SECTION II

Working in a Reduced Gravity Environment: “A Primer”

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The reduced gravity acceleration environment of an orbiting spacecraft in a low earth orbit is a very complex phenomenon. Many factors contribute to form the overall environment. In general, it can be considered as made up of the following three components:

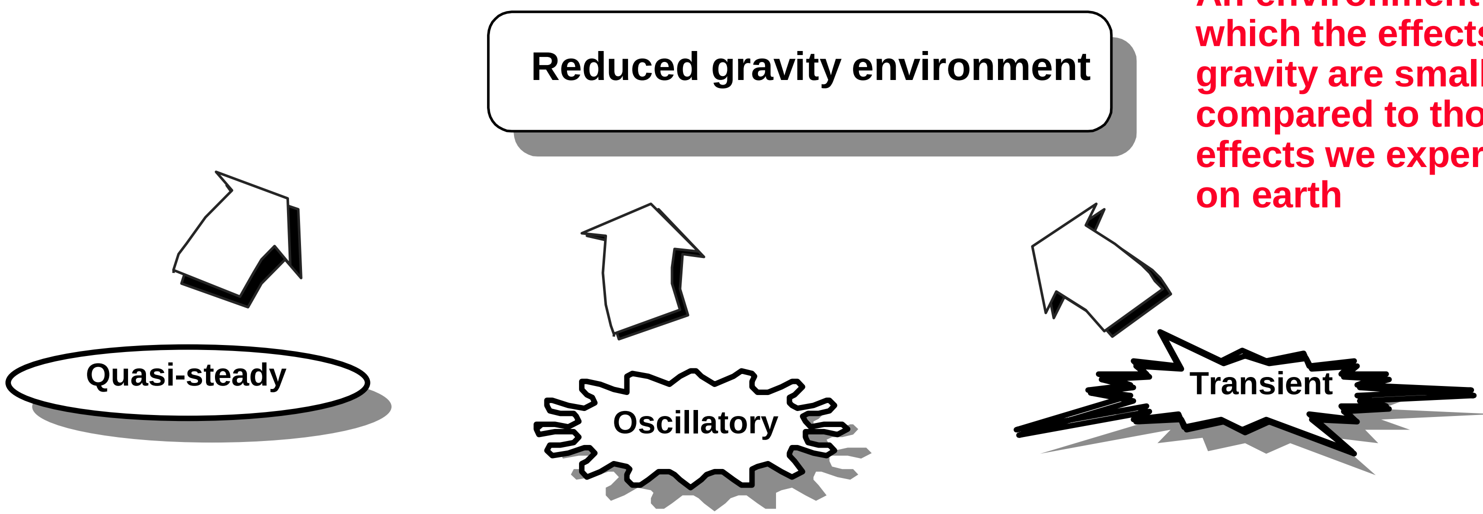
QUASI-STEADY: is composed of those accelerations that vary over long periods of time, typically longer than a minute for space-based platforms.

VIBRATORY: is composed of those accelerations that are harmonic and periodic in nature with a characteristic frequency.

TRANSIENT: is composed of those accelerations that last for a short period time, and are non-repetitive.

What is a *“reduced gravity environment”* ?

Major properties

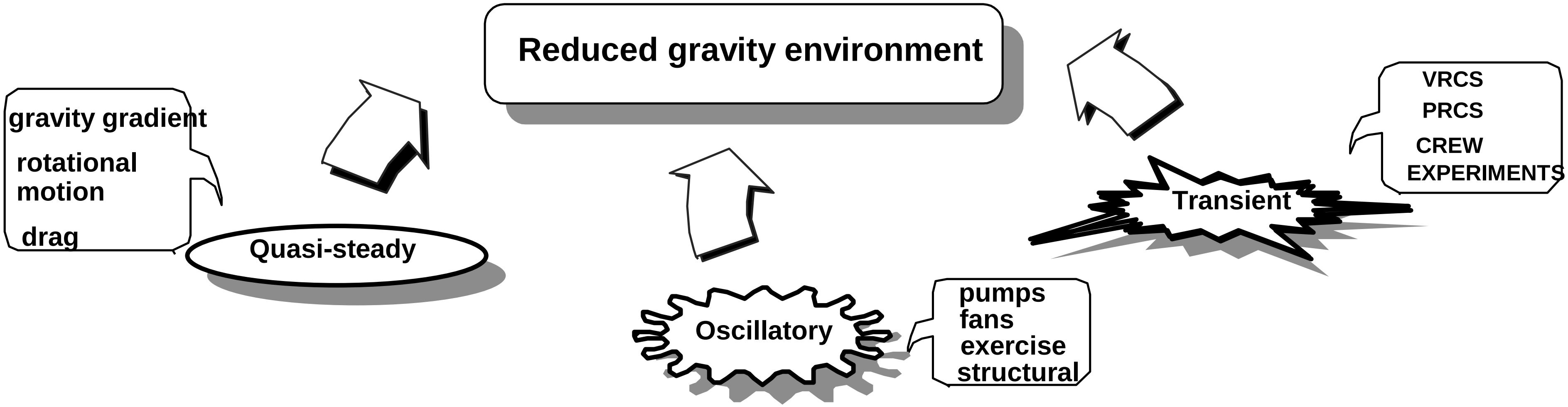


An environment in which the effects of gravity are small compared to those effects we experience on earth

What is a *“reduced gravity environment”* ?

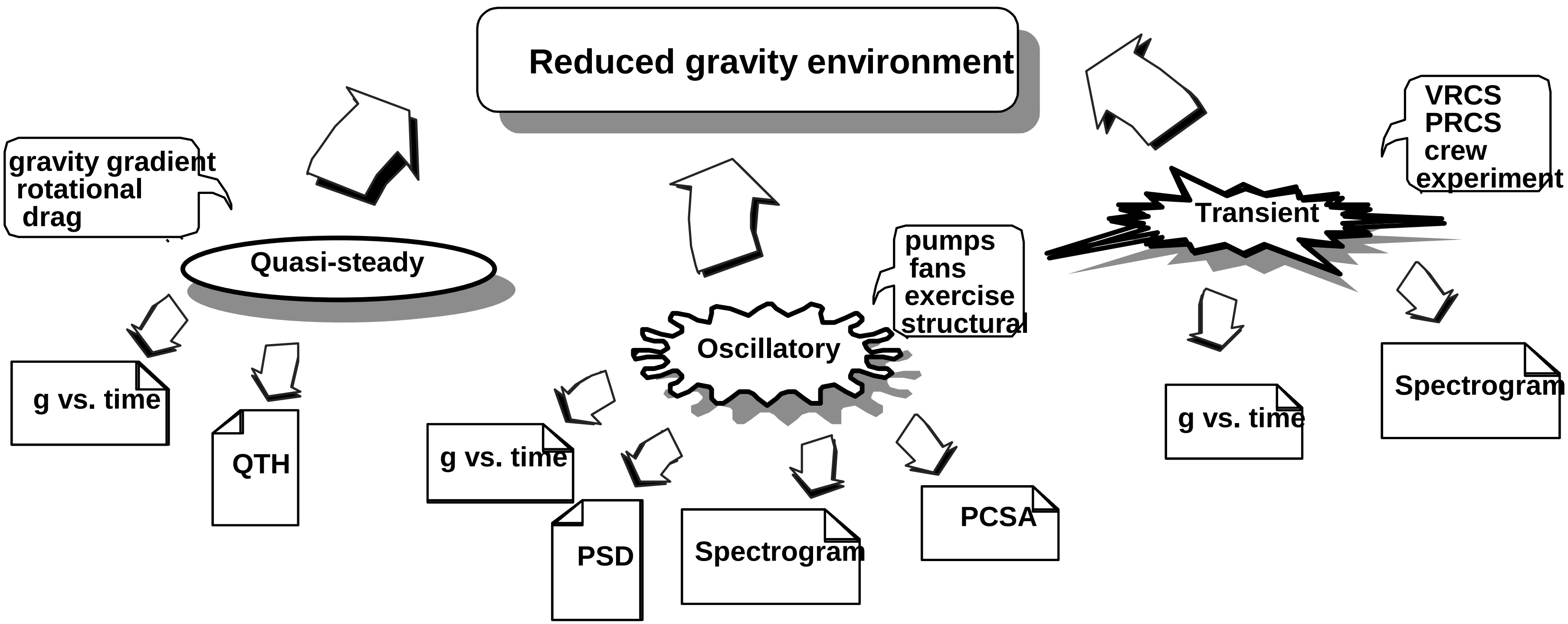
Major properties

What causes these accelerations?



What is a *“reduced gravity environment”* ?

- Major properties
- What causes these accelerations
- How do we display them?



Components of the Reduced Gravity Environment

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

Microgravity Environment

Component	Quasi-Steady	Vibratory	Transient
Frequency	$0 \leq f < 0.01$ Hz	$0.01 \leq f \leq 300$ 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

WHAT DO ALL THESE MEAN TO YOU?

- **The environment is NOT "zero-g"!**
- **Experiments may be affected by the reduced gravity environment**
- **This tutorial will explain to you what the environment is likely to be, how we measure it, how we interpret it, and will show you what impact the environment has had on some experiments.**

REDUCED GRAVITY ENVIRONMENT DESCRIPTION

Reduced gravity Facilities	Duration	Acceleration Levels	Notes
Drop Towers	< 10 seconds	10^{-3} g	NASA, Japan, Germany
Parabolic Aircraft	15 – 25 seconds	1.5×10^{-2} g	~ 40 parabolas per campaign
Rockets	Up to 600 seconds	10^{-5} g	Various countries
SPACEHAB Module	Up to 16 days	< 5.5×10^{-4} g (for the combined three axes	Frequency range: 0.01 – 25 Hz
Spacelab Module (MPESS)	Up to 16 days	< 1.4×10^{-3} g (for the combined three axes)	Frequency range: 0.01 – 25 Hz
Spacelab Module	Up to 16 days	< 3×10^{-3} g (for the combined three axes)	Frequency range: 0.01 – 25 Hz
STS overall Quasi-Steady environment	Up to 15 days	< 1×10^{-6} g	Frequency range: 0.0 – 0.01 Hz. Average values for typical orbiter attitudes
STS overall vibratory environment	Up to 15 days	Tens to thousands μg_{RMS}	Depending on what activity is taking place
STS overall transient environment	Up to 15 days	Tens of µg peak	Depending on what activity is taking place

NOTE:

The acceleration level values listed in this table are NOT to be used as a nominal value of the reduced gravity environment of any specific platform. The environment is very dynamic in nature. They are listed here to illustrate the non-zero nature of the reduced gravity environment. The actual value for any of the platform listed here, at any moment in time, is frequency dependent (mission timeline activity dependent).

Acceleration Measurement Systems

- **OARE:** Orbital Acceleration Research Experiment - instrument which measures low frequency accelerations from DC up to 0.01 Hz
- **MAMS:** Microgravity Acceleration Measurement System - instrument which measures acceleration levels to characterize the ISS reduced gravity environment provided to users. MAMS measures accelerations from DC to 1 Hz.
- **SAMS:** Space Acceleration Measurement System - instrument which measures accelerations from 0.01 Hz to 100 Hz on Shuttle, Mir, and KC-135.
- **SAMS-II:** Second generation SAMS - instrument which will measure accelerations from 0.01 Hz to 300 Hz on the ISS.
- **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. Measure accelerations from 0.01 to 300 Hz.

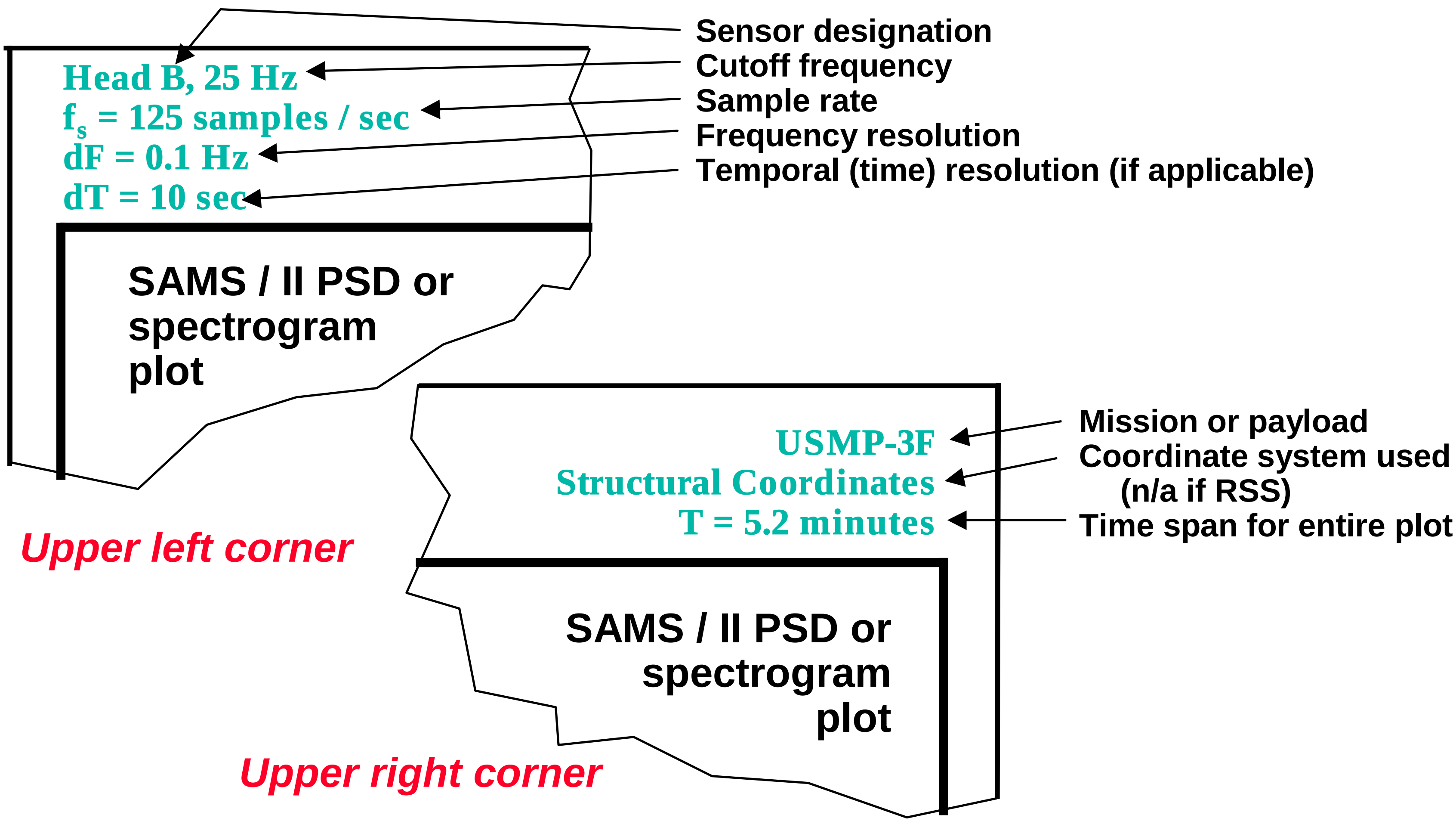
SOME DEFINITIONS

- **reduced gravity 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

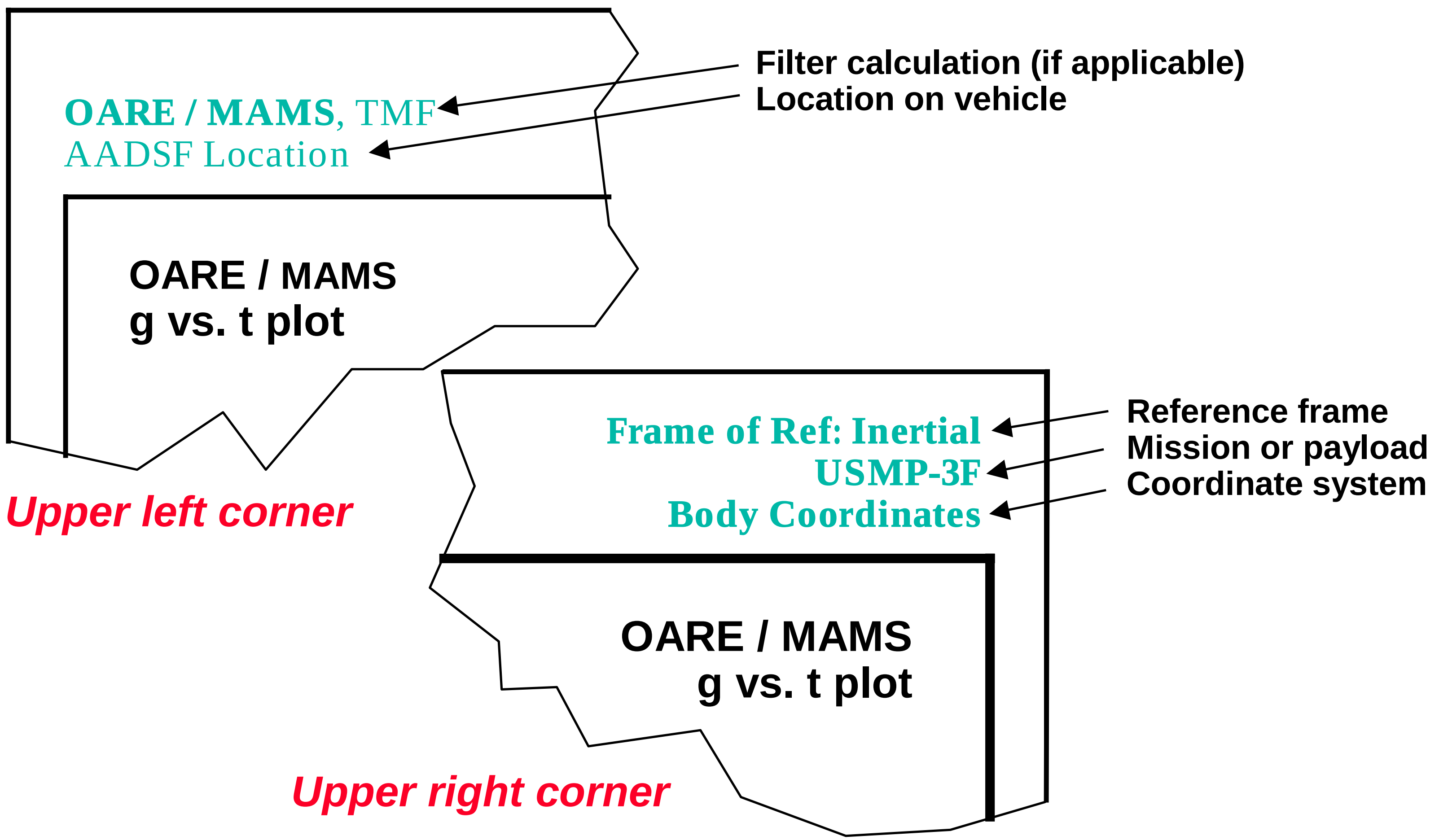
SOME DEFINITIONS

- **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 frequency and time

SAMS / II

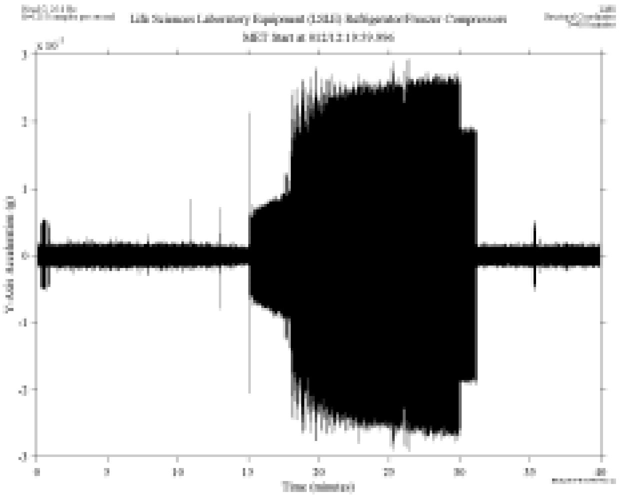

Head B, 25 Hz
f_s = 125 samples / sec
dF = 0.1 Hz
dT = 10 sec
Sensor designation
Cutoff frequency
Sample rate
Frequency resolution
Temporal (time) resolution (if applicable)
SAMS / II PSD or spectrogram plot
Upper left corner
USMP-3F
Structural Coordinates
T = 5.2 minutes
Mission or payload
Coordinate system used (n/a if RSS)
Time span for entire plot
SAMS / II PSD or spectrogram plot
Upper right corner

OARE / MAMS

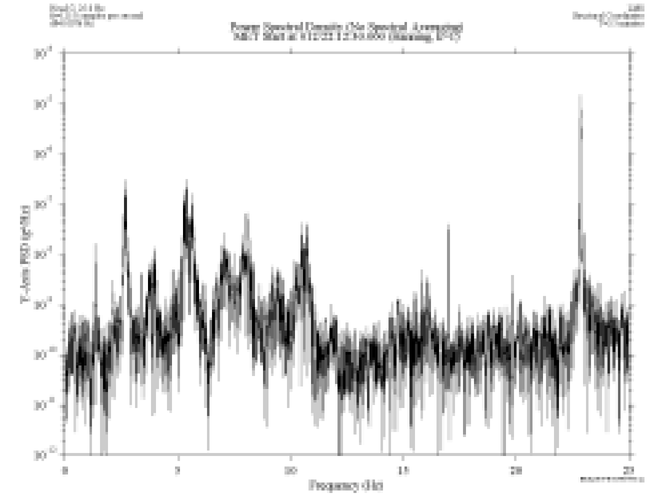

Filter calculation (if applicable)
Location on vehicle
OARE / MAMS, TMF
AADSF Location
OARE / MAMS
g vs. t plot
Upper left corner
Frame of Ref: Inertial
USMP-3F
Body Coordinates
Reference frame
Mission or payload
Coordinate system
OARE / MAMS
g vs. t plot
Upper right corner

SOME PLOT SAMPLES

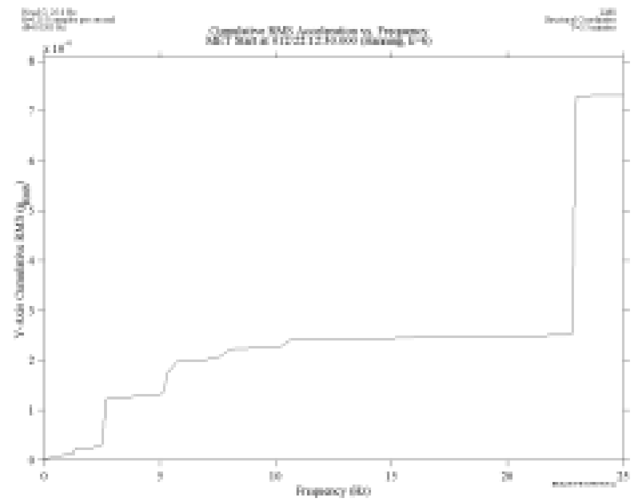
Acceleration vs. Time



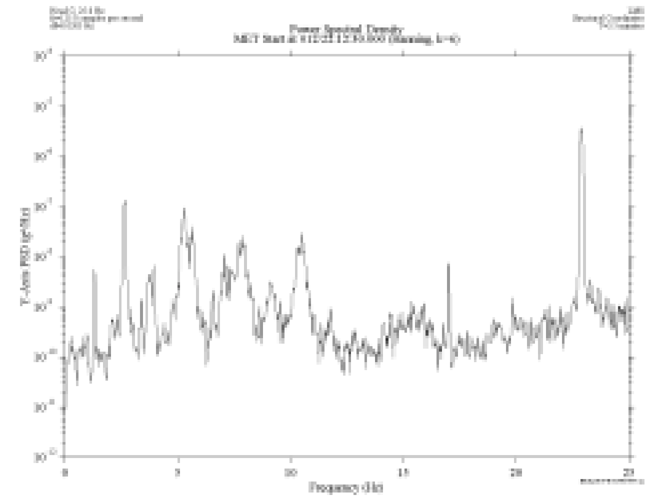
Power Spectral Density –no spectral averaging



Cumulative RMS acceleration vs. Frequency

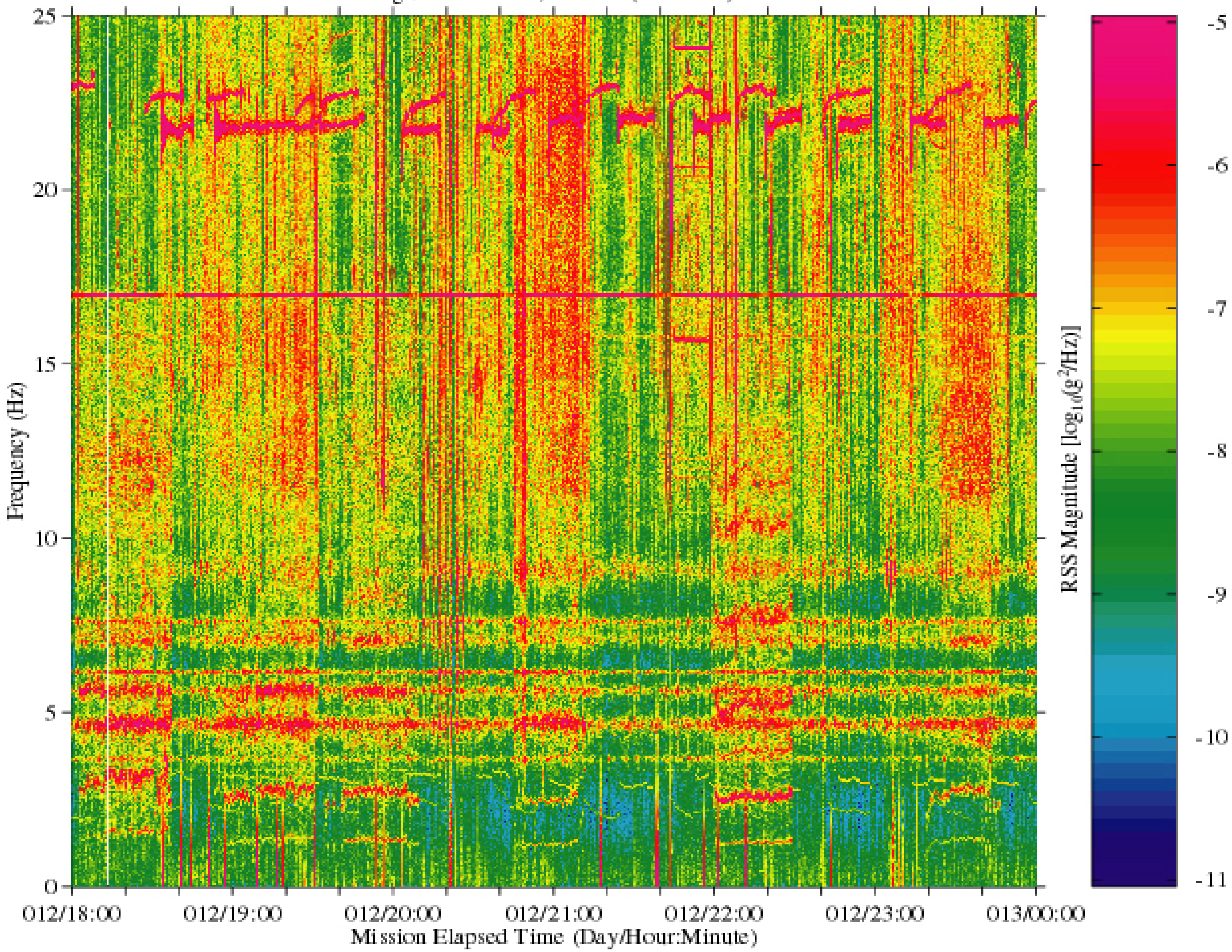


Power Spectral Density – with averaging



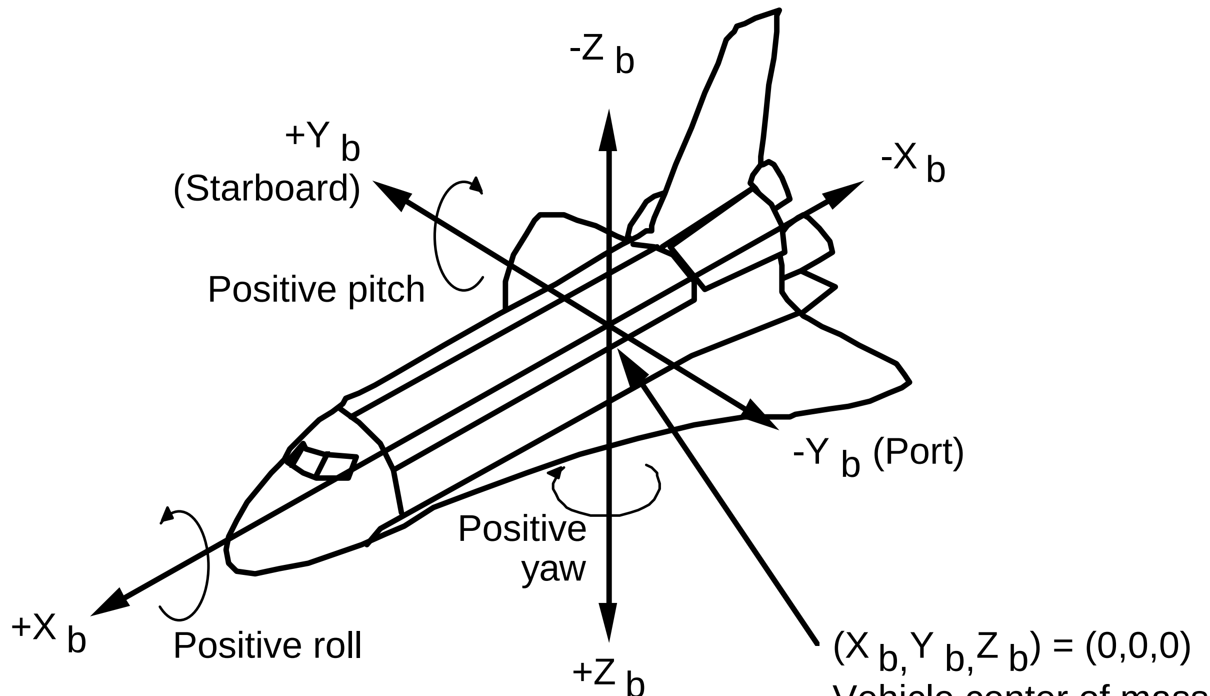
SOME PLOT SAMPLES

Figure 102: LMS, Head C (fc=25 Hz)



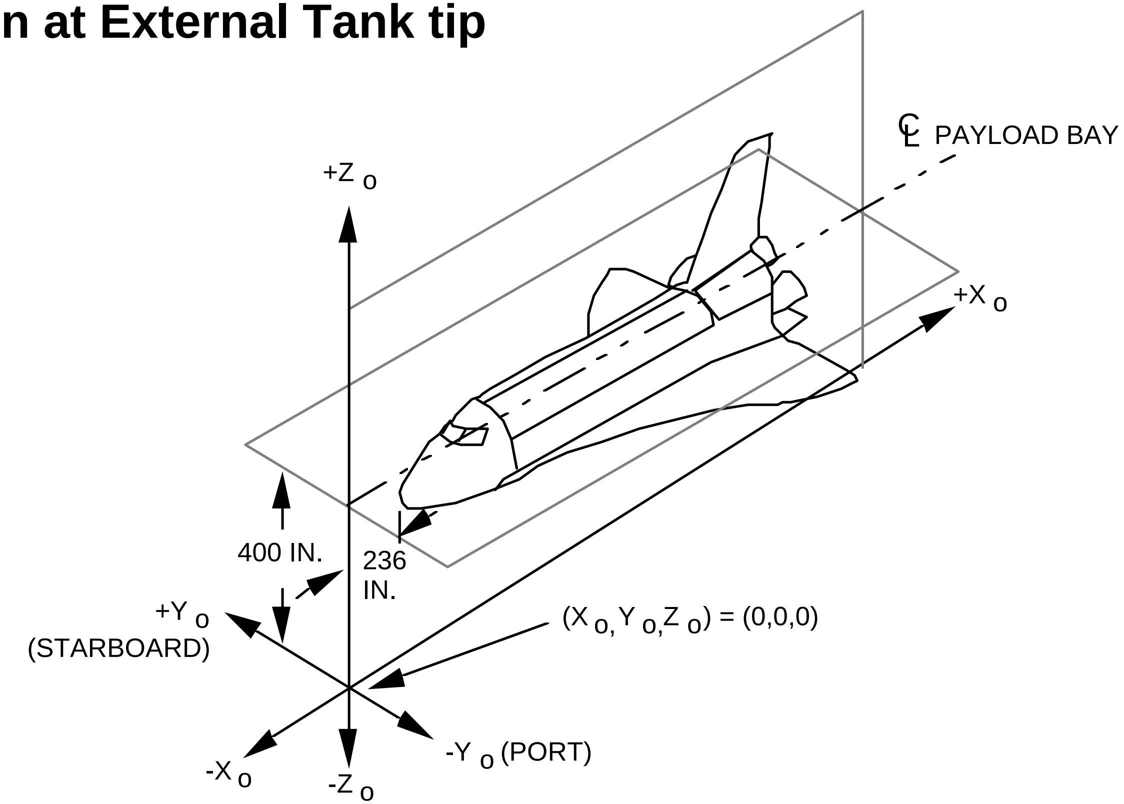
ORBITER

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



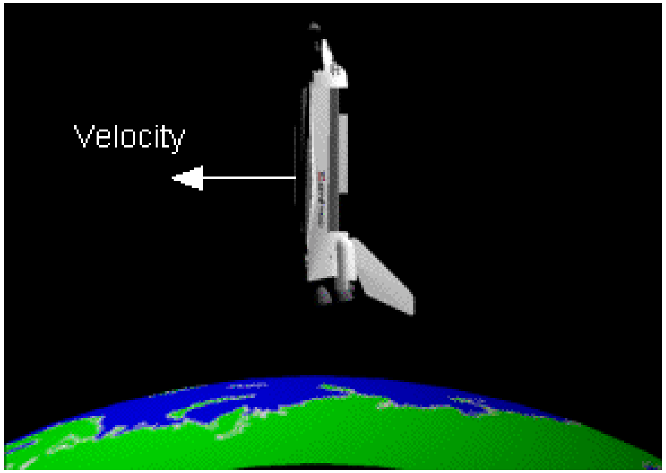
ORBITER

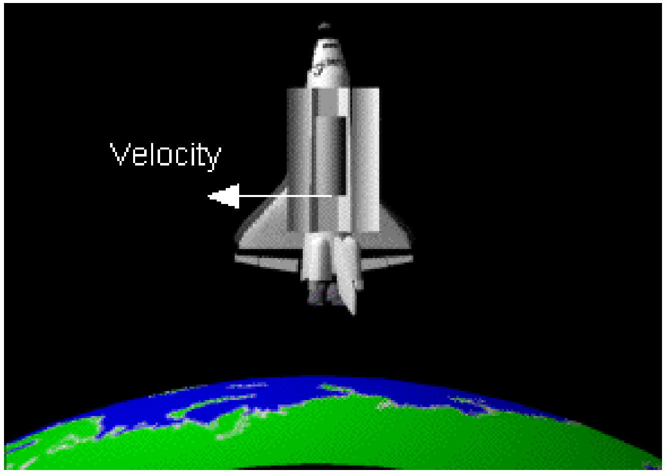
- **Structural coordinate system**
  - **origin at External Tank tip**



ORBITER

- **Orbiter has two main attitudes**
  - **Local vertical / local horizontal (Earth oriented)**
  - **Inertial (quite often sun oriented)**

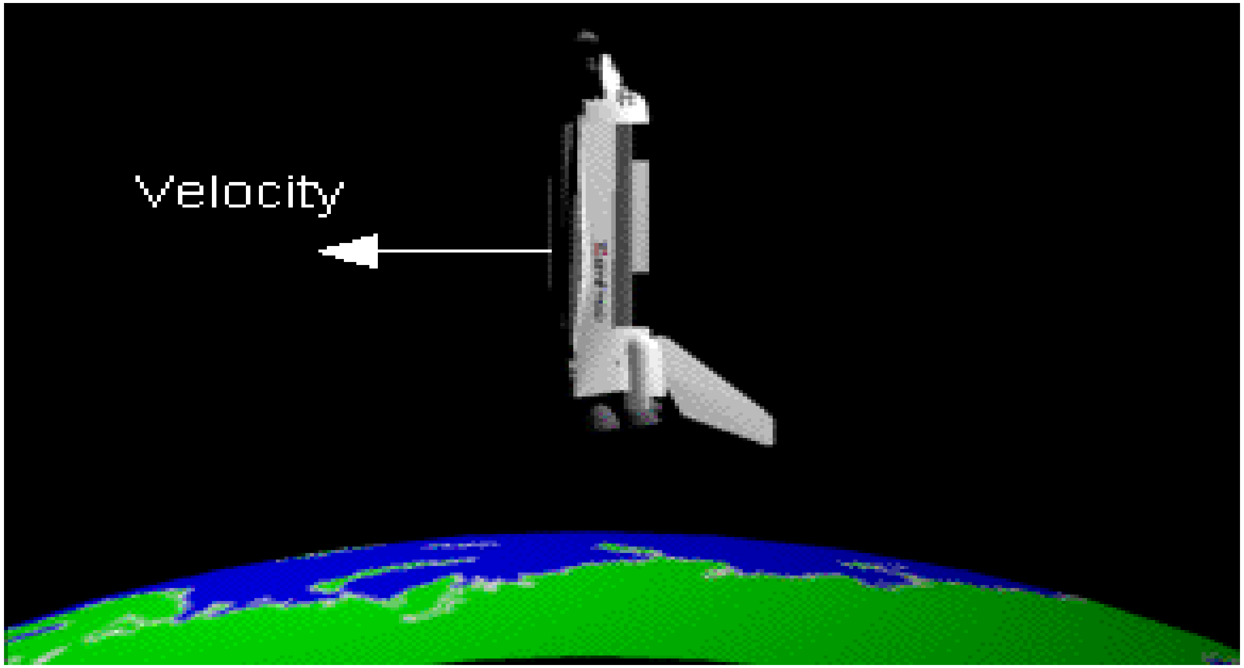




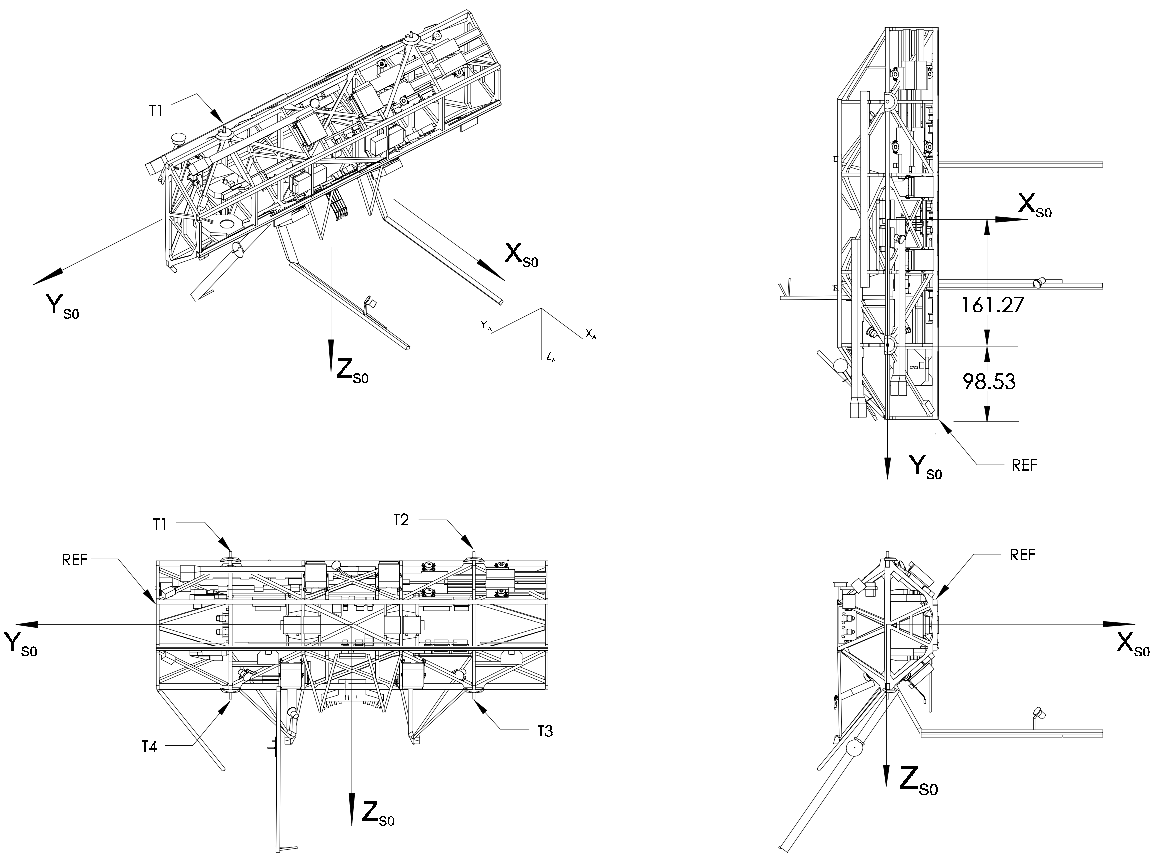
- **Designation of attitudes**
  - **pitch / yaw / roll angle relative to airplane mode**
    - -e.g. PYR: 90°, 0°, 90°
  - **body axes oriented to nadir (toward Earth) and flight direction**
    - -e.g. -XLV / +YVV

ORBITER

- **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**



ISS



Integrated Truss Segment S0 Coordinate System

Type

Right-Handed Cartesian, Body-Fixed

Description

This coordinate system defines the origin, orientation, and sense of the Space Station Analysis Coordinate System.

Origin

The YZ plane nominally contains the centerline of all four trunnion pins. The origin is defined as the intersection of two diagonal lines connecting the centers of the bases of opposite trunnion pins, running T1 to T3 and from T2 to T4.

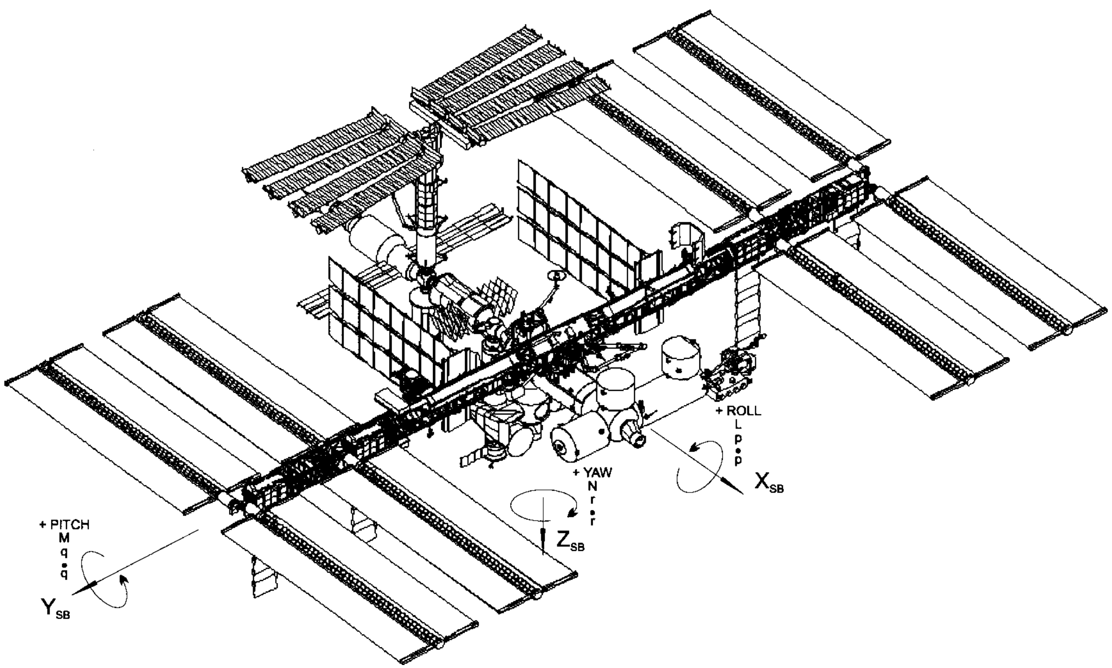
Orientation

X_{S0}: The X-axis is parallel to the vector cross-product of the Y-axis with the line from the center of the base trunnion pin T2 to the center of the base trunnion pin T3, and is positive forward

Y_{S0}: The Y-axis is parallel with the line from the center of the base of trunnion pin T2 to the center of the base of trunnion pin T1. The positive Y-axis is toward starboard.

Z_{S0}: The Z-axis completes the RHCS

ISS



SPACE STATION ANALYSIS COORDINATE SYSTEM

Type

Right-Handed Cartesian, Body-Fixed

Description

This coordinate system is derived using the Local Vertical Local Horizontal (LVLH) flight orientation. When defining the relationship between this coordinate system and another, the Euler angle sequence to be used is a yaw, pitch, roll sequence around the Z_A, Y_A, and X_A axes, respectively.

Origin

The origin is located at the geometric center of Integrated Truss Segment (ITS) S_0 and is coincident with the S_0 Coordinate frame.

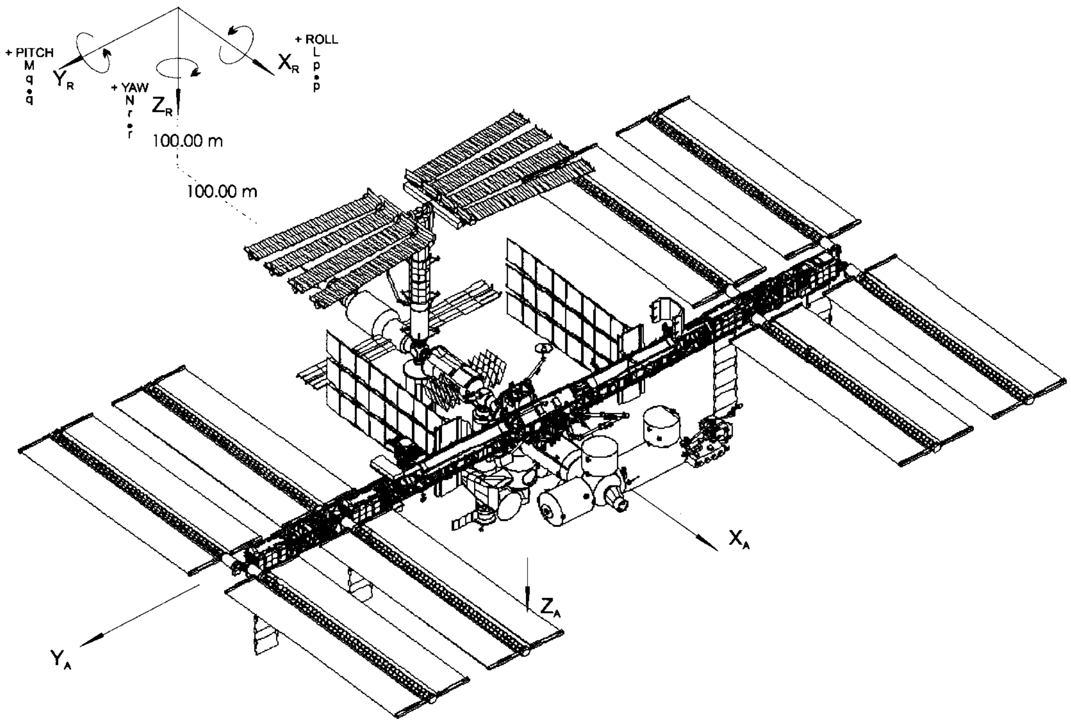
Orientation

X_A: The X-axis is parallel to the longitudinal axis of the module cluster. The positive X-axis is in the the forward direction

Y_A: The Y-axis is identical with the So axis. The nominal alpha joint rotational axis is parallel with YA. The positive Y-axis is in the starboard direction.

Z_A: The positive Z-axis is in the direction of nadir and completes the right-handed Cartesian system (RHCS).

ISS



SPACE STATION REFERENCE COORDINATE SYSTEM

Type

Right-Handed Cartesian, Body-Fixed

Description

This coordinate system is derived using the Local Vertical Local Horizontal (LVLH) flight orientation.

Origin

The datum point is located at the origin of the Space Station Analysis Coordinate System frame. The origin of the Space Station Reference Coordinate System is located such that the datum point is located at: $\mathbf{X_R=100}$, $\mathbf{Y_R=0}$, and $\mathbf{Z_R=100}$ meters

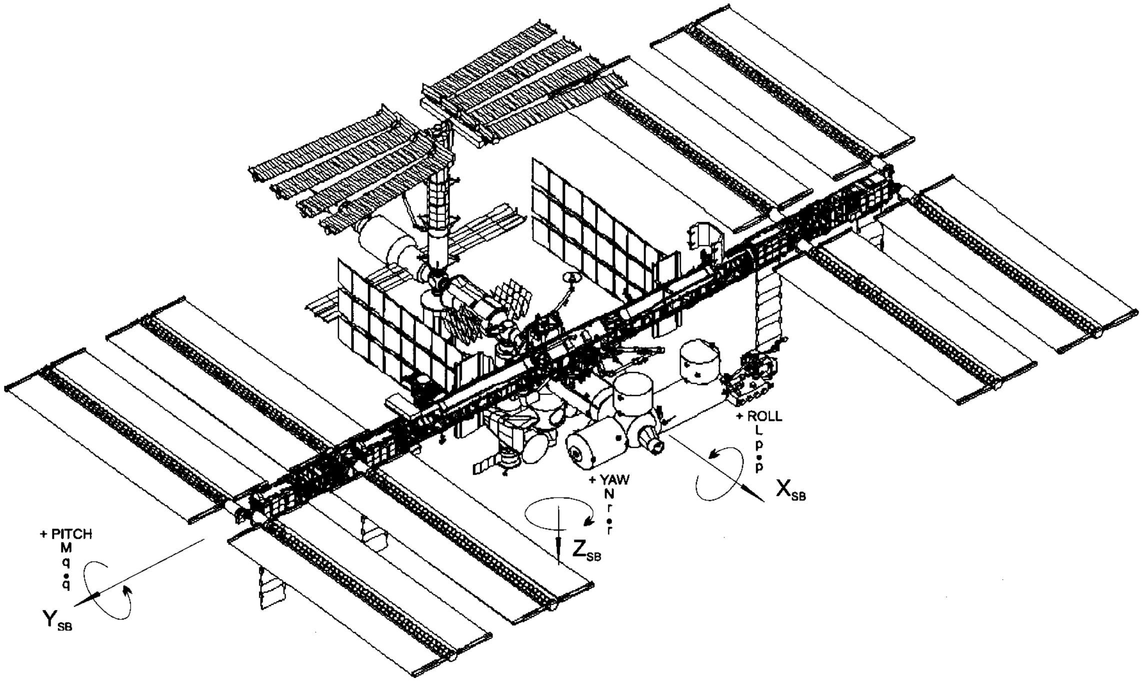
Orientation

$\mathbf{X_R}$: The X-axis is parallel to the X_A. The positive X-axis is in the forward direction

$\mathbf{Y_R}$: The Y-axis is coincident with the nominal alpha joint rotational axis, which is parallel to Y_A. The positive Y-axis is in the starboard direction.

$\mathbf{Z_R}$: The positive Z-axis is parallel to Z_A and is in the direction of nadir and completes the rotating right-handed Cartesian system.

ISS



SPACE STATION BODY COORDINATE SYSTEM

Type

Right-Handed Cartesian, Body-Fixed

Description

When defining the relationship between this coordinate system and another, the Euler angle sequence to be used is a yaw, pitch, roll sequence around the Z_{SB}, Y_{SB}, and X_{SB} axes, respectively

Origin

The origin is located at the Space Station center of mass.

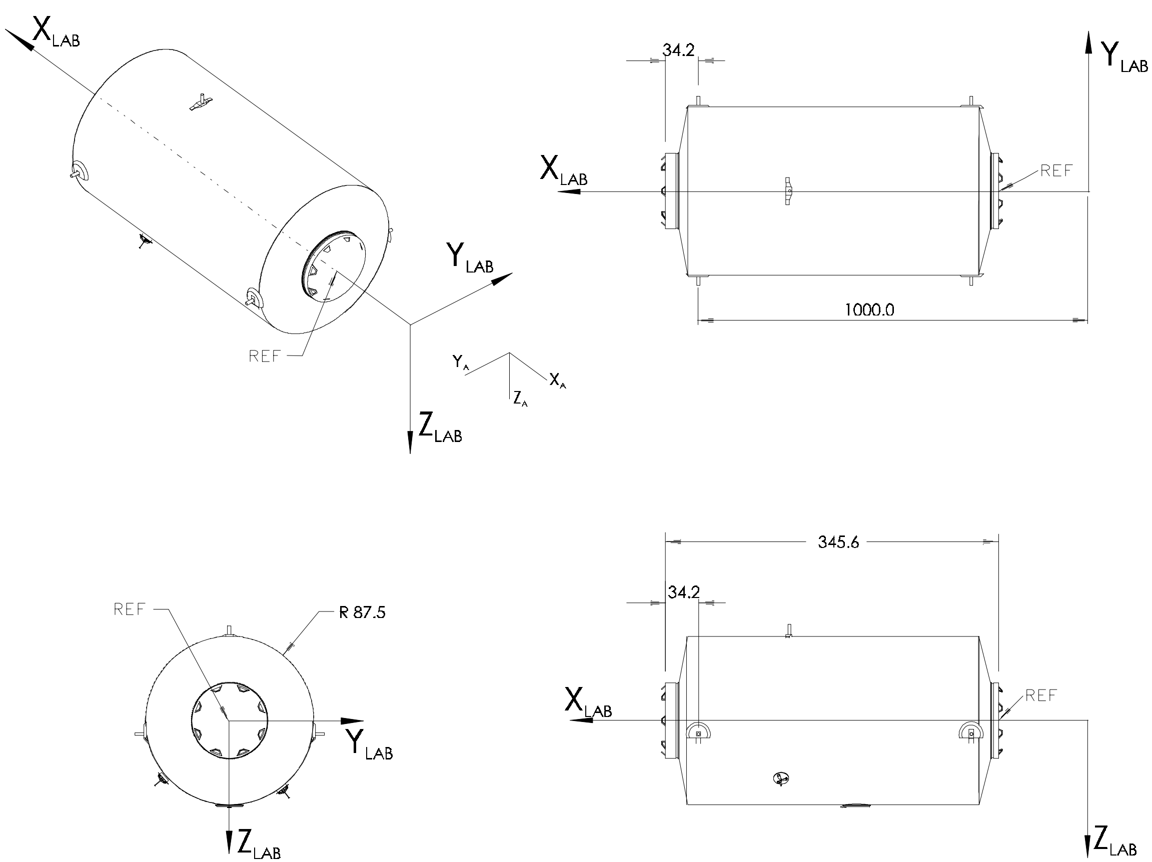
Orientation

X_{SB}: This axis is parallel to the X_A axis. Positive X_{SB} is in the forward flight direction.

Y_{SB}: This axis is parallel to the Y_A. Positive Y_{SB} is toward starboard.

Z_{SB}: This axis is parallel with the Z_A. Positive Z_{SB} is approximately toward nadir and completes the right-handed system: X_{SB}, Y_{SB}, Z_{SB}.

ISS



UNITED STATES LABORATORY MODULE COORDINATE SYSTEM

Type

Right-Handed Cartesian, Body-Fixed to the Pressurized Module

Origin

The origin is located forward of the pressurized module such that the center of the bases of the aft trunnions have X_{LAB} components nominally equal to 1000.000 inches.

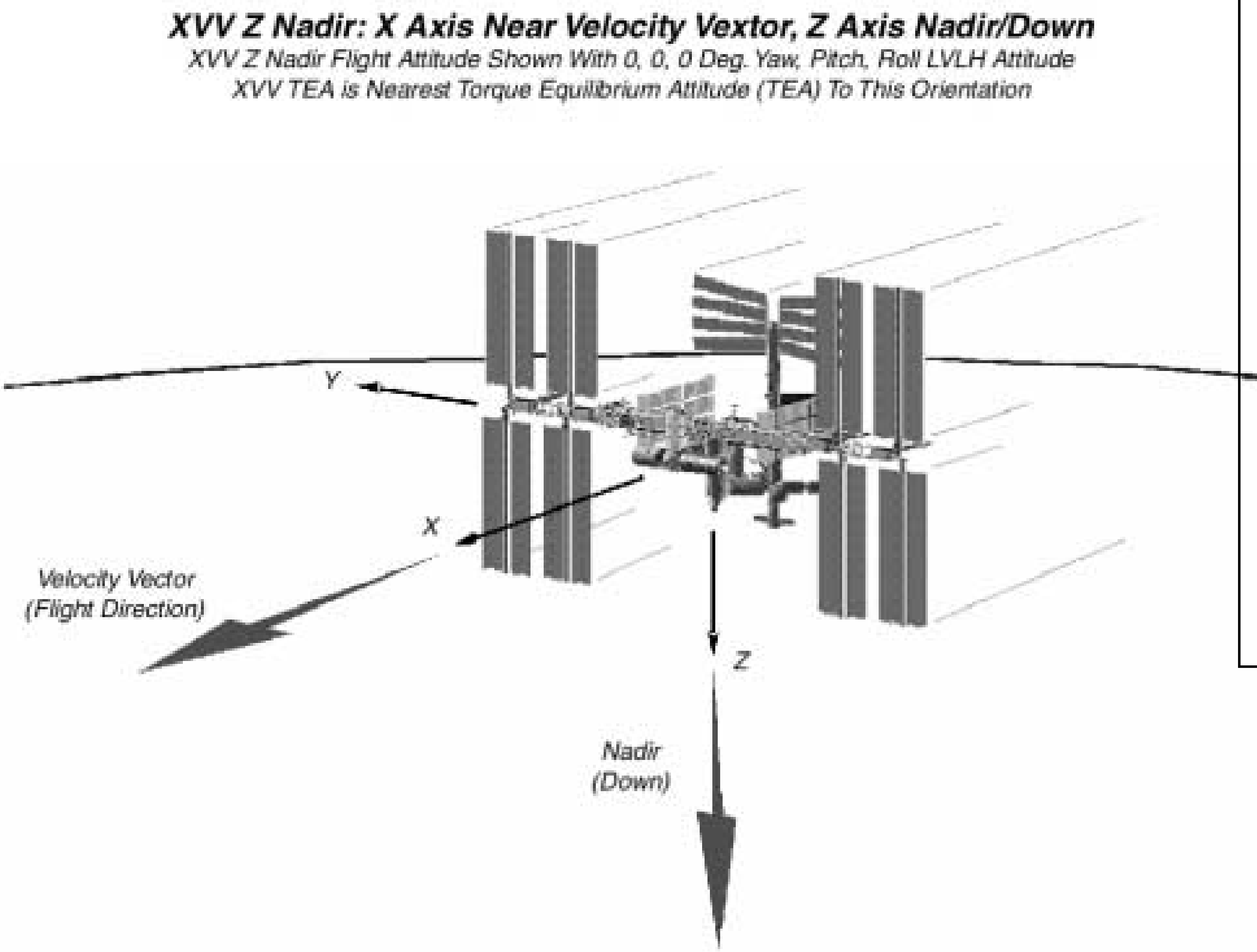
Orientation

X_{LAB}: The X-axis is perpendicular to the nominal aft CBM interface plane and pierces the geometric center of the array of mating bolts at the aft end of the pressurized module. The positive X-axis is toward the pressurized module from the origin.

Y_{LAB}: The Y-axis completes the right-handed Cartesian system (RHCS).

Z_{LAB}: The Z-axis is parallel to the perpendicular line from the X-axis to the center of base of the keel pin, and positive in the opposite direction as shown.

ISS



The basic flight attitude for ISS is called **XVV Z** Nadir. The vehicle design is optimized for this attitude. The **XVV** attitude:

- **places the most modules in the microgravity volume**
- **supports altitude reboosts**
- **service vehicle dockings**
- **minimizes aerodynamic drag**

The ISS is designed to tolerate deviations from perfect XVV Z Nadir of +/- 15 degrees in each axis. This envelope was expanded to –20 deg in pitch.

Available Reduced Gravity Carriers / Facilities

- STS Orbiters
- International Space Station (ISS)
- Sounding Rockets
- Parabolic Flight Aircraft (KC-135)
- Free-Flyers
- Drop Towers
- Microgravity Emission Lab (MEL)

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 attitude

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

Mission / Experiment Timeline

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**
- **Crew activity**
- **Thruster activity**
- **Other experiment operations**
- **Venting**

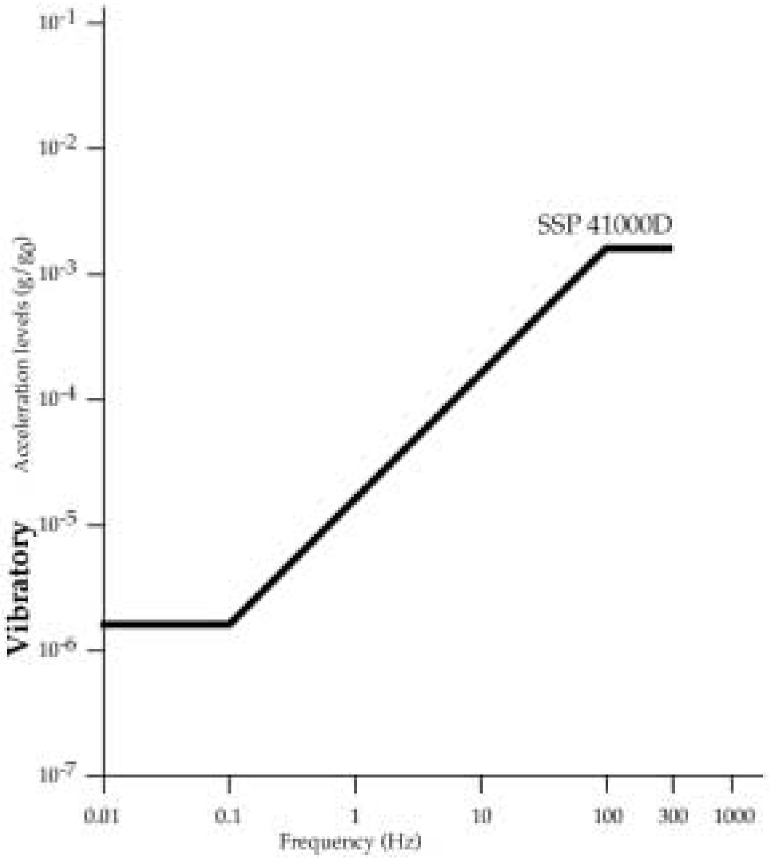
ISS Microgravity Requirements

Summary

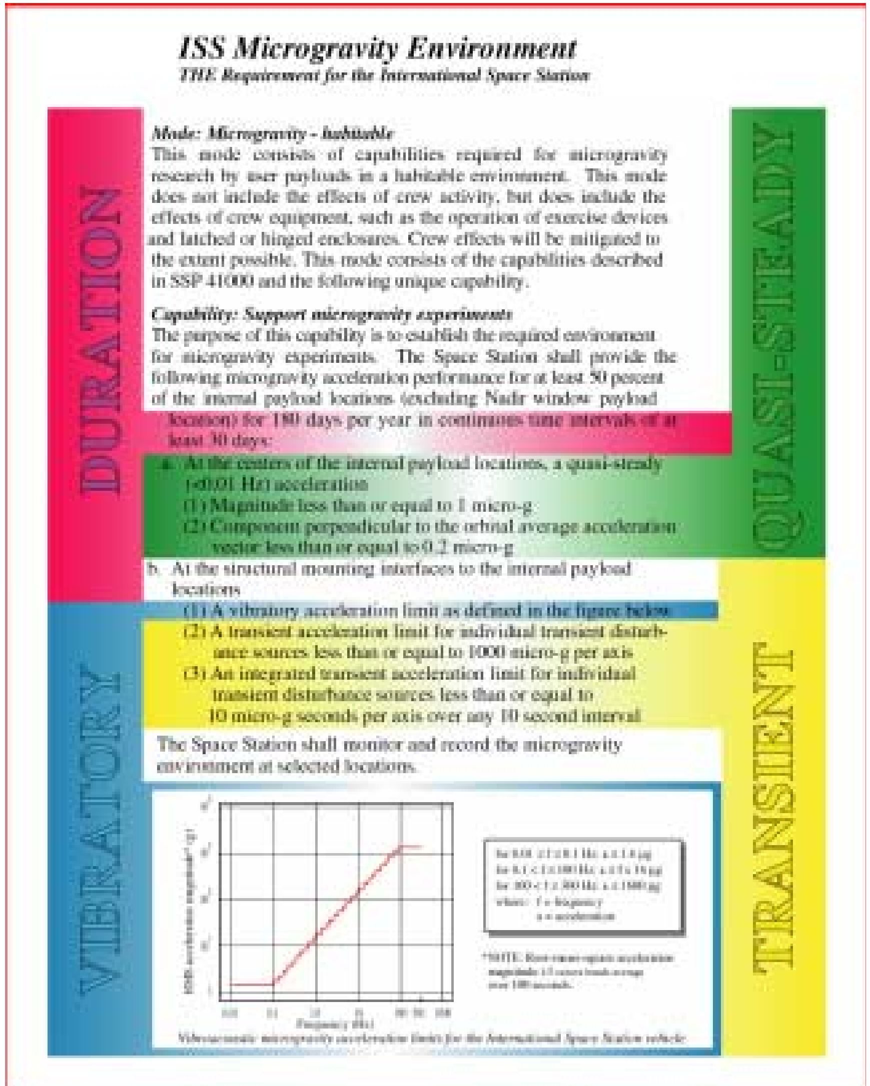
Quasi-steady
- Steady state < f < 0.01 Hz
- $g \leq 1\ \mu g_{rms}$
- Stability: perpendicular $g \leq 0.2\ \mu g_{rms}$

Vibratory
- Levels in figure at structural mounting interfaces
- RMS acceleration magnitude in one-third octave averaged over 100 seconds
- Does not include crew disturbances

Transient
- $g \leq 1000\ \mu g$ per axis
- $g \leq 10\ \mu g$-sec per axis (integrated over 10 sec)



EXPERIMENT SENSITIVITY ASSESSMENT



ISS Microgravity Environment

THE Requirement for the International Space Station

DURATION

QUASI-STEADY

Mode: Microgravity - habitable

This mode consists of capabilities required for microgravity research by user payloads in a habitable environment. This mode does not include the effects of crew activity, but does include the effects of crew equipment, such as the operation of exercise devices and latched or hinged enclosures. Crew effects will be mitigated to the extent possible. This mode consists of the capabilities described in SSP 41000 and the following unique capability.

Capability: Support microgravity experiments

The purpose of this capability is to establish the required environment for microgravity experiments. The Space Station shall provide the following microgravity acceleration performance for at least 50 percent of the internal payload locations (excluding Nadir window payload location) for 180 days per year in continuous time intervals of at least 30 days:

a. At the centers of the internal payload locations, a quasi-steady (<0.01 Hz) acceleration
   (1) Magnitude less than or equal to 1 micro-g
   (2) Component perpendicular to the orbital average acceleration vector less than or equal to 0.2 micro-g

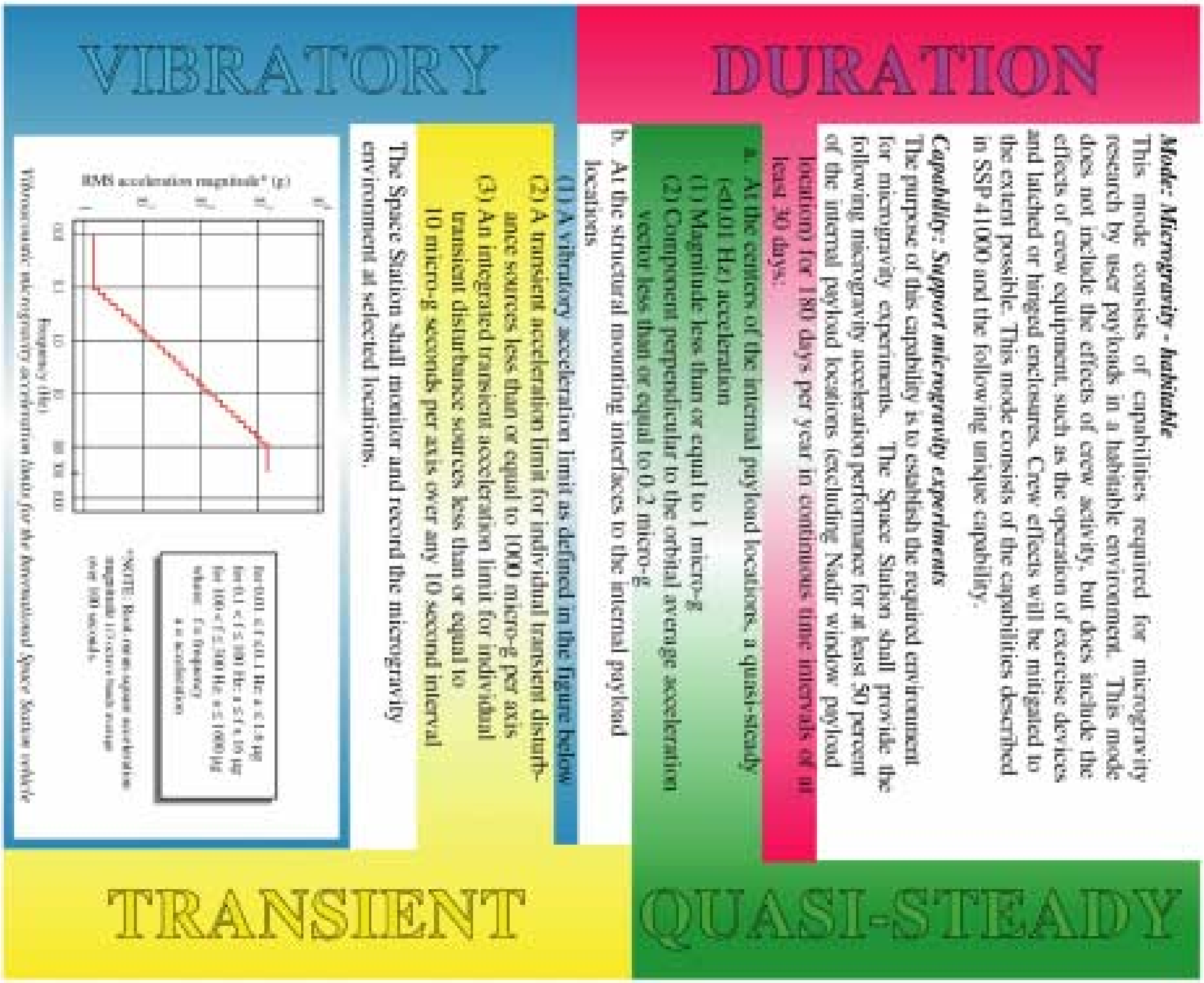
b. At the structural mounting interfaces to the internal payload locations
   (1) A vibratory acceleration limit as defined in the figure below
   (2) A transient acceleration limit for individual transient disturbance sources less than or equal to 1000 micro-g per axis
   (3) An integrated transient acceleration limit for individual transient disturbance sources less than or equal to 10 micro-g seconds per axis over any 10 second interval

The Space Station shall monitor and record the microgravity environment at selected locations.

VIBRATORY

TRANSIENT

Vibratory microgravity acceleration limits for the International Space Station vehicle


ISS Microgravity Environment
THE Requirement for the International Space Station
DURATION
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TRANSIENT
Mode: Microgravity - habitable
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The Space Station shall monitor and record the microgravity environment at selected locations.
RMS acceleration magnitude* (g)
Frequency (Hz)
Vibroacoustic microgravity acceleration limits for the International Space Station vehicle

Fundamental Physics

Quasi-steady
- A large quasi-steady level will destroy sample uniformity of critical fluid

Vibratory
- Primary concern is vibratory heating of sample and destruction of sample uniformity

Transient
- Primary concern is vibratory heating of sample and destruction of sample uniformity

Rationale
- Low temperature physics experiments rely on establishment of highly uniform sample in microgravity

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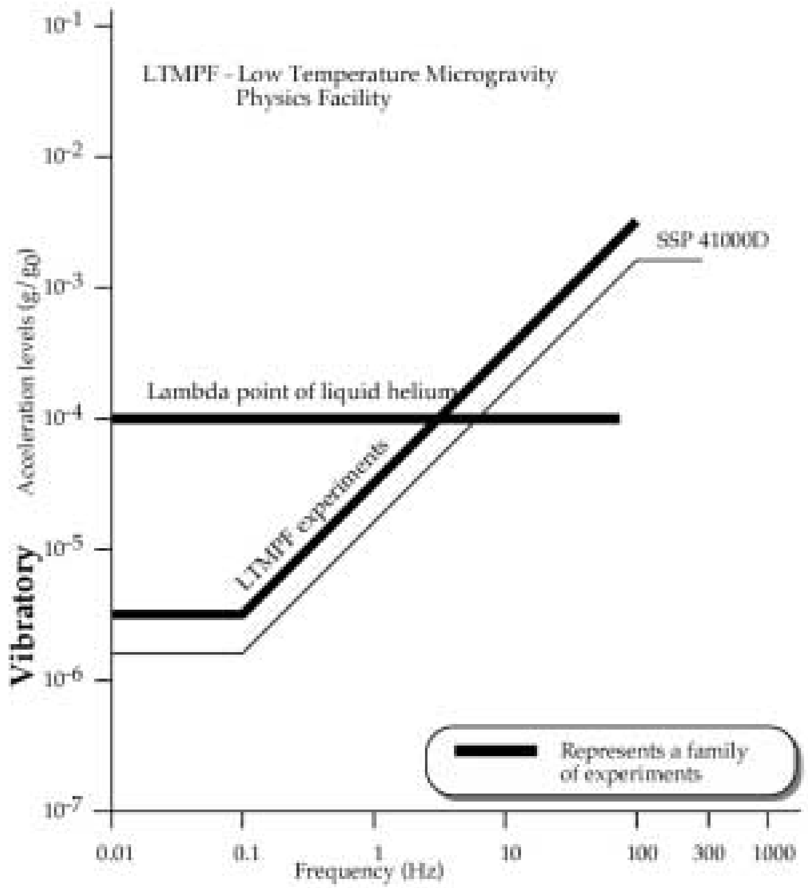
- NOTE: Many of these experiments are expected to be operated on the JEM-EF



Combustion Science

Quasi-steady

- Not a major concern (10^{-4} g_o)

Vibratory

- Typically low acceleration levels at low frequencies (< 1 Hz) disturb experiments
- Most experiments are above the ISS requirement curve but some are below the expected environment
- Low frequency g-jitter has been observed repeatedly to affect the combustion characteristics of a variety of flames, e.g., candle, gas jet, flame balls, etc.

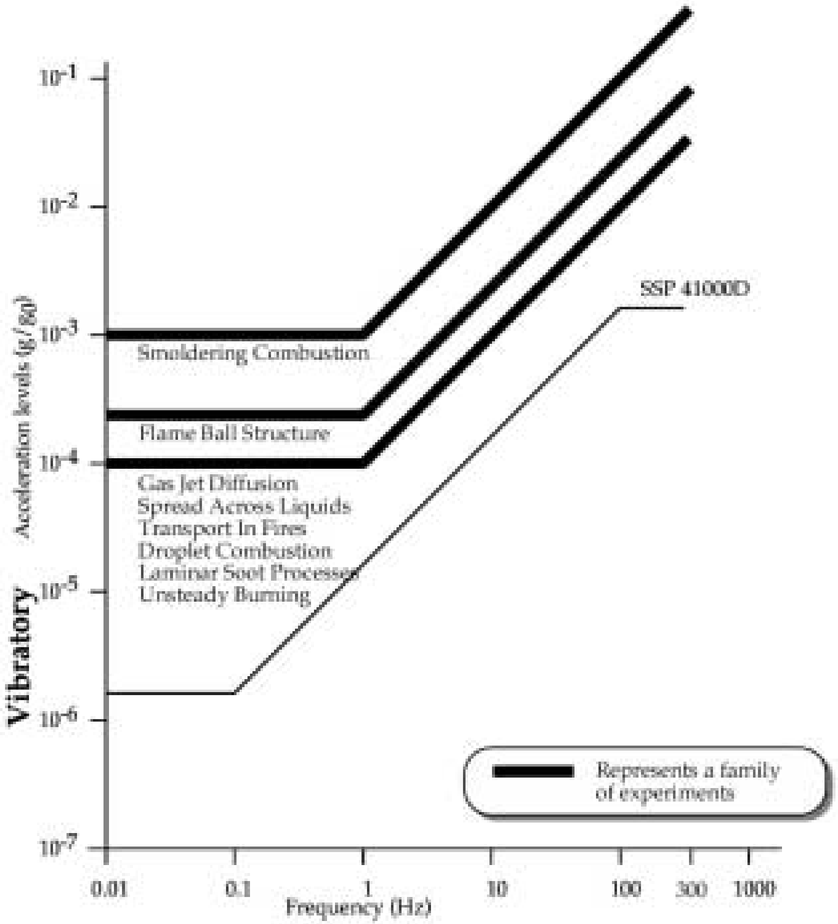
  ref: Dr. H. Ross / NASA LeRC

Transient

- Tolerable for most experiments with time and magnitude restrictions on the disturbance

Rationale

- Microgravity conditions allow:
  - isolation of gravity-driven mechanisms;
  - influence of transport phenomena
  - creation of symmetry and/or boundary & initial conditions
  - new diagnostic probing or testing of similitude
- Microgravity environment has attracted widespread external peer advocacy for combustion science in space



Biotechnology

Quasi-steady

- Not a major concern (10^{-3} to 10^{-4} g_O)

Vibratory

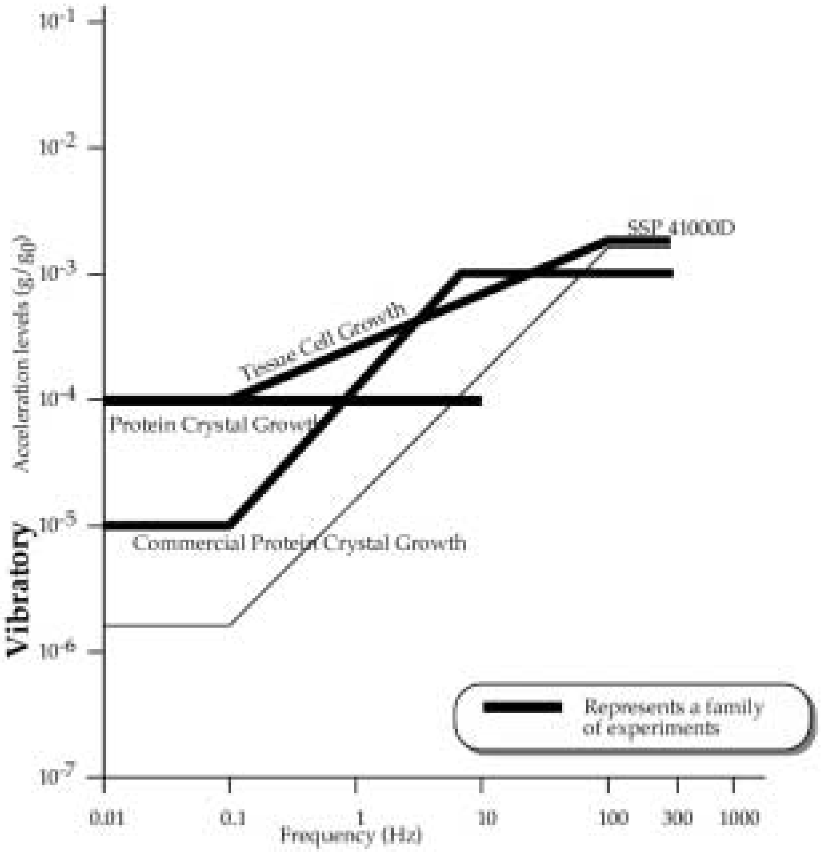
- Impact at higher frequencies of the desired operating level

Transient

- Primary concern is for large scale accelerations, such as Orbital Maneuvering System engines and crew disturbances

Rationale

- Large disturbances cause nucleations to occur in multiple sites destroying single crystal formation



Fluid Physics

Quasi-steady

- Quasi-steady accelerations disturb most fluid experiments $(2X10^{-6}\,g_o)$

Vibratory

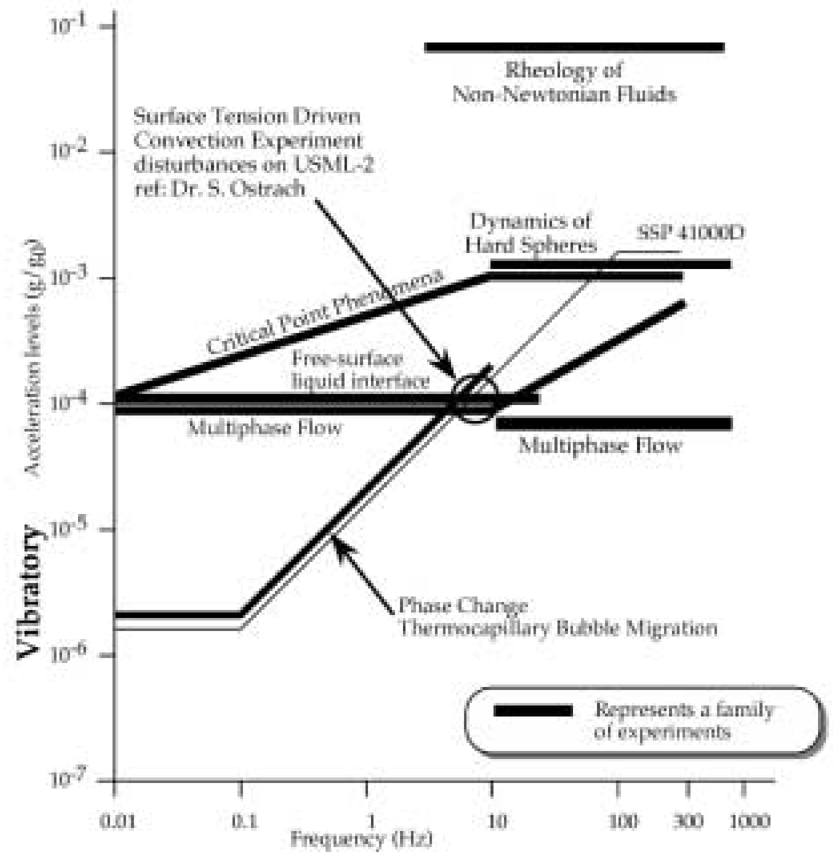
- Mid-range frequencies of expected environment will disturb fluid free surface experiments
- Some experiments require environment at lower levels than the ISS requirements curve
  - e.g. Thin Film Fluid Flows at Menisci
- Surface Tension Driven Convection Experiment experienced surface distortion due to g-jitter frequently throughout the USML-2 mission
  - ref: Dr. S. Ostrach/CWRU

Transient

- Transients disturb fluid experiments with lower viscosity fluids

Rationale

- Accelerations above a threshold cause interface instability, density settling, and density-driven convection & mixing



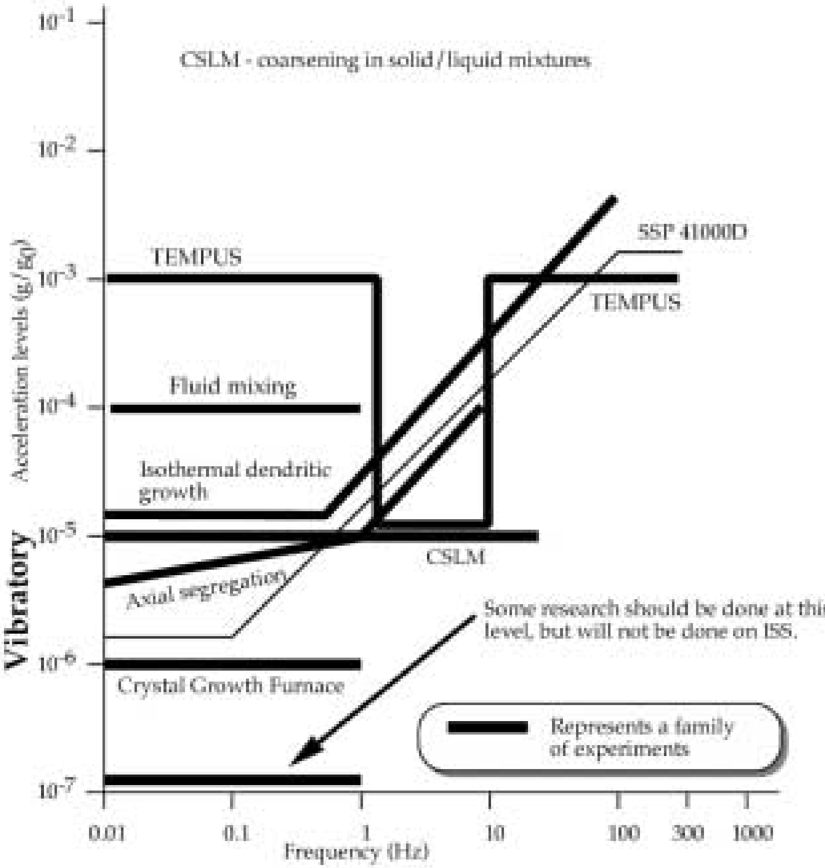
Materials Science

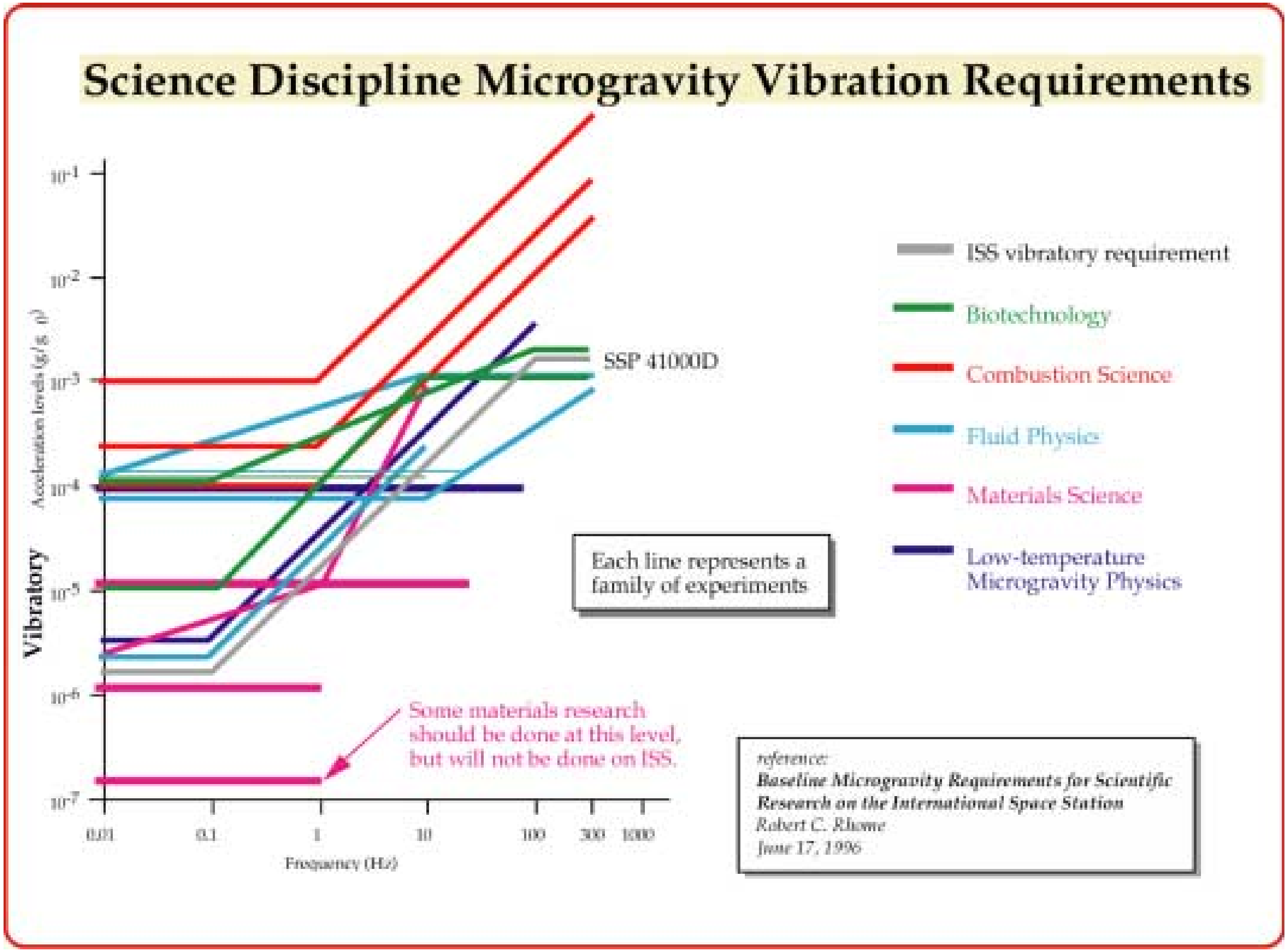
Quasi-steady
- Some samples and processes require very low quasi-steady acceleration levels (a < 0.1 micro-g)
  e.g., Stoke's settling, Bridgman growth, Float zone
- Residual acceleration direction and stability are important factors for crystallization processes
- A Crystal Growth Furnace sample was withdrawn from USML-2 due to a change in Orbiter attitude just before launch
  ref: Dr. S. Lehoczky/NASA MSFC

Vibratory
- Disturbances in various frequency ranges disturb experiments involving molten samples, suspended samples, etc.

Transient
- Some processes are very susceptible to transients such as thruster firings
- MEPHISTO (USMP-1 & USMP-3) experienced effects which lasted minutes from single thruster firings (0.01 g for 10 - 25 seconds)

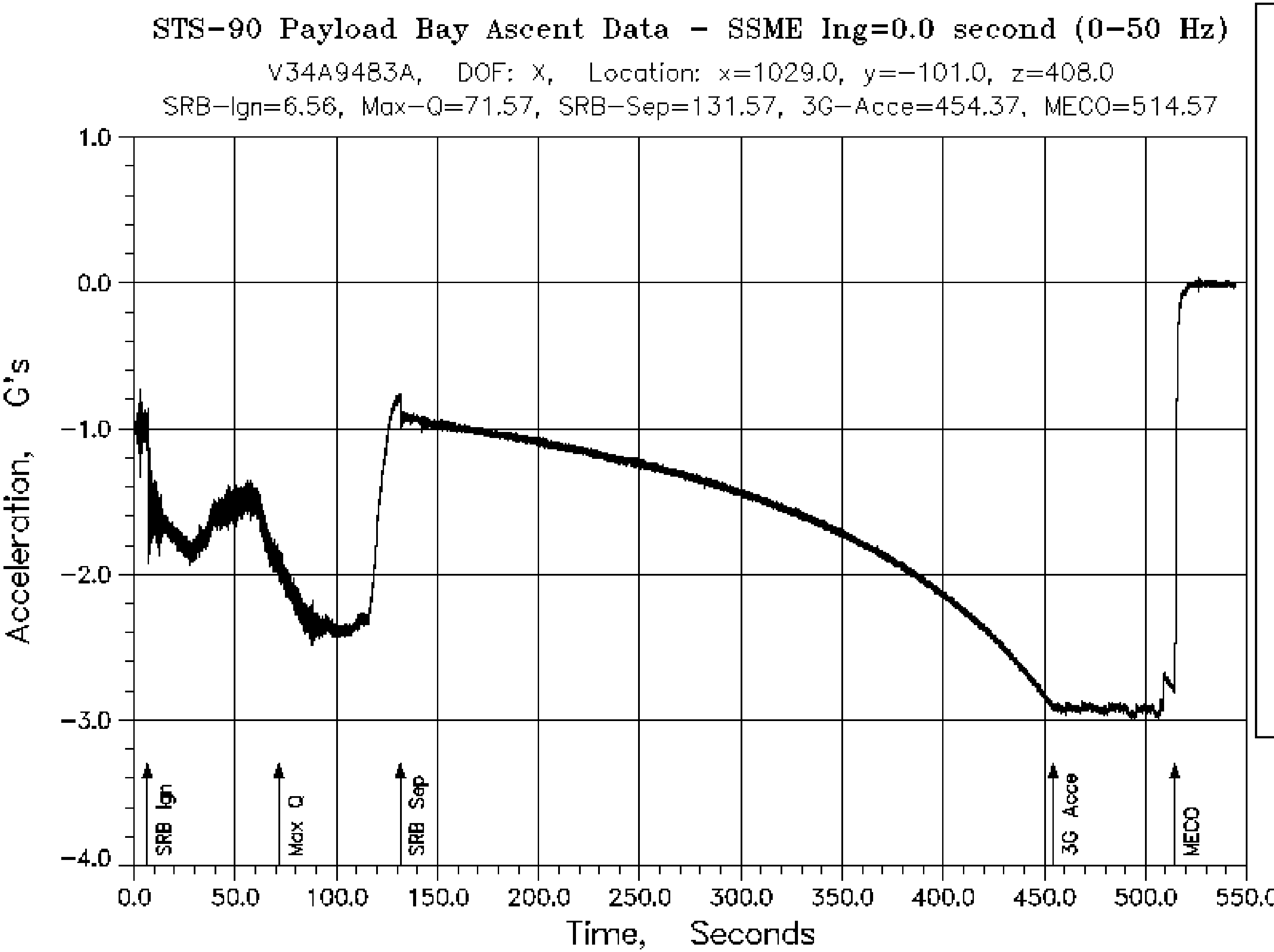
Rationale
- Accelerations above a threshold cause thermo-solutal convection and interface instability




Science Discipline Microgravity Vibration Requirements
Vibratory
Acceleration levels (g/g₀)
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
0.01
0.1
1
10
100
300
1000
Frequency (Hz)
SSP 41000D
ISS vibratory requirement
Biotechnology
Combustion Science
Fluid Physics
Materials Science
Low-temperature Microgravity Physics
Each line represents a family of experiments
Some materials research should be done at this level, but will not be done on ISS.
reference:
Baseline Microgravity Requirements for Scientific Research on the International Space Station
Robert C. Rhome
June 17, 1996

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

STS ASCENT PROFILE



STS = Columbia

SRB_{ign} = solid rocket boosters ignition

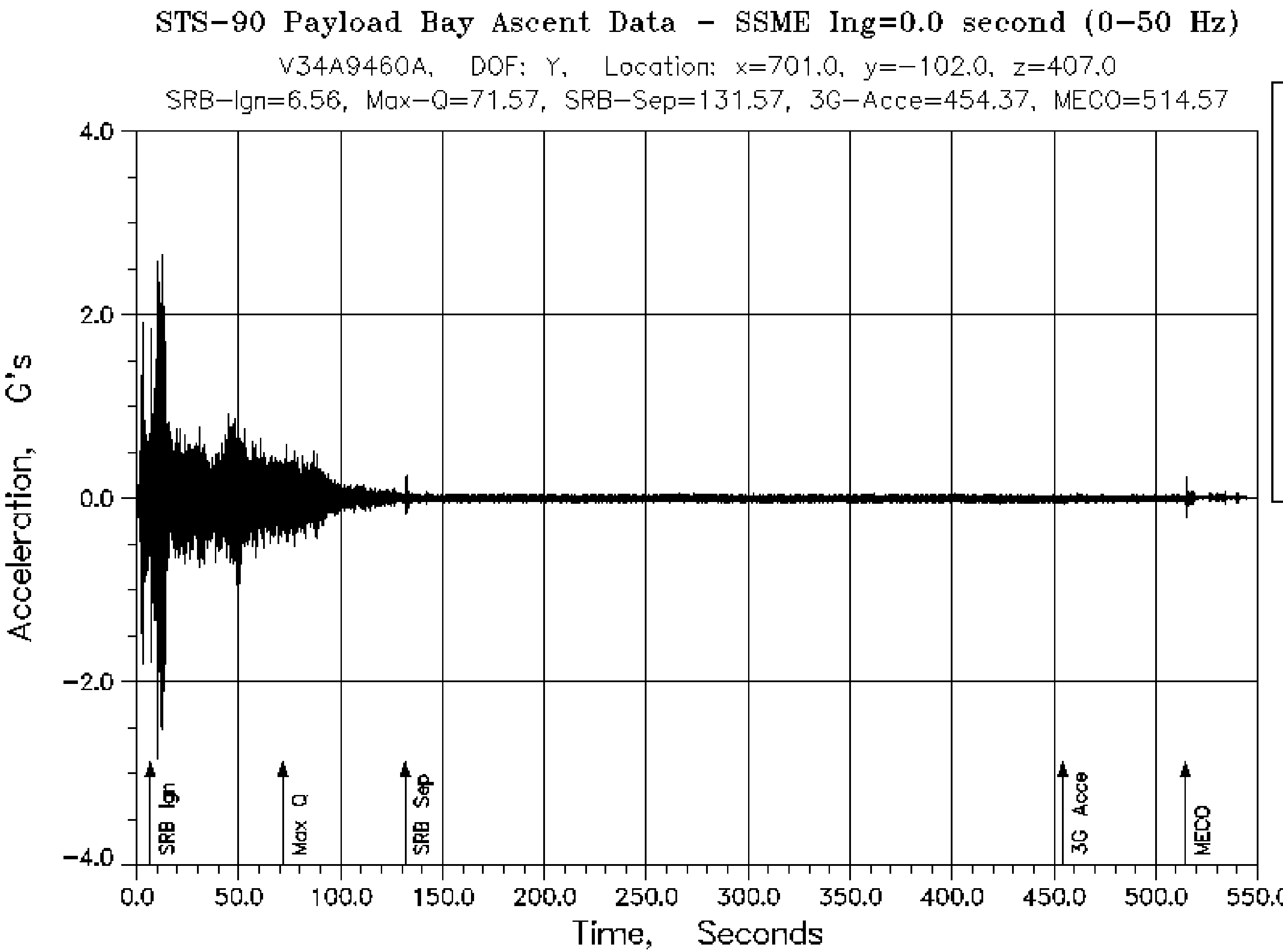
Max Q = time of maximum dynamic pressure

SRB_{Sep} = solid rocket boosters separation

3G Acce = time at which 3g acceleration is reached

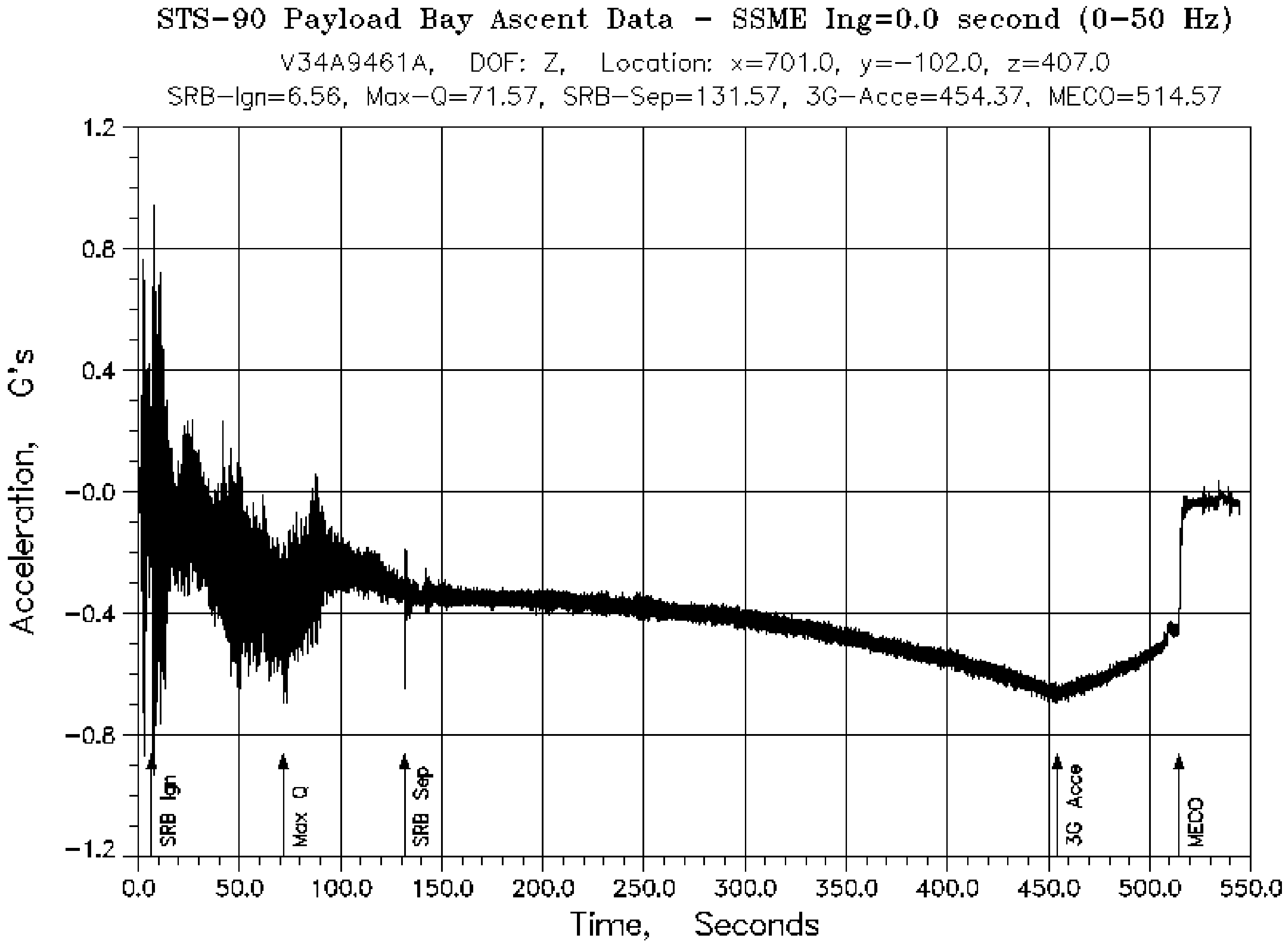
MECO = main engine cutoff

STS ASCENT PROFILE

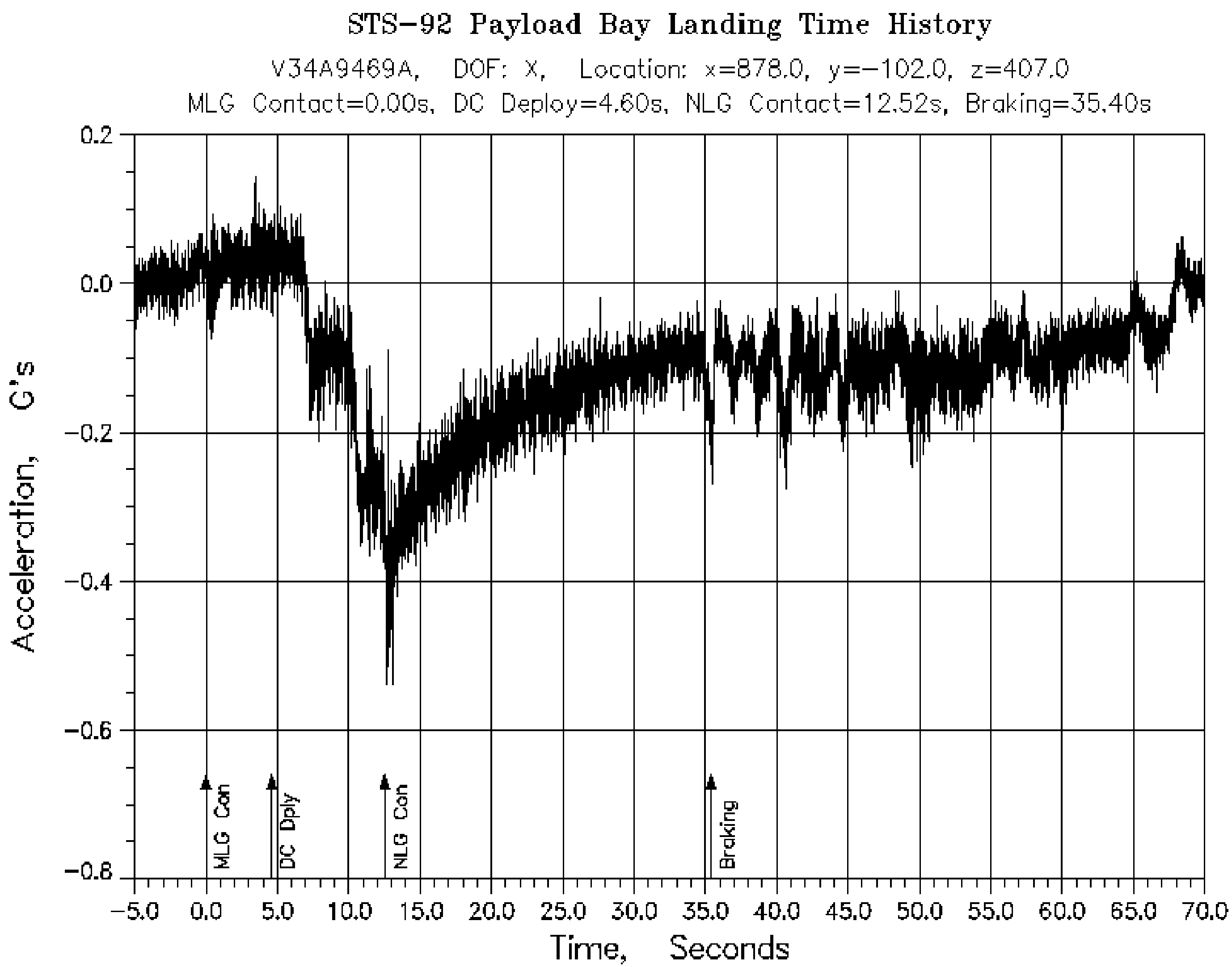


- **Sensor dynamic responses:**
  -10 to + 10 G range
- **Frequency response:**
  0 – 50 Hz
- **Sampling rate:**
  500 samples per sec.
- **Coordinate system:**
  Orbiter structural system

STS ASCENT PROFILE



STS LANDING PROFILE



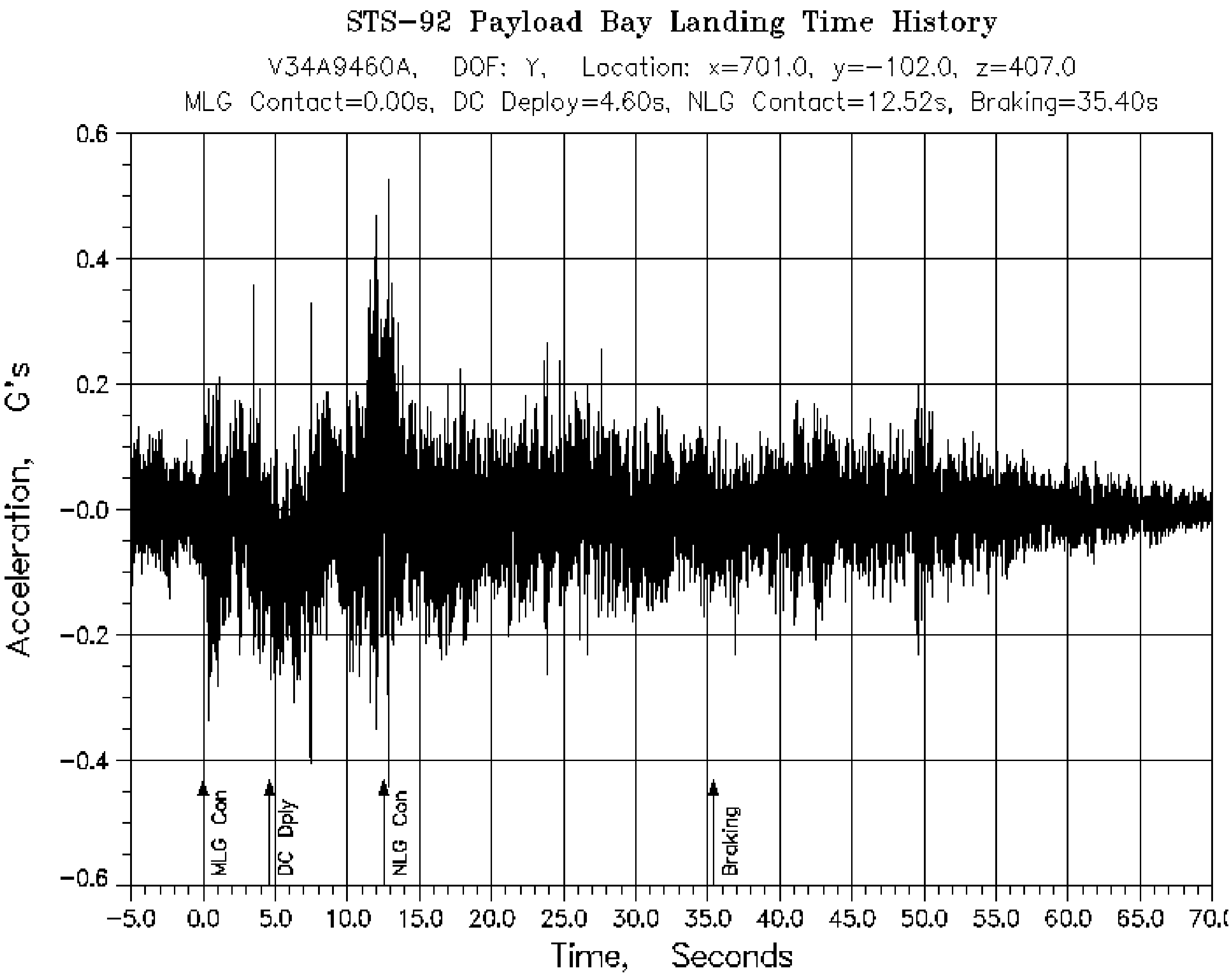
STS = Discovery

MLG_{cont}= main landing gear ground contact

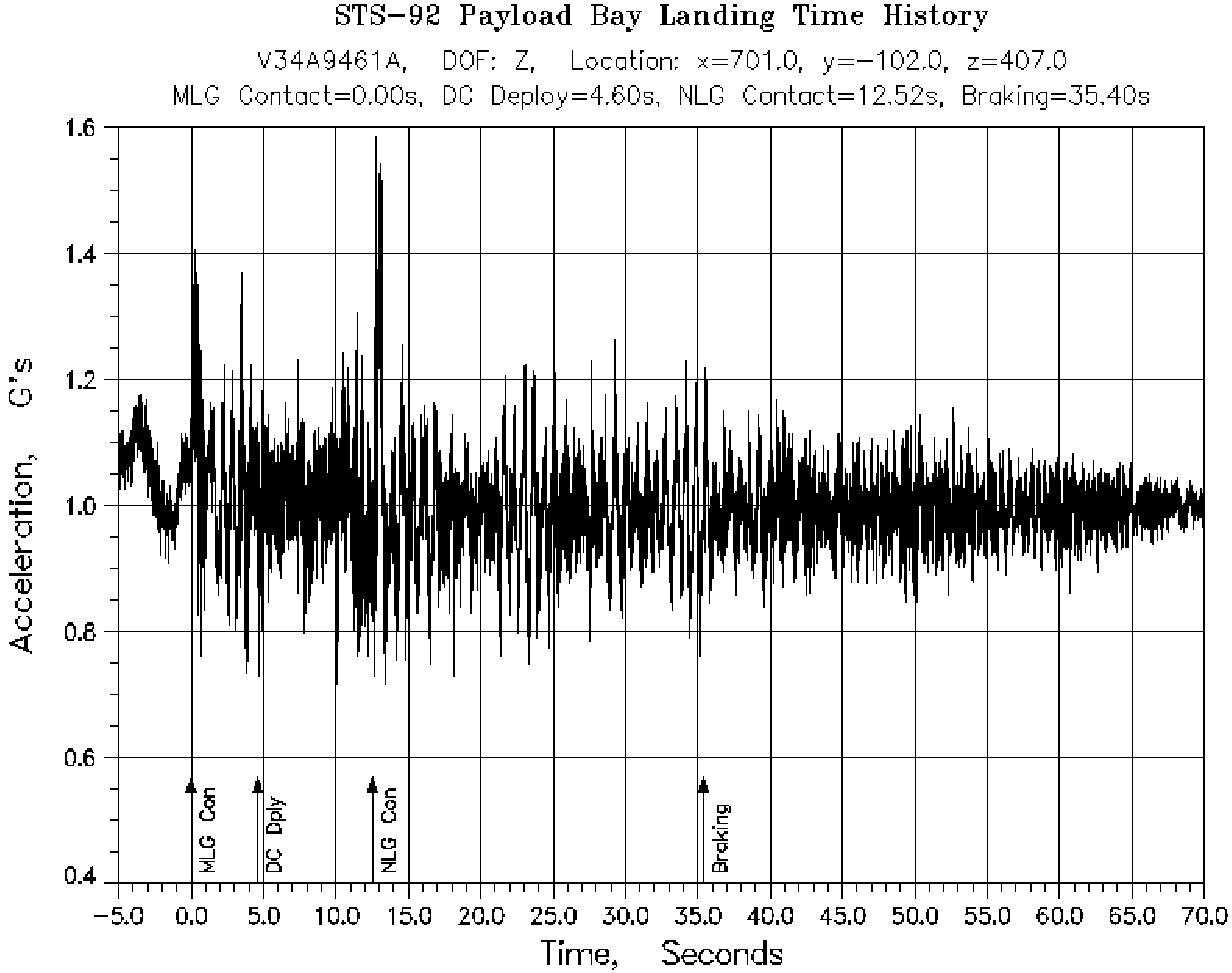
DC_{deploy} = drag Chute deployment

NLG_{CONT} = noise landing gear ground contact

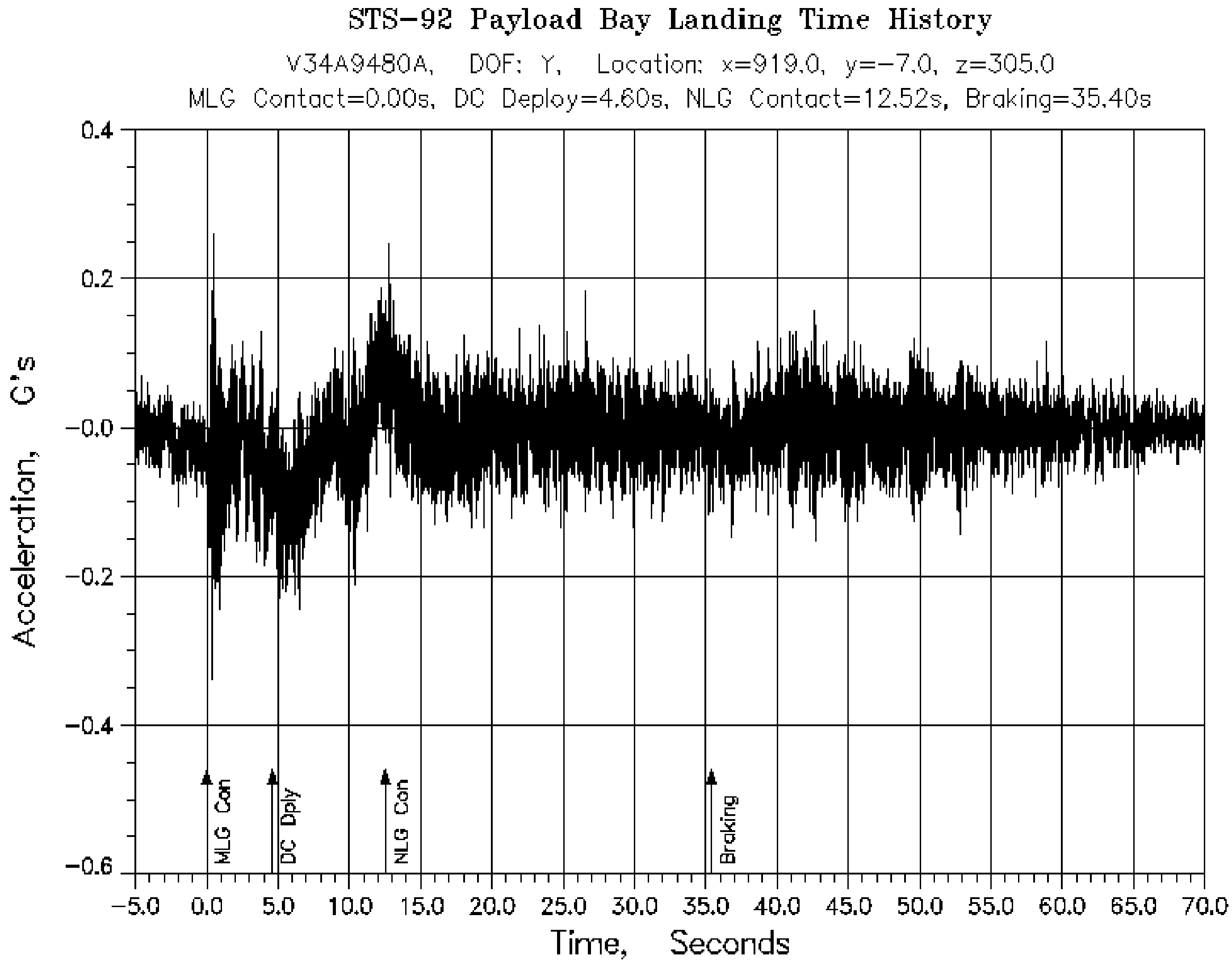
STS LANDING PROFILE



STS LANDING PROFILE



STS LANDING PROFILE



OVERALL SUMMARY

- The reduced gravity environment is not “zero-g” or even “zero-acceleration”. It is dynamic.
- The environment may (and will) 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 reduced gravity 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 environment with (for example) moving parts from their experiments or / and required crew actions.

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