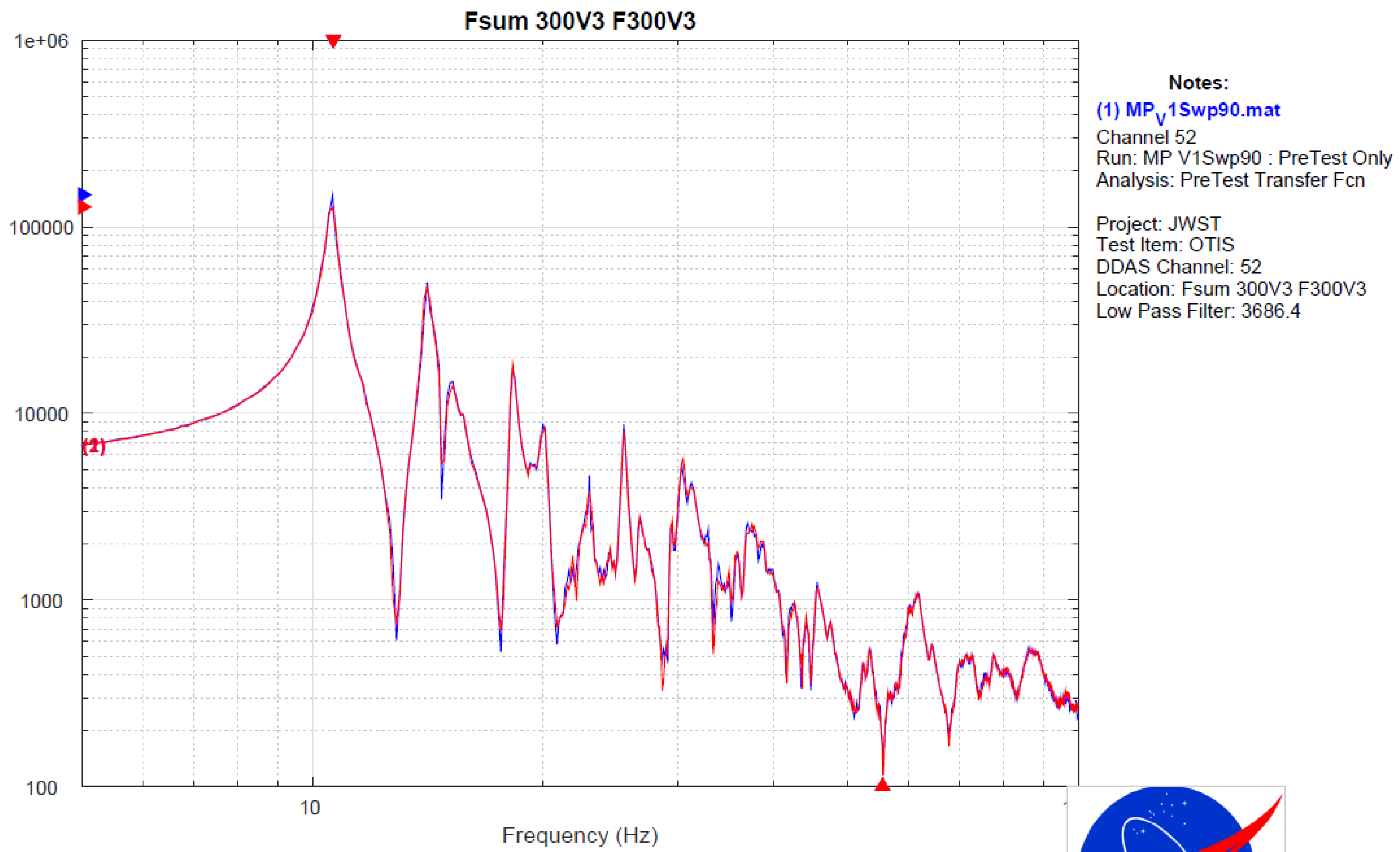
Pre/Post Signature



Pre/Post Signature

- Implemented method using open-loop pretest random for signatures
  - Computed transfer functions
    - Flat random drive signal does not result in uniform excitation, but transfer functions normalize the results
    - In axis input monitor accel as reference
  - SignalStar gives the user control over the pretest drive signal
    - Number of averages (indirectly controls duration)
    - Shaped pretest
      - Define breakpoints to set relative amplitudes
    - Burst random – need to experiment with this one
- This technique has the benefit of a built in signature in every test run

Example Response Signature Overlay



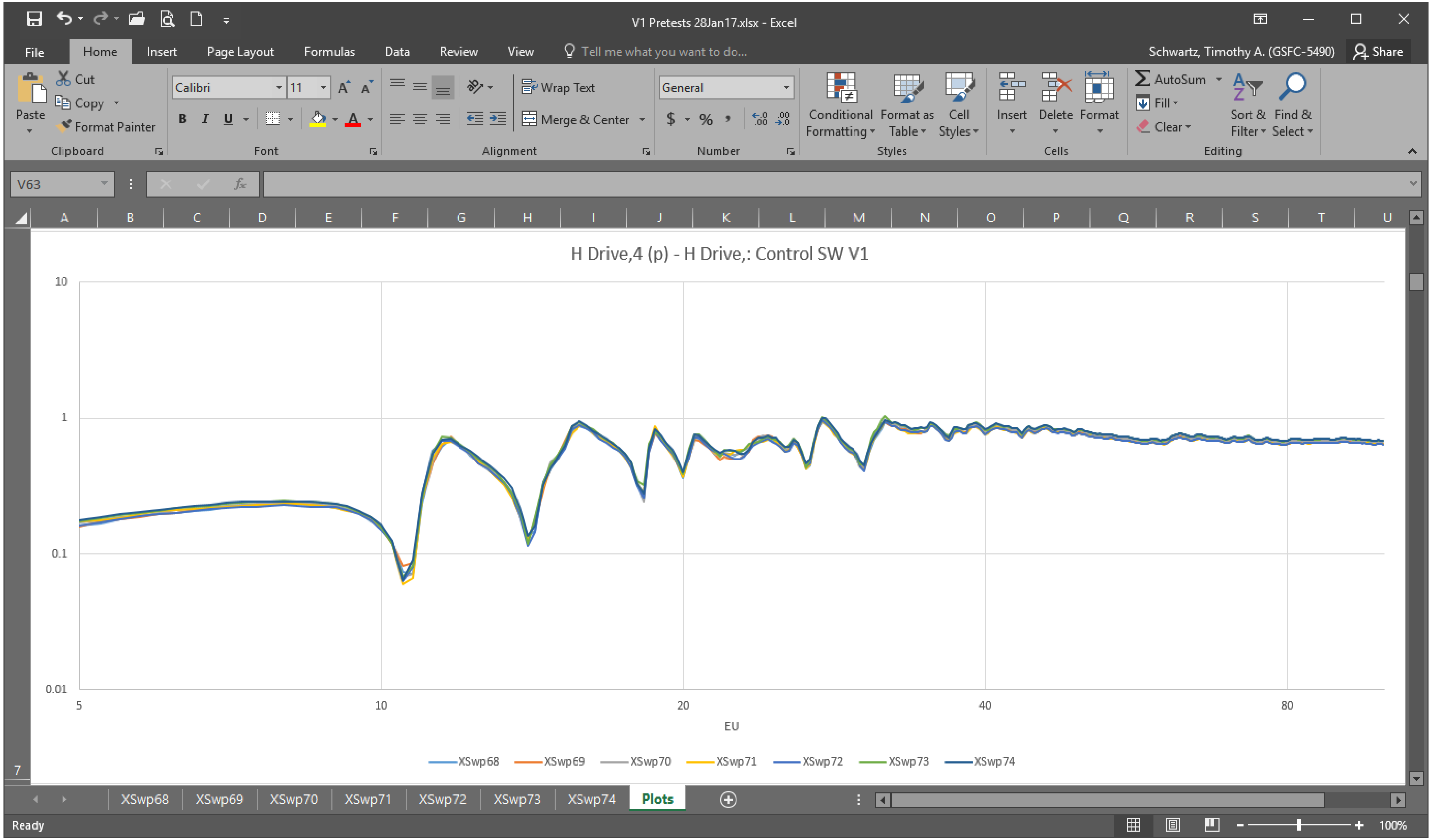
Data Source	Units	Max Amp / Freq	Min Amp / Freq
(1) MP_V1Swp90.mat	lb	1.47e+05 / 10.63	145 / 55.63
(2) MP_V1Swp88.mat	lb	1.27e+05 / 10.63	115 / 55.63

NASA Goddard Space Flight Center
Applied Engineering and Technology Directorate
Test & Integration Vibration Test Facilities

Pre/Post Signature

- The pretest results were also used to verify facility and test article health in a more limited fashion after the execution of every pretest.
- For the 32 channels on the controller, transfer functions relative to the drive are already computed in SignalStar.
- This data was copied to an excel file and pasted into its own sheet.
- A macro was written to generate a new sheet with a chart for each channel overlaying data for all the runs stored in the current file.
- In this way all channels can be check for trends against the previous 5 to 10 runs.
- The process is fast enough that it can be completed for every run prior to executing the sweep.
- Sensitive to changes in the gain knob setting

Example Controller Pretest Overlay



Questions