3rd Annual

Microgravity Environment Interpretation Tutorial

Sponsored by:

Principal Investigator Microgravity Services Project
Microgravity Science Division
NASA Glenn Research Center

December 7-9, 1999

Acceleration Measurement Program Overview

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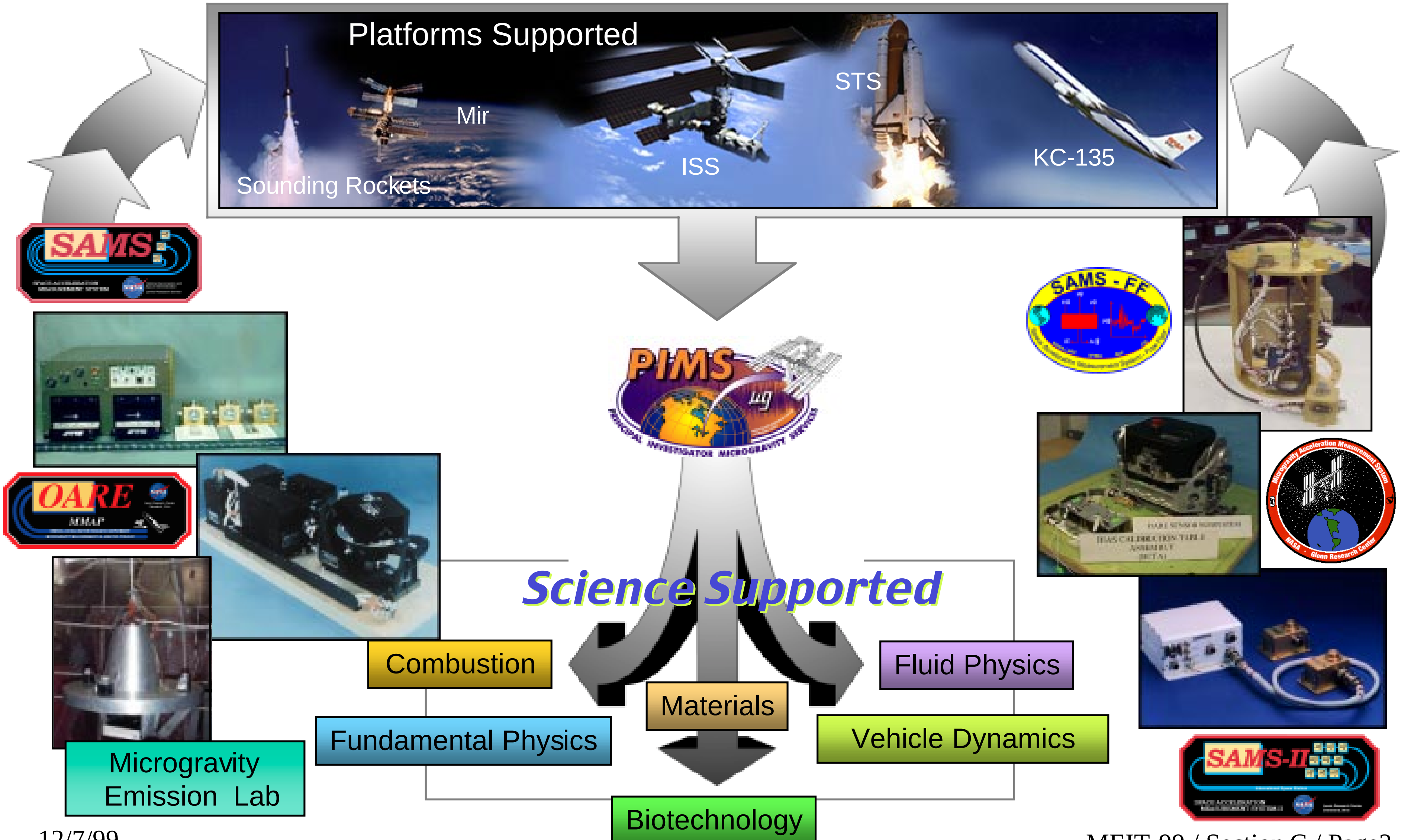
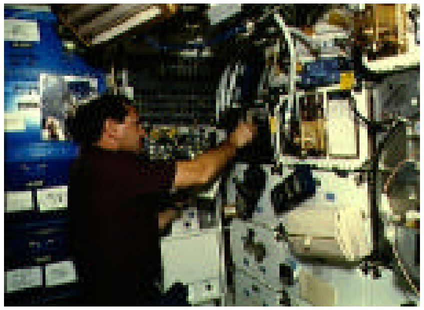
Microgravity Science Division
Acceleration Measurement Program
Glenn Research Center



Acceleration Measurement Program - GRC

- **Space Acceleration Measurement System(s) (SAMS) Development**
  - Supports PIs by mapping acceleration environment on multiple platforms: Ground based (KC-135 & Drop Towers), Sounding Rockets, STS, Mir and ISS



SAMS on STS

- Missions supported on Sounding Rockets, STS, Mir
  - **Mapped (flown) 20+ flights on STS & Mir**
    - SAMS-Mir flight unit recovered by STS-91 after 45 months on Mir.
    - SAMS-FF - Supported Hubble on STS 95, Terrier Orion Sounding Rocket - 1999
  - **OARE - Low frequency measurement System flown 10 times on STS**
- Hardware Development for International Space Station
  - SAMS- II - The Acceleration Measurement System for mapping acceleration environment on ISS (payloads and vehicle)
    - Scheduled launch 6A
    - First component delivered to ISS program 8/99
  - MAMS **- Microgravity Acceleration Measurement System -** Low frequency measurement system for ISS (payloads and vehicle) - 6A launch

SAMS II - ISS

Acceleration Measurement Program - GRC

- **PIMS - PI Microgravity Services -** These include services such as data analysis, logging and tracking of ancillary information pertinent to the microgravity environment measured during experiment operations, and preparation of mission summary reports aimed at furthering the PIs understanding of the microgravity environment.

- 1400 User Requests fulfilled (300 International). Annual International Micro-g Meeting, Astronaut Education for Classes & PI Interpretation Tutorials

- **Microgravity Requirement Verification** - Defend and interpret acceleration requirements for ISS.

- **Microgravity Emissions Lab**
  - Ground Based Facility to measure disturbances for all payloads on ISS. Fulfills ISS requirement to be a "good neighbor" on ISS.

All of these activities at Glenn are funded through NASA Code Ug, the Microgravity Research Program Office at MSFC and the Space Station Program Office at JSC.

Section 1:

Technical Introduction and Orientation

Presented by

Kenol Jules

PIMS Project Scientist

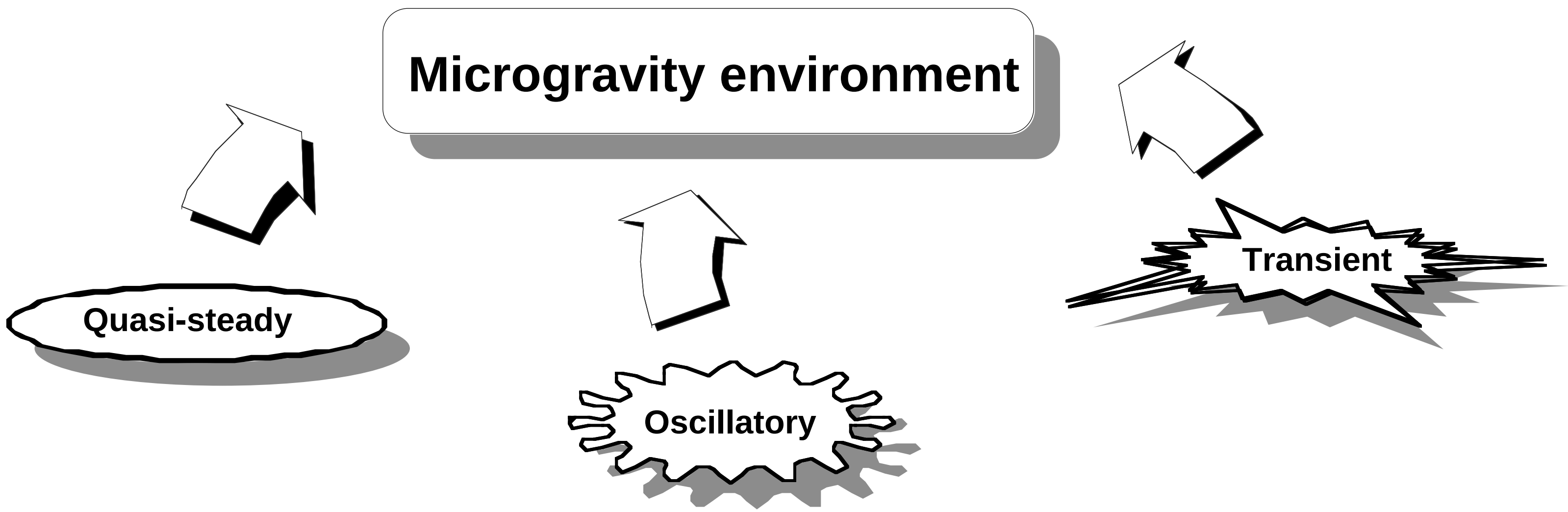
NASA Glenn Research Center

Introduction

- **Microgravity Environment Interpretation Tutorial (MEIT)**
  - ***Purpose:***
    - Convey significant features of the microgravity acceleration environment to the microgravity Principal Investigator teams and other interested parties.
  - ***Content*:**
    - Acceleration Measurement Systems
    - Advanced Acceleration Systems (SAMS-FF)
    - Basics of Signal Processing
    - Analysis Techniques for Quasi-Steady Data
    - Analysis Techniques for Vibratory Data
    - Microgravity Environment of Non-orbital Platforms
    - Highlights of the Microgravity Environment of the Orbiters and Mir
    - Implications for Microgravity Experimenters
    - ISS Acceleration Environment Predictions
    - PIMS Space Station Operation
    - ISS Acceleration Data Flow Demo
    - Vibration Isolation Techniques
    - Predicting Residual Acceleration Effects on Space Experiments
    - Impact of the Microgravity Environment on Experiments

What is a *"microgravity environment"* ?

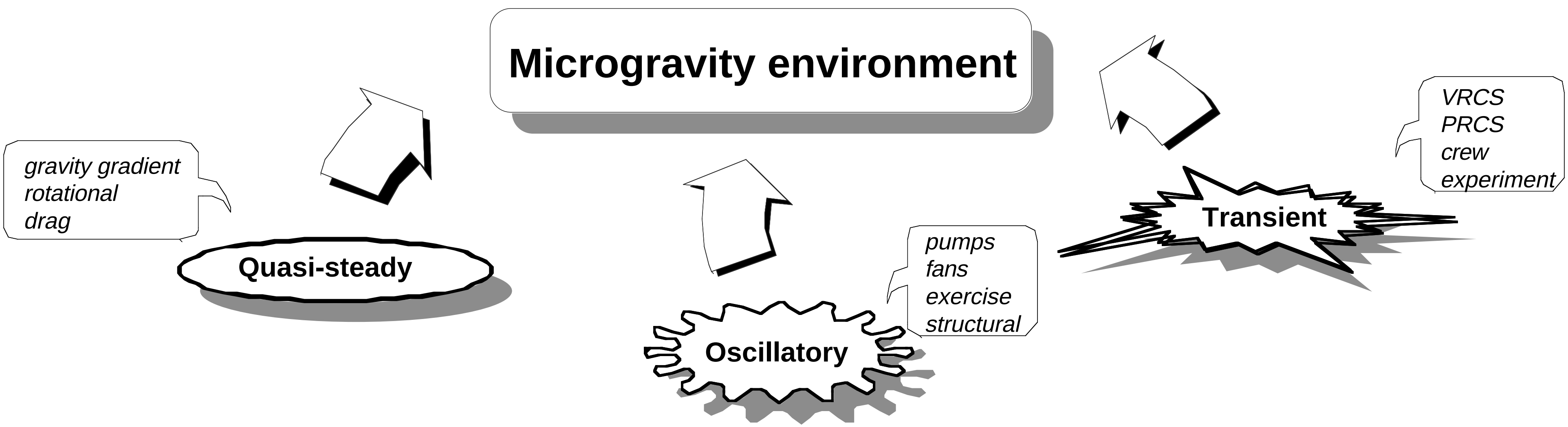
Major properties



What is a *“microgravity environment”* ?

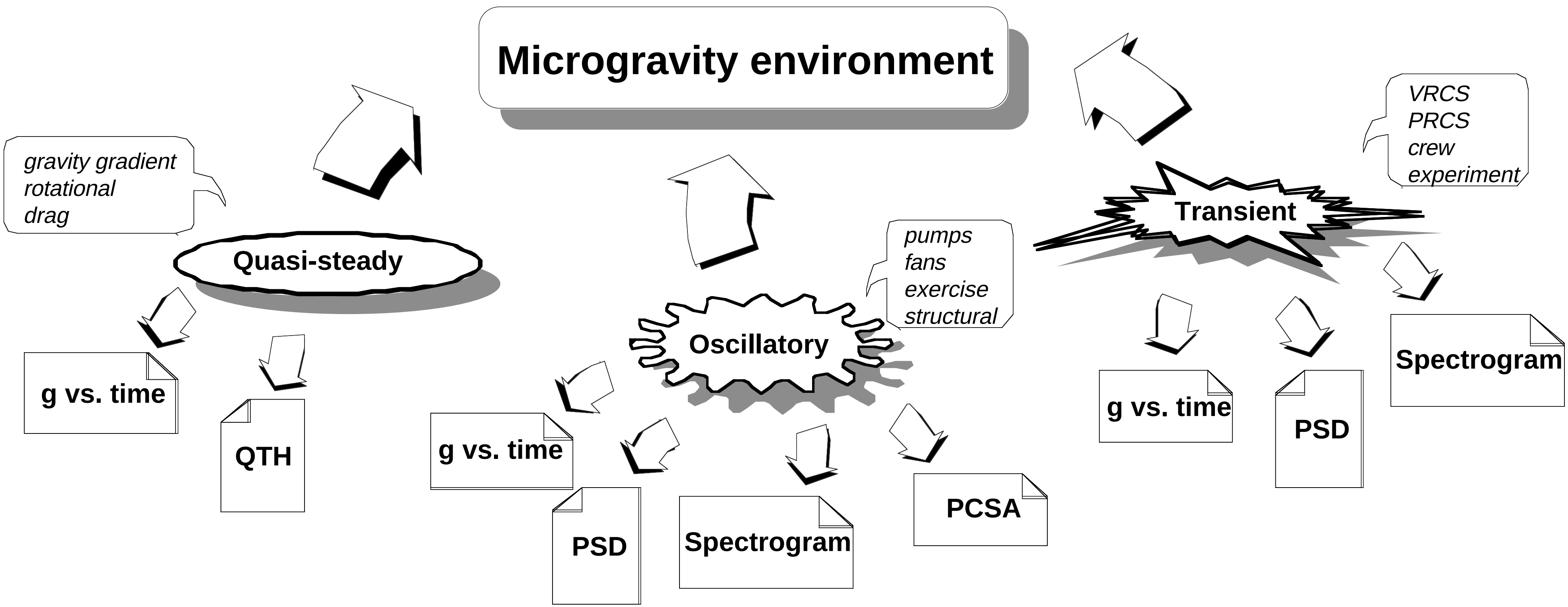
Major properties

What causes these accelerations?

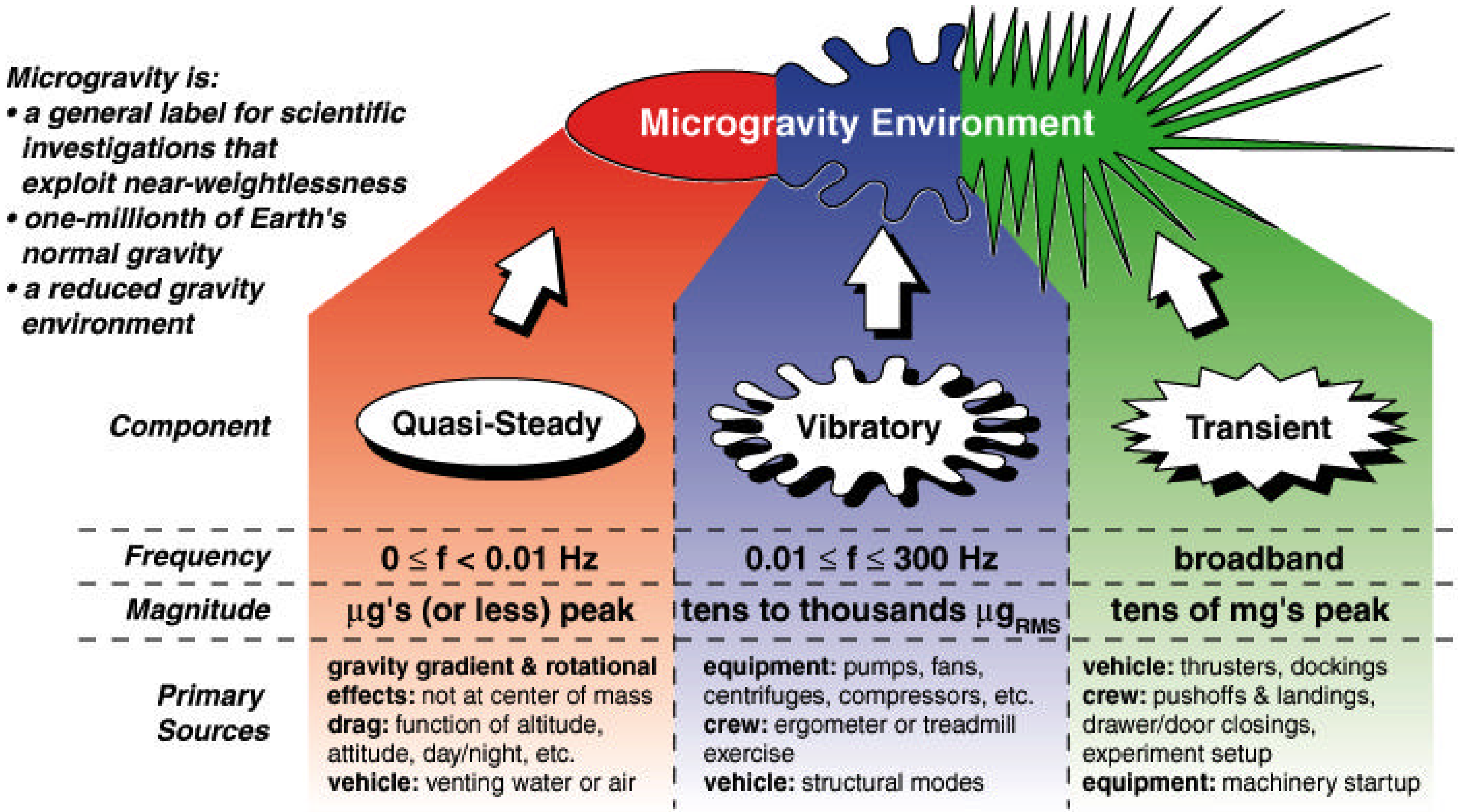


What is a *"microgravity environment"* ?

- **Major properties**
- **What causes these accelerations?**
- **How can we display it?**



Components of the Microgravity Environment



What does all this mean to me?

- The environment is NOT “zero-g”!
- Experiments may be affected by the microgravity environment
- This tutorial will explain what the environment is, how we measure it, how we explain it to you, and show what impacts the environment has had on some experiments.

Acceleration Measurement Systems (common)

- **SAMS:** Space Acceleration Measurement System - instrument which measures accelerations from 0.01 Hz to 100 Hz on Shuttle, Mir, and KC-135. (NASA Glenn)
- **SAMS-FF:** SAMS for Free Flyers - instrument for free flyers (e.g. sounding rockets), Shuttle, and KC-135 which measures linear and roll-rate accelerations. (NASA Glenn)
- **SAMS-II:** Second generation SAMS - instrument which will measure accelerations from 0.01 Hz to 400 Hz on ISS (NASA Glenn)
- **OARE:** Orbital Acceleration Research Experiment - instrument which measures low frequency accelerations from DC up to 1 Hz (NASA Glenn)
- **MAMS:** Microgravity Acceleration Measurement System - instrument which measures acceleration levels to verify the ISS microgravity environment provided to users (NASA Glenn for JSC)

Important terms

- **Consult the tutorial glossary for in-depth explanation of these and other terms**
- **g:** an acceleration unit equal to Earth's gravitational acceleration at sea level (nominally 9.8 $^{m}/_{sec^2}$)
- **mg (milli-g):** an acceleration unit equal to one-thousandth of 1g
- **μg (micro-g):** an acceleration unit equal to one-millionth of 1g
- **reference frame:** reference point for observations of effects of the accelerations experienced on microgravity science carriers, typically either an inertial reference or a vehicle reference

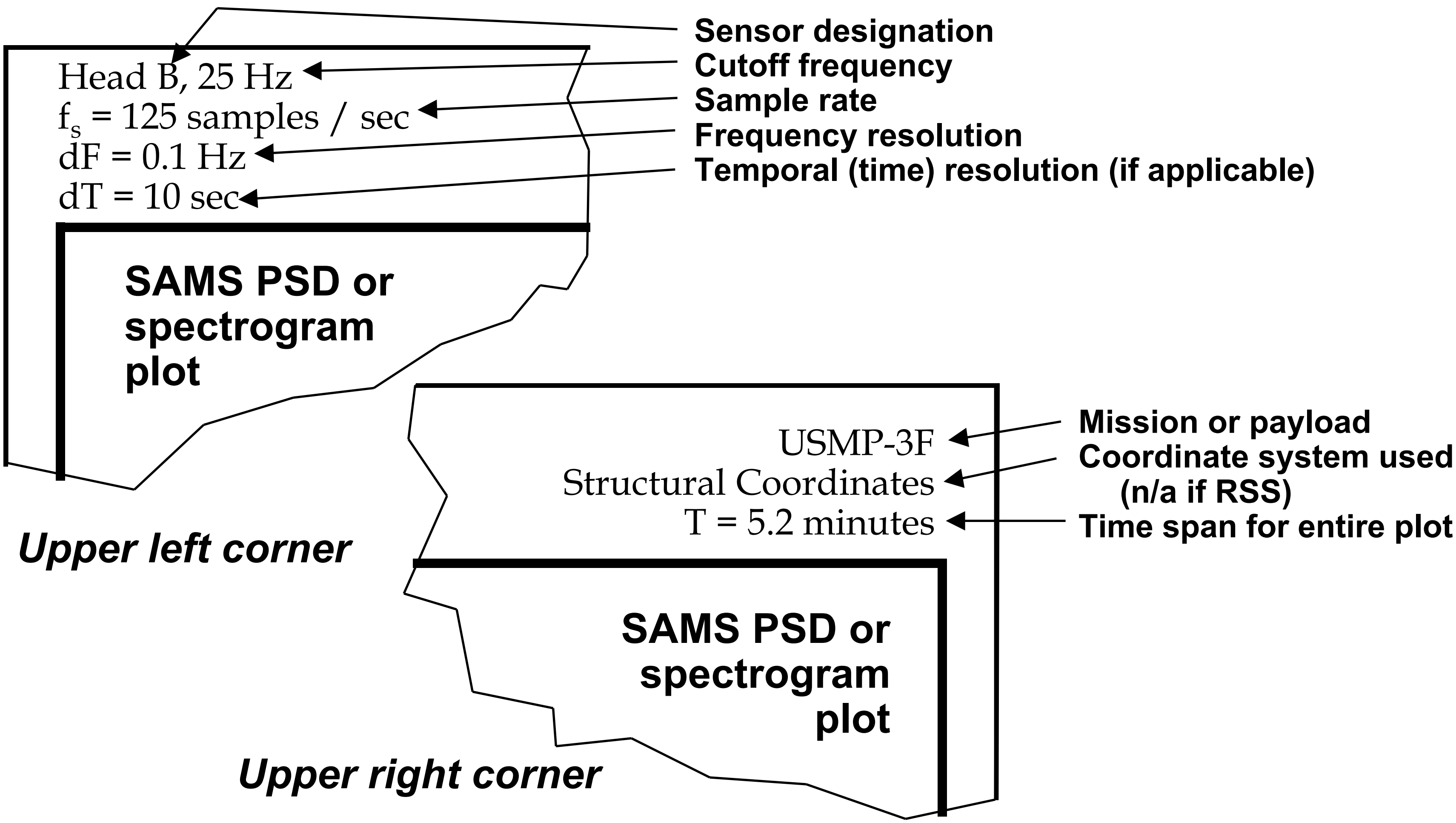
Important terms *(cont'd)*

- **microgravity environment:** an environment in which the effects of gravity are small compared to those we experience on Earth
- **oscillatory:** term used to describe vibratory disturbances with frequency content greater than 0.01 Hz
- **transient:** signals that are impulsive in nature; passing quickly into and out of existence
- **quasi-steady:** a signal which varies at a very low frequency, typically below 0.01 Hz

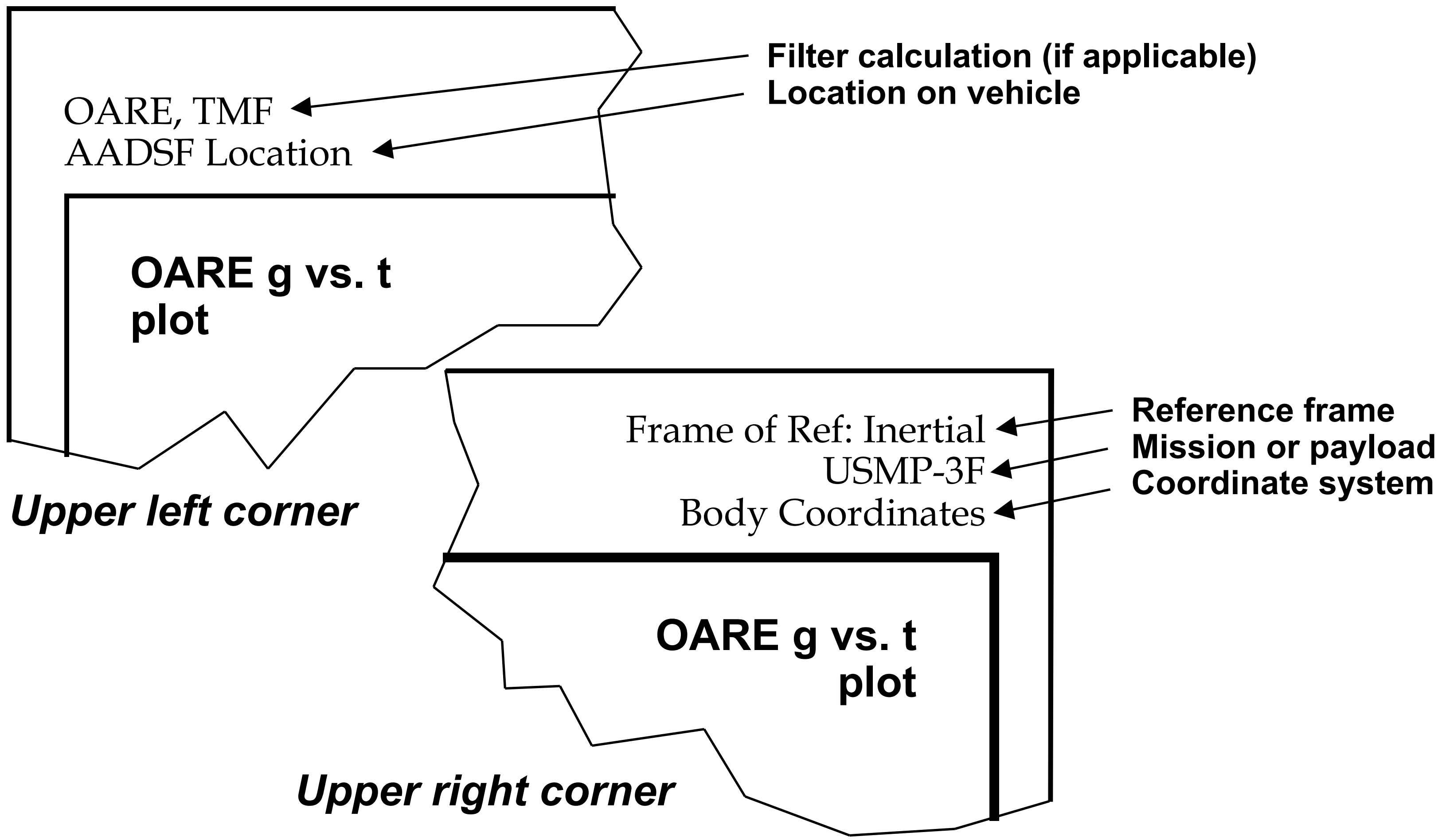
Important terms *(cont'd)*

- **Nyquist criteria:** sampling rate must be at least twice that of the highest frequency contained in the signal of interest
- **cutoff frequency (f_c):** corner frequency in filter response; highest unfiltered frequency of interest
- **sample rate (f_s):** rate at which an analog signal is sampled ($^{samples}/_{sec}$)
- **power spectral density:** a function that quantifies the distribution of power in a signal with respect to frequency
- **spectrogram:** a 3-D representation of the power spectral density as a function of time

SAMS Plot Information

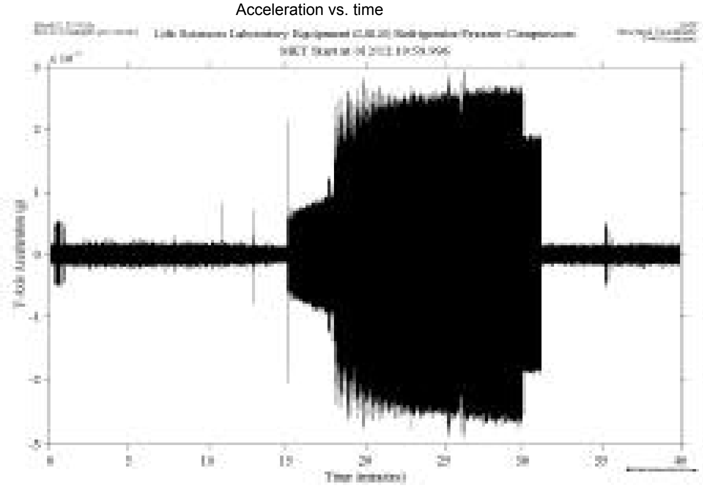


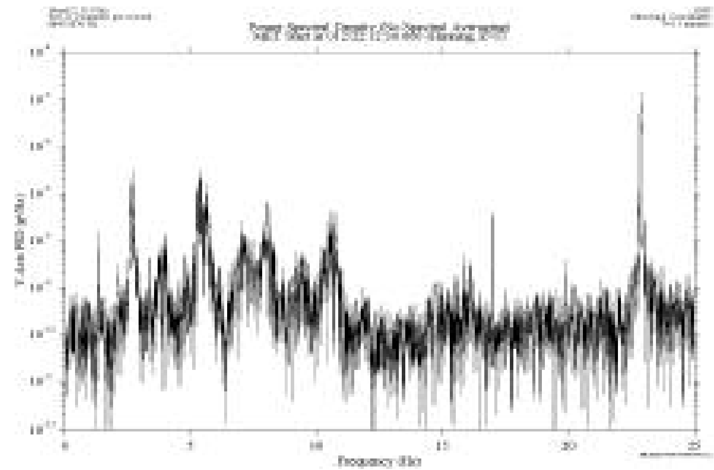
OARE Plot Information

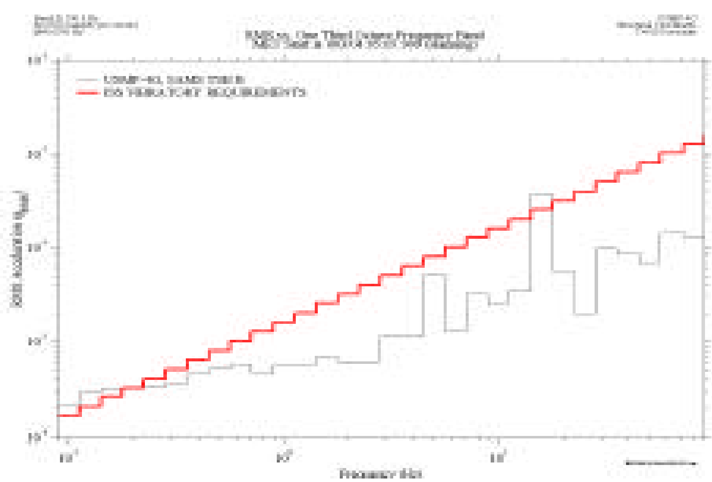


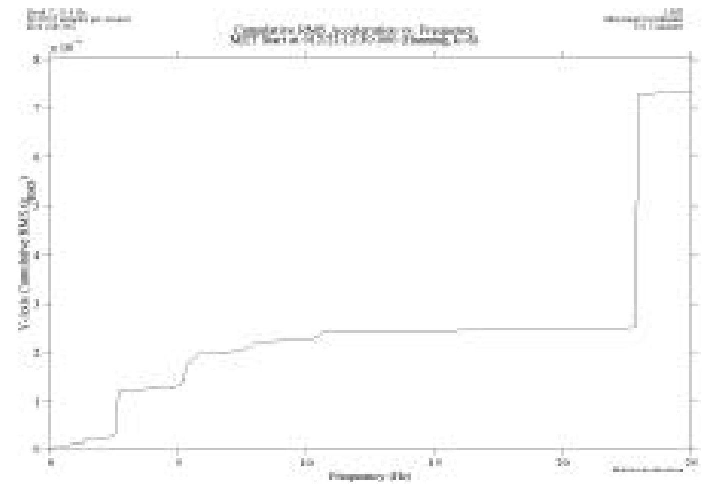
Plot Examples

Acceleration vs. time

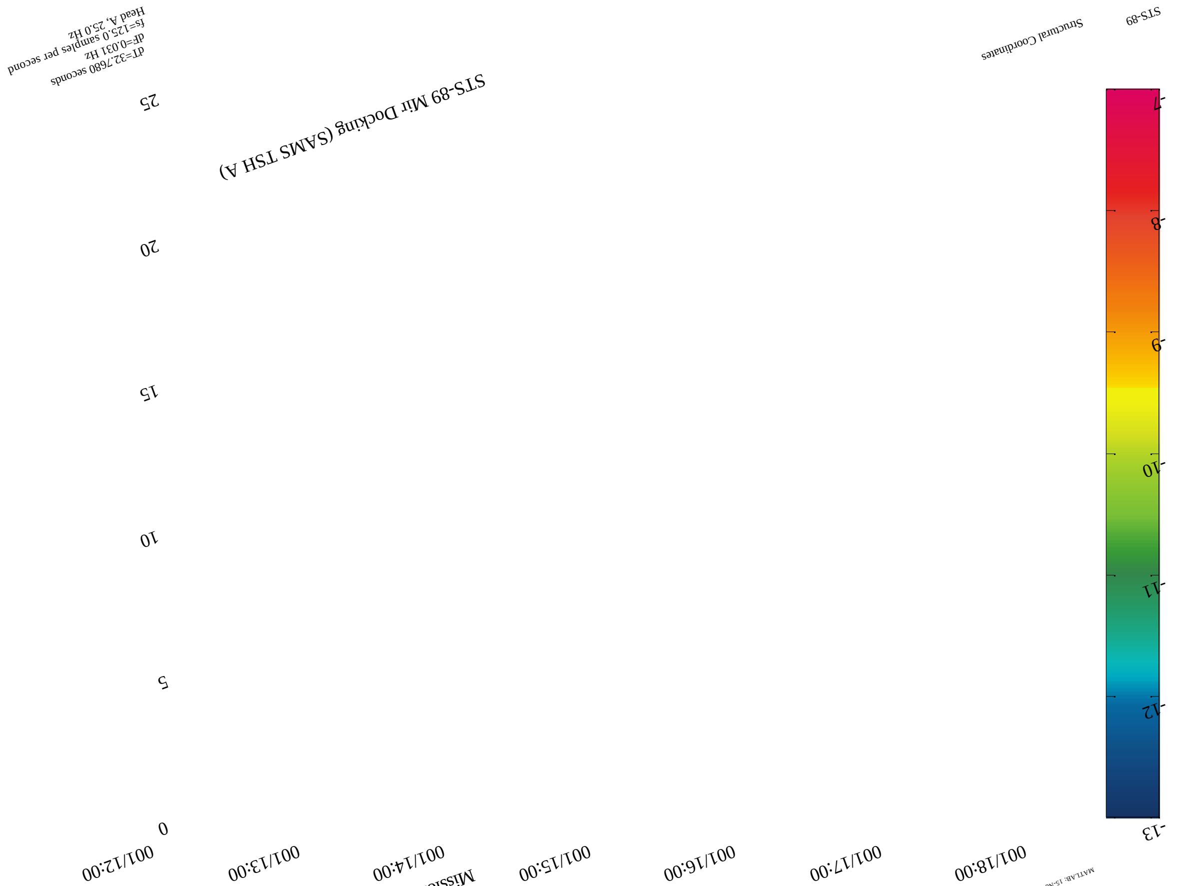








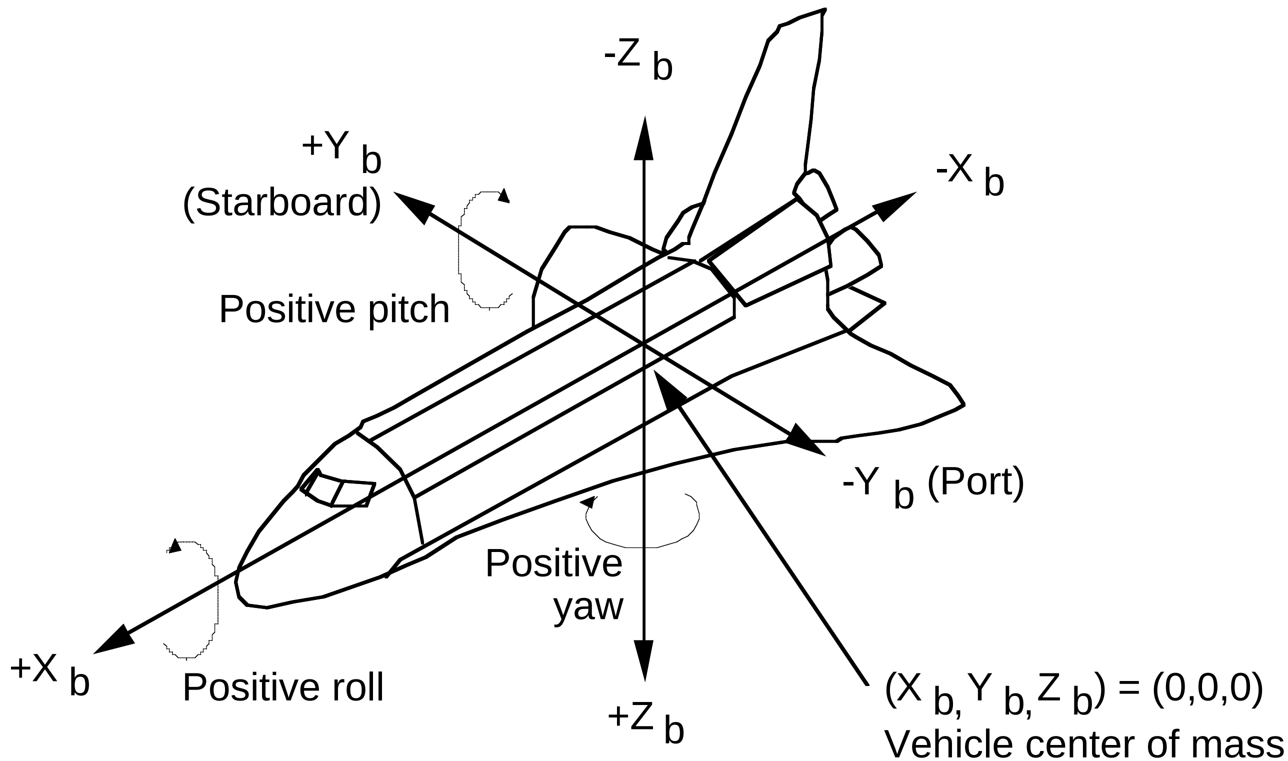
Plot Examples (cont'd)



Spectrogram (acceleration vs. frequency vs. time)
Shuttle/Mir docking

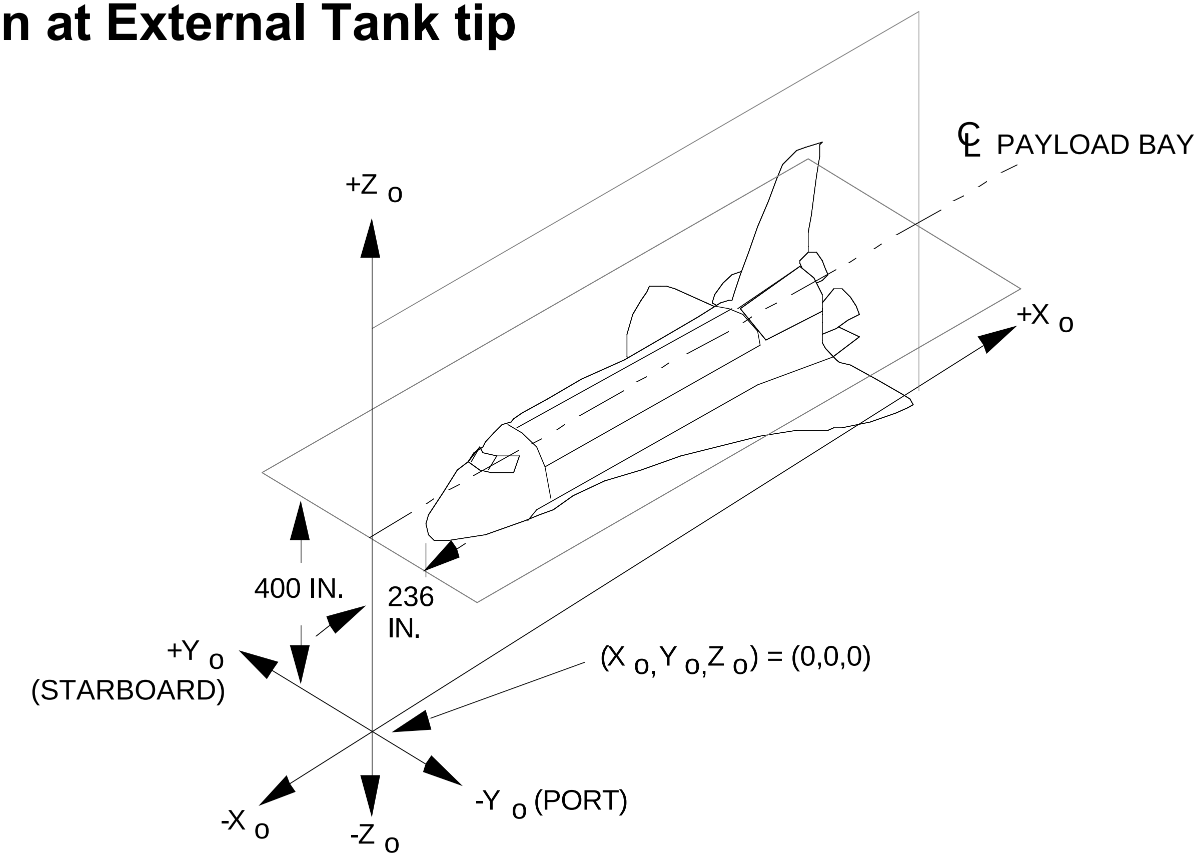
Orbiter Coordinate Systems

- **Body coordinate system**
  - **origin at vehicle center of mass**



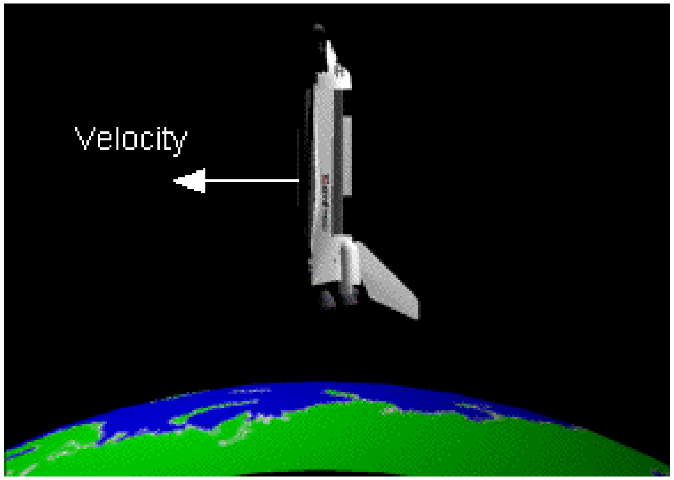
Orbiter Coordinate Systems (cont'd)

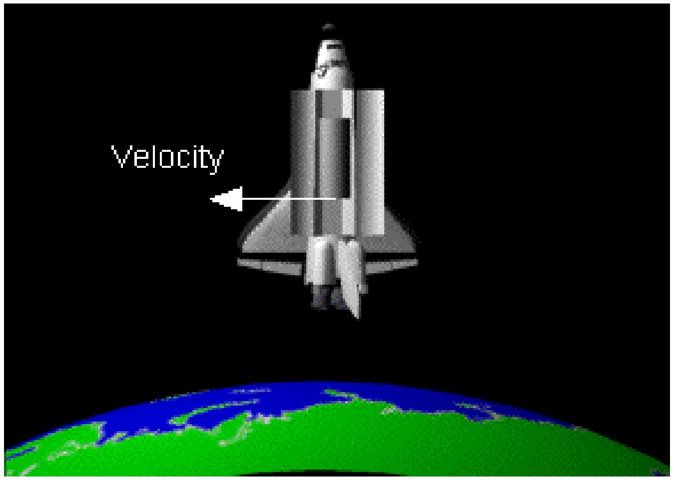
- **Structural coordinate system**
  - **origin at External Tank tip**



Orbiter Attitudes

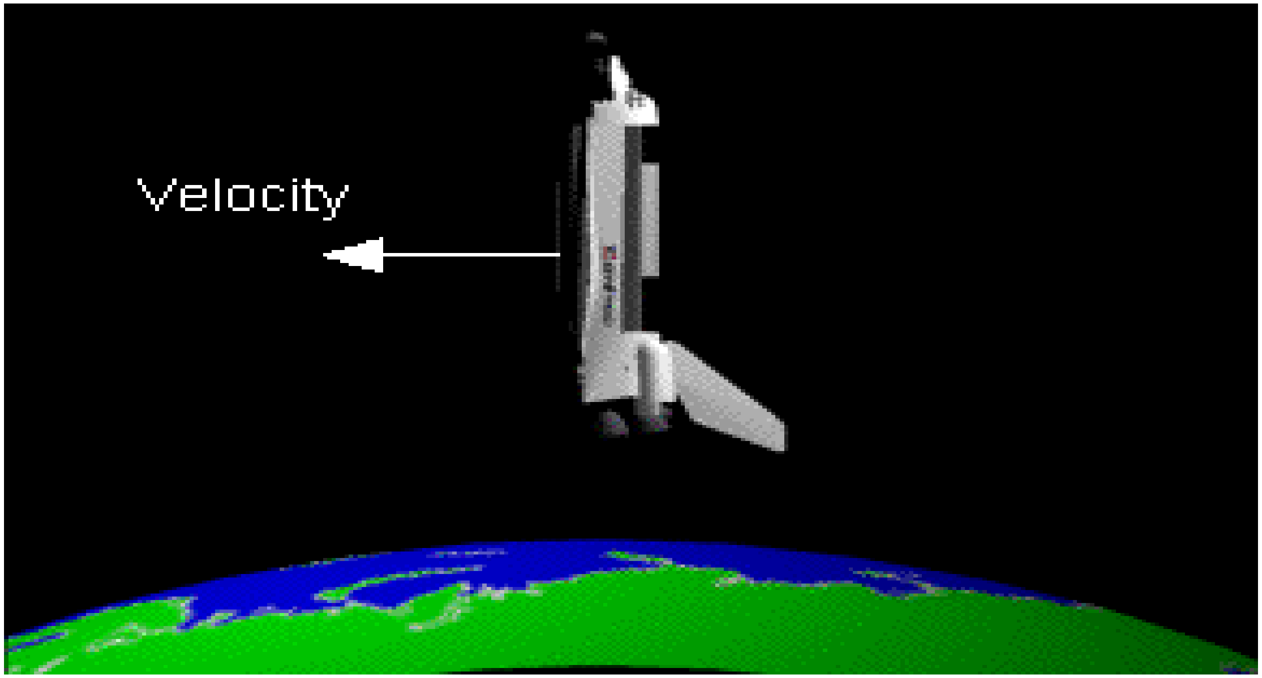
- **Orbiter has two main attitudes**
  - **Local vertical / local horizontal (Earth oriented)**
  - **Inertial (quite often sun oriented)**
- **Designation of attitudes**
  - **pitch / yaw / roll angle relative to airplane mode**
    - e.g. PYR: 90°, 0°, 90°
  - **body axes oriented to nadir (toward Earth) and flight direction**
    - e.g. -XLV / +YVV





Frame of Reference

- **Fixed frame of reference determines sense of observed acceleration**
  - **Inertial reference frame: frame fixed with respect to inertial space**
  - **Science reference frame: frame fixed with respect to vehicle**



References

- DeLombard, R.: "Compendium of Information for Interpreting the Microgravity Environment of the Orbiter Spacecraft." NASA TM-107032, 1996.
- Rogers, M. J. B., Hrovat, K., McPherson, K., Moskowitz, M. E., and Reckart, T.: Accelerometer Data Analysis and Presentation Techniques, NASA TM-113173, September 1997.
- DeLombard, R.; McPherson, K.; Hrovat, K; Moskowitz, M.; Rogers, M. J. B.; and Reckart, T.: Microgravity Environment Description Handbook, NASA TM-107486, 1997.
- Sutliff, T. J.: Requirements and Development of an Acceleration Measurement System for International Space Station Microgravity Science Payloads, NASA TM-107484, June 1997.

Section 2:

PIMS Interaction with Principal Investigator Teams

Presented by
Kenol Jules
PIMS Project Scientist
NASA Glenn Research Center

Principal Investigator Microgravity Services (PIMS)

- PIMS performs the project scientist role for the accelerometer instruments
  - PIMS works with the science experiment principal investigators, project scientists, and other program participants to assist in the understanding and use of the acceleration data and information
  - PIMS products include general and specific analyses, vehicle characterization, and mission summary reports
  - PIMS conducts the Microgravity Measurements Group (MGMG) meetings to foster interchange of data and information within the microgravity environment community and to the microgravity science community
  - PIMS conducts the Microgravity Environment & Interpretation Tutorial (MEIT) to convey significant features of the microgravity acceleration environment to the microgravity Principal Investigator teams and other interested parties

Principal Investigator Microgravity Services (PIMS)

support NASA's Microgravity Research Program Principal Investigators (PIs) by providing acceleration data processing, analysis, and interpretation for a variety of reduced gravity carriers such as:

- **Space Shuttle**
- **Parabolic Aircraft (KC-135)**
- **Sounding Rockets**
- **Drop Towers,**
- **Mir**
- **ISS**

Principal Investigator Microgravity Services (PIMS)

Analyze acceleration data from a number of acceleration measurement systems such as:

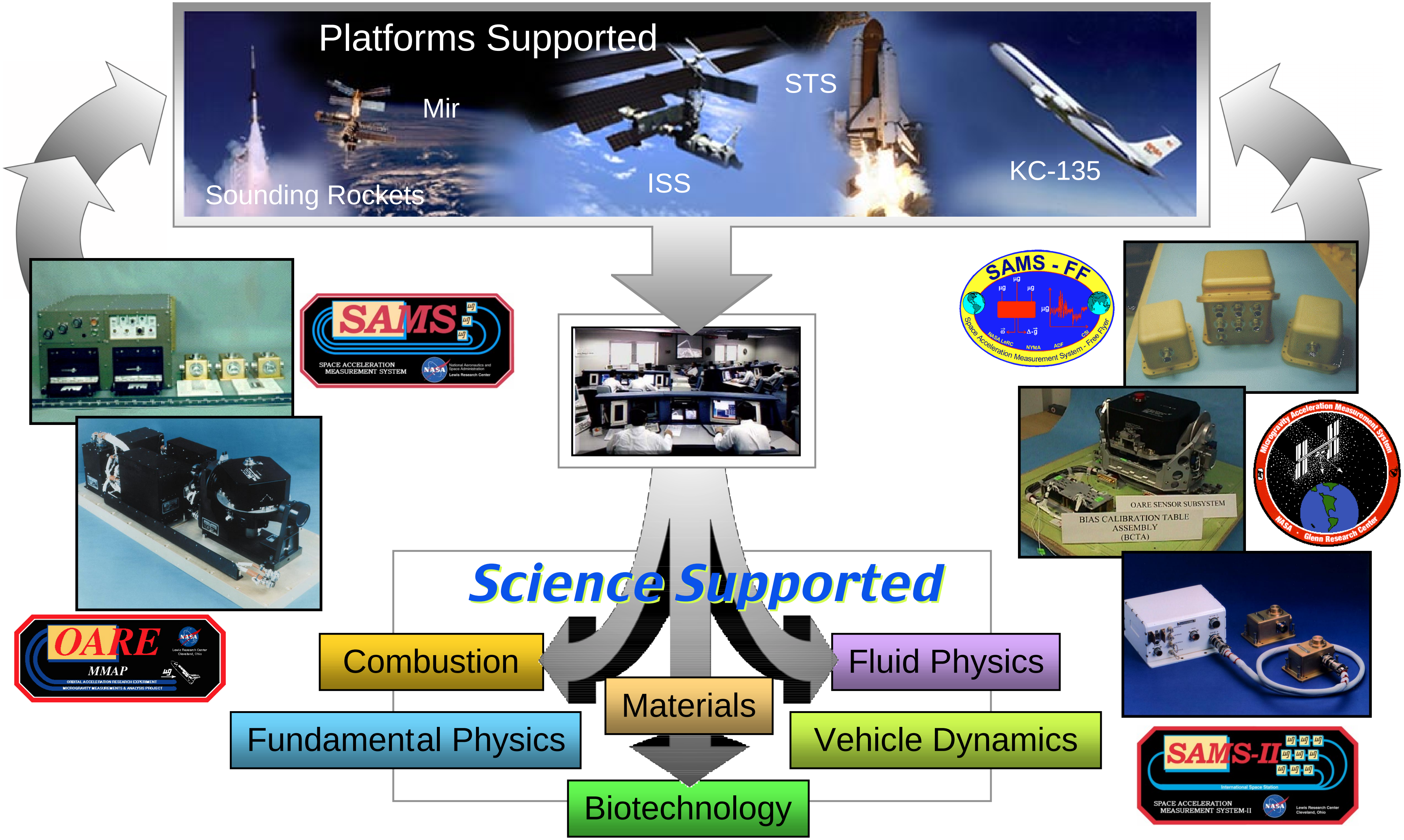
- **Space Acceleration Measurement System (SAMS)**
- **SAMS-II**
- **Space Acceleration Measurement System for Free-Flyers (SAMS-FF)**
- **Orbital Acceleration Research Experiment (OARE)**
- **Microgravity Acceleration Measurement System (MAMS)**

Principal Investigator Microgravity Services (PIMS)

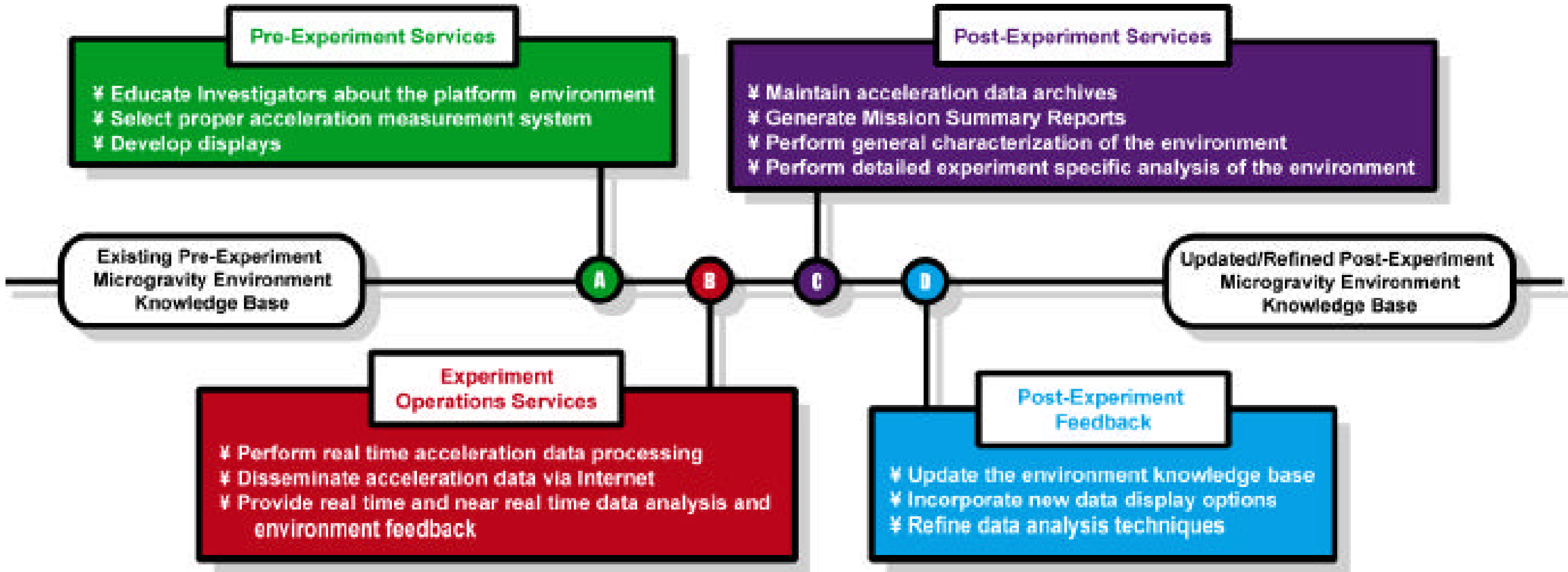
Support various scientific disciplines such as:

- Biotechnology
- Combustion Science
- Fluid Physics
- Materials Science
- Fundamental Physics
- Vehicle Dynamics

PIMS Interaction with Principal Investigator Teams



PIMS Functions During Experiment Life Cycle



PIMS' support of Principal Investigator Teams:

- Process, analyze, and interpret accelerometer data to characterize the microgravity environment of various platforms for the Principal Investigator Teams.
- Maintain archive of acceleration data from various microgravity platforms such as Mir, Space Shuttle, KC-135, sounding rockets and ISS.
- Store and distribute acceleration data:
  - CD-ROM
  - Internet file server
  - World Wide Web (WWW)
  - Mission reports
  - NASA Technical Memoranda (TM)

PIMS' support of Principal Investigator Teams:

- Provide PI teams easy access to plots of acceleration data via WWW
- Provide customized format plots to PI teams based on pre-mission inputs
- Provide near real time and off line access to acceleration data to PI teams
- Provide PI teams anonymous FTP access to processed acceleration data files
- PI can request plotted data or data files via the WWW
- PI can submit electronic request for data processing

Analyze acceleration data

- Development and maintenance of the Microgravity Environment Description Handbook (MEDH), NASA TM-107486
  - overview of known microgravity environment disturbances cross-referenced by carrier, source, acceleration magnitude, and frequency
  - Generation of Mission Summary Reports (MSRs)
  - analyze data from a given mission
  - summarize any unique features in the data
  - update the knowledge base in the MEDH
- various NASA Technical Memoranda (TM)
- Analysis based on PI specific requests
- Information on WWW (MEDH, MSRs, etc.)
  - http://www.lerc.nasa.gov/WWW/MMAP/PIMS

PIMS Plotted Data Options

Display Format	Regime(s)	Notes
Acceleration versus Time	Transient, Quasi-Steady, Vibratory	• precise accounting of measured data with respect to time; best temporal resolution
Interval Min/Max Acceleration versus Time	Vibratory, Quasi-Steady	• displays upper and lower bounds of peak-to-peak excursions of measured data • good display approximation for time histories on output devices with resolution insufficient to display all data in time frame of interest
Interval Average Acceleration versus Time	Vibratory, Quasi-Steady	• provides a measure of net acceleration of duration greater than or equal to interval parameter
Interval RMS Acceleration versus Time	Vibratory	• provides a measure of peak amplitude for pure sinusoids
Trimmed Mean Filtered Acceleration versus Time	Quasi-Steady	• removes infrequent, large amplitude outlier data
Quasi-Steady Mapped Acceleration versus Time	Quasi-Steady	• use rigid body assumption and vehicle rates and angles to compute acceleration at any point in the vehicle
Quasi-Steady Three-Dimensional Histogram (QTH)	Quasi-Steady	• summarize acceleration magnitude and direction for a long period of time • indication of acceleration "center-of-time" via projections onto three orthogonal planes

PIMS Plot Options

Display Format	Regime(s)	Notes
Power Spectral Density (PSD) versus Frequency	Vibratory	• displays distribution of power with respect to frequency
Spectrogram (PSD versus Frequency versus Time)	Vibratory	• displays power spectral density variations with time • identify structure and boundaries in time and frequency
Cumulative RMS Acceleration versus Frequency	Vibratory	• quantifies RMS contribution at and below a given frequency
Frequency Band(s) RMS Acceleration versus Time	Vibratory	• quantify RMS contribution over selected frequency band(s) as a function of time
RMS Acceleration versus One-Third Frequency Bands	Vibratory	• quantify RMS contribution over proportional frequency bands • compare measured data to ISS vibratory requirements
Principal Component Spectral Analysis (PCSA)	Vibratory	• summarize magnitude and frequency excursions for key spectral contributors over a long period of time • results typically have finer frequency resolution and high PSD magnitude resolution relative to a spectrogram at the expense of poor temporal resolution

Provide data processing tools

- Perform binary to ASCII conversions
- Access, retrieve, and display acceleration data using the same set of tools developed by the PIMS project
- Each PI has control over his / her own displays
- Offline analysis requests is submitted via a web-based system
  - processed results are made available within a given period of time
- Real-time displays are available via the WWW

PIMS support during ISS operation

- PIMS will receive, process, and store acceleration data for SAMS-II and MAMS data starting with flight 6A operations
- A universal storage format will be used for data storage
- Real-time data plots of the various available accelerometers will be available via the PIMS WWW page
- Offline access to plotted data and analysis capabilities available through PIMS and the PIMS WWW page
- General and specialized characterization of the ISS microgravity environment

In Closing, PIMS' mission is:

- To assist PI teams in understanding different aspects of measuring and interpreting the microgravity environment.

- To provide interpretation of the microgravity environment and perform detailed analyses for general and specialized characterization.

- To educate PIs, Project scientists and associates about the microgravity environment through MEIT tutorials and MGMG gatherings.

Principal Investigator Microgravity Services

Acceleration Measurement WWW links

- Microgravity Science Division at NASA Glenn Research Center
  - http://microgravity.grc.nasa.gov
- NASA Glenn Acceleration Measurement Program
  - http://microgravity.grc.nasa.gov/MSD/MSD_htmls/accel_meas.html
- Principal Investigator Microgravity Services Home Page
  - http://microgravity.grc.nasa.gov/MSD/MSD_htmls/PIMS.html

Microgravity Environment References

- Microgravity Environment Description Handbook TM
  - Compilation of major microgravity environment disturbances, their sources, and their effects as measured on the Shuttle Orbiters and the Mir Space Station
  - NASA TM-107486 July 1997
  - http://www.grc.nasa.gov/WWW/MMAP/PIMS/HTMLS/Micro-descpt.html
- Acceleration Data Analysis and Presentation Techniques TM
  - Detailed description of acceleration data analysis techniques
  - http:// www.grc.nasa.gov/WWW/MMAP/PIMS/HTMLS/adapt.html
- Mission Summary Reports
  - Mission specific characterizations for various Shuttle and Mir missions
  - http:// www.grc.nasa.gov/WWW/MMAP/PIMS/HTMLS/reportlist.html

Section 3:
Acceleration Measurement Systems

William M. Foster II

Space Acceleration Measurement Systems (SAMS)

Project Manager

Presentation Agenda

- **Overview**
- **Carriers/Facilities Support Requirements**
- ***Space* Acceleration Measurement Systems (SAMS)**
  - Forerunners to Current Systems
    - High Frequency Generation I: SAMS
    - Low Frequency Generation I: OARE
  - Systems Currently Being Deployed
    - High Frequency Generation II: SAMS-II Elements
    - High Frequency Generation III: SAMS-FF Elements
    - Low Frequency Generation II: MAMS
- **Mission Operations**
  - On-Orbit & Ground
- **Future Development**
- **Acceleration Measurement Customers**

Overview

- **Initial Acceleration Measurement Systems**
  - High Frequency Data (Space Acceleration Measurement System)
  - Low Frequency Data (Orbital Acceleration Research Experiment)

- **International Space Station**
  - High/Low Frequency Accelerations
  - Need for Microgravity Acceleration Data
    - Microgravity Community (PIs, Mission & Project Scientists, PIMS)
    - ISS Vehicle Characterization
    - Information to ISS Crew
  - Measure, Process, Record, & Downlink Acceleration Data
  - Distribute Sensors Throughout ISS
  - Long ISS Mission Duration (Years) vs. Shuttle (~ Two Weeks)
  - Real Time Data Analysis Required
  - Data Acquisition and Parameter Control at PI Sites
  - Real Time Operations

Overview (continued)

- **Future Shuttle Missions, Sounding Rocket, KC-135, and other**
  - High/Low Frequency Accelerations
  - Microgravity Community (PI's, Mission & Project Scientists, PIMS)
  - Measure, Process, & Record Acceleration Data
  - Distribute Sensors Throughout Payload
  - Short Duration Missions
  - Data Analysis Required (Supplied by PIMS)
  - Data Acquisition and Parameter Control by PI's

Carriers/Facilities Support Requirements

- **Support Requirements for the International Space Station**
  - Based on PIMS-001, Experiment Support Requirements Document
  - Frequency Measure Range: Quasi-Steady to 300 Hz
  - Quasi-Steady Specification: component perpendicular to the orbital average acceleration vector must be < 0.2×10^{-6} g
  - Acceleration Magnitudes: 0.01 µg to 100 mg
  - Disturbance Triggers: 1 µg to 1 mg
  - Triaxial Sensor Close to Test Cell
  - Align One Sensor Axis with Test Section Axis
  - Onboard Recording of Data for Later Retrieval
  - Experiment Run Time: 1 msec to 1 hr
  - Experiment Process Time: 1 min to 100 days
  - Data Presentation Planned During Operations
    - Acceleration vs. time continuously with running averages
    - Acceleration vs. frequency continuously
    - Power Spectral Density (5 minute updates)

ISS Experiment Measurement Requirements

Experiment Type	Frequency Range	Measurement Level
Biotechnology	QS – 10 Hz	100 µg and above
Fluid Physics	QS – 300 Hz	1 µg to 1 mg
Combustion Science	QS – 50 Hz	10 µg and above
Fundamental Physics	QS – 180 Hz	0.1 µg and above
Material Science	QS – 300 Hz	0.01 µg and above

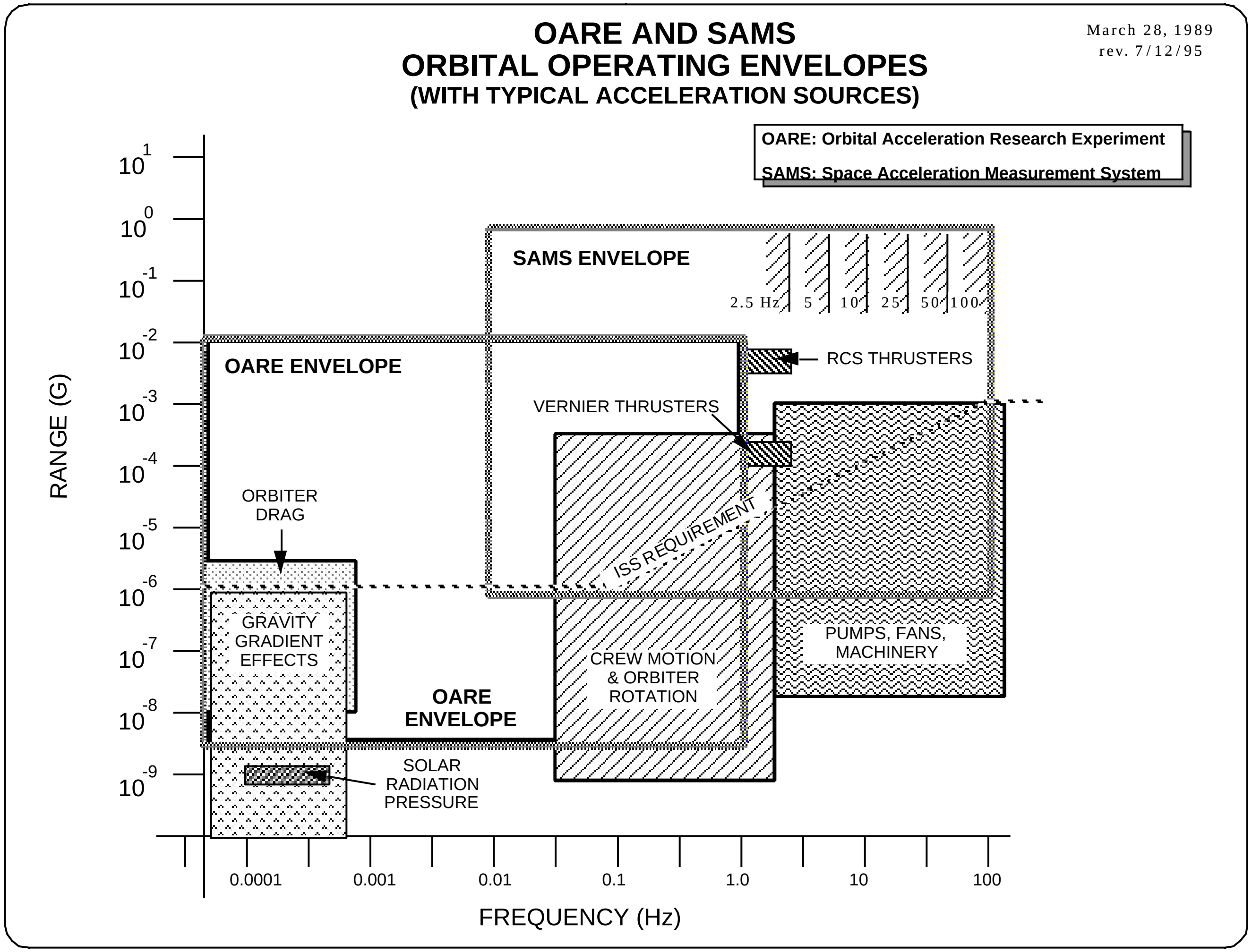
Carriers/Facilities Support Requirements (continued)

- **Future Shuttle Missions, Sounding Rocket, KC-135, and other**
  - Requirements compiled as customers are obtained
  - Frequency Measure Range: Quasi-Steady to 100 Hz
  - Acceleration Magnitudes: 0.01 μg to 100 mg
  - Configurable Modular Hardware and Service Package
  - Triaxial Sensor Close to Area of Interest
  - Align One Sensor Axis with Test Section Axis
  - Onboard Recording of Data for Later Retrieval
  - Support Short and Long Duration Activities
  - Experiment Process Time: 1 min to 100 days
  - Data Presentation Planned During Operations
    - Acceleration vs. time continuously with running averages
    - Acceleration vs. frequency continuously
    - Power Spectral Density (5 minute updates) (Shuttle only)

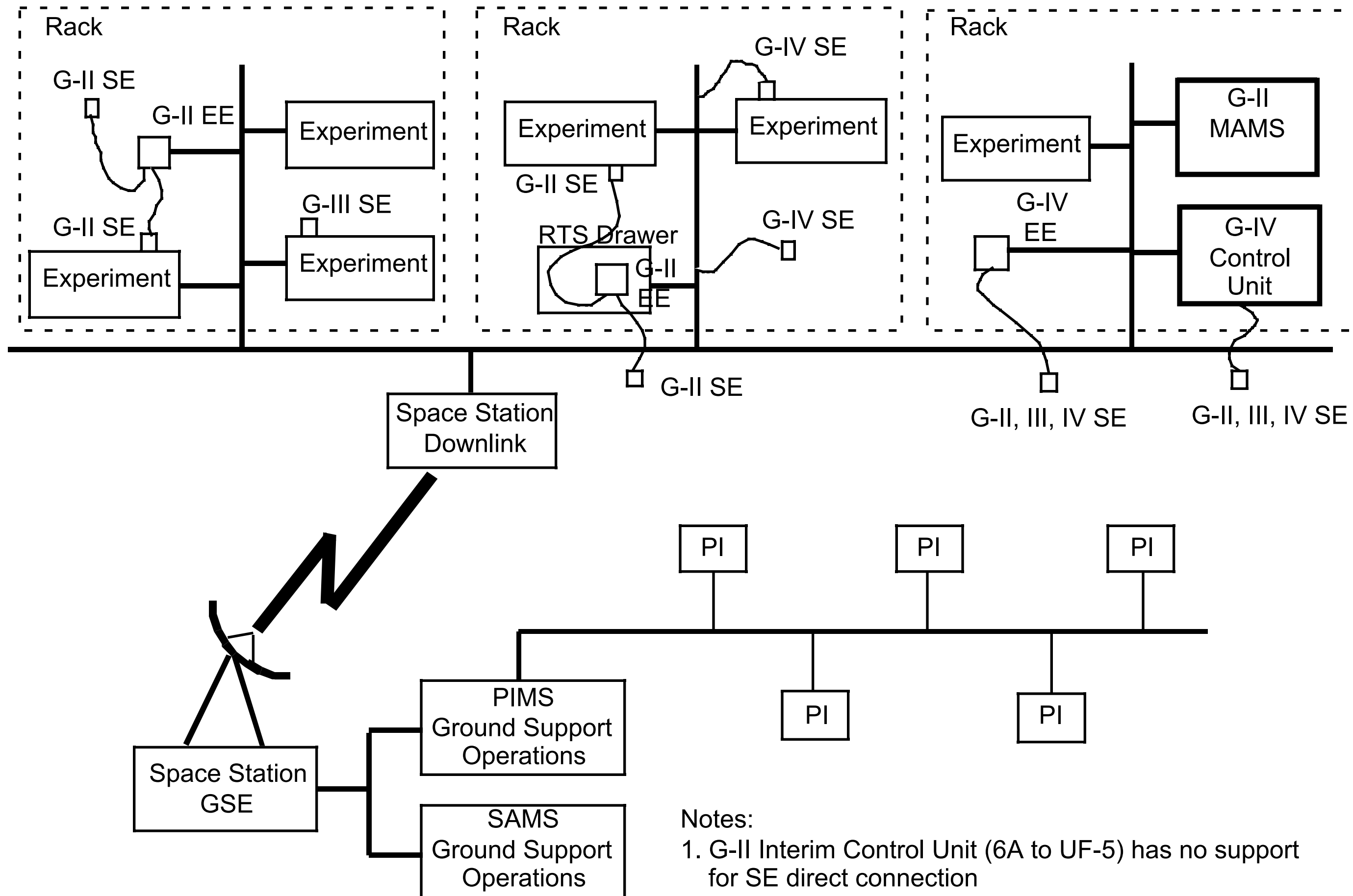
Early Shuttle Microgravity Measurements

- **Microgravity Environment Description Handbook (NASA TM 107486)**
- **Acceleration Data Stored on Web Server**
- **NASA Glenn Systems**
  - Space Acceleration Measurement System (SAMS)
    - 20 Shuttle Flights, 7 Units (1991 to 1998)
    - Measured Acceleration Range: 0.01 to 100 Hz
  - Orbital Acceleration Research Experiment (OARE)
    - 8 Shuttle Flights, 1 Unit (1991 to 1997)
    - Measured Acceleration Range: DC to 1 Hz
- **Other Systems**
  - High Resolution Accelerometer Package (HiRAP)
  - 3-Dimensional Microgravity Accelerometer (3DMA)
  - Microgravity Measurement Device (MMD)
  - Quasi-Steady Acceleration Measurement (QSAM)
  - Microgravity Measurement Assembly (MMA)

Early System Capabilities (Generation I)



Deployment of SAMS Generation II Elements on ISS



Notes:
1. G-II Interim Control Unit (6A to UF-5) has no support for SE direct connection
2. G-II Elements available 6A.
3. G-III Elements available UF-1.
4. Control Unit available UF-5.

High Frequency Generation II System: SAMS-II

- **Remote Triaxial Sensor (RTS) System**
  - Consists of one Electronics Enclosure and two Sensor Enclosure's
  - Acquires acceleration data
  - Performs initial processing of the acceleration data
  - Transmits the acceleration data to Control Unit
- **Interim Control Unit (ICU) Up to UF-5**
  - Stores acceleration data for later analysis
  - Provides control of the RTS systems
  - Provides acceleration data downlink capability
  - Facilitates display of acceleration data on crew laptops
- **Ground Operations Equipment (GOE)**
  - Acquires acceleration data from ISS downlink (SAMS/PIMS)
  - Stores acceleration data for later retrieval (PIMS)
  - Transmits acceleration data to PI sites for analysis (PIMS)

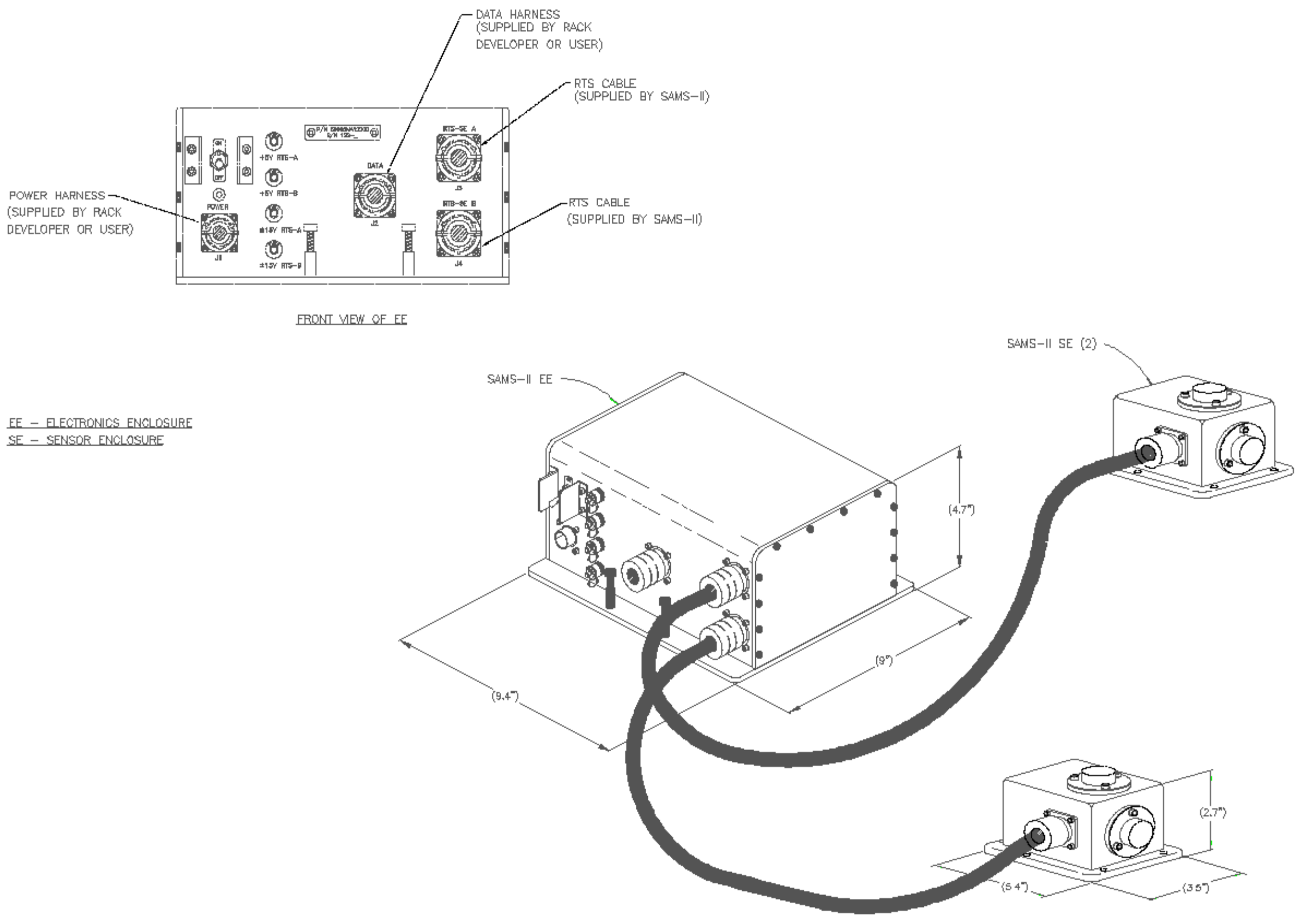
Initial High Frequency Generation II Deployment

- **Remote Triaxial Sensor (RTS) System**
  - Up to Ten RTS Electronics Enclosures (EE's)
  - Up to Two RTS Sensor Enclosures (SE's) per EE
- **One Control Unit (Interim Control Unit from UF-1 to UF-5)**
- **Utilization of ISS Payload Ethernet**
- **Ground Operations**
  - GRC Telescience Support Center (TSC)
  - PI Sites
- **Future Upgrades**

High Frequency Generation II: RTS Description

- **RTS Electronics Enclosure (EE)**
  - Located in EXPRESS or Facility Racks
  - Physical Properties: 9.1 in X 9.3 in. X 4.7 in. & 11.0 LB.
  - Up to Ten EE's for ISS modules
  - Receives Data from SE's
  - Performs Low Level Processing (Temp. Comp. & Axial Misalign.)
  - Transmits Processed Data to ICU/CU
- **RTS Sensor Enclosure (SE)**
  - Located near Microgravity Payloads
  - Physical Properties: 5.6 in X 4.0 in. X 3.5 in. & 2.5 LB.
  - Up to Two SE's per EE
  - Measures Acceleration Data

High Frequency Generation II: Remote Triaxial Sensor (RTS) System



SAMS-II REMOTE TRIAXIAL SYSTEM (RTS)

General Purpose Generation II RTS Capabilities

- **Orthogonal acceleration measurements at two locations**
- **24 Bit Resolution**
- **Single Gain**
- **Dynamic Range: 130 dB (0.1 µg to 1g)**
- **Selectable Frequency Ranges: 300, 200, 100, 50, 25 Hz**
- **Temperature measurement and acceleration data compensation**

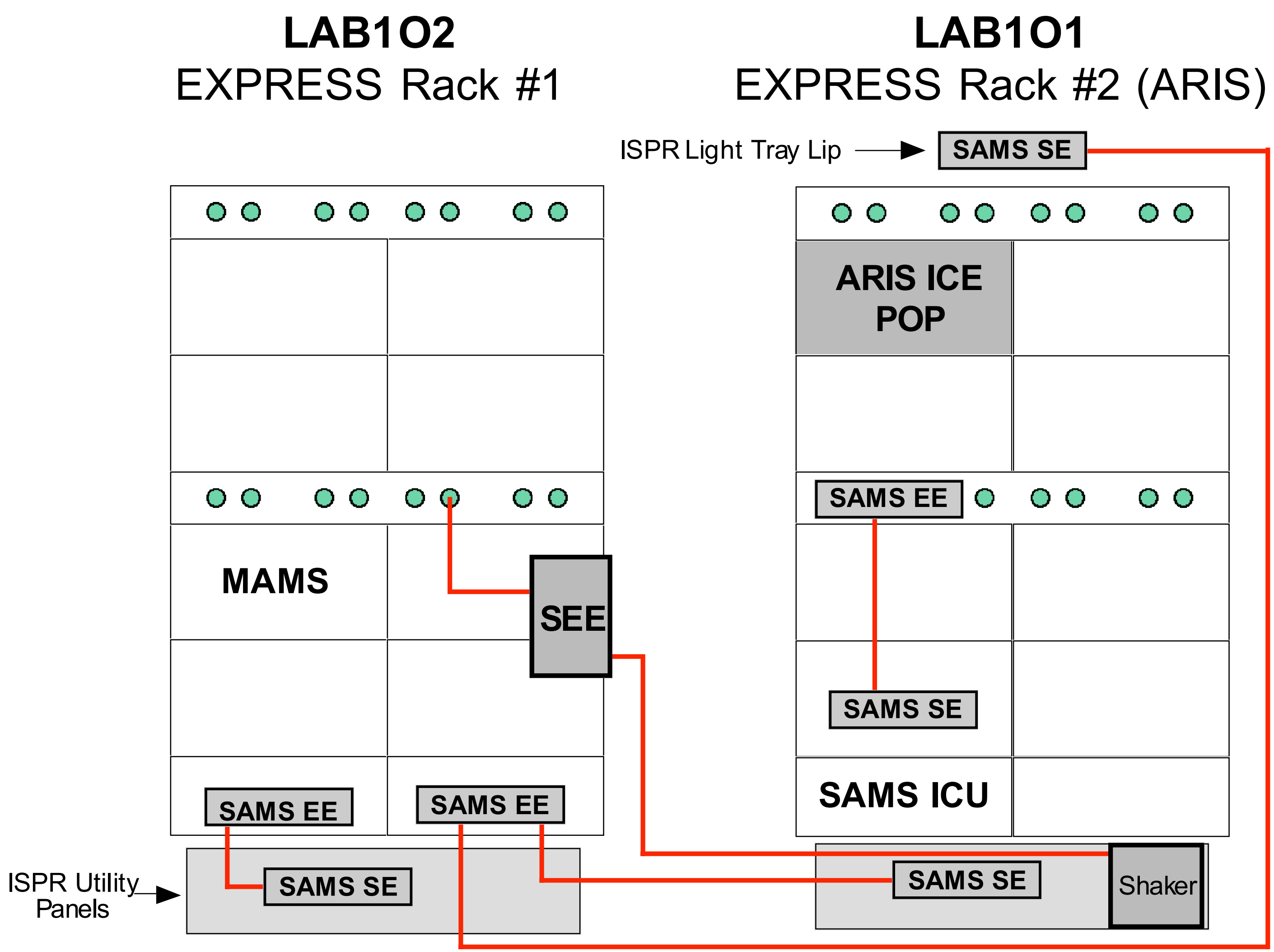
Generation II: Interim Control Unit (ICU)

- **Housed in EXPRESS Rack ISIS Drawer**
- **Connected to the Payload Ethernet Network**
  - For Acquisition of Acceleration Data
  - For Downlink to SAMS-II Ground Operations Equipment (GOE)
  - Receipt of Uplink Commands
- **Interim Control Unit (ICU) Components (UF-1)**
  - ISS Laptop Computer (Portable Computer System - PCS)
  - Power Control Box
  - Limited Data Storage
- **Generation IV Control Unit (CU) Components (UF-5)**
  - High Level Data Processing Capability
  - Removable Media
  - Direct Connection of Sensor Enclosure (Generation II,III,IV)

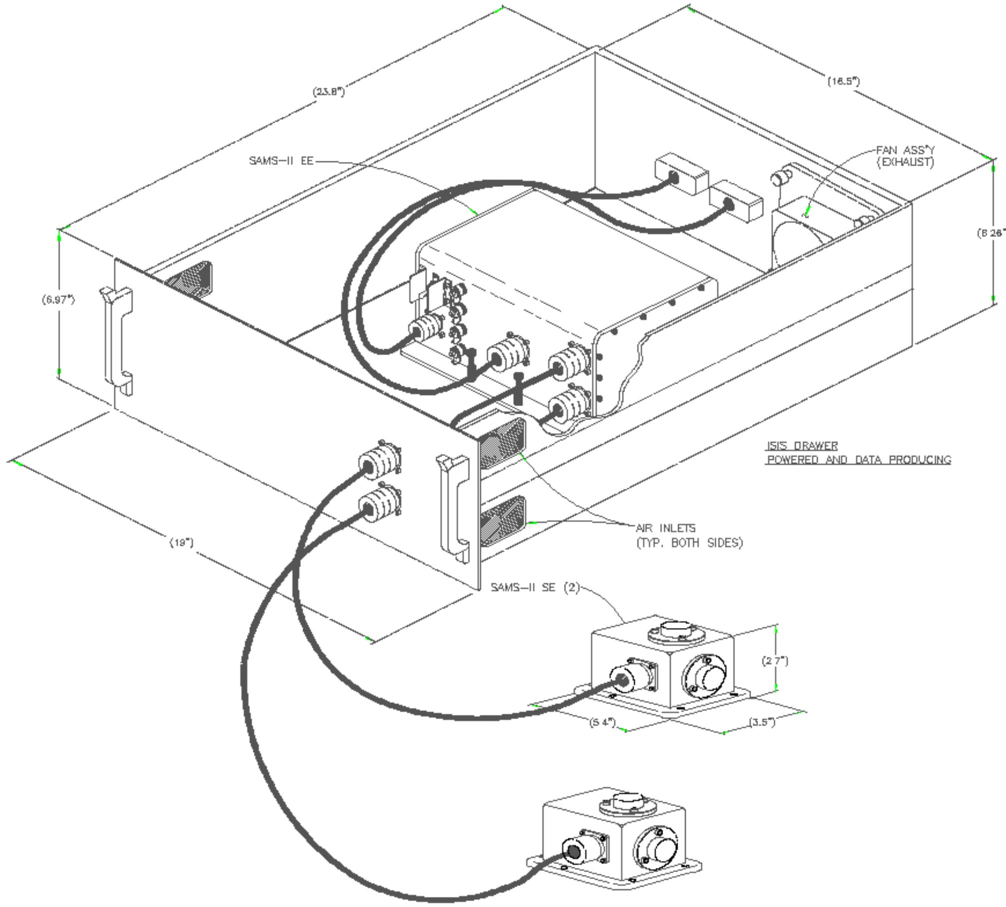
ARIS Initial Characterization Experiment

- **ARIS - Active Rack Isolation System (See Section 14)**
  - **Isolates Experiments from ISS Disturbances**
  - **Developed by Boeing for ISS Program**
- **ARIS ICE - ARIS Initial Characterization Experiment**
  - **Determines ARIS Performance Early in ISS Life**
  - **Utilizes Off-Rack Shaker and On-Rack & Off-Rack Accelerometers**
- **SAMS Support for ICE (UF-1 to UF-2)**
  - **On-Rack: One EE and One SE Dedicated to PCS Experiment**
  - **Off-Rack: Two EE's and Three SE's Dedicated to ARIS ICE**

ARIS Initial Characterization Experiment Layout



RTS-EE in ISIS Drawer for ARIS ICE



CONCEPT FOR SAMS-II RTS FOR ISIS DRAWER

Low Frequency Generation II: Specifications (MAMS)

- **MAMS contains a Miniature Electro-Static Accelerometer (MESA) which has a resolution of 3 x 10^{-9} g.**
  - **The MESA consists of an electro-statically suspended, beryllium, cylindrical proof-mass which is kept centered within an outer "cage" through the use of forcing electrodes.**
  - **The forcing voltage required to keep the cylinder centered is proportional to the acceleration of the outer cage.**
- **MAMS contains a Bias Calibration Table Assembly (BCTA) which allows for the measurement of the sensor bias.**
  - **Sensor bias arises from electro-static charge build-up and temperature gradients on the beryllium cylinder proof-mass.**
  - **Correcting MAMS acceleration data for bias results in an expected accuracy of approximately 50 x 10^{-9} g.**
- **MAMS Frequency Range: DC to 1 Hz.**

Generation III System: SAMS-FF

- **The modular SAMS-FF hardware package includes three different types of sensors, a control and data acquisition module, data storage devices, and ground support equipment interfaces.**
- **The three different types of tri-axial sensors combine to measure both high and low frequency accelerations and the roll rate of the spacecraft.**
- **Smaller, lighter, more flexible, and more power efficient than its predecessors**
- **Standard interface for "stand-alone" acceleration sensor head operation - connect to any computer serial port**
- **Choice of data storage mediums (flash memory, hard disk, etc.)**
- **Real-time data access when a telemetry downlink is available**
- **Custom system configurations for special needs (such as additional sensor heads) easily accommodated**
- **Post-mission data processing available through the PI Microgravity Services data-analysis team**

Generation III SE: Tri-axial Sensor Head (TSH)

- Allied Signal QA 3000 sensors
- Sensor output signal conditioning and filtering
- Adjustable frequency bandwidth, 0-200 Hz (under software control); can be changed during operation
- 24-bit Delta-Sigma analog-to-digital conversion for low noise and large dynamic range
- Over sampling rate at 3.8 to 1
- Full-scale range:
  - up to ~78 milli-g (for operation, at gain of 16)
  - up to 1.25 g (for ground calibration, at gain of 1)
- Sensor temperature measured on each individual axis
- RMS-to-DC measurements --- abbreviated sensor data
- RMS measurement at 600 Hz bandwidth and 0.1g full-scale with minimum crest factor of 5
- Digital signal output(RS-422): low noise, small cables (DB-9 connector)
- Can be used stand alone with a standard RS-422 interface and ±15V power supply
- Only 1.6 W power consumption (±15VDC)
- Compact, light enclosure: 2.9" x 2.9" x 2.8"

Generation III: Fiber Optic Gyro (FOG)

- **Designed to measure roll rate - data will tell how well the spacecraft stabilizes in orbit and the refinement of the satellite onboard control system pointing capability.**

  Some features:

  - **Fiber optical gyroscope with no moving parts**
  - **Low scale factor and bias**
  - **Random walk at 1 deg/hour on any axis**
  - **Low frequency acceleration data can be derived**
  - **Record of available onboard stabilization signals**
  - **Interface electronics in separate package.**

- **Planned deployment on Sounding Rocket and Shuttle.**

Generation III: Specifications

- Acceleration Sensitivity: 10 ng, 0-2 Hz (MSS); 0.6 µg, 0-10 Hz (TSH)
- Acceleration Bandwidth: 0-200 Hz (TSH) Software selectable during operation
- Acceleration Range: ±1.25 g (TSH)
- Number of high freq. sensor enclosures (TSH): 1, 2, 3 or more
- TSH cable length (max): 20 m
- Roll-Rate Sensitivity: 0.1 arc sec
- Roll-Rate Bandwidth: 190 deg/sec
- Data Storage flash(solid state) or hard drive
- Synchronization Options: IRIG-B, GPS, 8-bit digital control and status interface
- Downlink Interface: RS-232 or 422
- Operator intervention: Not Required
- Power Consumption: 1.6-50 W depending on configuration
- Size of CDU (main unit): approximately 5.3" x 5.3" x 5"

High Frequency Acceleration Measurement Systems Comparison

	SAMS	SAMS Upgrade	SAMS-FF	SAMS-II ICU	SAMS-II CU
Vehicle	Shuttle / Mir	Shuttle	Sounding Rocket, Free Flyer, Shuttle, or ISS	ISS	ISS
Concept Development	1987	1995	1996	1996	1994
First Flight	1991	1997	1997	2000	2002
No. of Flights	20 + Mir	2 + 3 more planned	1 + HOST mission (others planned)	Three years in ISS	Seven years in ISS
Sensors Heads	3 per unit	3 per unit	3 per unit	~ 10	~ 20
Frequency Range	Fixed @ 2.5, 5, 10, 25, 50, or 100 Hz	Fixed @ 2.5, 5, 10, 25, 50, or 100 Hz	Selectable in real time up to 200 Hz	Selectable in real time up to 400 Hz	Selectable in real time up to 400 Hz
Low Frequency Capability	Post Mission with OARE data	Post Mission with OARE data	MESA Sensor Subsystem	Real Time with MAMS	Real Time with MAMS
Sensor Distance from Unit	20 ft.	50 ft.	Limited only by RS-422 and / or power drop	Limited only by Ethernet	Limited only by Ethernet
Digital Conversion Location	In Main Unit	In Main Unit	In Sensor Head	In Sensor Head	In Sensor Head
Crew Display	Only for MPESS (1996)	Only for MPESS (1997)	GSE Laptop Display	Onboard Display via Crew Laptops	Integral Onboard Display on CU
Storage Devices	Optical Drives (200 MB per disk)	Hard Drives (2.1 GB per drive)	Configurable (Flash or Hard Drive)	PCS Laptop with Hard Drive	Magneto-Optical & Hard Drive
Data Collected	~ 2 GB per mission	~ 2 GB per mission	Mission dependent	~ 50 GB per inc.	~ 130 GB per inc.
Role Rate Sensor	No	No	Yes, Fiber Optic Gyroscope	No	No
Real Time Processing	Post Flight	Post Flight	Possible in future	Low Level	High Level (DSP)

ISS Initial Mission Operations On-Orbit

- Pre-mission installation of EE's and some SE's planned
- Ability to perform on-orbit EE replacement limited by accessibility within payload rack
- Installation or movement of additional SE's
- No RTS open box maintenance
- Set-up of ISS PCS laptop and associated cables in ICU
- Two removable laptop hard drives for onboard data collection
- ICU laptop can be exchanged for another ISS PCS laptop
- Selective acceleration displays available to the crew on ISS PCS laptops via Payload Ethernet

ISS Initial Mission Operations on Ground

- **SAMS Operations at GRC Telescience Support Center .**
  - Control SE, EE, or ICU on/off modes and SE frequency ranges
  - Communicate maintenance operations to the crew
  - Screen all PI commanding operations
  - Limit operations staff by utilizing selected programmed routines
- **PI Sites**
  - Communication links with GRC TSC via World Wide Web
  - Ability to selectively view PIMS acceleration data displays
  - Command SE frequency range, data start and stop times, and limited data recording (Fully implemented with Generation IV Control Unit)
- **PIMS Operations**
  - Control MAMS on/off modes.
  - Process SAMS data, provide data analyses for PI's, characterize ISS environment, and identify ISS disturbances.

Future Development

- Develop and deploy Generation IV Control Unit with increased processing capability and interfaces.
- SE and EE Size Reduction (Generation IV)
  - Generation III Packaging Improvements Utilized
  - Sensor Miniaturization Technology Considered
  - Universal Serial Port and Ethernet capabilities for SE's
- Software Modifications to support communication of other Acceleration Systems with Control Unit (MAMS)
- Package Acceleration System for External Facility on JEM Porch
- Identification of Disturbance Signatures on User Displays

Current Customers for SAMS

- **PI Measurement Services (PIMS)**
- **ISS Customers**
  - ARIS EXPRESS Racks (Eight Racks Planned)
  - Physics of Colloidal Spheres (PCS) Experiment for UF-1
  - ARIS ICE for UF-1
  - Combustion Integrated Rack (CIR) for UF-3
  - Material Science Facility
  - BioTechnology Facility (BTF)
  - Fluids Integrated Rack (FIR) for UF-5
  - Microgravity Science Glovebox (MSG)
  - Low Temperature Microgravity Physics Facility (LTMPF)
- **Shuttle**
  - STS-107 Payloads
  - STS-117 Payloads
- **Sounding Rocket**
  - Terrier Orion Characterization
  - SAL
- **KC-135 (6 flights planned FY2000)**

Section 4: DEMONSTRATION OF SAMS-FF

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Demonstration of SAMS-FF

SAMS Free Flyer

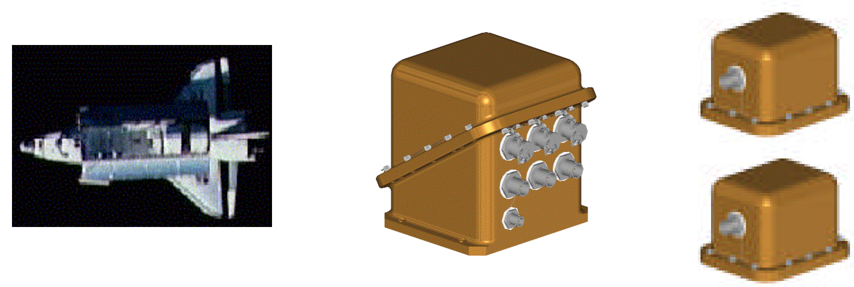
Flexible & Modular System

- **Same basic platform**
- **Easily adapted to experimenter and carrier requirements**
- **Has flown the following configurations**
  - **CDU, TSH, FOG**
  - **TSH & Laptop**
  - **Hermetic CDU & 2 TSHs**
- **Preparing for:**
  - **ISS, Shuttle, Sounding Rocket, KC-135 missions**
  - **Support Ground Characterization before flight**
  - **Evaluate Ground Facilities**

CDU: Control Data Unit
FOG: Fiber Optic Gyroscope
TSH: Triaxial Sensor Head

Basic System, in a Sounding Rocket

Compact System, with any Computer



Hermetically Sealed for Outdoor Operation

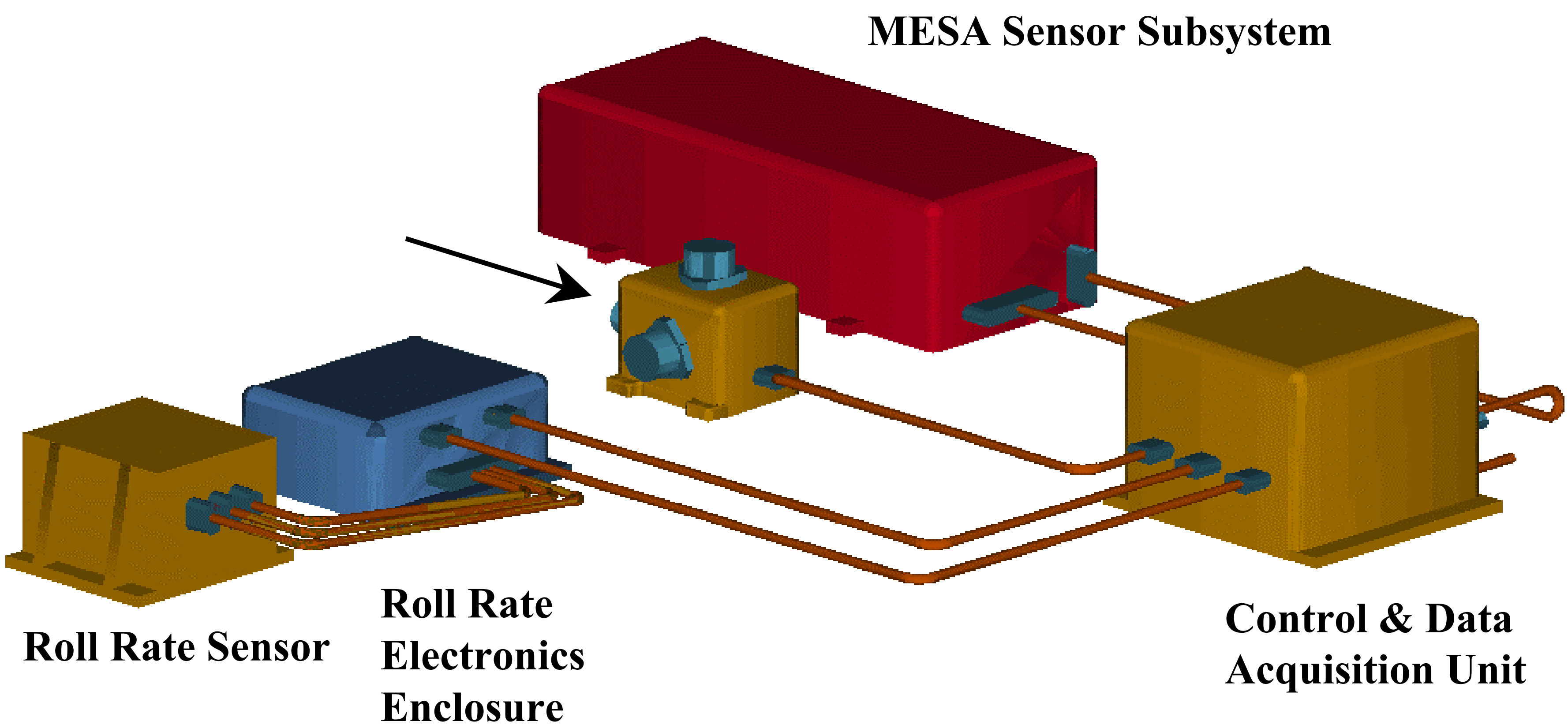
SAMS-FF is a complementary system to SAMS-II, which can support a variety of payloads on the KC-135, Sounding Rockets, STS and ISS.

It was developed in a modular, flexible package to fly on any spacecraft.

Complete Service Package from hardware through integration to data analysis.

SAMS-FF TSH

Flight System on STS-95 in support of the Hubble Space Telescope

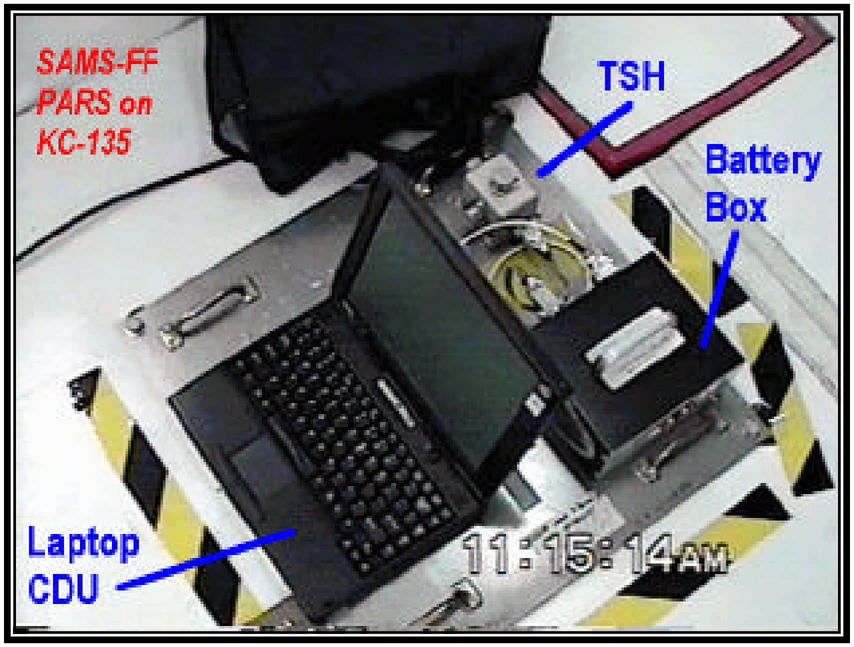

MESA Sensor Subsystem
Roll Rate Sensor
Roll Rate Electronics Enclosure
Control & Data Acquisition Unit

Sensor Specifications

Sensor	*TSH*	*MSS*	*Roll Rate*
Measured Quantity	Higher Freq. Acceleration	Low Frequency Acceleration	Roll Rate Velocity
Dimensions (L x W x H)	2.9” x 2.9” x 2.8”	11.3” x 4.8” x 3.4”	3.8” x 4.4” x 3.0” Gyro 4.8” x 5.0” x 2.2” Intf.
Weight (lbs.)	~1.1	7	3.75
Power (W)	1.6	16	3.6 nom. (temp dep)
Interface	RS422	PC/104 MIU & RS232	RS232
Bandwidth	dc to 200 Hz Selectable	dc to 2 Hz	10 Hz Sampling
Maximum Scale	1.25g	15 mg	190°/sec
Resolution	0.1 ug (sensor spec)	4 ng (1 sec. Period)	0.1 arc-sec (LSB)

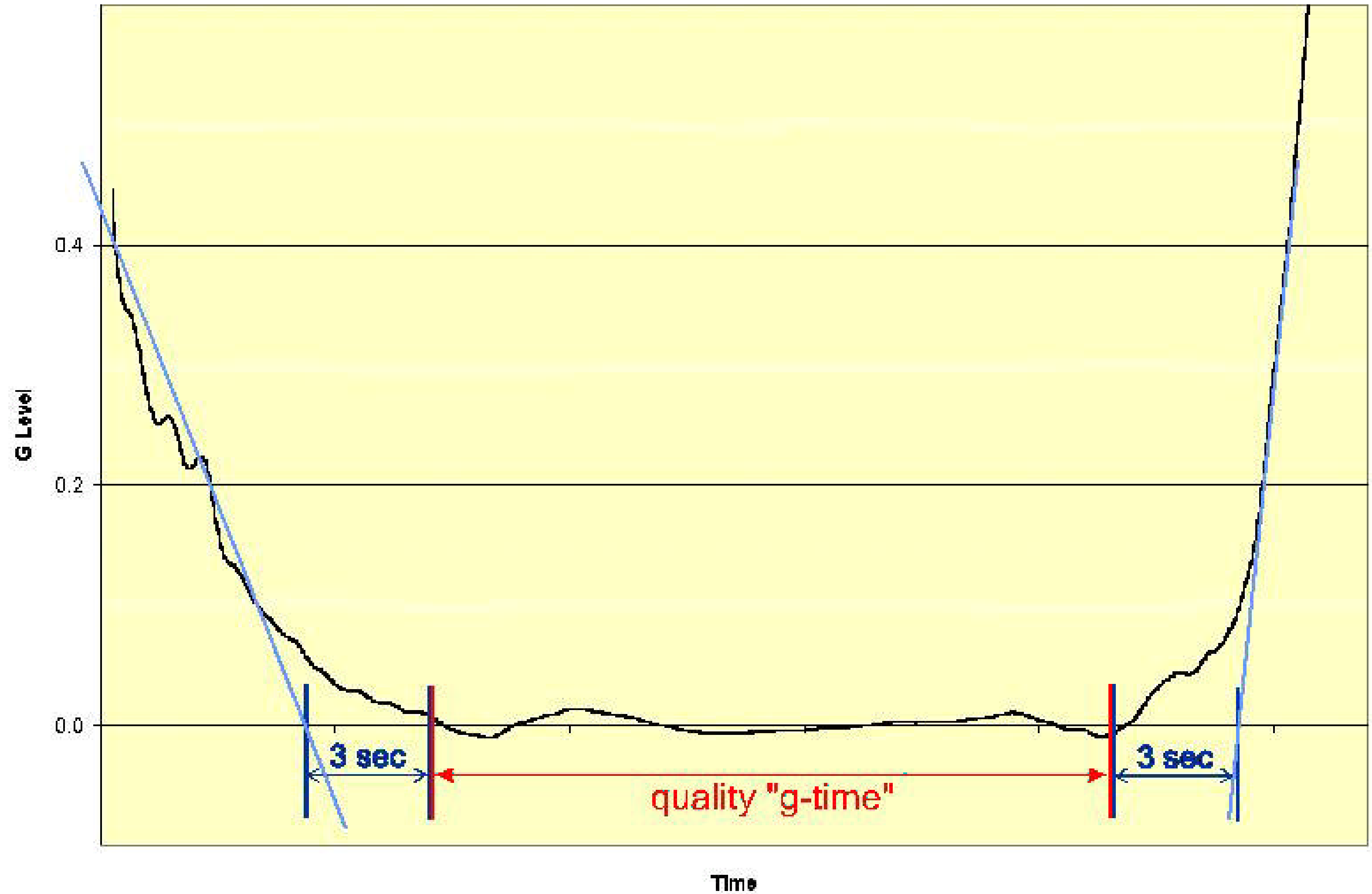
SAMS-FF supports many KC-135 experimenters by providing acceleration data

- **Small size and easily modified system have supported wide variety of payloads**
- **Serves as introduction to acceleration measurements for space payloads**
- **PARS System**
  - **Basic system to support payloads**
  - **Rates the acceleration environment of each parabola, duration and acceleration level data available immediately after each parabola**
  - **After flight, ratings of each parabola are available to all experimenters**
  - **Reduces amount of processing required to view data**



SAMS-FF PARS

Typical Parabola Data

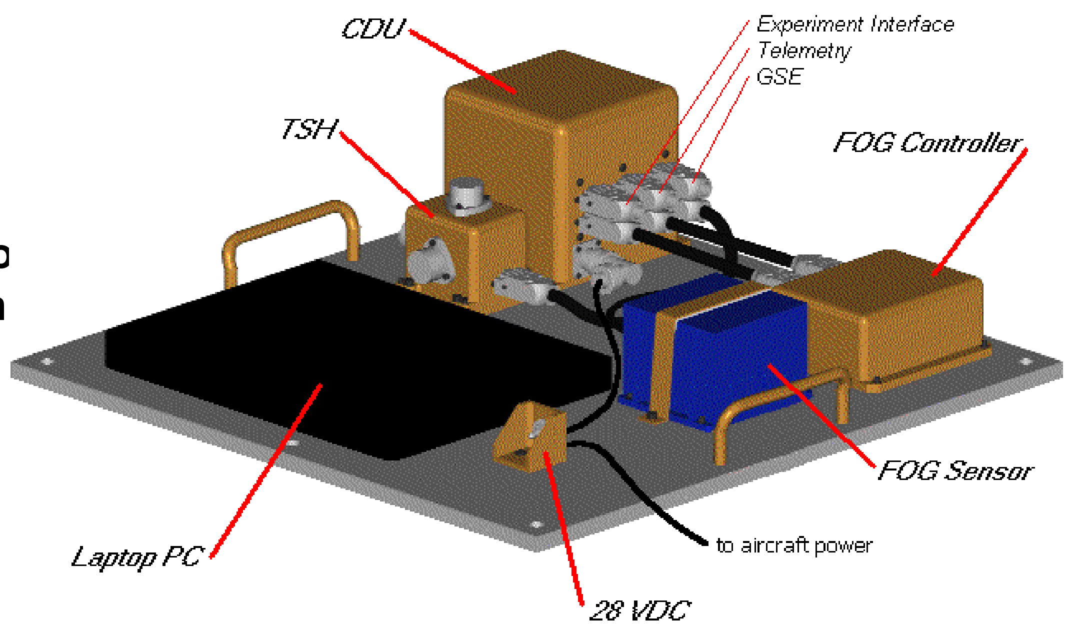


Demonstration of SAMS-FF

Terrier-Orion Sounding Rocket System Flown on KC-135

- **Tested successfully on KC-135 in 7/99**
- **Expanded support on the KC-135**
- **Additional TSHs and the FOG added**
- **Add interfaces to synchronize data collection to payload operation**
- **Example of expanded system fo more complete characterization for multiple payloads**

SAMS-FF KC-135 Terrier-Orion System Checkout Configuration



SUPPORT THAT SAMS-FF PRESENTLY PROVIDES

- -Ground Testing of Payloads (ERE, PCS)
- -Rating of KC-135 Parabolas (PARS)
- -Loan Triaxial Sensor Heads (TSH) to experiments (uGSEG)
- -Loan Control and Data Storage Units (CDU) and TSH for KC-135 (SAL)
- -Provide CDU and TSH as subpayload support Sounding Rockets (SAL-6)
- -Provide TSH for subpayload support on the Shuttle (CM-2)
- -Provide TSH for subpayload support on ISS (FCF)
- -Support experiments (MGM, VCD, PIMS) in SPACEHAB (STS-107)
- -Support experiments in the Shuttle Cargo Bay (HST/STS-95)

SAL: Spread across Liquid
ERE: Extensional Rheology Experiment
PARS: Parabolic Aircraft Reading Systems
PCS: Physics of Colloids in Space
FCF: Fluids and Combustion Facility
MGM: Mechanics of Granular Material
VCD: Vapor Collection Distillation

CONCLUSION:

- **SAMS-FF Project has existing hardware and/or expertise to support all elements (ground, KC- 135, sounding rocket, Shuttle and ISS) of the Microgravity Program.**
- **Basic KC-135 and ground support is usually provided at no cost.**
- **Contact Tom Kacpura with technical questions and Ron Sicker with programatic questions.**

Section 5

Basics of Signal Processing

Eric Kelly
PIMS Data Analyst
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Outline

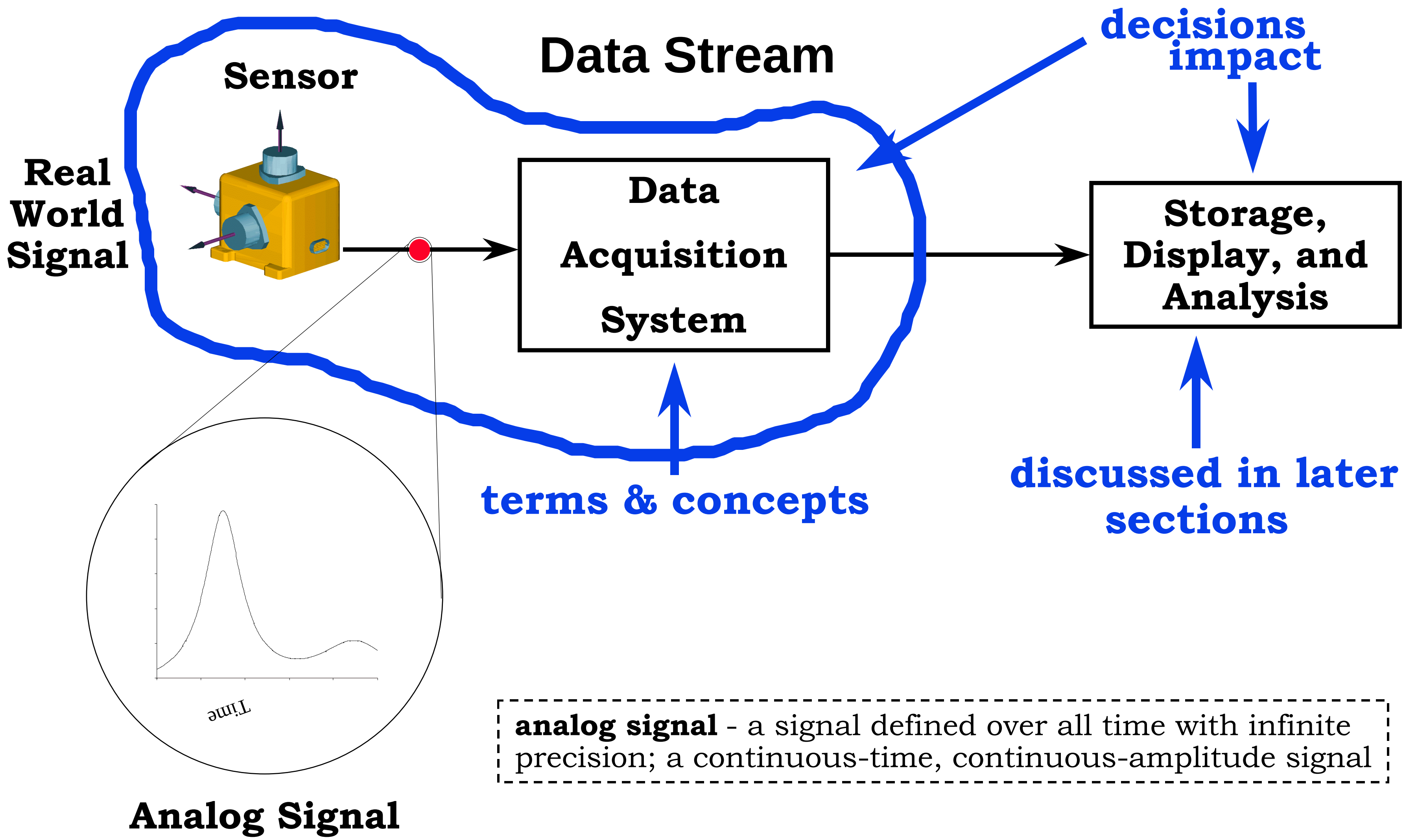
1. **Block Diagram of Data Stream**

2. **Motivation for Analog-to-Digital Conversion**

3. **Basic Concepts**
   - processing depends on and impacts the Principal Investigator

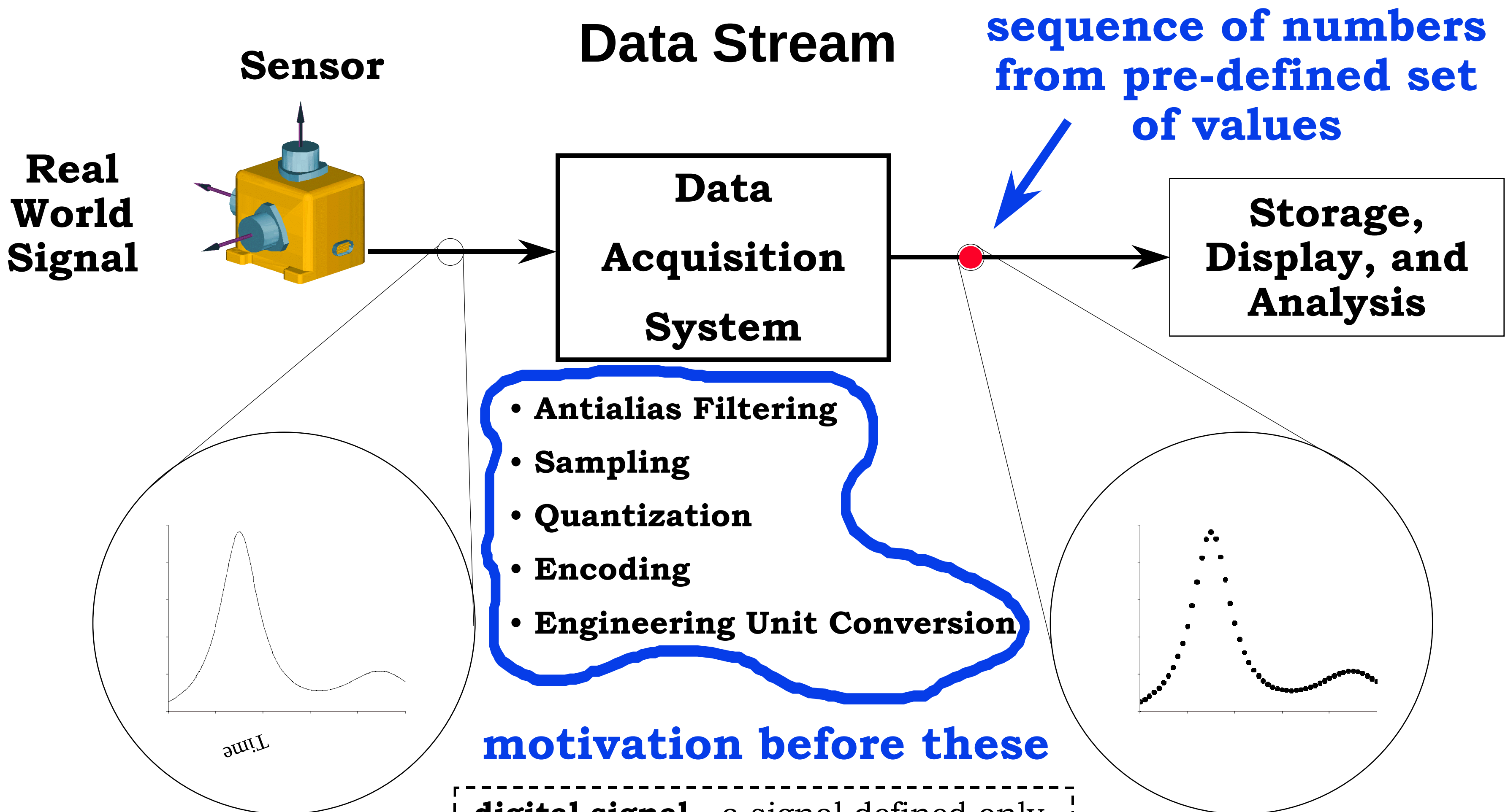
4. **Tradeoffs and Summary**

Basics of Signal Processing



analog signal - a signal defined over all time with infinite precision; a continuous-time, continuous-amplitude signal

Basics of Signal Processing



Analog Signal

Digital Signal

digital signal - a signal defined only at sampling times with finite precision; a discrete-time, discrete-amplitude signal

Motivation for Analog-to-Digital Conversion

- **Computers**
  - Flexibility. Software does the digital signal processing.
  - Take advantage of the full depth and breadth of processing tools available for this platform.
  - Processing performance does not vary with temperature or time.

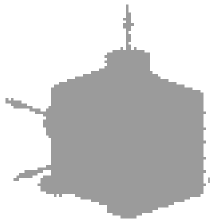
- **Reproducibility**
  - No degradation when copying signal.

- **Other factors**

Data Stream

Sensor

Real World Signal

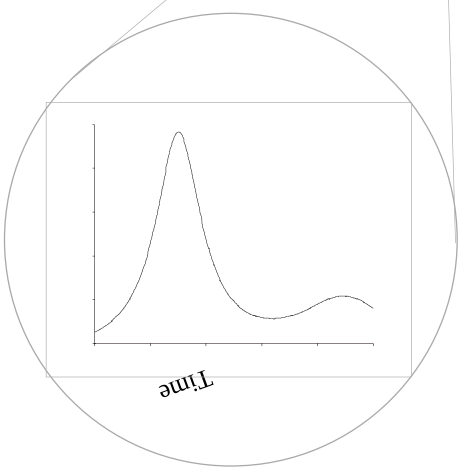


Data Acquisition System

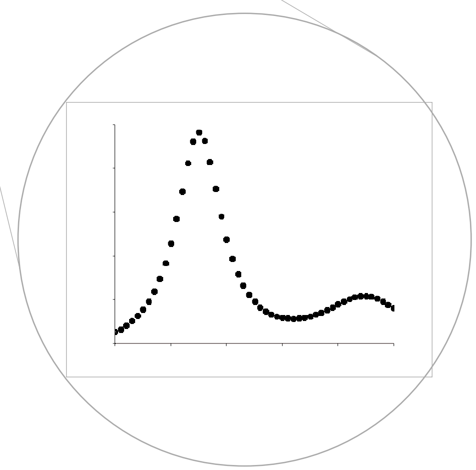
Storage, Display, and Analysis

- Antialias Filtering 1st 2nd
- Sampling 2nd 1st
- Quantization
- Encoding
- Engineering Unit Conversion

proper sequence



Analog Signal



Digital Signal

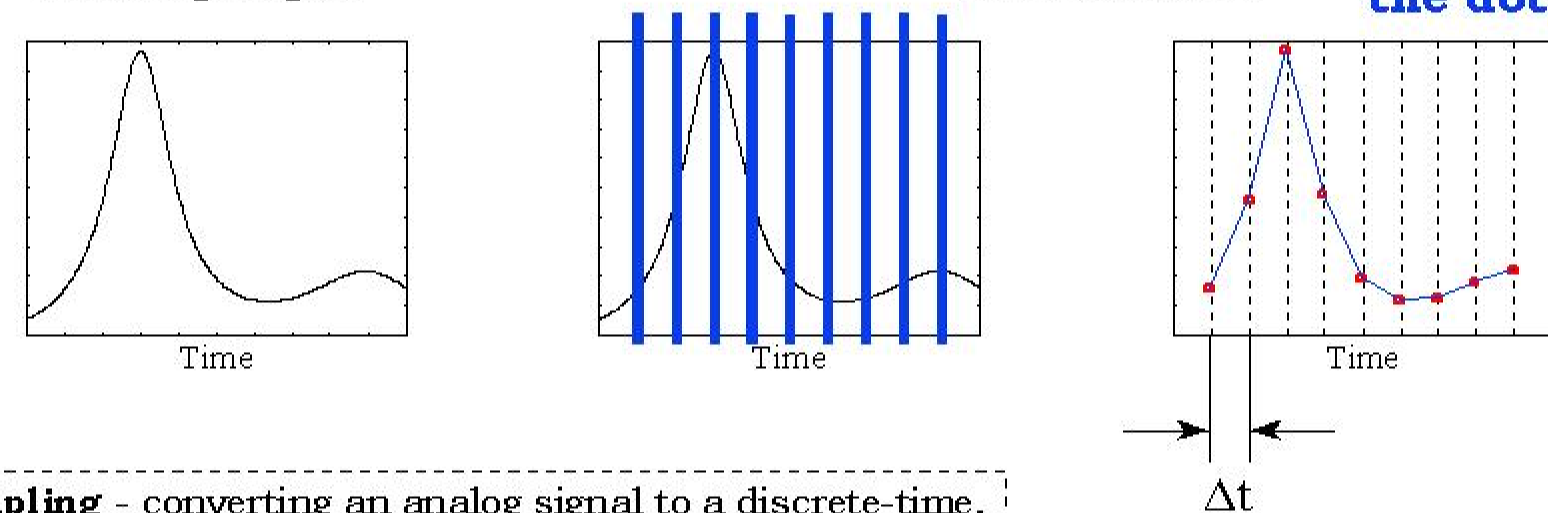
Sampling

has critical implications regarding the information our measurements contain

Analog Signal

discretization

connect the dots

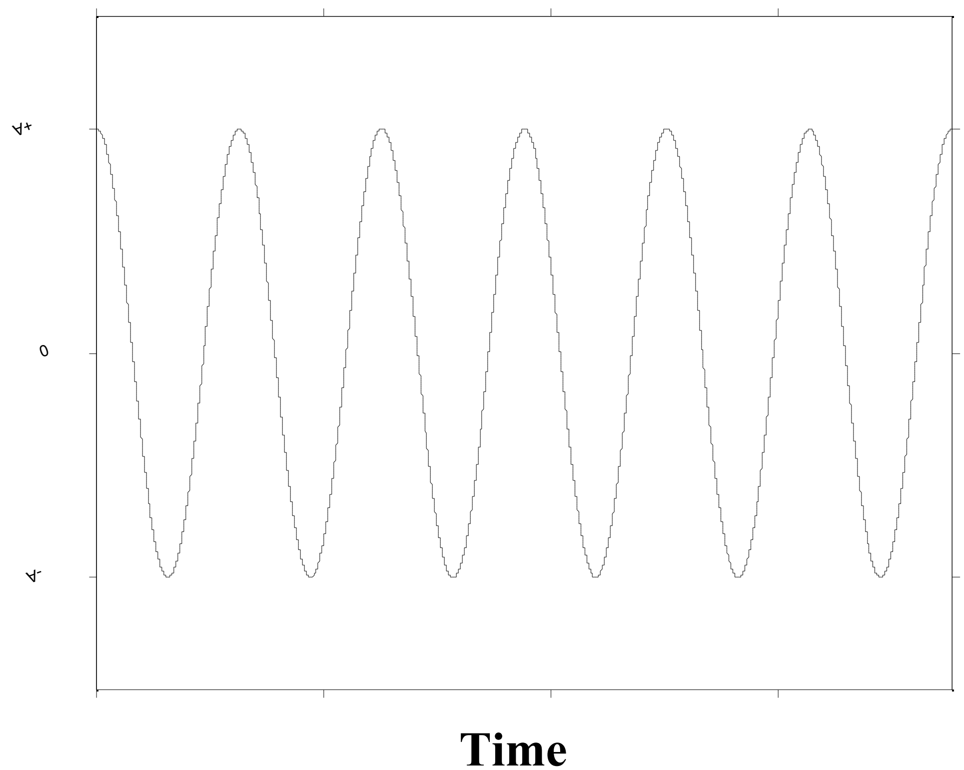


sampling - converting an analog signal to a discrete-time, continuous-amplitude signal

$$f_s = 1/\Delta t$$

sample rate (f_s) - frequency with which analog signal is sampled (samples per second)

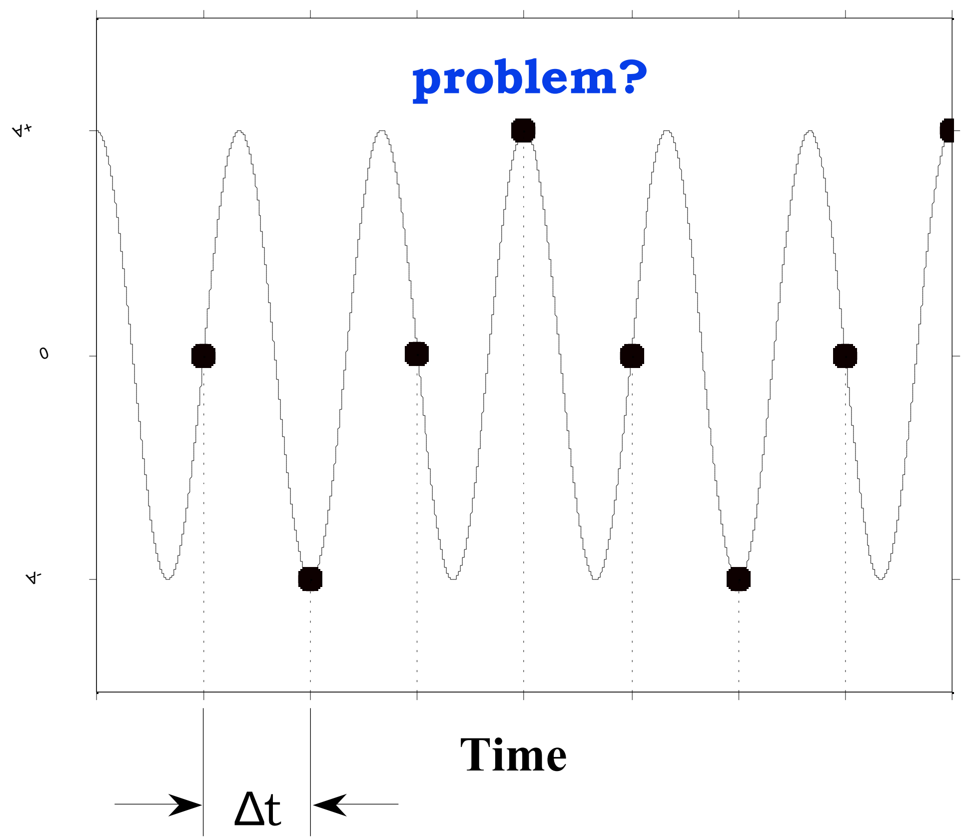
Sampling



harmless-looking sinusoid

Real World (Analog) Signal of Interest

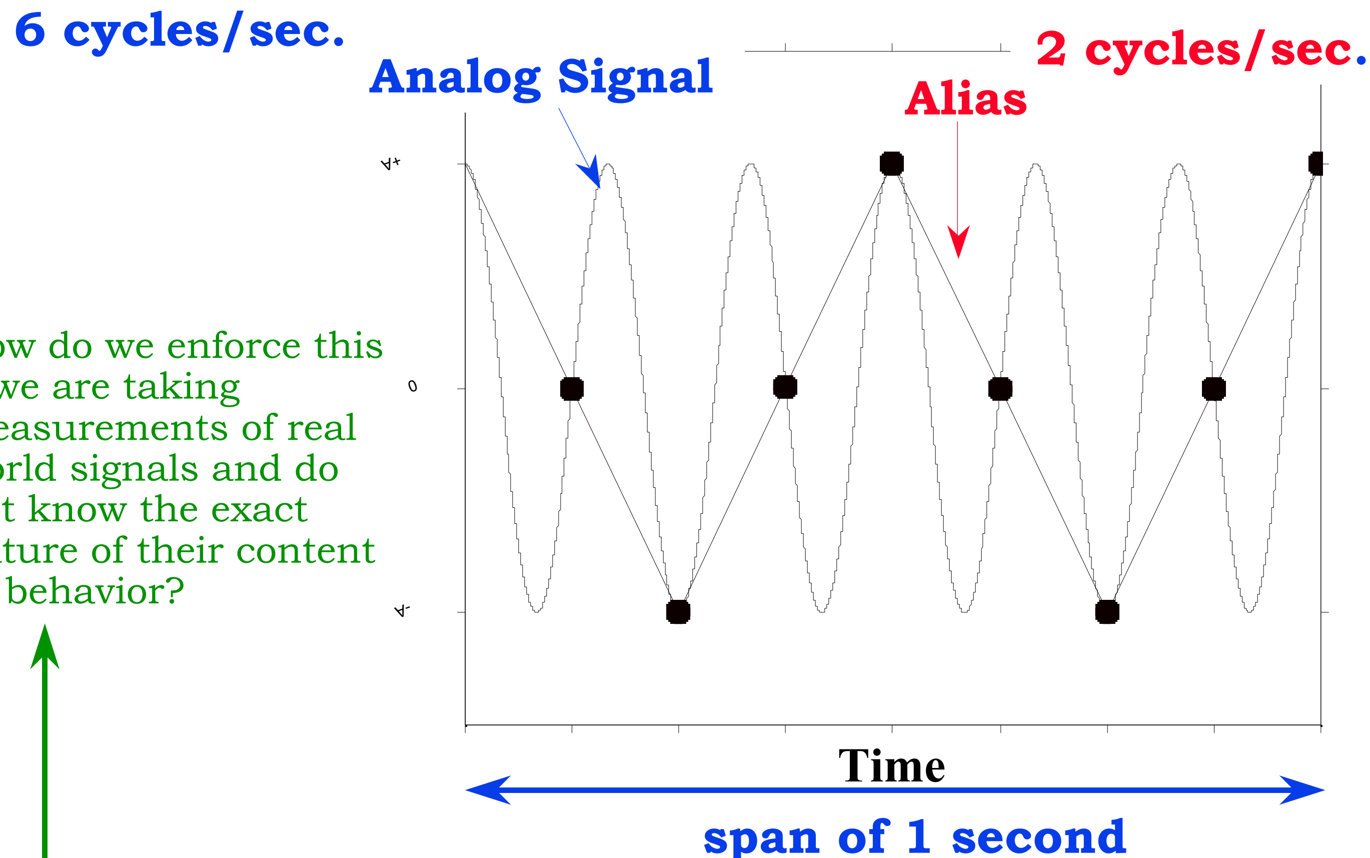
Sampling



sample it

Discretized Signal

Sampling



How do we enforce this if we are taking measurements of real world signals and do not know the exact nature of their content or behavior?

How do we avoid aliasing?

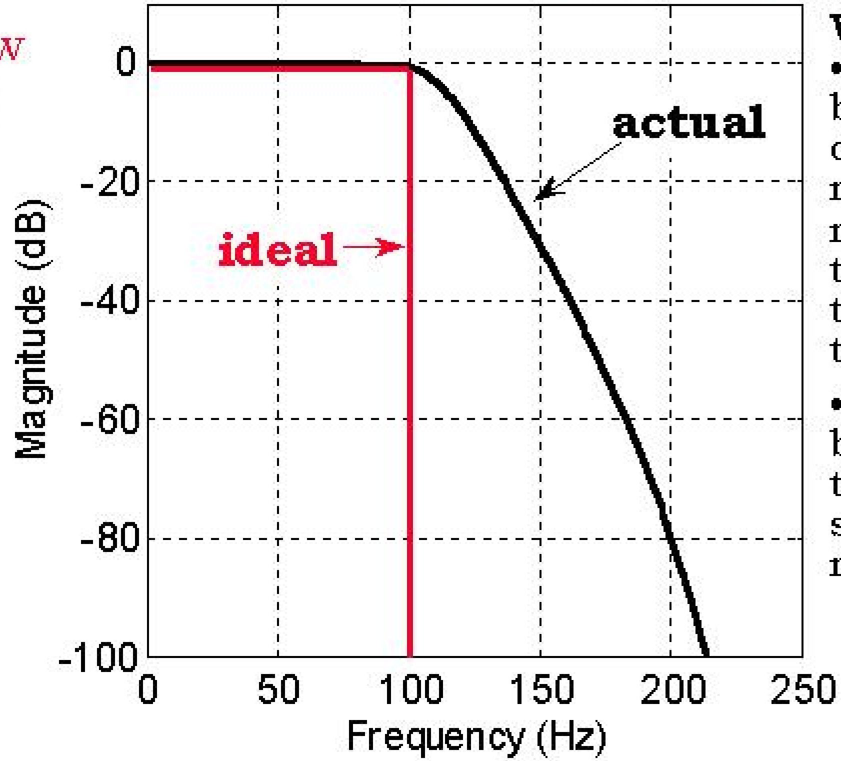
aliasing - high frequency signals manifested as low frequency signals

Nyquist criteria - sample rate at least twice highest frequency contained in the signal of interest

Antialias Filtering

pass without attenuation or amplification below cutoff frequency

total attenuation above cutoff frequency



Frequency response of a lowpass (antialiasing) filter

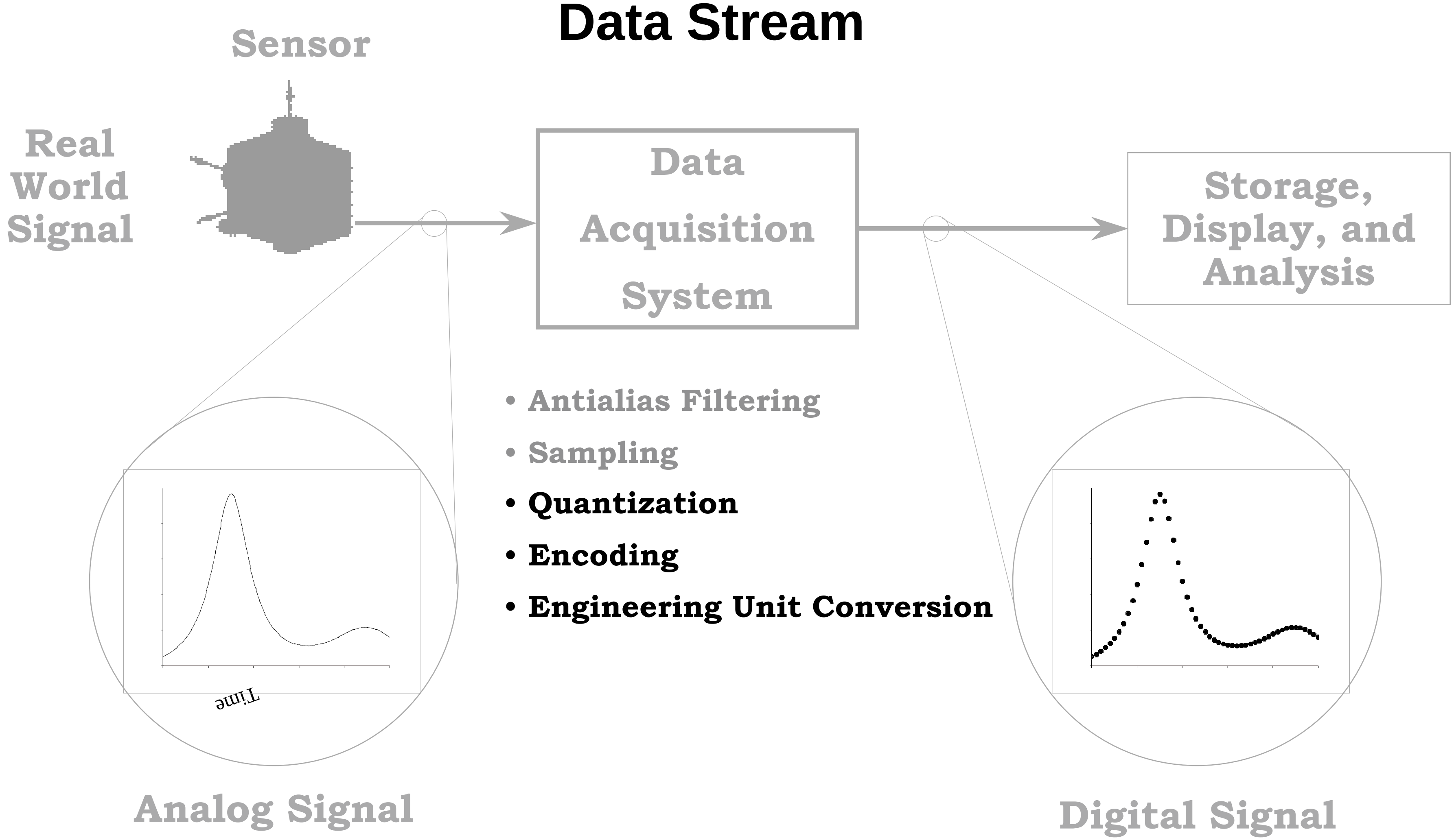
Why does cutoff, f_c, matter?

- For acceleration data, besides sensor location, the cutoff frequency (f_c) is one of most important decisions you make. It should be greater than the highest frequency that is of interest or concern to you.
- Higher f_c means higher f_s, but limitations on the transmission bandwidth, storage, and processing resources put a limit on f_s.

antialias filtering - lowpass (bandlimit) analog signal to reduce effects of aliasing

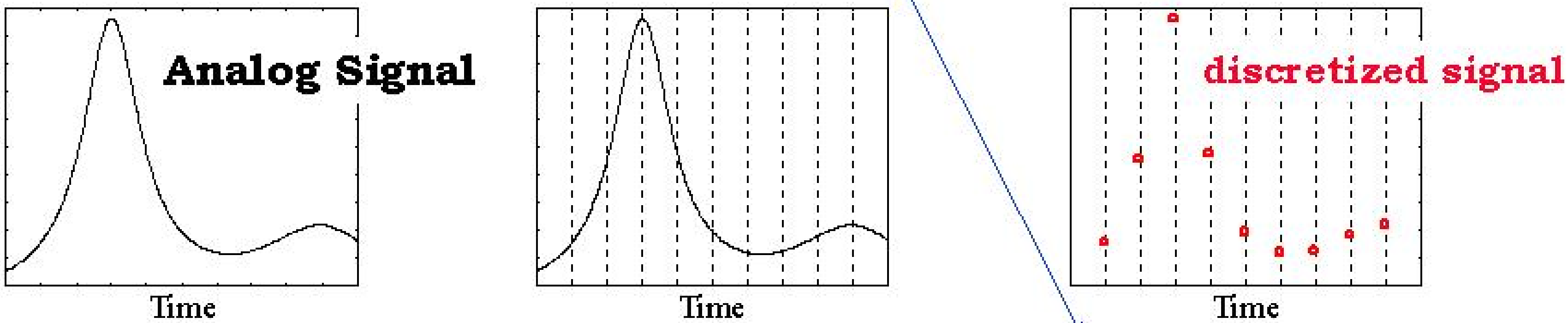
cutoff frequency (f_c) - highest frequency of interest

Data Stream



- Antialias Filtering
- Sampling
- **Quantization**
- **Encoding**
- **Engineering Unit Conversion**

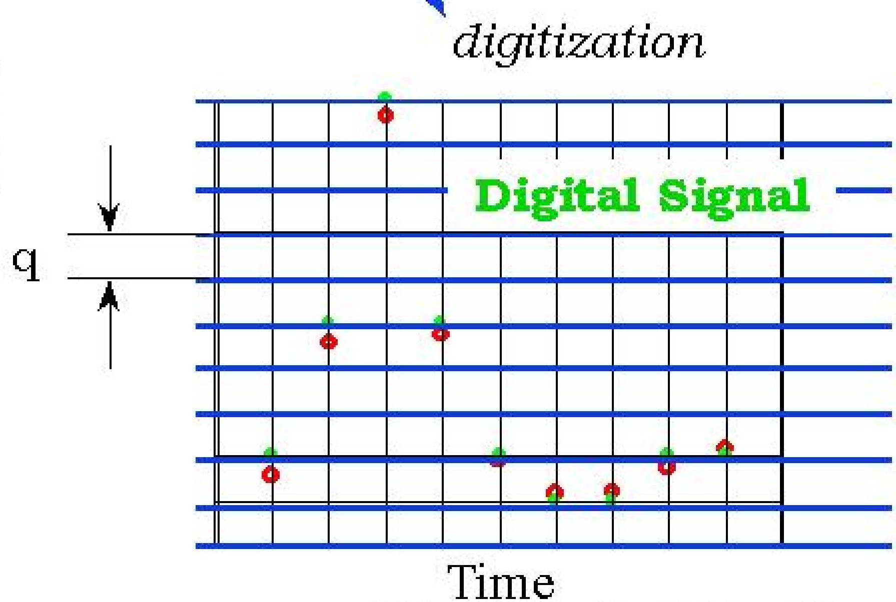
Quantization



quantization - conversion of discrete-time, continuous-amplitude signal to discrete-time, discrete-amplitude signal

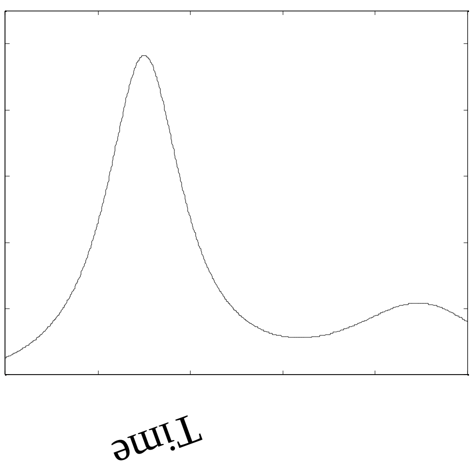
$$q = V_{fs} / (2^{b} - 1)$$

b = # of bits

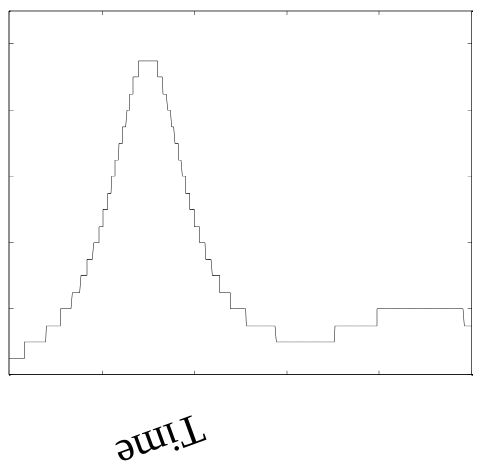


Quantization

Analog Signal

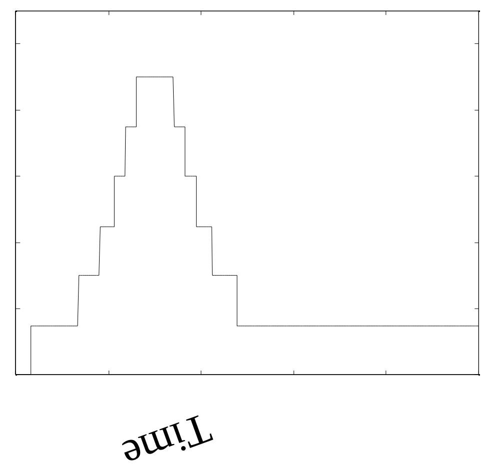


"Noticeable" Quantization Error



some imprecision

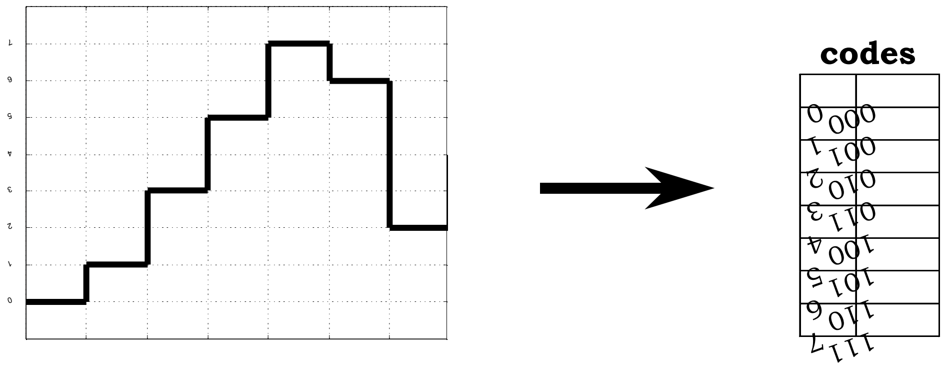
"Significant" Quantization Error



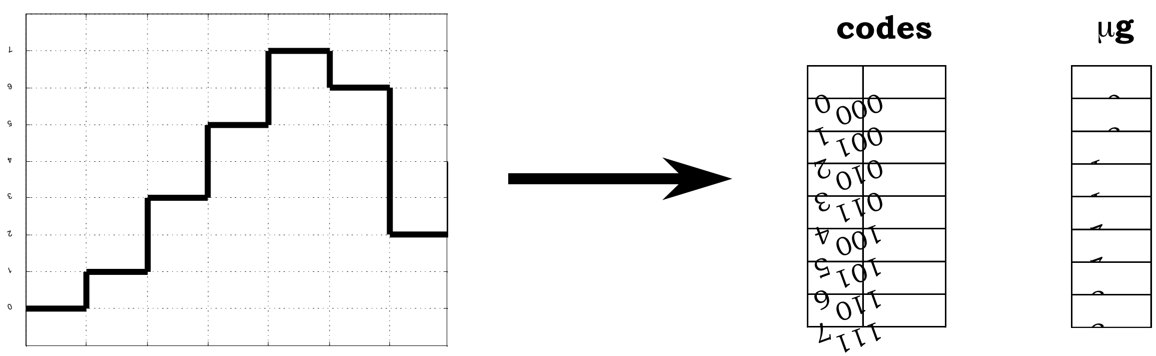
even more imprecision

Encoding & Engineering Unit Conversion

- **Encoding** - assigning unique codes to the quantized samples



- **Engineering Unit Conversion** - translation of encoded values to desired "final" representation



Tradeoffs and Summary

Analog-to-Digital Conversion - computer processing is the motivation

1. Antialias Filtering
   - lowpass filter → leads to loss of high frequency information
2. Sampling
   - sample rate ← transmission, storage, and processing
   - discretization in time → aliasing
3. Quantization
   - digitization of amplitude → precision limited by number of bits
4. Encoding
5. Engineering Unit Conversion

Section 6:

Analysis Techniques for Quasi-Steady Data

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PIMS Data Analyst

NASA Glenn Research Center

Quasi-Steady Topics for Discussion

- **OARE description**
- **Description of trimmean filter (TMF)**
- **Bias calibration**
- **Data storage**
- **Analysis and display of quasi-steady data**

Orbital Acceleration Research Experiment

- **Three axis Miniature Electrostatic Accelerometer (MESA) with an electrostatically suspended proof mass**
- **Full in-flight calibration station for bias and scale factor adjustments**
- **On-board microprocessor for in-flight experiment control, processing, and storage of data**
- **OARE coordinate system vs. Orbiter body coordinate system**

$$\begin{bmatrix} X_b \\ Y_b \\ Z_b \end{bmatrix} = \begin{bmatrix} X_{OARE} \\ Z_{OARE} \\ -Y_{OARE} \end{bmatrix}$$

Orbital Acceleration Research Experiment

- **OARE data is recorded in an inertial frame of reference**
  - **an acceleration of the Orbiter in the positive x_b-axis direction is reported as a positive x_b-axis acceleration even though a free particle may appear to move in the negative x_b-axis relative to the accelerating Orbiter**
- **Designed to measure low-frequency (< 1 Hz), low-level acceleration (nano-g sensitivity)**
  - **frequency ranges are x-axis 0-1 Hz, y and z axis 0-0.1 Hz**

Orbital Acceleration Research Experiment

- **Typical (STS-78) OARE sensor ranges and resolution**

	X-Axis	Y,Z-Axis
Range	Resolution (nano-G)	Resolution (nano-G)
A	305.2	762.9
B	30.52	60.12
C	3.052	4.578
Range	Full Scale Range (micro-g)	Full Scale Range (micro-g)
A	10,000	25,000
B	1,000	1,970
C	100	150

Trimmean Filter (TMF) Description

- **Necessary to mitigate the effects of higher amplitude, higher frequency accelerations**
  - **removes infrequent, large amplitude, outlier data**
- **TMF utilizes a sliding window to operate on a segment of data of pre-defined length**
- **The sliding window operates such that a segment of the Nth window of data is included in the (N+1)th window, resulting in some portion of data being considered in two consecutive TMF operations (see Figure 6-1)**
- **Most PIMS implementations of the TMF operate on 500 sample window every 25 seconds or on 3000 sample window every 8 seconds**

Trimmean Filter (TMF) Description

- **Consider a window of data of length t seconds (Figure 6-1)**
  - **Step 1 - Divide the data into overlapping segments**
  - **Step 2 - Sort the acceleration data in order of increasing magnitude**
  - **Step 3 - Calculate the parameter Q according to the equation below**

$$Q = \frac{[U(20\%) - L(20\%)]}{[U(50\%) - L(50\%)]}$$

- where U(x%) is the average of the upper x% of the ordered sample and L(x%) is the average of the lower x% of the ordered sample
- Q is a measure of the departure of the distribution contained in the sample from a normal distribution

Trimmean Filter (TMF) Description

- **Step 4A - Trim off each tail of the ordered distribution according to the value of the trimmean parameter alpha**

$$alpha(Q) = \begin{cases} 0.05 & Q <= 1.75 \\ 0.05 + 0.35 * \dfrac{(Q - 1.75)}{0.25} & 1.75 < Q < 2.0 \\ 0.4 & Q >= 2.0 \end{cases}$$

- **Step 4B - Calculate the mean of the remaining trimmed distribution**
- **TMF parameters example (Figure 6-2)**

Trimmean Filter (TMF) Description

- **For a pure Gaussian distribution of data, 5 percent of the data is trimmed from each tail of the original sorted distribution**
- **For a given segment of time, a maximum of 40 percent of the data is trimmed off each tail**
- **Typical values for Q and alpha result in 30-50 percent of the original data being discarded for a nominal shuttle mission**

OARE/MAMS Bias Operations

- **OARE bias is caused primarily by dielectric charging of the ceramic insulator material that surrounds the cylindrical axis electrodes**
- **Bias calibrations are nominally performed throughout each mission at regularly programmed intervals**
  - **in-flight correction for bias**
  - **performed for the following additional conditions**
    - sensor instrument temperature change of 5 degrees Celsius since the completion of the last calibration sequence
    - sensor “down ranges” to range not calibrated in the previous calibration sequence
    - ground command initiation

OARE Bias Operations

- **Bias calibration sequence of steps**
  - **50 seconds of data collected**
  - **trimmean filter (TMF) applied to the resulting 500 data points**
  - **sensor is rotated 180 degrees and another 50 seconds of data are collected**
  - **TMF applied to the second 500 data points**
  - **the outputs of the two TMF operations are summed and divided by two**
  - **resulting value represents the bias value**

Analysis and Display of Quasi-Steady Data

Display Format	Regime(s)	Notes
Acceleration versus Time	Transient, Quasi-Steady, Vibratory	• precise accounting of measured data with respect to time; best temporal resolution
Interval Min/Max Acceleration versus Time	Vibratory, Quasi-Steady	• displays upper and lower bounds of peak-to-peak excursions of measured data • good display approximation for time histories on output devices with resolution insufficient to display all data in time frame of interest
Interval Average Acceleration versus Time	Vibratory, Quasi-Steady	• provides a measure of net acceleration of duration greater than or equal to interval parameter
Trimmed Mean Filtered Acceleration versus Time	Quasi-Steady	• removes infrequent, large amplitude outlier data
Quasi-Steady Mapped Acceleration versus Time	Quasi-Steady	• use rigid body assumption and vehicle rates and angles to compute acceleration at any point in the vehicle
Quasi-Steady Three-Dimensional Histogram (QTH)	Quasi-Steady	• summarize acceleration magnitude and direction for a long period of time • indication of acceleration "center-of-time" via projections onto three orthogonal planes

Analysis and Display of Quasi-Steady Data

- **No frequency domain analysis performed on quasi-steady acceleration data**
- **Data recorded at a rate of 10 samples per second**
- **Time domain plot types available**
  - **Raw acceleration data**
    - g vs. t plot of 10 sample per second data
  - **TMF acceleration data**
    - g vs. t plot, t is a function of the TMF interval selected
      - for Canopus Systems, Inc. provided data, TMF interval is 1 data point every 25 seconds
  - **Interval average acceleration data**

$$x_{avgk} = \frac{1}{M}\sum_{i=1}^{M} x_{[(k-1)*M+i]} \qquad k = 1,2,\ldots,\left\lfloor \frac{N}{M} \right\rfloor$$

    - M=number of points in the time series interval selected, typically 1 second intervals
    - N=total number of points in the time series being considered

Analysis and Display of Quasi-Steady Data

- **Time domain plot types available**
  - **Quasi-Steady Three-dimensional histograms (QTH)**
    - displays a summary of acceleration vector magnitude and alignment projected on three orthogonal planes
    - time series analysis using a 2-dimensional histogram for each combination of the three axes: XY, XZ, YZ
    - accumulates the number of times the acceleration vector magnitude falls within user-defined 2-dimensional bins
    - count is divided by the total number of points considered to normalize the results
      - gives a percentage of time representation of the magnitude and orientation of the quasi-steady acceleration vector
      - makes comparisons of quasi-steady data from [QTH plots] STS mission to STS mission or ISS increment to ISS increment more meaningful

Analysis and Display of Quasi-Steady Data

- **Additional options for all time domain plots**
  - **Map quasi-steady acceleration data to the Orbiter CG or to an experiment location**
    - requires use of the vehicle (Orbiter or ISS) body rates and body angles
    - mapping is accomplished via the following calculations
      - determine the acceleration at the CG via

$$a_{CG} = a_{ML} - a_{ggML} - a_{EulerML}$$

      - where ML = measurement location
      - determine the acceleration at the new location via

$$a_{new} = a_{CG} + a_{ggnew} + a_{Eulernew}$$

Analysis and Display of Quasi-Steady Data

- **Additional options for all time domain plots**
  - **Select frame of reference as either inertial or science community**
  - **Select the coordinate system based on vehicle**
    - For Orbiter, use either Orbiter body, Orbiter structural, or specialized coordinate system (i.e., CGF coordinates on USML-2)
    - For ISS, many coordinates systems are available

Post-Mission Quasi-Steady Data Storage

- **OARE data stored on NASA GRC file server *beech.lerc.nasa.gov***
- **Each OARE supported STS mission since USML-2 has the following subdirectories under pub/OARE/<mission>**
  - **canopus**
    - stored in ASCII format
    - contains OARE TMF data provided by Canopus Systems, Inc. after the mission
    - data stored in body coordinate system, inertial frame of reference
  - **MAWS data**
    - stored in ASCII format
    - MAWS = Microgravity Analysis Workstation
    - contains analytical prediction data for the quasi-steady environment
    - data available for STS-73, STS-75, and STS-78
    - data stored in body coordinate system, science community frame of reference (opposite of inertial frame of reference described earlier)

Quasi-Steady Data Storage

- **Each OARE supported STS mission since USML-2 has the following subdirectories under pub/OARE/<mission>**
  - **msfc-processed**
    - stored in binary format
    - contains 10 sample per second data where the acceleration data are represented in acceleration units
    - stored in OARE sensor coordinates, inertial frame of reference
  - **msfc-raw**
    - stored in binary format
    - contains completely unprocessed raw data where the acceleration data are represented in raw counts form
    - stored in OARE sensor coordinates, inertial frame of reference

Analysis and Display of Quasi-Steady Data

- **Raw OARE acceleration data**
  - **Figure 6-3 LMS Water Dump and Attitude Change**
  - **Figure 6-5 USML-2 Solar Inertial Attitude**
  - **Figure 6-7 USMP-3 Vernier Thruster Firings**

- **TMF OARE acceleration data**
  - **Figure 6-4 LMS Water Dump and Attitude Change**
  - **Figure 6-6 USML-2 Solar Inertial Attitude**
  - **Figure 6-8 USMP-3 Vernier Thruster Firings**
  - **Figure 6-9 USML-2 Supply Water Dump**

Analysis and Display of Quasi-Steady Data

- QTH plots
  - Figure 6-10 LMS Mission Plot
  - Figure 6-11 USML-2 Solar Inertial Attitude
  - Figure 6-12 USMP-2 Mission Plot
  - Figure 6-13 LMS Crew Active Period
  - Figure 6-14 LMS Crew Sleep Period

Section 7
Analysis Techniques for Vibratory Data

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Outline and References

Outline:

- Overview
- Time Domain Analysis
- Frequency Domain Analysis
- Summary

PIMS Internet References:

http://www.grc.nasa.gov/Other_Groups/MMAP/PIMS/meit3/

- Details for Power Spectral Density (PSD) and Parseval's Theorem
- Electronic version of this presentation

Overview

Objectives:

- characterize significant traits of the measured data
  - *qualify* – identify significant features or parameters
  - *quantify* – enumerate some aspect
- compare measured data to history, requirements, or predictions
- summarize measured data

Motivations:

- assist investigators and update/maintain knowledge base
- provide feedback to those interested in a data set's relativity
- manage large volume of data

Approaches:

- time domain analysis
- frequency domain analysis

Time Domain Analysis

Objectives:

- isolate acceleration events with respect to time
- threshold acceleration data for limit checking
- correlate acceleration data with other information

Approaches:

- acceleration vs. time → interval processing

- interval average (AVG) acceleration vs. time
- interval root-mean-square (RMS) acceleration vs. time
- interval minimum/maximum (MIN/MAX) acceleration vs. time

Time Domain Analysis

Acceleration vs. Time

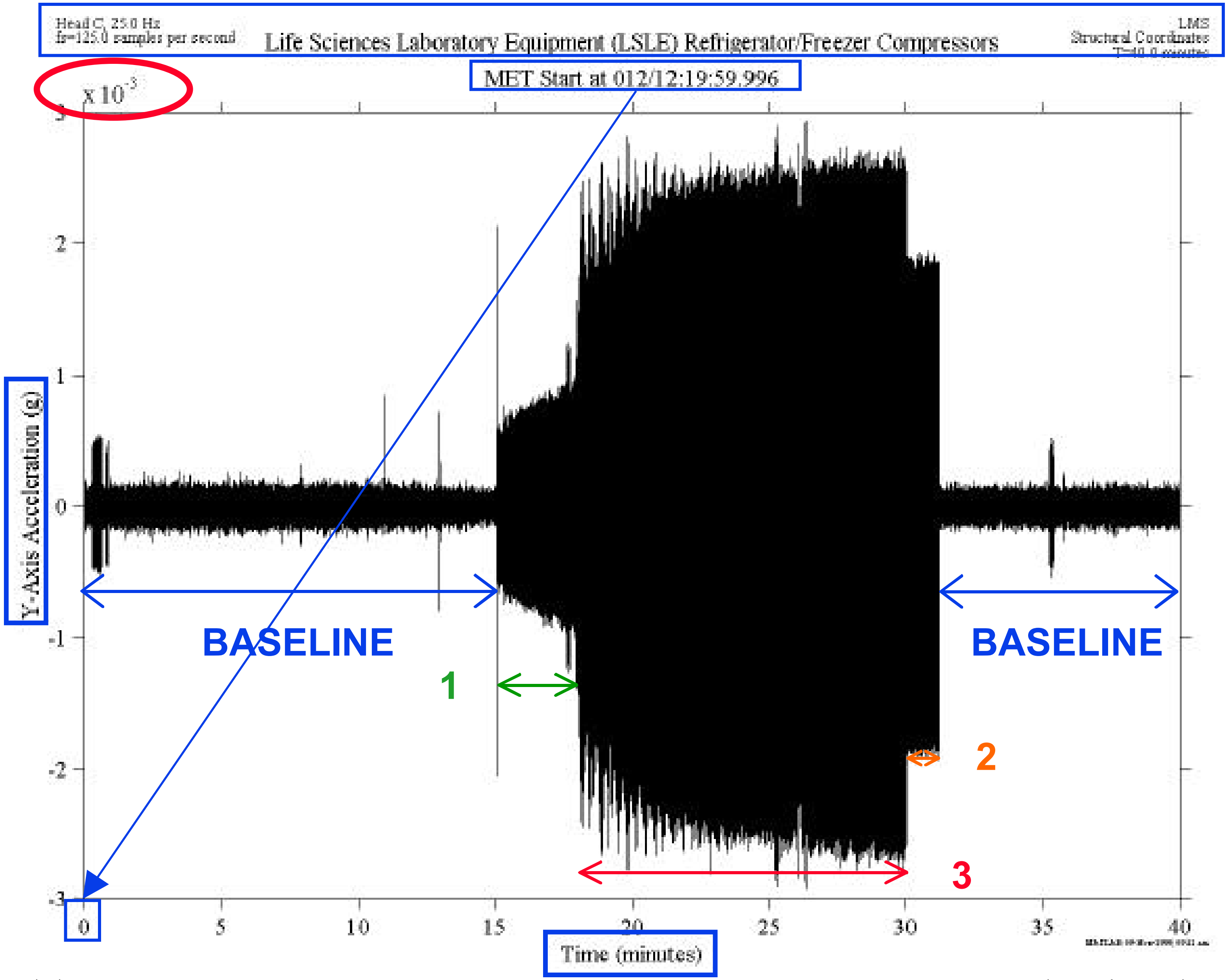
Advantages:

- most precise accounting of the measured data with respect to time
- fundamental approach to quantifying acceleration environment
- “purest” form of the data collected

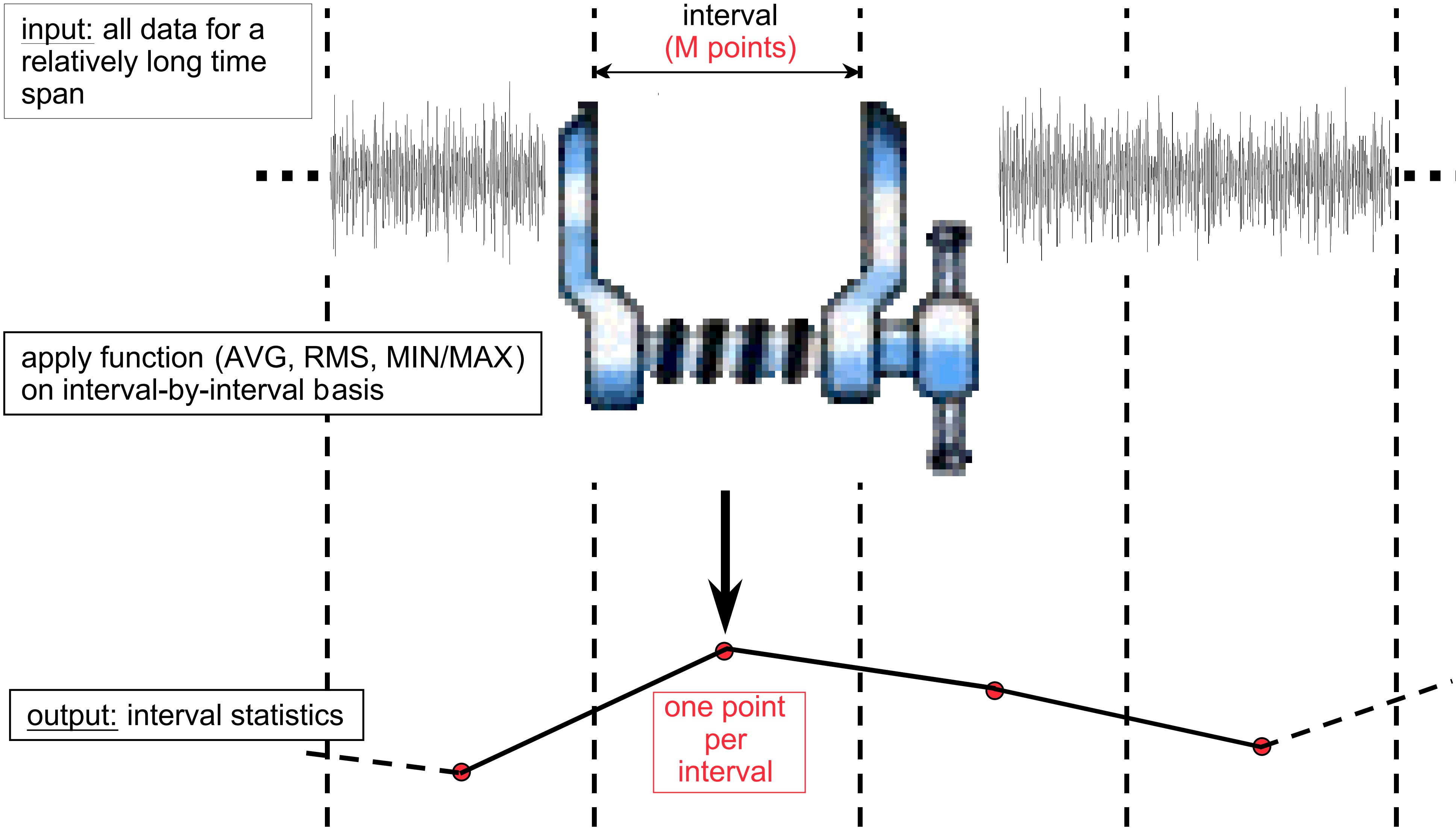
Disadvantages:

- display device (video, printer) constrains resolution for long time spans
- usually not good for qualifying (identifying) acceleration environment

Acceleration vs. Time



Interval Processing



Interval AVG, RMS, MIN/MAX vs. Time

Mathematical Description:

- **AVG**: average (mean) value for each interval

$$x_{AVG}(m) = \frac{1}{M}\sum_{i=1}^{M} x((m-1)M+i); \quad m = 1, 2, ..., \left\lfloor \frac{N}{M} \right\rfloor$$

- **RMS**: root-mean-square value for each interval

$$x_{RMS}(m) = \sqrt{\frac{1}{M}\sum_{i=1}^{M} x((m-1)M+i)^2}; \quad m = 1, 2, ..., \left\lfloor \frac{N}{M} \right\rfloor$$

- N is number of data points that span the entire interval of interest
- M is the number of data points that span a processing interval
- m is the interval index

and $\lfloor\ \rfloor$ is the floor function

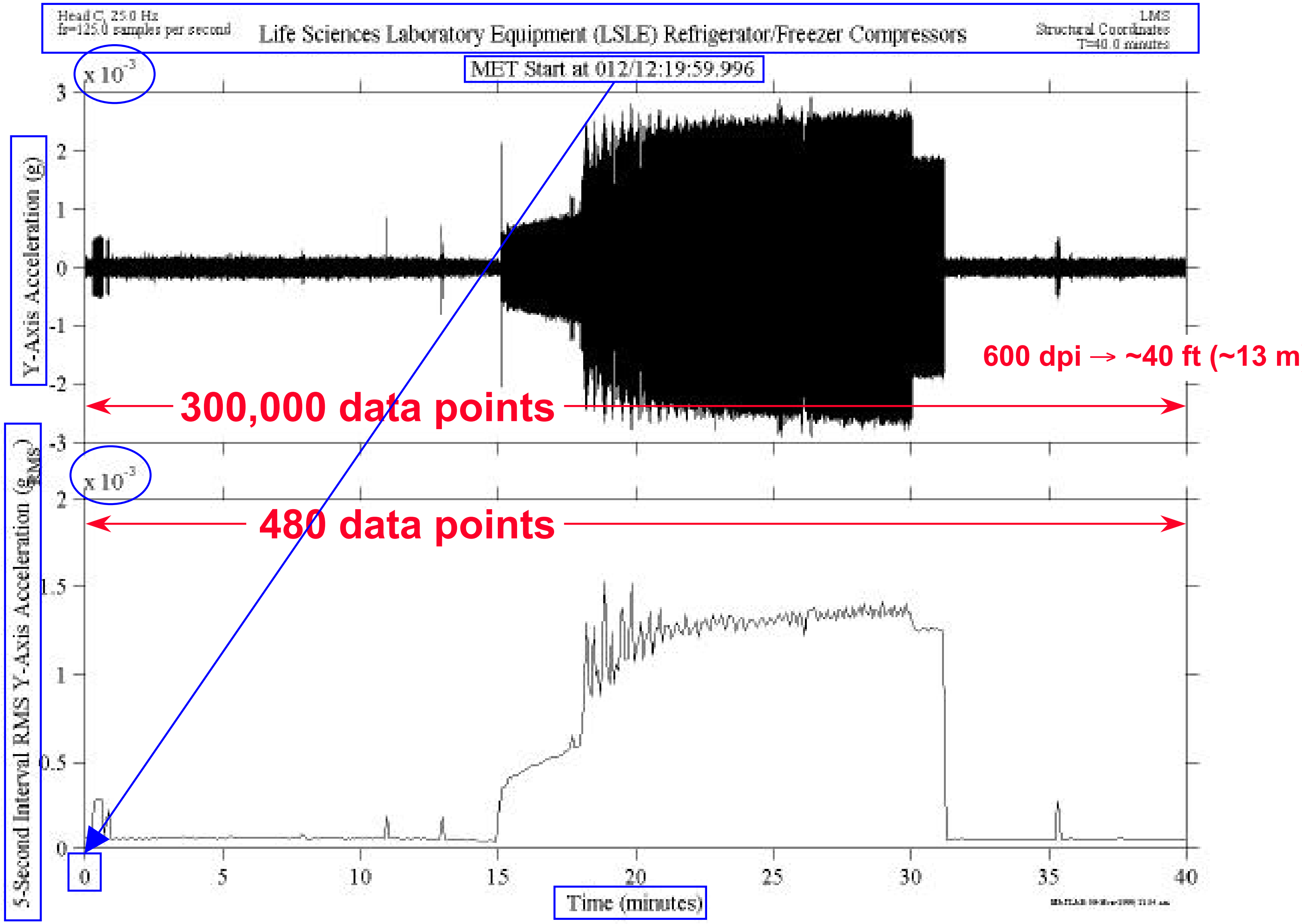
- **MIN/MAX**: both minimum and maximum values are plotted for each interval – a good display approximation for time histories on output devices with insufficient resolution to display all data in time frame of interest

Advantages:

Disadvantage:

- descriptive statistics……………………………..not-fully-descriptive statistics
- decimation (lossy compression)

Acceleration vs. Time & Interval RMS



Frequency Domain Analysis

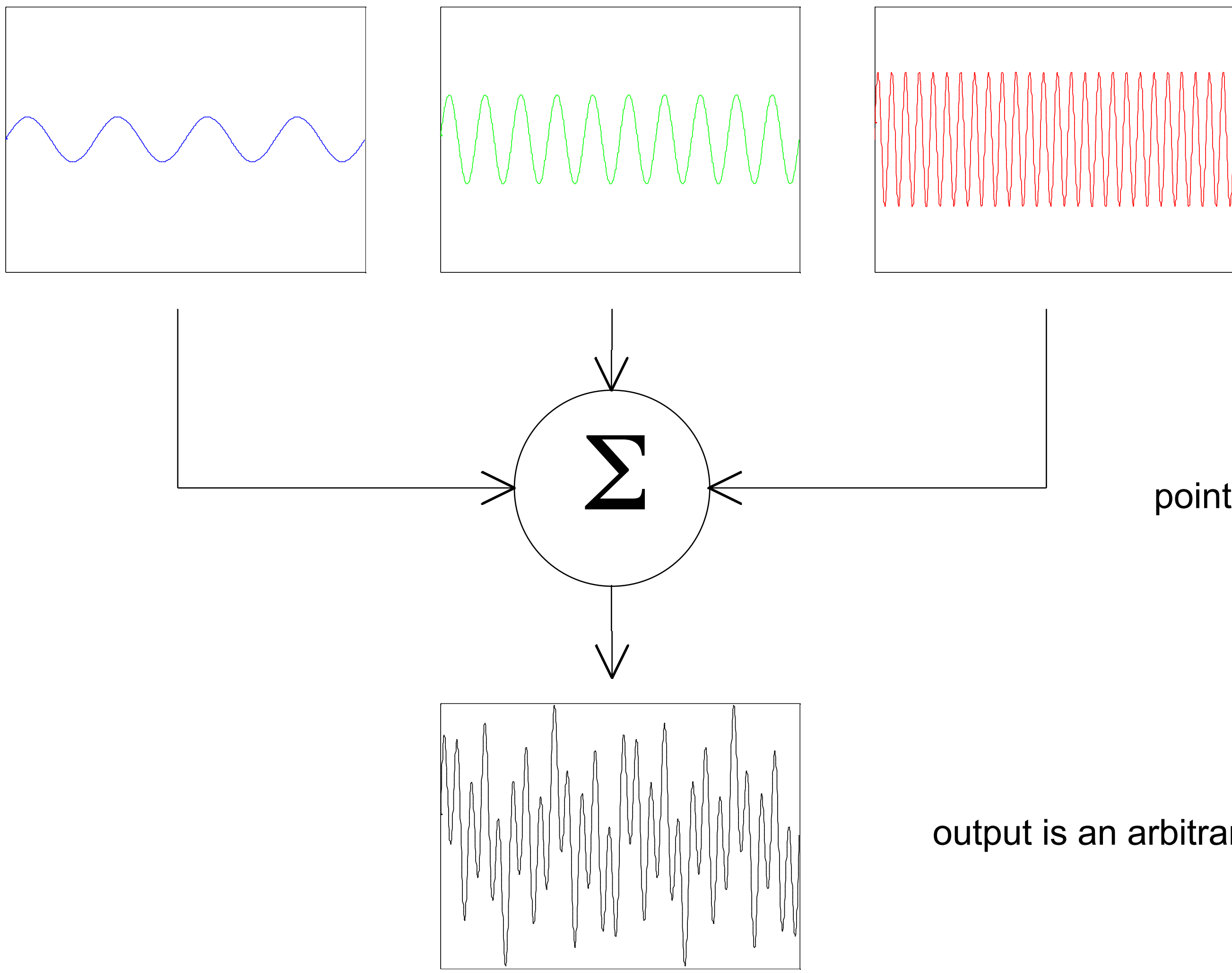
Objectives:

- identify and characterize oscillatory acceleration disturbances
- selectively quantify the contribution of various disturbance sources to the overall measured microgravity environment

Approaches:

- acceleration power spectral density (PSD) → Parseval's Theorem
- cumulative RMS acceleration vs. frequency
- RMS acceleration vs. one third octave frequency bands
- acceleration spectrogram (PSD vs. *time*)
- principal component spectral analysis (PCSA) vs. frequency

Build Arbitrary-Looking Signal

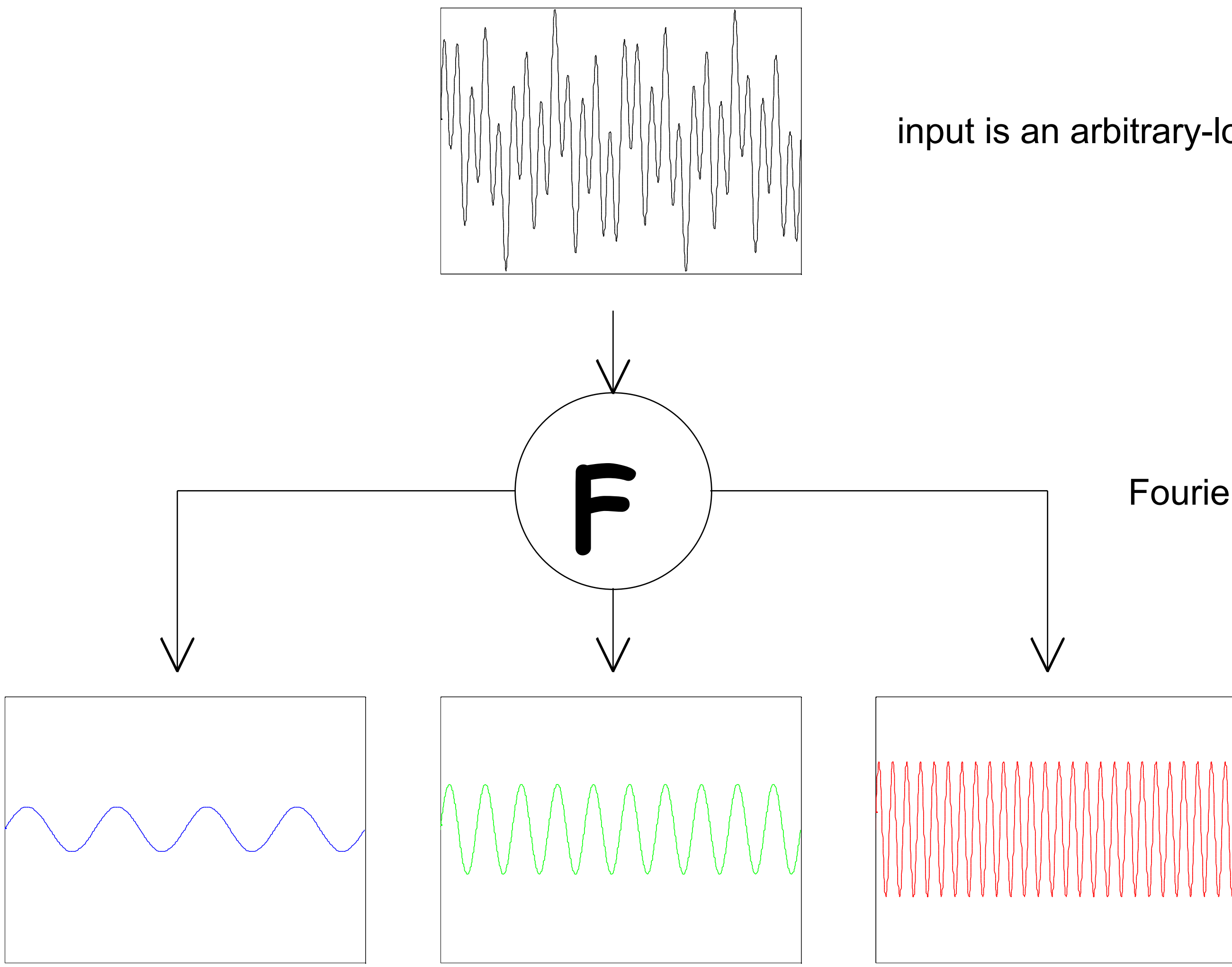


sinusoids with different amplitudes & different frequencies

point-by-point sum

output is an arbitrary-looking signal

Fourier Transform: Graphical Interpretation



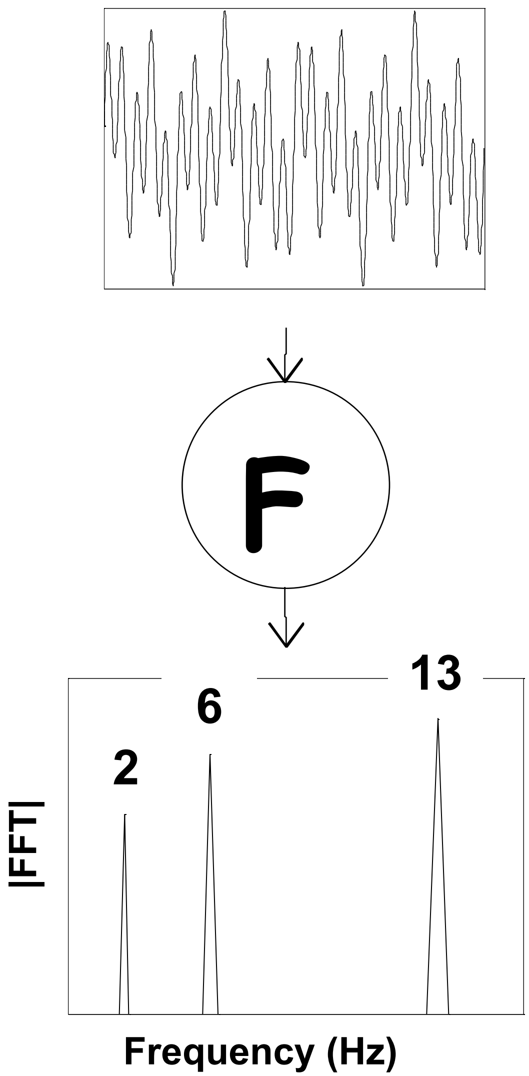
input is an arbitrary-looking signal

Fourier transform

<u>output :</u>

sinusoids with different amplitudes & different frequencies

Fourier Transform: Graphical Description



input is an arbitrary-looking signal

Fourier transform

<u>output :</u>

sinusoids with different amplitudes & different frequencies

Fourier Transform: Mathematical Description

- **What is it?** It's a mathematical transform which resolves a time series into the sum of an average component and a series of sinusoids with different amplitudes and frequencies.
- **Why do we use it?** It serves as a basis from which we derive the power spectral density.
- Mathematically, for continuous time series, the Fourier transform is expressed as follows:

$$X(f) = \int_{-\infty}^{+\infty} x(t) e^{-j2\pi f t} dt \, ; \;\; j = \sqrt{-1}$$

- For finite-duration, discrete-time signals, we have the discrete Fourier transform (DFT):

do not include this factor

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j2\pi nk/N} \cancel{\Delta t} \qquad k = 0,1,2, \; \ldots, (N-1)$$

$$\boxed{\text{Äf} = \frac{f_s}{N} = \frac{1}{T}} \; - \; \boxed{k\Delta f} \qquad \boxed{n\Delta t} \; - \; \boxed{\text{Ät} = \frac{1}{f_s}}$$

- N is the number of samples in the time series
- T is the span in seconds of the time series
- f_s is the sample rate in samples/second (Hz)
- Δf is the frequency resolution or spacing between consecutive data points (Hz)

- For a power of two number of points, N, a high-speed algorithm that exploits symmetry is used to compute the DFT. This algorithm is called the fast Fourier transform (FFT).

Power Spectral Density (PSD): Mathematical Description

- **What is it?** It's a function which quantifies the distribution of power in a signal with respect to frequency.
- **Why do we use it?** It is used to identify and quantify vibratory (oscillatory) components of the acceleration environment.
- Mathematically, we calculate the PSD as follows:

$$P(\underbrace{k}_{\boxed{k\Delta f}}) = \begin{cases} \dfrac{2|X(k)|^2}{NUf_s} & [g^2/Hz] \text{ for } k = 1, 2, \ldots, (N/2) - 1 \\ \dfrac{|X(k)|^2}{NUf_s} & [g^2/Hz] \text{ for } \underbrace{k = 0}_{\text{DC}} \text{ and } \underbrace{k = (N/2)}_{\text{Nyquist}} \end{cases}$$

$$\boxed{U = \frac{1}{N}\sum_{n=0}^{N-1} w(n)^2}$$

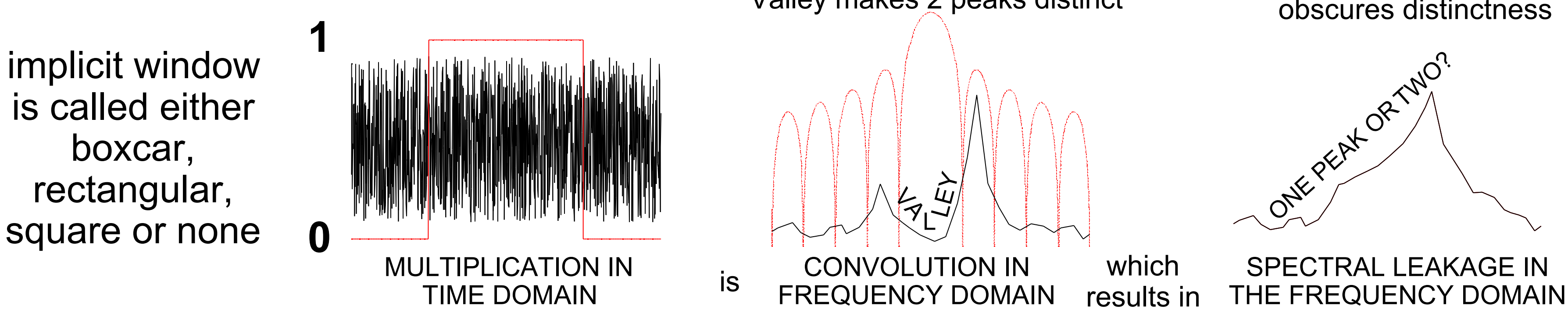
- $X(k)$ is the "Δt-less" FFT of $x(n)$
- N is the number of samples in the time series (power of two)
- f_s is the sample rate (Hz)
- U is window compensation factor
- $w(n)$ is window (weighting) function

see **Internet References** from earlier slide

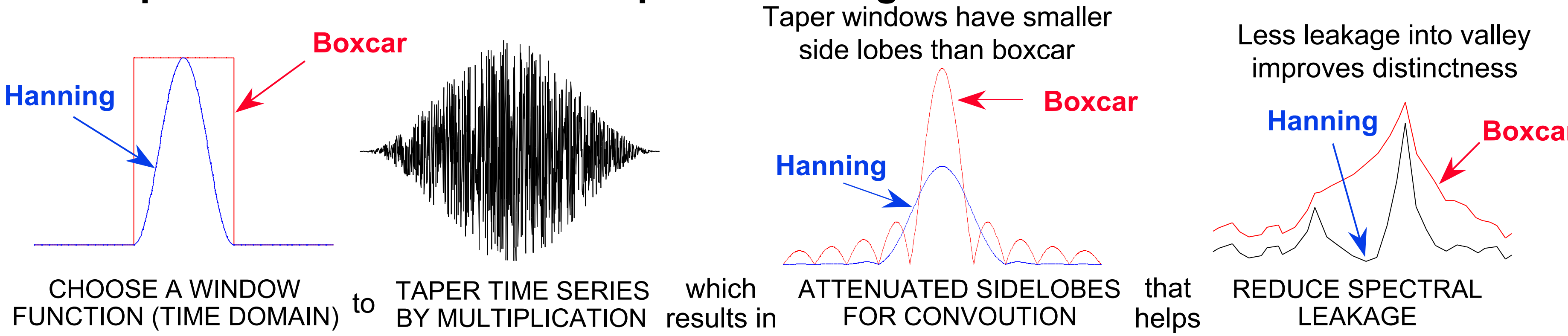
- DC is an electrical acronym for direct current that has been generalized to mean average value
- Nyquist frequency (f_N) is the highest resolvable frequency; half the sampling rate ($f_N=f_s/2$)
- Symmetry in the FFT for real-valued time series, $x(n)$, results in one-sided PSDs; only the DC and Nyquist components are unique – that's why no factor of 2 for those in the equation
- Caution: some software package PSD routines scale by some combination of f_s, 2, or N

Windowing to Suppress Spectral Leakage

- **Convolution →spectral leakage**



- **Taper time series to reduce spectral leakage:**



- **Window compensation factor** – to account for attenuation of the signal introduced by tapering we apply a compensation factor, U, as shown on the PSD mathematical description slide; U = 1 for the boxcar window

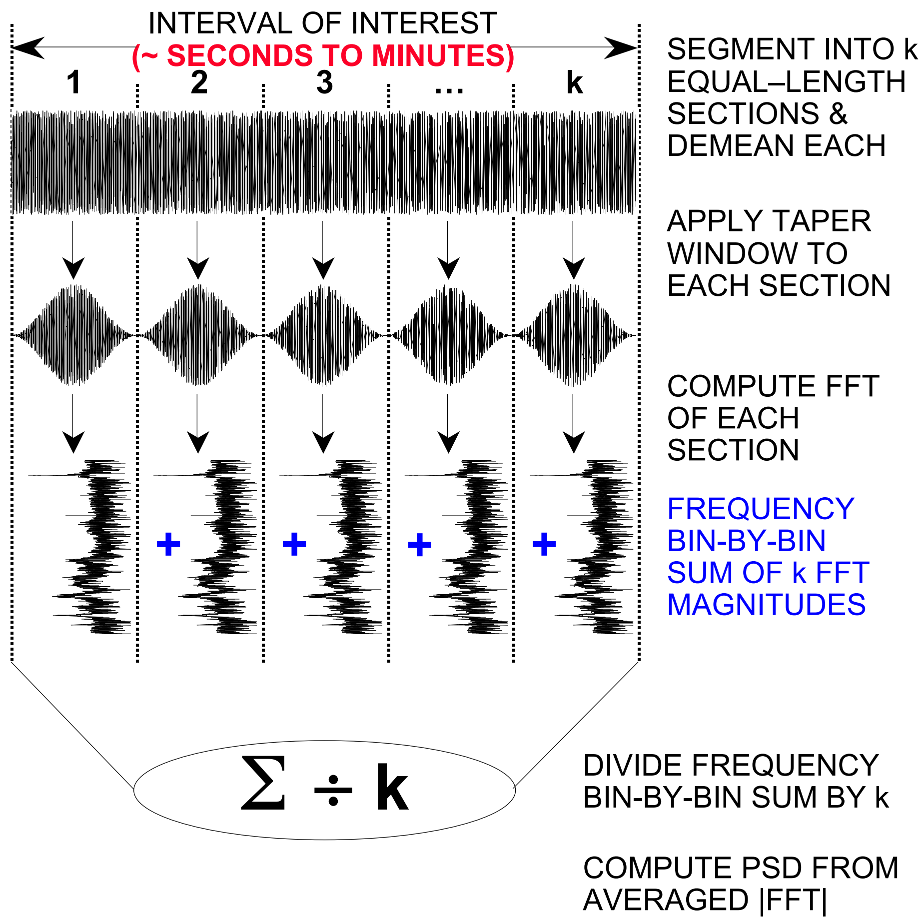
Spectral Averaging

- Assume stationary data
- **Why?** To reduce spectral variance

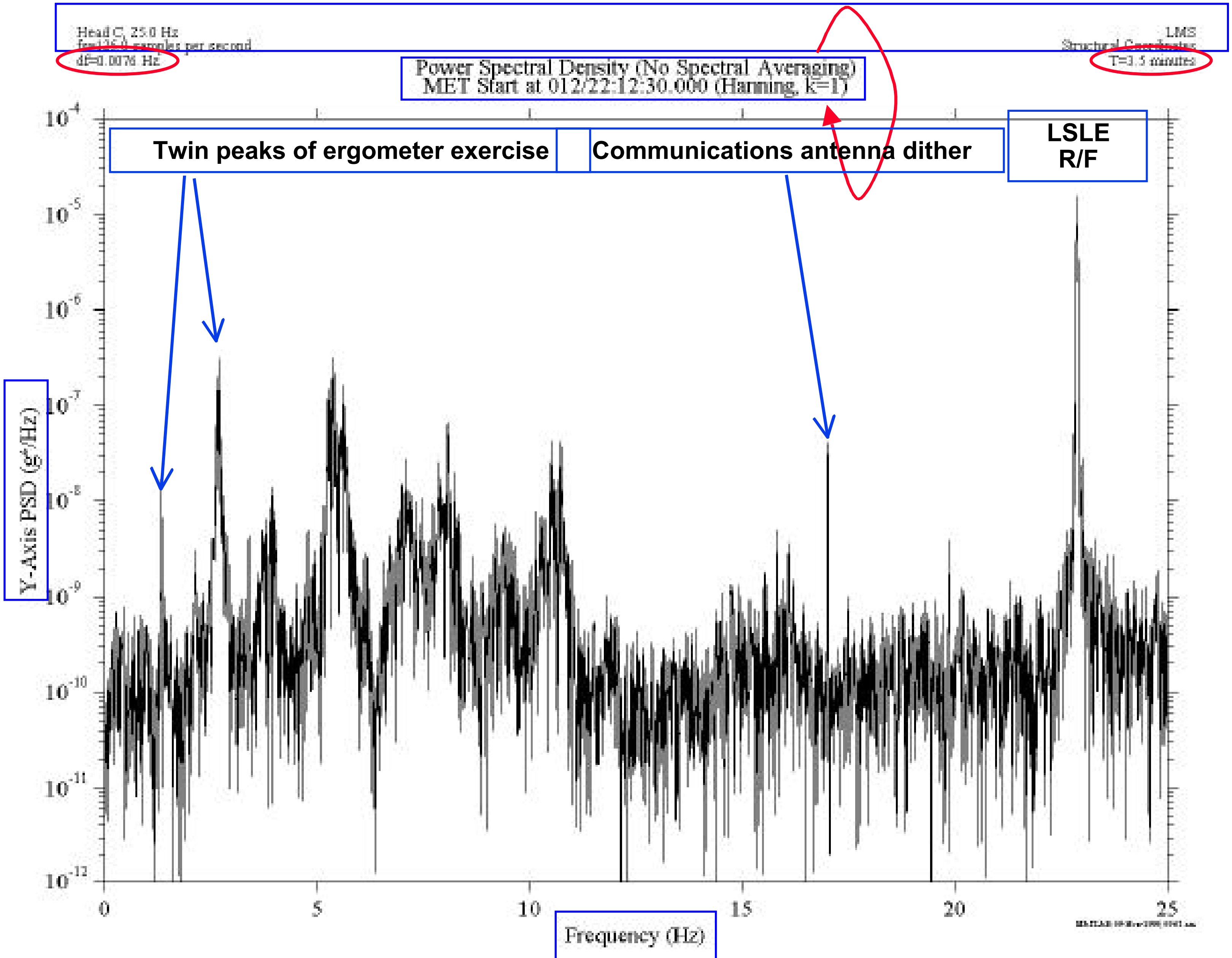
  The averaging in this process causes the variance of the PSD estimate to be reduced by a factor of k.
- **How?** Welch's (periodogram) method
- **Tradeoff:** Degraded frequency resolution

  As the number of averages (or sections, k) increases, the spectral variance decreases, but this comes at the expense of diminished frequency resolution. This stems from the fact that for a given time series, the more sections you have, the fewer the number of points you get in each section.

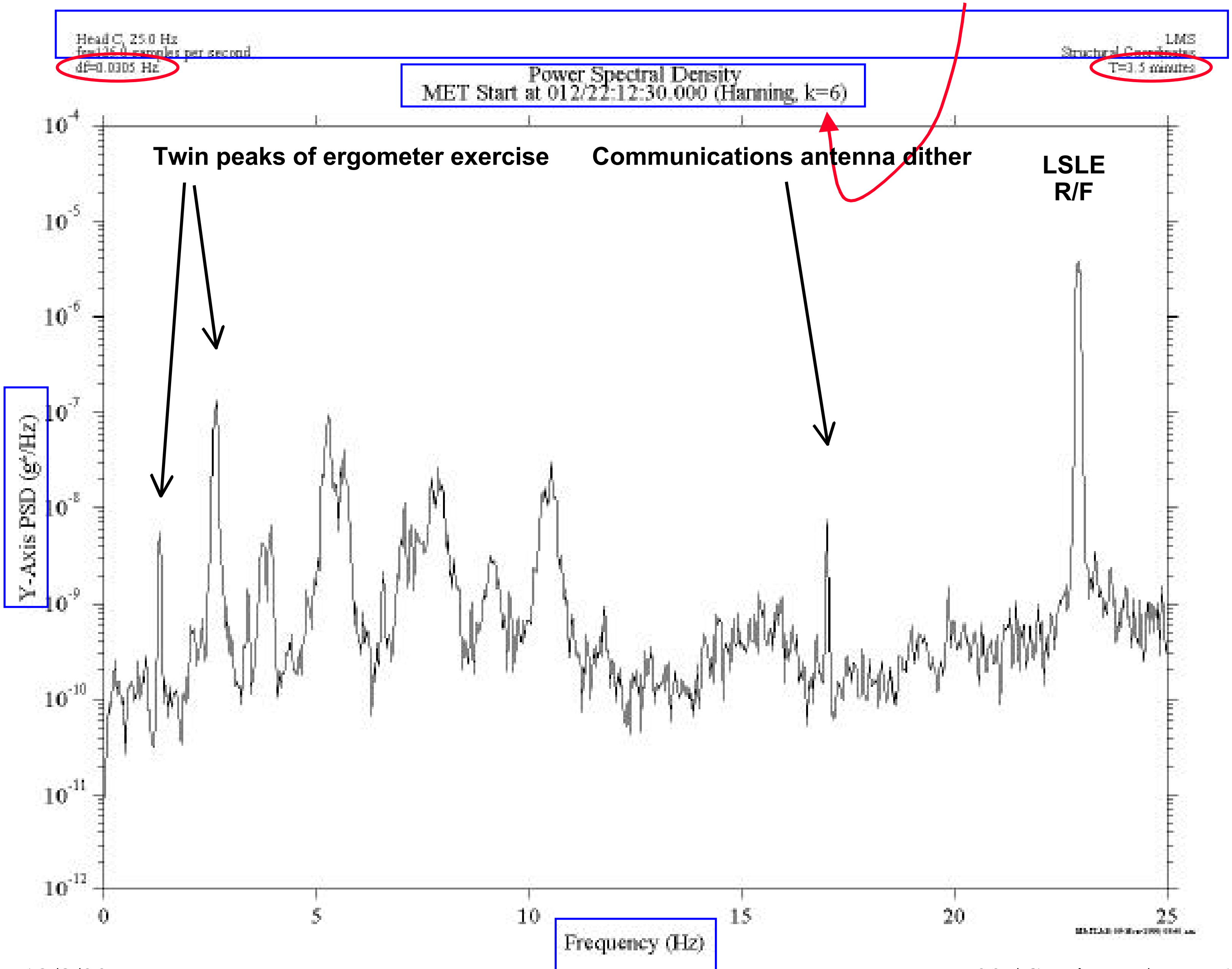
Welch's (Periodogram) Method



Power Spectral Density (no spectral averaging)



Power Spectral Density (with spectral averaging)



Parseval's Theorem

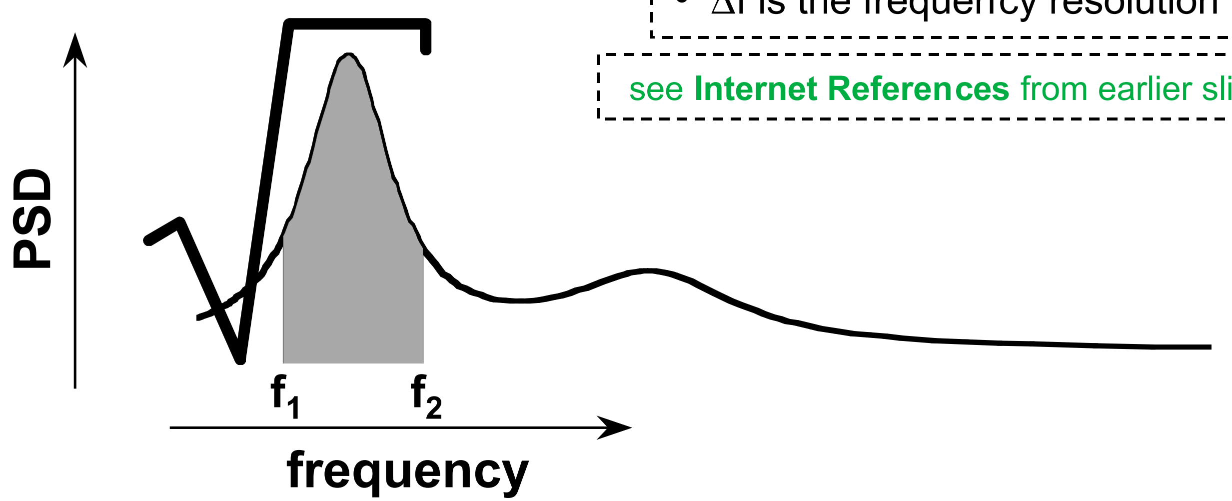
- **What is it?** It's a relation that states an equivalence between the RMS value of a signal computed in the time domain to that computed in the frequency domain.
- **Why do we use it?** It can be used to attribute a fraction of the total power in a signal to a user-specified band of frequencies by appropriately choosing the limits of integration (summation).
- Mathematically, this theorem can be expressed as:

$$\sqrt{\frac{1}{N}\sum_{n=0}^{N-1}\left|x(n)\right|^2} = \sqrt{\sum_{k=0}^{N/2} P(k)\Delta f}$$

- x(n) is time series
- N is the number of samples in the time series
- P(k) is the PSD of x(n)
- Δf is the frequency resolution

see **Internet References** from earlier slide

$$\left. \mathrm{RMS}\right|_{f_1}^{f_2} =$$



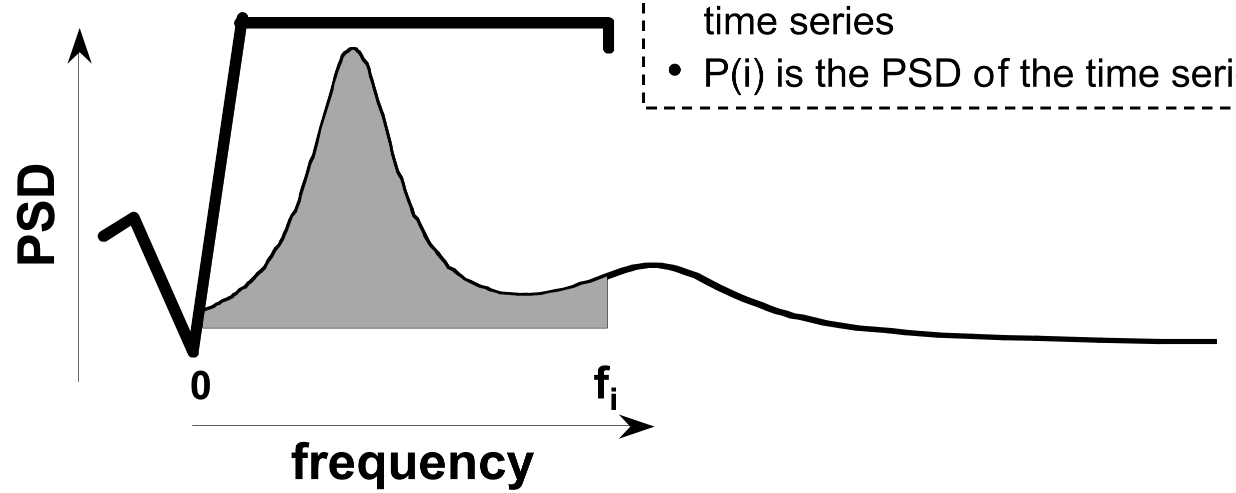
Cumulative RMS vs. Frequency

- **What is it?** It's a plot that quantifies the contributions of spectral components *at and below* a given frequency to the overall RMS acceleration level for the time frame of interest.
- **Why do we use it?** This type of plot highlights, in a quantitative manner, how various portions of the acceleration spectrum contribute to the overall RMS acceleration level.
  - steep slopes indicate strong narrowband disturbances
  - shallow slopes indicate quiet, broadband portions of the spectrum
- Mathematically, we have:

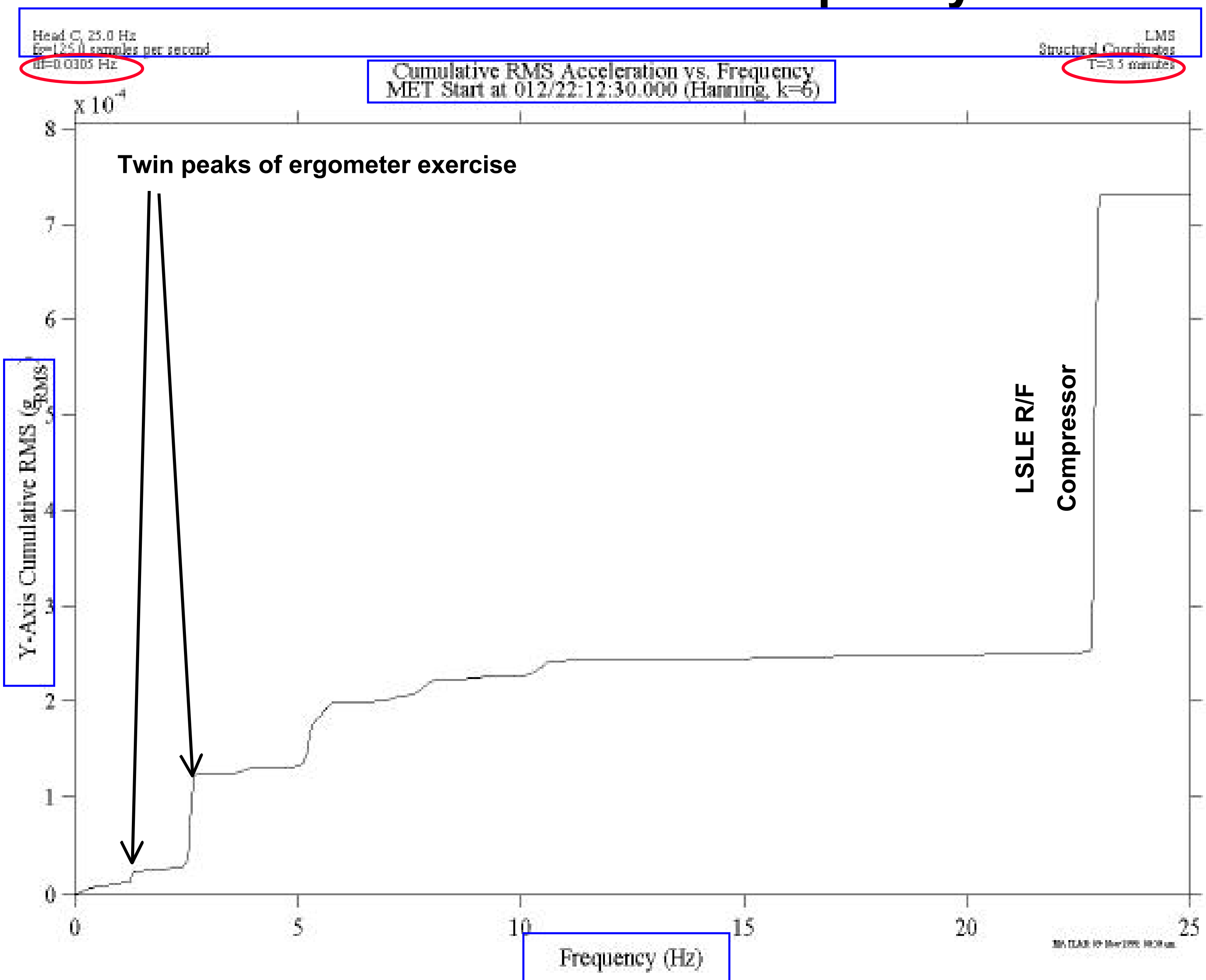
$$a_{RMS}(k) = \sqrt{\sum_{i=0}^{k} P(i)\Delta f} \qquad k = 0,1,2\ldots,(N/2)$$

- Δf is the frequency resolution
- N is the number of samples in the time series
- P(i) is the PSD of the time series

$$\mathrm{RMS}\Big|_{0}^{f_i} =$$



Cumulative RMS vs. Frequency



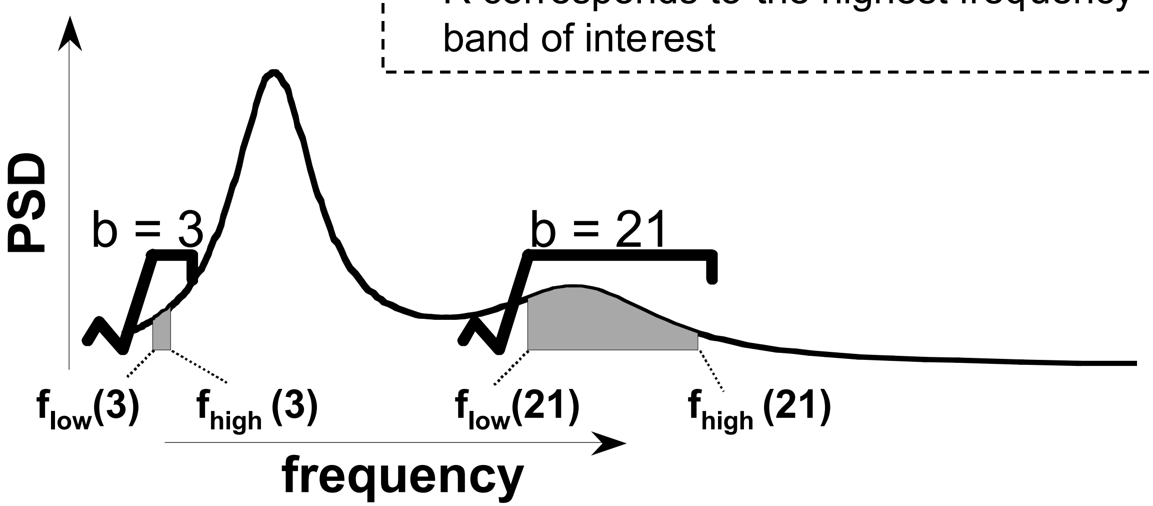
RMS vs. One Third Octave Frequency Bands

- **What is it?** It's a plot that quantifies the spectral content in proportional bandwidth frequency bands for a given time interval of interest.
- **Why do we use it?** The International Space Station vibratory limit requirements are defined in terms of the RMS acceleration level for each of 31 one third octave bands with the time interval specified as 100 seconds.
- Mathematically, we have:

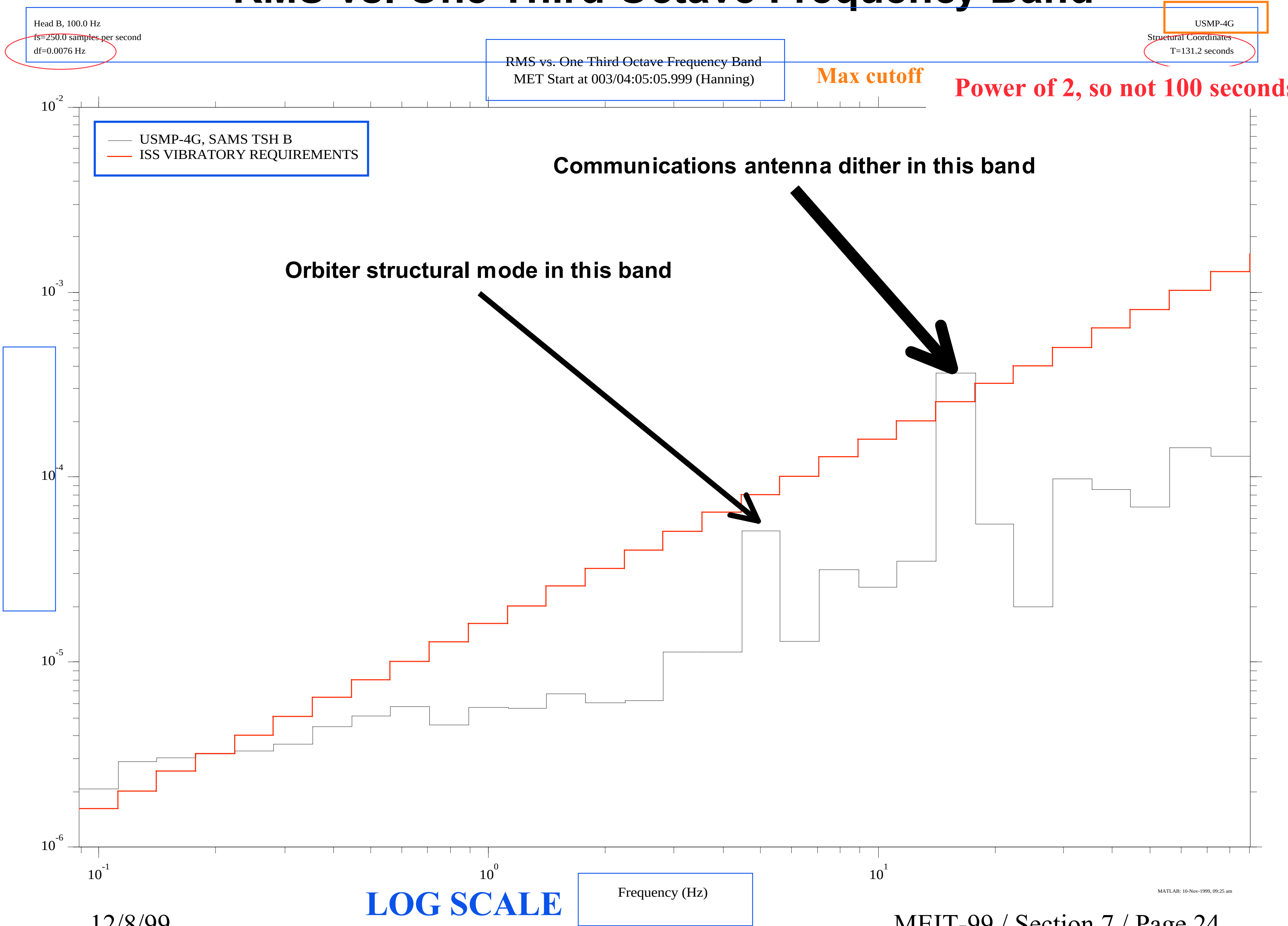
$$a_{RMS}(b) = \sqrt{\sum_{i=f_{low}(b)}^{f_{high}(b)} P(i)\Delta f} \qquad b = 1,2\ldots,R$$

- $f_{low}(b)$ and $f_{high}(b)$ are frequency indices for the b^{th} one third octave band
- P(i) is the PSD of the time series
- Δf is the frequency resolution
- R corresponds to the highest frequency band of interest

$$RMS_b \Big|_{f_{low}(b)}^{f_{high}(b)} =$$



RMS vs. One Third Octave Frequency Band

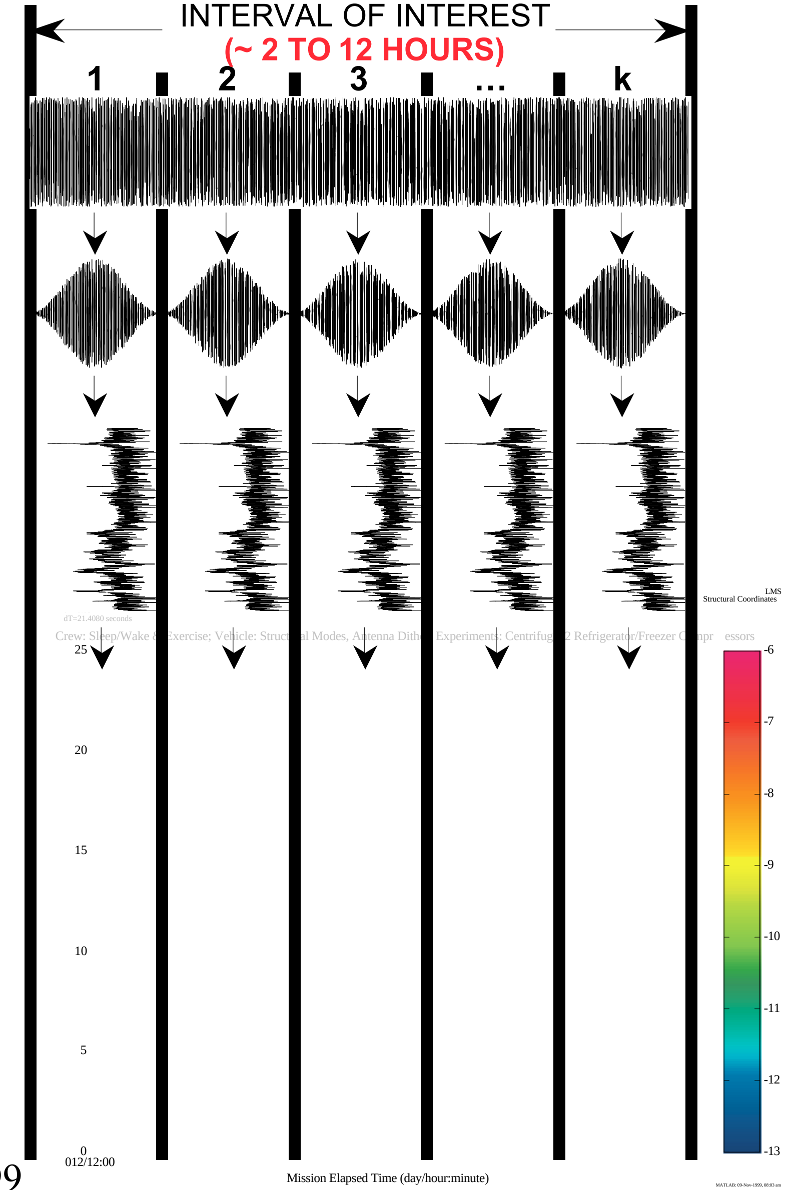


Spectrogram

- **What is it?** It's a three-dimensional plot that shows PSD magnitude (represented by color) versus frequency versus time.
- **Why do we use it?**
  - It is a powerful qualitative tool for characterizing long periods of data
  - Identification and characterization of boundaries and structure in the data
    - Determine start/stop time of an activity within temporal resolution, dT (dT is not Δt ← overlap)
    - Track frequency characteristics of various activities within frequency resolution, Δf
- **Things you should NOT do with a spectrogram:**
  - Quantify disturbances in an absolute sense. The cumulative RMS or one-third octave versus frequency plots are better suited for this objective.
  - Rely entirely on it to check for the presence of a disturbance which is either known or expected to be relatively weak. A PSD with appropriate spectral averaging works better for this.

Frequency Domain Analysis

How to Build a Spectrogram



1. SEGMENT INTO k EQUAL–LENGTH SECTIONS AND DEMEAN EACH SECTION

2. APPLY TAPER WINDOW TO EACH SECTION

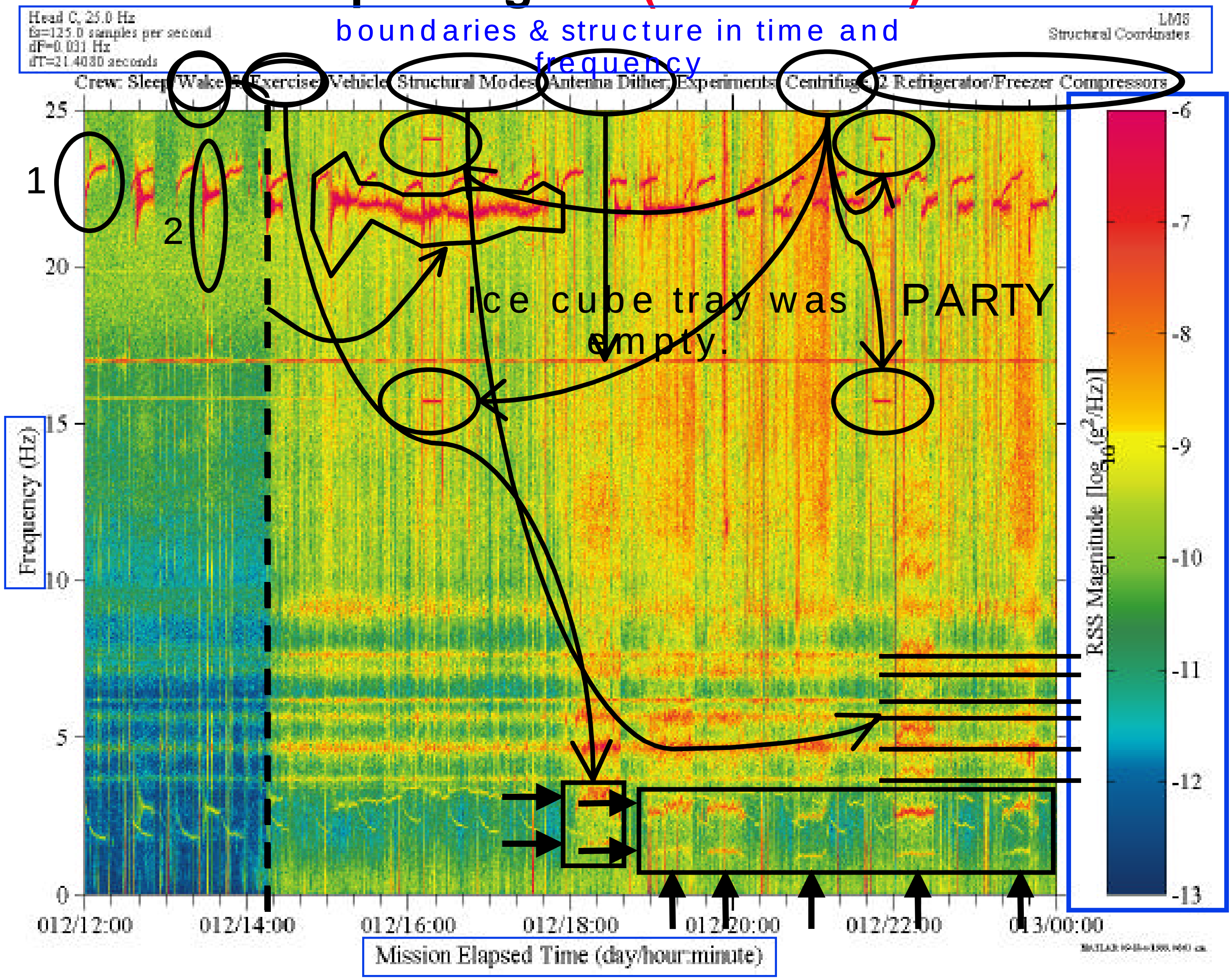
3. COMPUTE PSD OF EACH SECTION

4. CALCULATE LOG_{10} OF |PSDs| AND MAP NUMERIC VALUES TO COLORS SUCH THAT THE BLUE (BOTTOM) PART OF THE COLOR MAP REPRESENTS SMALLER VALUES THAN THOSE TOWARD THE RED (TOP) PART

5. DISPLAY EACH OF THE k PSD SECTIONS AS A VERTICAL STRIP OF THE SPECTROGRAM (LIKE WALLPAPERING), SUCH THAT TIME INCREASES FROM LEFT TO RIGHT AND FREQUENCY INCREASES FROM BOTTOM TO TOP

Note: The width of each strip is the temporal resolution and the height of each distinct color patch is the frequency resolution.

Spectrogram (12 HOURS)



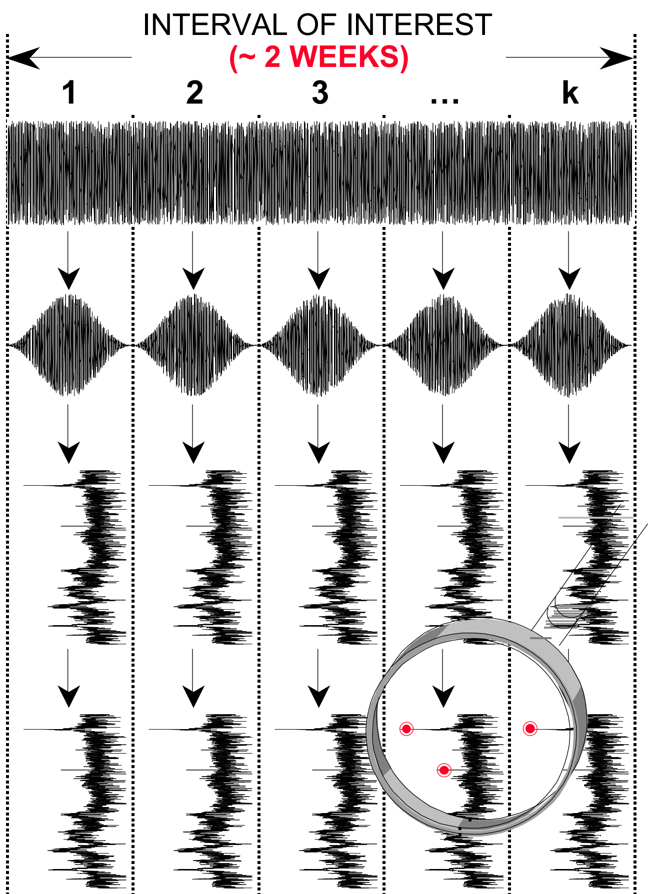
Principal Component Spectral Analysis (PCSA)

- **What is it?** A frequency domain analysis technique that employs a peak detection algorithm to accumulate PSD magnitude and frequency values of dominant or persistent spectral contributors and display them in the form of a 2-D histogram.

- **Why do we use it?** To examine the spectral characteristics of a long period of data.
  - serves to *summarize* magnitude and frequency variations of key spectral contributors
  - better frequency and PSD magnitude resolution relative to a spectrogram

- **Tradeoff:** Poor temporal resolution – no direct way of correlating with time

PCSA Procedure



1. SEGMENT INTO k EQUAL–LENGTH SECTIONS AND DEMEAN EACH SECTION

2. APPLY TAPER WINDOW TO EACH SECTION

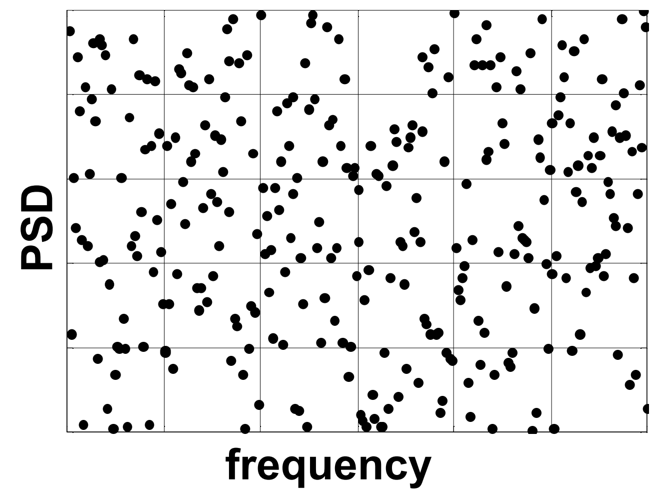
3. COMPUTE PSD OF EACH SECTION

4. PASS EACH PSD THROUGH A PEAK DETECTOR (FIND ALL THE PEAKS THAT ARE LOCAL MAXIMA AND AT LEAST AS HIGH AS ANY OTHER POINT WITHIN A USER-DEFINED NEIGHBORHOOD OF FREQUENCY BINS) TO YIELD PEAK PSD MAGNITUDES VERSUS FREQUENCY

5. STORE THESE PEAKS AND CORRESPONDING FREQUENCIES AS INTERMEDIATE RESULTS

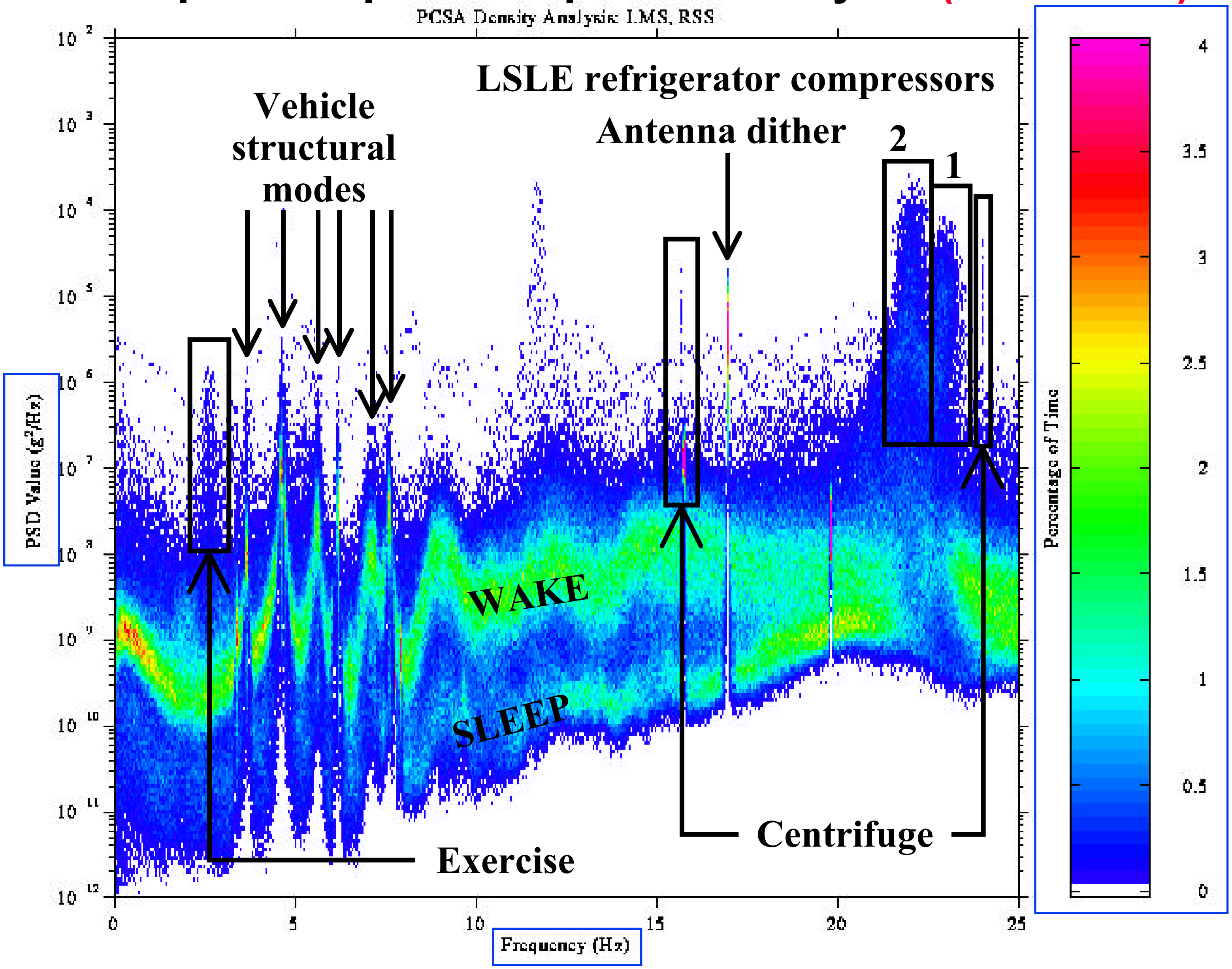
6. PLOT THE ACCUMULATED PSD PEAKS VERSUS FREQUENCY AS A TWO-DIMENSIONAL HISTOGRAM COLOR DENSITY PLOT

Magnitude-Frequency Bins for 2-D Histogram



NOTE: DESIRED FREQUENCY RESOLUTION AND POWER-OF-TWO CONSIDERATIONS WILL DETERMINE THE INTERVAL USED IN STEP 1; HOWEVER, THIS PROCEDURE ALLOWS FOR ARBITRARILY LARGE TIME SPANS TO BE CONSIDERED

Principal Component Spectral Analysis (15+ DAYS)



Time Domain Summary Table

<table>
<tr><th>DISPLAY</th><th>NOTES</th></tr>
<tr><td>Acceleration vs. Time</td><td>• most precise accounting of measured data with respect to time
• display device constrains resolution for long time spans</td></tr>
<tr><td>Interval Minimum/Maximum Acceleration vs. Time</td><td>• displays upper and lower bounds of peak-to-peak excursions
• good display approximation for time histories on output devices with resolution insufficient to display all data in time frame of interest</td></tr>
<tr><td>Interval Average Acceleration vs. Time</td><td rowspan="2">• descriptive statistics
• not fully descriptive (lossy compression)</td></tr>
<tr><td>Interval Root-Mean-Square (RMS) Acceleration vs. Time</td></tr>
</table>

Frequency Domain Summary Table

DISPLAY	NOTES
Power Spectral Density (PSD) vs. Frequency	• quantifies distribution of power with respect to frequency • windowing (tapering) to suppress spectral leakage • spectral averaging to reduce spectral variance (degraded Δf)
Cumulative RMS Acceleration vs. Frequency	• quantifies RMS contribution at and below a given frequency • quantitatively highlights key spectral contributors
RMS Acceleration vs. One Third Octave Frequency Bands	• quantify RMS contribution over proportional frequency bands • compare measured data to ISS vibratory requirements
Spectrogram (PSD vs. Frequency vs. Time)	• displays power spectral density variations with time • good *qualitative* tool for characterizing long periods • identify structure and boundaries in time and frequency
Principal Component Spectral Analysis (PCSA)	• summarize magnitude and frequency excursions for key spectral contributors over a relatively long period of time • results typically have finer frequency resolution and high PSD magnitude resolution relative to a spectrogram at the expense of poor temporal resolution

Section 8:

Microgravity Environment of Non-Orbital Platforms

Kevin M. McPherson

PIMS Data Analyst

NASA Glenn Research Center

Topics for Discussion

- **Non-orbital platforms**
  - **Terrier-Black Brant sounding rocket**
  - **KC-135 aircraft for bolted and free-float conditions**
- **Accelerometer systems used to measure the environments**
  - **SAMS (Space Acceleration Measurement System)**
  - **SAMS-FF (SAMS-Free Flyer)**

Non-Orbital Platforms

- **Terrier-Black Brant sounding rocket**
  - **Launched from White Sands, NM in support of the DARTFire experiment (September, 1997)**
  - **Achieves approximately 500 seconds of reduced gravity environment**
- **KC-135 Aircraft**
  - **Operated by Johnson Space Center**
  - **Achieves reduced gravity environment by flying parabolic trajectories**
  - **Parabolas provide 15-20 seconds of reduced gravity environment**
  - **Approximately 40-50 parabolas per campaign**

Accelerometer Systems

- **SAMS characteristics**
  - **Sampling rate and cut-off frequency are selected and fixed pre-mission**
  - **For support of KC-135 flights, three SAMS heads are flown**
    - head A, f_s=250 and cut-off frequency of f_c=100
    - head B, f_s=500 and cut-off frequency of f_c=100
    - head C, f_s=25 and cut-off frequency of f_c=5
- **SAMS-FF characteristics**
  - **Sampling rate and cut-off frequency are selectable during the mission**
  - **DARTFire mission utilized this variable sampling rate capability**
  - **uSEG experiment utilized two sampling rates during KC-135 testing (f_s=800 and f_s = 100)**

Sounding Rocket Environment Characterization

- **Terrier-Black sounding rocket DARTFire flight timeline is shown in the graphic in Figure 8-1**
- **Figure 8-2 illustrates the acceleration vector magnitude for the time period when the sampling rate was 25 samples per second**
  - **environment measured at less than 30 ug root sum square for the time interval analyzed**
- **Figure 8-3 is the RSS power spectral density for the time period when the sampling rate was 25 samples per second**
  - **frequency domain characteristics track known disturbance sources originating internal to the DARTFire equipment**
    - Intensified Multispectral Imager filter wheel operates at 5 Hz
    - Infrared Imager filter wheel operates at 1 Hz

KC-135 Environment Characterization

- **Figure 8-4 illustrates the KC-135 overall environment over multiple parabolas during a typical campaign as recorded by SAMS**
- **Figure 8-5 is a detailed plot of the KC-135 environment during the reduced gravity portion of the parabola as recorded by SAMS-FF**
- **Figure 8-6 is a plot of KC-135 parabola recorded in support of SAL experiment. Shows free-float of SAL test equipment and timelines the activity within the parabola**
- **Figure 8-7 is a detailed plot of the free-float period of the parabola**

Section 9:
Highlights of the Microgravity Environment
NASA Space Shuttle Orbiters and Mir Space Station

Richard DeLombard
Acceleration Measurement Discipline Scientist
NASA Glenn ResearchCenter

MICROGRAVITY ENVIRONMENT

The microgravity environments of all Earth-orbiting laboratories are similar in that they are composed of the same basic contributors.

Gravity gradient effects, atmospheric drag, and rotational motion all contribute to relative motions between free-floating particles (or experiment samples) and a fixed reference frame. Such motion is typically viewed as quasi-steady accelerations.

On-going life support, station-keeping, and experiment operations contribute to transient disturbances and a background vibratory (oscillatory) environment in the frequency range 0.1 Hz up to at least 300 Hz.

Microgravity Environment Description Handbook

- **compilation of our knowledge (through April 1997) of the microgravity environment of various payload carriers on the Orbiters and of Mir**
  - **NASA TM-107486, July 1997**
  - **http://www.lerc.nasa.gov/WWW/MMAP/PIMS/HTMLS/Micro-descpt.html**

Mission-Specific Descriptions

- **mission-specific environment characterizations in mission summary reports; see reference list**

Definitions

- **Quasi-steady**
  - **signals that vary with extremely long periods**
    - periods longer than 100 seconds
- **Oscillatory**
  - **a signal that varies above and below a mean value**
    - with some degree of periodicity
    - periodicity may vary with time
  - **particularly used to describe vibratory disturbances with frequency content greater than 0.01 Hz**
- **Transient**
  - **signals that are impulsive in nature**
  - **passing quickly into and out of existence**
    - while source of these disturbances may pass quickly, effects may, and generally do, linger

Quasi-steady Environment

- **quasi-steady effects measured by OARE on Columbia**
  - **aerodynamic drag, gravity gradient, and vehicle rotation**
  - **effects of crew activity**
  - **effects of thruster firings, venting, cabin depressurization**
  - **Figures 9-1, 9-2**
- **modelling of Mir quasi-steady environment takes into account drag, gravity gradient, rotation**
  - **Sazonov, Komarov, Polezhaev, Nikitin, Ermakov, Stazhkov, Zykov, Ryaboukha, Acevedo, Liberman: "Microaccelerations on Board the Mir Orbital Station and Quick Analysis of the Gravitational Sensitivity of Convective Heat/Mass Transfer Processes," MGMG 16, May 1997.**
  - **Belyaev, Zykov, Ryabukha, Sazonov, Sarychev, Stazhkov: "Computer Simulation and Measurement of Microaccelerations On the Mir Orbital Station," Fluid Dynamics, Vol. 29, No. 5, 1994.**
  - **Figure 9-3**

Oscillatory Sources

- **Mir Structural Modes**
  - **differ slightly among Mir configurations**
  - **typical in Priroda: 0.5, 0.6, 0.9, 1.1, 1.4, 2.2, 3.6, 5.8, 6.4, 7.5 Hz**
- **Orbiter Structural Modes**
  - **differ slightly among missions and Orbiters**
  - **typically 2.4, 3.5-3.6, 4.7-4.8, 5.2, and 7.4 Hz**
  - **tend to increase in amplitude with increased crew activity**
- **Orbiter / Mir Structural Modes**
  - **structural modes depend on the size and configurations of the combined vehicle**
  - **structural modes from combined Orbiter & Mir vehicle are different from those of the Orbiter or of Mir alone**

Oscillatory Sources, cont.

- **Crew Exercise**
  - **Ergometer: 2-3 Hz legs pedalling, 1-1.5 Hz body rocking**
  - **Treadmill: 1-2 Hz footfall frequency, 0.5-1Hz body rocking**
  - **Both types also have harmonics**
- **Ku-band Antenna Dither**
  - **dithers at ~17.03 Hz**
  - **intensity varies with time (periodic)**
    - 40-120 μg_{RMS} during STS-65 (IML-2)
    - 50-300 μg_{RMS} during STS-87 (USMP-4)
      - for USMP-4, about 10 μg_{RMS} when Ku dither deactivated
  - **transmission to Mir when vehicles docked**
    - related to Orbiter resonating at this frequency
- **SAMS Optical Disk Drives (last used on Mir and STS-79)**
  - **just under 20 Hz but very weak**

Oscillatory Sources, cont.

- **Fans**
  - **Glovebox fans on Orbiters: for different models of GBX, have seen vibrations at 20, 38, 43, 48, 53, 63.5, 66.5, 98.6, and 127 Hz**
  - **multiple life support system fans on Mir around 40 Hz, harmonics at 80 Hz**
- **Compressors**
  - **LSLE R/F: 20-22 Hz, cycles on/off throughout missions seen on Orbiters and transmitted to Mir when docked**
  - **Vozkukh Compressors (BKV-3 dehumidifier, life support) on Mir; evident at 24 Hz with harmonics at 48, 72, 96 Hz**
- **Pumps**
  - **TEMPUS water pump: nominal 4,800 rpm (80 Hz) on STS-65, 2,000-2,600 rpm (41.7-43.3 Hz) on STS-83, STS-94**
    - isolation mountings used for MSL-1 reduced accelerations by at least 3,500 μg_{RMS}
  - **Mir life support vacuum valve pumps operate at 88-92 Hz**

Oscillatory Sources, cont.

- **Unknown Sources**
  - **continuous; constant frequency; variable frequency**
  - **seen throughout frequency range available with current accelerometer systems: 0.01 to 250 Hz**
- **Mir Gyrodynes**
  - **operate at 10,000 rpm (166.7 Hz) for attitude maintenance**
  - **above SAMS filter cut-off frequency, so measured g-levels appear lower than actual**
  - **spin up and spin down activities**
- **Figures 9-4, 9-5**

Transient Disturbances

- **Thruster Systems**
  - **Orbiter Reaction Control System (RCS) Thrusters**
    - firings produce dc-offset, followed by a damped ringing behavior
    - OMS firings impart 20-50 milli-g, typically up to 40 seconds duration
    - PRCS firings impart tens of milli-g, can last up to tens of seconds
    - VRCS firings impart tenths of milli-g, usually lasting fraction of a second
  - **Orbiter Flight Control System (FCS) Checkout**
    - vents exhaust gas (0-30 lb. thrust) at 1 to 1.5 second intervals
    - increased use of VRCS jets for attitude maintenance
    - impulse train causes an oscillatory signal
  - **Progress Engine Burn (altitude)**
    - longer duration, lower intensity than Orbiter OMS firing
    - induces a dc-offset, increased ringing/oscillation during event
  - **Mir Maneuvering Thruster (attitude)**
    - imparts an offset on the order of 1-2 milli-g, shorter duration than Progress Engine Firing

Transient Disturbances, cont.

- **Experiment Operations**
  - **CM-1 setup on STS-94 (mallet impacts)**
    - hammering at Spacelab Rack 8, SAMS sensor at Rack 12
    - series of 4 hits, reaching 2 milli-g magnitude, directionality evident
    - damped ringing observed after each impact
  - **MEPHISTO latch release (USMP-2)**
    - performed to introduce localized disturbance to experiment
    - characteristic behavior most noticeable on Orbiter Z-axis
  - **Orbiter Cargo Bay Radiator Latch Release**
  - **Mir / Orbiter Docking & Undocking Transients**
    - docking shows two transient (broad-band) disturbances
      - soft mate and hard mate
    - undocking shows one transient
- **Crew Movement**
- **Figures 9-6, 9-7, 9-8, 9-9**

References

- Belyaev, Zykov, Ryabukha, Sazonov, Sarychev, Stazhkov: Computer Simulation and Measurement of Microaccelerations On the Mir Orbital Station, Fluid Dynamics 29 (1994).
- DeLombard, R., K. Hrovat, M. Moskowitz, K. McPherson: SAMS Acceleration Measurements on Mir from June to November 1995, NASA Technical Memorandum TM-107312, September 1996.
- DeLombard, R., K. McPherson, K. Hrovat, M. Moskowitz, M.J.B. Rogers, T. Reckart: Microgravity Environment Description Handbook, NASA Technical Memorandum TM-107486, July 1997.
- Hakimzadeh, R., K. Hrovat, K.M. McPherson, M.E. Moskowitz, M.J.B. Rogers: Summary Report of Mission Acceleration Measurements for STS-78, NASA Technical Memorandum TM-107401, January 1997.
- Moskowitz, M.E., K. Hrovat, D. Truong, T. Reckart: SAMS Acceleration Measurements on Mir from March to September 1996, NASA Technical Memorandum TM-107524, August 1997.
- Rogers, M.J.B., R. DeLombard: Summary Report of Mission Acceleration Measurements for STS-73, NASA Technical Memorandum TM-107269, July 1996.
- Rogers, M.J.B., K. Hrovat, K.M. McPherson, M.E. Moskowitz, R. DeLombard: Summary Report of Mission Acceleration Measurements for STS-75, NASA Technical Memorandum TM-107359, November 1996.
- Rogers, M.J.B., M.E. Moskowitz, K. Hrovat, T. Reckart: Summary Report of Mission Acceleration Measurements for STS-79, NASA Contractor Report CR-202325, March 1997.
- Sazonov, Komarov, Polezhaev, Nikitin, Ermakov, Stazhkov, Zykov, Ryaboukha, Acevedo, Liberman: Microaccelerations on Board the Mir Orbital Station and Quick Analysis of the Gravitational Sensitivity of Convective Heat/Mass Transfer Processes, MGMG 16, May 1997.
- Moskowitz, M.E., K. Hrovat, P. Tschen, K. McPherson, M. Nati, T.A. Reckart: Summary Report of Mission Acceleration Measurements for MSL-1, NASA Technical Memorandum TM-1998-206979, May 1998.

Section 10:

Implications for Microgravity Experimenters

Presented by:
Kenol Jules
PIMS Project Scientist
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Available Microgravity Carriers

- Drop Towers
- Parabolic Flight Aircraft (KC-135)
- Sounding Rockets
- STS Orbiters
- Free-flyers
- International Space Station

Experiment Location and Orientation

- **proximity to carrier / vehicle center of mass**
  - sensitivity to quasi-steady variations
- **proximity to other equipment**
  - sensitivity to vibration sources
- **alignment**
  - sensitivity to quasi-steady acceleration direction

Carrier Attitude

- **issues related to experiment location**
  - gravity gradient effects
- **issues related to experiment orientation**
  - design attitude that points experiment in desired direction
- **sensitivity to quasi-steady variations with time**
  - atmospheric drag effects
  - local vertical / local horizontal attitudes versus inertial attitudes

Accelerometer Selection

- **frequency range**
  - cutoff frequency based on experiment sensitivity
  - sampling rate and filter characteristics specified by accelerometer system team to provide frequency selected by experimenter

- **location and alignment**
  - close to experiment sensitive location
  - mounting technique
  - away from sources which may disturb accelerometer and mask disturbances of interest
  - knowledge of sensor orientation relative to experiment axes

Experiment Timelining

If at all possible, schedule your experiment operations to avoid any activities which might negatively impact it. Keep the following points in mind:

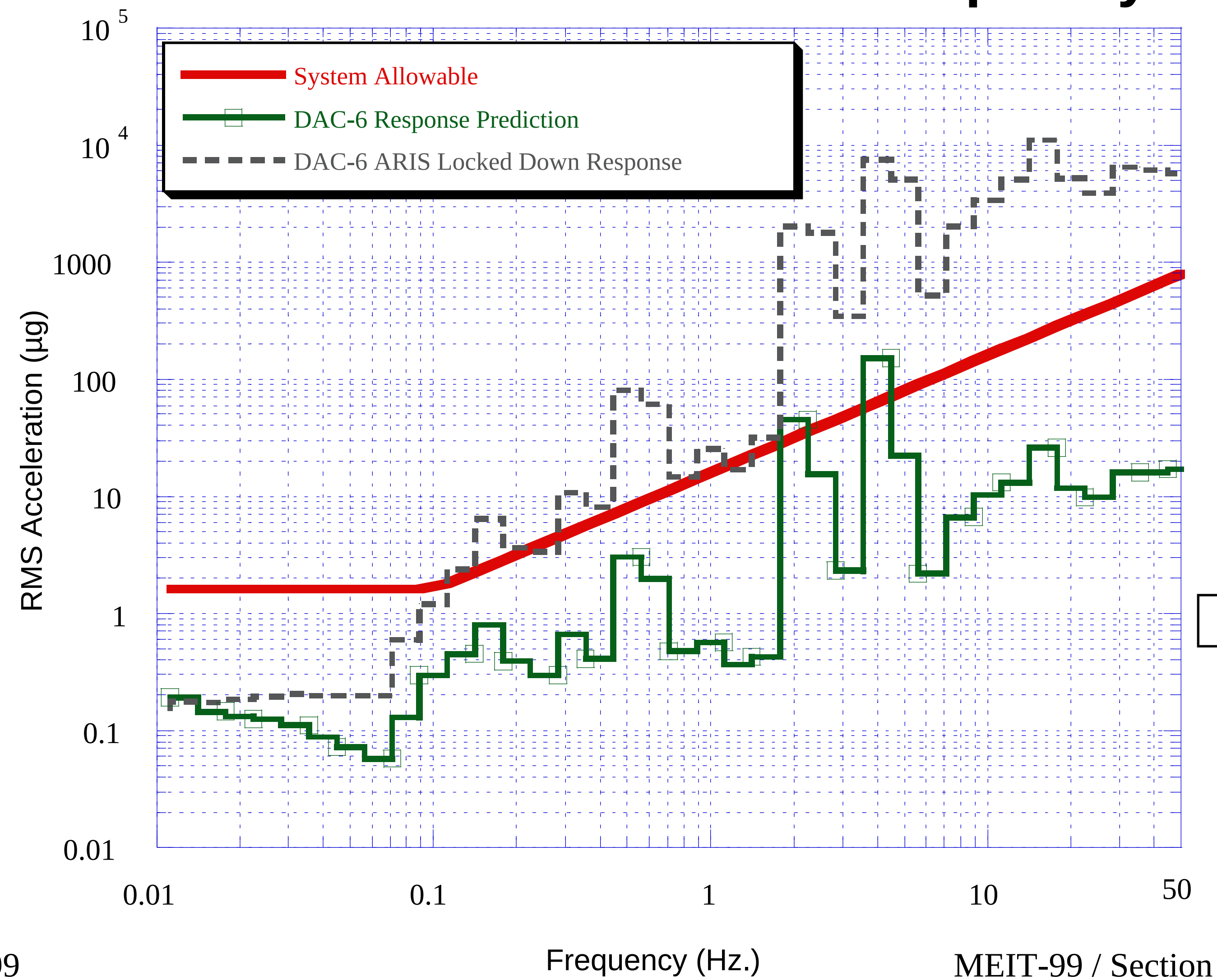
- **experiment sensitivity to acceleration sources**
  - quasi-steady, vibratory and transient
- **crew exercise**
- **thruster activity**
- **other experiment operations**
- **crew activity**
- **venting**

Section 11:

ISS Acceleration Environment Predictions

Richard DeLombard
Acceleration Poobah ad Infinitum
– Guardian of THE Requirement –
NASA Glenn Research Center

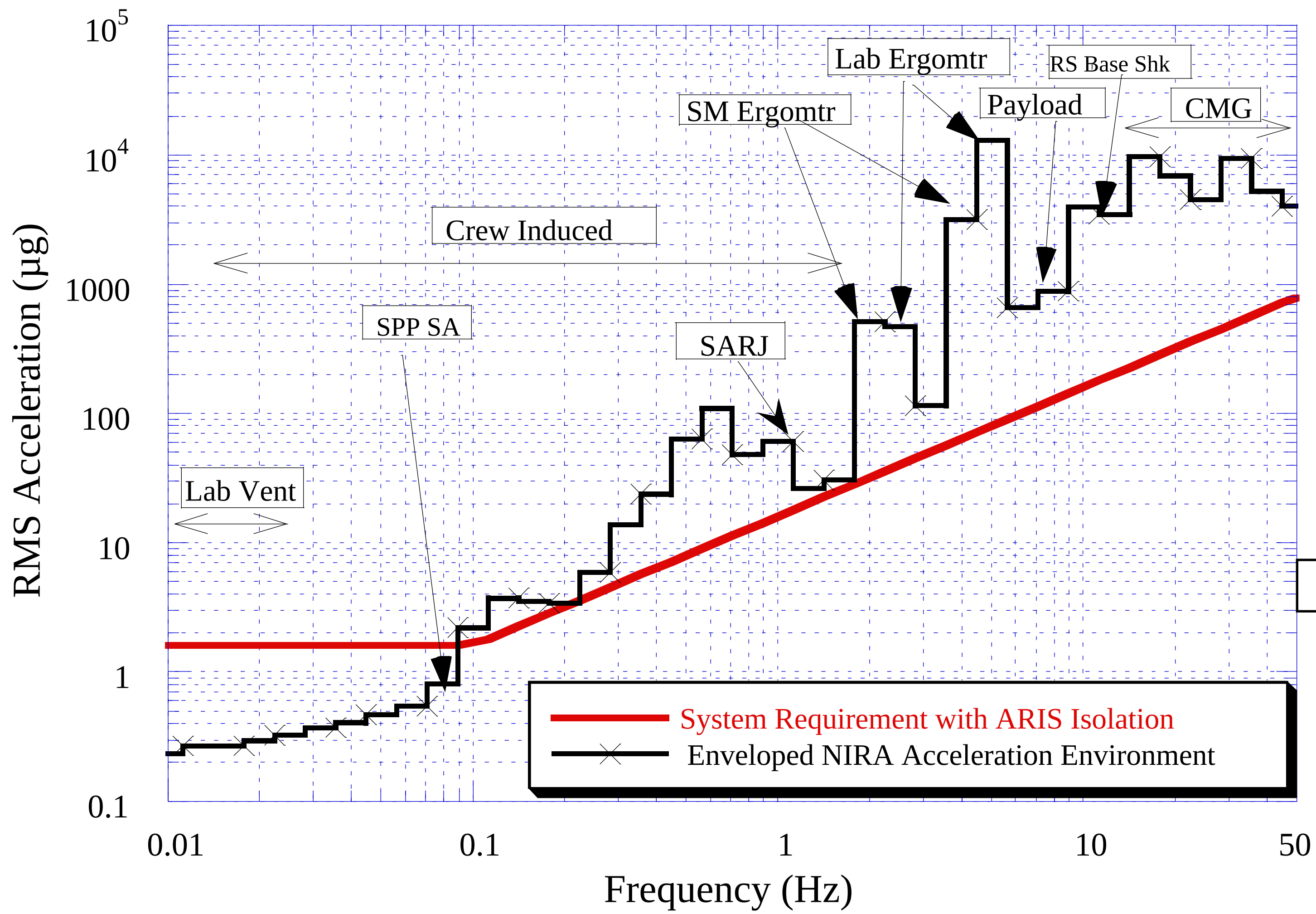
ARIS Locked Down - Low Frequency



DAC #6
6/98

Data from Boeing

Non-Isolated Rack Assessment - Low Frequency



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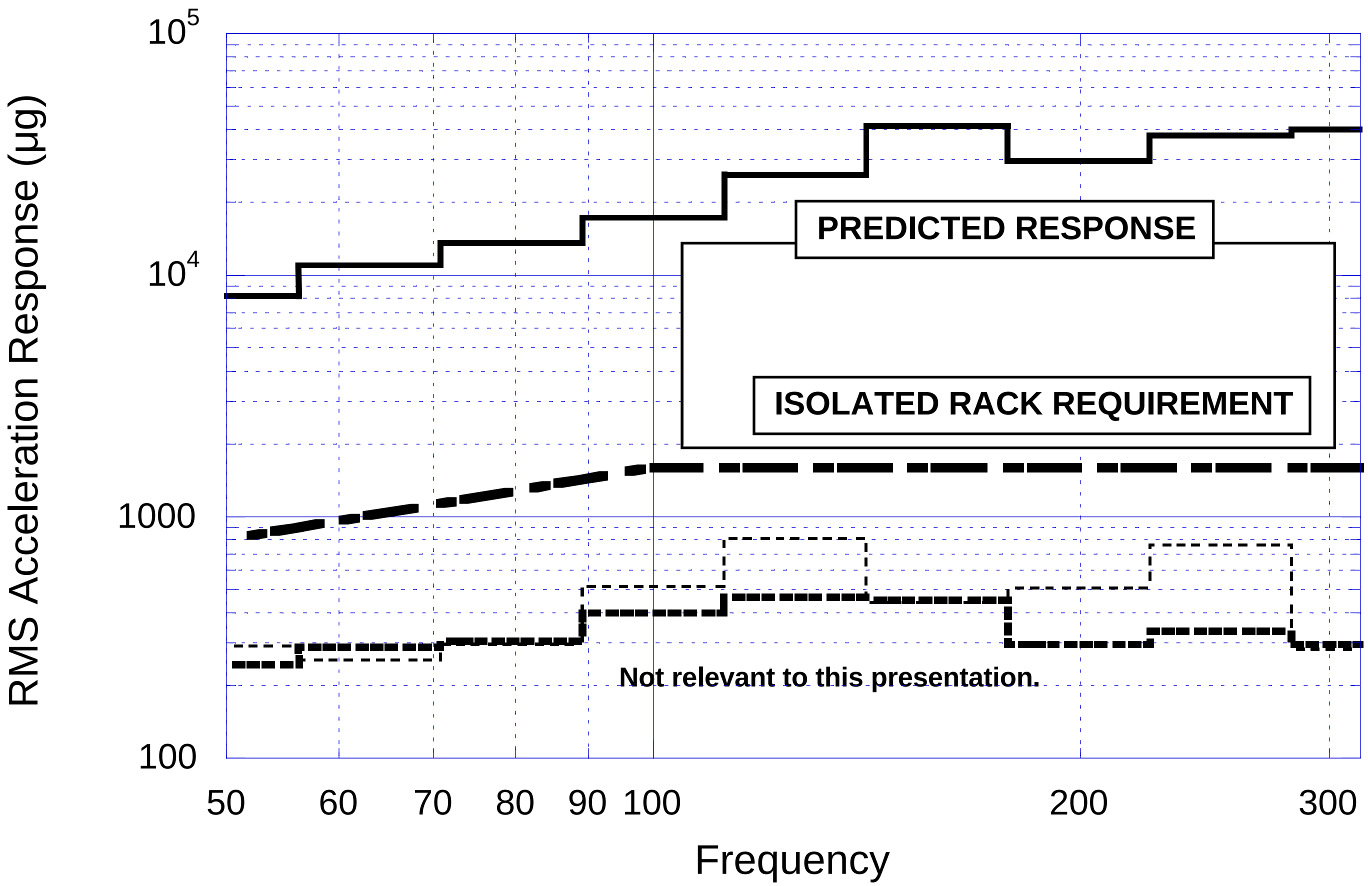
Data from Boeing

Non-Isolated Rack Assessment - High Frequency

Fig. (1A) NIRA Response at US/ISPR due to All Disturbances



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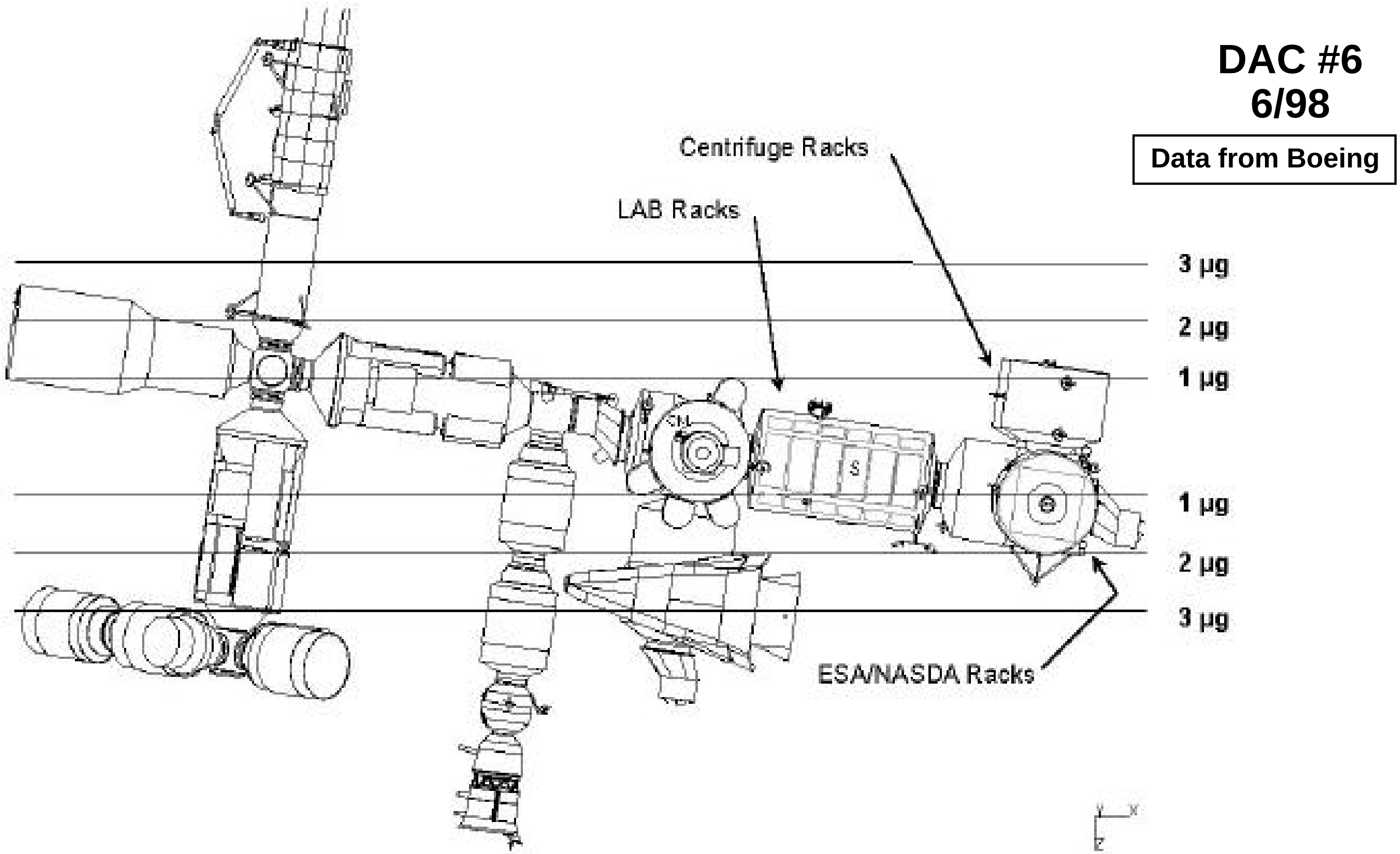
Data from Boeing

DAC-6 Quasi-steady AC Results - Side View



DAC-6 Quasi-steady AC Results - Front View

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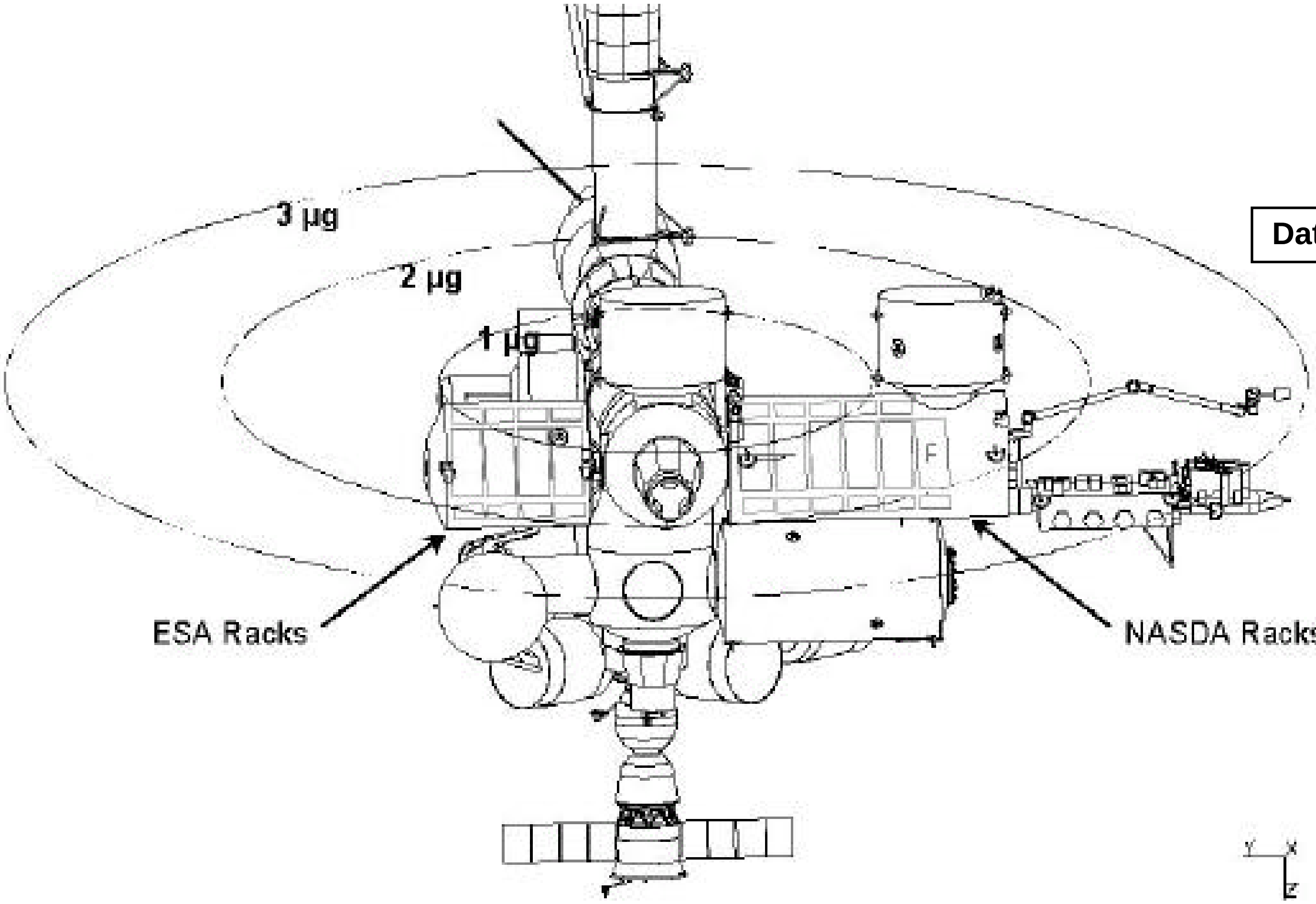
Data from Boeing

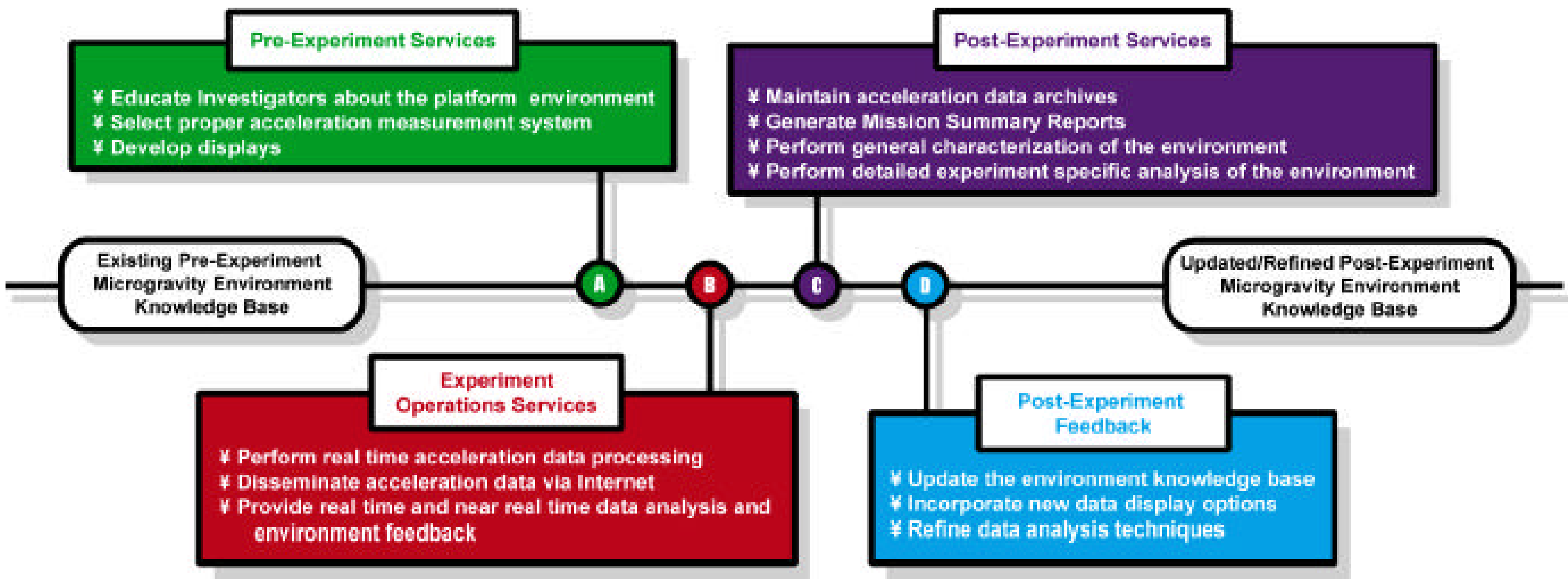


Section 12:

PIMS International Space Station Operations

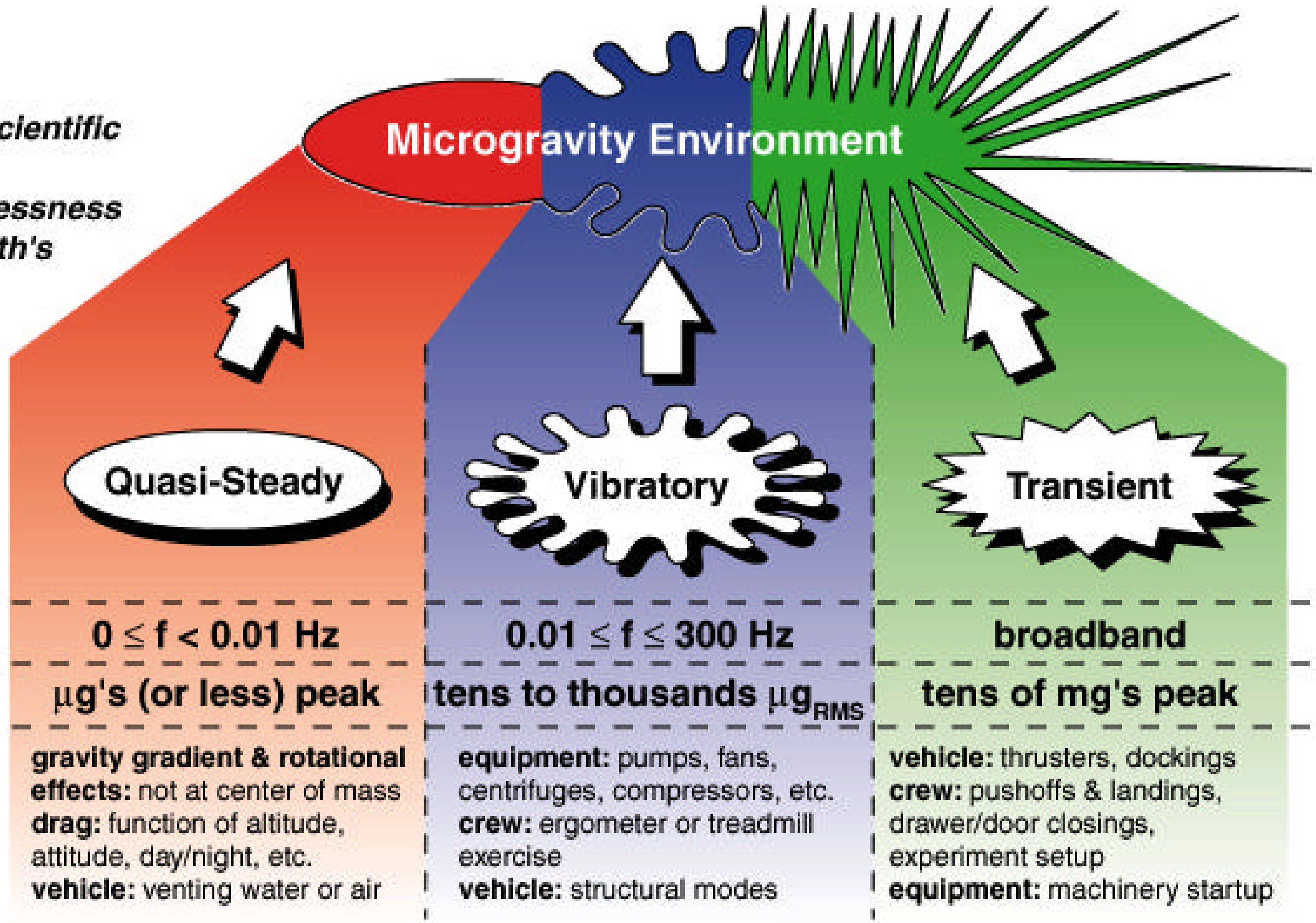
Kevin M. McPherson
PIMS Data Analyst
NASA Glenn Research Center

PIMS Functions During Experiment Life Cycle



Components of the Microgravity Environment

Microgravity is:
- ***a general label for scientific investigations that exploit near-weightlessness***
- ***one-millionth of Earth's normal gravity***
- ***a reduced gravity environment***



Component	Quasi-Steady	Vibratory	Transient
Frequency	$0 \le f < 0.01$ Hz	$0.01 \le f \le 300$ Hz	broadband
Magnitude	μg's (or less) peak	tens to thousands μg_{RMS}	tens of mg's peak
Primary Sources	**gravity gradient & rotational effects:** not at center of mass **drag:** function of altitude, attitude, day/night, etc. **vehicle:** venting water or air	**equipment:** pumps, fans, centrifuges, compressors, etc. **crew:** ergometer or treadmill exercise **vehicle:** structural modes	**vehicle:** thrusters, dockings **crew:** pushoffs & landings, drawer/door closings, experiment setup **equipment:** machinery startup

Space Acceleration Measurement System-II

- **Provide distributed measurement of the vibratory and transient acceleration environment ($0.01 \leq f \leq 300$ Hz) on the ISS in support of various microgravity payloads**
- **Components**
  - **Control Unit**
    - Responsible for data and command routing
  - **Remote Triaxial Sensor (RTS) System**
    - Up to Ten RTS Electronics Enclosures (EE's)
    - Up to Two RTS Sensor Enclosures (SE's) per EE
- **Flight 6A configuration and operations**
  - **Three EE's and 5 SE's**
  - **Real-time data downlinked from the ISS**

Microgravity Acceleration Measurement System

- **Measure the ISS quasi-steady acceleration ($f \leq 0.01$ Hz) and the ISS vibratory acceleration environment**

- **Components**
  - **Miniature Electro-Static Accelerometer (MESA)**
    - sensor is a flight spare from the OARE program
    - measure the quasi-steady acceleration environment
  - **High-Resolution Accelerometer Package (HiRAP)**
    - measure the vibratory environment at the MAMS location only

- **Flight 6A configuration**
  - **MESA and HiRAP instruments active**
  - **Real-time data downlink from the ISS**

- **Additional features**
  - **Quasi-steady acceleration data can be mapped to various locations within the ISS using ISS body rates and body angles**
  - **Provides on orbit bias calibration capabilities**

Operational Philosophy

- **Operations are divided into three sections:**
  - **1) Real-time operations**
  - **2) Near real-time operations**
  - **3) Offline operations**
    - general characterization and specialized analyses
- **Acceleration measurement using SAMS-II and MAMS planned for the duration of ISS operations beginning with Flight 6A operations**
- **Potential for nearly continuous operations to characterize the environment**
  - **includes measurement of the environment, where possible, outside of "microgravity mode"**
- **AOS/LOS profiles call for 30 - 60 percent AOS coverage**
  - **requires the ability to deal with AOS and LOS data streams**

Operational Philosophy

- **Flight 6A operational configuration calls for 5 SAMS-II Sensor Enclosures (SE), MAMS MESA, and MAMS HiRAP**
  - **not all sensors will be active all the time resulting in a variety of acceleration measurement profiles**
- **PIMS has developed a core set of techniques for processing and displaying the acceleration data**
  - **Based on real-time and offline experience gained from SAMS and OARE data during Space Shuttle and Mir operations**
  - **Customized processing or displays as required by the microgravity user community**
- **Microgravity acceleration data will be available to Principal Investigators**
  - **Working with international partners on establishing a universal file format standard for acceleration data**

PIMS Data Analysis Techniques

Display Format	Regime(s)	Notes
Acceleration versus Time	Transient, Quasi-Steady, Vibratory	• precise accounting of measured data with respect to time; best temporal resolution
Interval Min/Max Acceleration versus Time	Vibratory, Quasi-Steady	• displays upper and lower bounds of peak-to-peak excursions of measured data • good display approximation for time histories on output devices with resolution insufficient to display all data in time frame of interest
Interval Average Acceleration versus Time	Vibratory, Quasi-Steady	• provides a measure of net acceleration of duration greater than or equal to interval parameter
Interval RMS Acceleration versus Time	Vibratory	• provides a measure of peak amplitude for pure sinusoids
Trimmed Mean Filtered Acceleration versus Time	Quasi-Steady	• removes infrequent, large amplitude outlier data
Quasi-Steady Mapped Acceleration versus Time	Quasi-Steady	• use rigid body assumption and vehicle rates and angles to compute acceleration at any point in the vehicle
Quasi-Steady Three-Dimensional Histogram (QTH)	Quasi-Steady	• summarize acceleration magnitude and direction for a long period of time • indication of acceleration "center-of-time" via projections onto three orthogonal planes

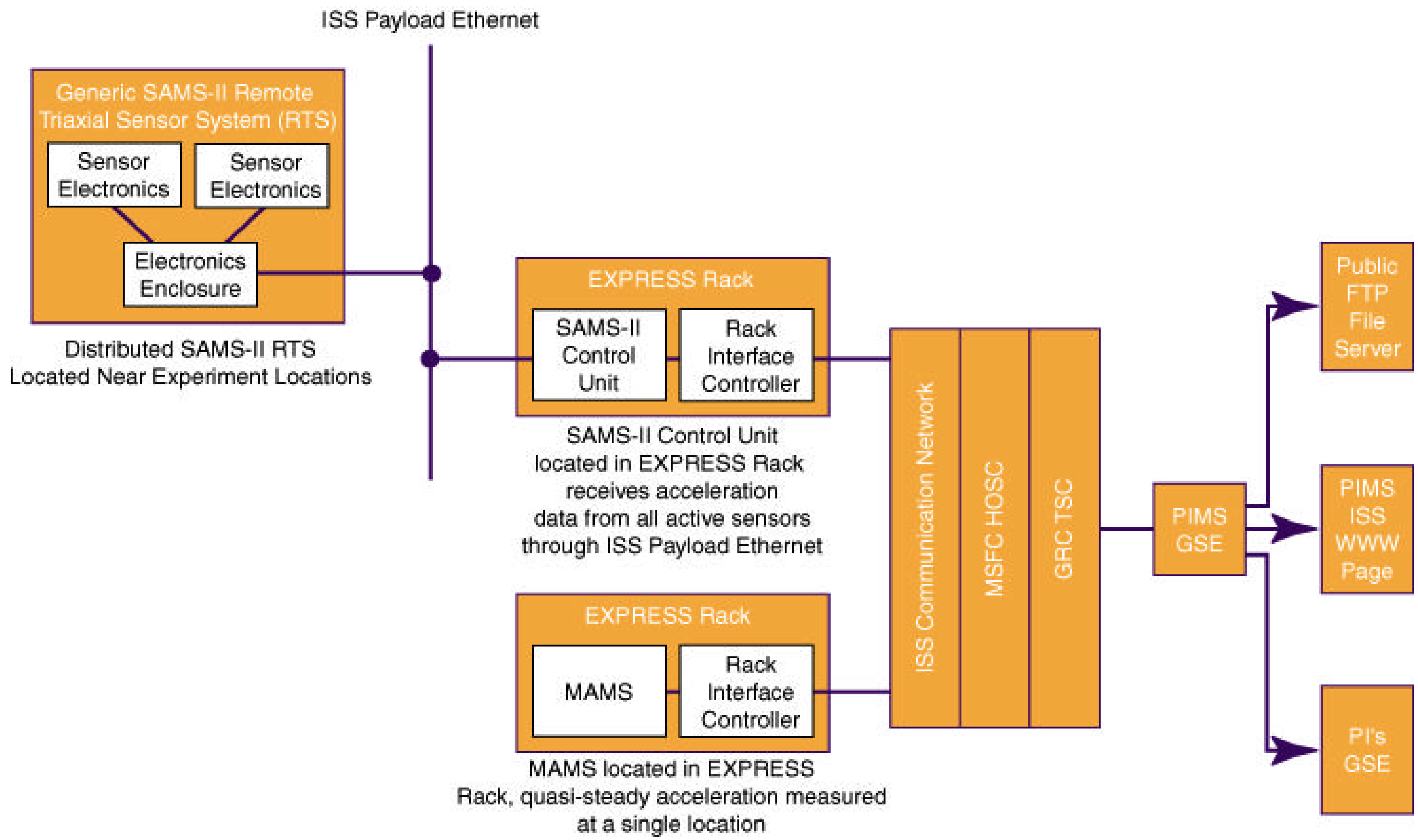
PIMS Data Analysis Techniques

Display Format	Regime(s)	Notes
Power Spectral Density (PSD) versus Frequency	Vibratory	• displays distribution of power with respect to frequency
Spectrogram (PSD versus Frequency versus Time)	Vibratory	• displays power spectral density variations with time • identify structure and boundaries in time and frequency
Cumulative RMS Acceleration versus Frequency	Vibratory	• quantifies RMS contribution at and below a given frequency
Frequency Band(s) RMS Acceleration versus Time	Vibratory	• quantify RMS contribution over selected frequency band(s) as a function of time
RMS Acceleration versus One-Third Frequency Bands	Vibratory	• quantify RMS contribution over proportional frequency bands • compare measured data to ISS vibratory requirements
Principal Component Spectral Analysis (PCSA)	Vibratory	• summarize magnitude and frequency excursions for key spectral contributors over a long period of time • results typically have finer frequency resolution and high PSD magnitude resolution relative to a spectrogram at the expense of poor temporal resolution

Real-Time Operations

- Crux of real-time operations involves receiving, processing, and displaying microgravity acceleration data via the WWW
- Acceleration data displays via the WWW
  - PIMS displays are updated in real-time
  - Electronics snapshots are routed to the PIMS WWW page
  - Interested Principal Investigators can view the environment by accessing the PIMS WWW page
- Example real-time plots
  - Figure 12-1 USMP-4 (STS-87) IDGE Experiment Turn Off
  - Figure 12-2 USMP-4 (STS-87) Cabin De-Pressurization for EVA
  - Figure 12-3 LMS (STS-78) Nominal Microgravity Environment

PIMS ISS Acceleration Data Flow



Near Real-Time Operations

- **Two primary functions performed**
  - **Merge AOS and LOS data streams**
  - **Generate processed (t,x,y,z) data files**
    - store the data in a universal storage format
- **Universal file format standard details**
  - **Develop a standard file format for ISS acceleration data from any ISS acceleration measurement system**
  - **Simplify access to acceleration data for Principal Investigators**
  - **Store ancillary data with acceleration data in a single file**
    - ancillary data describes the conditions and circumstances under which the acceleration data were obtained
    - current ancillary data parameters include: t-zero, t-end, sampling rate, cutoff frequency, head ID, gain, ISS CM, station configuration, location, orientation, coordinate system, bias coefficients, scale factor, and Data Quality Measure (DQM)

Offline Operations

- **Primary function is to allow access to acceleration data for non-time-critical processing**
  - **In general, allows a more detailed analysis of the measured microgravity environment**
  - **Capable of processing and analyzing a long period of data**
  - **Overall access to acceleration data greatly simplified by a universal storage format**

- **PIMS WWW page offline functions**
  - **Provide the capability to request plotted data or data files**
  - **Provide the capability for submitting an electronic request for data processing**
  - **Provide means for anonymous FTP access to the processed acceleration data files**

Offline Operations

- **Example Near Real-time Plots**
  - **Figure 12-4 MSL-1 (STS-94) SOFBALL Radiometry Data**
- **Example Offline Plots**
  - **Figure 12-5 LMS (STS-78) Principal Component Spectral Analysis**

Summary

- PIMS will receive, process, and store acceleration data for SAMS-II and MAMS data starting with flight 6A operations
- A universal storage format will be employed for data storage
  - simplify access to acceleration data
  - standardize formats for data storage to maximize access to all existing acceleration data by international partners
- Real-time data plots of the various available accelerometers will be available via the PIMS WWW page
- Offline access to plotted data and analysis capabilities available through PIMS and the PIMS WWW page
- General and specialized characterization of the ISS microgravity environment

Section 14:
Fundamentals of Vibration Isolation

Presented by:

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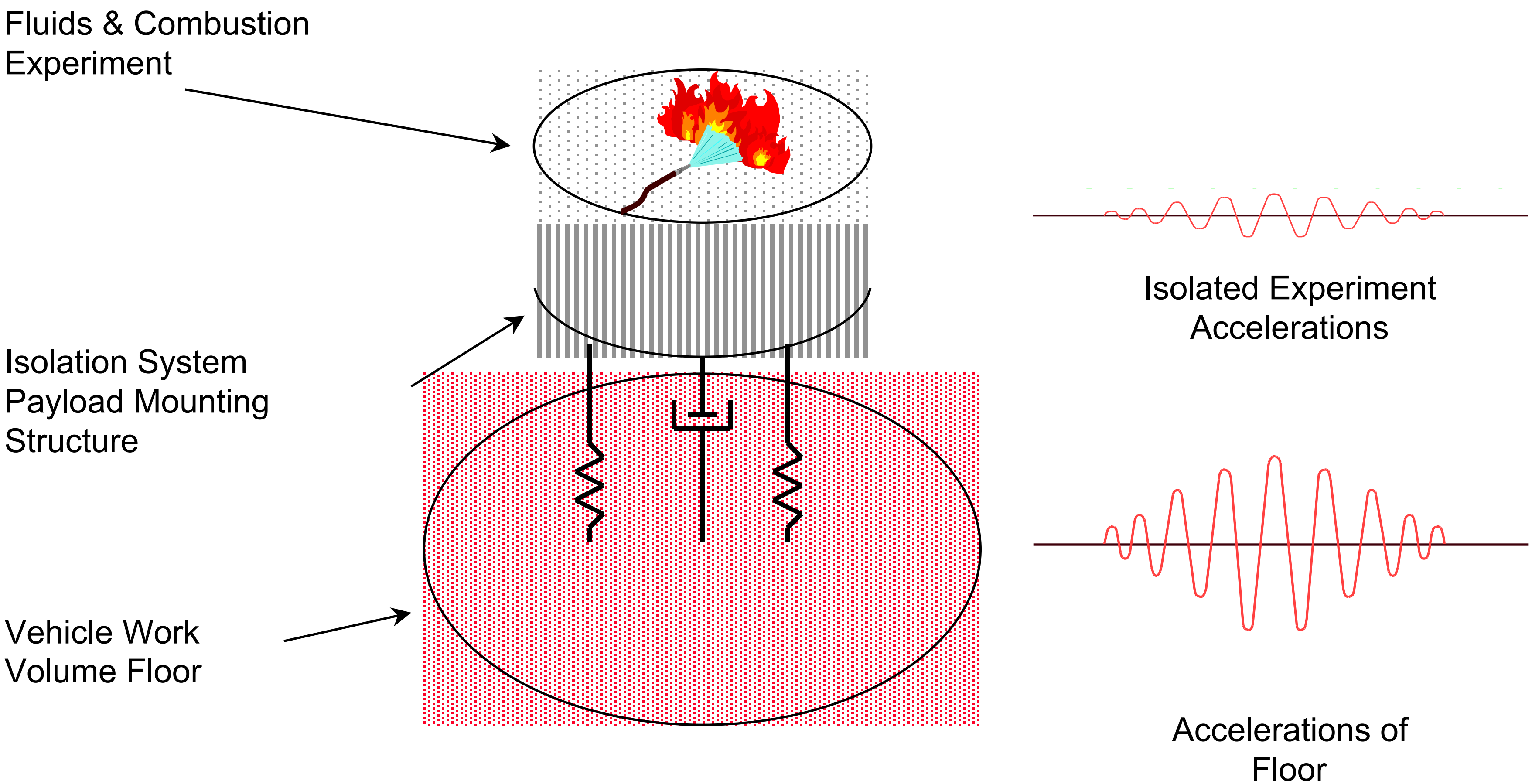
Outline:

- Vibration Isolation Technology
  - Dynamics of Systems
  - Active Control Concepts
  - Isolation Performance Measures
- Flight Hardware Systems
  - STABLE
  - MIM
  - ARIS
  - g-LIMIT

Introduction

- The ambient spacecraft acceleration levels are often higher than allowable from a science perspective.
- To reduce the acceleration levels to an acceptably quiescent level requires vibration isolation.
- Either passive or active isolation can be used depending on the needs or requirements of a specific application.

What is Vibration Isolation?



System Dynamics: Transmissibility

• The ***transmissibility*** is the transfer function that relates the acceleration (or position) response of the mass to the base acceleration (or position) input.

• The magnitude of the transmissibility function specifies the attenuation of base motion as a function of frequency.

• Use of springs, masses, and dampers for attenuation is known as "***passive vibration isolation***"

Active Control Concepts

• ***Active vibration isolation*** seeks to minimize the inertial motion of the payload by directly sensing the inertial motion and applying forces to the platform to directly counter the measured motion.

• Using a passive isolation analogy, active control can effectively change the system mass, stiffness and damping and thus change the dynamics -- i.e. the time response of the system.

Active Control Concepts

However, it isn't as easy as it seems --

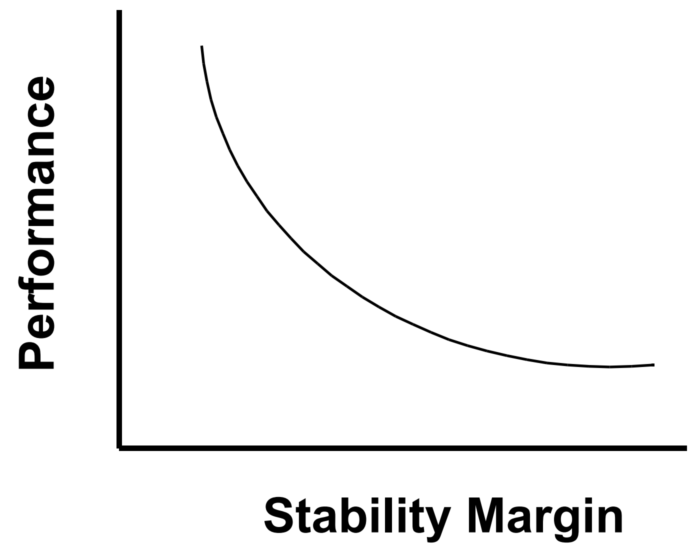
- Real systems aren't simple one degree of freedom lumped masses with discrete springs and dampers.
- Control system design is a function of system properties which typically aren't well known.

The two key control design issues are ***stability*** and ***performance***.

- ***Stability***: will the system return to an equilibrium position when disturbed?
- ***Performance***: how well is isolation achieved?

Active Control Concepts

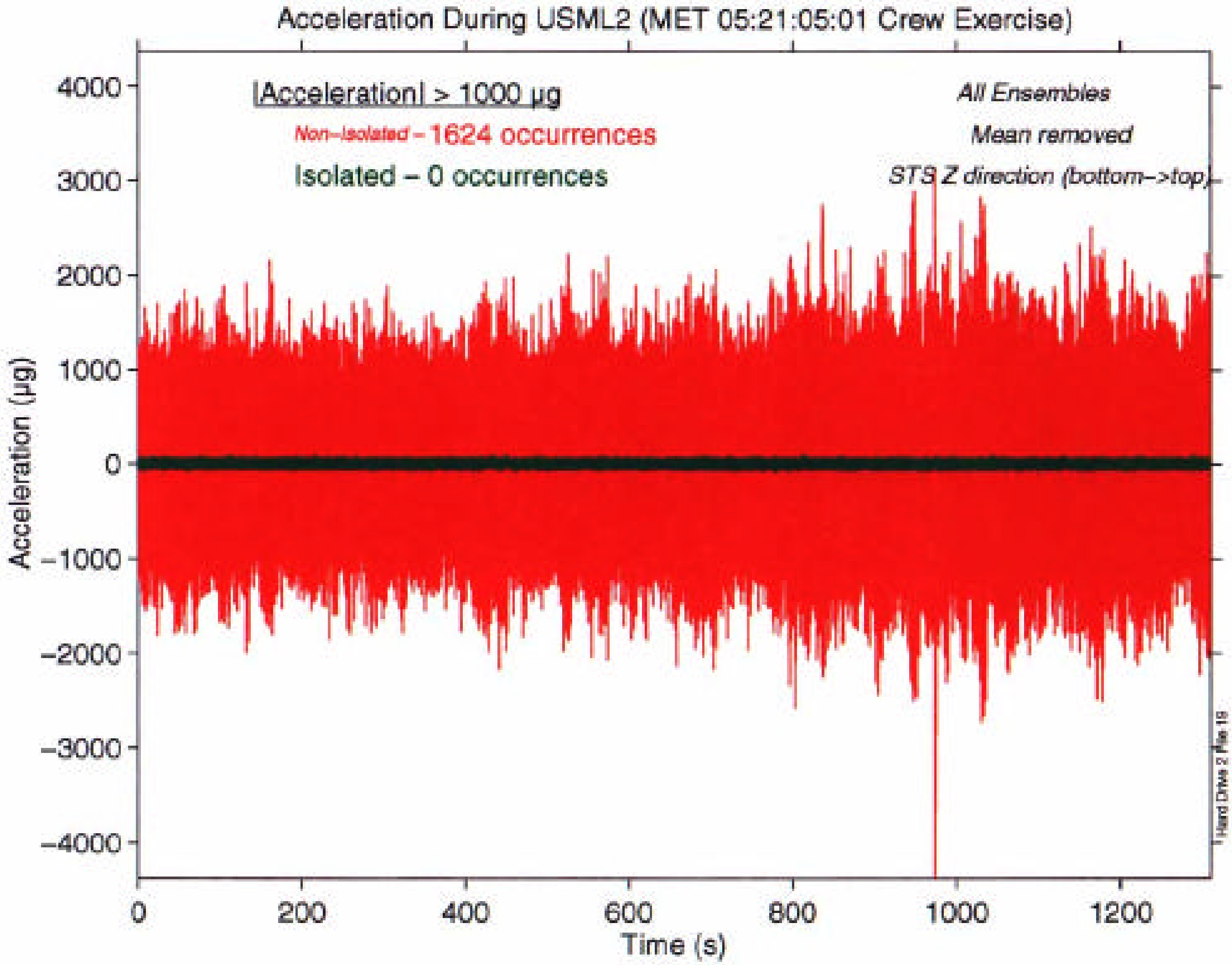
Stability margin and **performance** of a closed loop system are ***always*** in opposition



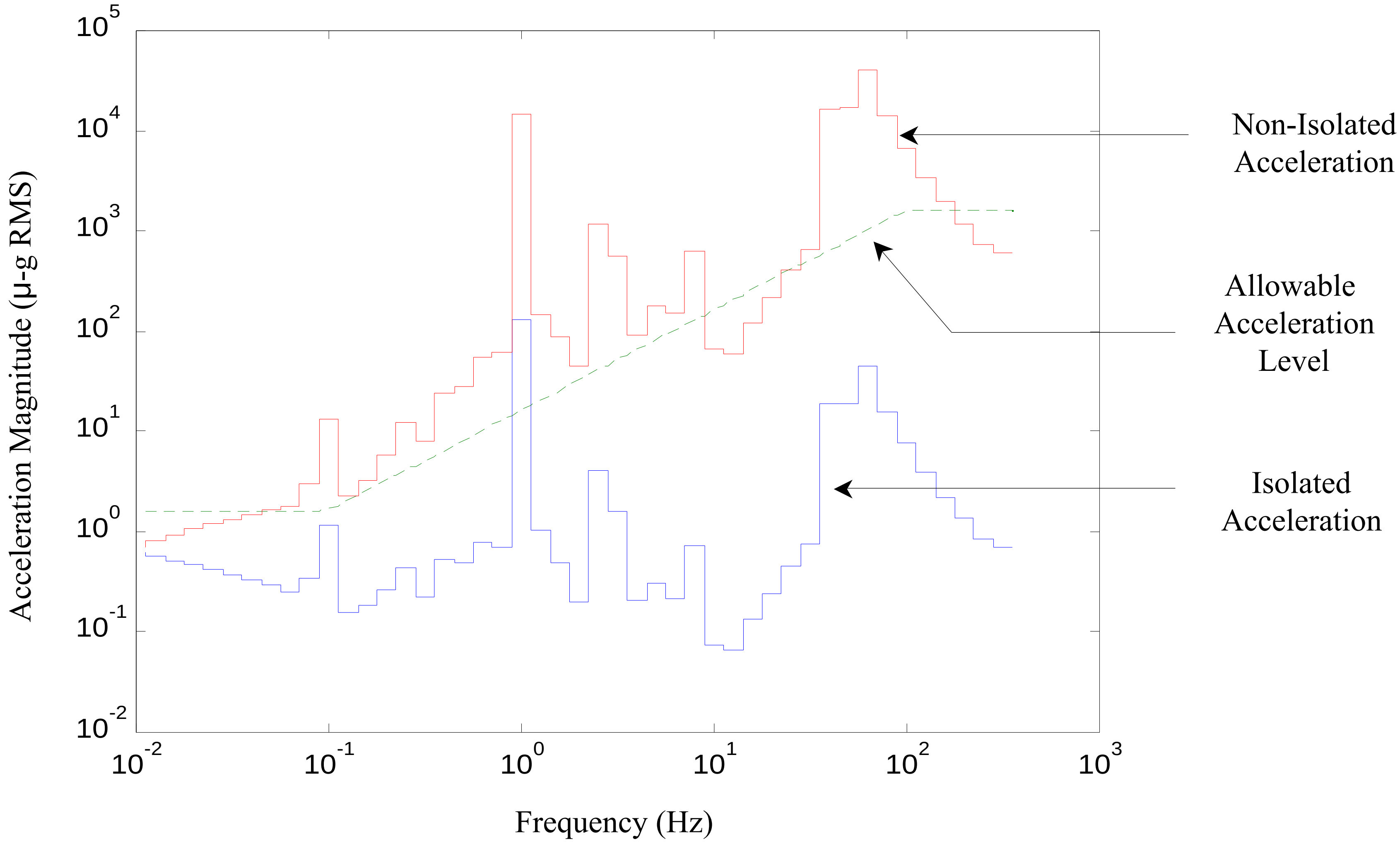
The trade depends on:

- uncertainties in the dynamics of the system:
    - structural stiffness
    - multivariable coupling
    - unmodeled flexible modes
- nonlinearities
- disturbances

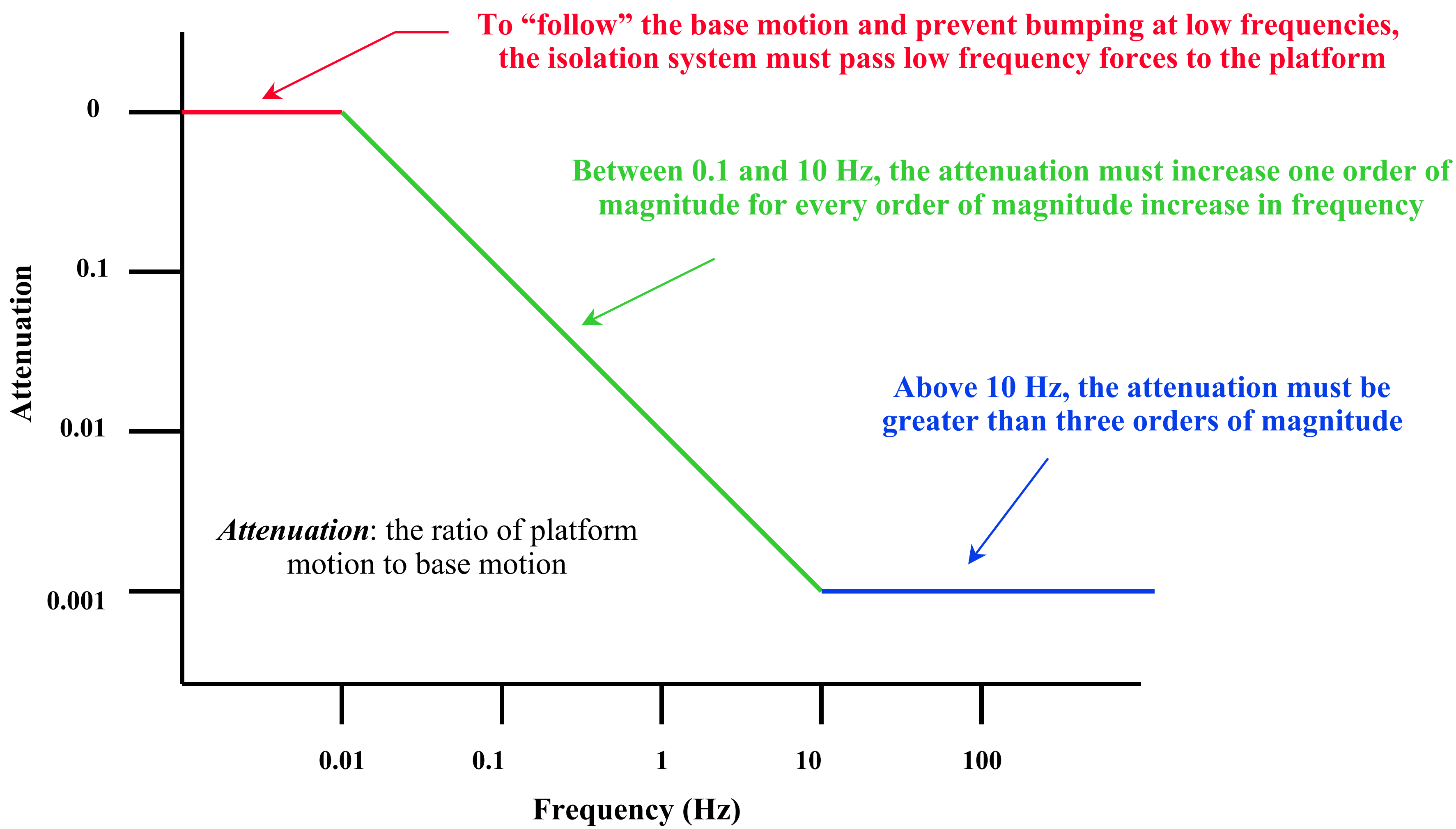
STABLE: Typical Active Isolation Time Response



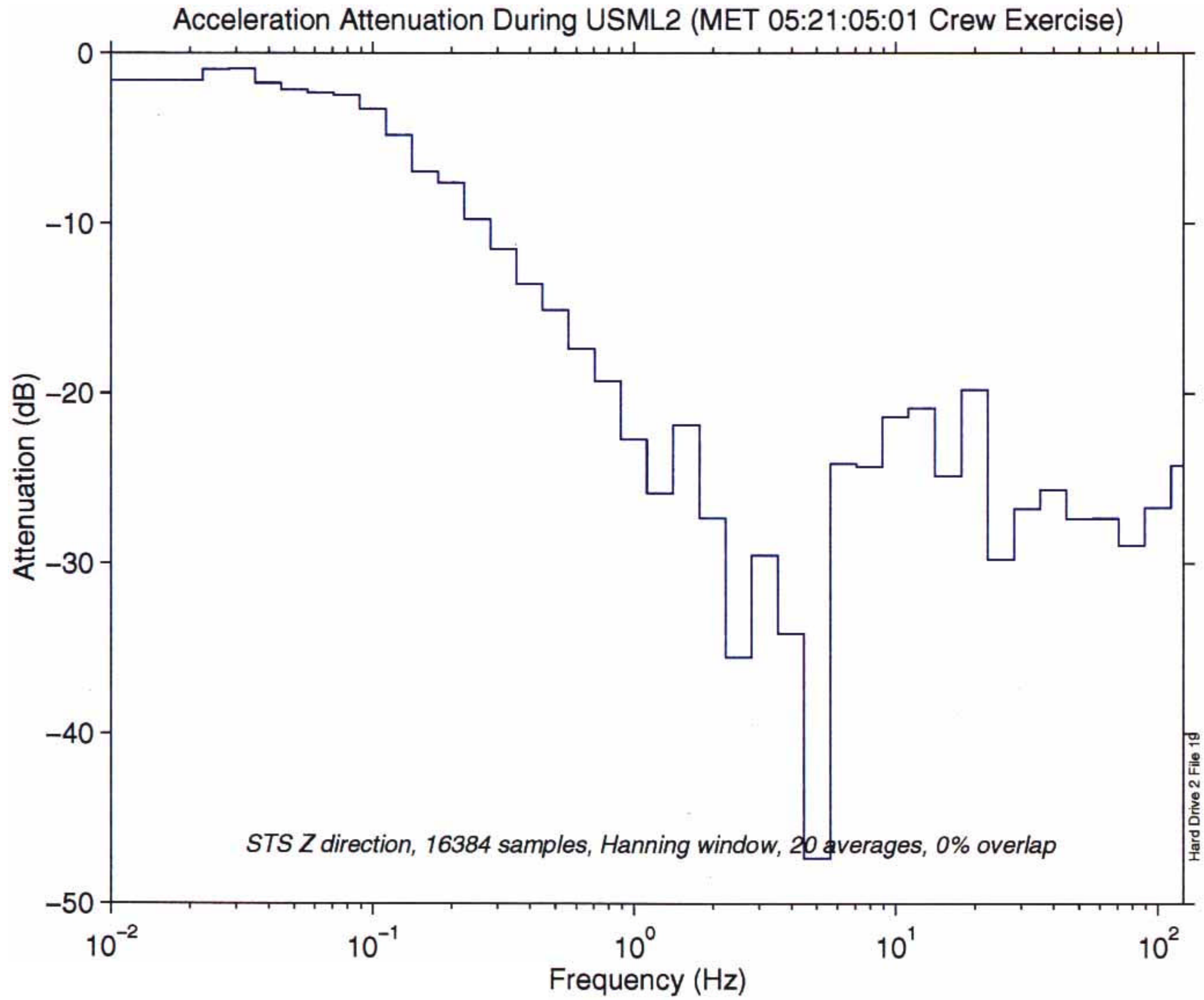
ISS Accelerations



Attenuation Requirement



STABLE: Typical Active Isolation Attenuation



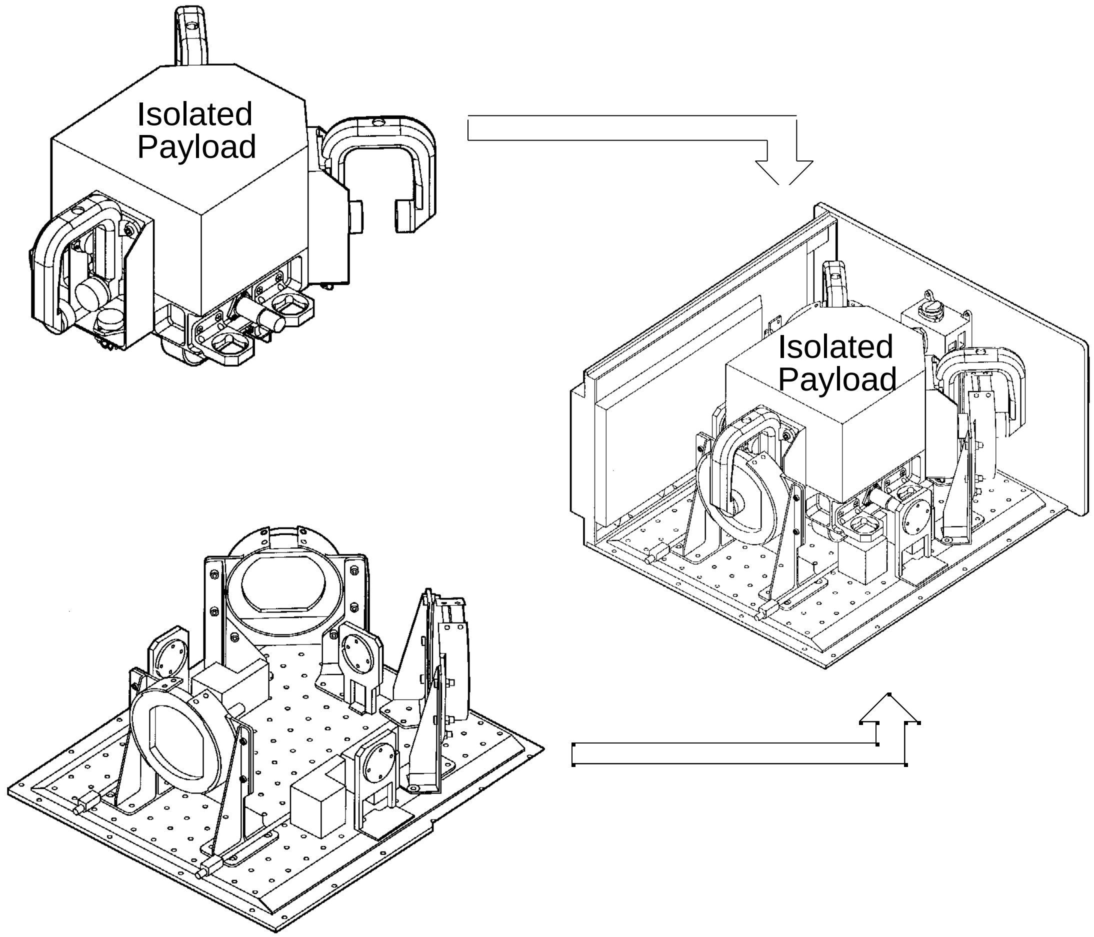
Flight Proven Systems

Isolation System	STABLE (MSFC/MDAC)	MIM (CSA)	ARIS (Boeing)
Application	Individual Experiment Isolation	Individual Experiment Isolation	Full Rack Isolation
Mission/Date	USML-2, STS-73, 10/95	Priroda/Mir, 4/96; STS-	Mir-4, STS-79, 8/96
Volume Used	<50% middeck locker	one full middeck locker	external to user volume
Current Status	Evolved to g-LIMIT; launch on UF-2	Evaluation Testing on UF-1	ARIS-ICE manifested on 6-A

Fundamentals of Vibration Isolation

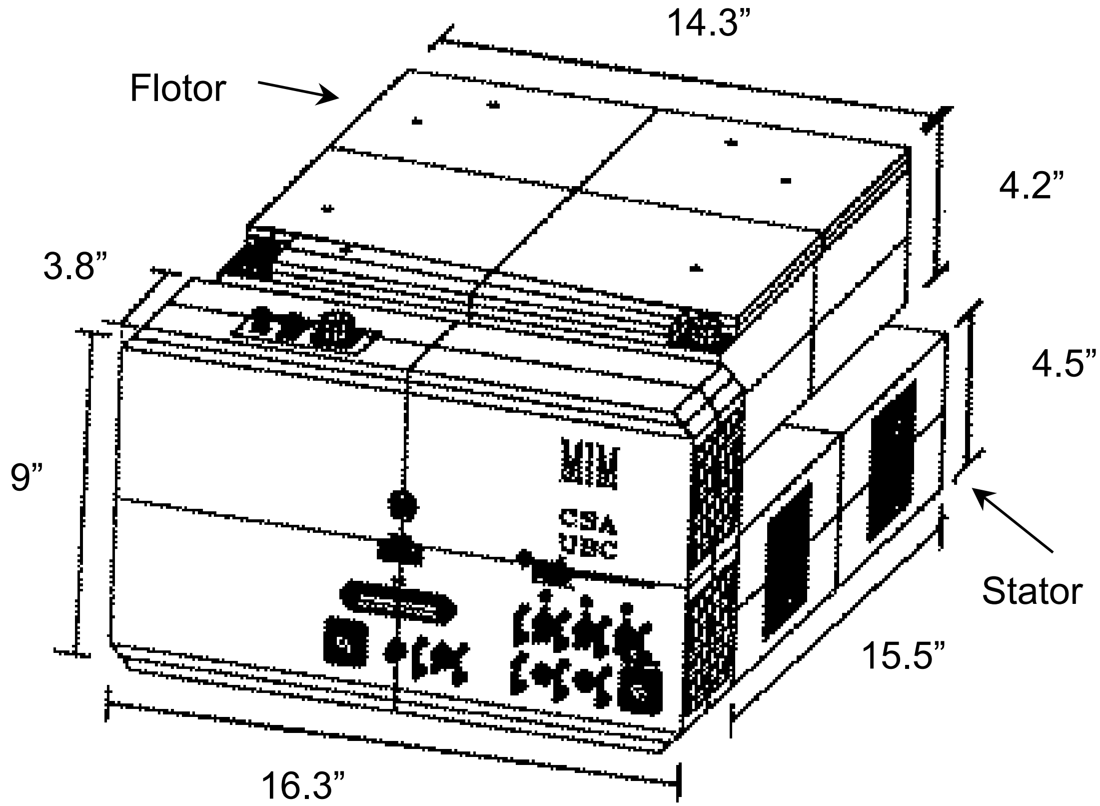
The MSFC/MDAC STABLE Vibration Isolation System

- Sub-rack isolation system
- Requires partial locker for isolation system
- High frequency active control
- Will likely meet attenuation requirement
- Well suited for dynamic payloads



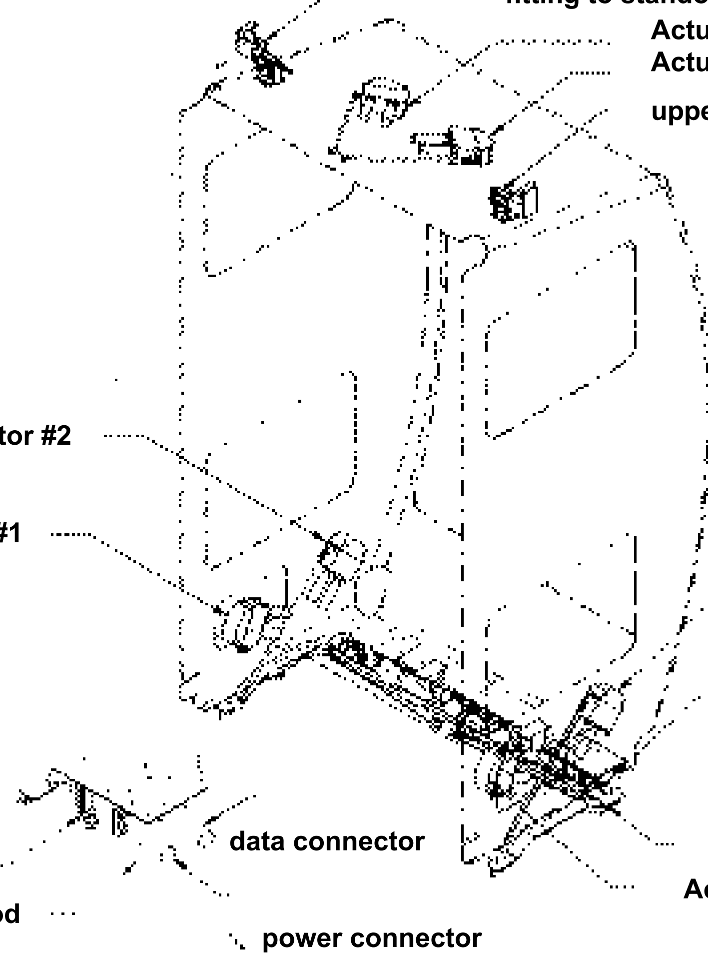
The Canadian Space Agency Microgravity Isolation Mount (MIM)

- **Sub-rack isolation system**
- **Requires full locker for isolation system**
- **High frequency active control**
- **Will likely meet attenuation requirement**
- **Well suited for dynamic payloads**



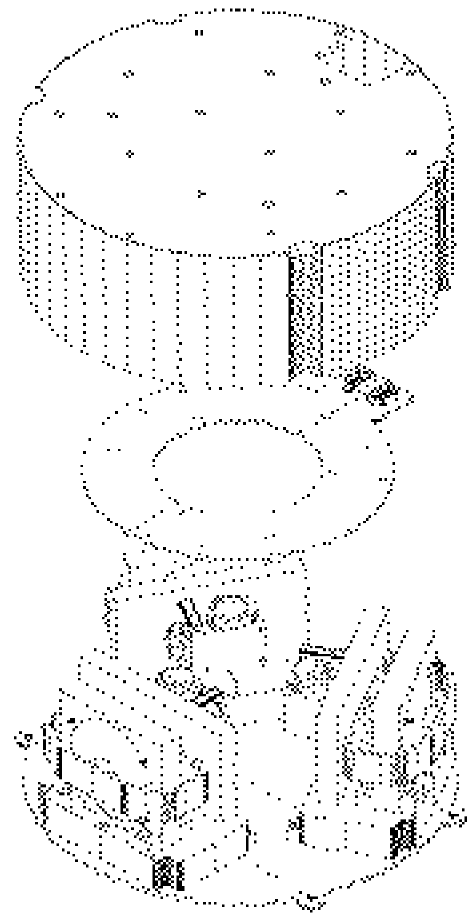
The Boeing Active Rack Isolation System (ARIS)

- Full rack isolation system
- Active control augments passive isolation
- Will likely meet attenuation req't in nominal cases
- Not well suited for dynamic payloads



g-LIMIT

A Vibration Isolation System for the Microgravity Science Glovebox



Dimensions:
approx. 15” dia. x 5” tall

Key Features:

- Small Volume / Low Power
- Standard MSG interfaces
- Permits multiple experiment operation
- Allows crew contact with MSG during ops
- Accomodates larger payloads
- Modular/reconfigurable design
- Scheduled for launch: UF2/August 2000
- In-house development by NASA/MSFC

Comparison of Approaches

Type	Advantages	Disadvantages
Passive	•Low Cost •Low Maintenance •Reliable •No Power	•Isolate only higher freq (> 1-10 Hz) •Typically requires large volume •Cannot mitigate payload induced vibrations •Resonance vs attenuation trade
Active Rack Level (ARIS)	•Low freq attenuation •Least power & volume (mult. payloads/single unit) •standard user interface	•Cannot mitigate payload induced vibrations •requires payloads to be "good neighbors" •highly sensitive to crew contact •Potential high maintenance
Active Sub-Rack Level (g-LIMIT, STABLE, MIM)	•Low freq attenuation •Mitigates payload induced vibration •can be optimized for individual user	•More power & volume than rack-level (single payload/single unit)

Section 15:
Predicting residual acceleration effects on space experiments

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GOAL:

Predict sensitivity of the experiment to the acceleration environment

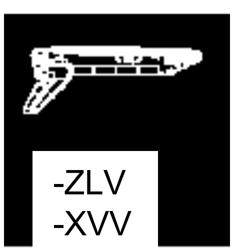
- PI must justify ***need for microgravity***
- PI must be able to predict ***tolerable*** (and intolerable) ***environments***

PI's choices (and assignments) affect the quality of the μg environment

- ***flight mode*** ***(attitude of the carrier with respect to the earth)***
- ***deadband*** ***(allowable angular displacement from the desired mode)***
- ***location*** of experiment relative to CG
- ***orientation*** of the experiment w.r.t. Shuttle (or ISS) body axes
- scheduling of ***crew activities***
- operation of ***other apparatus*** or experiments

Recommendations to minimize g-jitter effects based on flights of MEPHISTO (directional solidification)

- Use flight modes which do not require ***Shuttle maneuvers*** for water dumps, etc. (e.g., -ZLV,+YVV) for long-duration microgravity (>3 days)
- To minimize large accelerations, ***specify a flight mode*** requiring fewer thruster firings to maintain attitude; ***2° deadband*** required fewer thruster firings than 1° -- better µg
- Experiments should be ***aligned with Shuttle's z body axis*** for these flight modes to minimize transient acceleration effects (least transmission of disturbances along this axis)



MEPHISTO I: STS-52 10/92

x_{CG} = (27.7, 0, 9.3) m

x_{MI} = (25.5, 1.05, 10.8) m

(a) –ZLV,–XVV at 300 km

← velocity

↓ Earth

MEPHISTO II: STS-62 3/94

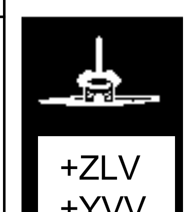
x_{CG} = (27.8, 0, 9.5) m

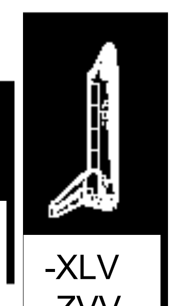
x_{MII} = (25.5, 1.05, 10.8) m

(b) –ZLV,+YVV at 300 km

(c) +ZLV,+YVV at 260 km

(d) –XLV,–ZVV at 300 km





– de Groh and Nelson, 1994

Strategy for assessing experiment sensitivity to the µg environment

(1) Identify the ***tolerance criterion***

(2) ***Correlate acceleration*** to the tolerance criterion

(3) Perform "simple" analyses to determine ***range of sensitivity***

(4) As necessary, perform a ***detailed analysis*** in the range of sensitivity

(5) Develop ***detailed µg tolerance specifications***

1. Identify tolerance criterion

Tolerance criteria are:

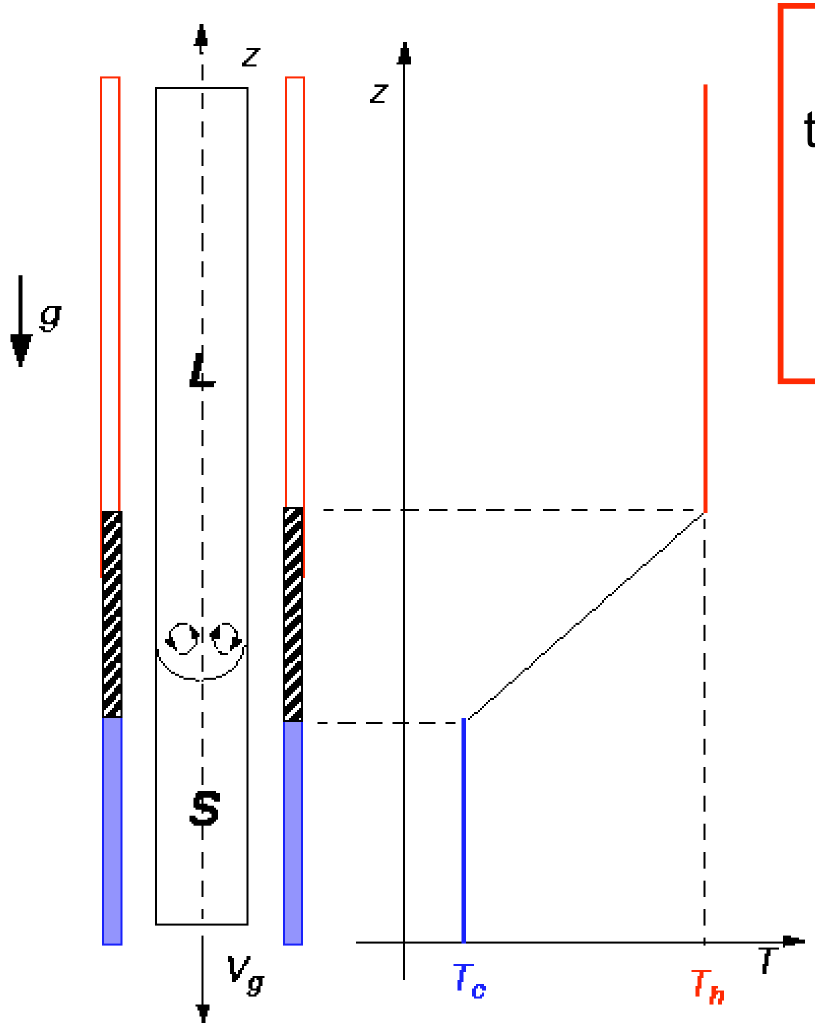
- ***subjective***
- ***arbitrary (to some extent)***
- functions of ***many parameters***
  - physics
  - experiment goal
  - composition of system (thermophysical properties, etc.)
  - geometry of system (aspect ratio, length of test section, etc.)
  - applied boundary conditions (applied thermal or pressure field, velocity of boundaries, etc.)

A good tolerance criterion is a function both of the ***specific experiment design*** and the ***specific environment*** in which it is placed

Two examples

- ***directional solidification:*** buoyancy-driven flow of a passive scalar field (natural convection)
  - goal is to *suppress convection* to maximize homogeneity of the crystal (diffusion-controlled growth)
  - *highly sensitive* to residual acceleration (orientation, magnitude, frequency)
  - requires very *long duration* microgravity (hours to days)
  - *lots of previous studies*, including space experiments
- ***granular flow:*** segregation of a binary mixture of particles in a collision-dominated flow
  - uses kinetic theory of gases as analog to grain fluctuation energy, T
  - *relatively insensitive* to residual acceleration
  - *relatively short-duration* microgravity (minutes)
  - *no similar previous investigations*

Bridgman growth of semiconductor crystals



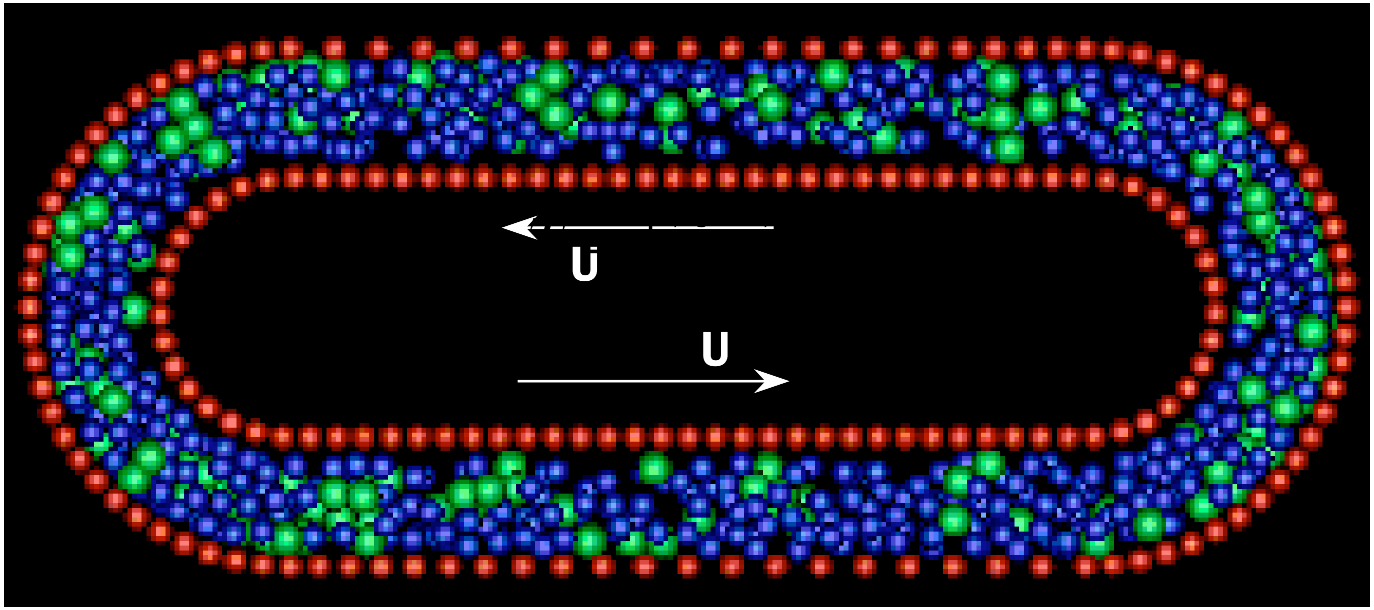
First, develop the tolerance criterion in terms that are ***physically meaningful w.r.t. the experiment***

<u>Tolerance criterion</u>:
1% variation in solute concentration at solid/liquid interface (for example)

$$\xi = \frac{c_{max_{interface}} - c_{min_{interface}}}{c_{bulk}}$$

Microgravity segregation of energetic grains (µgseg)

Test section



Test section

Tolerance criterion: g-jitter can contribute up to **5% variation in mean granular temperature, T,** across test section

$$T = \frac{1}{3}\tilde{u}_i' \cdot \tilde{u}_i'$$

– Jenkins and Louge, 1998

2. Correlate acceleration to tolerance criterion

- All experiments will have some dependence on acceleration ***magnitude***, ***frequency***, ***orientation***, and ***duration***
- Experimental system ***response varies enormously***, e.g.,:
  - may be very sensitive to *specific* frequencies, orientations, etc. esp. for interfaces, critical point experiments
  - require examination of *overall* momentum input, esp. for bulk flows
  - may need *long recovery times* for short disturbances, esp. for flows with large Schmidt or Prandtl number

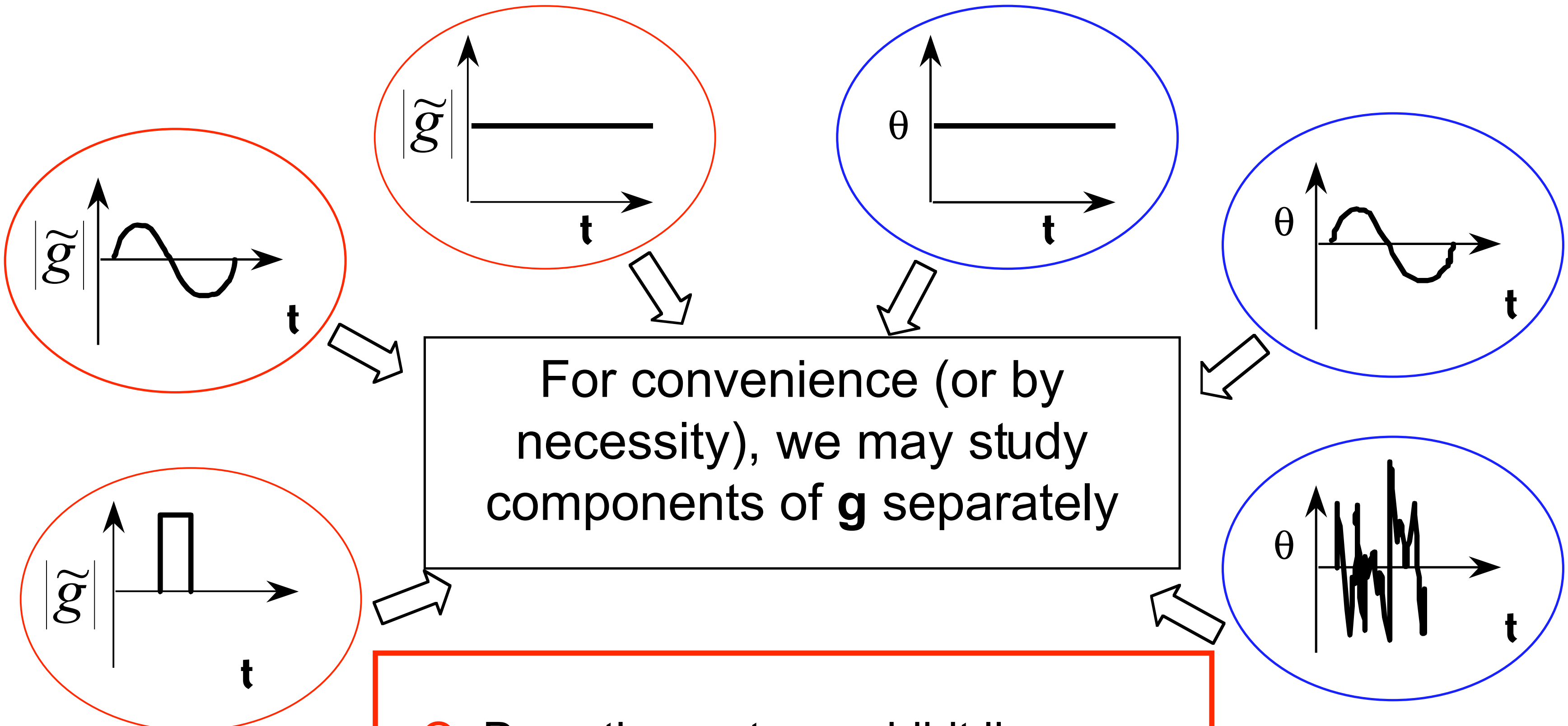
Key: what drives the sensitivity?

Analysis tools include:

- ***theoretical*** analysis
  - order-of-magnitude analysis
  - exact solution of a simplified problem
- ***numerical*** simulation
  - traditional FD/FE/FV approach
  - direct numerical simulation
  - stochastic approach
- ***experimental*** testing (ground-based)
  - ground-based facilities, e.g., KC-135, drop tower
  - vibrating platforms
  - centrifuge

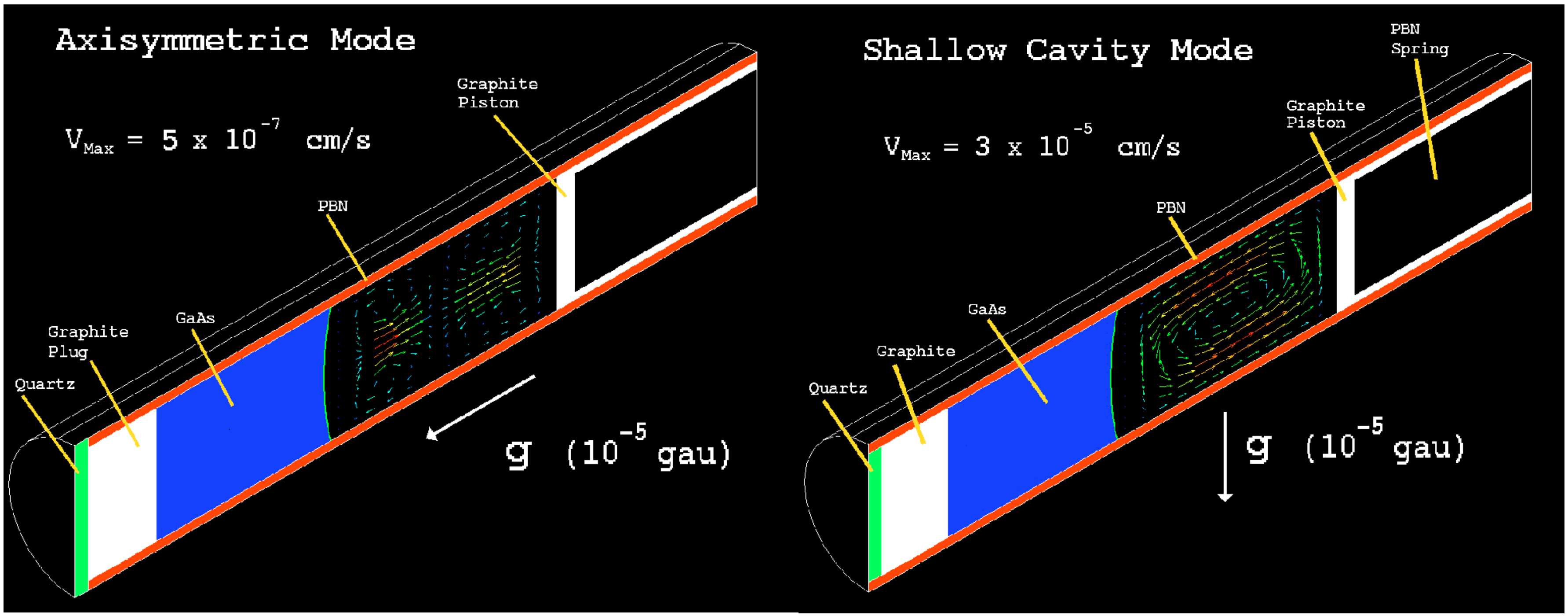
FD: Finite Difference
FE: Finite Element
FV: Finite Volume

Develop a model of experiment response to acceleration input

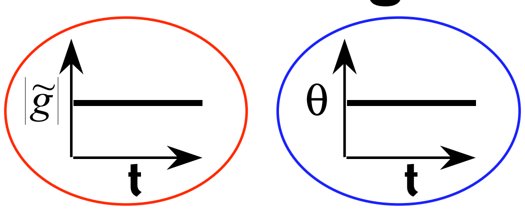


Q: Does the system exhibit linear response to acceleration input?

Develop a model of experiment response to acceleration input (cont'd)

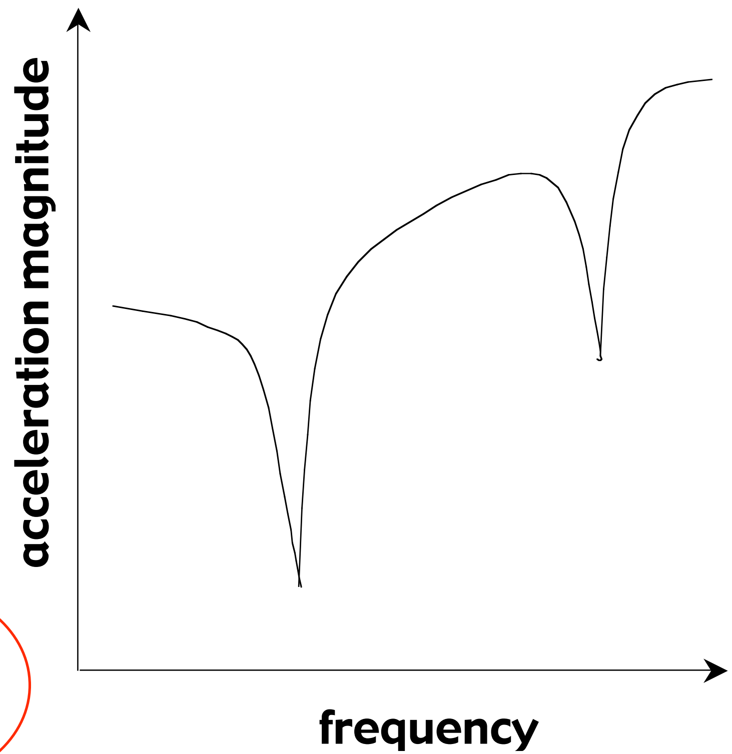


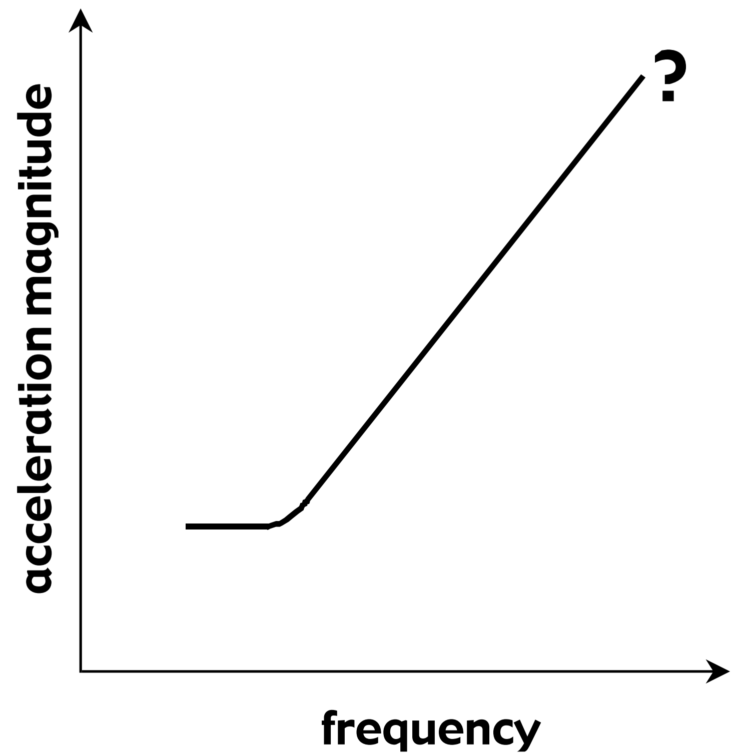
Effect of g orientation on directional solidification

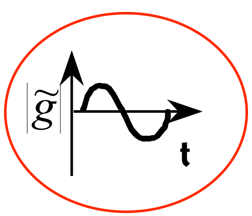


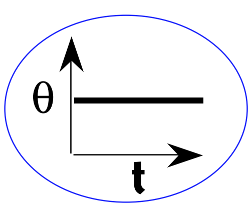
– Arnold et al., 1991

Develop a model of experiment response to acceleration input (cont'd)





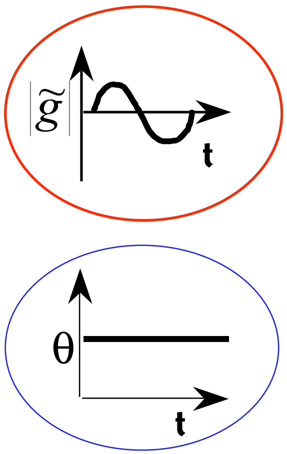


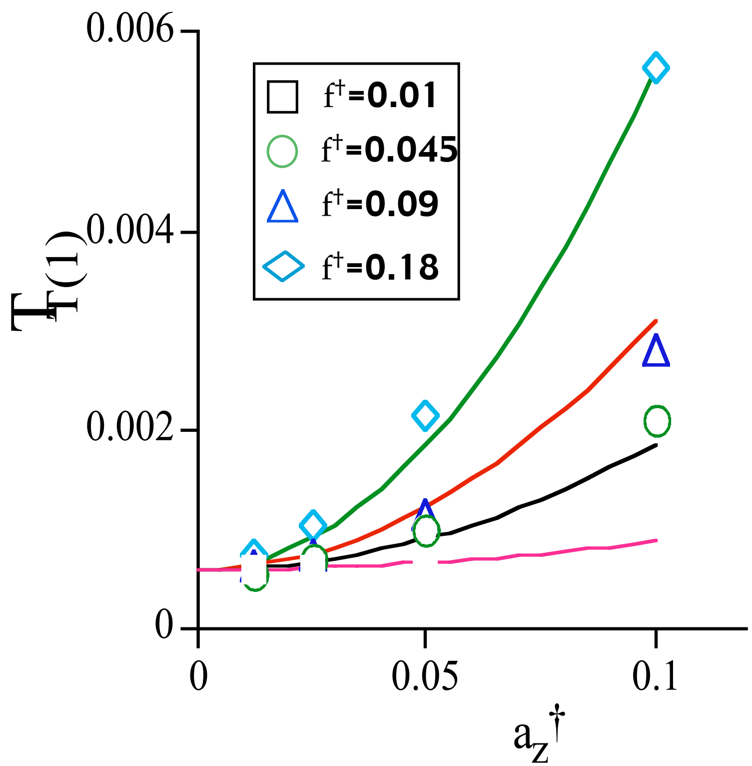


liquid bridges

natural convection

Develop a model of experiment response to acceleration input (cont'd)





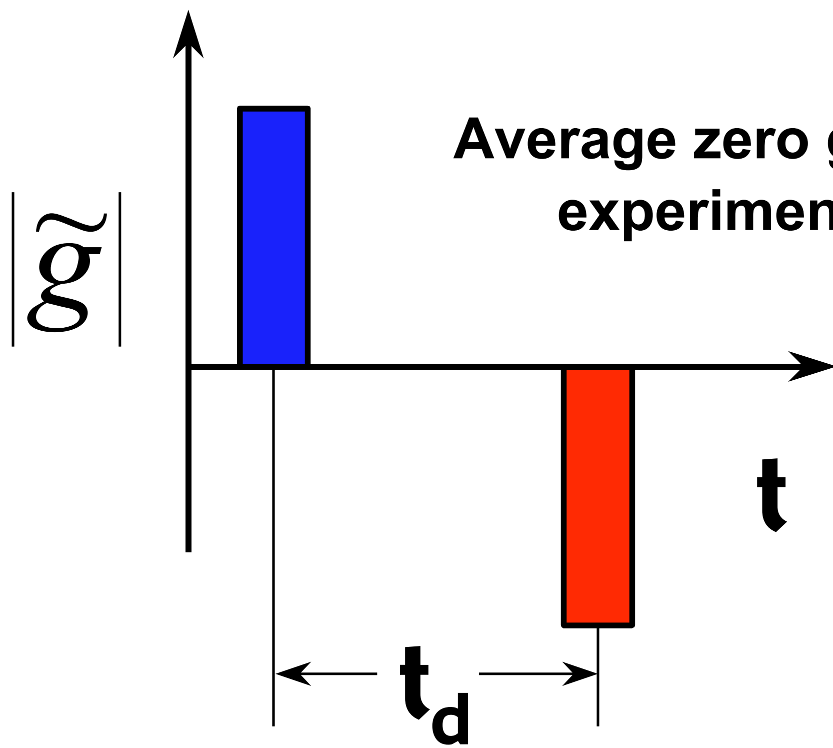
Mean granular temperature as a function of acceleration frequency and amplitude

$$\boxed{T = T_0 + c_i\, f^\dagger a^{\dagger 2}}$$

granular shear flows

– Jenkins and Louge, 1998

Develop a model of experiment response to acceleration input (cont'd)

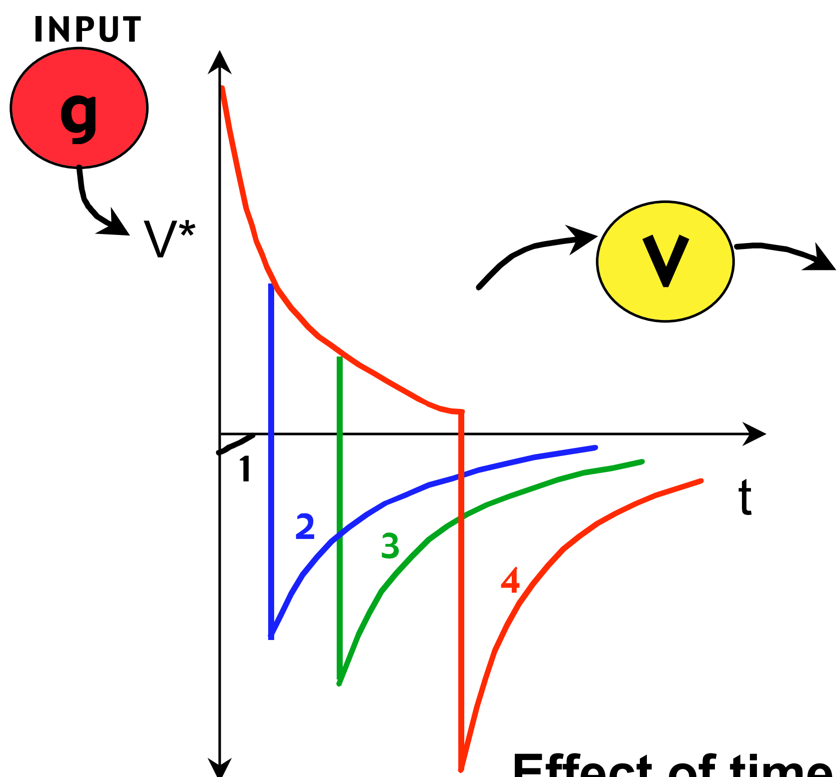


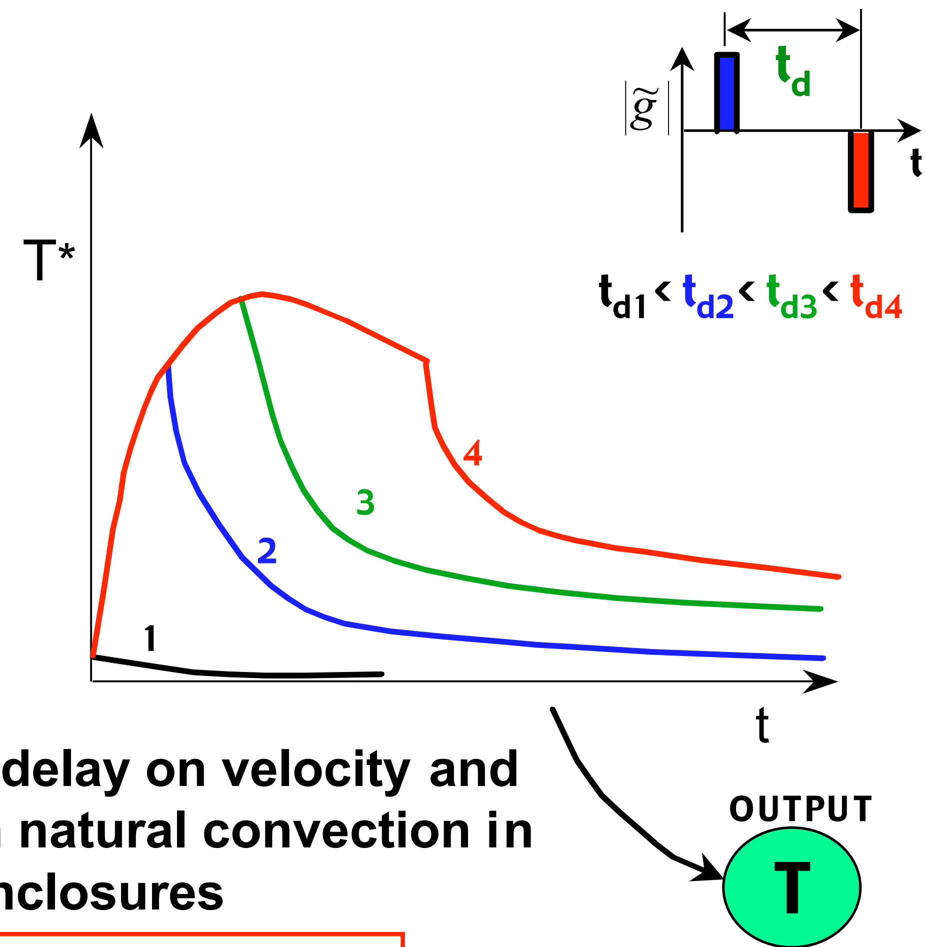
Average zero g ≠ zero effect on experiment necessarily

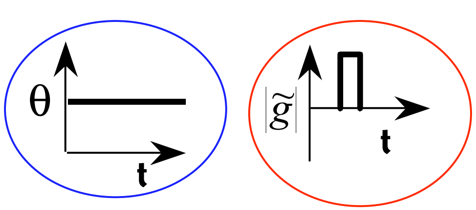
Net acceleration=0, *but* system reacts in a *transient* manner with finite response time

⇒ Net system response may be nonzero

Develop a model of experiment response to acceleration input (cont'd)







Effect of time delay on velocity and temperature in natural convection in enclosures

NOTE: Especially important for high Pr or Sc number flows

- Monti et al., 1990

Develop a model of experiment response to acceleration input (cont'd)

But eventually, we must consider the actual acceleration environment for the carrier of interest, e.g.:

- International Space Station
- sounding rocket
- Space Shuttle
- free flyer
- low-g aircraft, e.g., KC-135
- Mir

Develop a model of experiment response to acceleration input (cont'd)

To describe the actual environment for numerical or theoretical analysis:

- use ***actual acceleration data*** at or near location of experiment

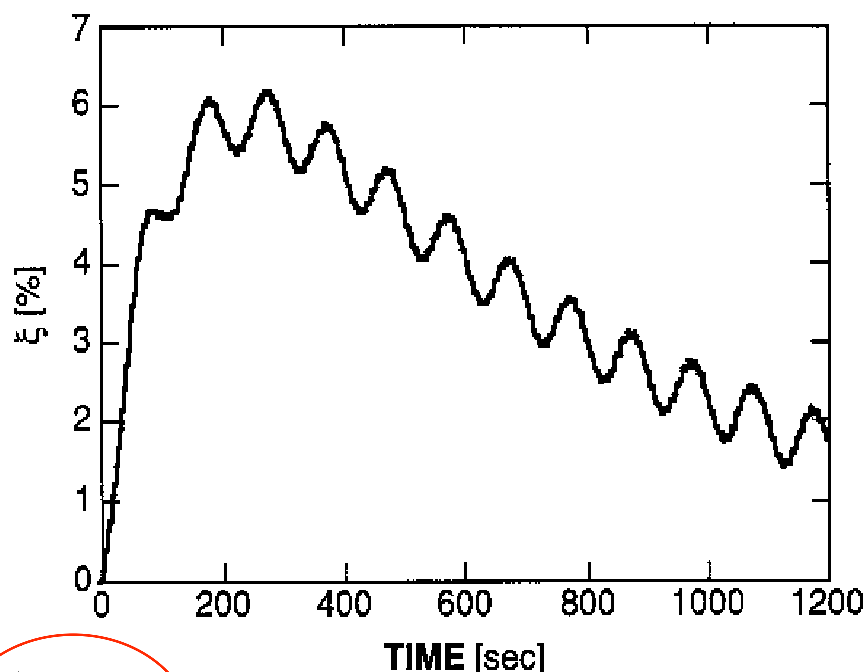
$$g_i(t), \quad i = x, y, z$$

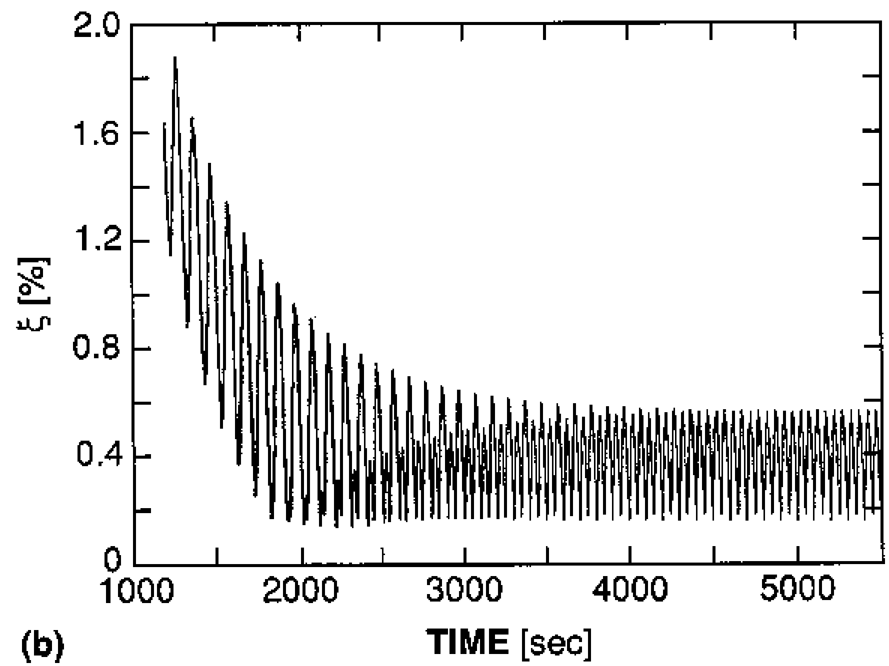
- construct g in the ***time*** domain using ***predicted spectral data***, e.g., from ISS predictions, simplified data spectrum

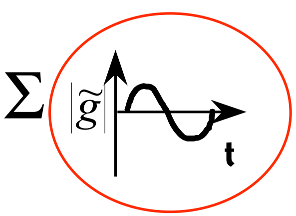
$$g_i(t) = g_{qs,_i} + \sum_n g_{o,i} \sin(2\pi f_n t) + g_{t,_i}(t)$$

- examine predicted or actual data in ***spectral*** domain

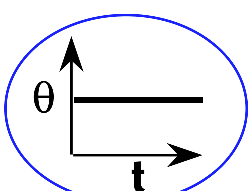
Develop a model of experiment response to acceleration input (cont'd)







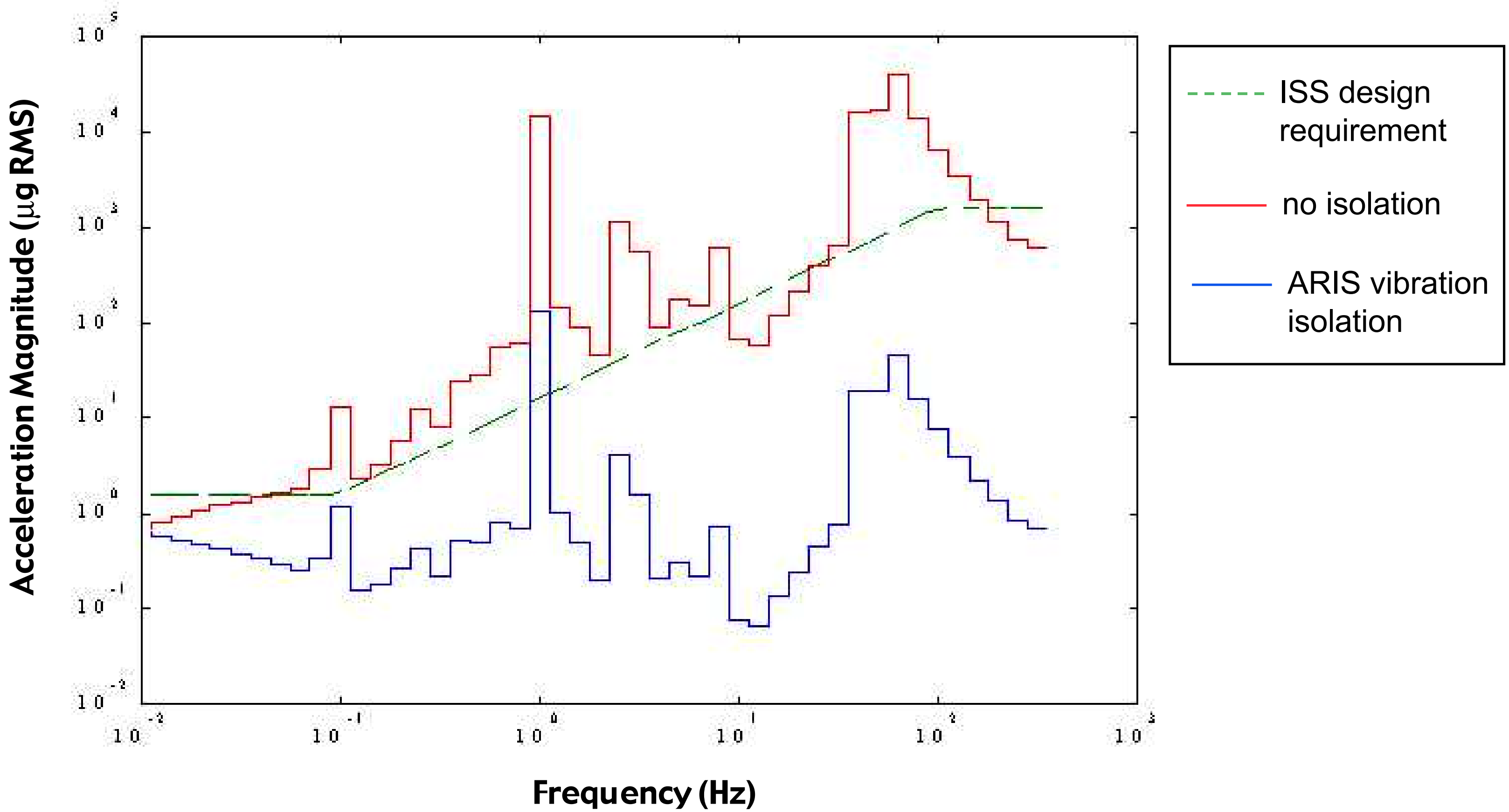
(Concentration variation at solid/liquid interface as a function of time using a simplified spectrum of the Shuttle acceleration environment)



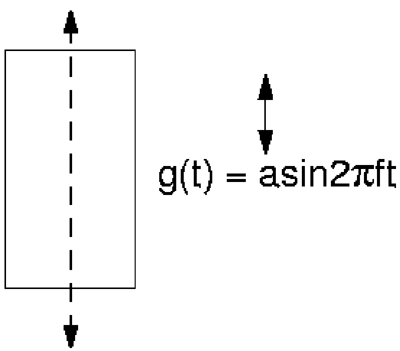
Initial transient in natural convection in enclosures: Startup of multifrequency sinusoidal disturbance

- Alexander et al., 1991

3. Identify range of sensitivity

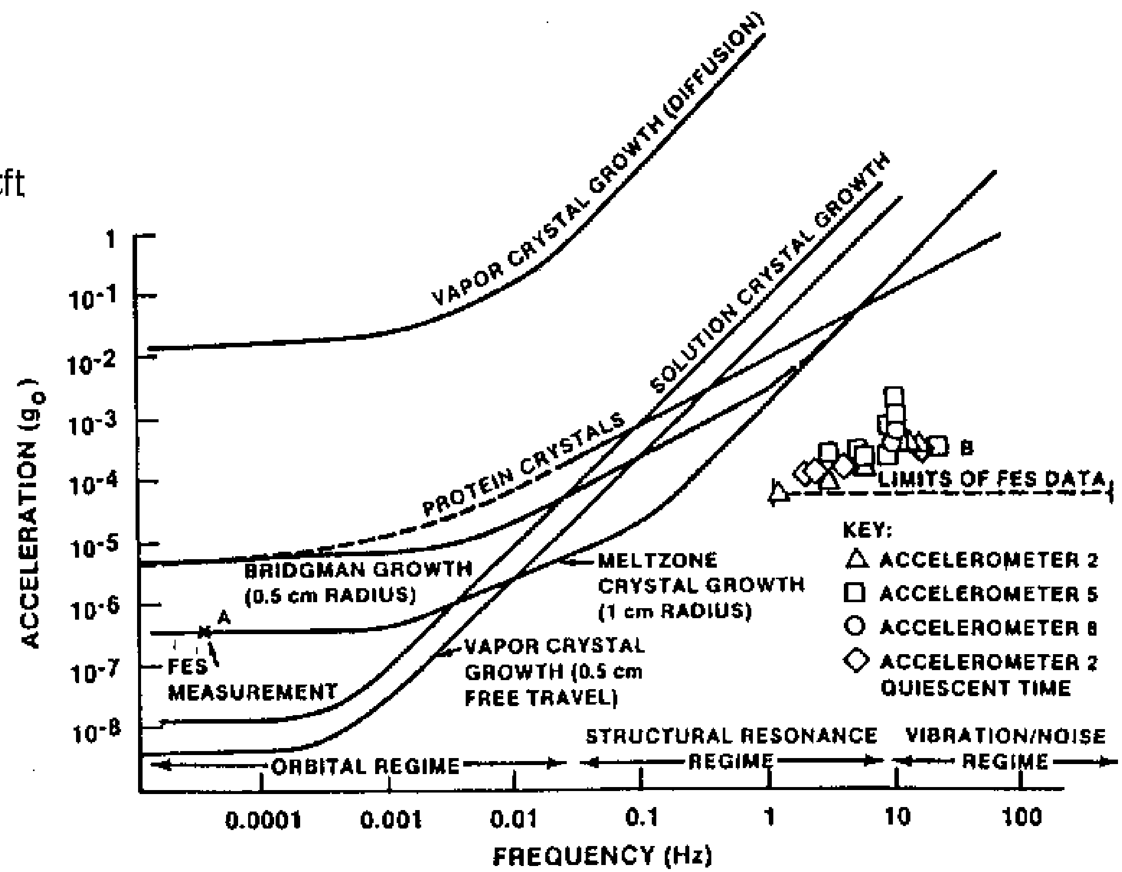


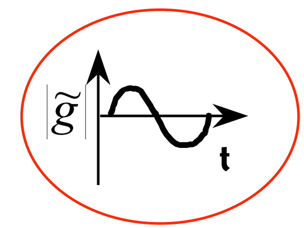
Tolerability limits for buoyancy-driven flows in enclosures

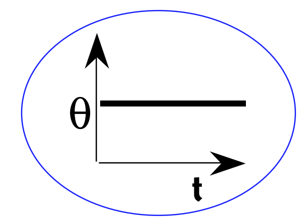


FREQUENCY VS ACCELERATION

G-LEVEL TOLERANCE FOR MONOCHROMATIC OSCILLATING DISTURBANCES POINTS AT A & B ARE SPACE LAB 3 ACCELERATION MEASUREMENTS

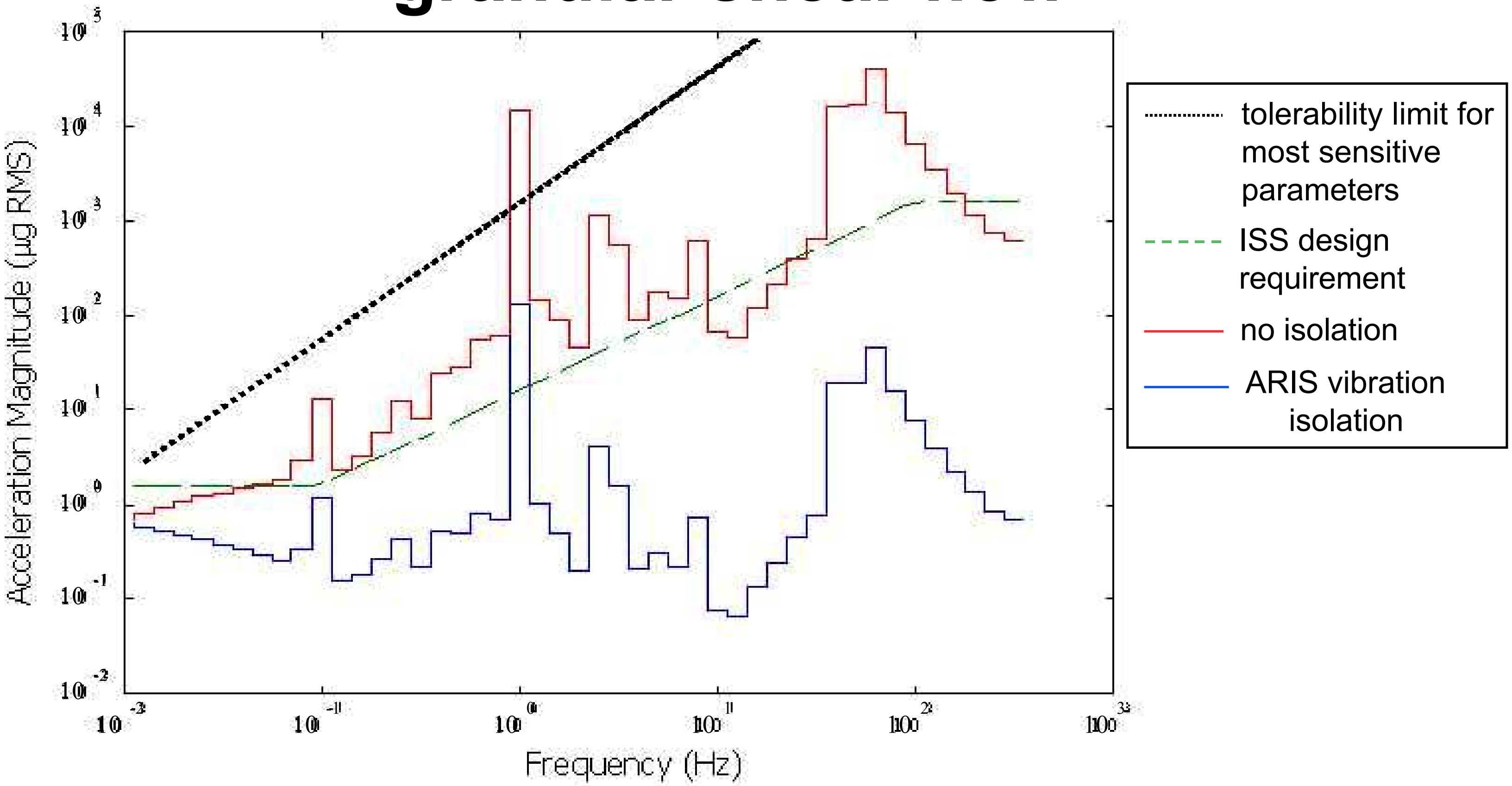






– Demel, 1986

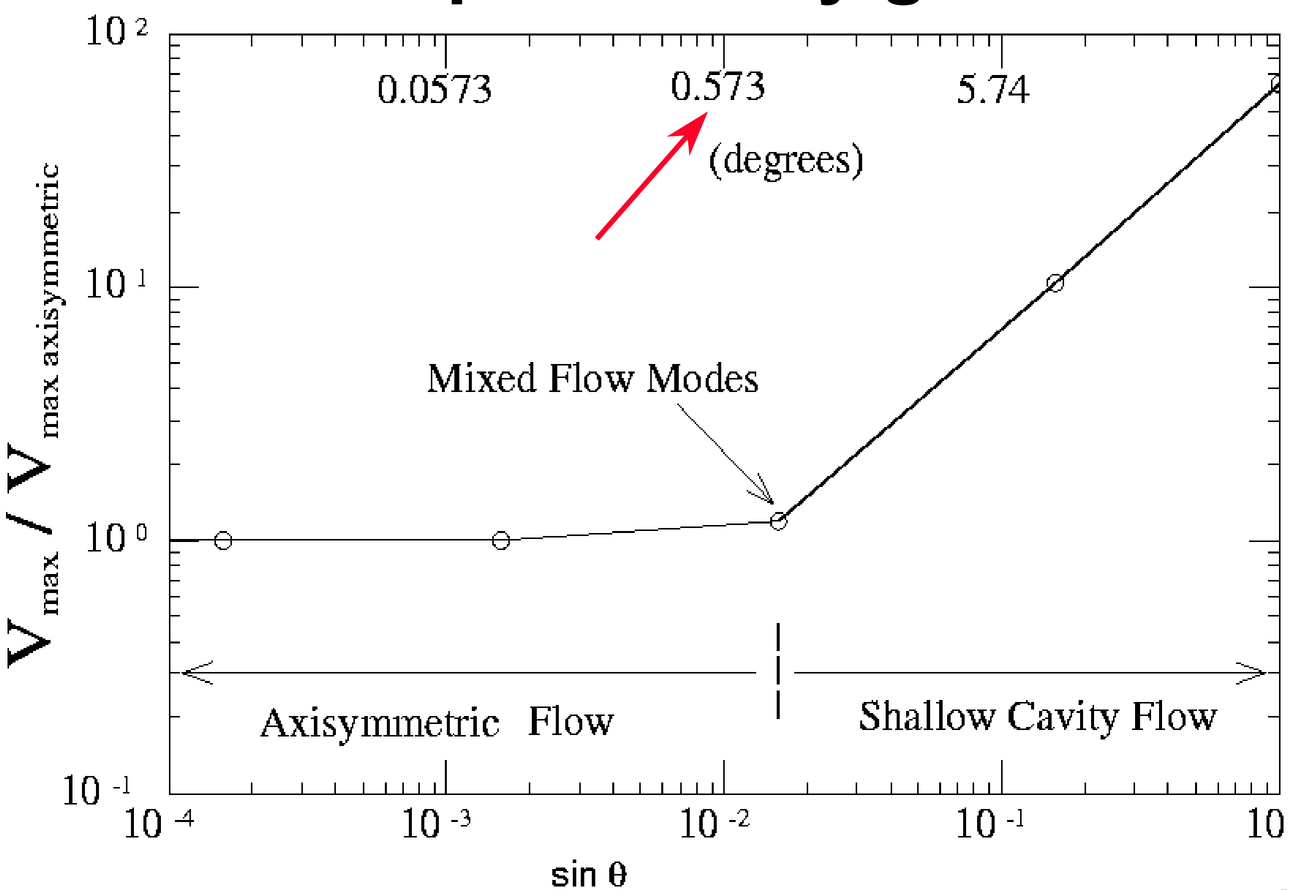
Effect of single-frequency g-jitter on T in granular shear flow



<u>CONCLUSION</u>: suitable environment can be found on ISS

– Jenkins and Louge, 1998

Sensitivity of directional solidification to quasisteady g orientation

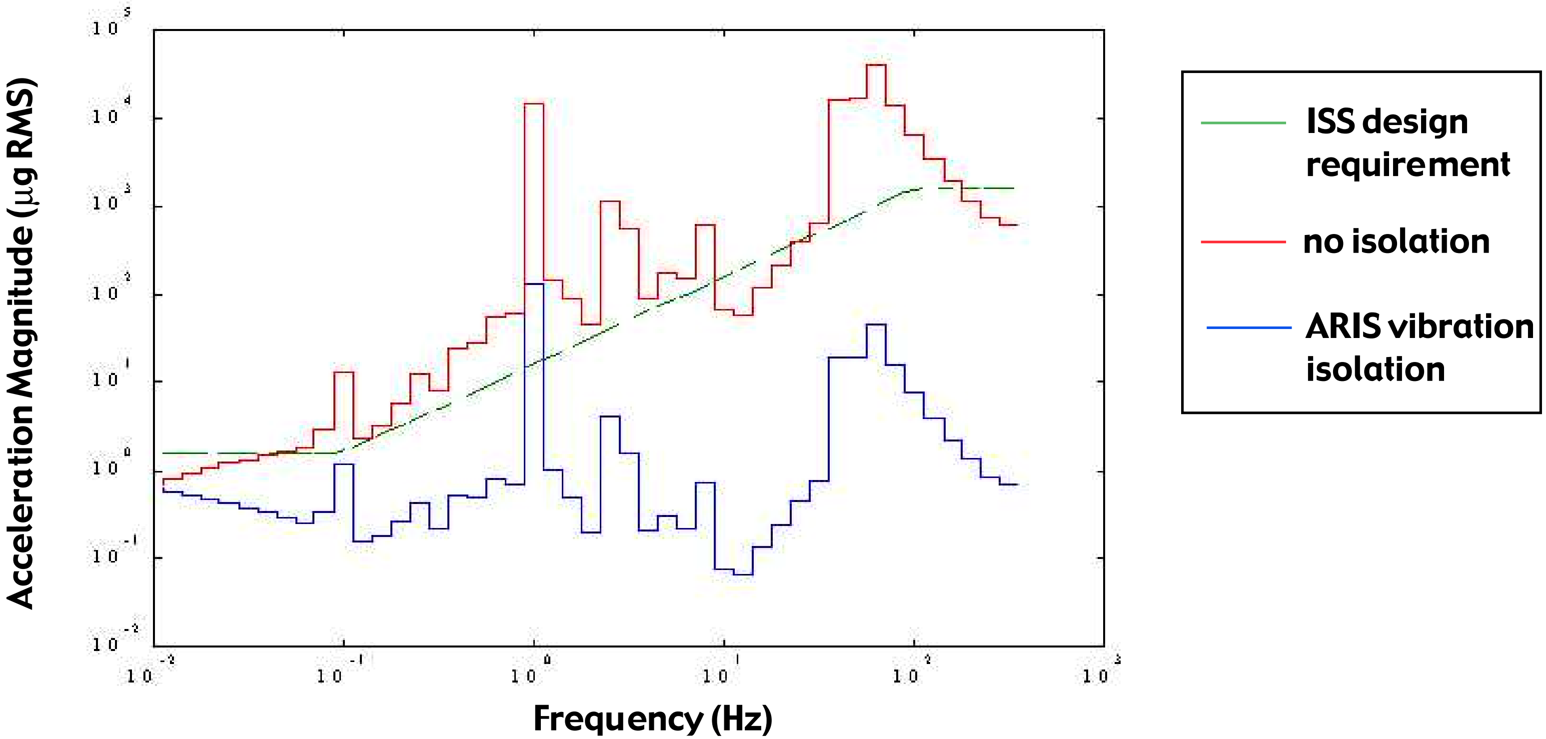


Be aware that any inhabited spacelab is likely to be ***extremely*** variable in θ due to the rich variety of acceleration sources!

NOTE: For other experiments, this tendency towards improved mixing may actually be beneficial!

Arnold et al., 1991

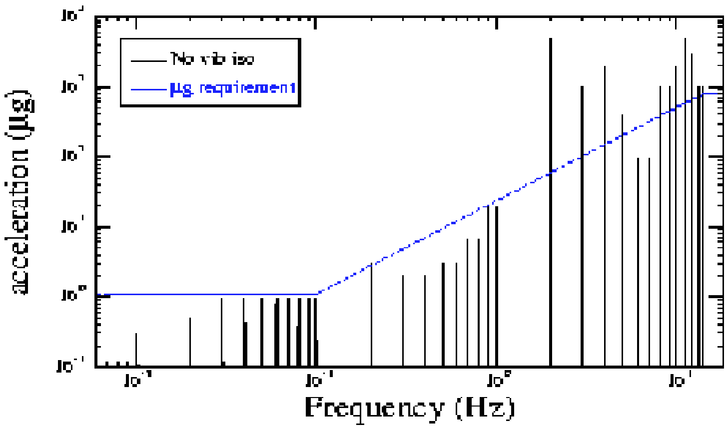
4. Perform detailed analysis



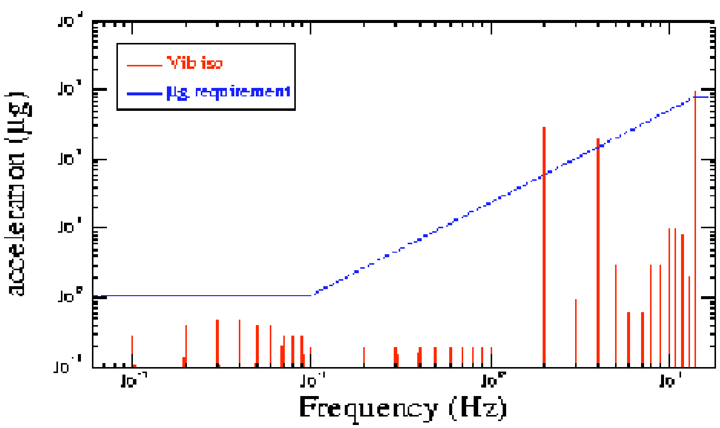
Q: Is vibration isolation necessary?

Effect of vibration isolation on directional solidification

No vibration isolation



ARIS vibration isolation



Idealized ISS environment:

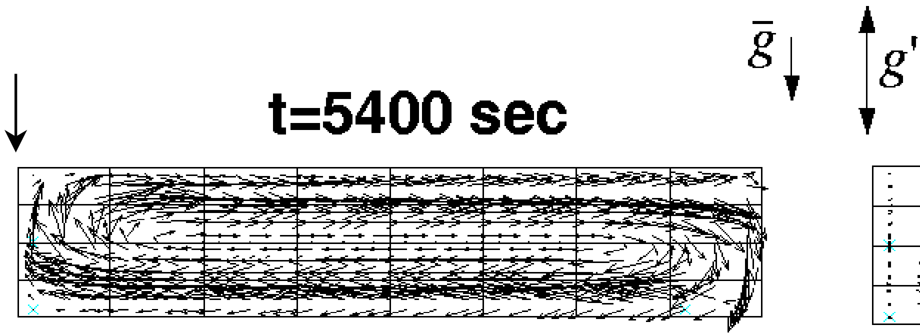
- constructed from DAC-3 (Design Analysis Cycle #3)
- used a frequency range from 0.01 to 14 Hz for several hours of simulated μg
- neglected effects of robot arm (big peak at 0.1 Hz), but included treadmill and other facility operations

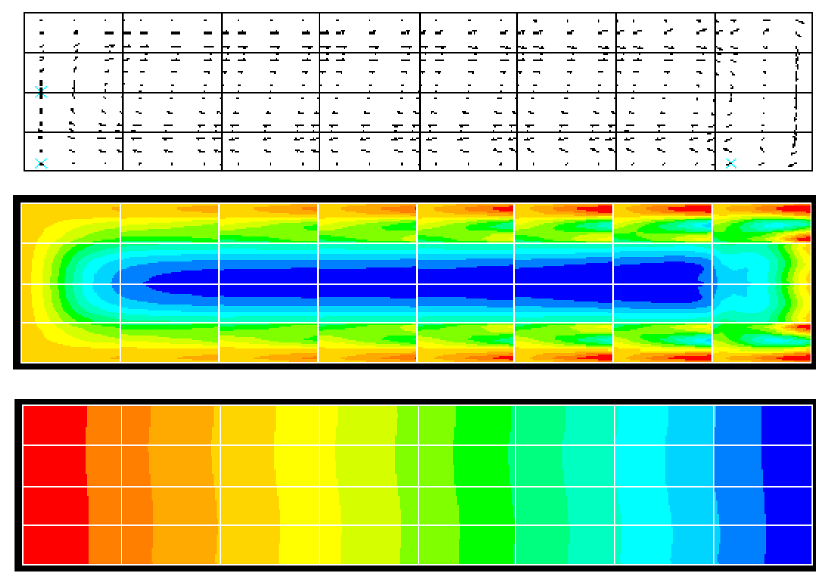
Use this data to create g(t):

$$g_i(t) = g_{qs,_i} + \sum_n g_{o,_i} \sin(2\pi f_n t)$$

– Nelson and Kassemi, 1997

Effect of vibration isolation on directional solidification (cont'd)

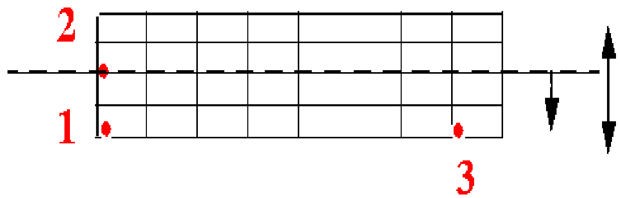


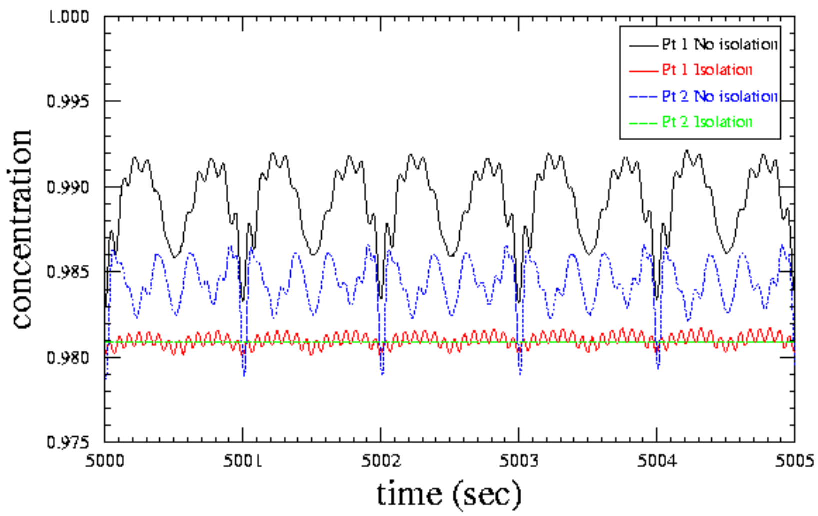


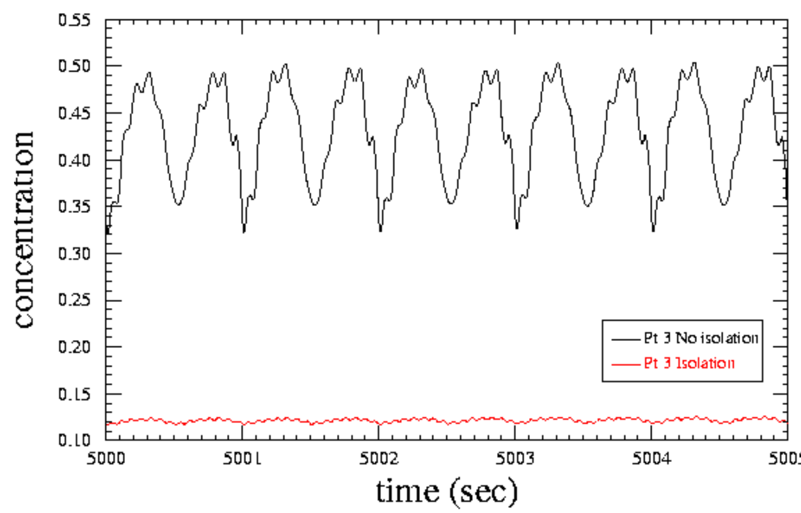
No vibration isolation **Vibration isolation**

Nelson and Kassemi, 1997

Effect of vibration isolation on directional solidification (cont'd)







Nelson and Kassemi, 1997

Effect of vibration isolation on directional solidification (cont'd)

Q: Is vibration isolation necessary for this case?

A: Yer darn tootin'!

5. Develop detailed microgravity tolerance specs

- **Specify *duration* of experimental runs**
    - *typical* length
    - anticipated *maximum/minimum* length
    - expected *number of runs* per 30-day microgravity period
- **Describe the *quasisteady* acceleration limits**
    - upper bound of QS *magnitude* (expect several μg on ISS)
    - desired *orientation* (if choices are available); angular *tolerance* about that orientation (e.g., align experiment with torque equilibrium attitude (TEA) of ISS with a tolerance of ± 0.05 . Maintain QS **g** orientation to within TEA ± 10

- **Identify *oscillatory* acceleration limits**
  - *specific frequencies at particular magnitudes* of concern
  - frequency *cutoff* (frequencies above or below the cutoff are of no concern)
  - *thumbs up/down for specific environments*, e.g.,
    - acceleration data from Shuttle, sounding rocket, KC-135, ISS...
    - predicted ISS environment, e.g., from DAC-xx for a specific configuration and disturbance environment:
      - unisolated rack
      - ARIS vibration isolation
      - passive vibration isolation
      - MIM, g-LIMIT, or other active sub-rack isolation unit
- **Describe *transient* acceleration limits**
  - *thumbs up/down for identified transients* (based on thruster firings, impulsive crew activity, etc., e.g., 100 μg for up to 2 sec);
  - specify *integrated acceleration input* subject to limits (e.g., 300 μg sec with magnitude ≤ 150 μ

Recap:

Prediction of experiment sensitivity to the μg environment through modeling

- Identify the ***tolerance criterion***
- ***Correlate acceleration*** to the tolerance criterion
- Perform "simple" analyses to determine ***range of sensitivity***
- As necessary, perform ***detailed analysis*** in the range of sensitivity
- Develop detailed ***μg tolerance specs***

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Section 16:

Impacts of the Microgravity

Environment on Experiments

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Introduction

- Earth-bound experiments are affected by normal gravity and vibrational forces which exist in ground laboratories.
  - gravity, elevators, air conditioner, traffic, people
- Most microgravity experiments desire:
  - zero-gravity,
  - constant, uni-directional acceleration, and/or
  - constant conditions.
- Taking experiments to orbit removes effects of gravity but trades above disturbances for others
  - gravity gradient, aerodynamic drag, thrusters, other experiments, crew members, Shuttle subsystems

Improve the Environment

- **Microgravity environment is close to “zero-g” conditions, but still precautions need to be taken.**
  - **operational inhibits**
    - typical: attitude free-drift, crew exercise, & equipment operations
    - non-typical: Ku-band antenna & crew motion
  - **Orbiter attitude and altitude requirements**
    - Shuttle attitude determines the relative direction of the quasi-steady acceleration
    - slight attitude changes have effect on frequency of VRCS jet firing
    - amount of deadband in attitude control has effect on frequency of VRCS jet firing
    - Shuttle altitude has effect on the magnitude of the drag component and fluctuations thereof, especially if orbit is not circular

Microgravity Science Experiment Successes

- **Vast majority of microgravity science experiments have been successful**
  - **success has been due to a number of factors**
    - prior ground based research
    - PI involvement and extensive review process during experiment design and development
    - mission planning and operational simulations
    - crew interest and training
    - support for PI teams during mission
    - microgravity environment which can be supplied by the Shuttles, Mir, parabolic flight aircraft, sounding rockets, and free flyers
- **Some problems have occurred with experiments**
  - **difficulties with a few factors**
    - hardware failures on-orbit
    - modified mission parameters
    - unexpected operational scenarios
    - microgravity environment violated requirements

Advanced Automated Directional Solidification Furnace on USMP-2 / Lehoczky

- High temperature furnace
  - five zones, Bridgman-Stockbarger-type furnace
  - reduced stratification and fluid flow desired in microgravity
  - three Orbiter attitudes created different quasi-steady acceleration levels at furnace location
- Two attitudes presented unstable conditions
  - acceleration aligned with sample cold-to-hot
  - convective situation liable to lead to fluid flow
- Perpendicular / transverse acceleration ratio
  - less than one for all three attitudes
  - also conducive for fluid flow

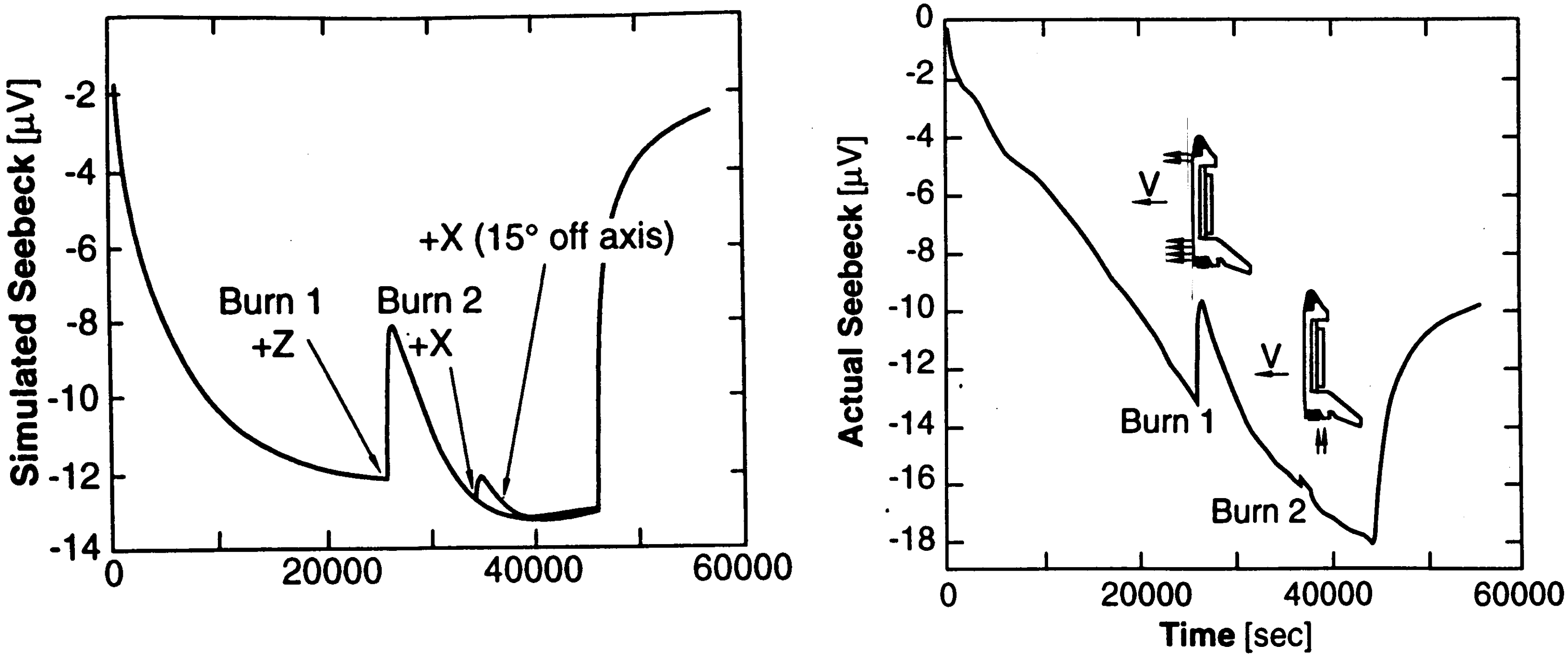
AADSF on USMP-3 / Fripp

- **Objective of experiment:**
  - **The primary objective of this flight experiment was to examine the effect of the direction of the microgravity vector on the convective mixing of the liquid during directional solidification.**
- **Method:**
  - **three sample cells**
  - **three Shuttle attitudes (one for each cell)**
    - thermally stable but solutally unstable in a one dimensional analysis
    - solutally stable but thermally unstable in a one dimensional analysis
    - horizontal growth
- **Unplanned attitude change**
  - **cell #1 processing interrupted for free drift**
  - **acceleration vector alignment angle went from 2° to 45°**
  - **result appears to be solidification in accordance with a fully mixed condition as opposed to the desired diffusion condition**

MEPHISTO on USMP-3 / Favier

- High temperature furnace
  - metal alloy samples
  - in-situ measurement of Seebeck voltage indicating average melt composition at interface
- One objective was to quantitatively characterize microgravity effects on an actual crystal growth experiment
- Thruster firing effects
  - high acceleration levels cause convective mixing
  - interfacial composition disturbed
- Summary results
  - PRCS thruster: approximately one hour to recover from short thruster firing of 10 to 25 seconds durations
  - OMS thruster: approximately sixteen minutes to recover from short (35 seconds) duration OMS firing

Response to PRCS & OMS Thruster Burns



Indium Float-zone Furnace on STS-32 / Dunbar & Thomas

- **Fluid Experiment Apparatus**
  - **float-zone materials processing furnace in middeck**
  - **Indium sample**
  - **Eigen-frequencies in 0.1 to 10 Hz range**
  - **crew treadmill exercise and thruster firing disturbances**
- **Acceleration measurements made with Honeywell In-Space Accelerometer (HISA)**
  - **mounted on front of Fluid Experiment Apparatus**

Movement of Particles on IML-1 / Trolinger

- Movement of particles with different densities
  - secondary science experiment within the Fluids Experiment System facility to grow triglycine sulfate crystals
  - tracer particles of three sizes (small, medium, large)
  - tracer particle motion was studied relative to fluid convection and the microgravity environment
  - correlations established between particle motion and acceleration environment
  - the growth solution is still far from the static system originally envisioned by microgravity scientists

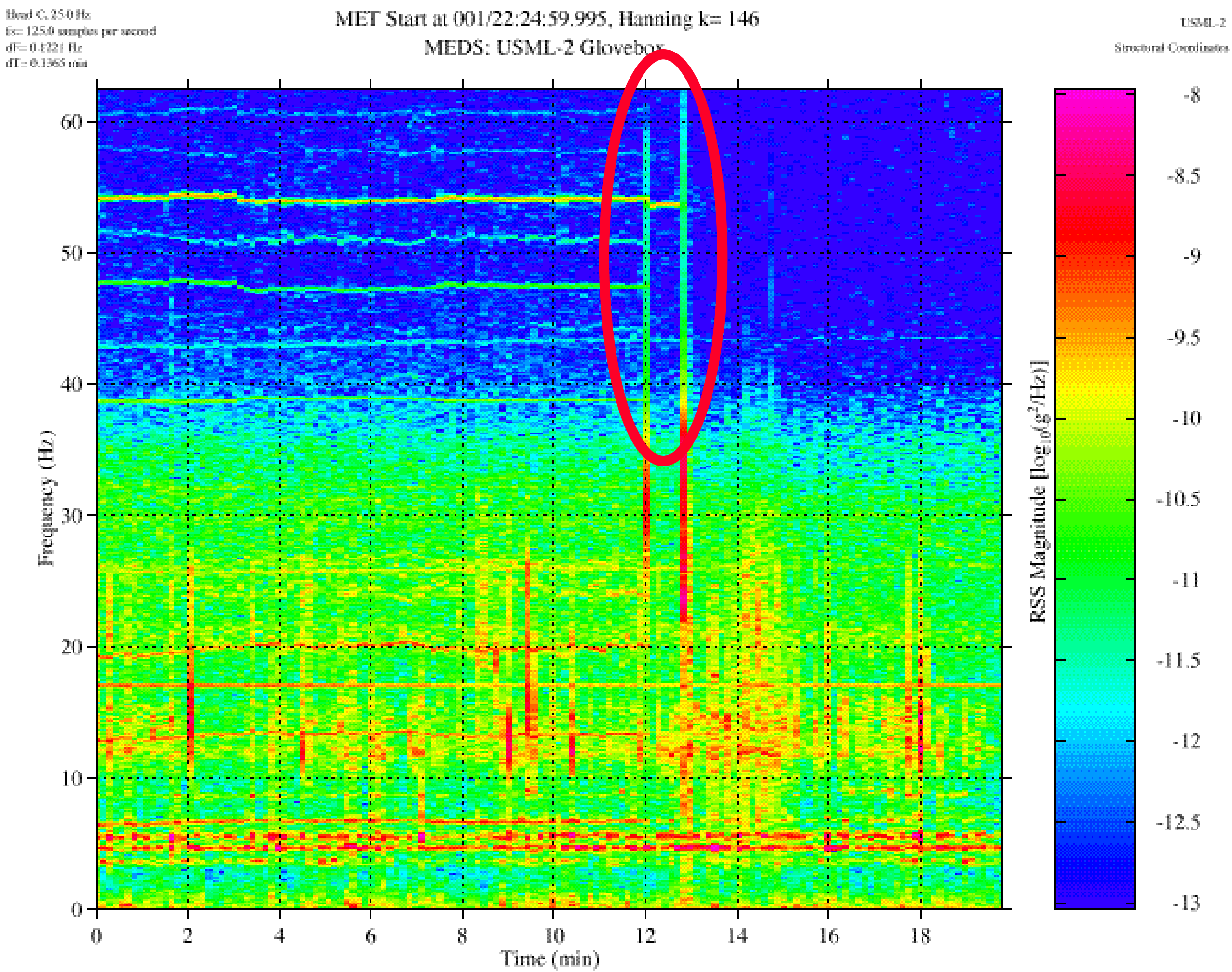
GaAs crystals during USML-1 / Matthiesen

- **Experiment conducted in the Crystal Growth Furnace**
  - **examined the radial dopant distribution with the quasi-steady microgravity vector**
  - **microgravity vector acted perpendicular to the growth direction (i.e. transverse acceleration)**
- **Results**
  - **microgravity environment was quantitatively linked to the quality of the crystal**
  - **complete-mixing profile of the crystal was caused by the crucible-melt interface shape and not by the microgravity environment**

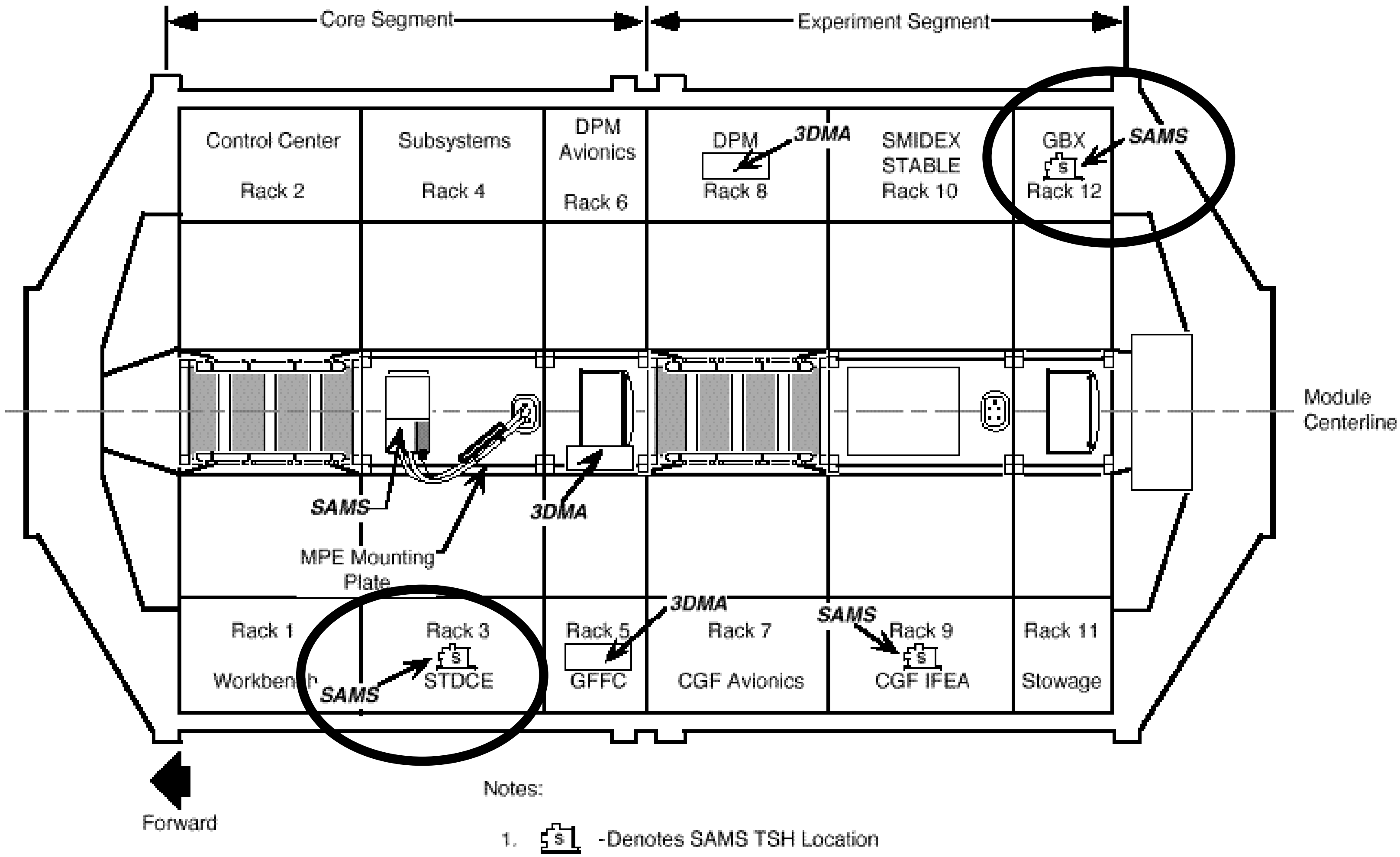
Surface Tension Driven Convection Experiment on USML-2 / Ostrach

- **STDCE sample container**
  - **free liquid surface of silicone oil**
  - **study of surface tension driven convection with different fill levels**
- **Disturbances noted during operations**
  - **ripples on free liquid surface**
  - **correlation established between glovebox fan operation, experiment video downlink, and downlink acceleration data**
  - **disturbance transmitted along and across aisle of Spacelab module**

USML-2 Glovebox Fan De-activation



Location of STDCE and Glovebox on USML-2



Confined Helium Experiment on USMP-4 / Lipa

- Liquid helium sample
  - temperature about 2 K
  - low mass
- Pre-mission concern about structural resonances
  - narrow frequency bands around 55, 75, & 119 Hz
  - 3rd harmonic of Ku-band antenna dither (~51 Hz) was a particular concern
  - Unexpected disturbance was observed around 56 Hz during initial part of mission
  - evaluated SAMS data in real-time and off-line to determine source

USMP-4 Inter-Experiment Disturbance

- **Early in the mission, an unexpected signature appeared around 56 Hz**
- **PIMS notified the CHeX team of the observation, as well as the other USMP-4 science team via flight notes**
- **Near real-time plots were provided to the CHeX team in an effort to characterize this disturbance source**
  - **Based on the stability observed in these plots, the CHeX team was able to adequately compensate the CHeX data for this disturbance**
  - **Analysis of the activation times for the other USMP-4 payloads indicated the IDGE experiment introduced the 56 Hz disturbance to the environment upon their activation**

USMP-4 Disturbance Source Identification

- **Source of the 56 Hz disturbance was determined to be IDGE cooling fans**
- **Additional disturbance sources at 37 Hz and 74 Hz were introduced by the IDGE experiment hardware**
- **Although IDGE had flown on previous USMP missions, the disturbances were unknown because of lower cutoff frequencies for SAMS sensors flown on those previous USMP missions**
- **Post-mission ground test with IDGE flight experiment hardware and SAMS flight hardware confirmed the flight data conclusions**

USMP-4 Operations Dodged a Bullet

- One of the IDGE cooling fans operated in the 37 Hz region
  - The operating speed of this fan was variable
  - Thus the vibration disturbance was a varying frequency
- LPE compensation
  - A variable frequency disturbance near a structural mode of LPE would have been very difficult or impossible to compensate
  - Likely would have resulted in curtailed operation of LPE, IDGE, or both during USMP-4

Protein Crystal Growth / various PIs

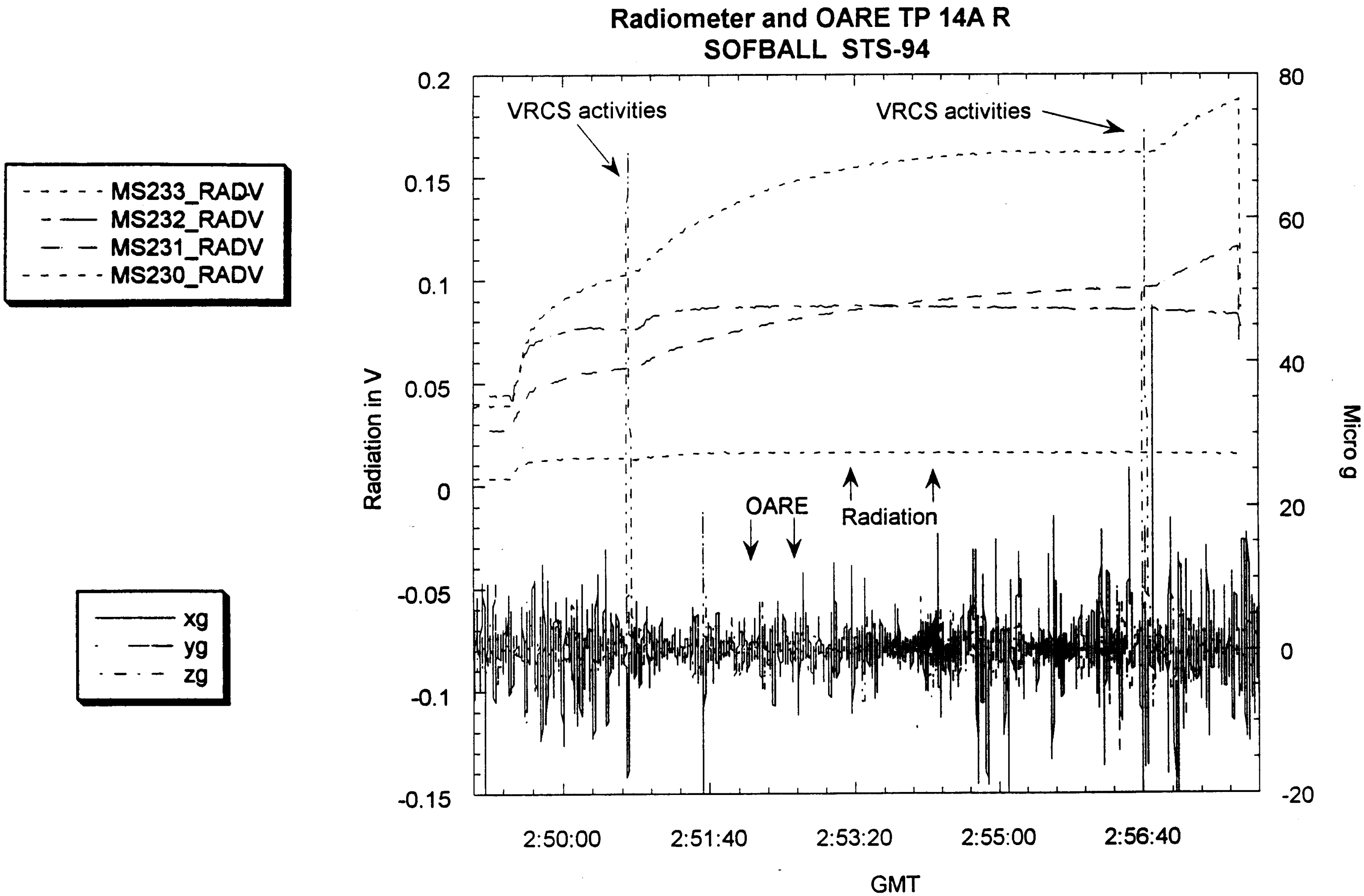
- Nominal operations require quiet vibratory acceleration environment ($<10^{-4}$ g) for first 24 - 48 hours for crystal nucleation
- On missions with significant disturbances, showers of small crystals have been observed
- Correlations between growth rate and crew exercise periods have been observed

Impacts of the Microgravity Environment on Experiments

Structure of Flameballs at Low Lewis Numbers on STS-94 / Ronney

- **Thruster (VRCS jets) disturbances caused significant, long-lasting perturbations to the radiation readings**
  - **effect appears to last several minutes**
- **PI did not request free-drift periods pre-mission**
  - **need became apparent during early experiment operations**
  - **another PI team had a pre-mission "no-free drift" requirement**
  - **SOFBALL monitored the location of the Orbiter within the attitude deadband and initiated operations accordingly**
  - **Achieved maximum 5-minutes in deadband drift at beginning of their 14 minute test sequence**
- **PI is investigating the cause**
  - **flame ball surrounded by much larger region (a few cm in diameter) of hot gas - very sensitive to any acceleration**
  - **radiometers respond sharply when acceleration deforms the hot gas and shifts closer to or further away from the radiometer**

Impacts of the Microgravity Environment on Experiments



Structure of Flameballs at Low Lewis Numbers (SOFBALL) / Ronney

- Planned re-flight of SOFBALL on STS-107
- PI included requirements for low-frequency acceleration measurements
- PI has re-affirmed these requirements during PAYLOAD manifesting negotiations
  - Initial difficulty in manifesting OARE accelerometer
  - PI's requirements ensured that OARE would be manifested

Isothermal Dendritic Growth Experiment on USMP-2 & -3 / Glicksman

- **For all practical purposes, with respect to dendritic growth for the chamber size and temperature range selected, the microgravity environment aboard the Shuttle is at "zero-g," i.e., convective effects are not seen on-orbit.**
  - **convection exists at 1 g**
  - **convection not apparent at 1 μg**
  - **convection not apparent at 40 μg during Tether Satellite System deployment on STS-75**
  - **no disturbance for 40 -> 0.5 μg transition when TSS broke**
  - **threshold somewhere between 1 μg and 1 g but apparently above the Shuttle environment**

Summary

- The microgravity environment is not "zero-g" or even "zero-acceleration". It is dynamic.
- The microgravity environment may influence the results of a science experiment.
- Analyses and/or tests should be performed before flight to investigate the sensitivity of an experiment to the microgravity environment.
- Environments of past missions should be considered in planning future experiments.
- Experiment teams should be concerned about what disturbances they may be causing to the microgravity environment with (for example) moving parts or required crew actions.

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