Section 19
ISS Payload Microgravity Control & Disturbance Predictions

Microgravity Environment Interpretation Tutorial
NASA Glenn Research Center
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Presentation Agenda

- Rack Vibration Isolation Approaches
- Payload Microgravity Control Requirements
- Microgravity Control Verification Process
- Disturbance Control & Predictions
- Contact List

Acronyms

- ARIS – Active Rack Isolation System
- ATCU – Air Thermal Control Unit
- CIR – Combustion Integrated Rack
- EPCU – Electrical Power Control Unit
- EXPPCS – EXPeriment Physics of Colloids in Space
- EXPRESS – EXpedite the PRocessing of Experiments to Space Station
- FEA – Finite Element Analysis
- FCF – Fluids Combustion Facility
- FIR – Fluids Integrated Rack
- FSAP – Fluid Science Avionics Package
- HHR – Habitat Holding Rack
- ICE – ISS Characterization Experiment
- IOP – Input/Output Processor
- IPSU – Image Processing Storage Unit
- ISPR – International Standard Payload Rack
- LMM – Light Microscopy Module
- MAC – Microgravity Analysis Cycle
- MAMS – Microgravity Acceleration Measurement System
- MDCA – Multi-Droplet Combustion Apparatus
- MDSU – Mass Data Storage Unit
- MEL –Microgravity Emissions Laboratory
- MIPT – Microgravity Integrated Product Team
- MSRR – Material Science Resource Rack
- NIRA – Non-Isolated Rack Assessment
- PaRIS – Passive Rack Isolation System
- REU – Remote Electronics Unit
- RTS – Remote Triaxial System
- RUP – Rack Utility Panel
- SAMS – Space Acceleration Measurement System
- SE – Sensor Enclosure
- SEA – Statistical Energy Analysis
- SM – Service Module
- SRED – Science Requirement Envelope Document

Microgravity Control Team Background

- **FCF CIR and FIR Microgravity Predictive Analyses**
- **Developing FEA Predictive Models**
- **Involved with FCF ATCU Design**
- **Involved with MEL Testing of FCF Disturbers**
- **Working with Boeing on ARIS and PaRIS**
- **EXPPCS Microgravity Requirement Assessment for EXPRESS Rack Verifications**
- **Provided Assistance to NIRA 2003 Effort at GRC**
- **ISS Microgravity Predictive Modeling with MAC**

ISS Rack Vibration Isolation Approaches

Active Rack Isolation System (ARIS)

- Active Rack Isolation Bandwidth ~ 0.01 to 2 Hz (Conf. Dependent)
- Passive Rack Isolation Bandwidth ~ 2 Hz & Up (Conf. Dependent)
- Connected to ISS by 8 Pushrods and Conf. Dependent Umbilicals
- Use of Isolation Plate Attached to US Lab Structure
- Use of 6 Snubbers & Snubber Cups
- Foam Inserts for Front 4 Snubbers Available for Passive Isolation
- Alignment Guides Used to Lock Down Rack at Front 4 Snubbers
- Programmable Controller
- Actuates Rack by Responding to Sensed Position and Accelerations
- Currently Working in EXPRESS Rack Nos. 2 & 3 in U.S. Lab Module
- Scheduled for 7 ISPR's (4 EXPRESS Racks, FIR, MSRR, & TBD)

ARIS Overview Design

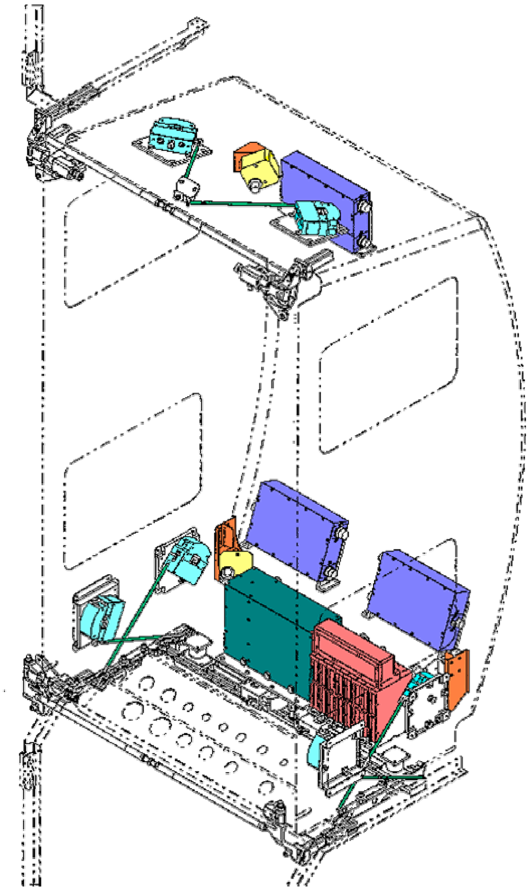
ARIS Controller (Control & input/output): Decoupling implemented in controller allows freedom to place actuators and sensors. Payloads have extensive command, data acquisition, and control options.

3 Remote Electronic Units : Programmable analog filters & gains & 16 bit analog-to-digital converters.

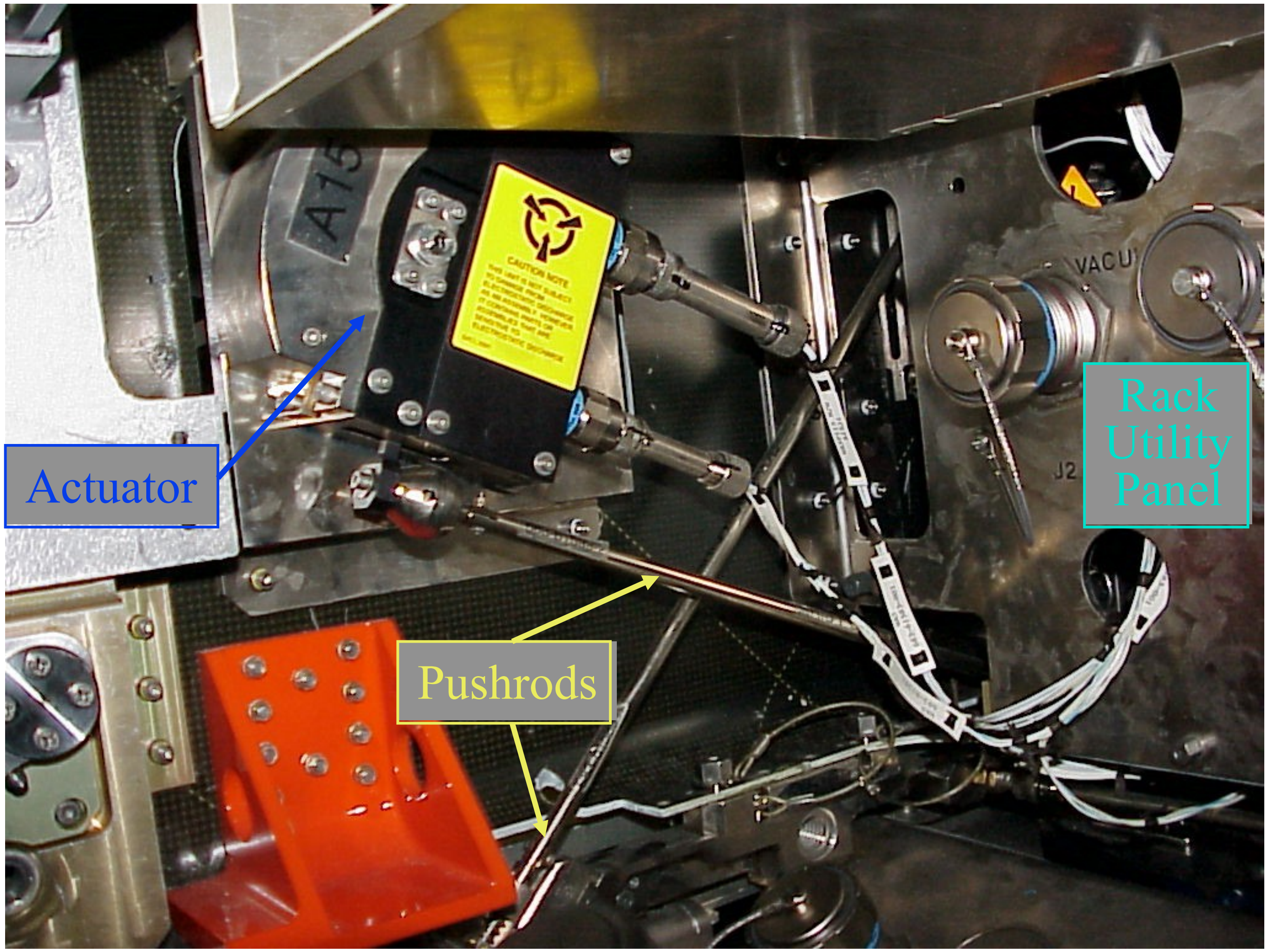
3 Tri-axial Accelerometer Heads : Built small to fit in rack corners

1 Actuator Driver : Pulse width modulation used to reduce power consumption

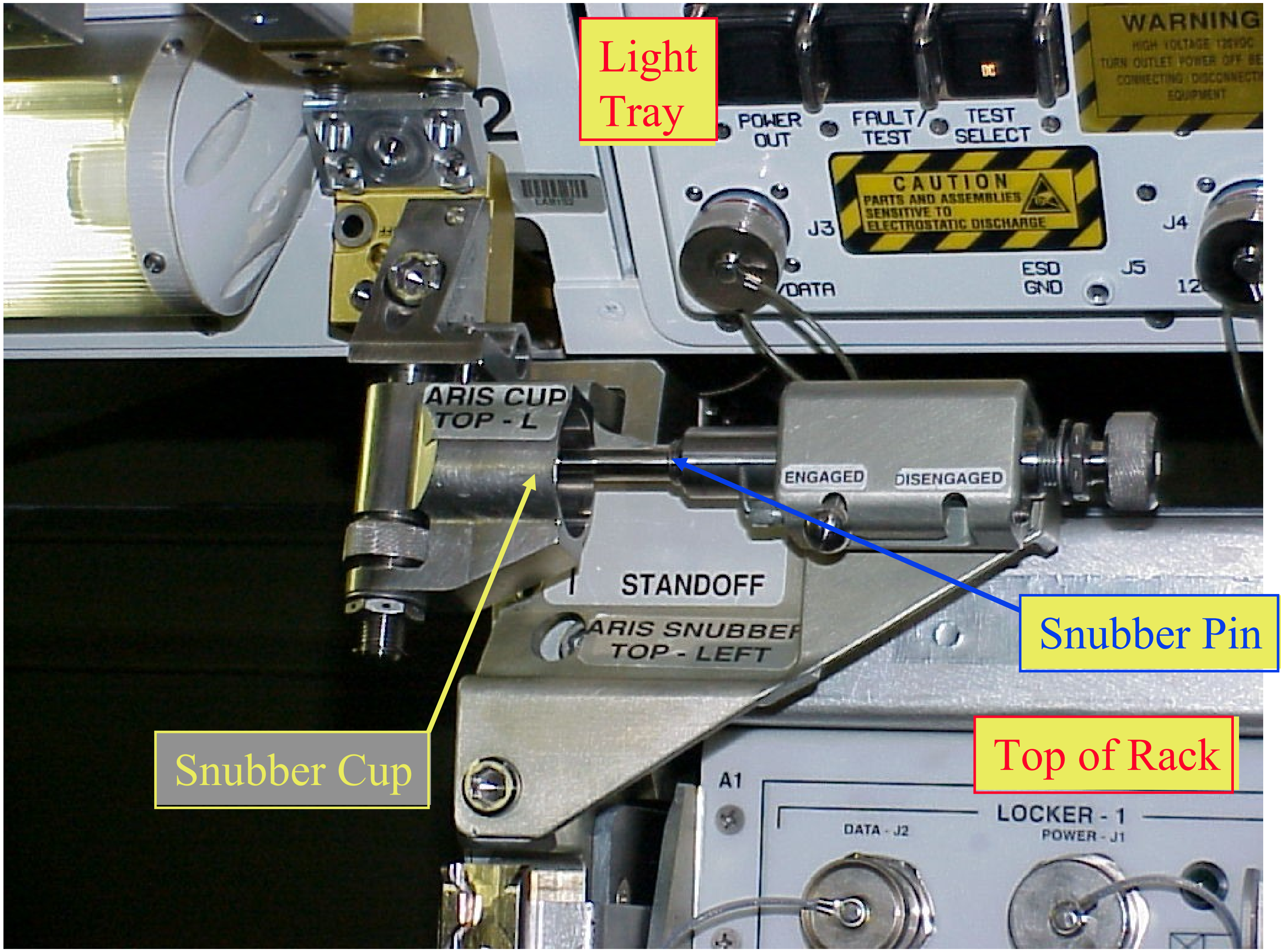
8 Actuators : Voice coil rotary actuator used to reduce profile and power consumption.



ARIS Actuator & Pushrods



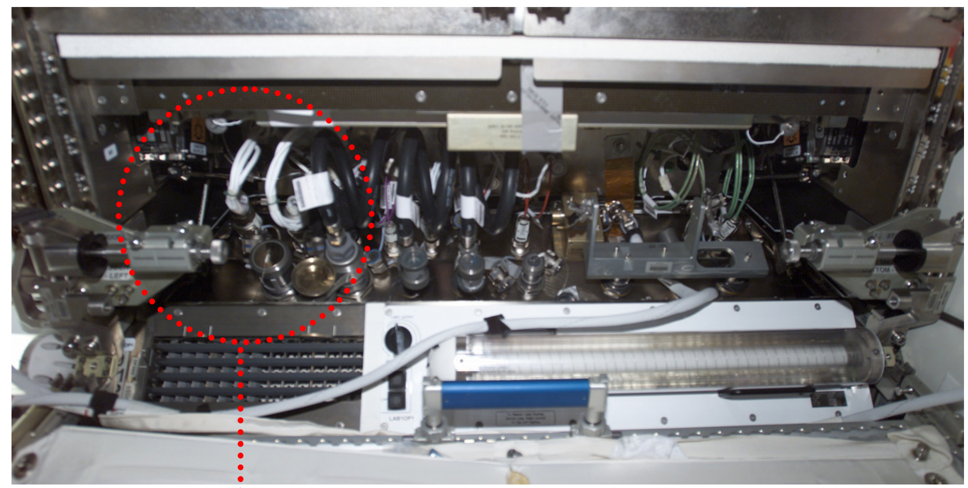
ARIS Snubber & Cup



Umbilicals

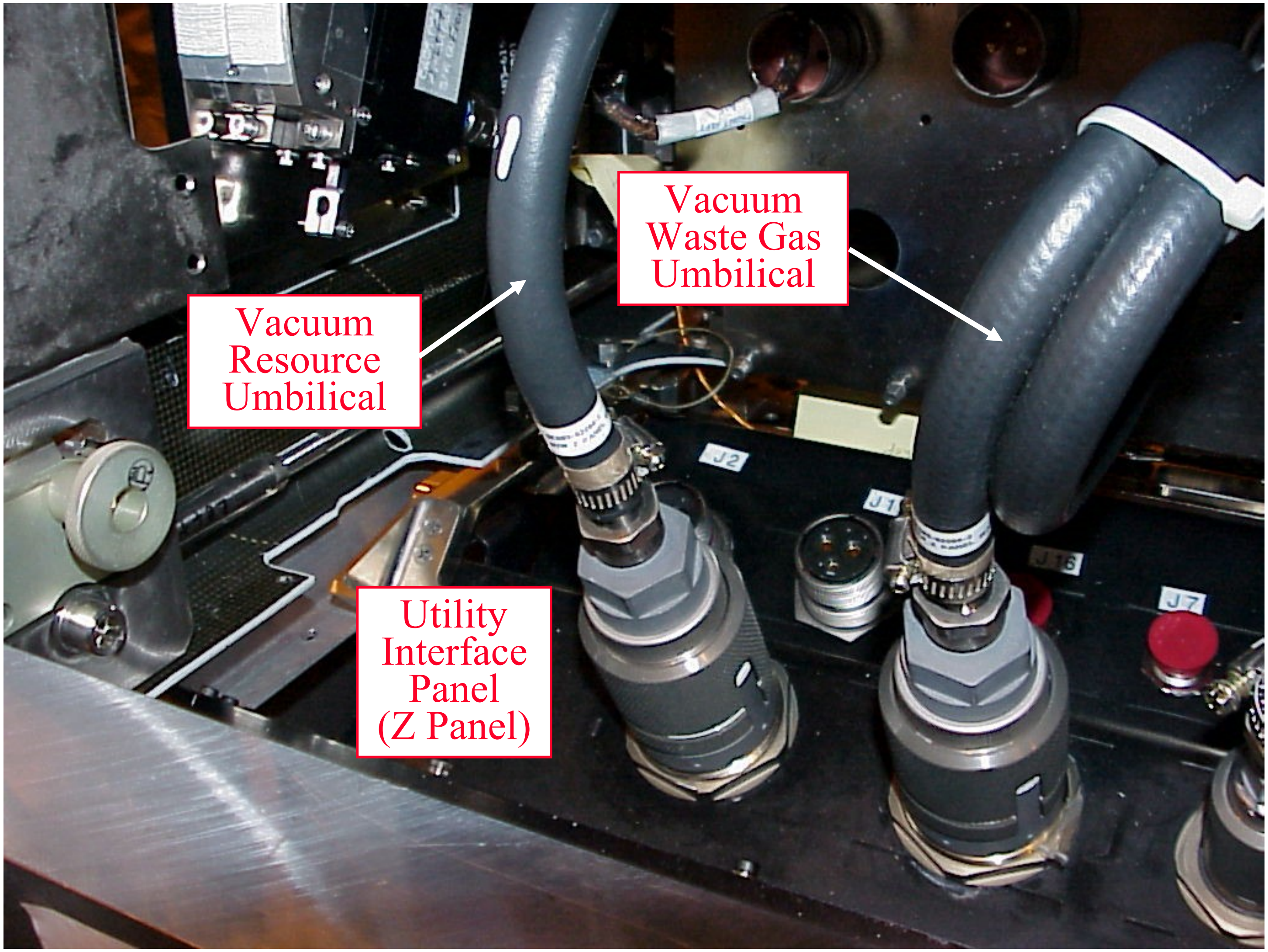
13 Standard ARIS Umbilicals Integrate Rack with ISS Utilities:

- Used by both ARIS and PaRIS Racks
- Power (J1 and J2)
- GN2 Gas
- Vacuum/Waste Exhaust
- Moderate Temp. H_2O Supply & Return
- Diagnostics
- Data
- Communications
- 14th Umbilical – Vacuum Resource (FIR)
- Umbilical Stiffness Characterization Completed Jan. 2004 (Boeing)



Side Effects: Umbilical Stiffness and Dynamics Transmit ISS Vibratory Loads into Rack

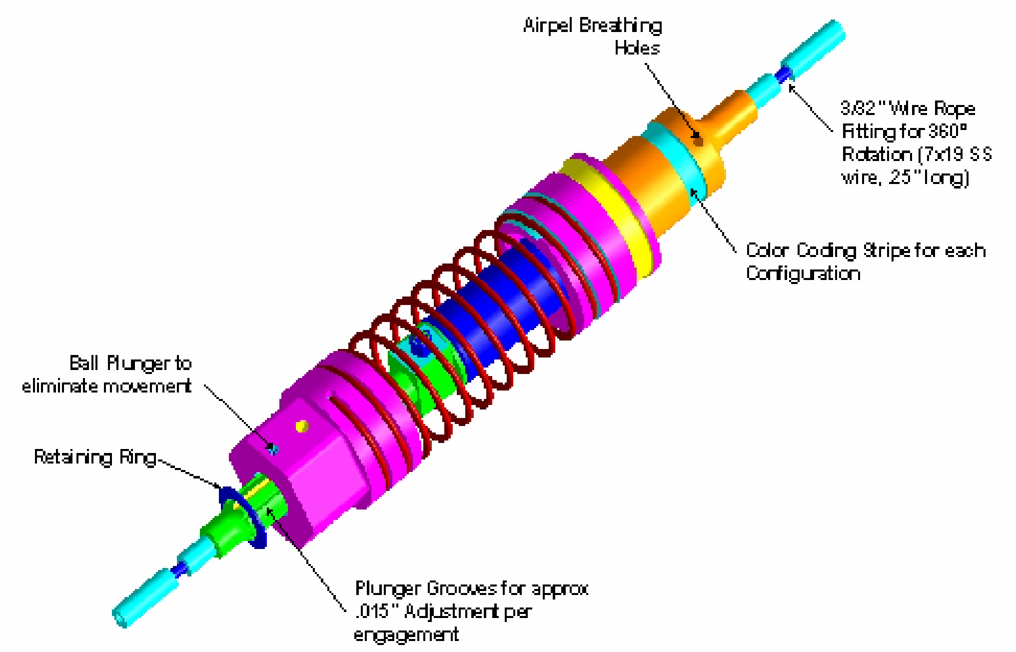
Vacuum Umbilicals on Z Panel



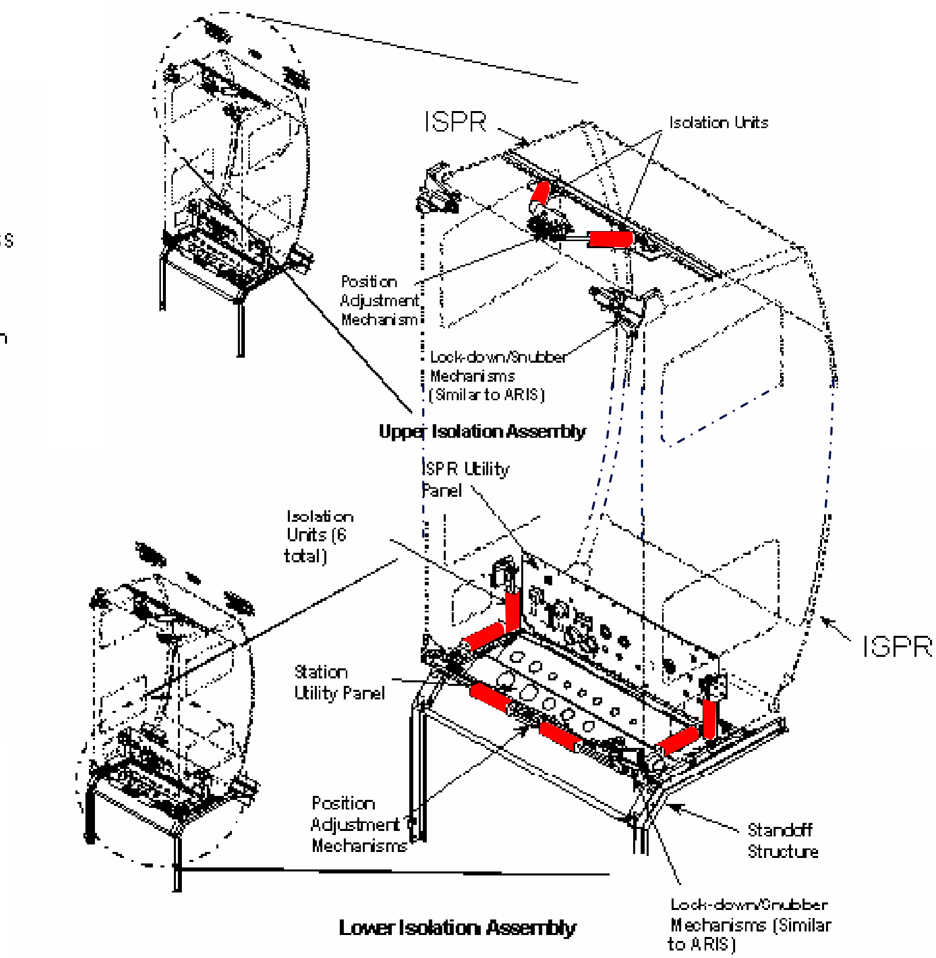
Passive Rack Isolation System (PaRIS)

- **Utilizes Some Existing ARIS Hardware**
- **Passive Rack Isolation Bandwidth ~ 0.5 Hz & Up (Conf. Dependent)**
- **Connected to ISS by 8 Spring/Damper Isolators & Conf. Dependent Umbilicals**
- **Use of Isolation Plate Attached to US Lab Structure**
- **Use of 6 Snubbers & Snubber Cups**
- **Alignment Guides Used to Lock Down Rack**
- **Scheduled for 3 ISPR's (two for HHR & one for CIR)**

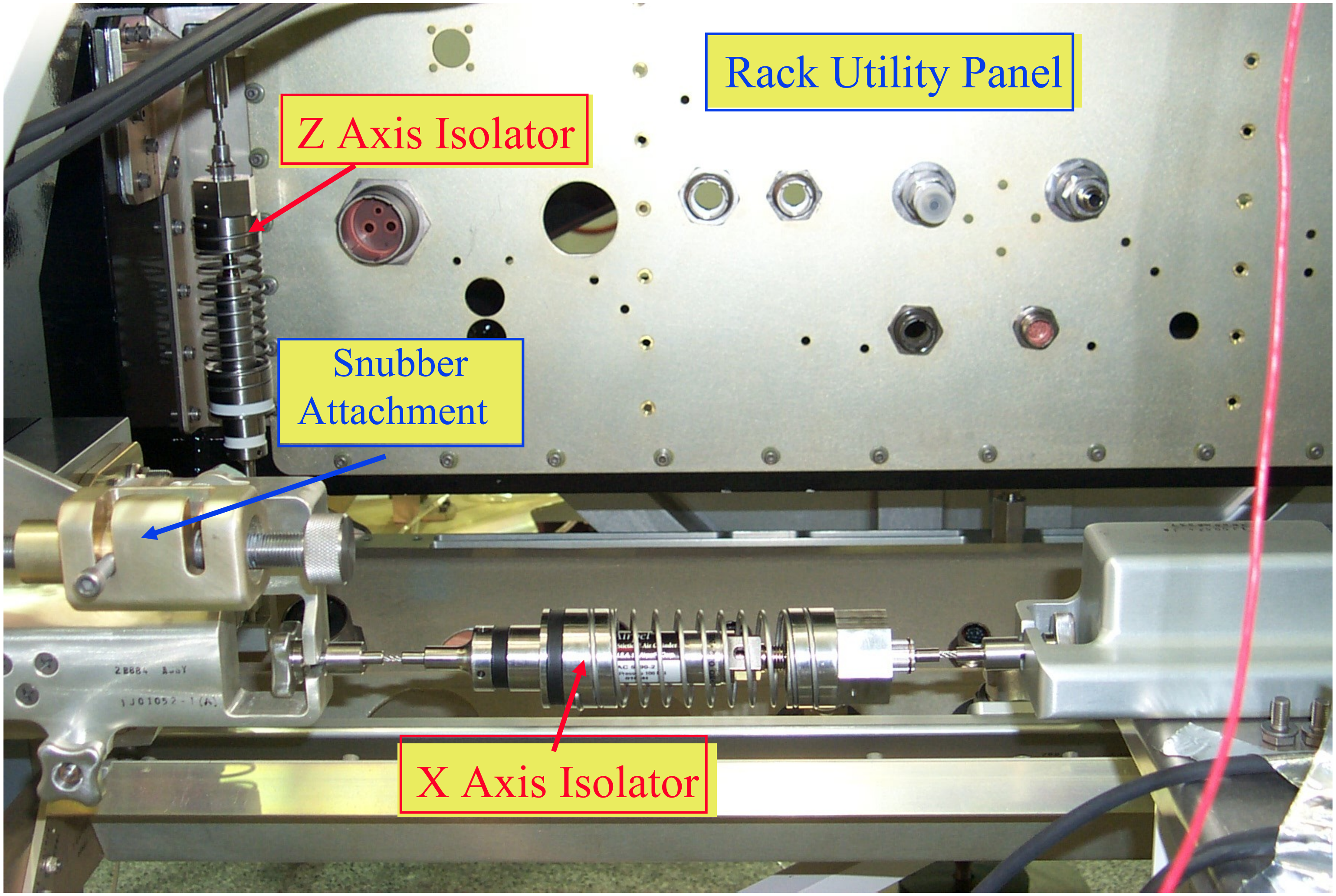
PaRIS Overview Design



PaRIS Isolator



PaRIS X & Z Axis Isolators



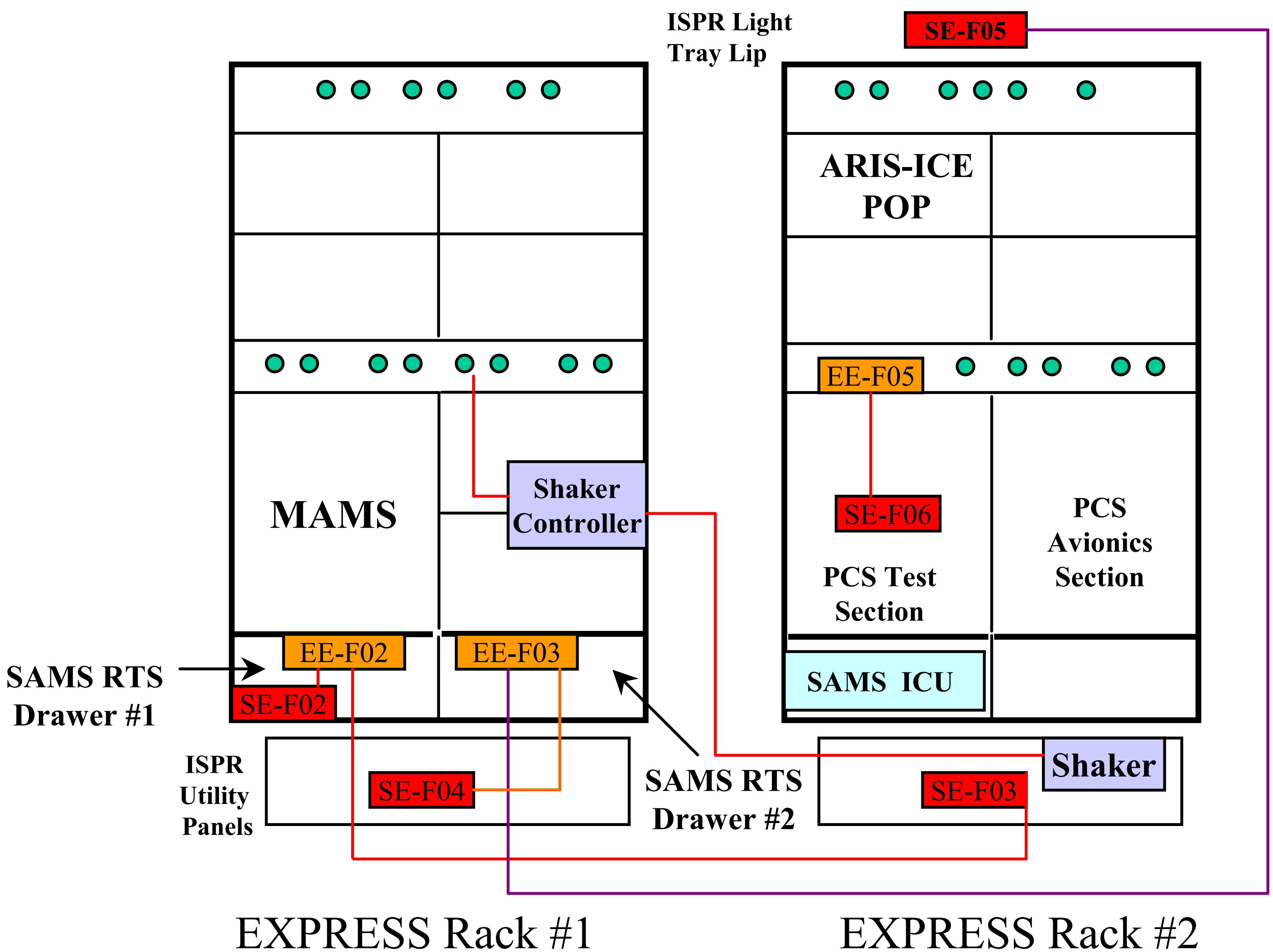
Microgravity Rack Barrier

- **EXPRESS Rack 2 in US Lab Module**
- **Used for Microgravity Racks**
- **Attached to Rack during Initial Set-up**
  - **Protects from Crew Induced Loads**

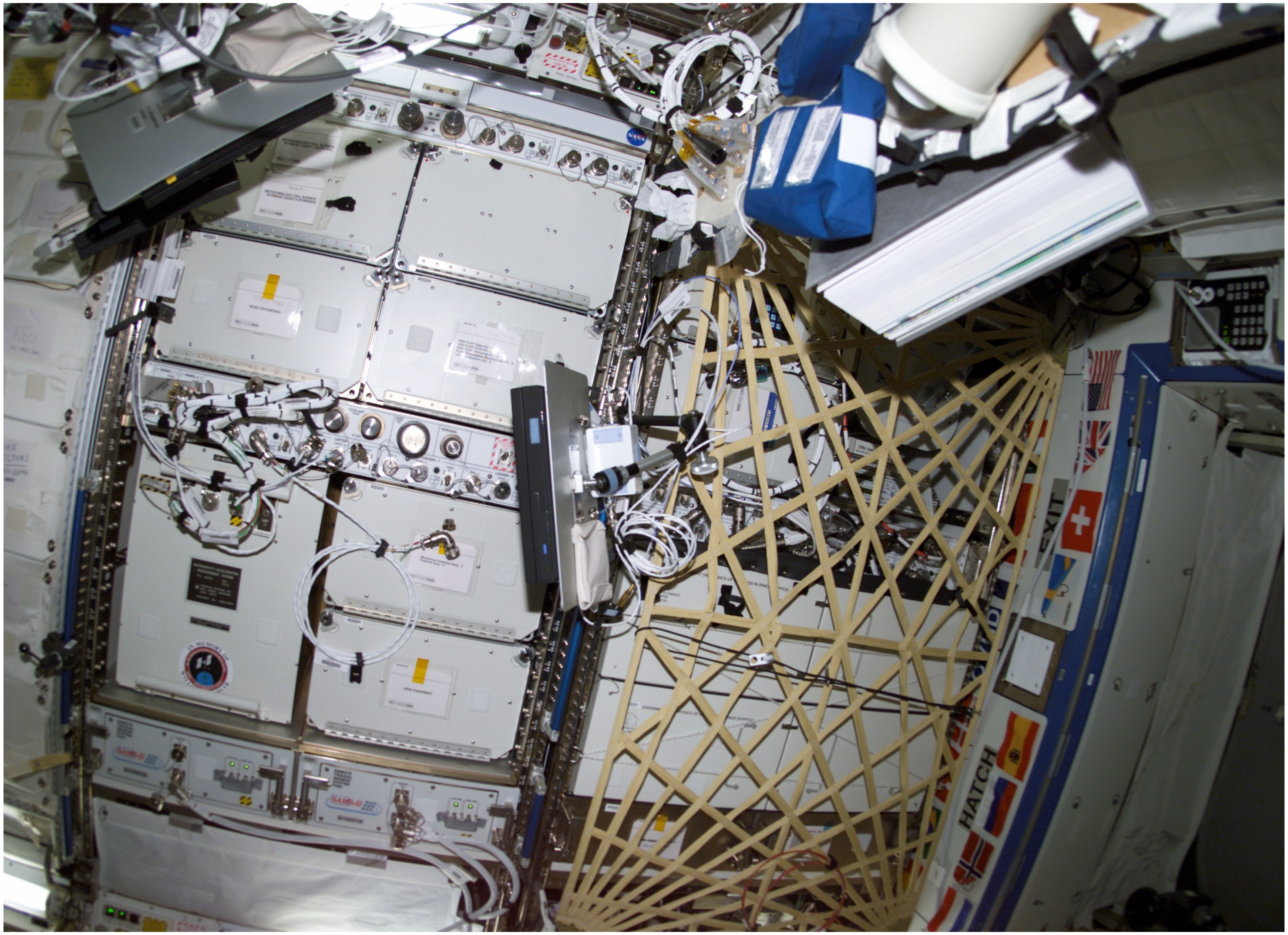
Evaluation of ARIS Performance Based on SAMS

- **Five SAMS SE's Utilized for ARIS-ICE Assessment**
  - **SE-F02 in RTS Drawer #1 in EXPRESS Rack #1 (Non-ARIS)**
  - **SE-F03 on US Lab Z-Panel below EXPRESS Rack #2**
  - **SE-F04 on US Lab Z-Panel below EXPRESS Rack #1**
  - **SE-F05 on US Lab Light Tray above EXPRESS Rack #2**
  - **SE-F06 on EXPPCS located in EXPRESS Rack #2 (ARIS)**
- **Compare Microgravity Levels of Onboard Rack with Offboard Rack Locations**
- **Compare ARIS Rack with Non-ARIS Rack Microgravity Levels**
- **Compare Predicted Behavior with Actual Measured Behavior**

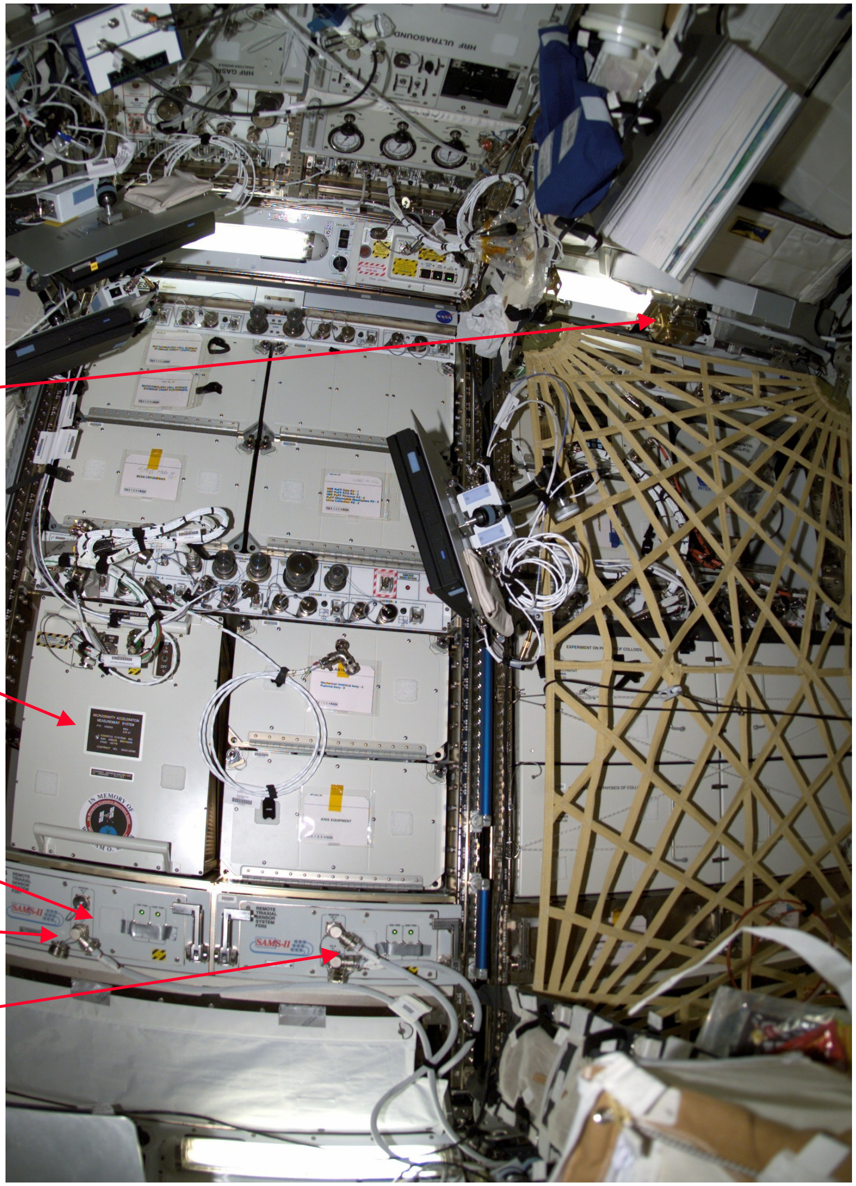
Location of SAMS Sensors during ISS Increment 2



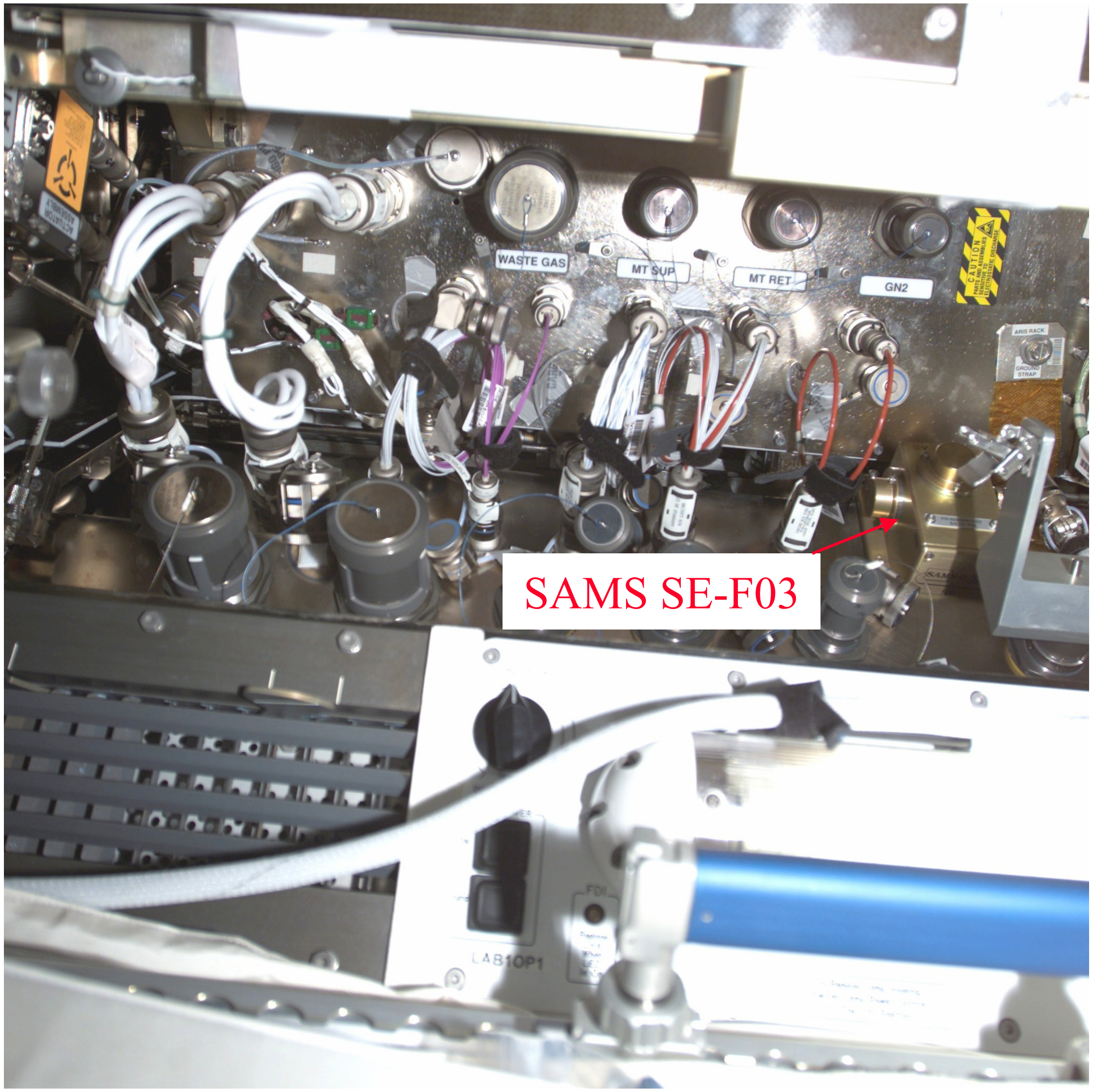
EXPRESS Racks 1 & 2 Onboard US Lab Module



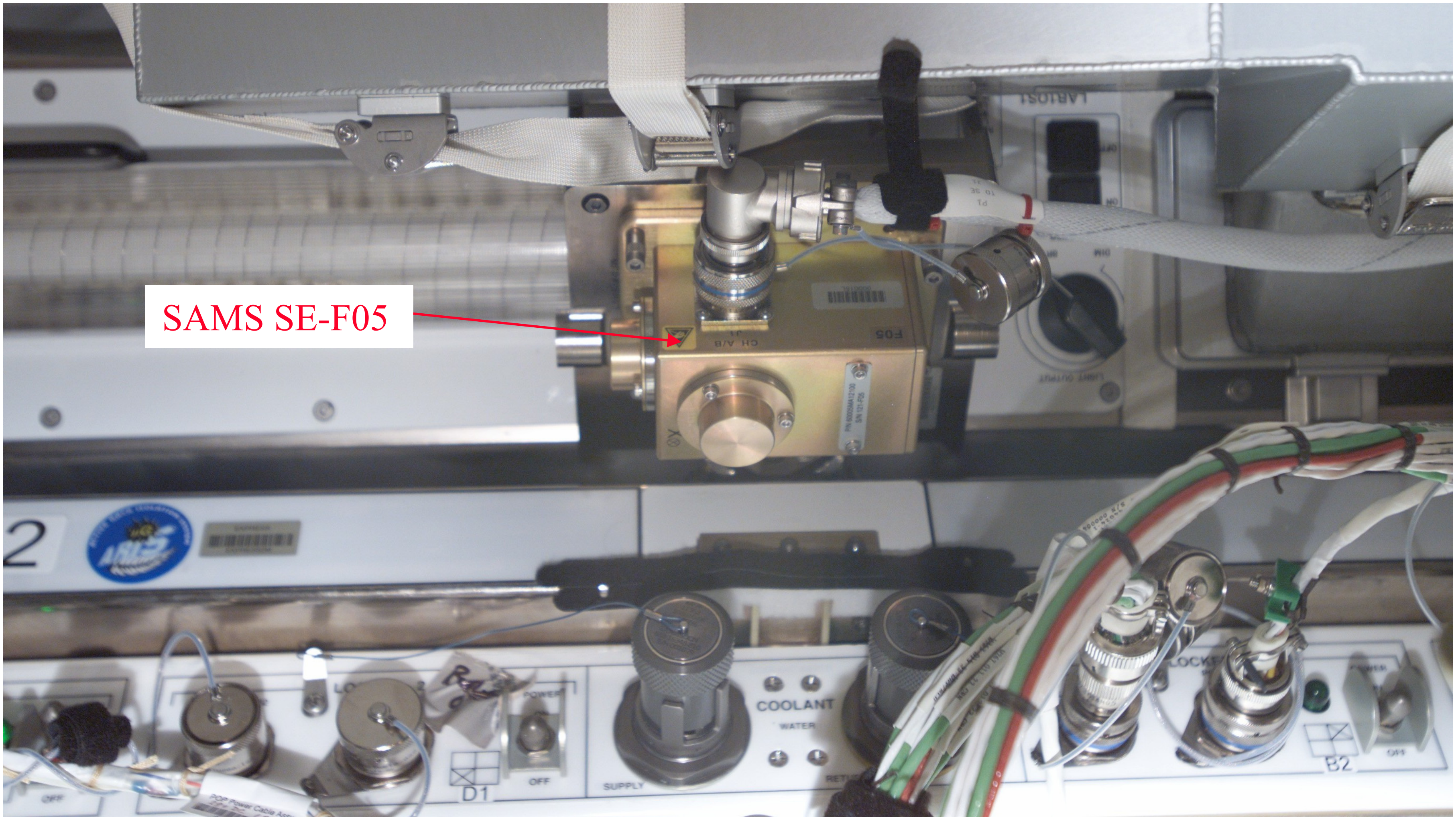
Microgravity Environment Hardware for EXPRESS Racks 1 & 2



EXPRESS Rack 2 Rack Utility Panel with Umbilicals & SAMS SE-F03

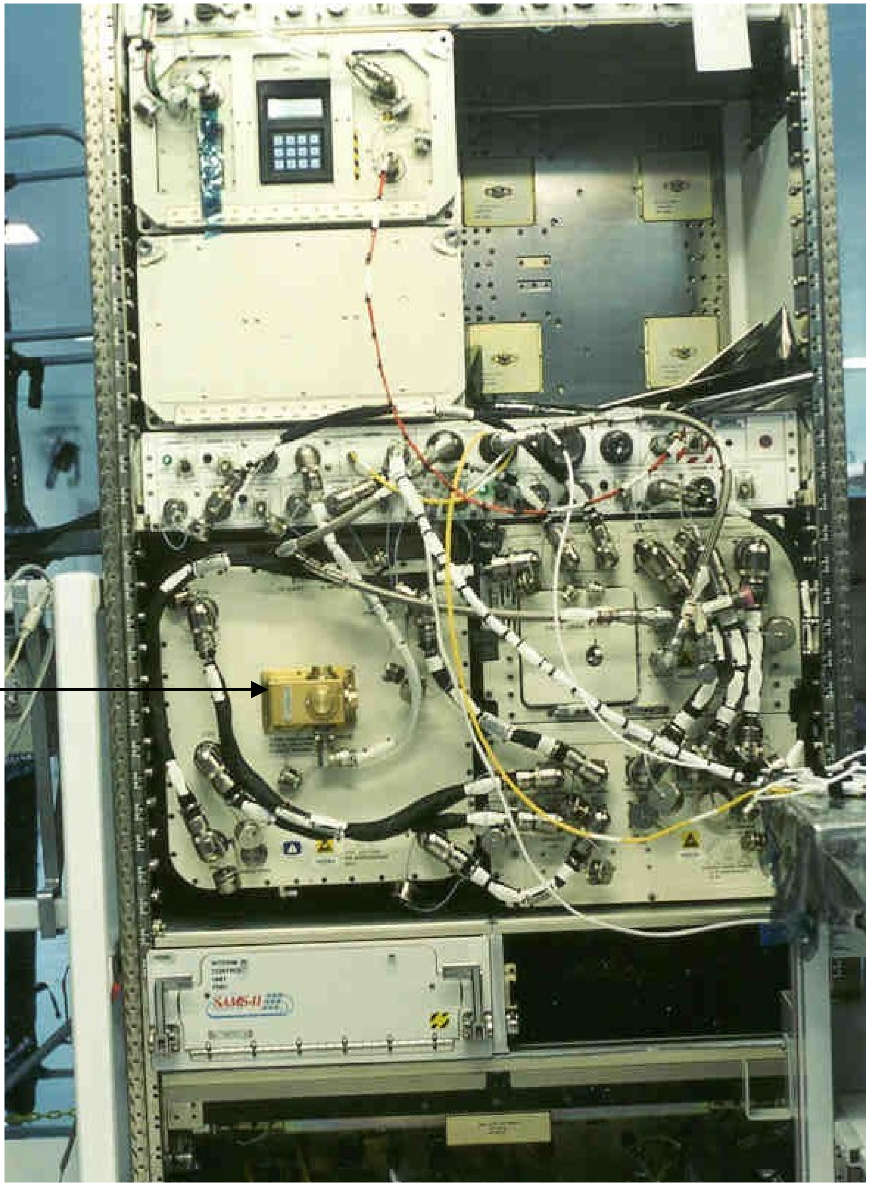


SAMS SE-F05 Above EXPRESS Rack 2

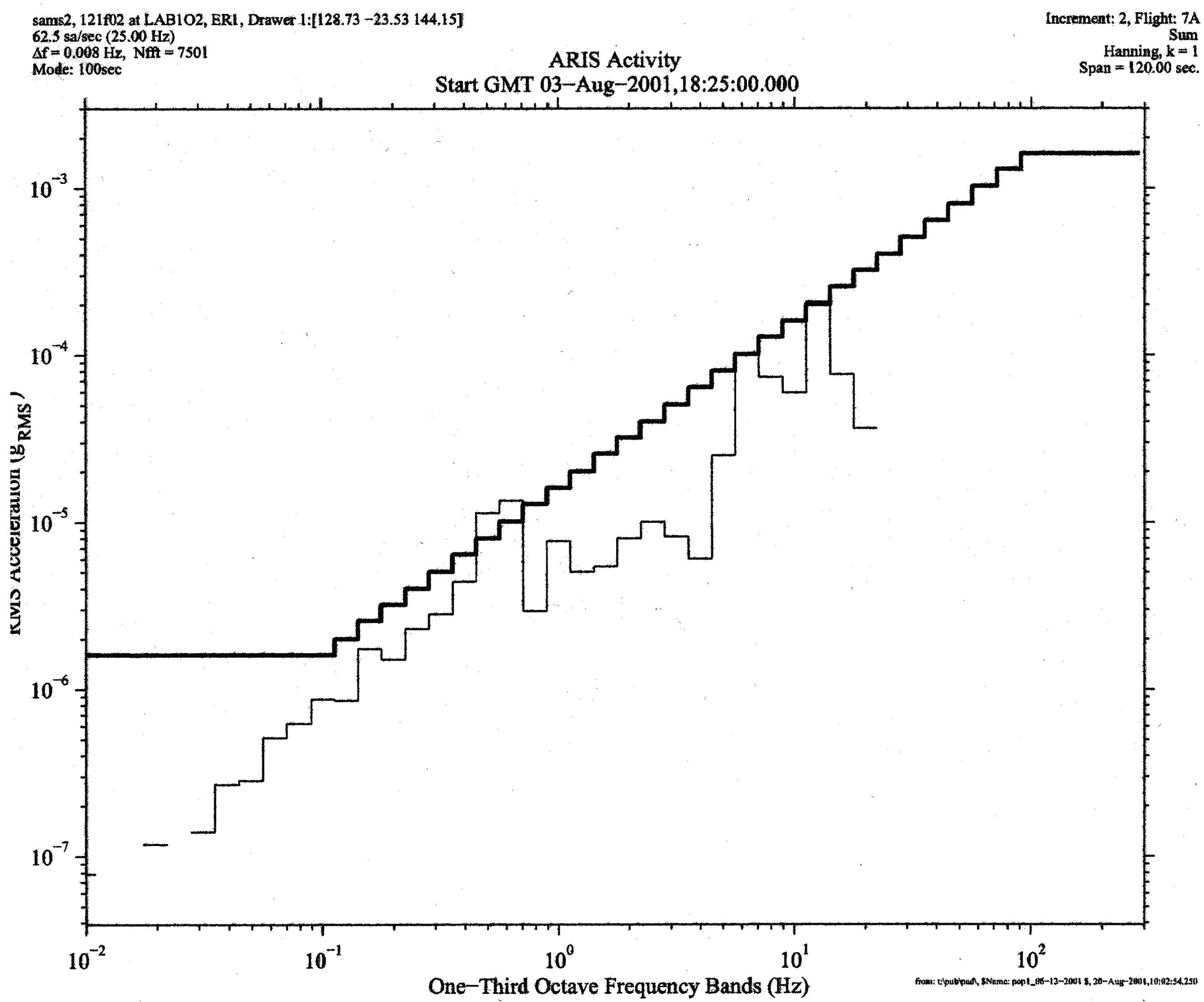


SAMS SE-F06 Mounted on EXPPCS Test Section of EXPRESS Rack 2

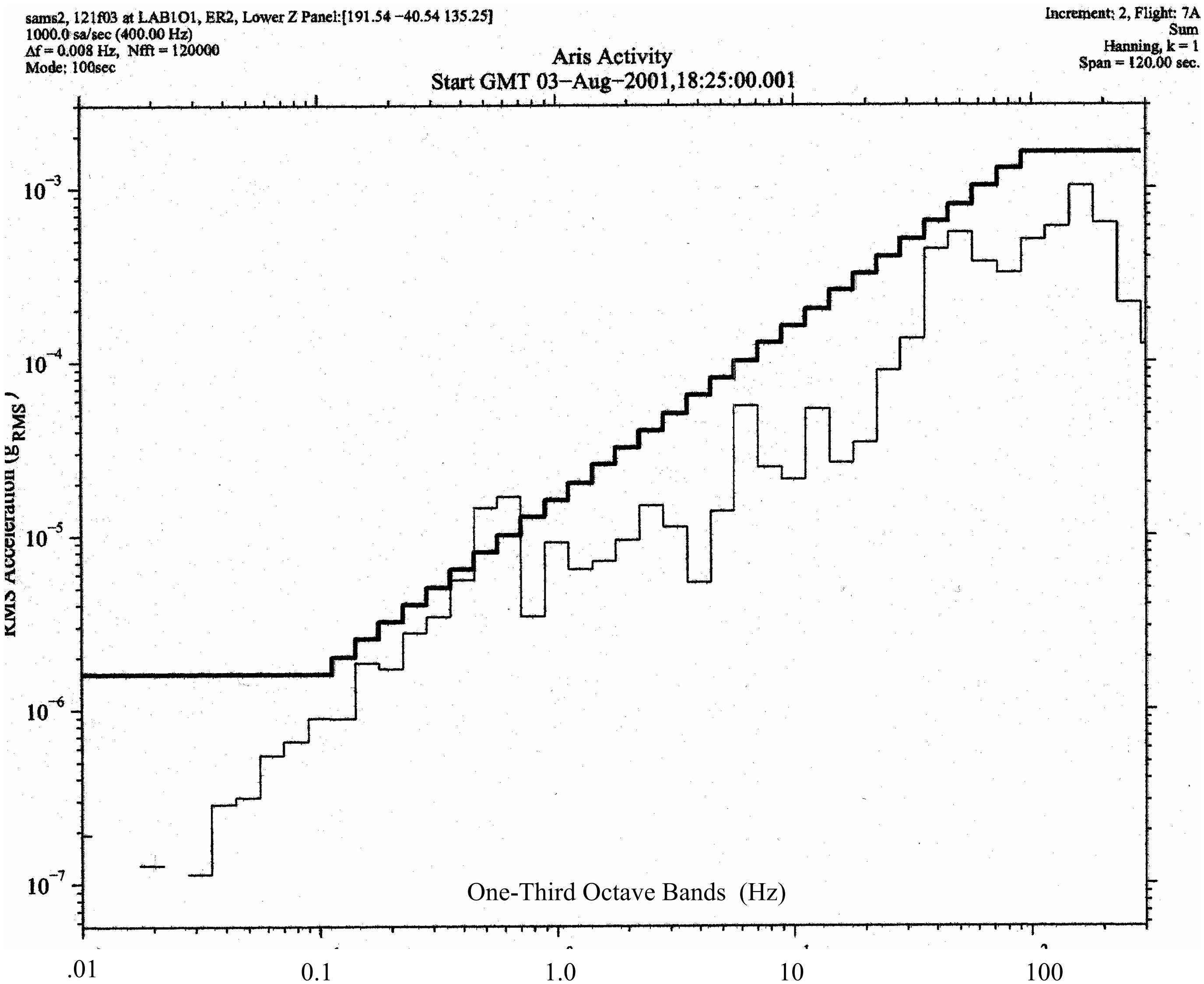
SAMS SE-F06



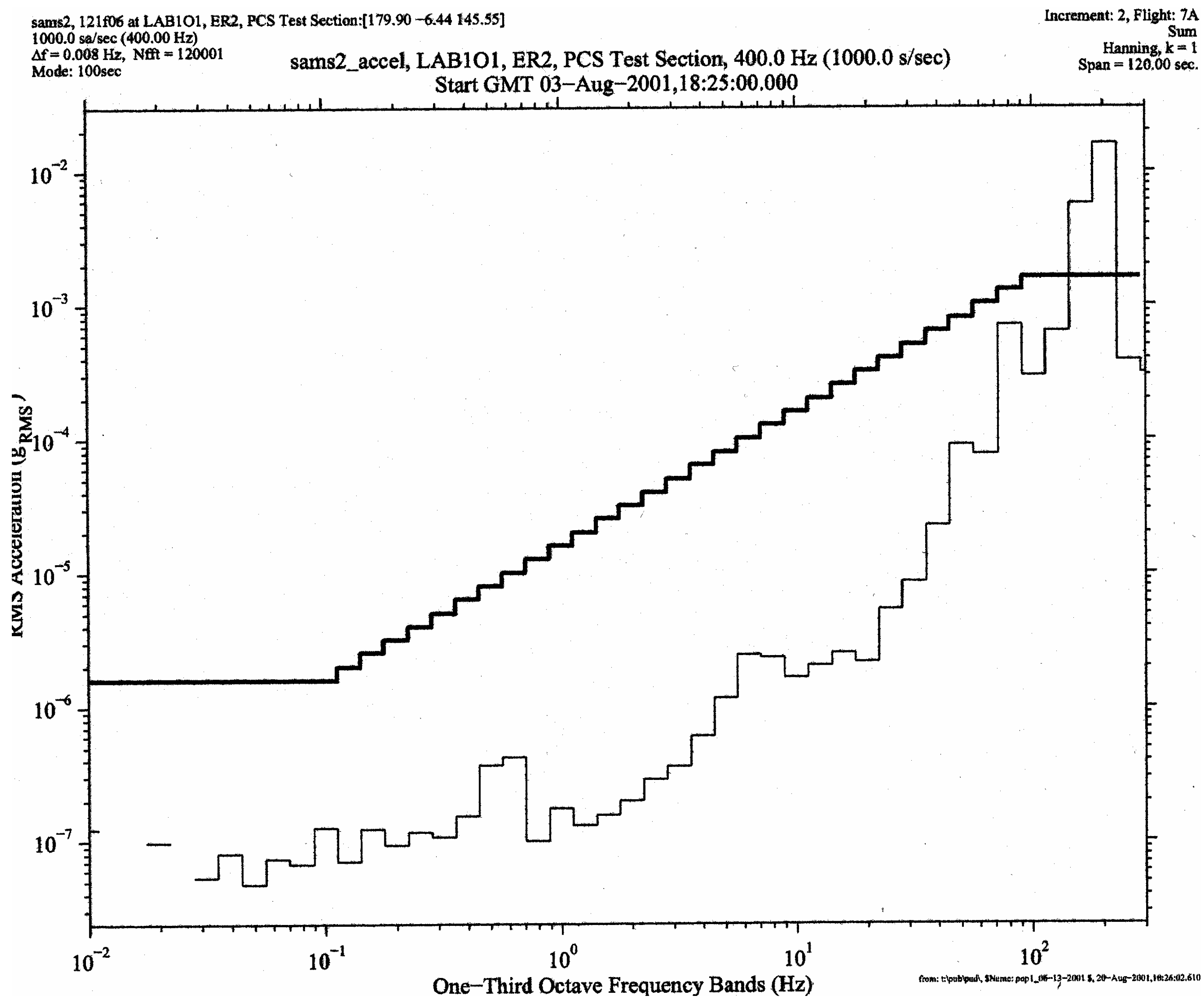
ARIS Active – EXPRESS Rack 1 (SE-F02)



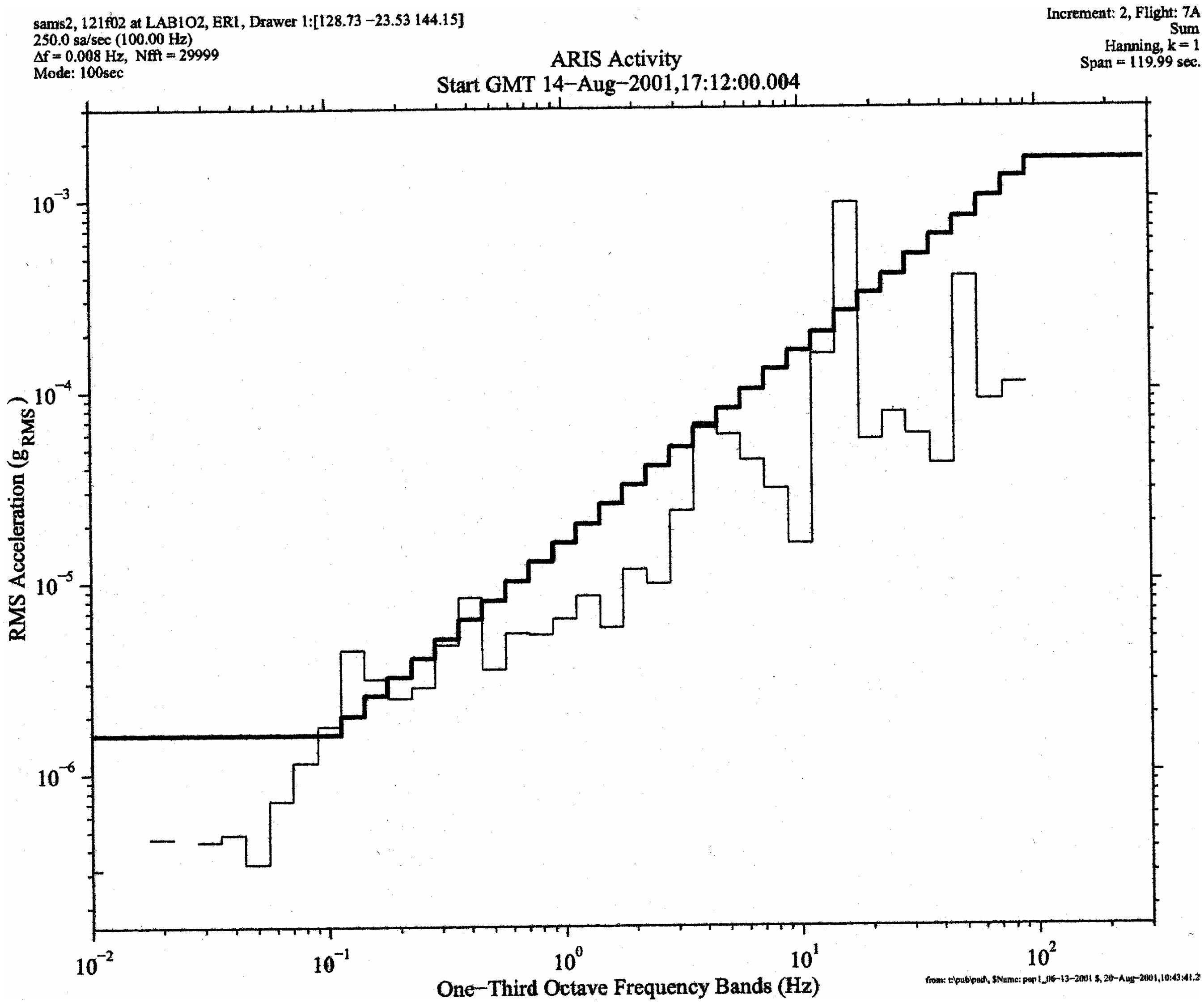
ARIS Active – Z Panel Offboard ER 2 (SE-F03)



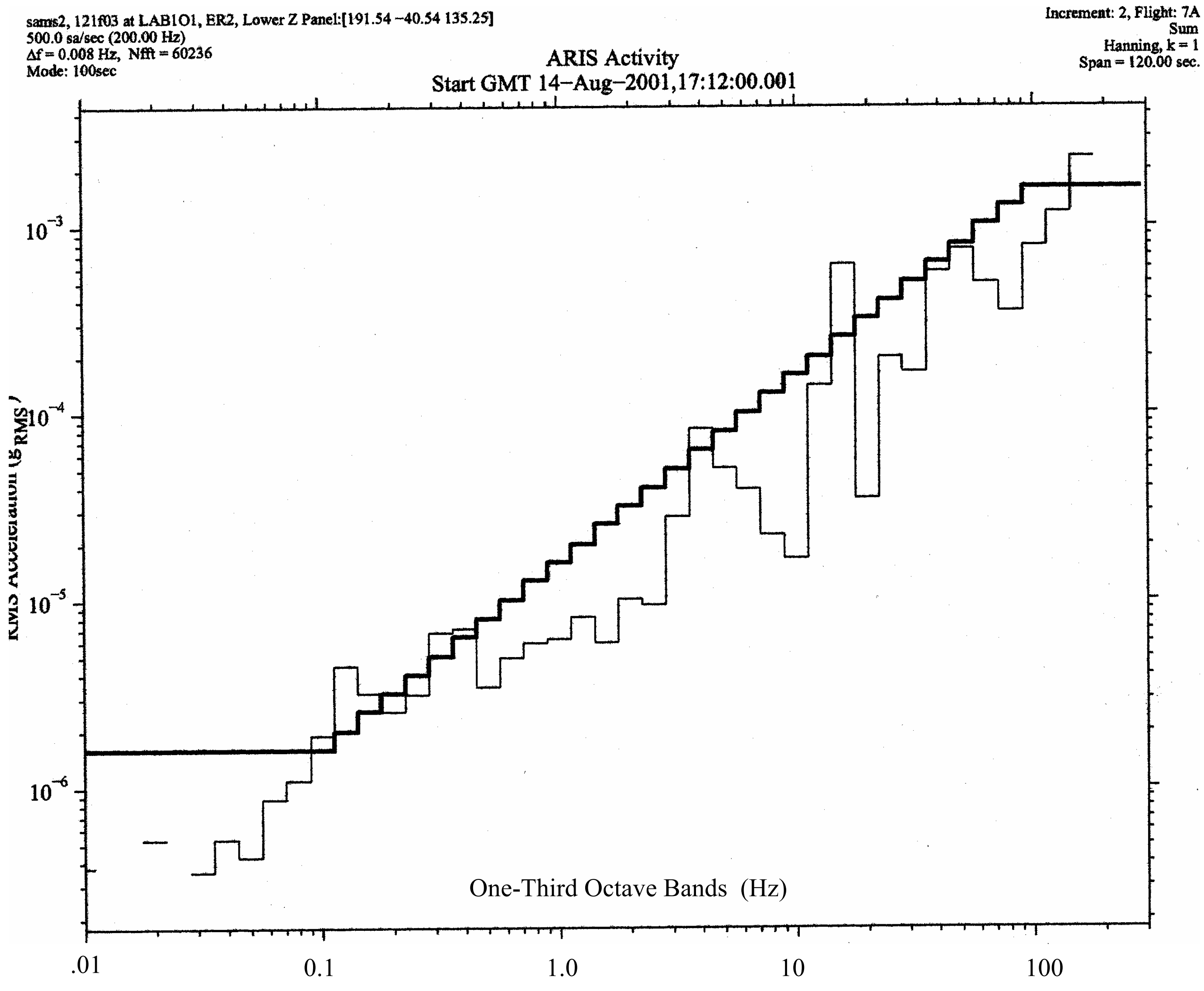
ARIS Active – EXPRESS Rack 2 (SE-F06)



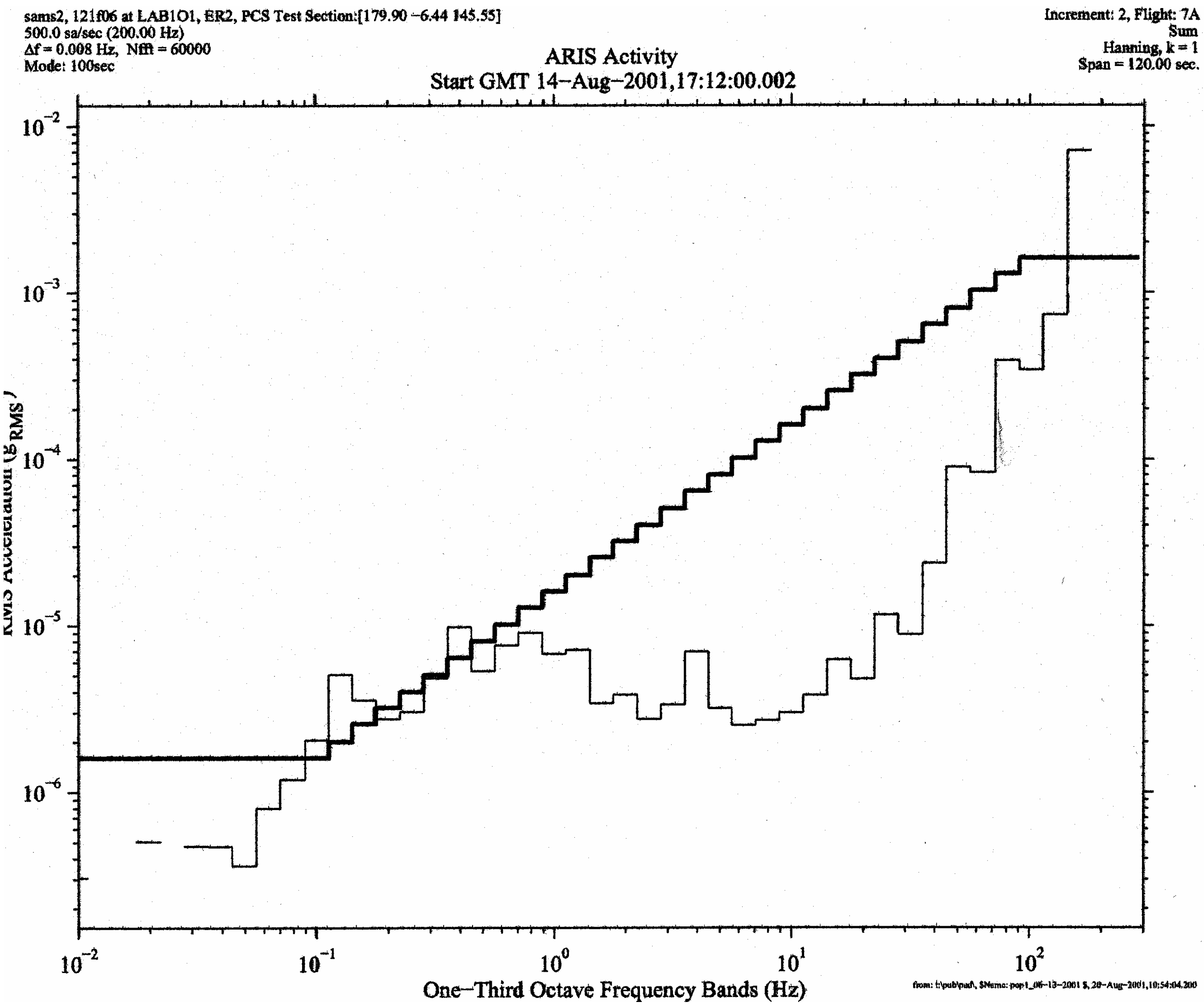
ARIS Idle – EXPRESS Rack 1 (SE-F02)



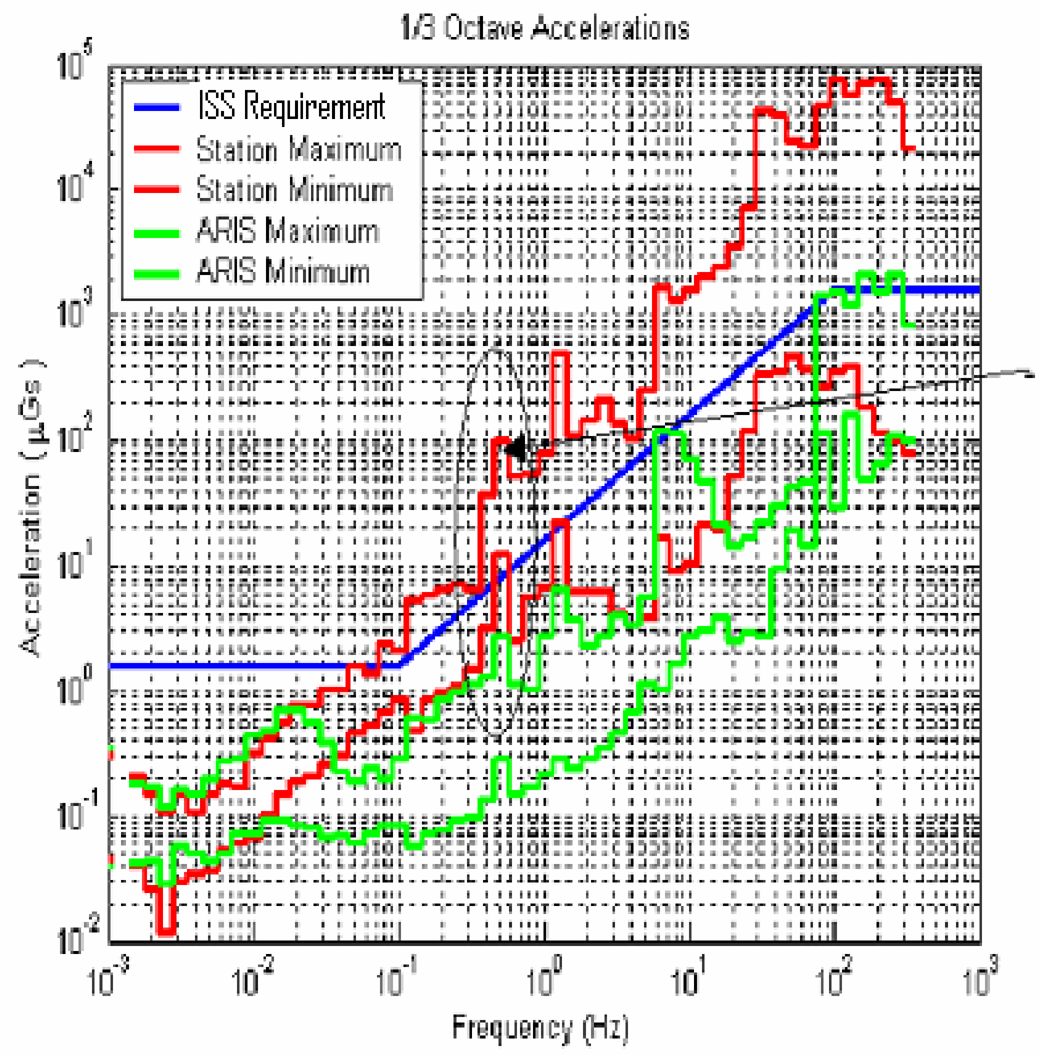
ARIS Idle – Z Panel Offboard ER 2 (SE-F03)



ARIS Idle – EXPRESS Rack 2 (SE-F06)



On-Orbit Measured ISS Acceleration Levels



ISS Payload Microgravity Control Requirements

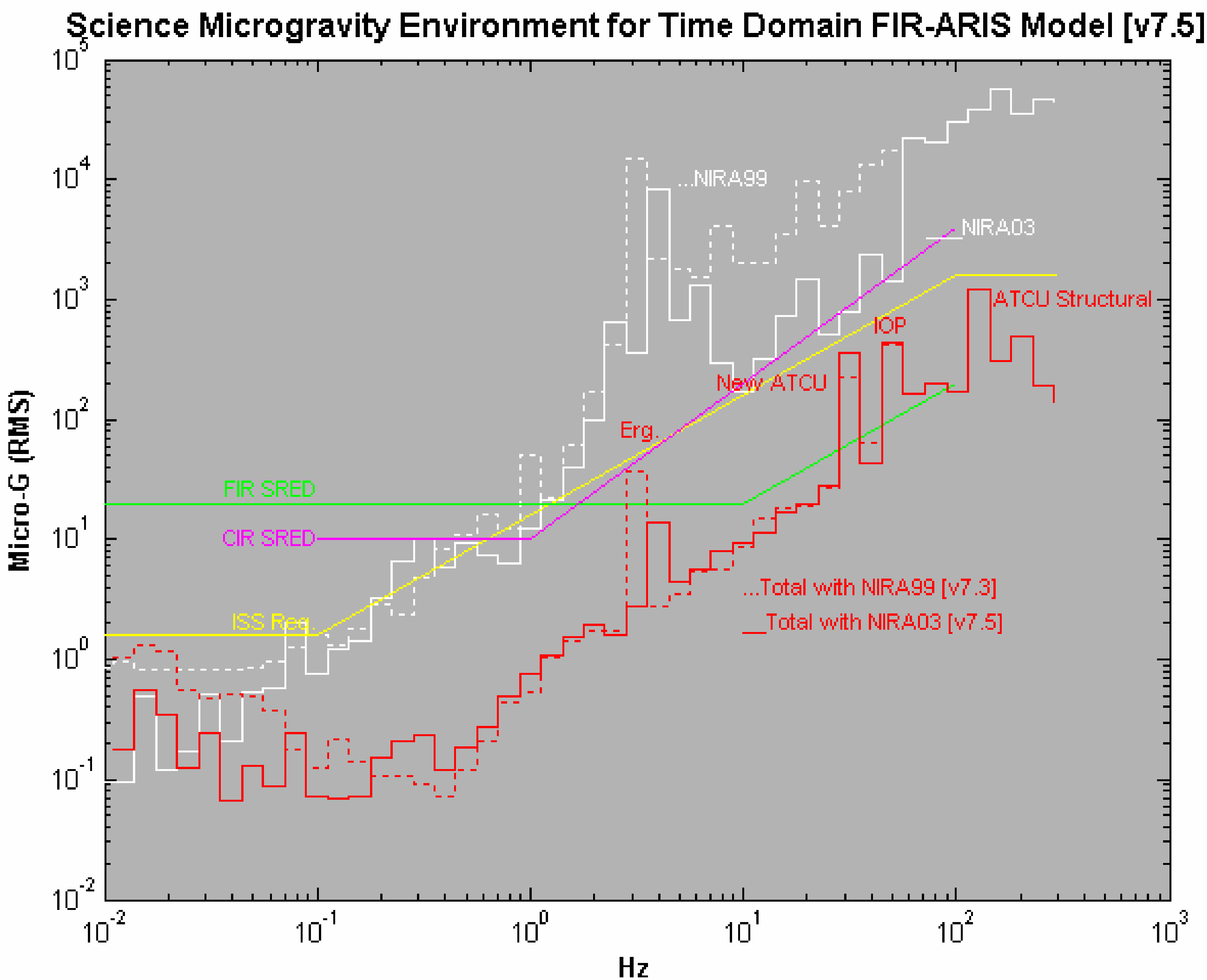
ISS Requirements

Document: <u>SSP 41000 (ISS System Specification)</u>

Responsibility: ISS Program

Requires that 50% of the internal payload volume has the following environment for at least 180 days per year:

- **Quasi-steady acceleration less than or equal to 1 micro-G magnitude, with component perpendicular to orbital acceleration less than 0.2 micro-G**
- **ISS Vibratory Spectrum Requirement, ISS Requirement (Nauman Curve), below that shown on next slide**
- **Transient acceleration less than 1000 micro-G peak per axis, and less than 10 micro-G-second impulse over any 10 second period**


Science Microgravity Environment for Time Domain FIR-ARIS Model [v7.5]
Micro-G (RMS)
Hz
...NIRA99
NIRA03
ATCU Structural
IOP
New ATCU
Erg.
FIR SRED
CIR SRED
ISS Req.
...Total with NIRA99 [v7.3]
__Total with NIRA03 [v7.5]

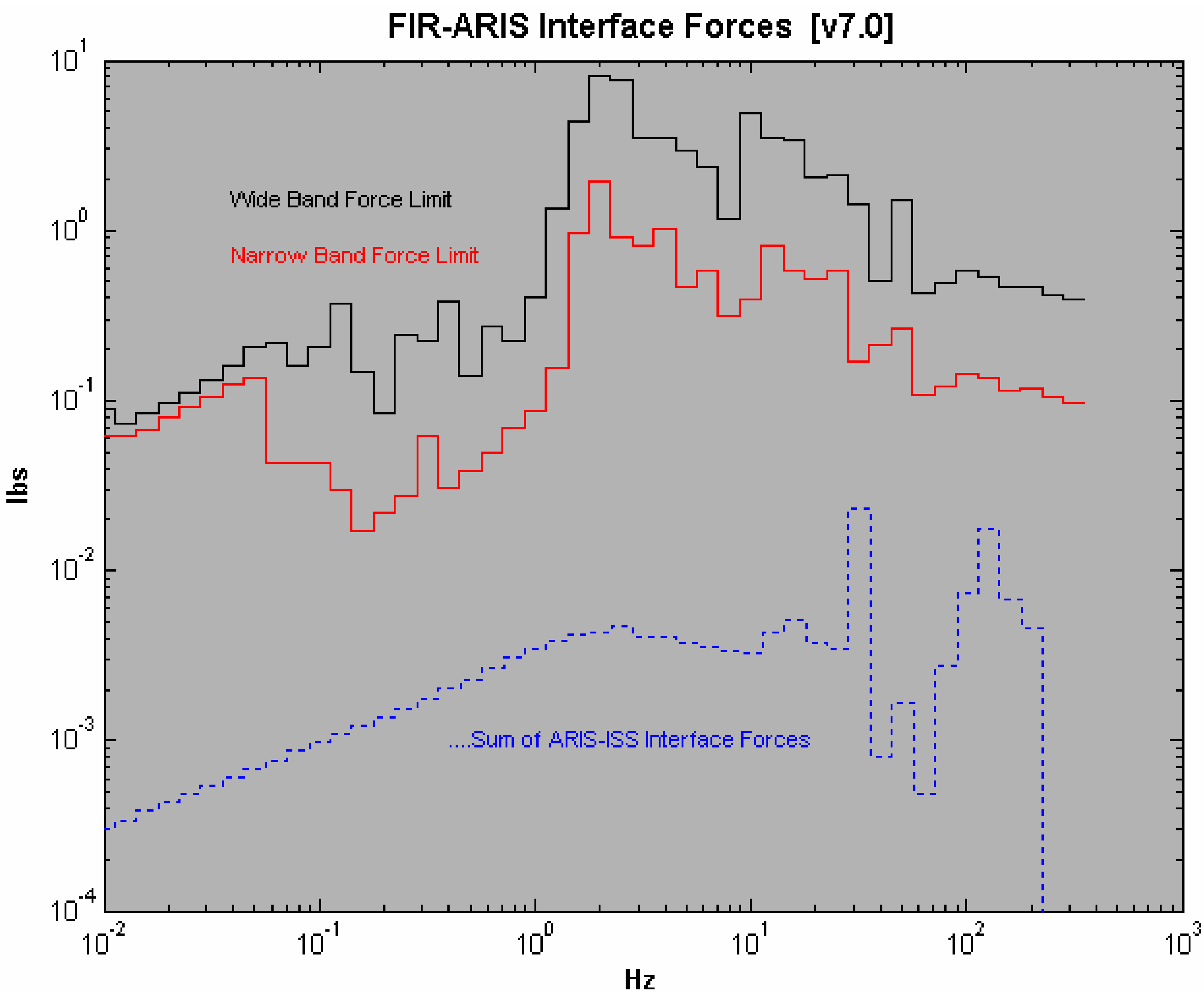
"Good Neighbor" Requirement

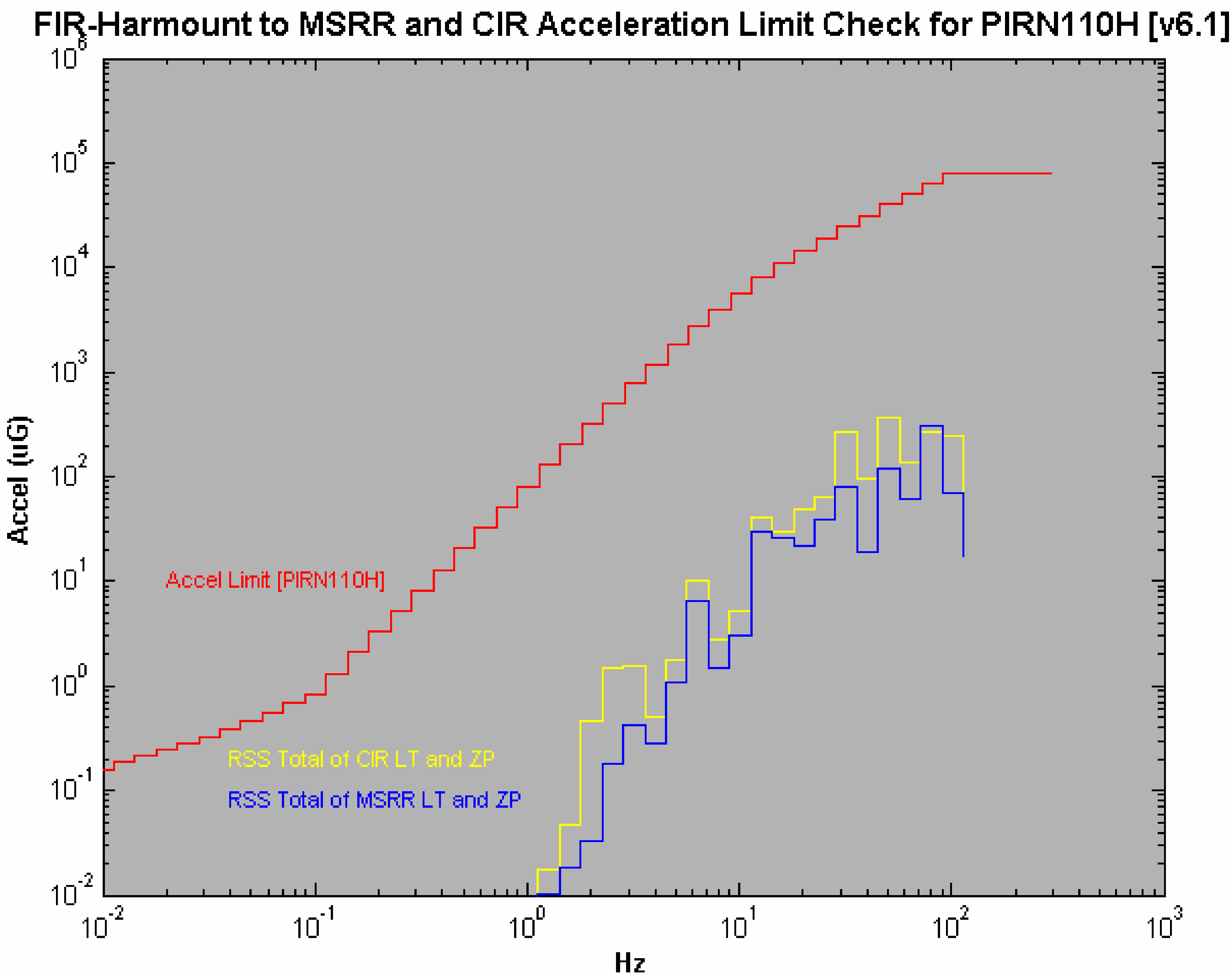
Document: SSP 57000 (Pressurized Payloads IRD)

Responsibility: Rack Facility Developer

Requires that payload racks limit their disturbances:

- **For quasi-steady frequencies (below 0.01 Hz), payload racks must limit unbalanced translational average impulses to less than 10 lbs-sec within any 10 to 500 second period in any direction.**
- **Interface forces in the vibratory range (0.01-300 Hz) are limited to below the curves on the next slide for non-ARIS racks.**
- **Transient loads on the rack are limited to 10 lb-sec in any direction over a 10 second period, and a 1000 lb peak force.**


FIR-ARIS Interface Forces [v7.0]
Wide Band Force Limit
Narrow Band Force Limit
....Sum of ARIS-ISS Interface Forces
lbs
Hz
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-2
10^-1
10^0
10^1
10^2
10^3


FIR-Harmount to MSRR and CIR Acceleration Limit Check for PIRN110H [v6.1]
Accel (uG)
Hz
Accel Limit [PIRN110H]
RSS Total of CIR LT and ZP
RSS Total of MSRR LT and ZP
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6

Science Requirements

Document: <u>FCF-DOC-002, Scientific Requirements Envelope Document</u>

Responsibility: Rack Facility Developer and Payload Developer

- **Curve envelopes the requirements of ~15 basis experiments**
- **Each experiment has different level of its own**
- **Only represents the environment required that will not disturb the natural phenomenon**
- **Does not address engineering requirements, e.g., vibration may disrupt imaging; functionality**
- **Note: High frequencies lower than Nauman curve – not ISS program's problem!**

ARIS Requirements

Document: SSP57006A, ARIS User's Guide

Responsibility: Mostly the Rack Facility

- **Accelerometer Saturation, Swayspace, CG, etc.**
- **First flexible mode above 25 Hz**

Payload Sub-Allocations

Documents: FCF-CIR-IDD, FCF-FIR-IDD, FCF-Payload Specific-ICD

Responsibility: Payload Developer

- **Rack Facility defines a certain portion of the total allowable disturbances for the rack that the payload may generate**
- **Includes Vibratory, Quasi-steady, and Transient Limits**
- **Must refer to the FCF-Payload Specific-ICD**
- **Example from MDCA and LMM:**

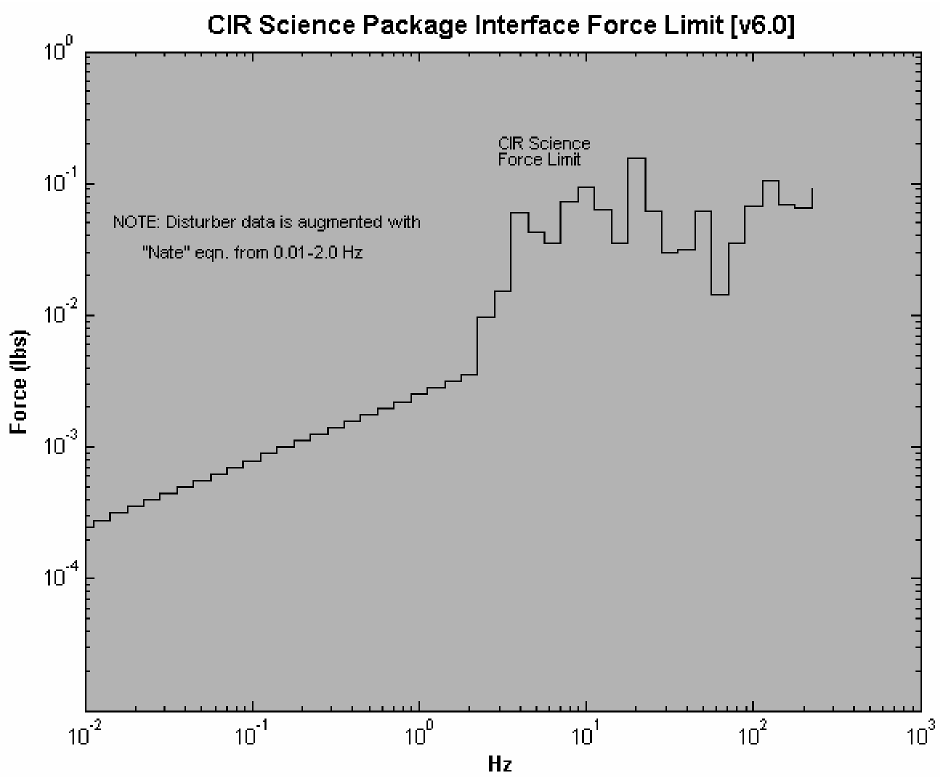
Payload Quasi-Steady Limit

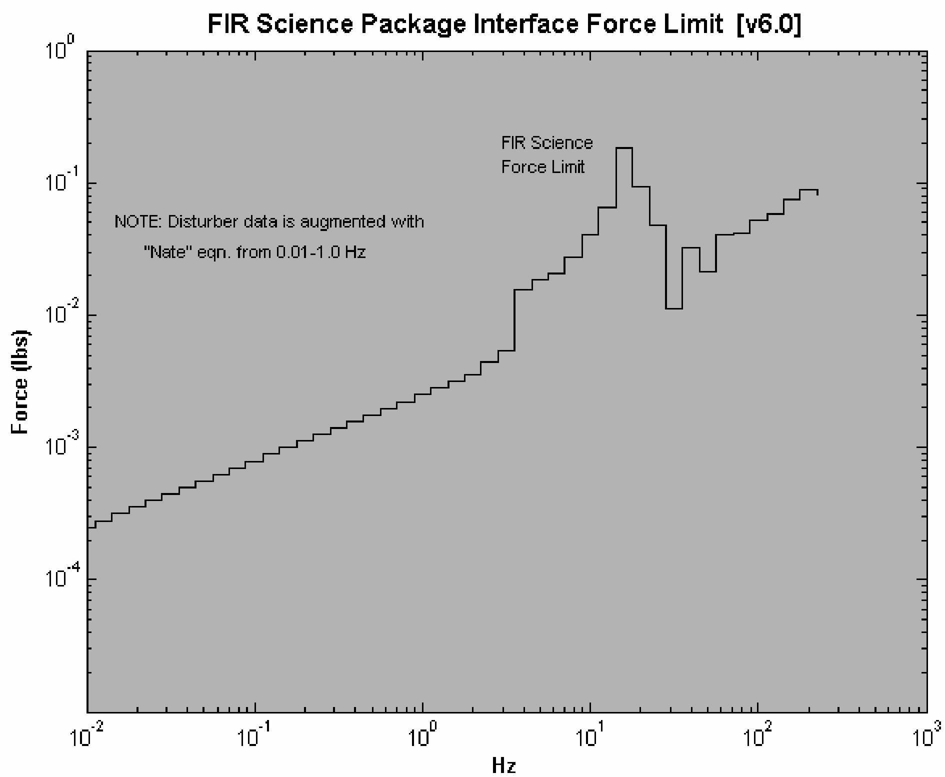
For frequencies below 0.01 Hz, payload components shall limit unbalanced translational average impulses to less than 2 lbs-sec within any 10 to 500 second period in any direction. This translates to 20% of the quasi-steady limits for the entire rack as defined in SSP 57000, section 3.1.2.1.

Payload Transient Impulse Limit

The payload shall keep its total combined transient impulses under 2.0 lb-sec in any direction over a 10 second period. The payload shall keep its peak load under 200 lb, or 20% of the entire integrated rack allowance of 1000 lb, or 10 lb-sec over a 10 second period as defined in SSP 57000, section 3.1.2.3.

Vibratory Force Limits for MDCA and LMM



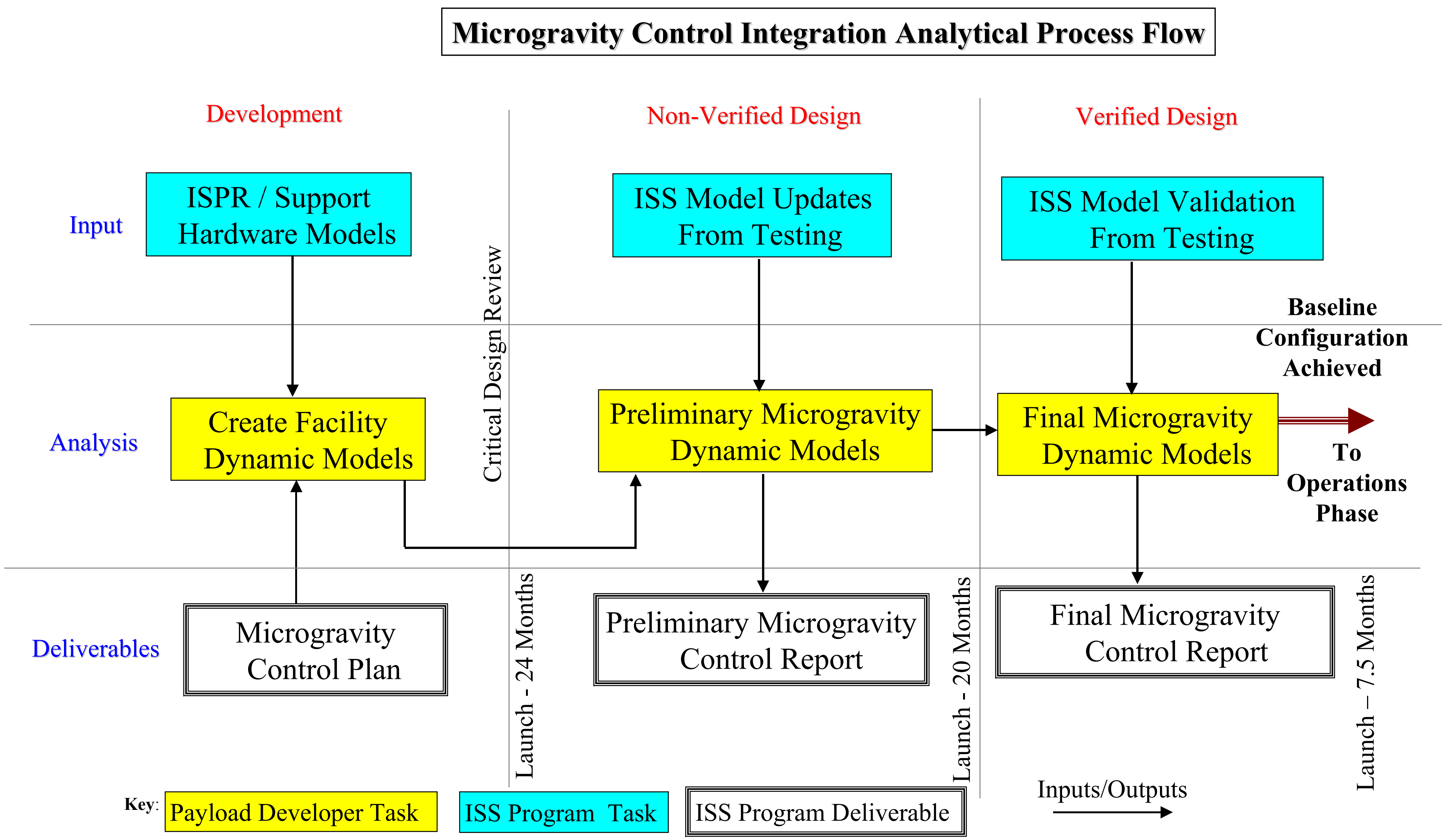


Microgravity Control Verification Process

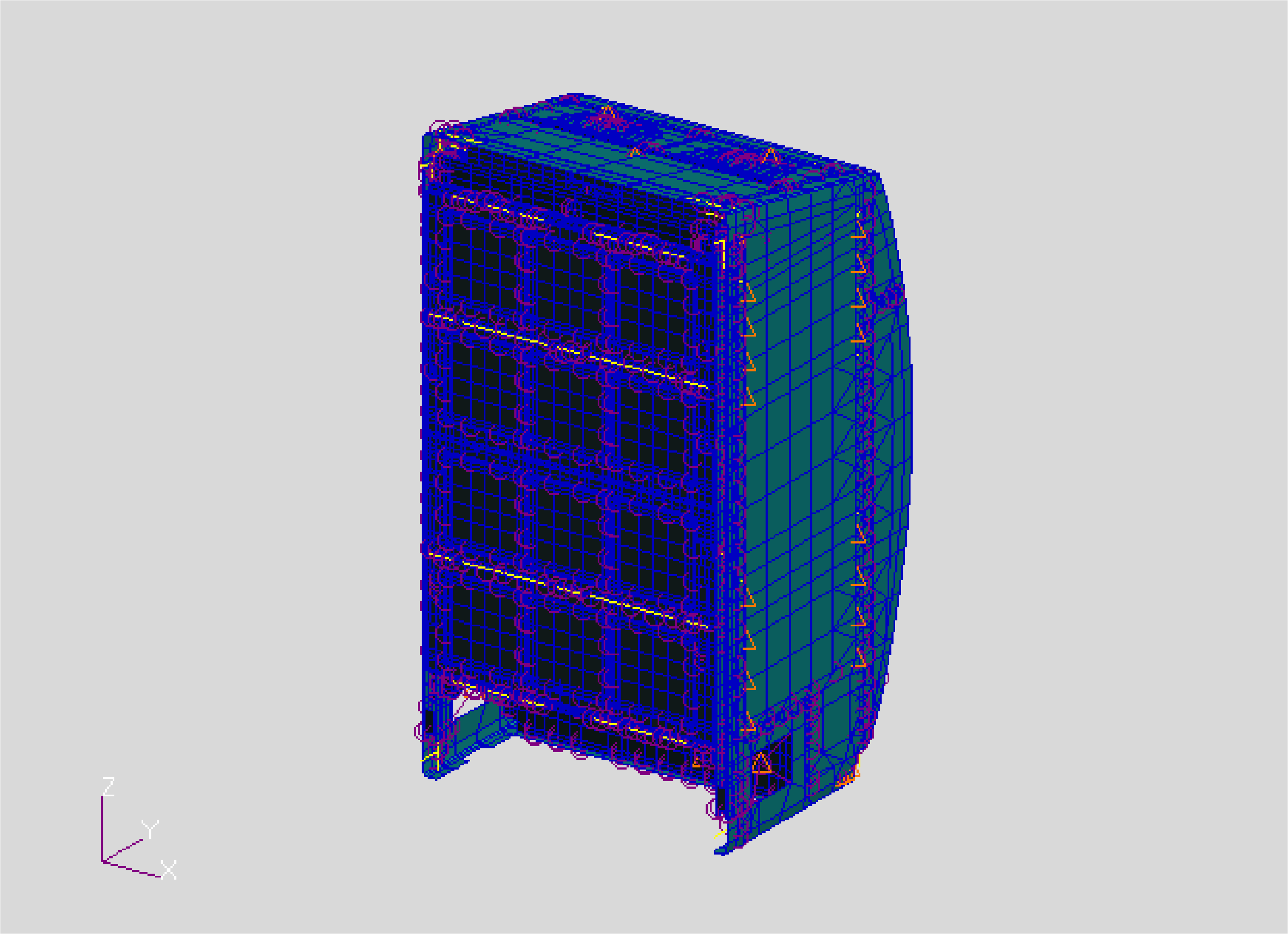
Verification Data Responsibilities

- ISS Program (NASA)
  - On-Orbit ISPR NASTRAN Model (with or w/o ARIS or PaRIS)
  - Reduced US Lab NASTRAN & SEA Models
  - ISS Offboard Rack Vibration Environment (NIRA)
- Isolation System (Boeing)
  - Umbilical & Isolator Stiffness & Damping for Analytical Models
  - Simulink Model of ARIS / PaRIS System and Generic Rack & Umbilicals
  - Tune ARIS Controller for Payload Rack
  - Verify ISS System Requirement (Nauman)
- Rack Facility Developer (FCF)
  - Identify & Assess Rack Disturbers (MEL testing)
  - Facility On-Orbit NASTRAN Model with Disturber & Science Locations
  - Facility Simulink Model with Transfer Functions for Key Interfaces
  - Modify Model for Different On-Orbit Configurations
  - Verify all Rack-level requirements (Good Neighbor, SRED, ARIS)
- Payload Developer (Experiment)
  - Identify & Assess Payload Disturbers (MEL testing)
  - Payload NASTRAN Model
  - Verify Payload Requirements (Interface Force Sub-allocation, Science)

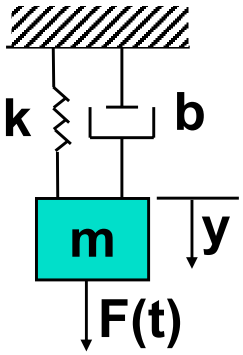
Verification Process



Verified NASTRAN Model



Dynamic System Simulink Model



$$F(t) = m\ddot{y} + b\dot{y} + ky$$

where

$$k = \omega_n^{\,2} m$$

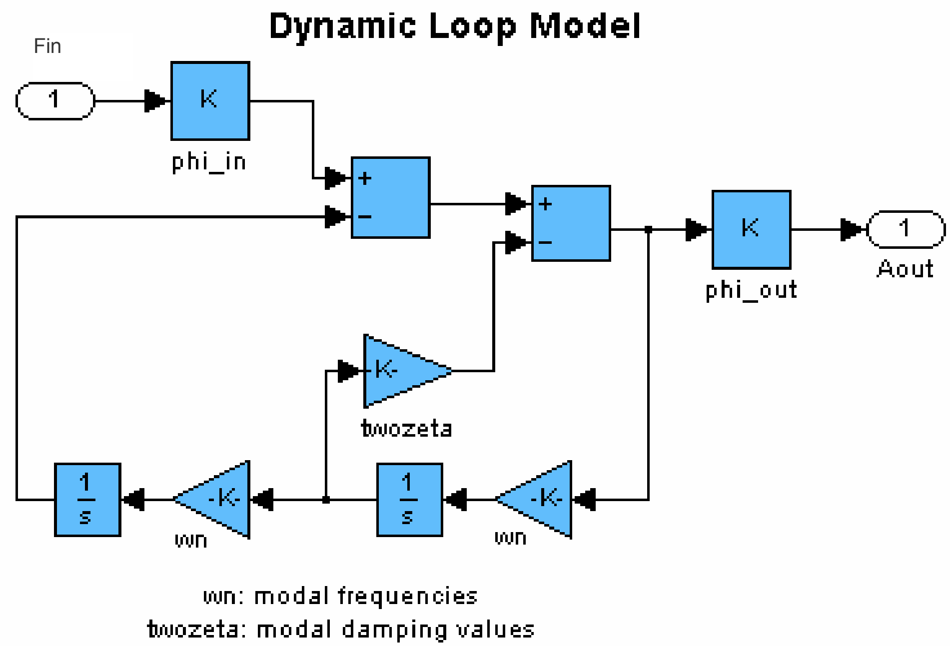
$$b = 2\zeta\sqrt{km}$$

rewrite

$$A(t) - 2\zeta\omega_n \int \ddot{y} - \omega_n^{\,2} \iint \ddot{y} = \ddot{y}$$

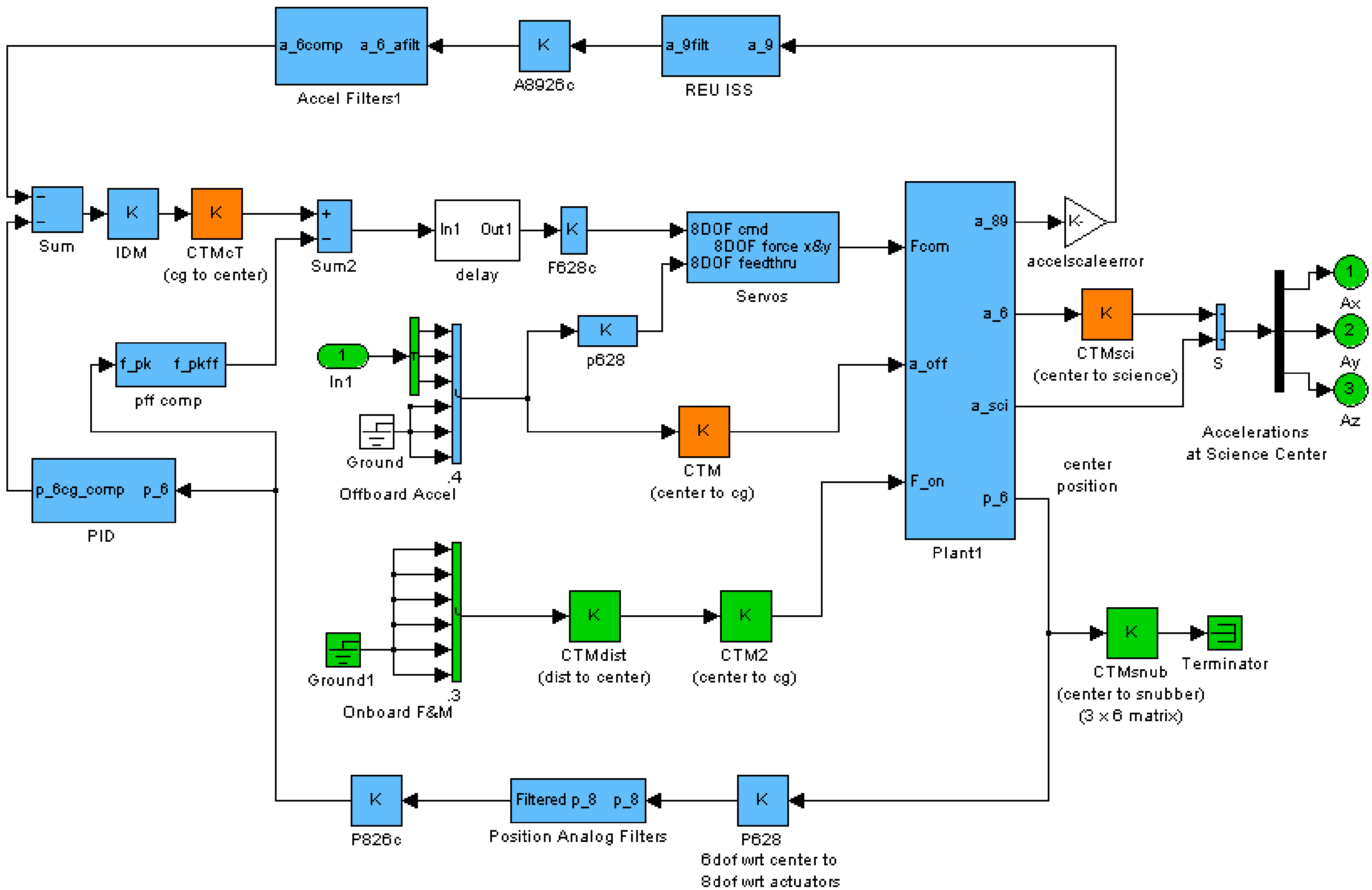
F = *force*
A = *acceleration*
m = *mass*
b = *damping*
k = *stiffness*
y = *displacement*
ω_n = *frequency*
ζ = *damping ratio*

⇒

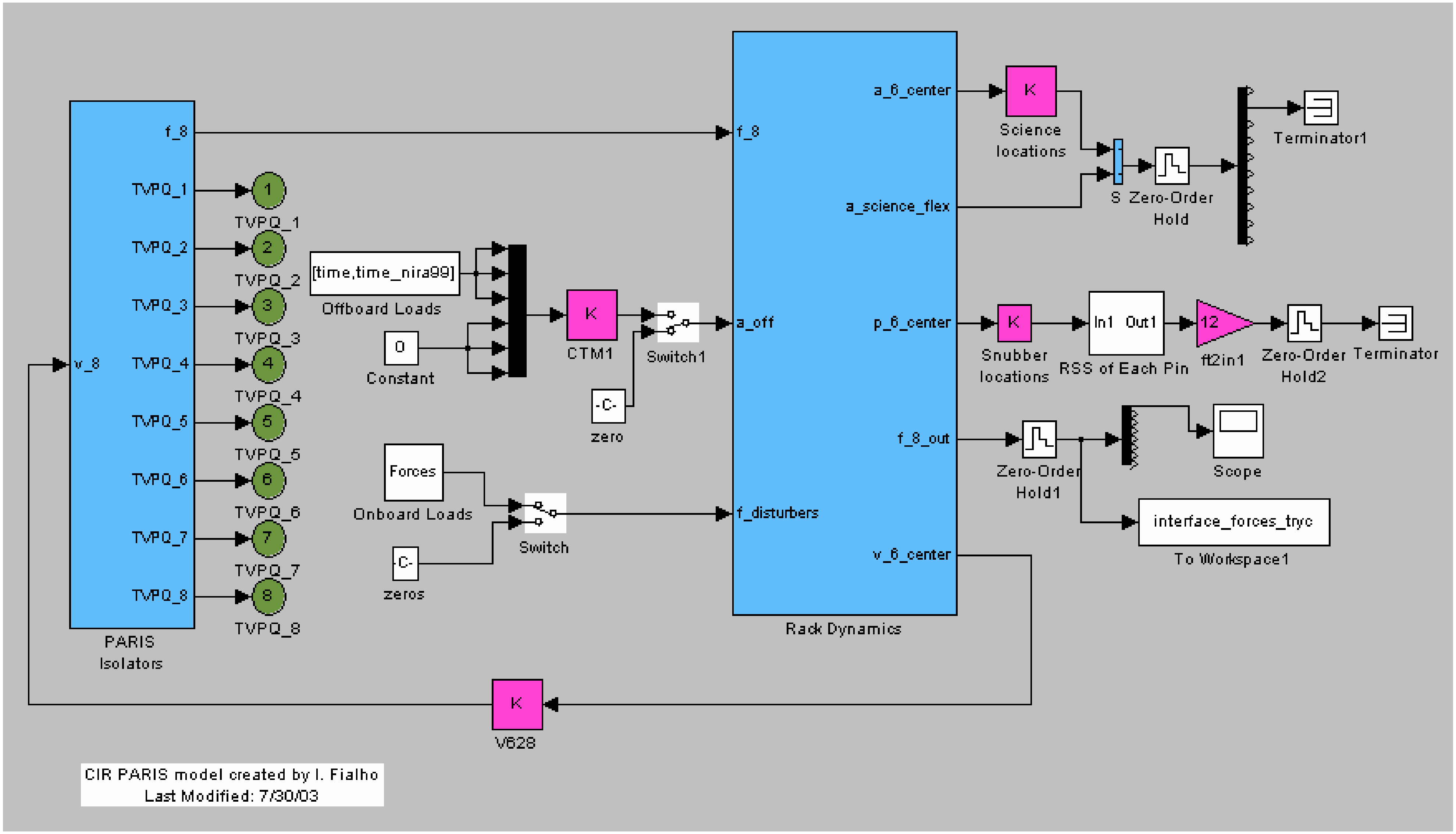


NASTRAN Eigenvectors (PHI)
Are mass normalized so that
units are 1/√m

FIR-ARIS Simulink Model



CIR-PaRIS Simulink Model



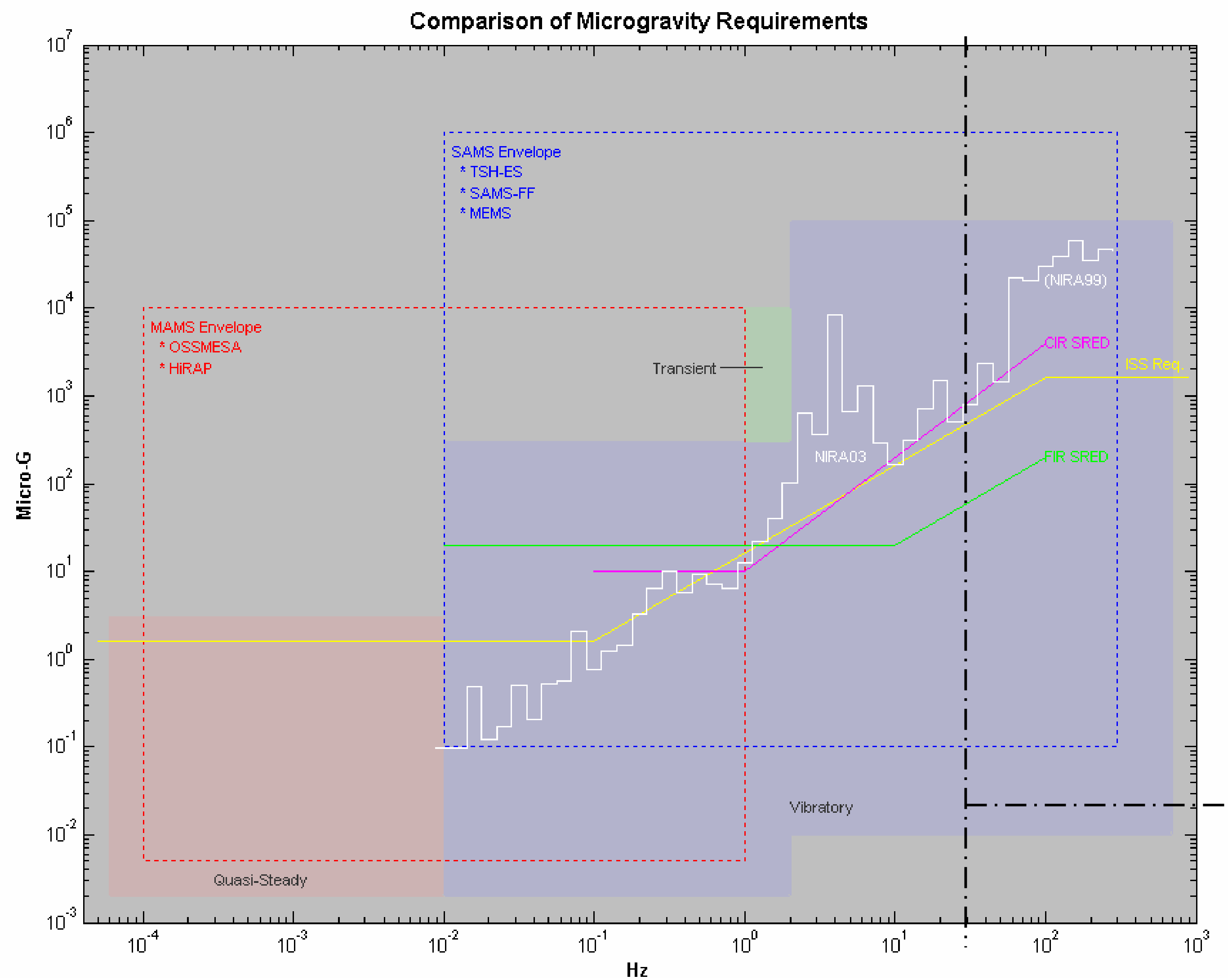
Disturbance Control & Predictions

Larry Moss

Presentation Agenda

1. **Know Your Microgravity Requirements**
2. **Know Your Vibration Isolation Systems**
   - Active Rack Isolation System (ARIS)
   - Passive Rack Isolation System (PaRIS)
3. **Know Your Payload Design**
   - Development of Payload FEA Models
   - Understand your Payloads Dynamics
   - Develop Test Verified Predictive FEA Models
4. **Know Your Disturbers**
   - Identify Microgravity Disturbers
   - Identify Disturber Operations
   - MEL Testing
   - Disturber Operational Scenarios

Know Your Microgravity Requirements



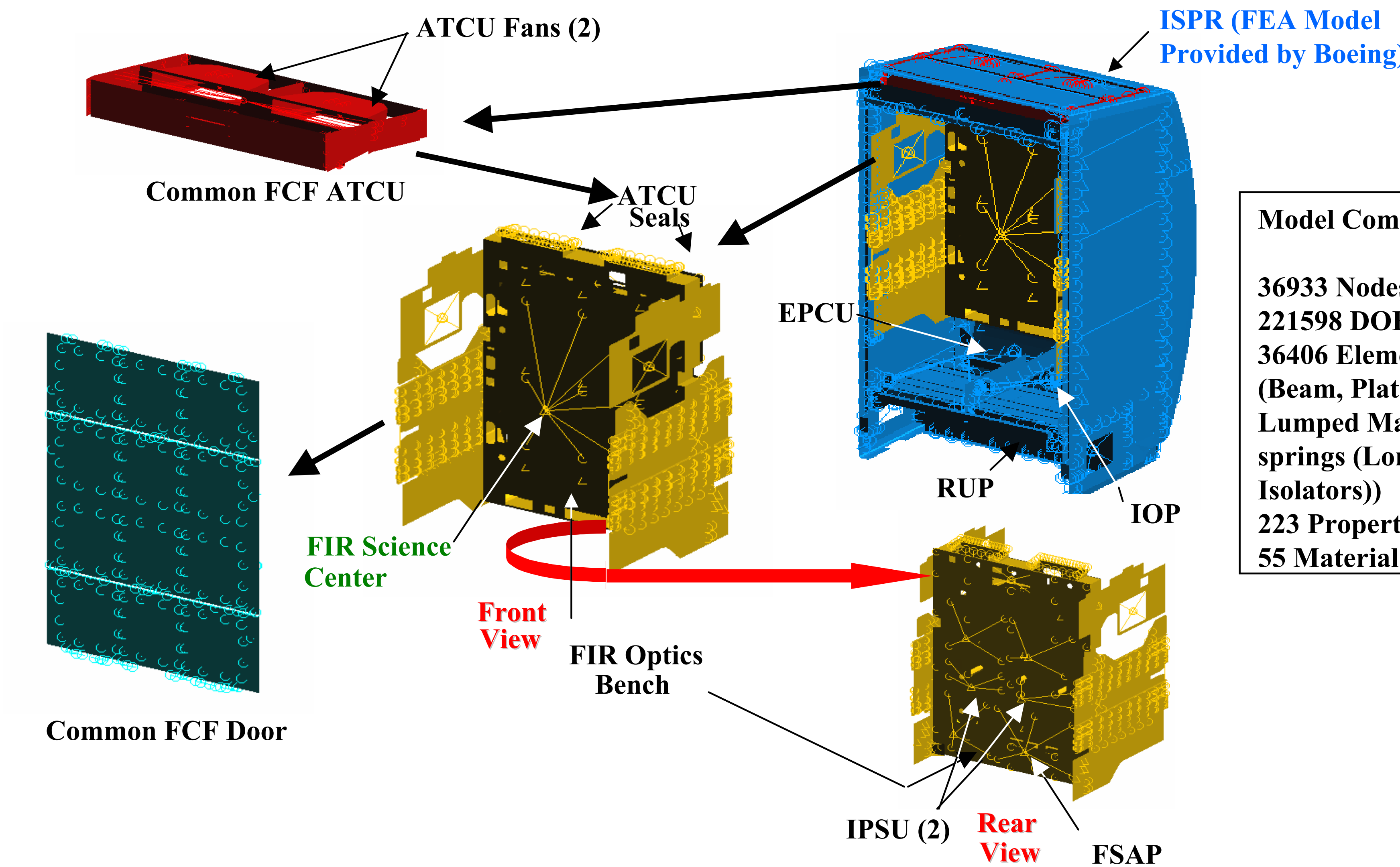
- **Protect Science for 30 Day Microgravity Periods**
- **Rack Vibration Isolation Approaches (ARIS, PaRIS, Other)**

On-Orbit Rack Structural Modes > 25 Hz

Know Your Payload Design

- **Development of Payload FEA Models**
  - Develop "On-Orbit" FEA Model of rack + payload. "On-Orbit" Boundary Conditions and "On-Orbit" Mass Properties.
  - Perform normal modes analysis of the FEA Model. (Frequency > 25 Hz)
  - Obtain mass-normalized eigenvector information for specific points of interest (Critical Science Locations, Disturbers, Actuator/Isolator, Accelerometer Heads, Umbilical, Snubber)
  - Input the eigenvector information to the ARIS MATLAB/Simulink dynamic model and calculate transfer functions, e.g., disturber points to critical science location.
  - Multiply the transfer functions by the disturber data to obtain the response at the science location. Frequency Domain Analysis.

Integrated FIR Finite Element Model



Model Components:

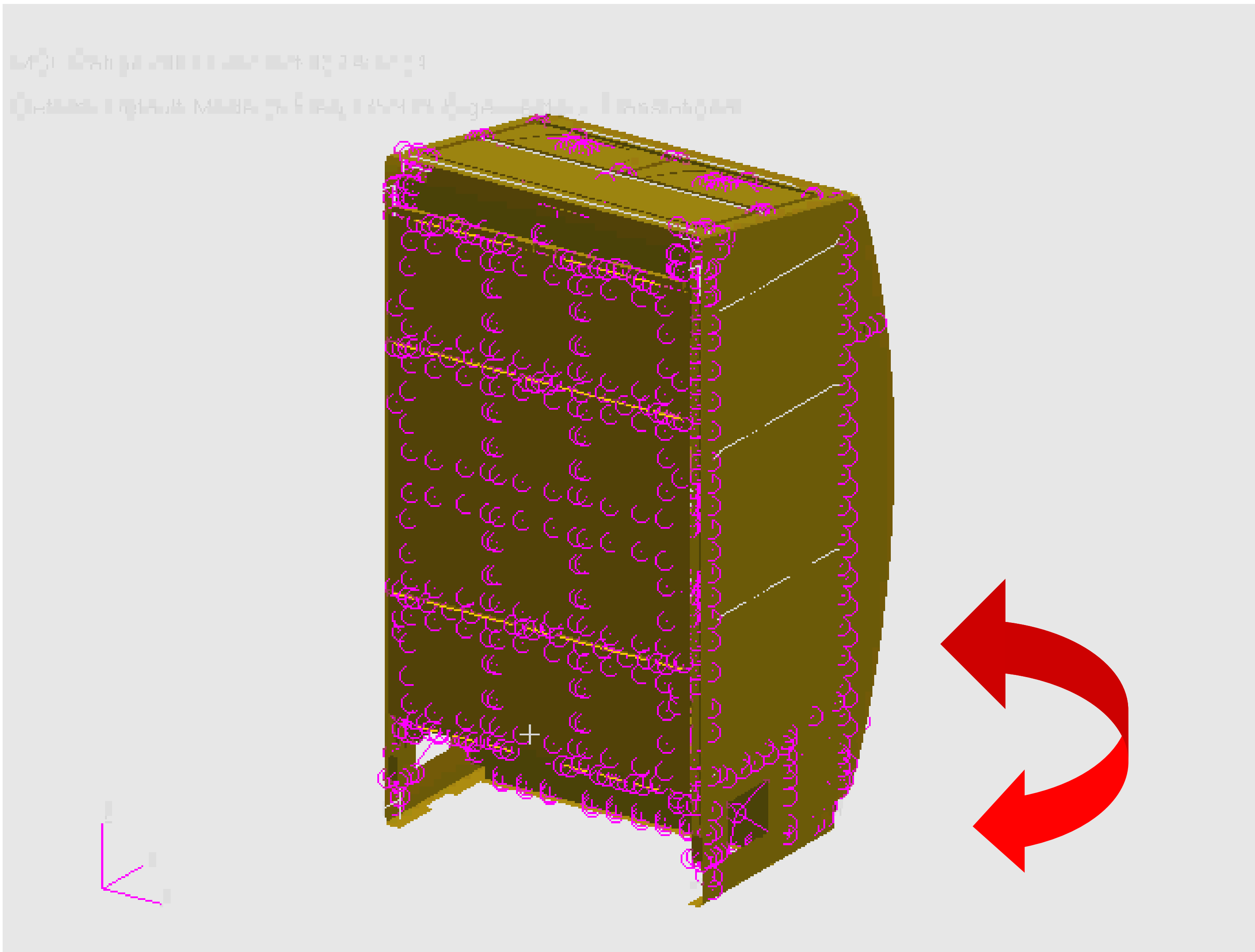
36933 Nodes
221598 DOFs
36406 Elements (Beam, Plate, Solid, Lumped Masses, springs (Lord Isolators))
223 Property ID's
55 Material ID's

Understand Your Payloads Dynamics

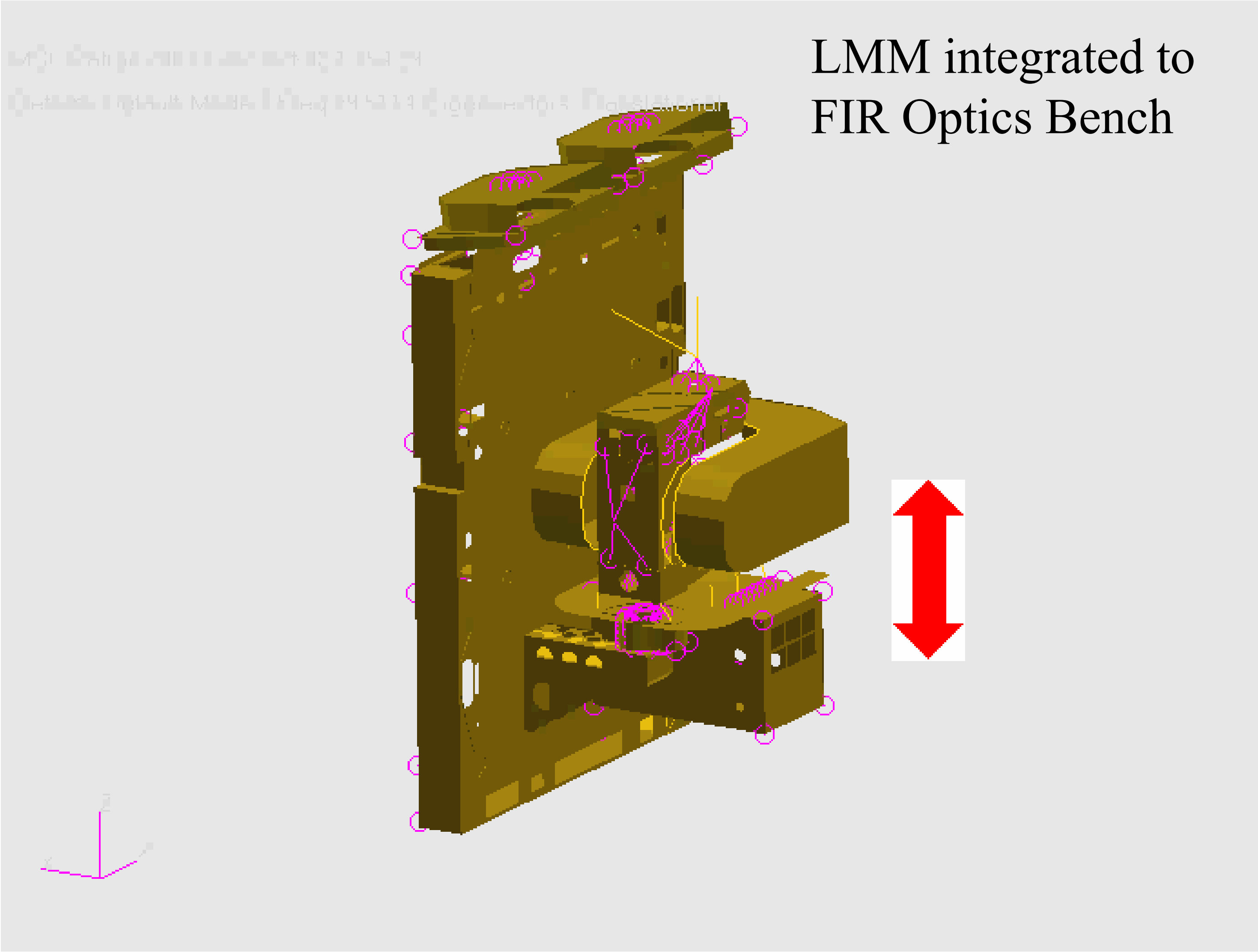
Mode No.	Frequency Hz	Description
1 – 6	0.0	First Six System Rigid Body Modes
7 -13	10.86 – 23.86	ATCU Modes
14	25.16	Lower Intercostal – REU's – Local Mode
15 -17	25.51 – 25.99	ATCU Modes
18	27.23	Upper Rack Skin – Local Mode
19	28.16	Lower Intercostal – REU's – Local Mode
20 -21	29.06 – 29.16	ATCU Modes
22	30.80	Top Door Bending in Y Direction – Local Mode
23	33.89	Structural Mode - Rack/Optics Bench Movement – Bending Mode in X Direction
24	34.13	Bottom Door Bending in Y Direction – Local Mode
25	35.38	Structural Mode - Rack Twisting Mode – Z Axis
26	35.54	ATCU Structure – Doors Bending Y Direction – Local Mode
27	37.53	Upper Intercostal - REU
28	42.82	Structural Mode -Optics Bench Top Door Bending in Y Direction
29	43.80	Top Door Bending
30	44.78	Top Rack Skin – Local Mode

FIR Normal Modes Analysis – "Free – Free" Boundary Conditions

FIR Structural Mode: Rack Twisting (35.38 Hz)

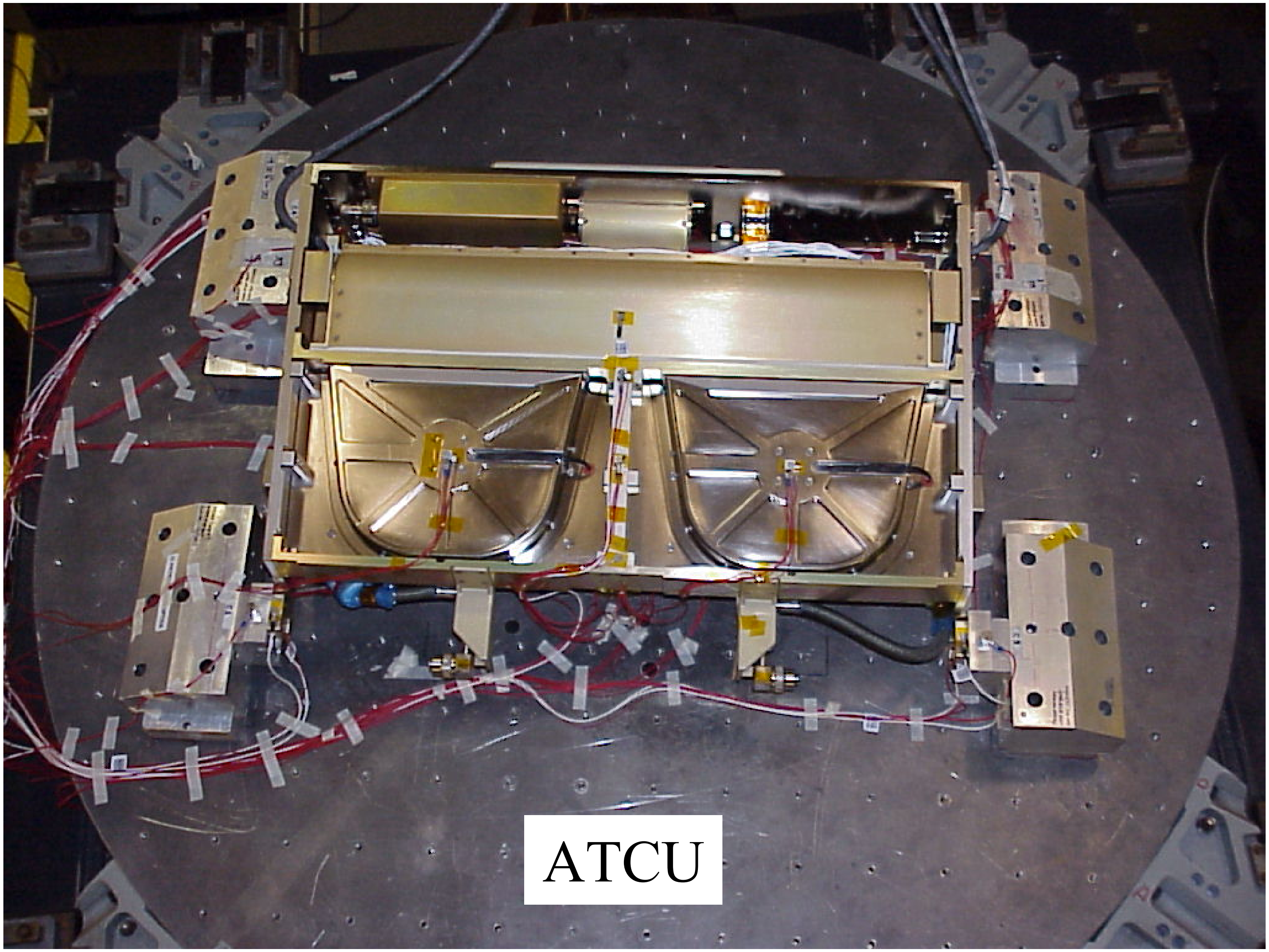


Science Structural Mode: Cantilever Bending (9.5 Hz)



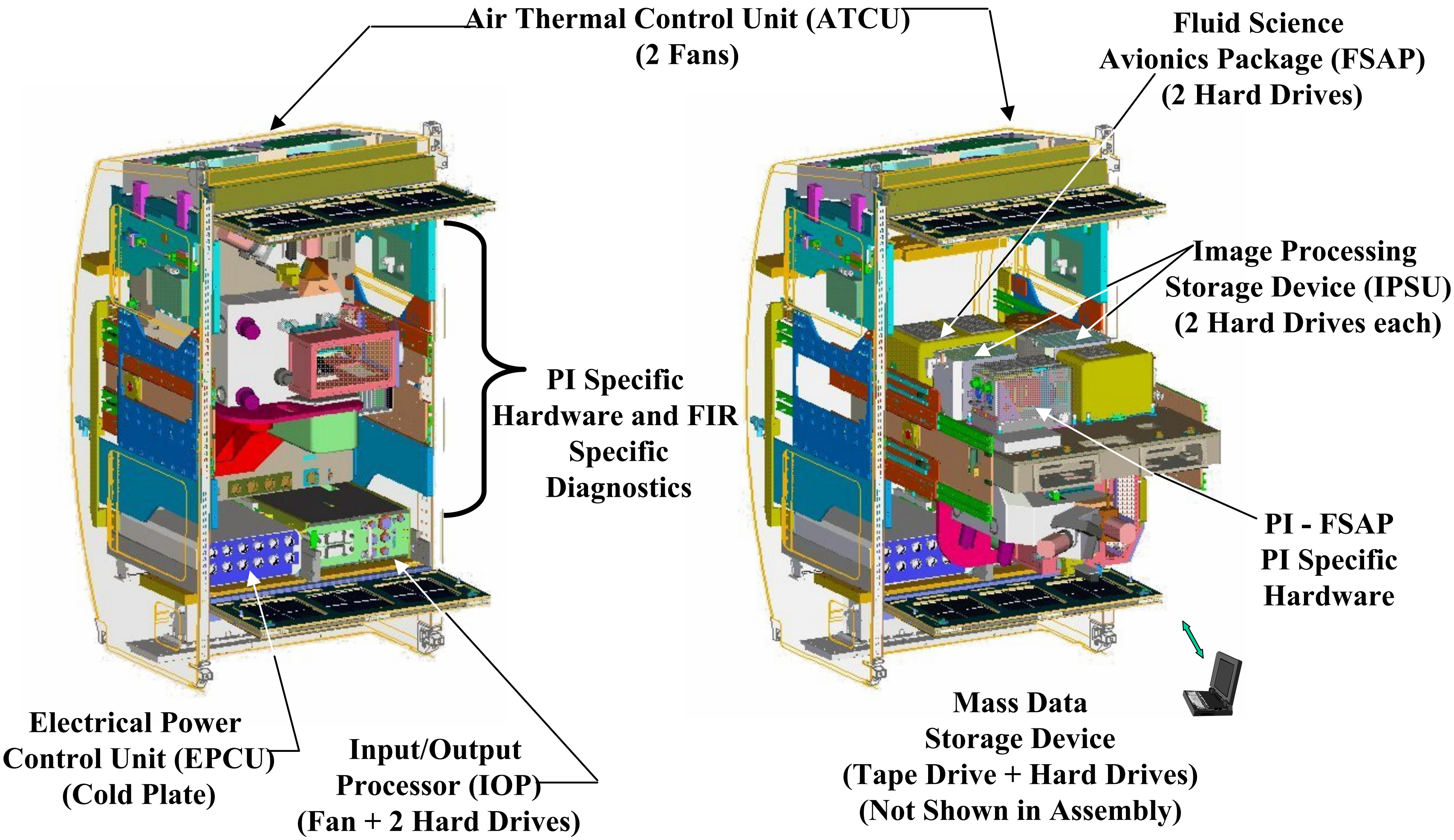
LMM integrated to
FIR Optics Bench

Develop Test Verified FEA Models



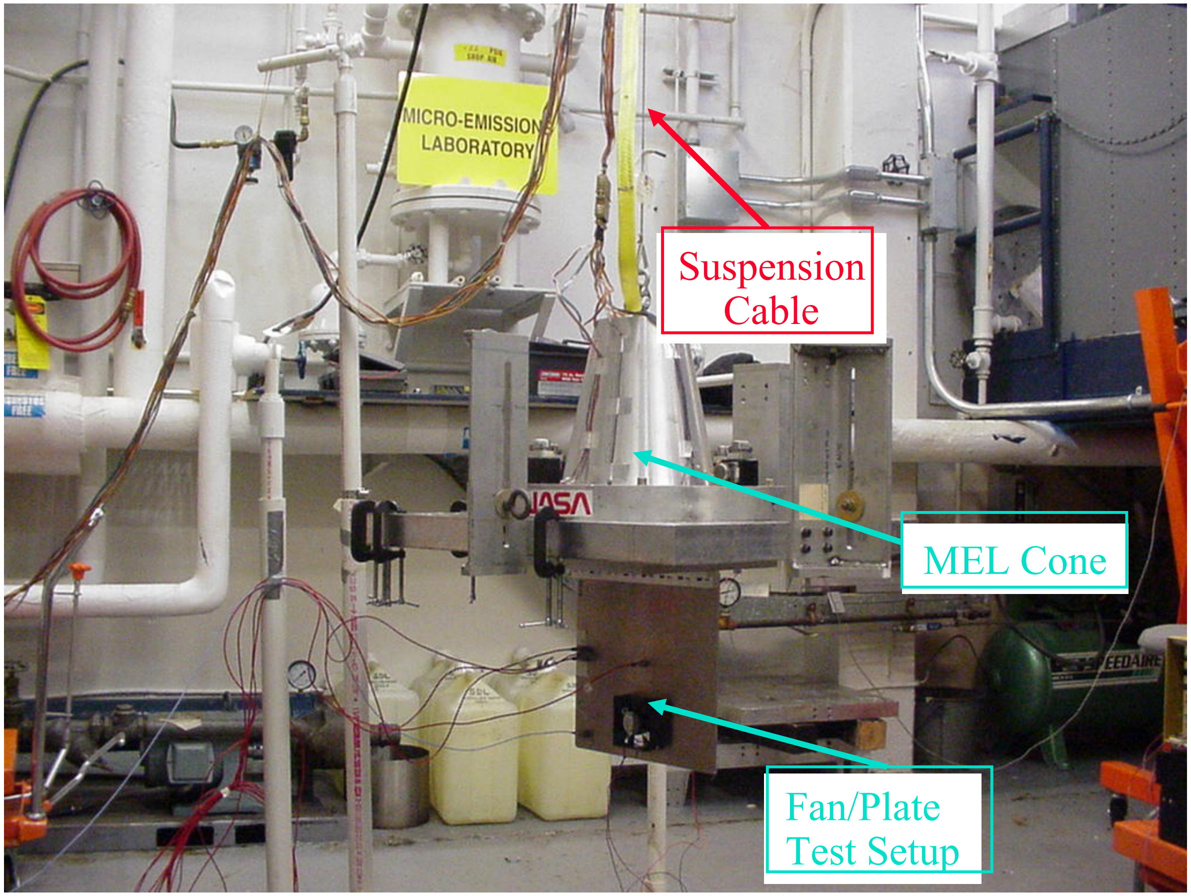
Know Your Disturbers

- Identify Microgravity Disturbers, Locations, and Operation



MEL Testing

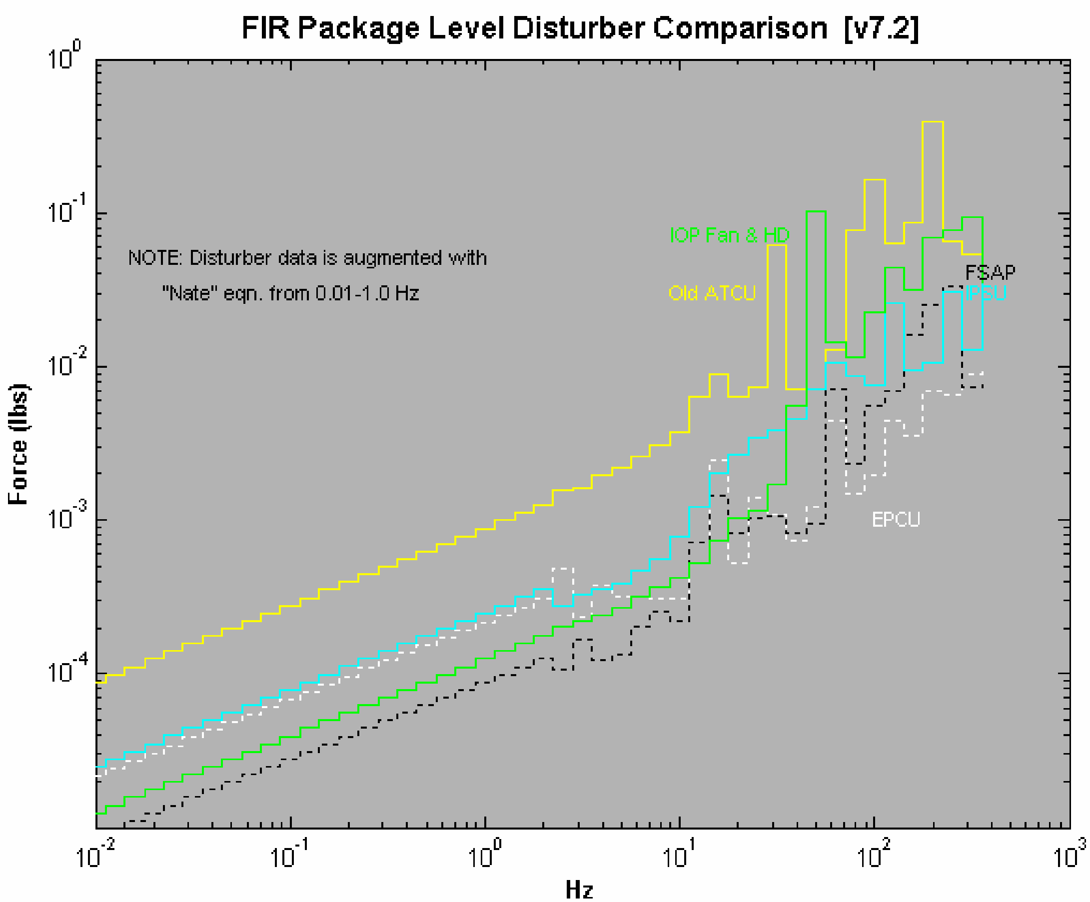
- **6 Degree Of Freedom Inertial Measurement System**
  - **98 lb. Mushroom Cone**
  - **33 foot Suspension Cable**
  - **Zero Rate Spring Mechanism and Pneumatic Suspension System (0.3 Hz)**
  - **10 QA-700 Servo Control Accelerometers**
- **Defines Forces & Moments at the Test Unit Center of Gravity**
- **Test ASAP**



Example:

FCF ATCU Fan

FIR Microgravity Disturbers

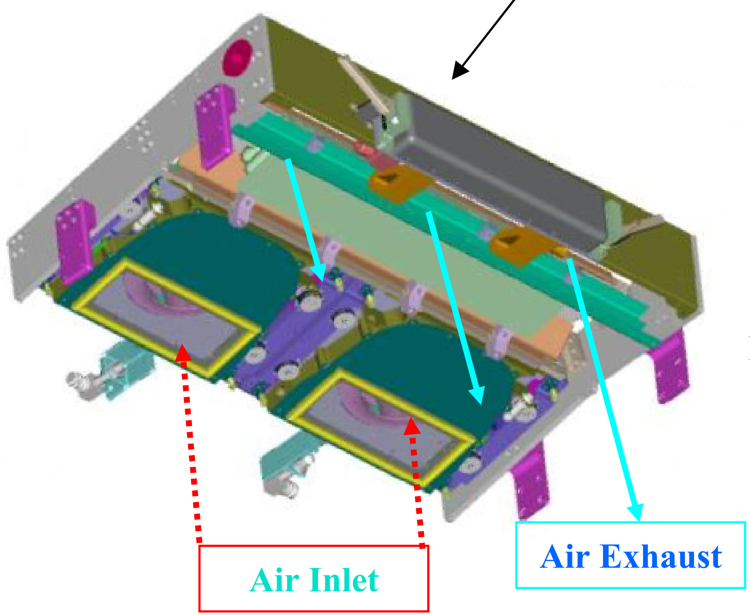


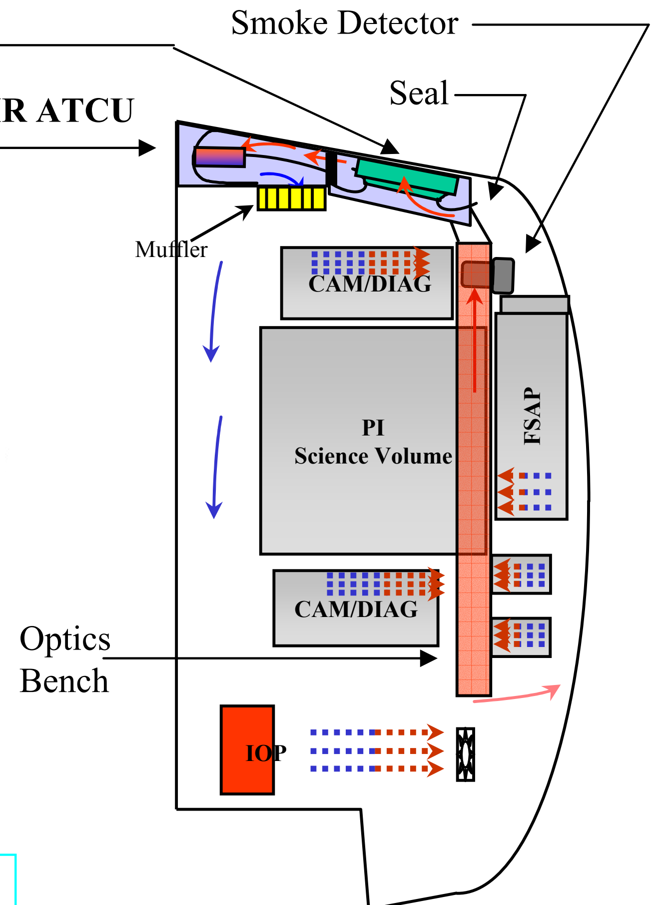
- **Inventory of FIR Specific On Board Disturbers.**
- **Disturbance force spectrum obtained from Microgravity Emissions Laboratory (MEL).**
- **Dominate On Board Disturbance Source is the ATCU Fan.**

FIR ATCU Background Information

- Common FCF Cooling System.
- The FIR ATCU draws warm air through the optics bench from the experiment support packages.
- Flexible seal between ATCU air inlet and optics bench.
- FIR Fan operating range: 1600 RPM to 2000 RPM (26.6 Hz to 33.3 Hz). Minimum airflow at 1600 RPM for smoke detectors.
- FIR ATCU air inlet is offset with a restricted opening.
- Fluid Experiments are **SENSITIVE** to microgravity disturbances


EBM Fan (2)





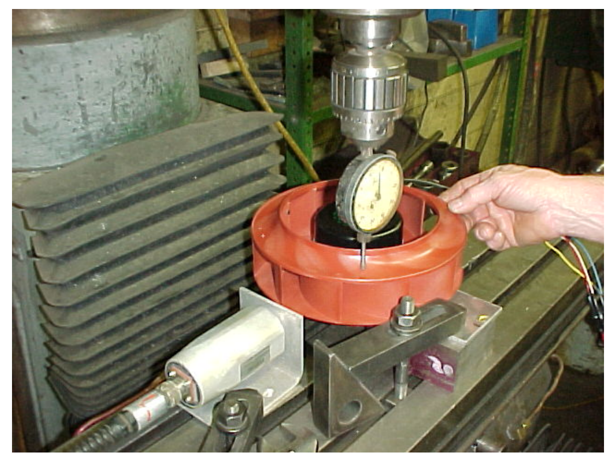
Minimize Mechanical Disturbances

1. The low grade bearings in the COTS fans were replaced with high precision, double shielded, roller bearings, ABEC-5.

   ✓ High precision bearings rolled freely.
   ✓ Fan RPM did not drift during operation.
   ✓ Impeller wobble and run out was reduced.
   ✓ Gap at shroud reduced to obtain improve air flow performance
   ✓ Lower fan imbalance.
   ✓ Improved quality of final dynamic balancing.

- **Better bearings and improved balance will increase the fans life.**

COTS Bearing ABEC-5



Run Out Check

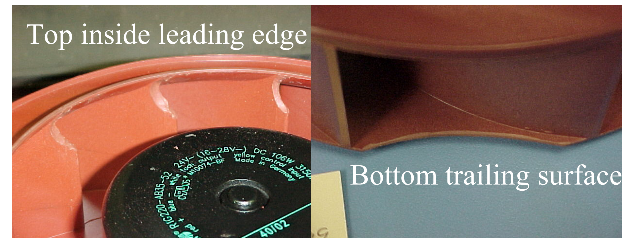
Minimize Mechanical Disturbances

2. Dynamically balance COTS fans.

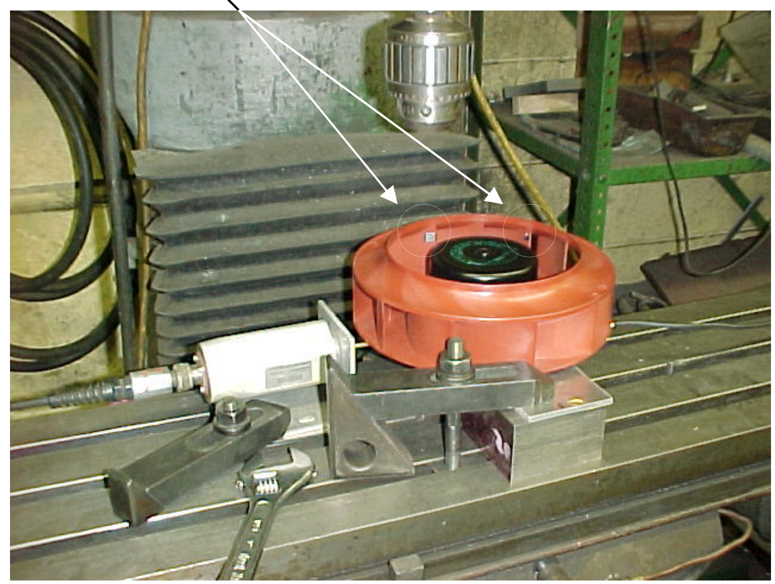
- ✓ Eliminated factory installed balancing clips to maintain the fan balance.
- ✓ Clips potentially could move on the fan impeller due to handling or during operation.
- ✓ Clips potentially could egress from the the fan impeller ending up as foreign objects within the air ducting and rack.
- ✓ Achieved two plane balance of fan.
- ✓ No effects on acoustics and airflow output.

- **The worst fan was modified to become the best fan with the lowest mechanical imbalance.**

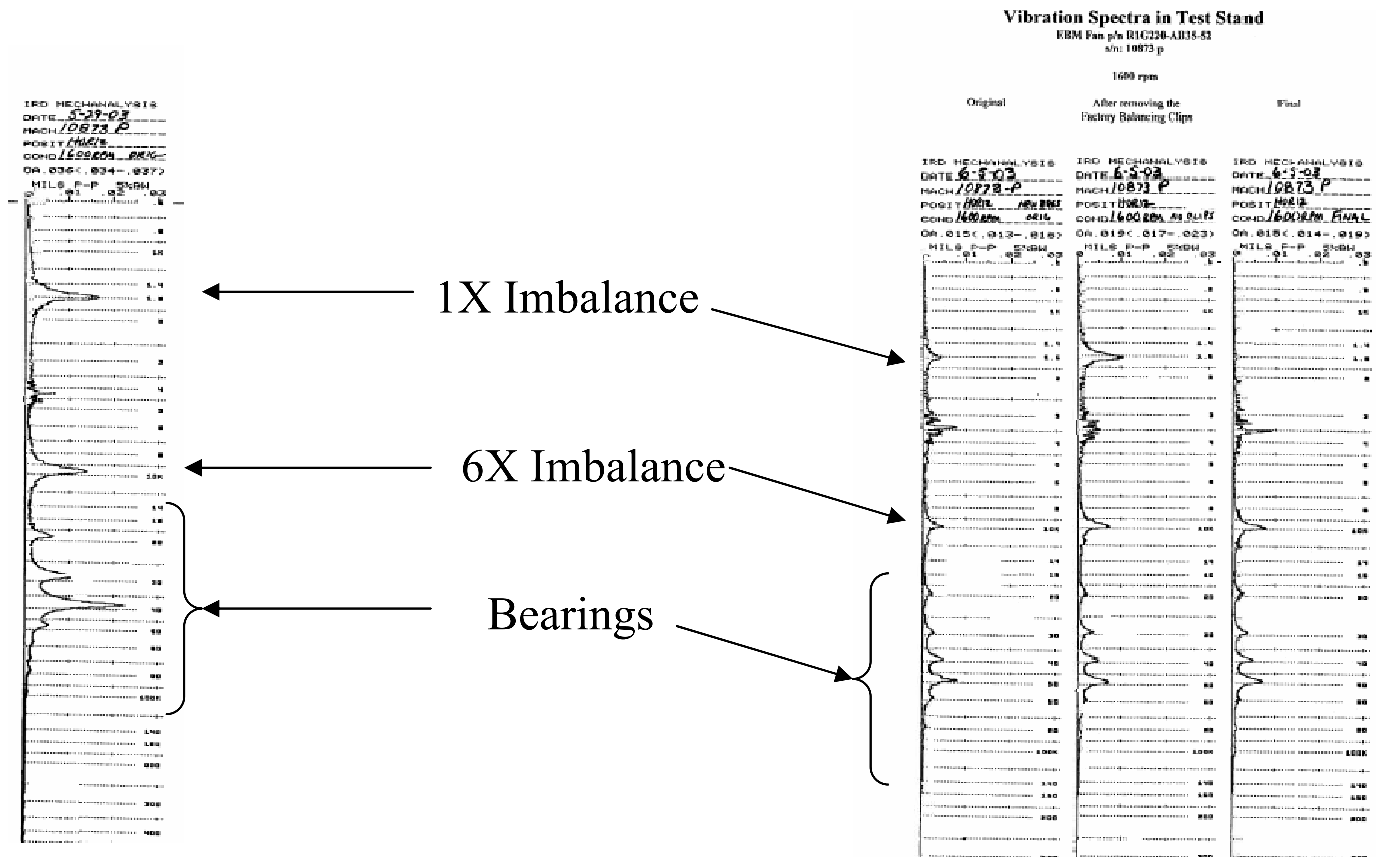
Balancing Clips



Dynamic Balancing Locations



EBM Fan Upgrades – 1600 RPM



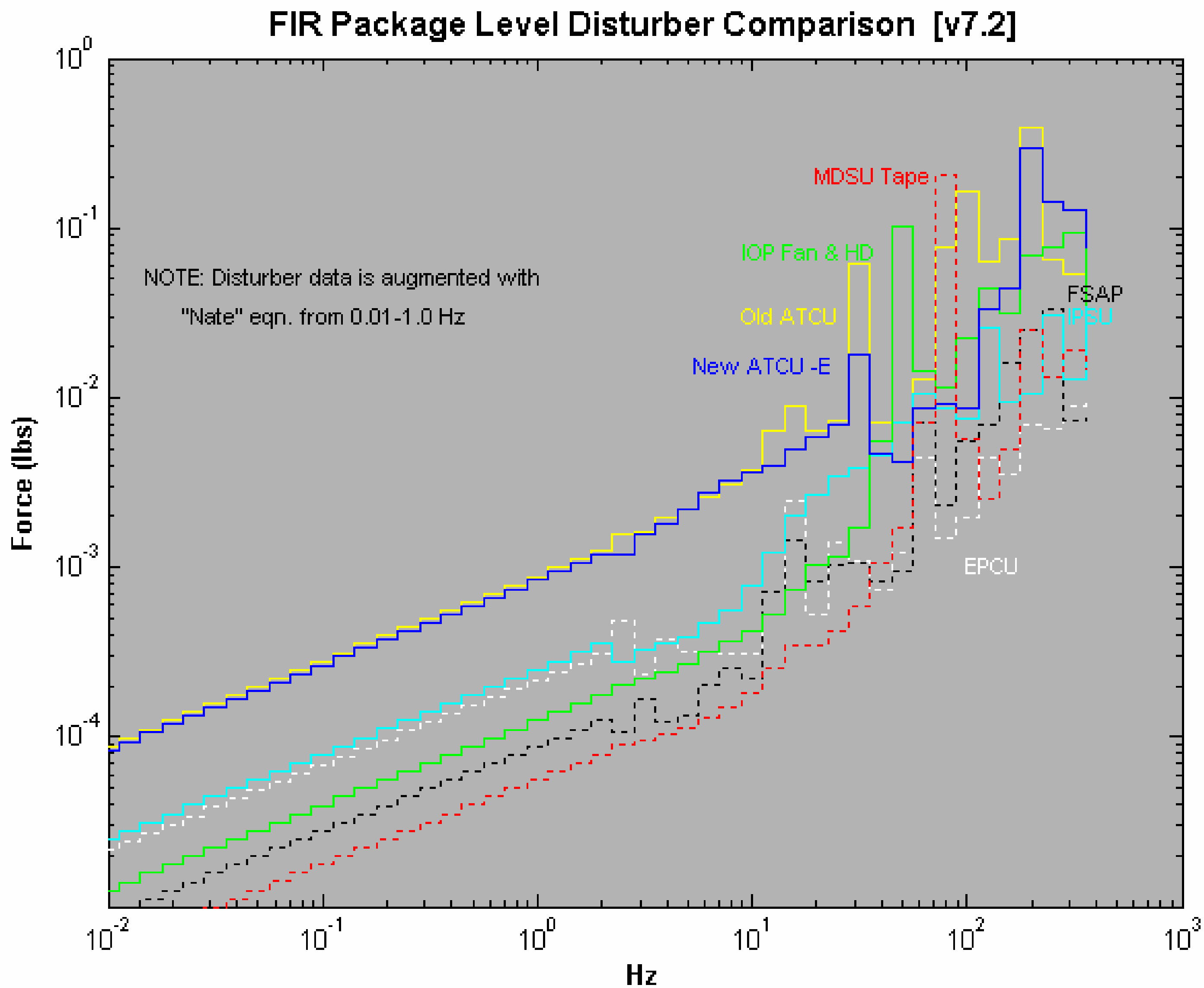
Factory Settings
Bearings and Clips

New Bearings
With Clips

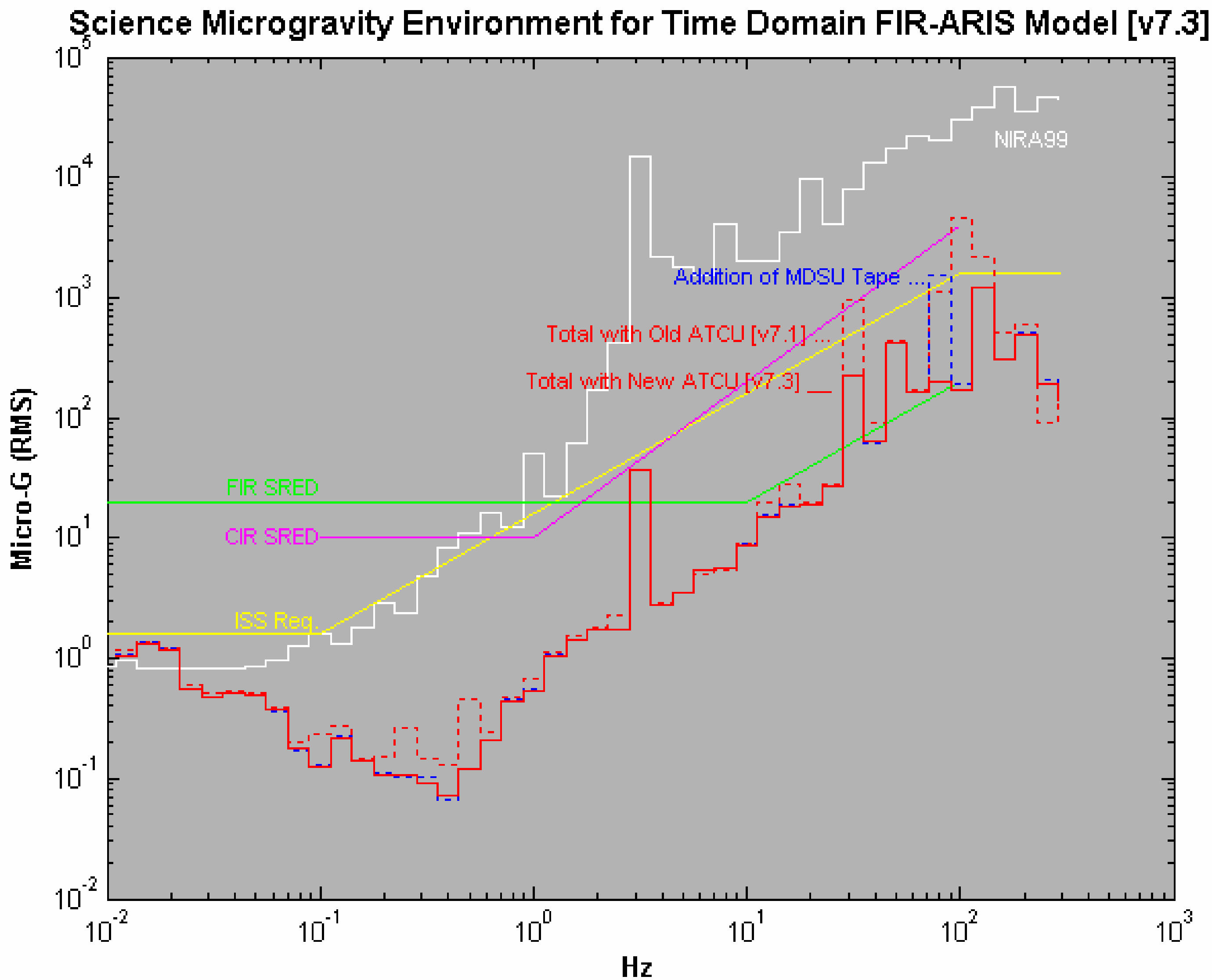
New Bearings
No Clips

Dynamically
Balanced
No Clips

Updated FIR Microgravity Disturbers



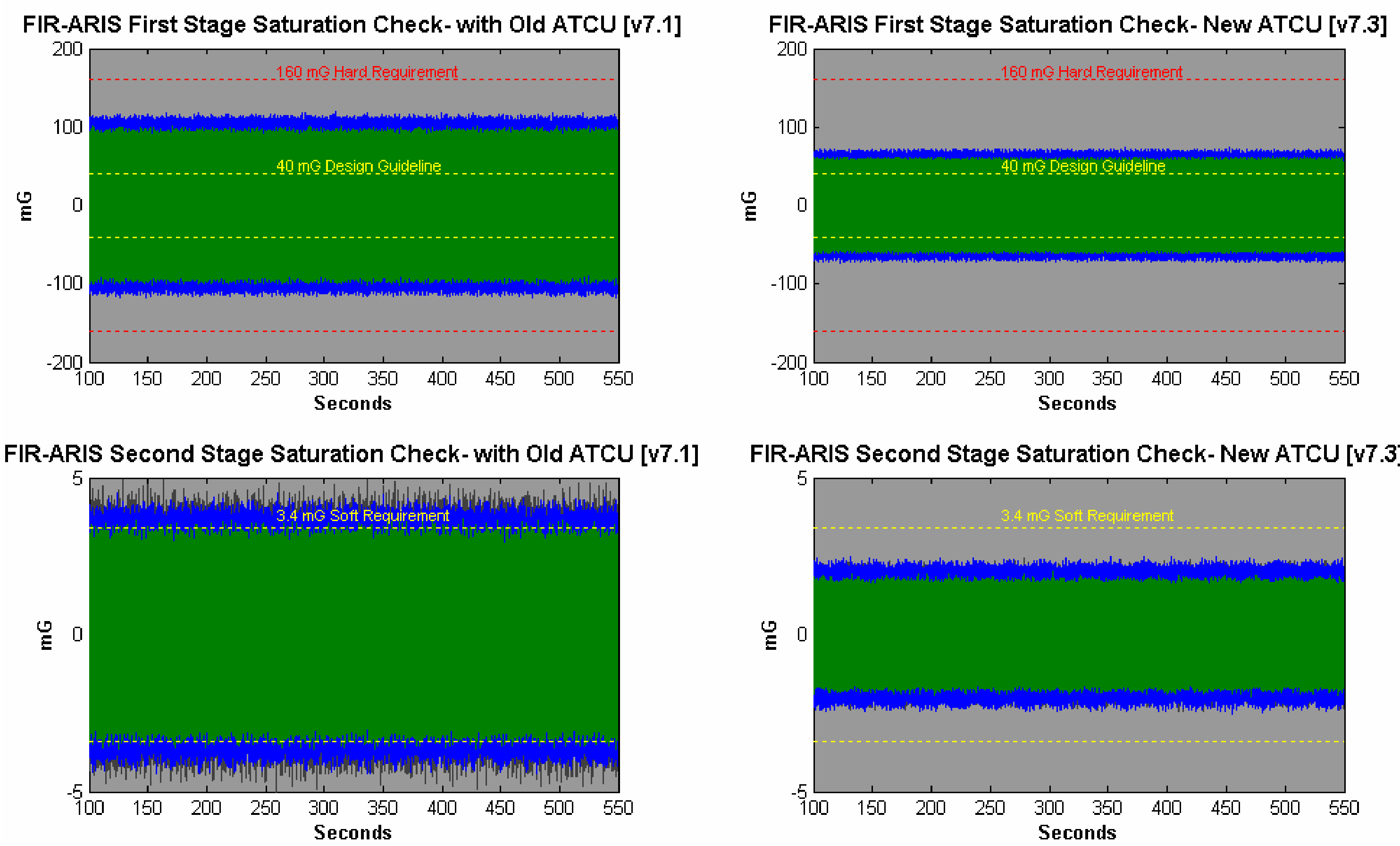
FIR Science Microgravity Environment



ARIS Accelerometer Saturation Check

- **First Stage Saturation Check: Acceleration at each ARIS Head < 160 milli-g's. A 4 times margin of safety translates into a 40 milli-g Design Guideline.**

- **Second Stage Saturation Check: Acceleration at the 25 Hz Low Pass Filter < 3.4 milli-g's.**



Unbalanced Fan

Balanced Fan

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