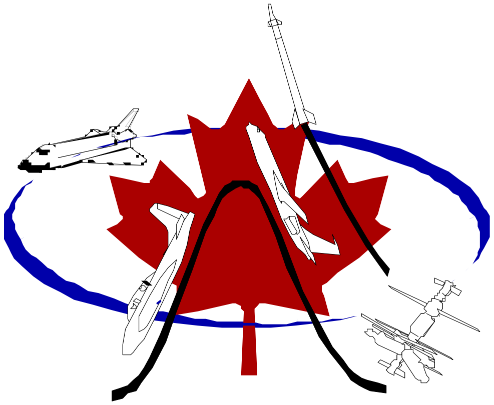
# The Effect of G-Jitter on Fluid Based Experiments

**Bjarni Tryggvason**
**Canadian Space Agency**



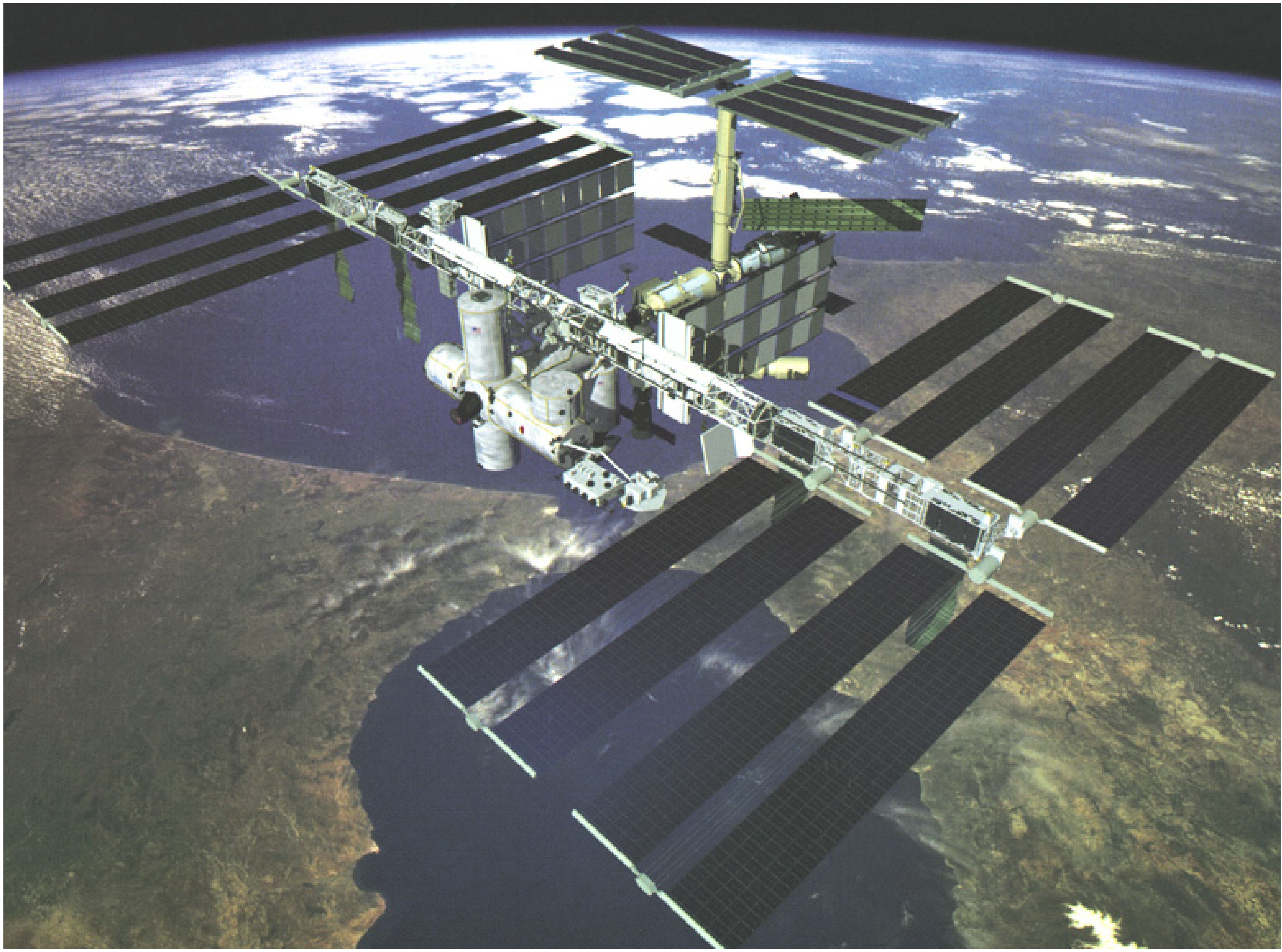
*MEIT 2004*

*March 2-4, 2004*

*Cleveland, Ohio*

# International Space Station (ISS)

## A laboratory for performing research in a free fall environment



**PARTNERS**

United States
Russia
Canada
Japan
11 European Nations

# Primary Role of the ISS

- Support experiments in
  - Material Science
  - Crystal growth
  - Protein crystal growth
  - Basic fluid physics
  - Life and biological sciences
- Near free fall conditions reduce gravity driven convection by several orders of magnitude
  - potential to increase understanding of phenomena observed in ground based experiments

# Confusion About Zero-G:

## How far do we need to go?

# Misleading Terminology

No gravity in space
Zero-g
Micro-g

# Newton’s Law of Gravitation

We are all attracted to one another

The attraction decreased with distance

Mir, STS, ISS orbit only 300 km above the Earth’s surface, which is 6374 km from c.m.

# Newton's Law:
# No Micro-G Near Earth!

$$a_g := \frac{G \cdot M}{r^2}$$

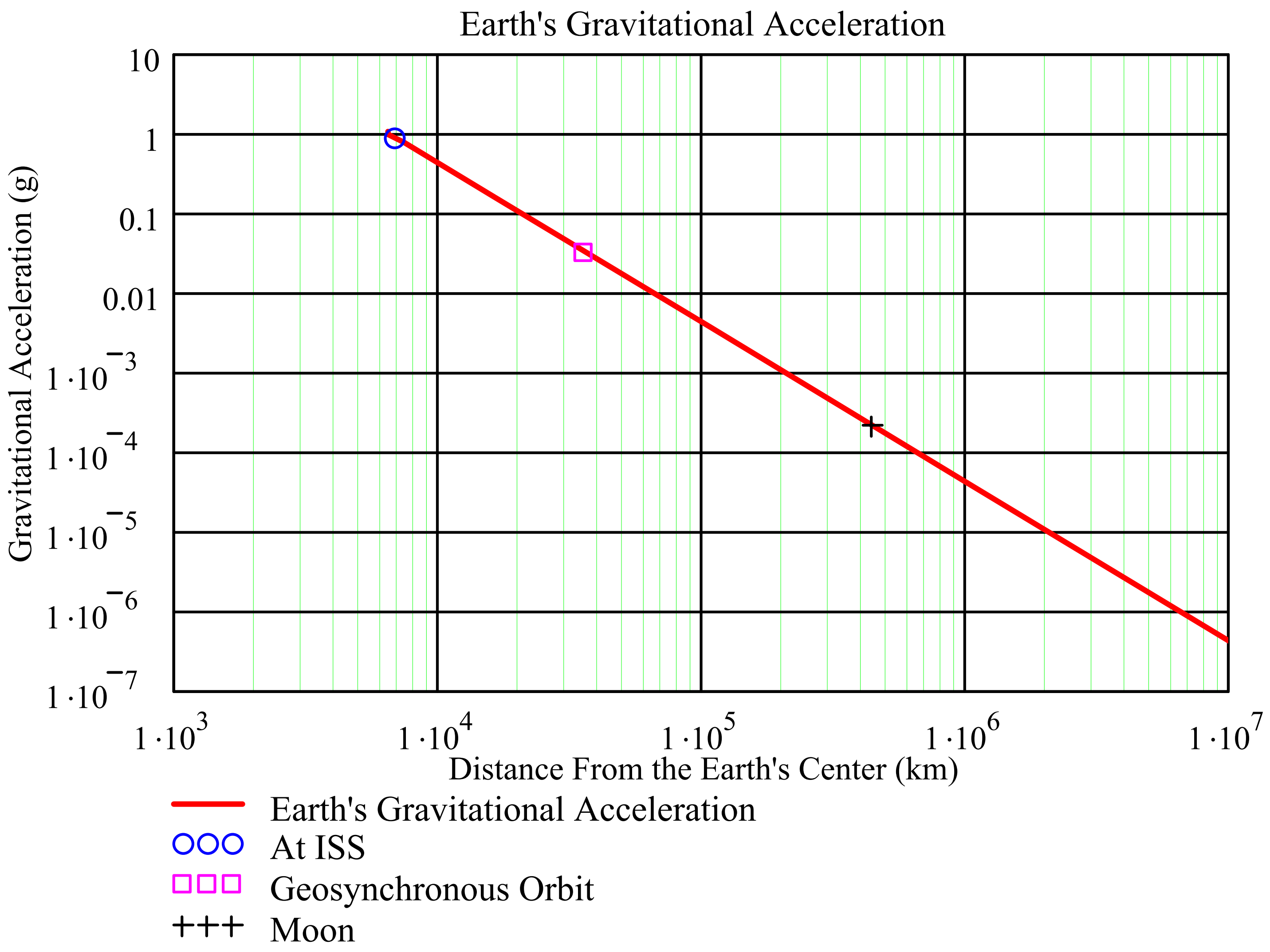
Re:6374 km

Me = $5.9736 * 10^{24}$ kg

G = $6.67259 * 10^{-11}$ $m^3/kg/s^2$

| | |
|---|---|
| At the Earth's surface | $g_e = 9.8108\ m/s^2$ |
| At ISS altitude | $g_e = 8.6864\ m/s^2$ |

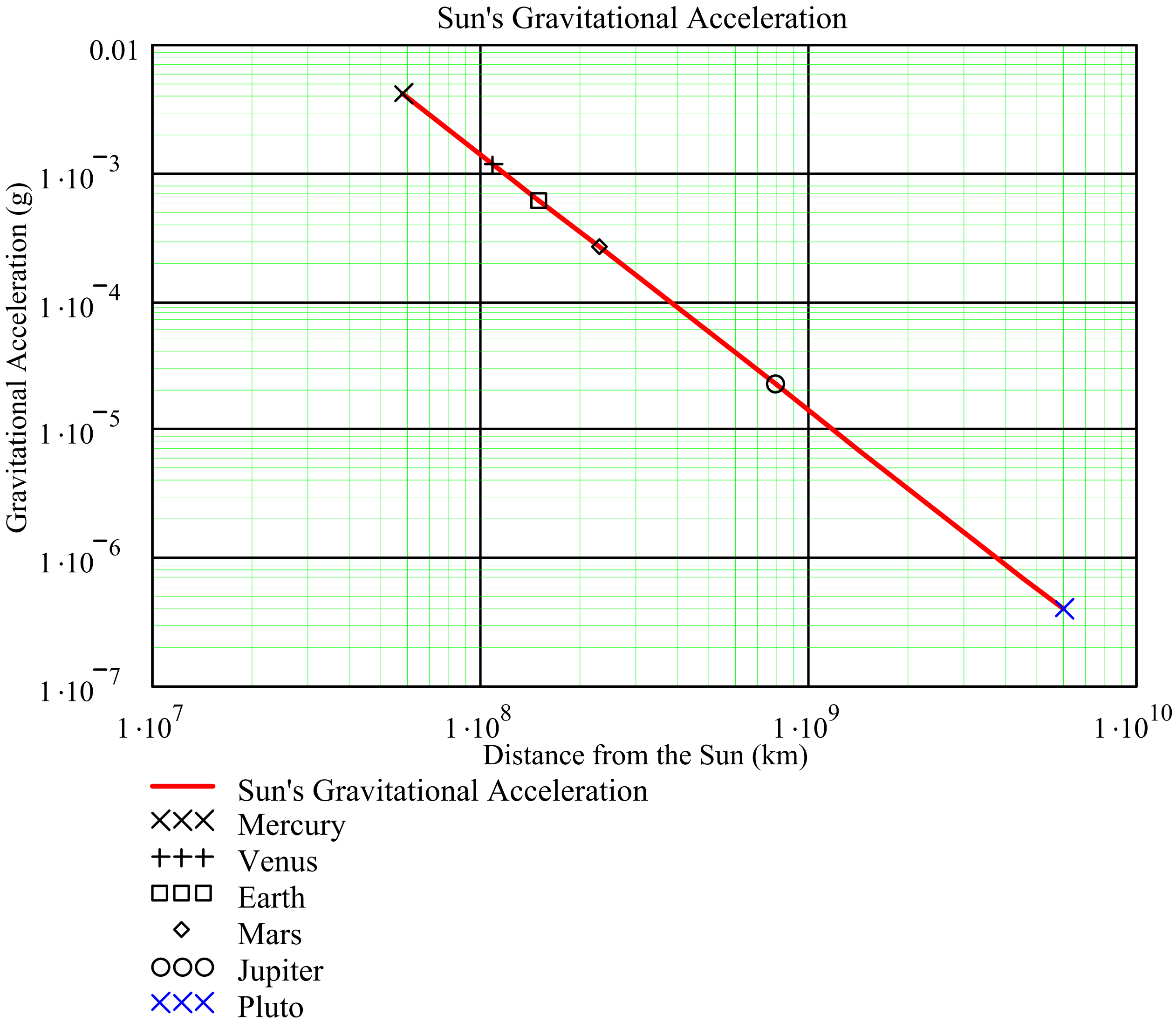
# Gravitational Acceleration Due to the Earth



# Of What Concern is a Little Micro-g?

Earth is kept in orbit by 600 micro-g

Pluto is kept in orbit by 0.38 micro-g



# The Free Fall State

Spacecraft are in *near ideal* state of *free fall* as they orbit Earth, i.e., accelerating towards the Earth at nearly *1-g*.

Objects within a spacecraft are *in nearly the same state* of *free fall.*

Hence *relative accelerations* of objects are *very small: micro-g range.*

Hence *internal stresses* are *very small* compared to what they would be on the ground.

…..**but stresses are not zero!**

# Disturbances from the Ideal Free Fall

## Quasi-Static (<< 0.01 Hertz) Disturbances

### Atmospheric Drag

Order of 1 micro-g, with variations of the same order

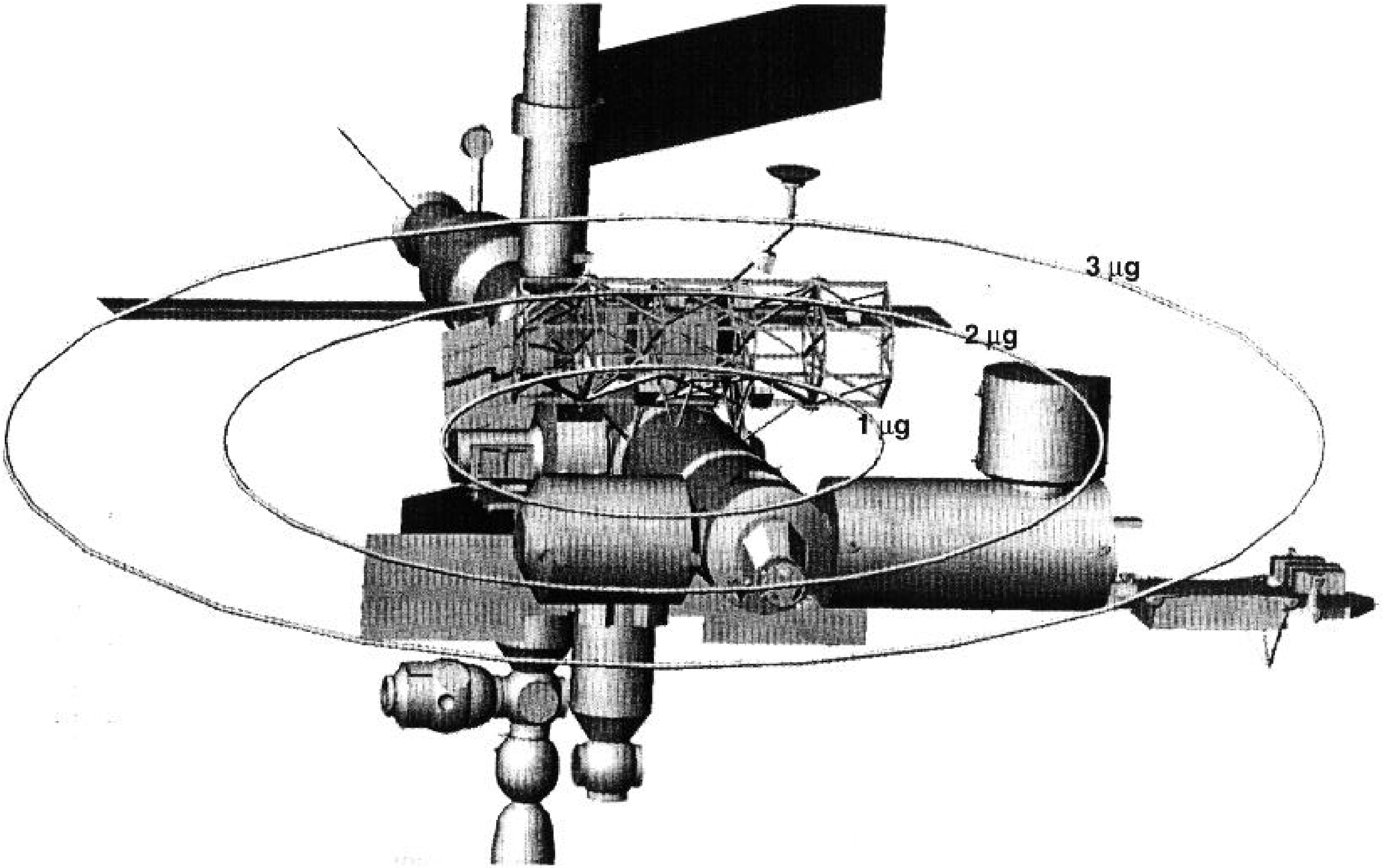
### Gravity Gradients

0.26micro-g/m from spacecraft c.m. vertically
0.13micro-g/m from spacecraft c.m. horizontally

### Spacecraft Rotations

ISS rotates once per orbit (92minutes)
Centripetal accelerations are 0.13micro-g/m from axis of rotation

# ISS Torque Equilibrium Attitude



# Of What Concern is a Little Micro-g?

## Displacement time scales:

At the Earth's surface an object falls 10cm in 0.143 sec.

In the micro-g environment inside the ISS it takes 142.8 sec.

On object released inside the ISS would take 638.7 sec.  to strike a wall.

# Disturbances

- Quasi-Static (<< 0.01 Hertz) Disturbances
  - External Disturbances
    - Gravity Gradient Effects
    - Atmospheric Drag
    - Spacecraft Rotations
- Vibratory (> 0.01 Hz)
  - Spacecraft Internal Disturbances
    - Attitude Controllers
    - Power Generation Systems
    - Thermal and Environmental Control Systems
    - Maintenance Systems
    - Crew Disturbances
    - Experiment Disturbances

# The Micro-g Environment

- Space Shuttle and Space Station provide a unique free-fall environment for science experiments
  - Fluid physics
  - Material science
- However, the environment is not the ideal disturbance free environment that the science community expected
- The quasi-static (<0.01Hz) disturbances to the free fall state are of the order of micro-g ($10^{-6}$g)
- Onboard disturbances lead to vibratory disturbances of milli-g ($10^{-3}$g), three orders magnitude higher than the often-quoted micro-g ($10^{-6}$g)

# Experiments Conducted on Mir and the Space Shuttle

- ISS Phase-I on Mir:
  - Measurement of diffusion in liquid metal systems
  - Observations of nucleation in glasses
  - Particle pushing
- STS-85:
  - Brownian motion (basis for diffusion)
  - Motion of encapsulated bubbles
  - Interface dynamics in a liquid-liquid system
  - Interface dynamics in liquid-vapour systems

# QUELD-II Mounted on MIM-1 as in Mir Installation

Queen’s University Experiment in Liquid Diffusion

◆Operational on Mir space station from May 1996 to January 1998

◆Operating temperature up to 900 °C

◆ Two independent furnaces

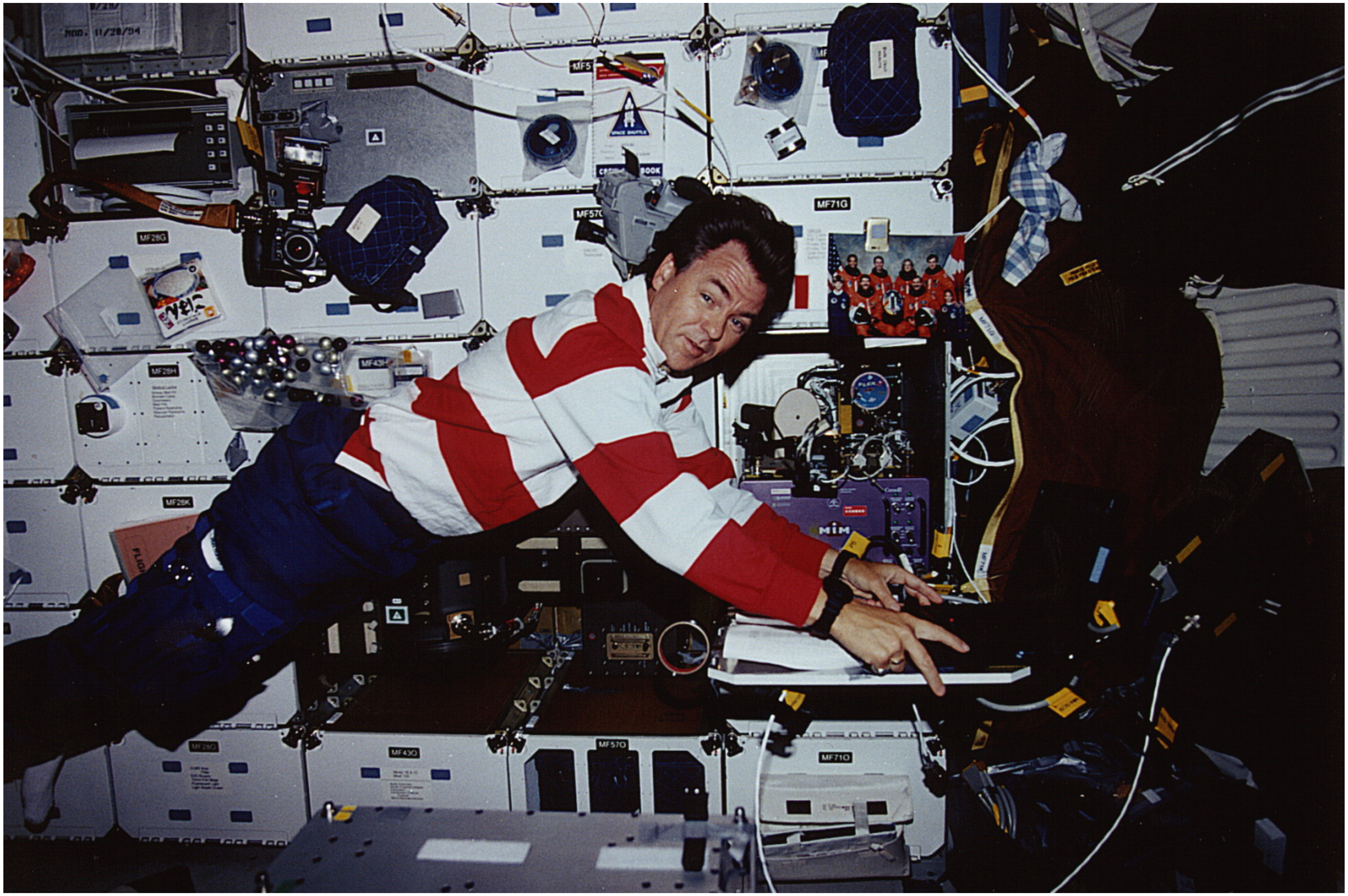
◆ Automatic sample processing

# MIM-1 on the Mir Space Station

# The Microgravity Vibration Isolation Mount

- Isolates experiments from spacecraft vibrations
- 6 DOF magnetic levitation system
- Optical tracking system and accelerometers for monitoring and control of the flotor
- Provides data acquisition services and control functions to an experiment mounted on the flotor
- Capable of “shaking” an experiment with acceleration levels from several micro-g to 25 milli-g over range 0.01 Hz to 50 Hz.

# MIM-2 on Shuttle Mission STS-85



# Determining Intrinsic Diffusion Coefficient

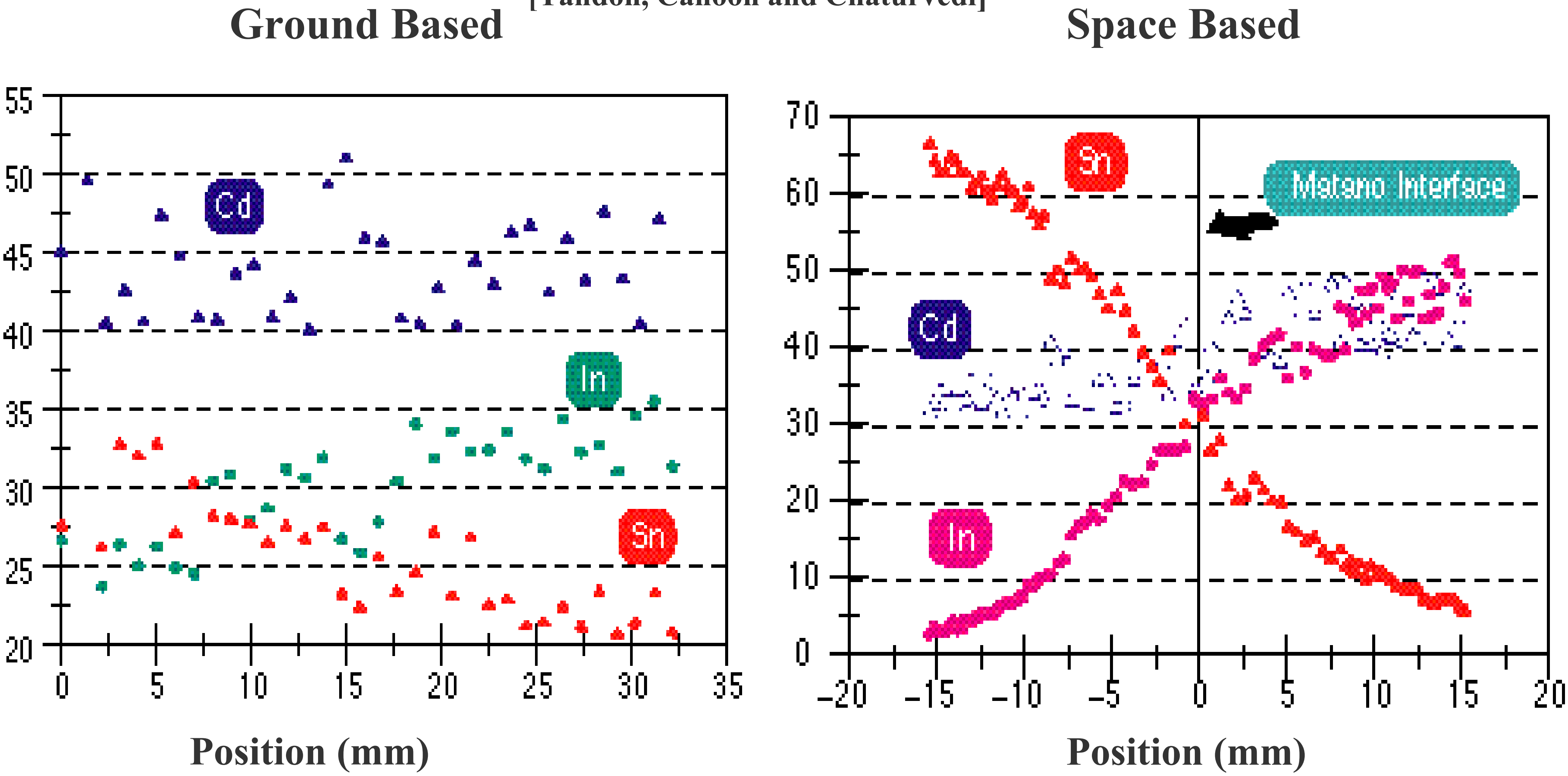
- Free fall environment eliminates buoyancy effects.
- Effect of the container is controlled by varying the sample diameter.
- Sample design controls surface tension induced (Marangoni) convection.
- An isothermal furnace reduces thermal gradient induced motion.
- G-jitter adds to mixing in the fluid

# Comparison of Terrestrial and On-Orbit Data

- CdIn/CdSn diffusion couple specimens processed terrestrially and in on the Mir space station free fall environment at 690 C for 90 minutes

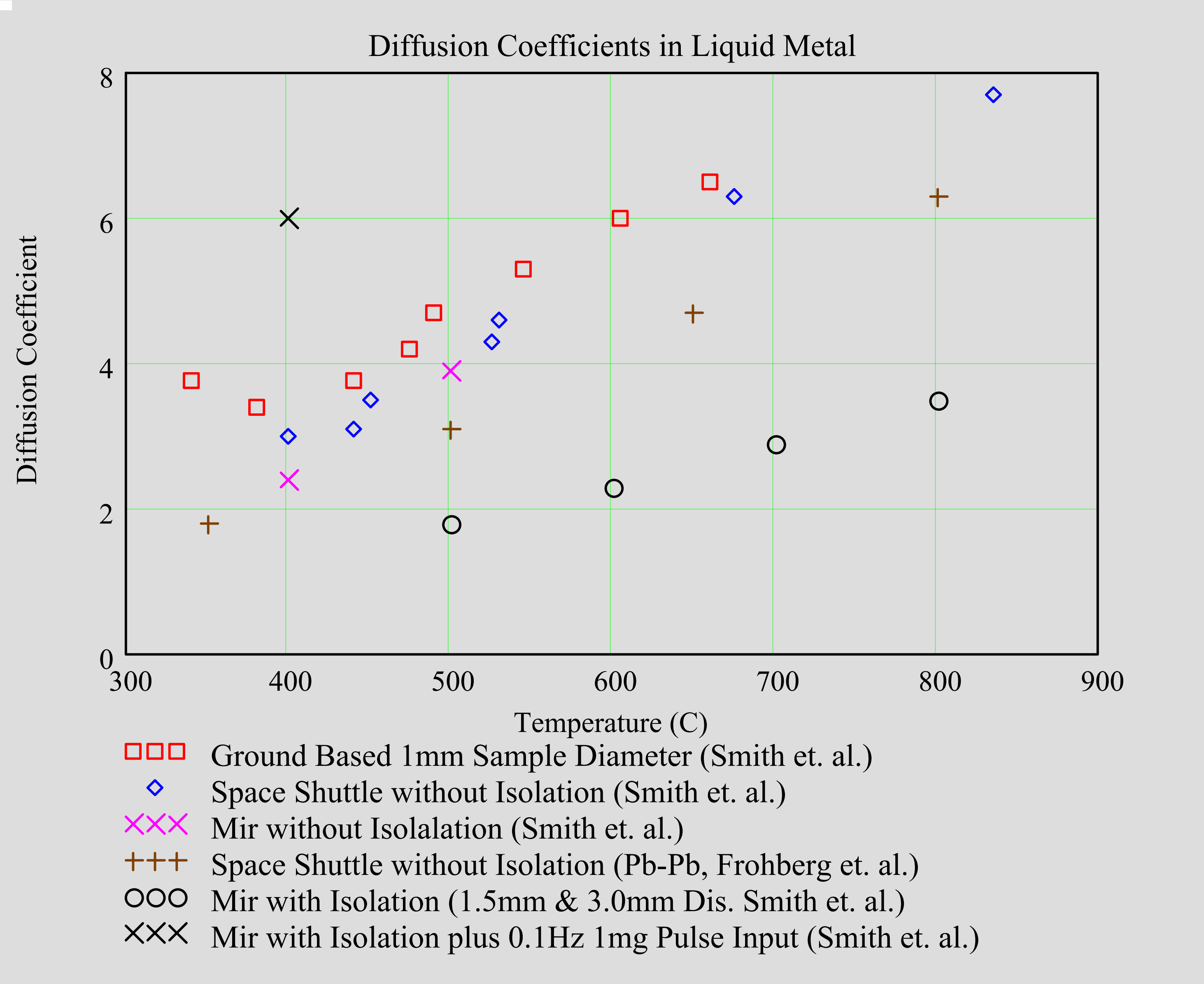
# The Effect of G-Jitter on Fluid Based Experiments

Comparison of Terrestrial and Space Based Experiments
[Tandon, Cahoon and Chaturvedi]



**CdIn/CdSn diffusion couple for specimen at 690 C for 90 minutes**

## Diffusion in Liquid Metals
Reginald Smith, Queens University



# Brownian Motion

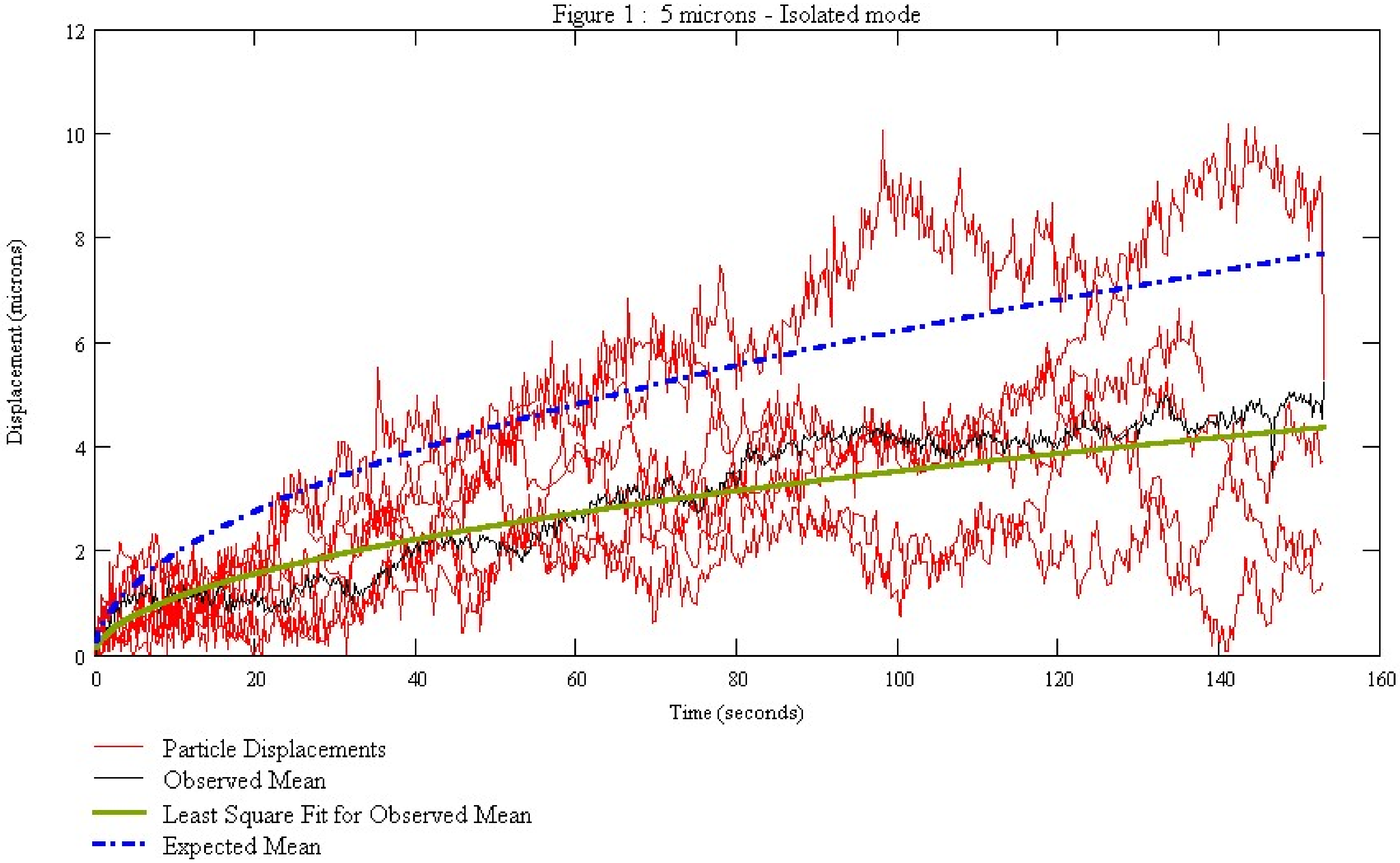
Bjarni V Tryggvason
Canadian Space Agency

Effect of g-jitter on the random drift of micron sized particles in a fluid, under condition of:

- Non-isolating mode, i.e., g-jitter present
- Isolated mode
- Driven mode
  - Sinusoidal
  - Random broad band

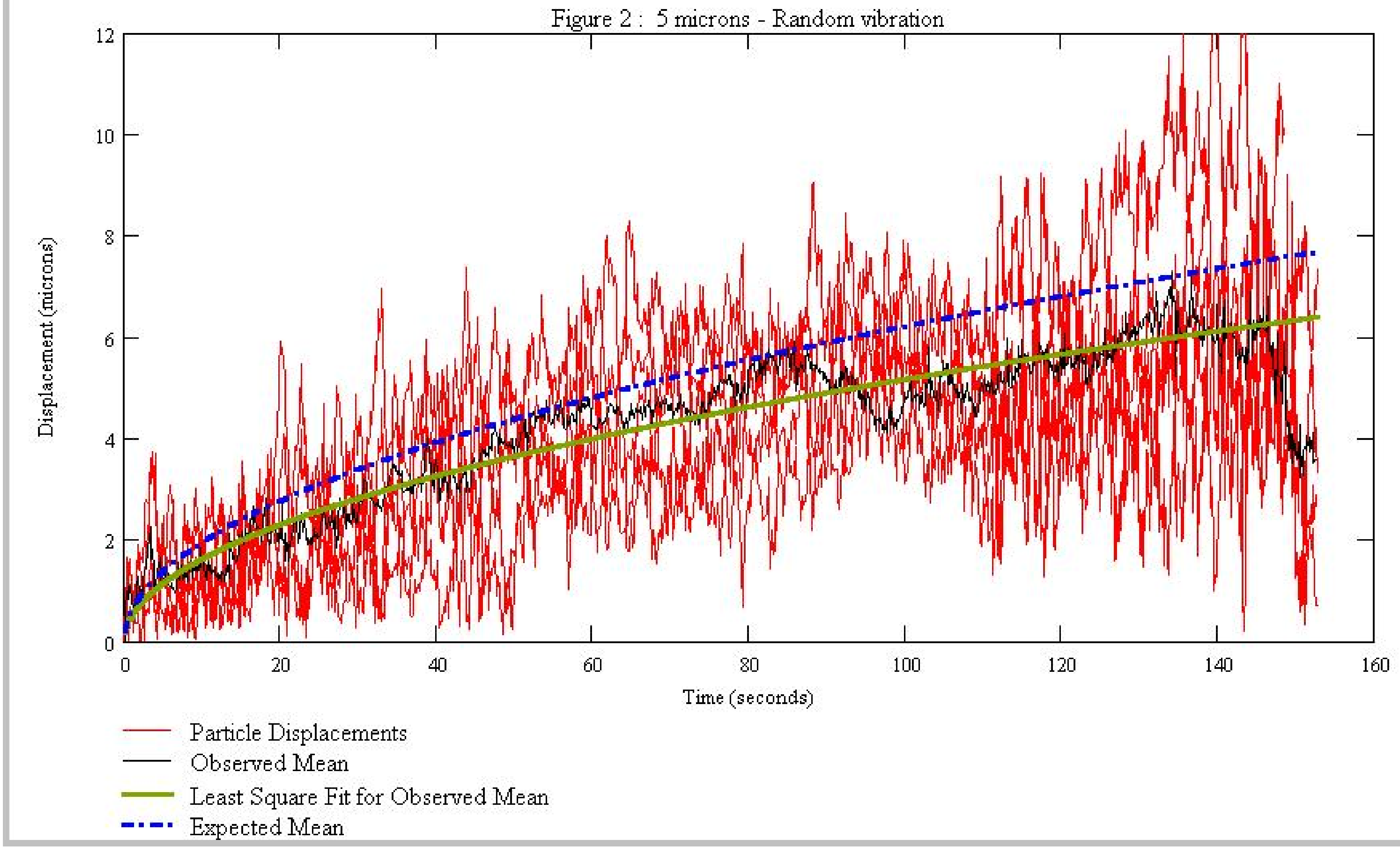
# Brownian Motion:

## 5 Micron Diameter: Isolated



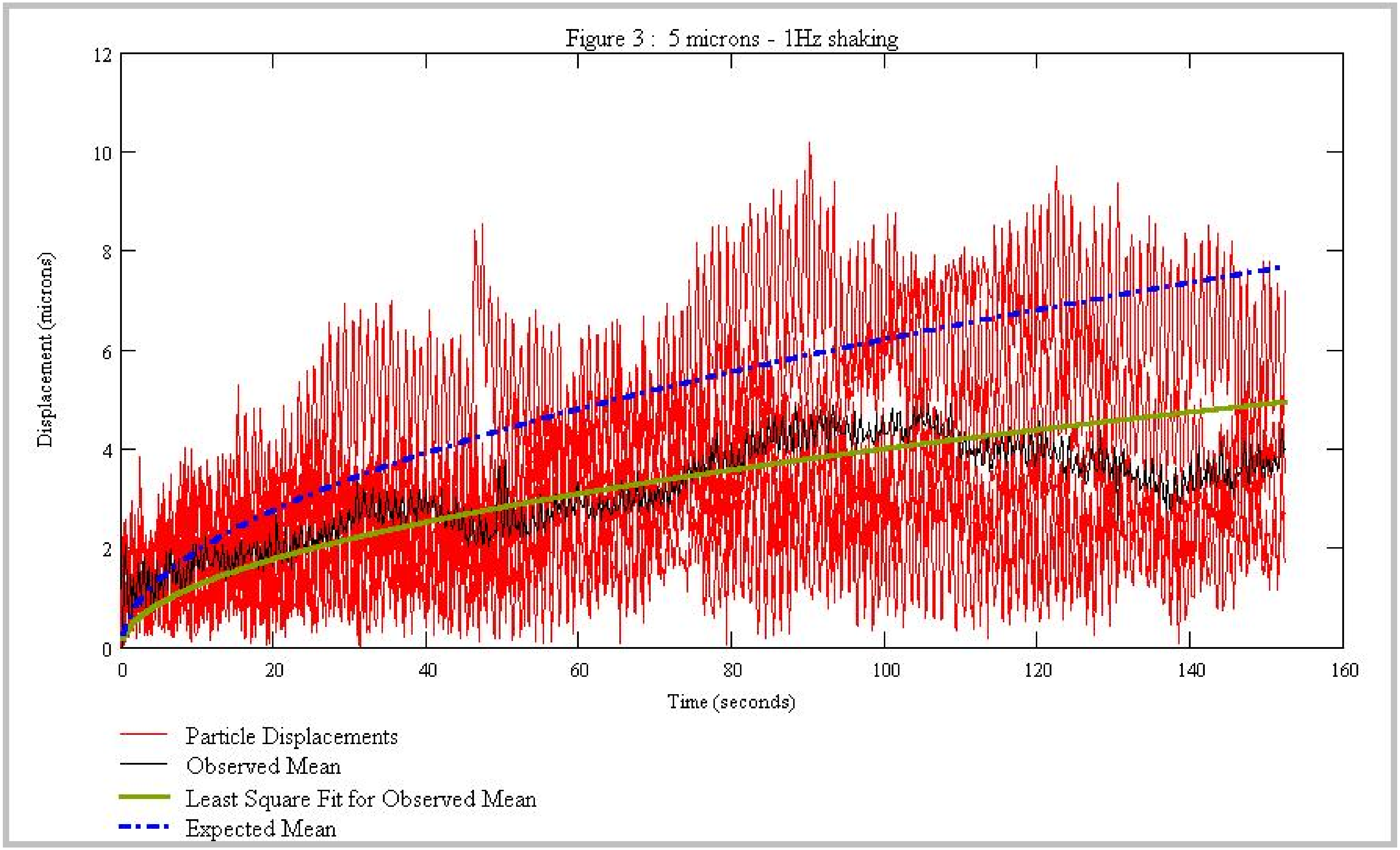
# Brownian Motion:

## 5 Micron Diameter: Random Vibration



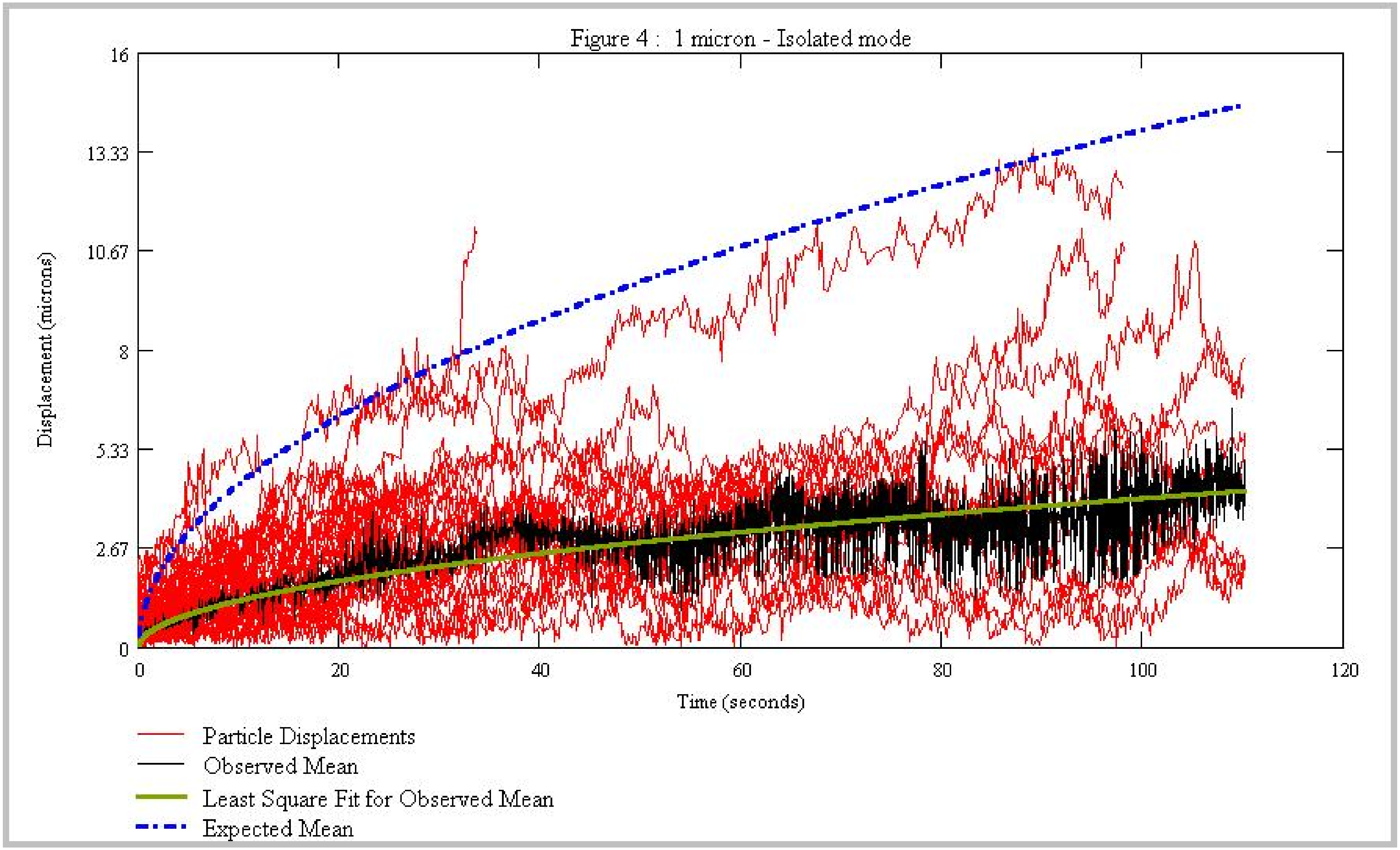
# Brownian Motion:

## 5 Micron Diameter: 1Hz Oscillation



# Brownian Motion:

## 1 Micron Diameter: Isolated



# Fluid Behavior In Absence Of Gravity: Confined Fluids and Phase Change

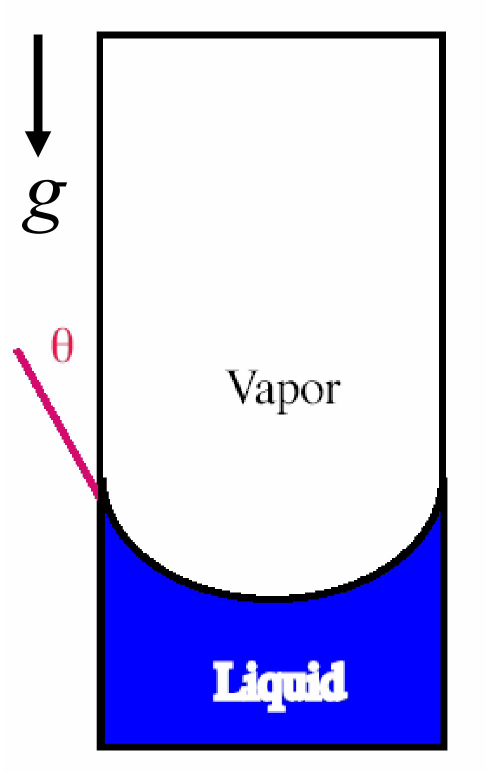
Charles A. Ward

Thermodynamics and Kinetics Laboratory,

University of Toronto

# Configuration of a Confined Fluid at g $\longrightarrow 0$

## Prediction from thermodynamics



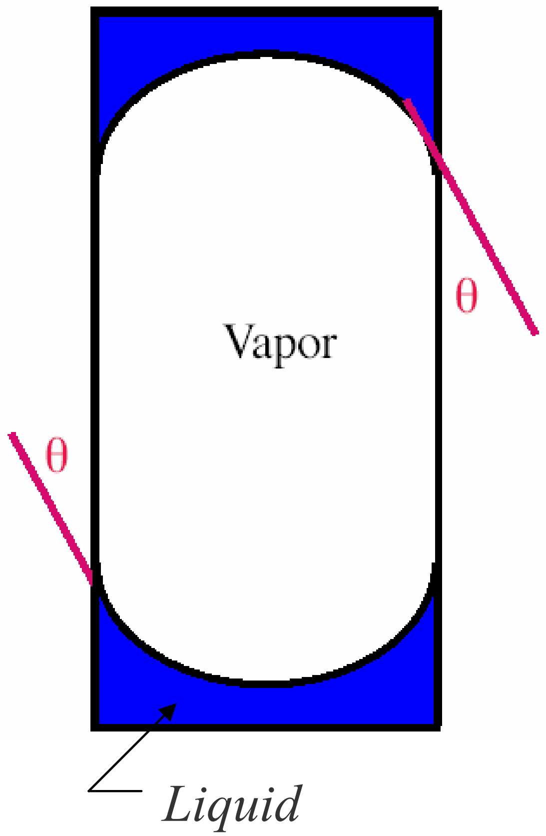
$\theta$: Contact Angle

IF

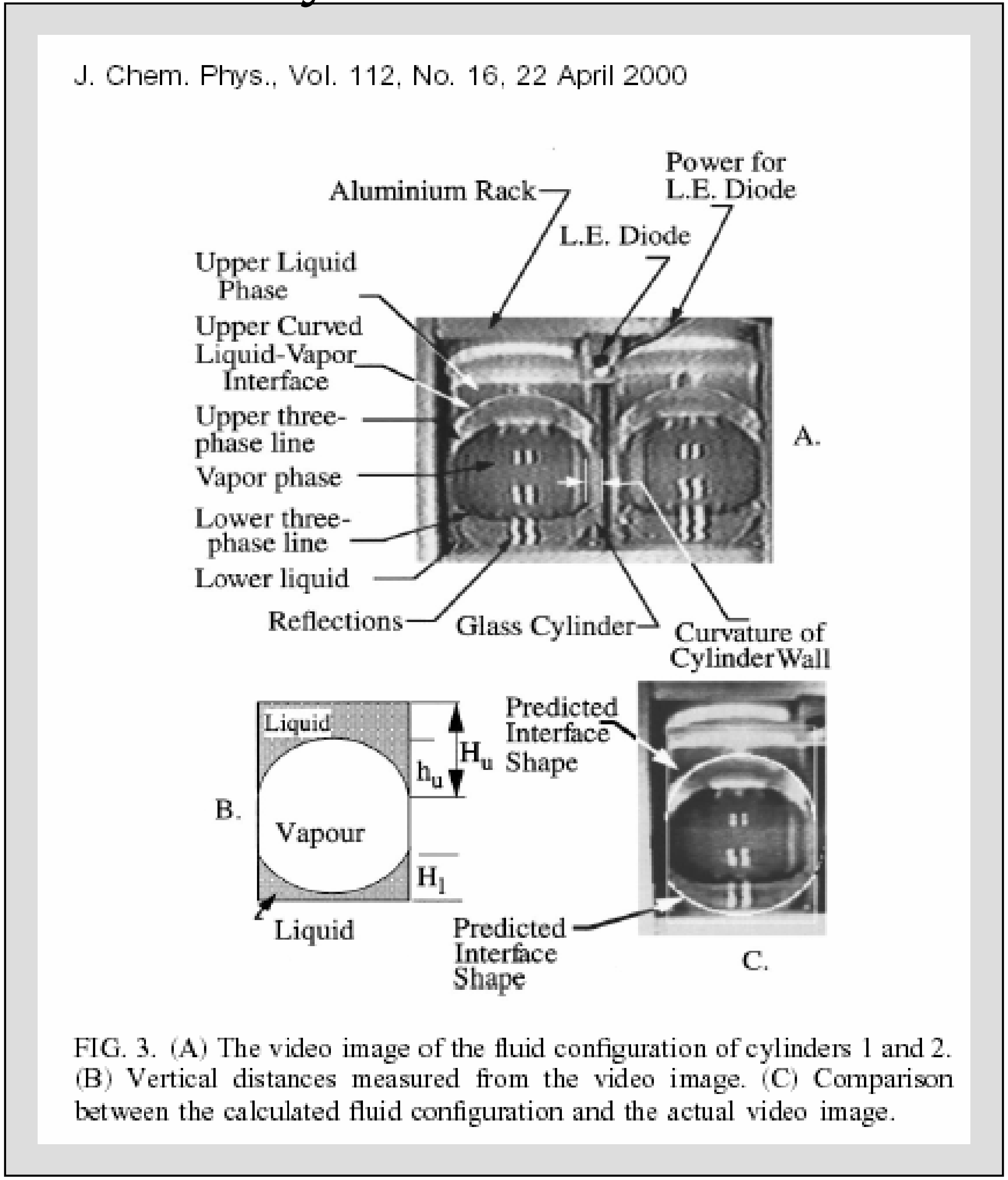
$g \equiv 0$

$\theta < 36°, N_l < N < N_u$

Then $\Rightarrow$



# Way it looks and the Way It Should Look!

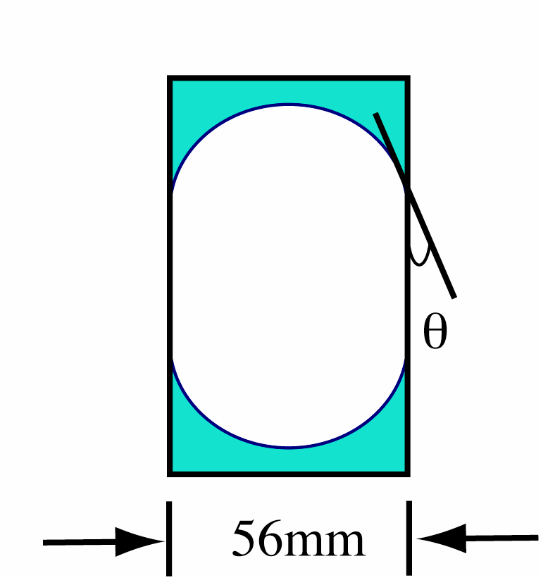


J. Chem. Phys., Vol. 112, No. 16, 22 April 2000

FIG. 3. (A) The video image of the fluid configuration of cylinders 1 and 2. (B) Vertical distances measured from the video image. (C) Comparison between the calculated fluid configuration and the actual video image.

Water in glass cylinder, if

$$a \longrightarrow 10^{-6}\ g_0$$

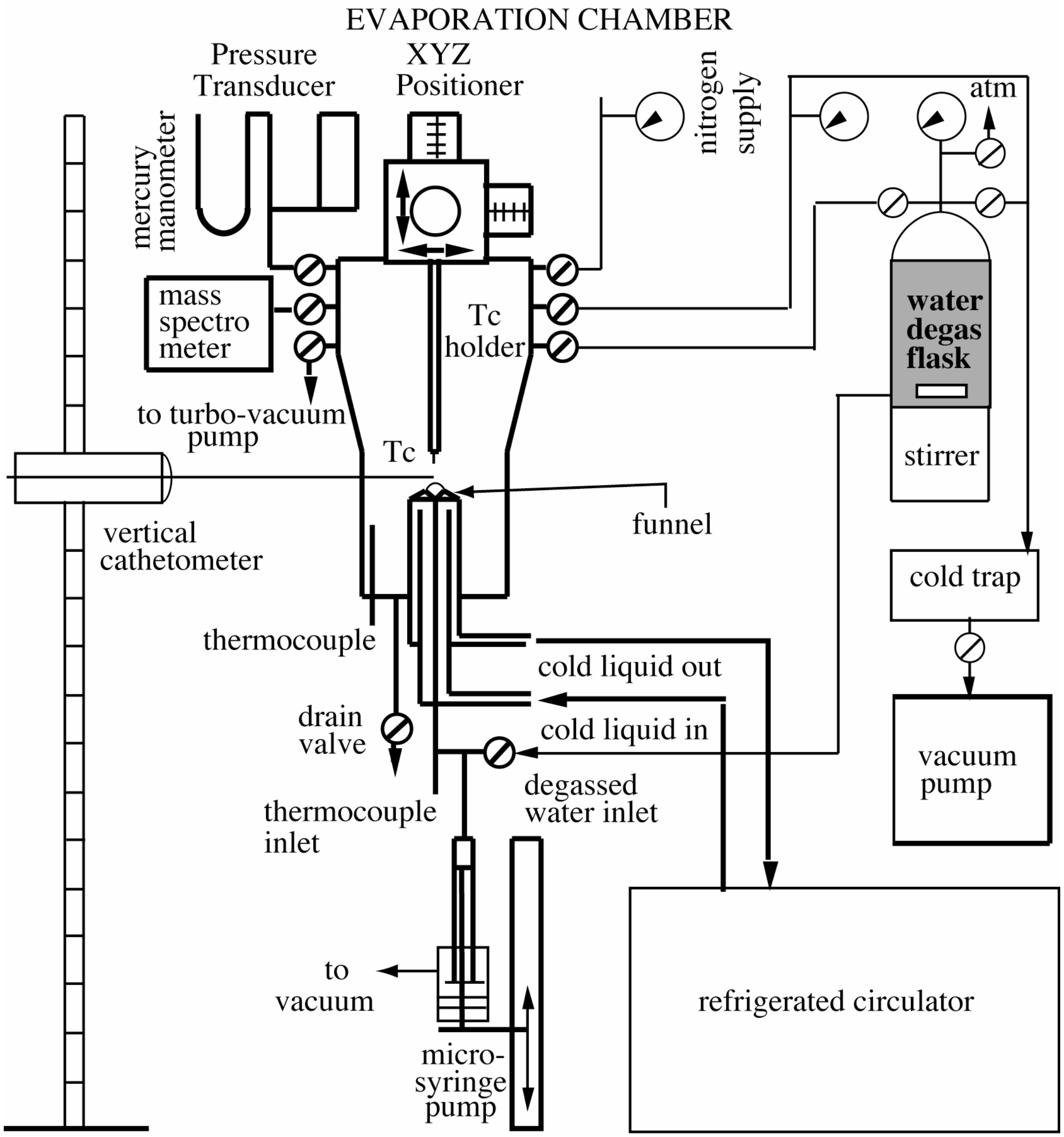


$$\mu^L = \mu^V = \mu^{SV} = \mu^{SL}$$

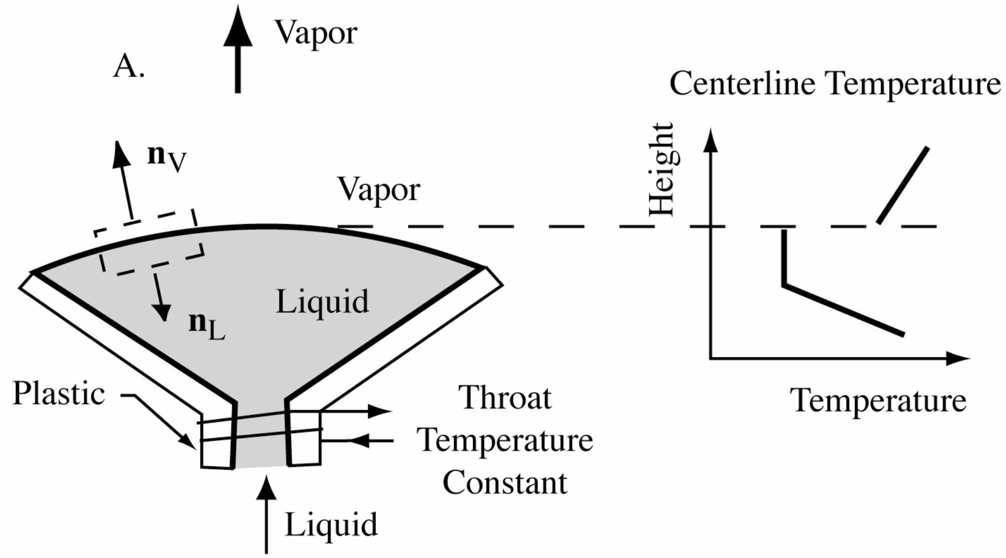
$$P^V - P^L = \gamma^{LV}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

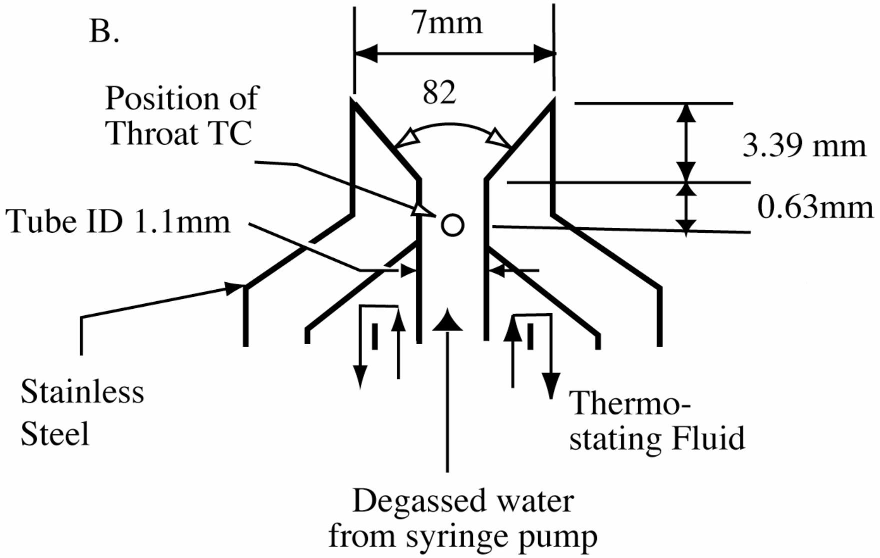
$$n^{SV} = f(T, P^V) \Rightarrow \theta = g(T, P^V)$$

# Experimental Apparatus Used to Study Liquid-Vapour Phase Change Processes



# The Effect of G-Jitter on Fluid Based Experiments





# The Effect of G-Jitter on Fluid Based Experiments

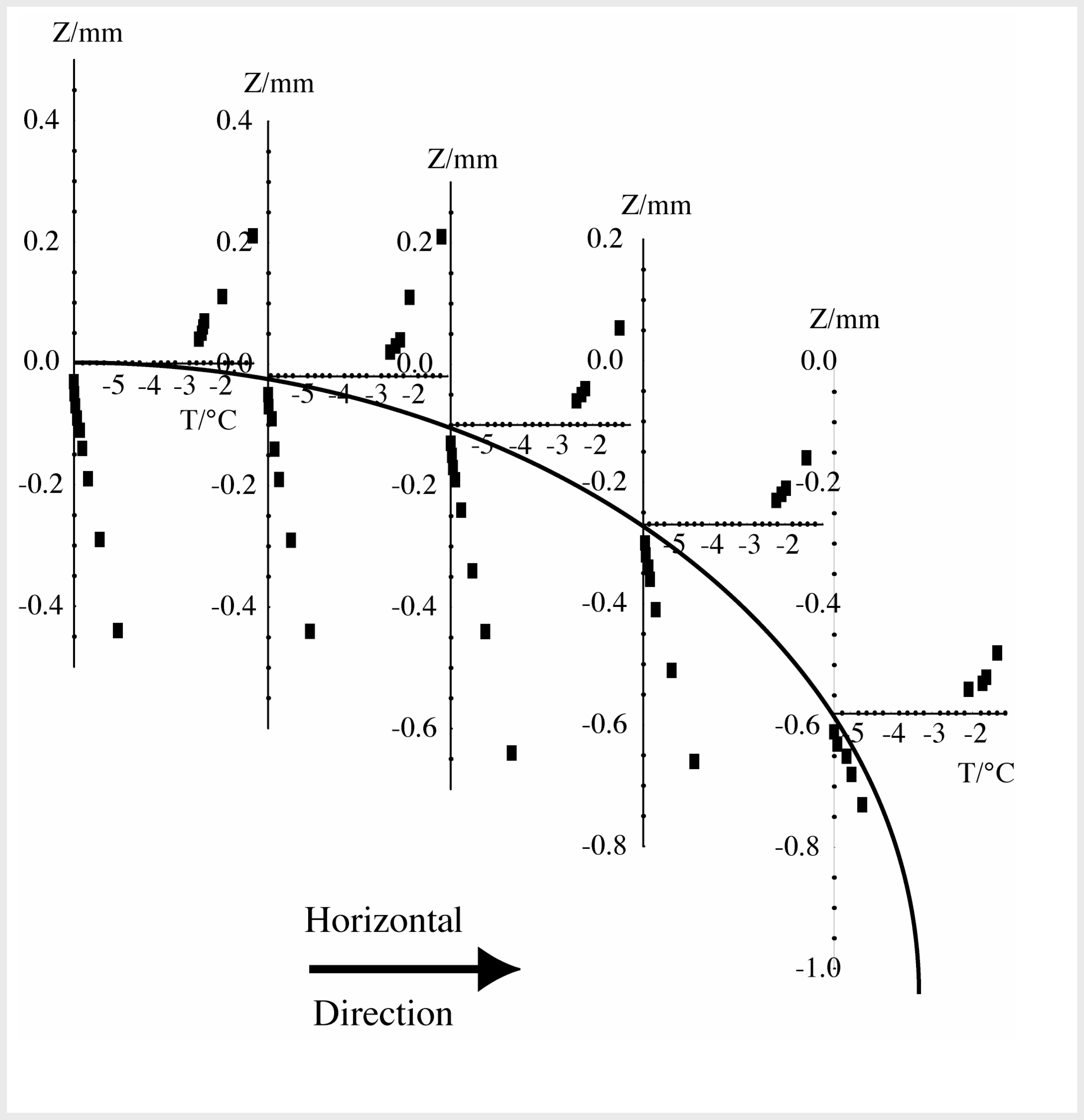
**1. Measure in *one horizontal direction*.**

A. No evaporation when pressure was 820 Pa.

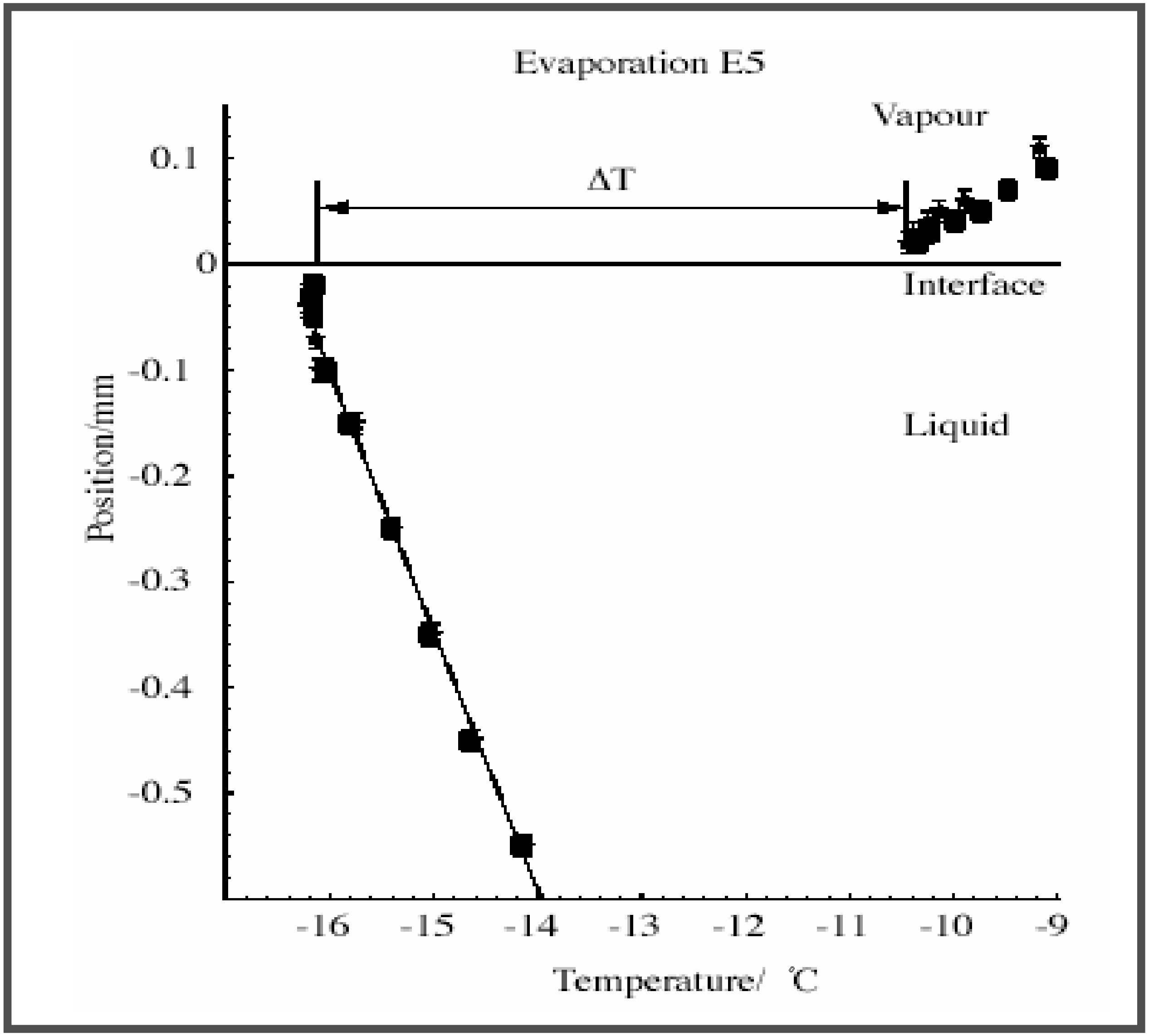
B. Pressure in the vapor 775Pa,

$j = 0.407 \pm 0.006\ \mathrm{g/m^2s}$

***2. Without opening the system, rotate the 3-dimensional positioner 90° and measure in the second horizontal direction.***



## Temperature During Steady State Evaporation of Water



# Protein Crystal Growth & Residual Motion

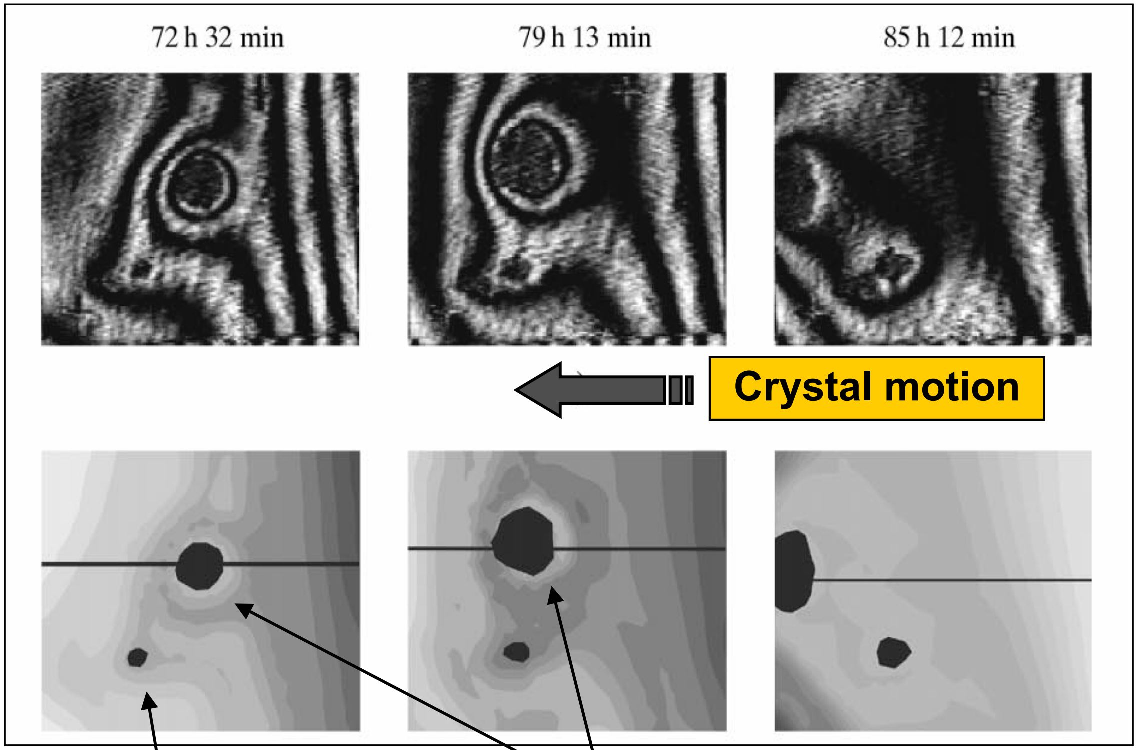
**Jurgen Sygusch**

**Biochemistry**

**Université de Montréal**

**Montréal, Canada**

# Residual Motion on STS-95
# Ferritin PCG



**Crystal motion**

**Small crystal with CDZ**

**Large crystal with CDZ**

**Otalora *et al.* (2001) Acta Cryst. D57, 412-417**

**Crystal movement**

**$v_{12}$ = 104 µm/hr**
**$v_{23}$ = 256 µm/hr**

↓

**Flow velocity of solute molecules towards crystal**

**$k_D$=D/(CDZ thickness)**

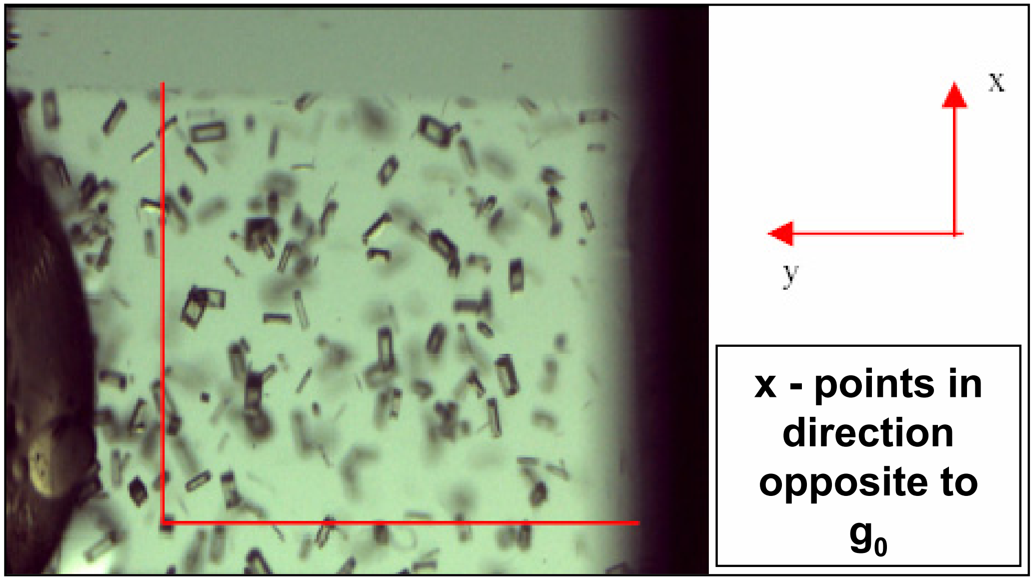
**$k_{12}$ = 115 µm/hr**

**$k_{23}$ = 82 µm/hr**

↓

- **image 1 → 2, CDZ modification**
- **image 2 → 3, CDZ alteration**

# Drifting PPG$_{10}$ crystals on ISS

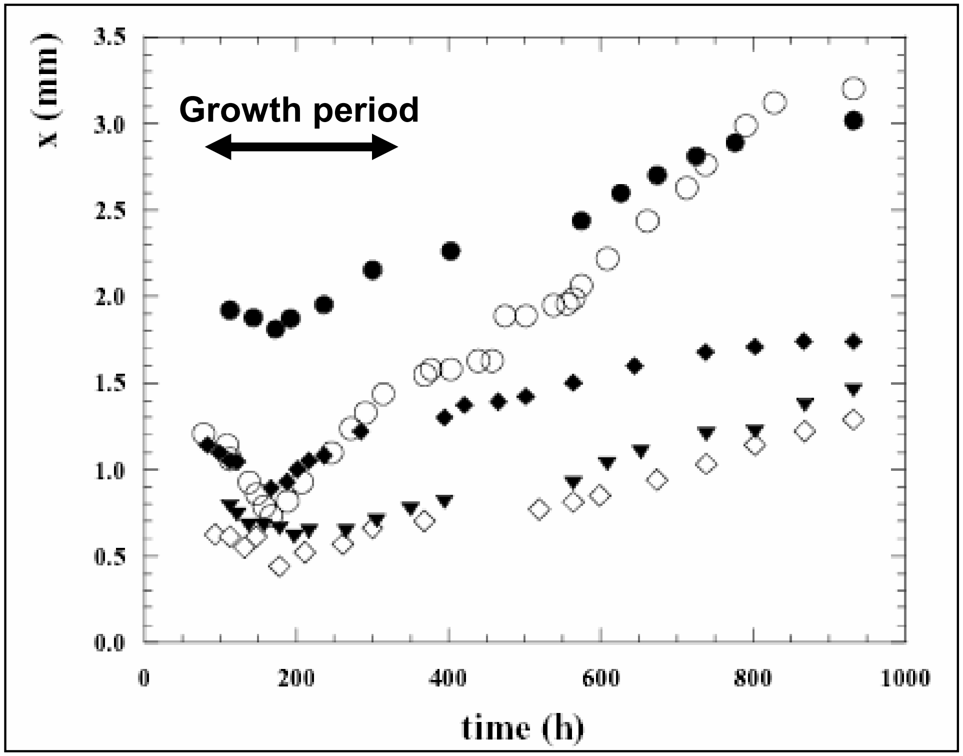


x - points in direction opposite to $g_0$

**PCG in the APCF reactor**

**<velocity> ~ 1 µm $h^{-1}$**
**Residual acceleration ~ 1 µg**

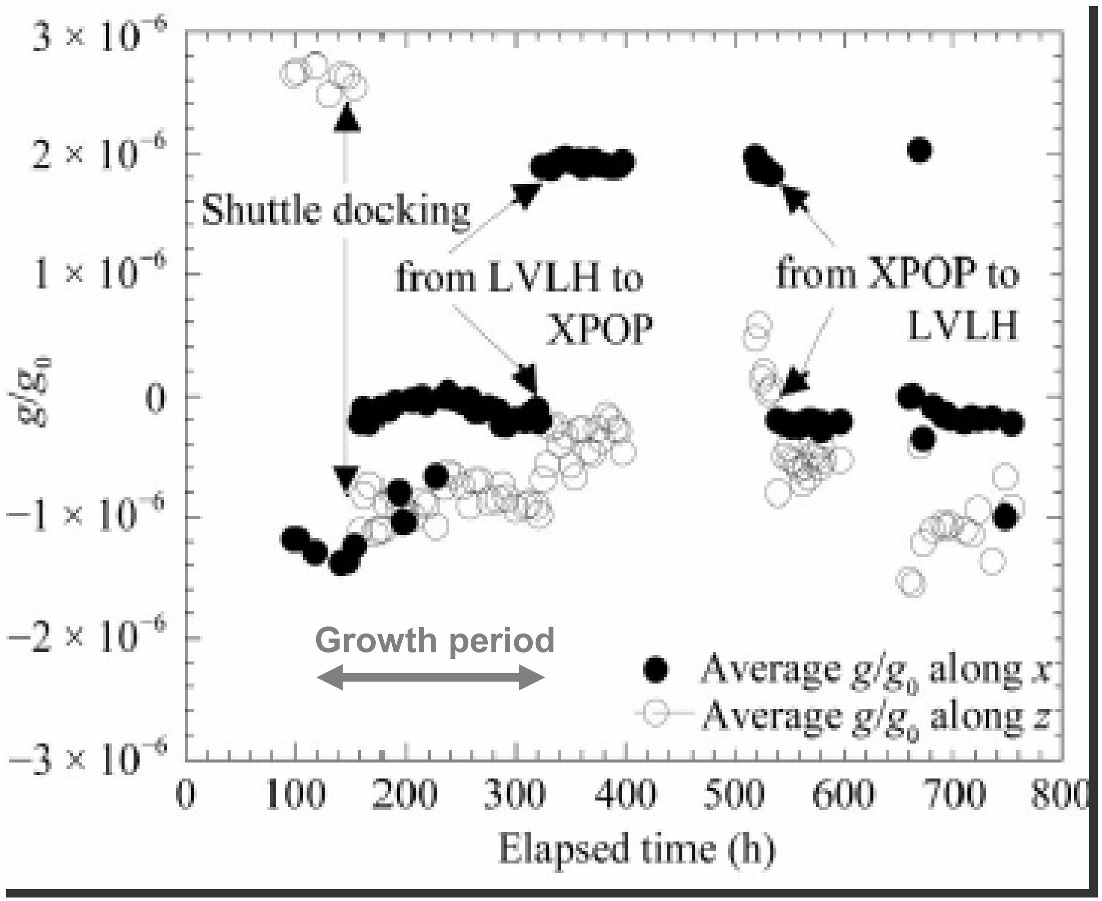
**Coherent displacement of five selected crystals along the x direction; no significant motion in other directions**



Vergara et al, Acta Cryst. (2002). D58, 1690-1694

# Residual Motion and ISS acceleration levels

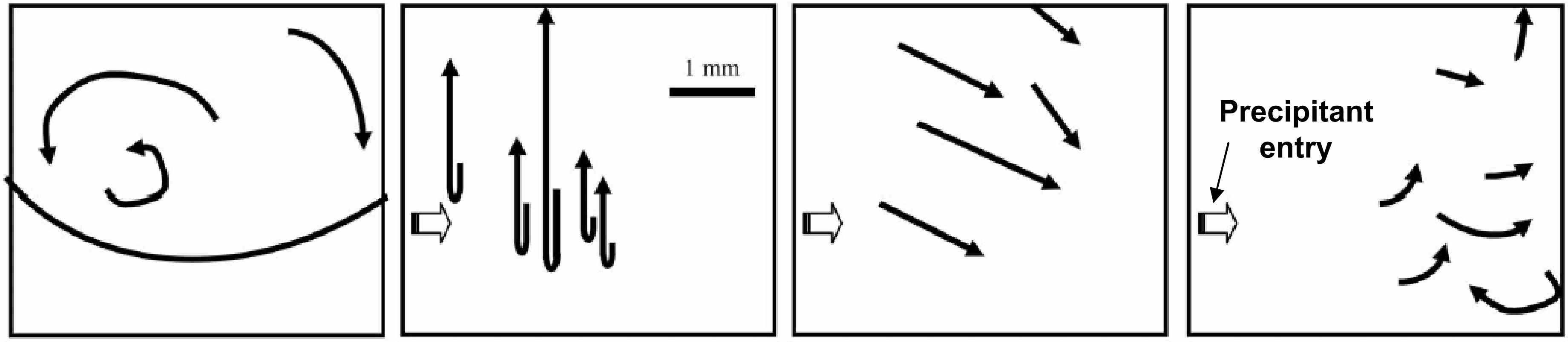
## Accelerations on $PPG_{10}$ crystals during and after growth



-x – direction of $g_0$
z – direction of ISS velocity vector

# Trajectories of Crystal Motion

Vergara *et al* (2003) Acta Cryst. D59, 2-15



**IML-2**
Circular motion

**ISS-3**
Synchronous and coherent motion

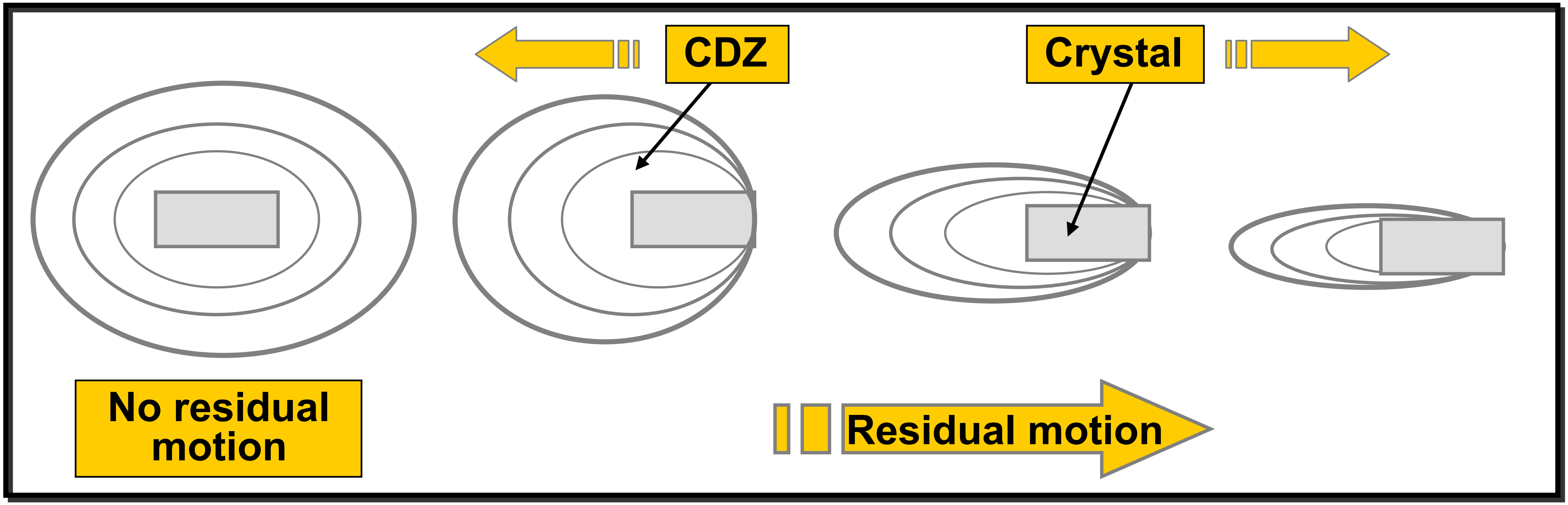
**USML-2**
Synchronous but incoherent motion

**LMS**
Asynchronous and incoherent motion

**Crystals undergo diverse residual motion in microgravity**

# Motion compromises CDZ

**Because $\rho_{crystal} > \rho_{medium} > \rho_{CDZ}$**
**CDZ movement in direction opposite to crystal motion**



**Result: CDZ deformation and suppression**

- **Mitigation of residual acceleration is needed**

# Effect of G-Jitter on the Motion of an Encapsulated Bubble

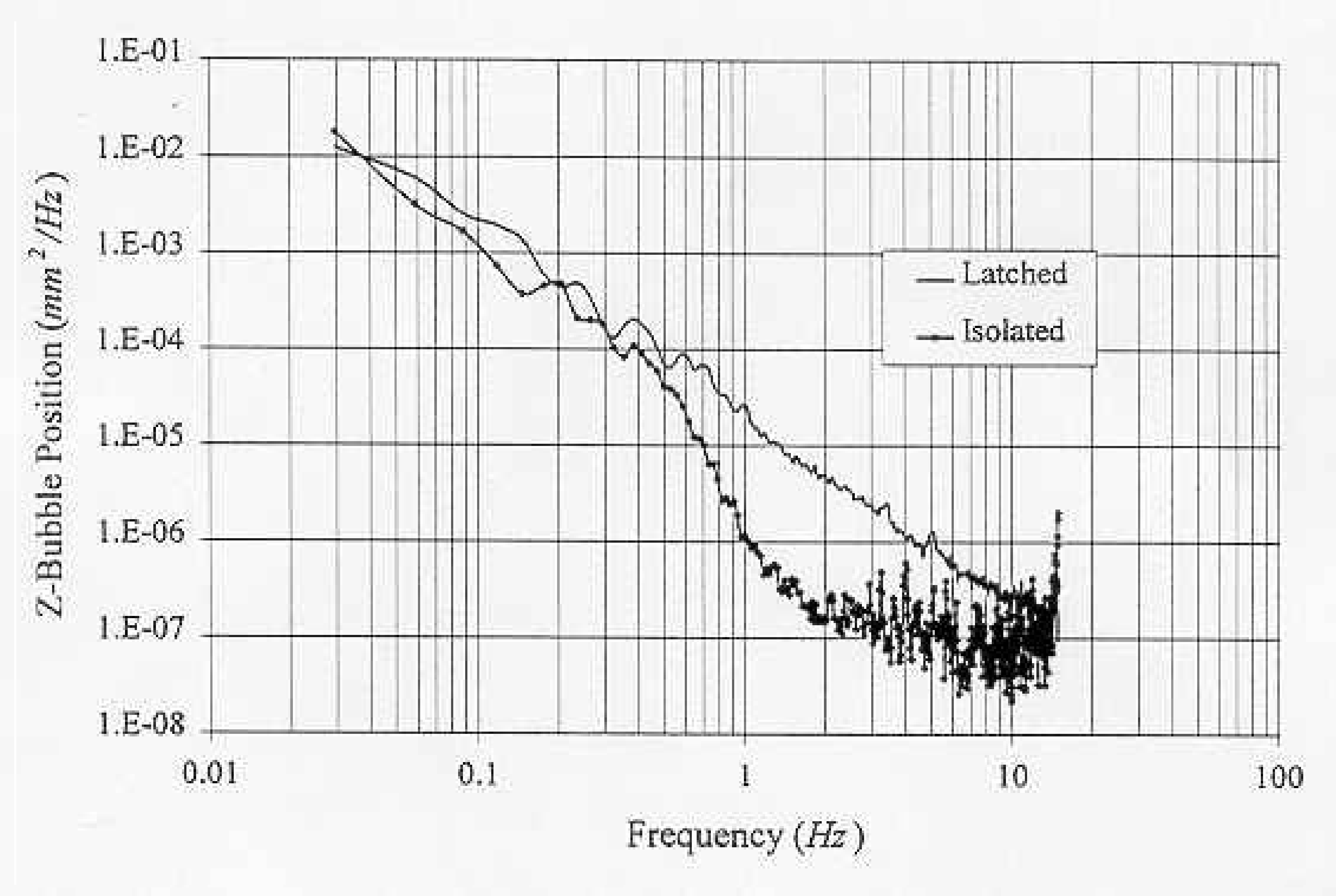
**Kameil Rezkallah,** University of Saskatchewan

The motion of a bubble several mm in diameter was recorded on video

The motion was compared for cases with and without isolation

# Effect of G-Jitter on Motion of a Bubble Encapsulated in Water

(Rezkallah, et. Al., Experiment performed on STS-85)



# Our Experience Base on Orbit: Micro!

Total time on orbit for the space shuttle:

112 flights at 10 days ~ 1120 days ~ 3 years

ISS crewed time thus far ~ 2 years, but with only a small experiment complement

This is a small experience base, compared to our ground experience base: ~ 400 Universities

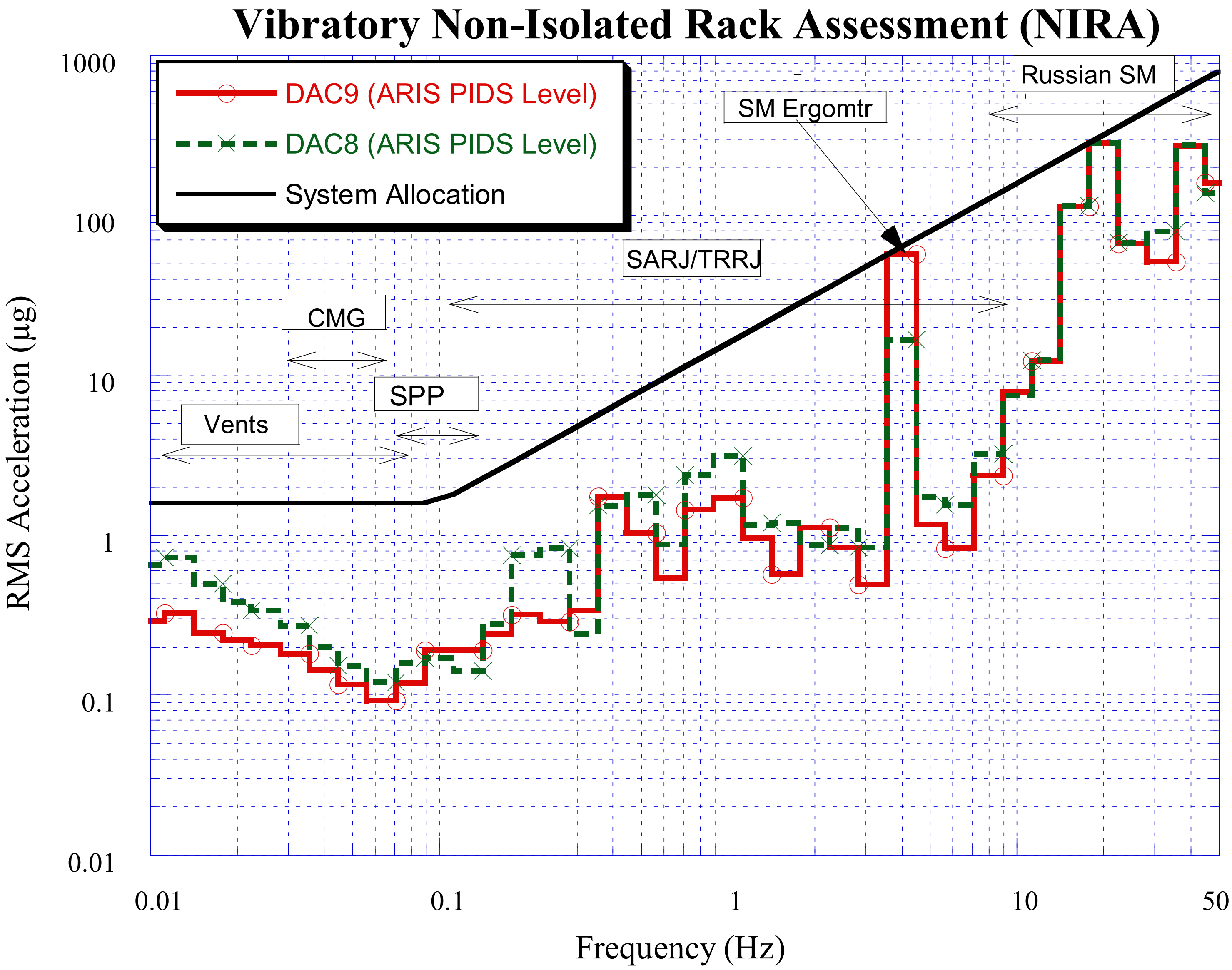
# The Vibration Environment on the Mir and the Shuttle

MIM-1 Operational on Mir May 1996 to January 1998
3000+ hours of operation

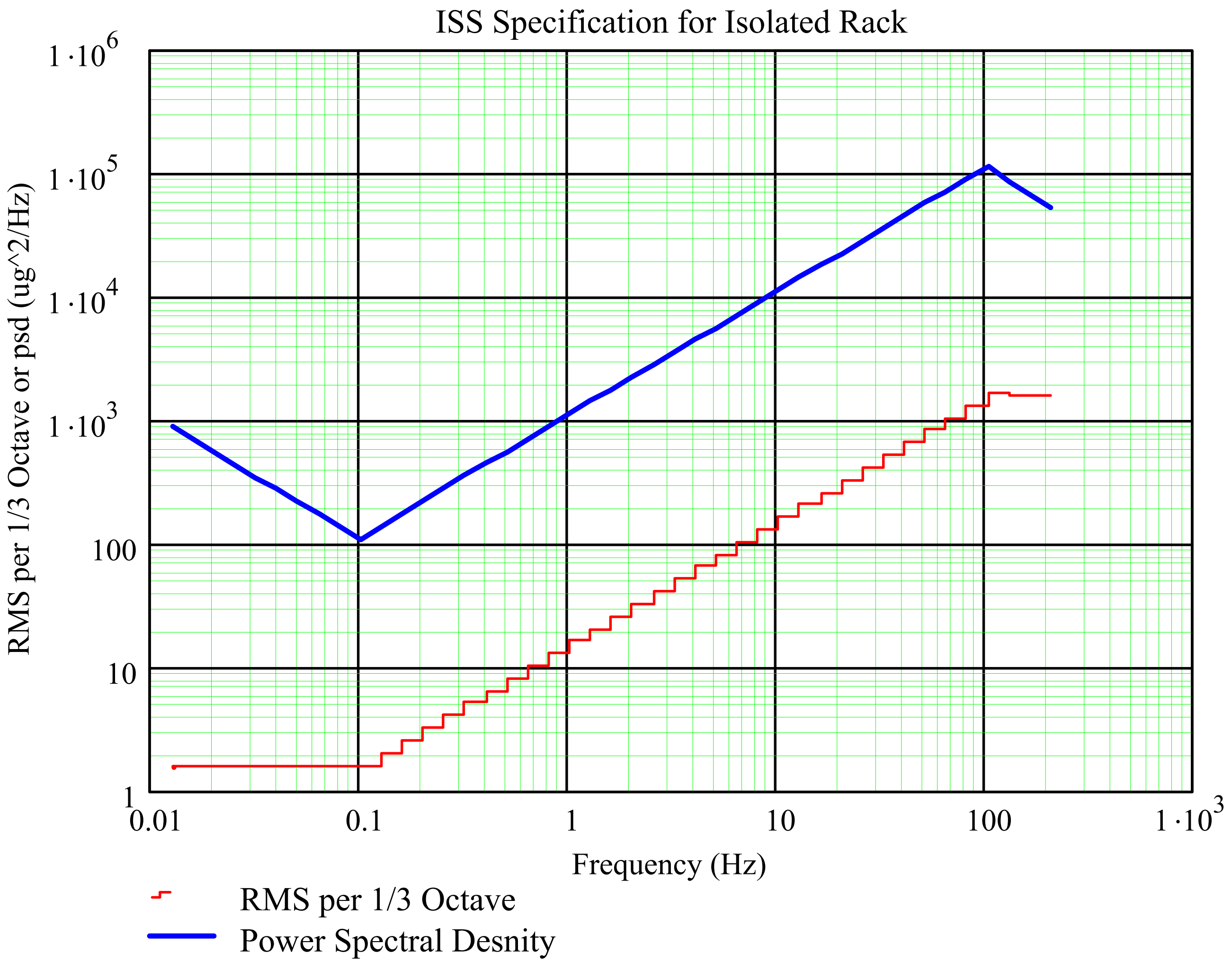
MIM-2 On shuttle mission STS-85, August 7-19, 1997
100 hours of operation

Acceleration data collected at 1000 samples/s for short (several minutes) and for up to seven days continuously at lower sampling rates (as low as 5 samples/s)

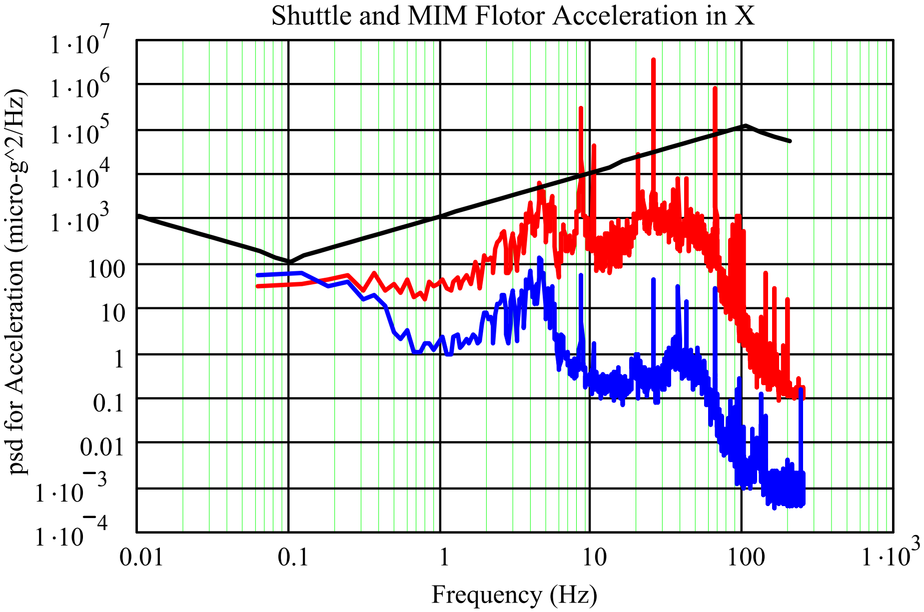
# ISS Vibratory Requirement for Isolated Payloads

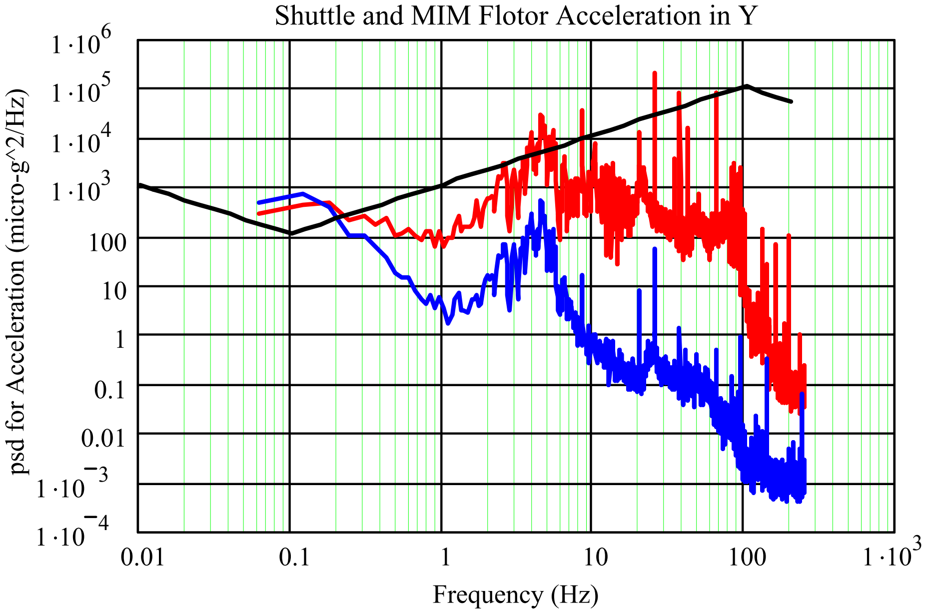


# ISS Vibratory Requirement for Isolated Payloads



# Power Spectral Densities for Accelerations of the Shuttle and MIM Flotor

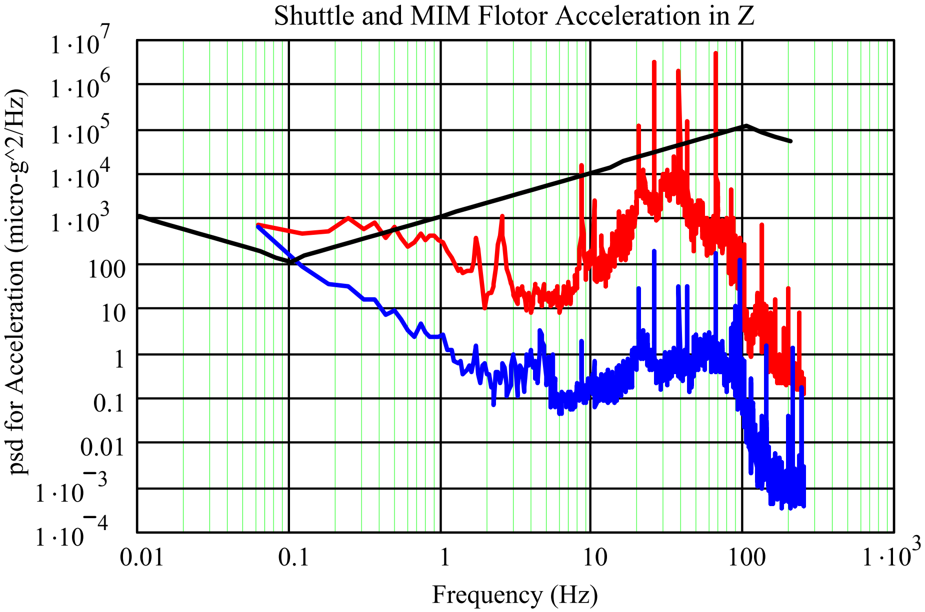




🟥 Stator (non-isolated)

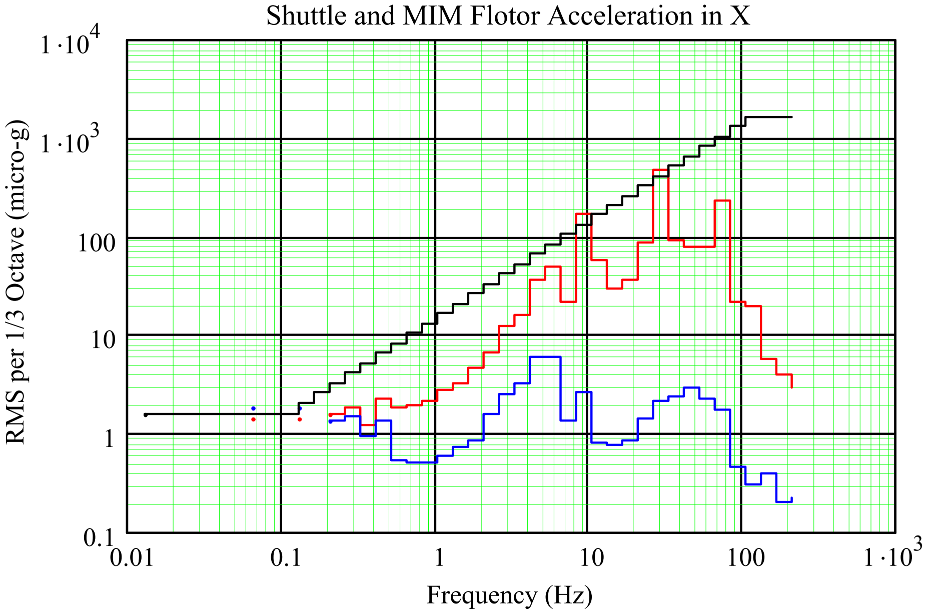
- - - Flotor (isolated)

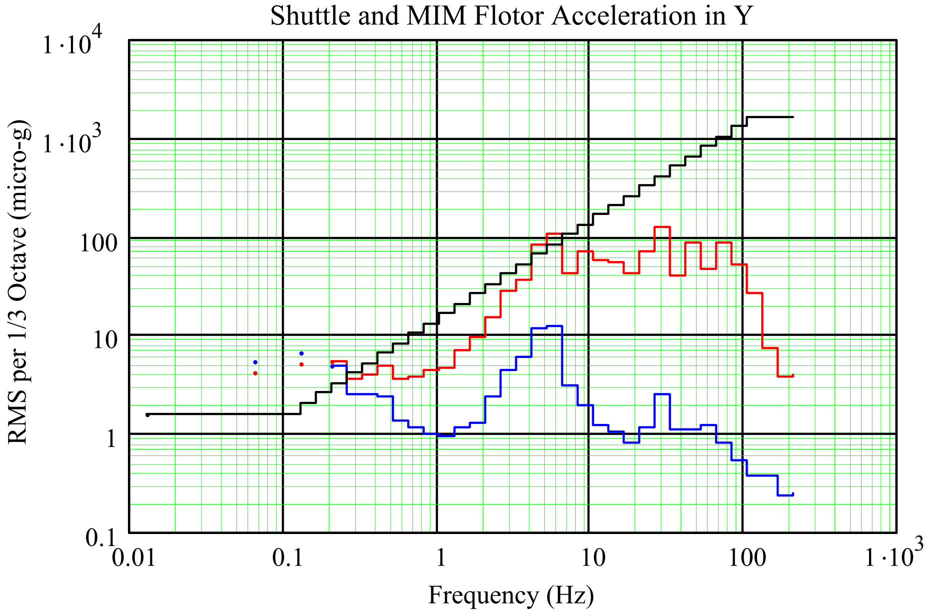
— - ISS Specification



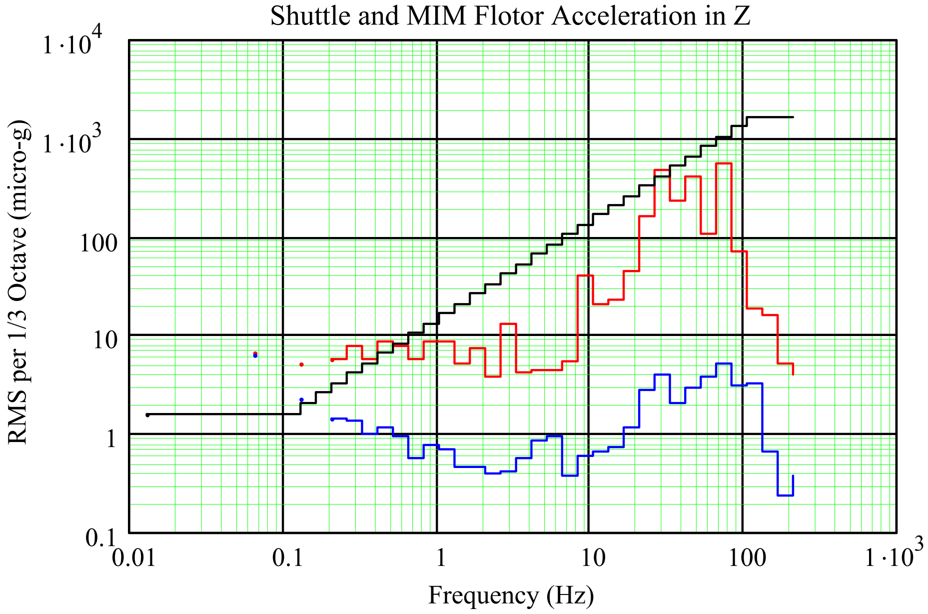
DPID: X,Y~2 Hz Z~0.1Hz
File: D7081649

# Power Spectral Densities for Accelerations of the Shuttle and MIM Flotor





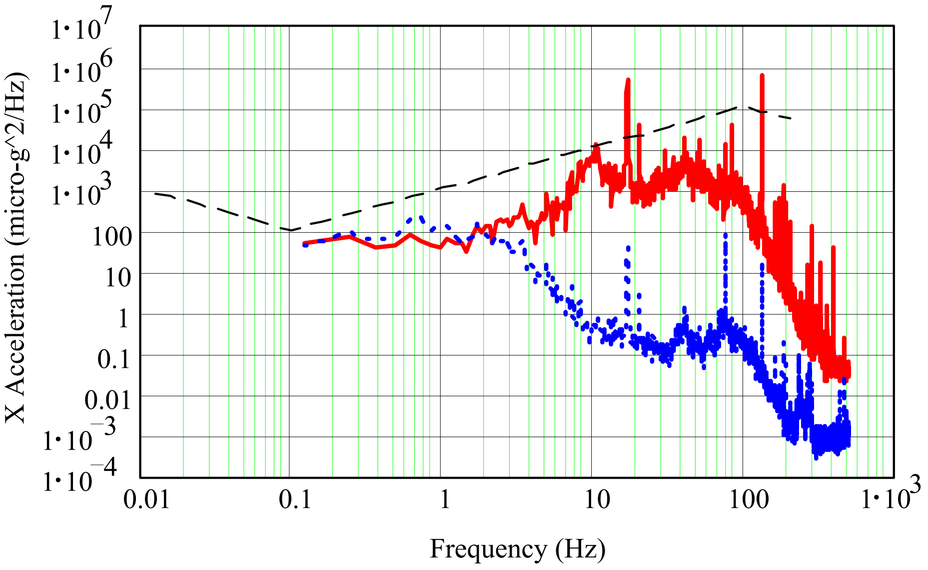
━ Stator (non-isolated)
┅ Flotor (isolated)
— - ISS Specification

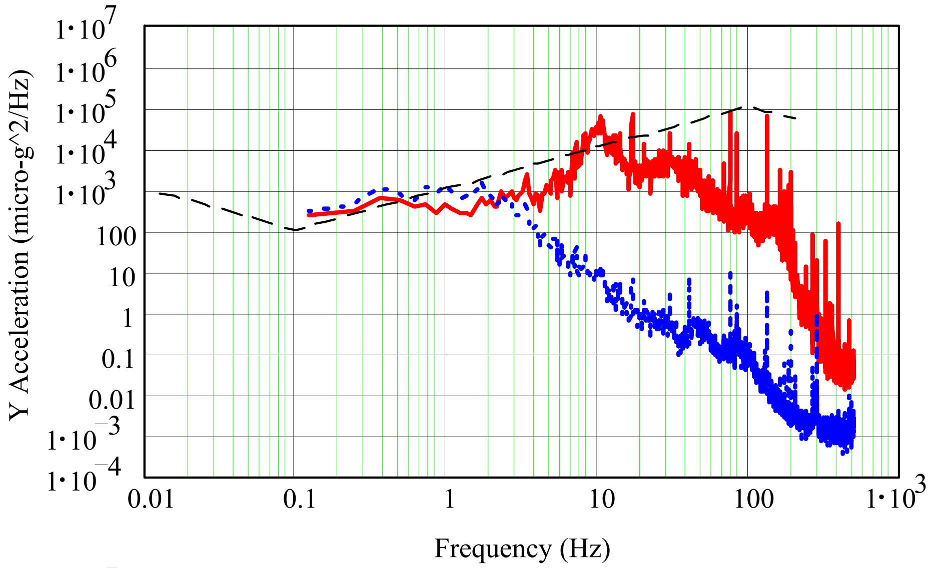


DPID: X,Y~2 Hz  Z~0.1Hz

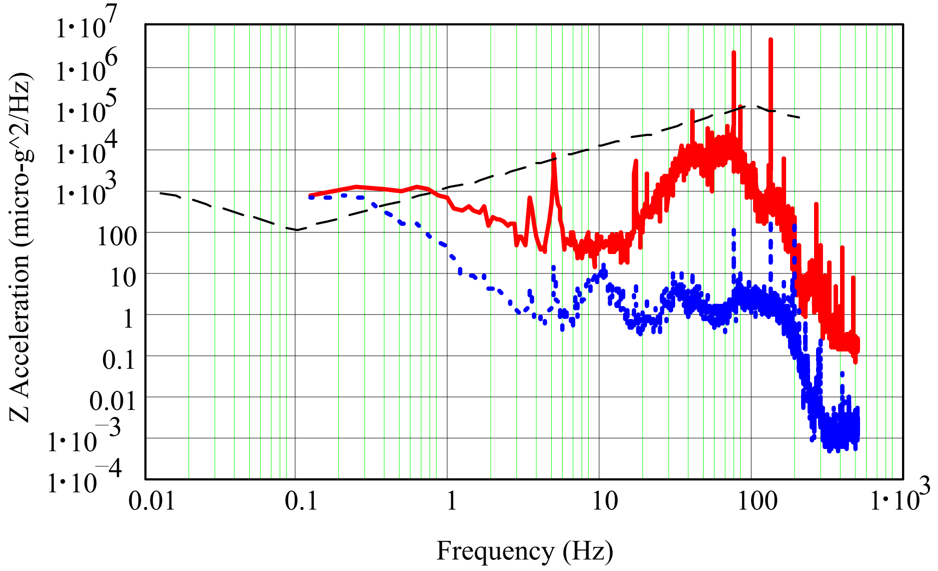
File: D7081649

# Power Spectral Densities for Accelerations of the Shuttle and MIM Flotor



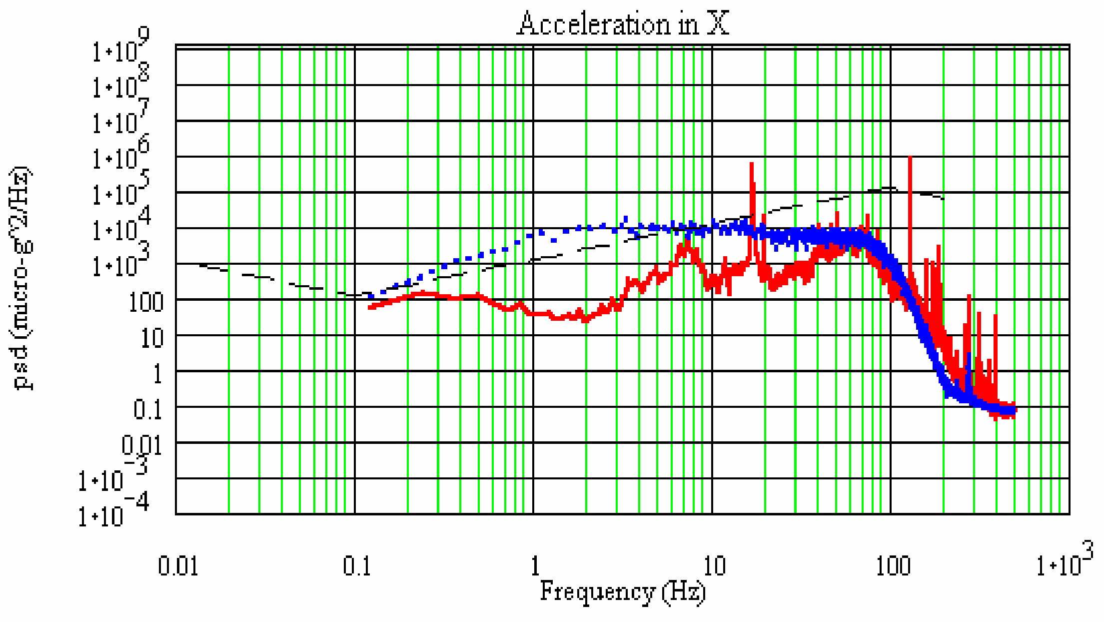


— Stator (non-isolated)
- - Flotor (isolated)
— - ISS Specification



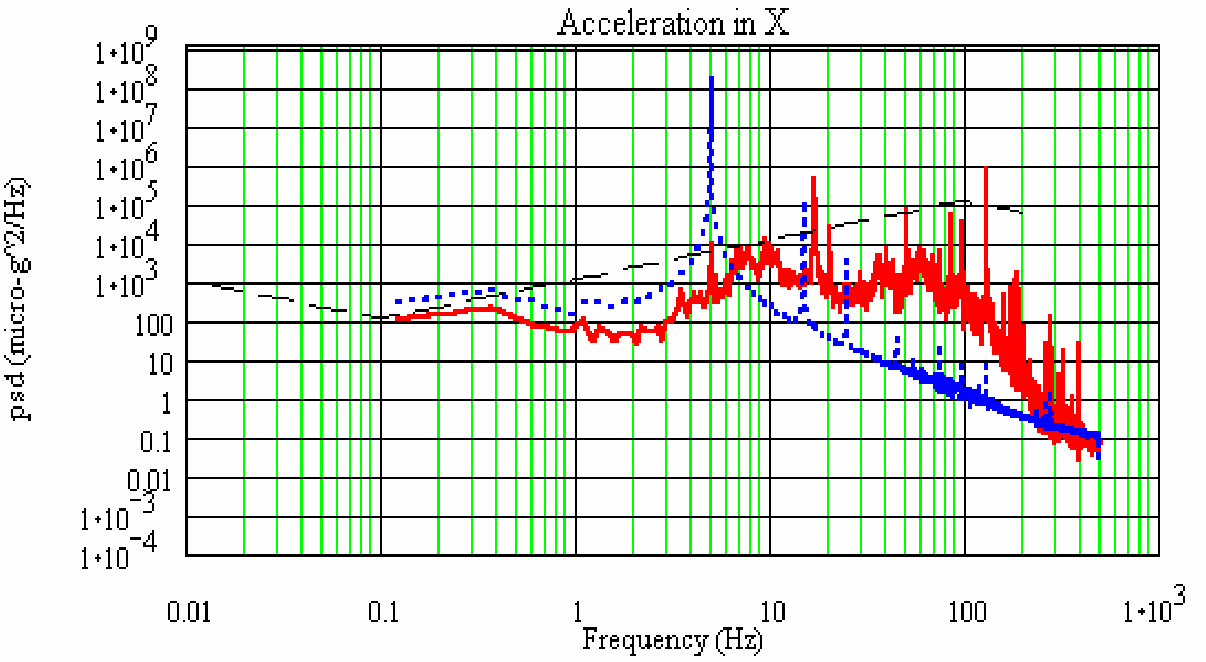
DPID, XY: 2 Hertz, Z: 0.1 Hertz
File: D7081621

## MIM Driven Modes



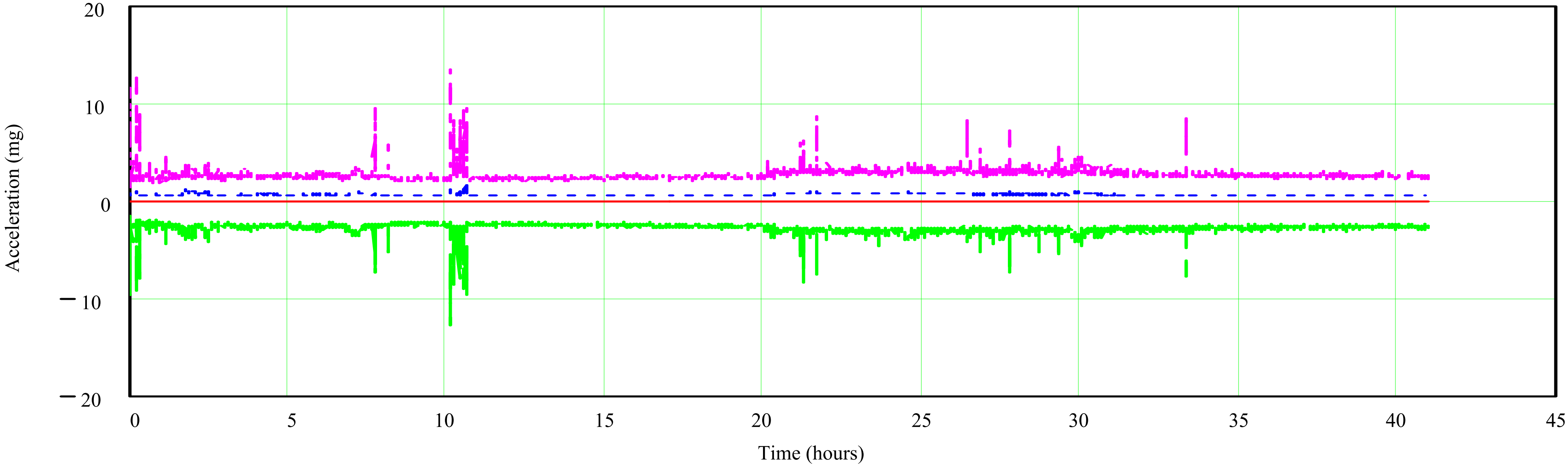
**Single frequency**

**Random with uniform broadband spectrum**

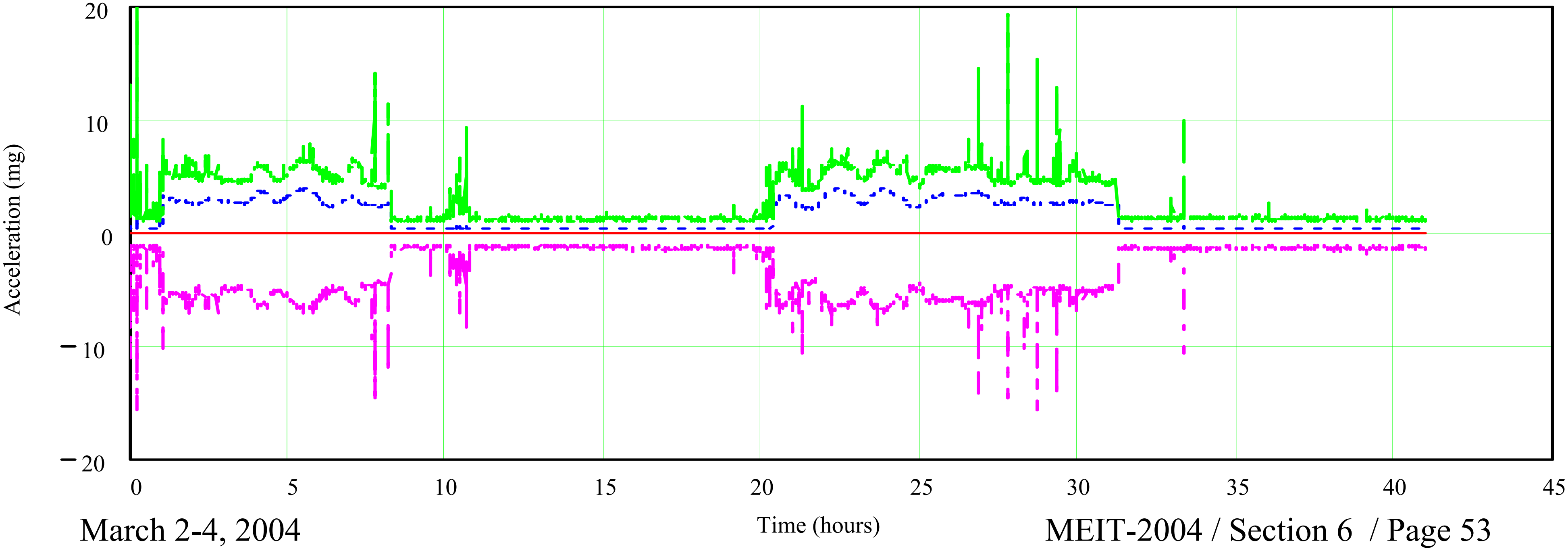


# Mir Accelerations: max,min,mean, rms over 10s

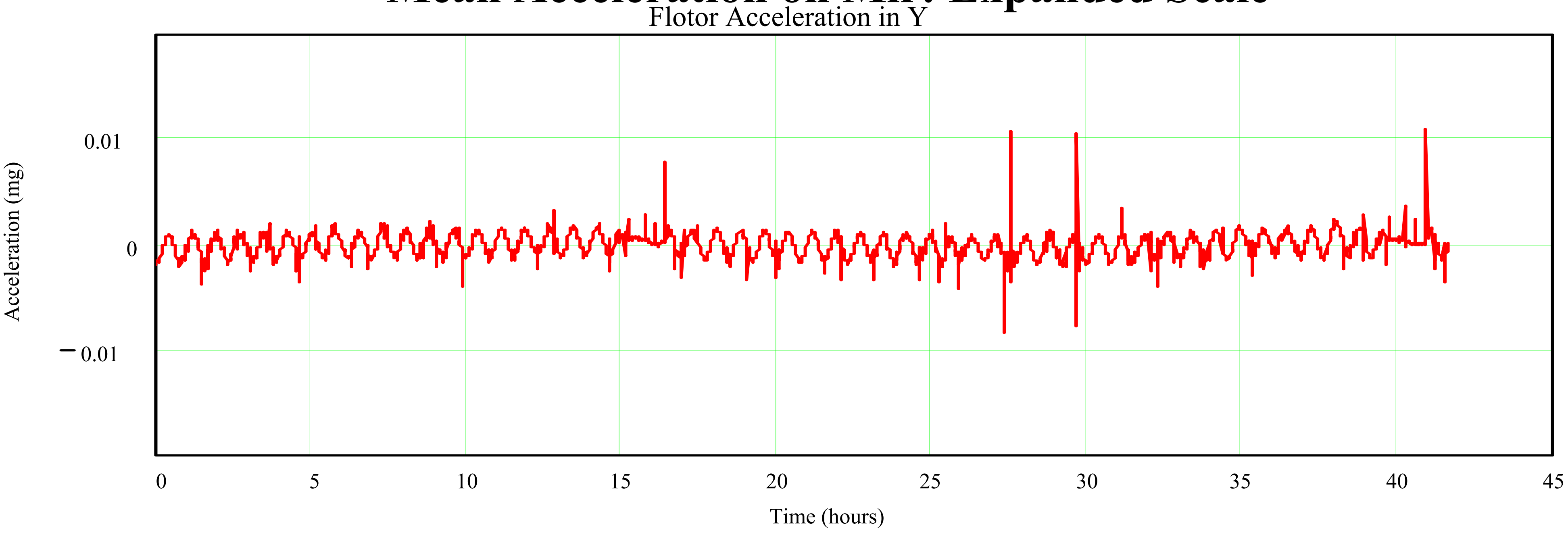
Flotor Acceleration in Y

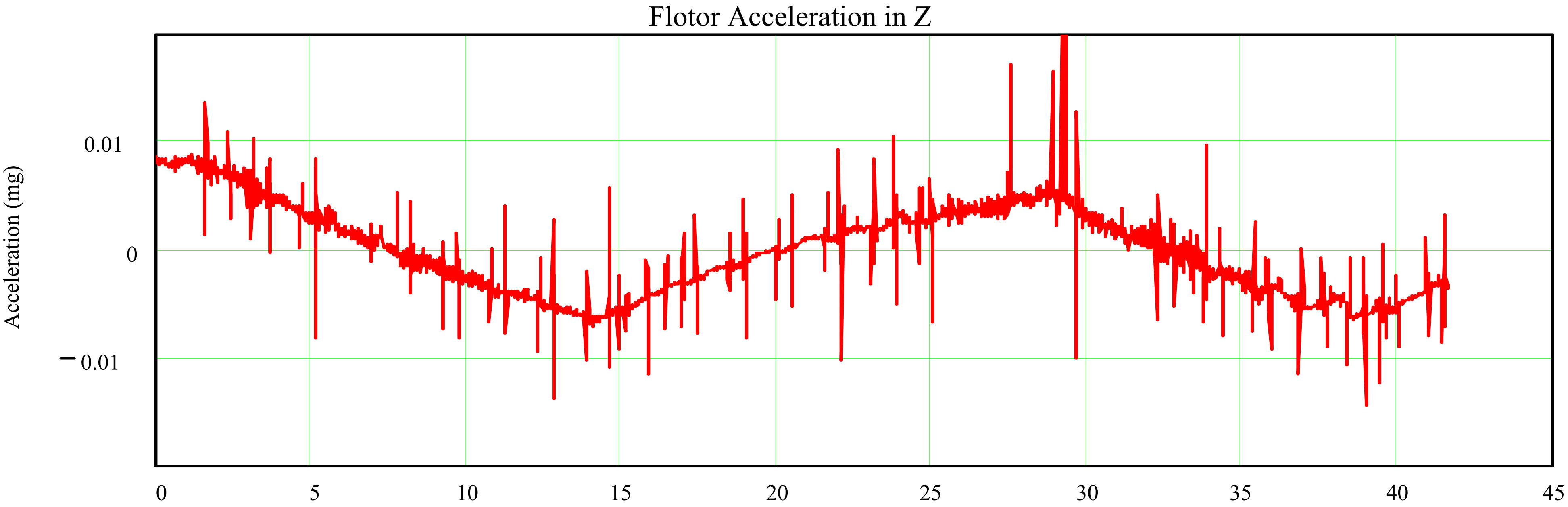


Flotor Acceleration in Z

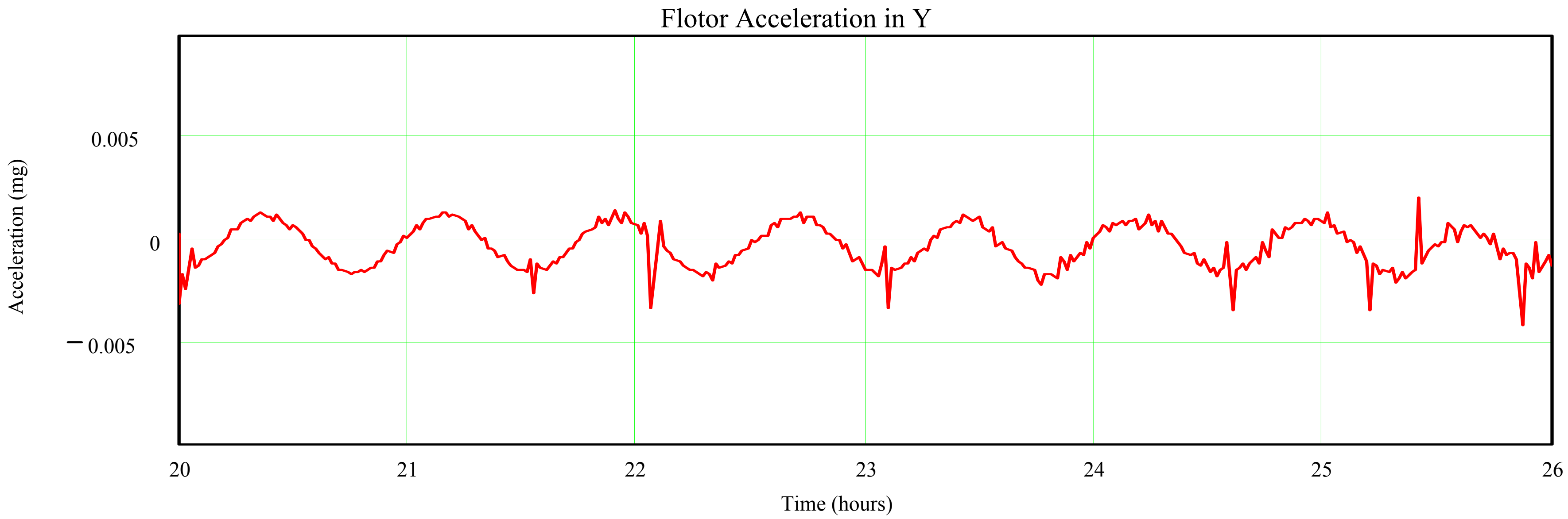


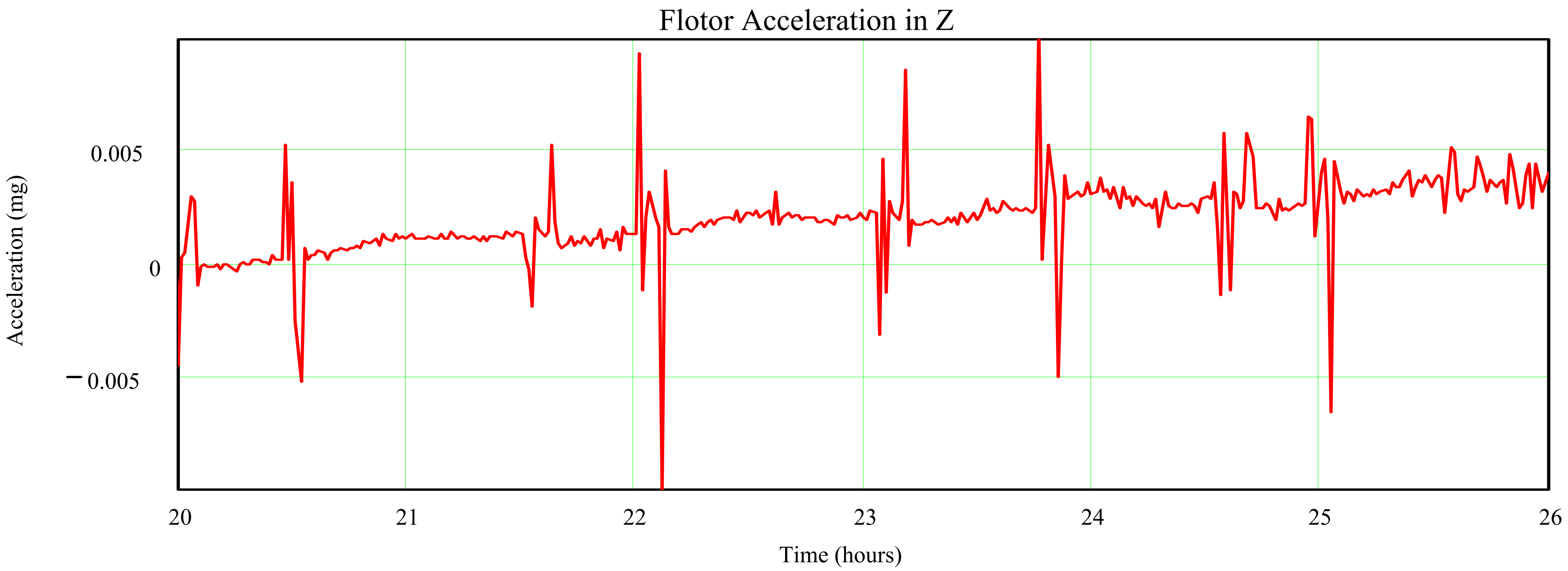
# Mean Acceleration on Mir: Expanded Scale



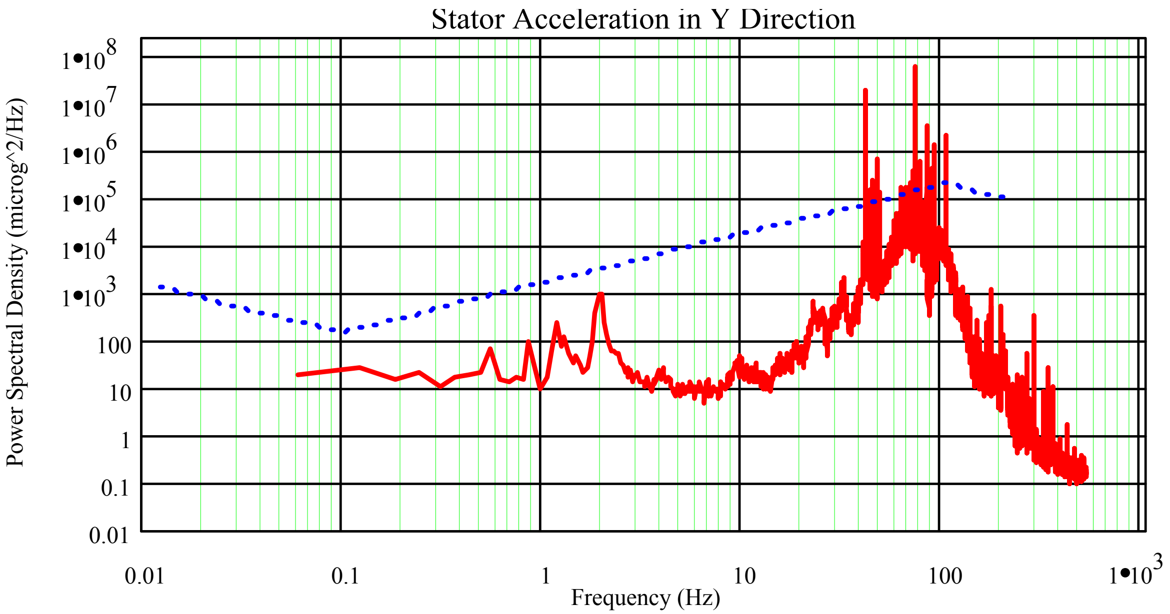


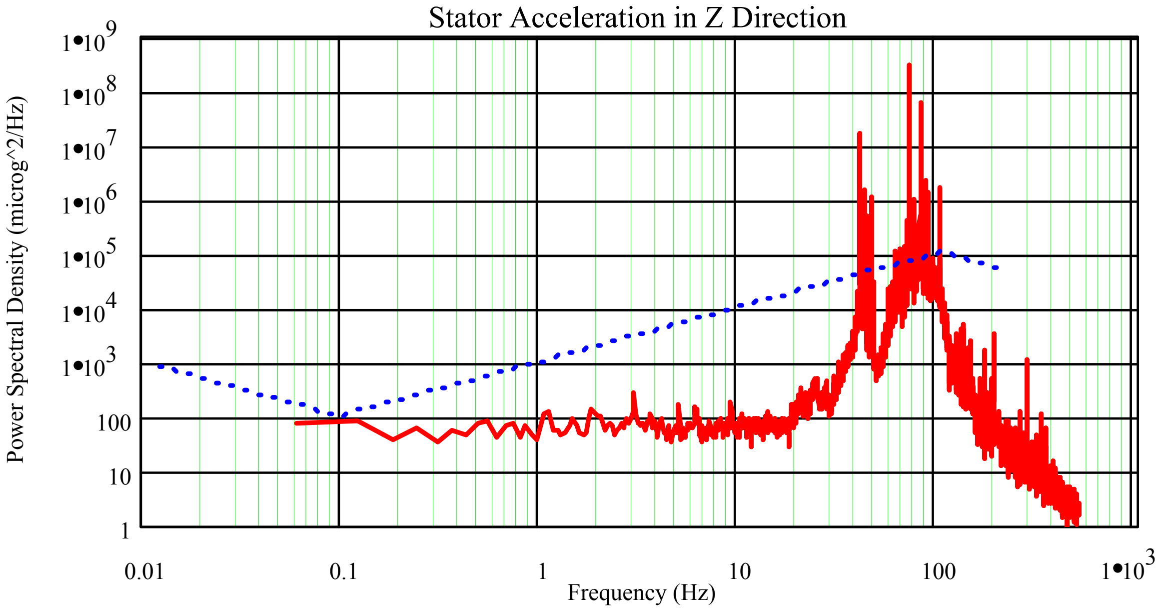
# Mean Acceleration on Mir: Expanded Scale



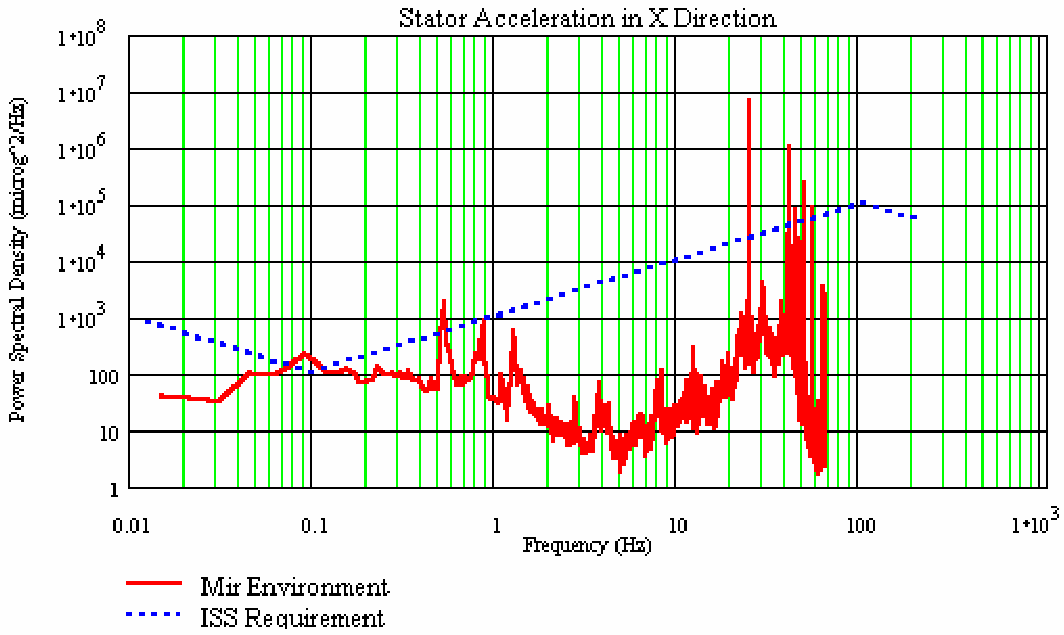


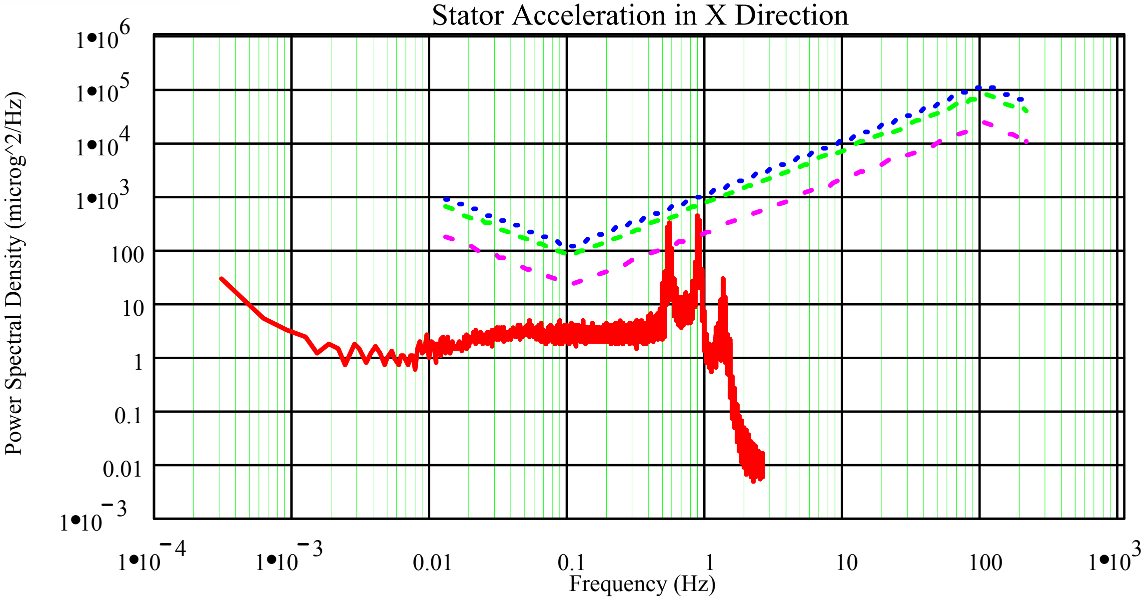
# Accelerations on Mir: Power Spectral Density





# Accelerations on Mir: Power Spectral Density





# Summary of Acceleration Environment on Mir and the Shuttle

- **Over most of the frequency band covered by the ISS specification for an isolated rack:** *the acceleration levels on the Mir and shuttle were below the ISS requirement for an isolated rack*

- **Coupled with the observed sensitivity of diffusion and internal fluid flow to g-jitter at these levels:** *this indicates that the current specification for isolated racks on the ISS is not conservative for fluid based experiments*

# CSA Science Plan for the ISS

## Three Research Facilities

| | |
|---|---|
| ATEN | - materials science furnace |
| PROSPECT | - protein crystal growth facility |
| SURD | - Fluid science facility |

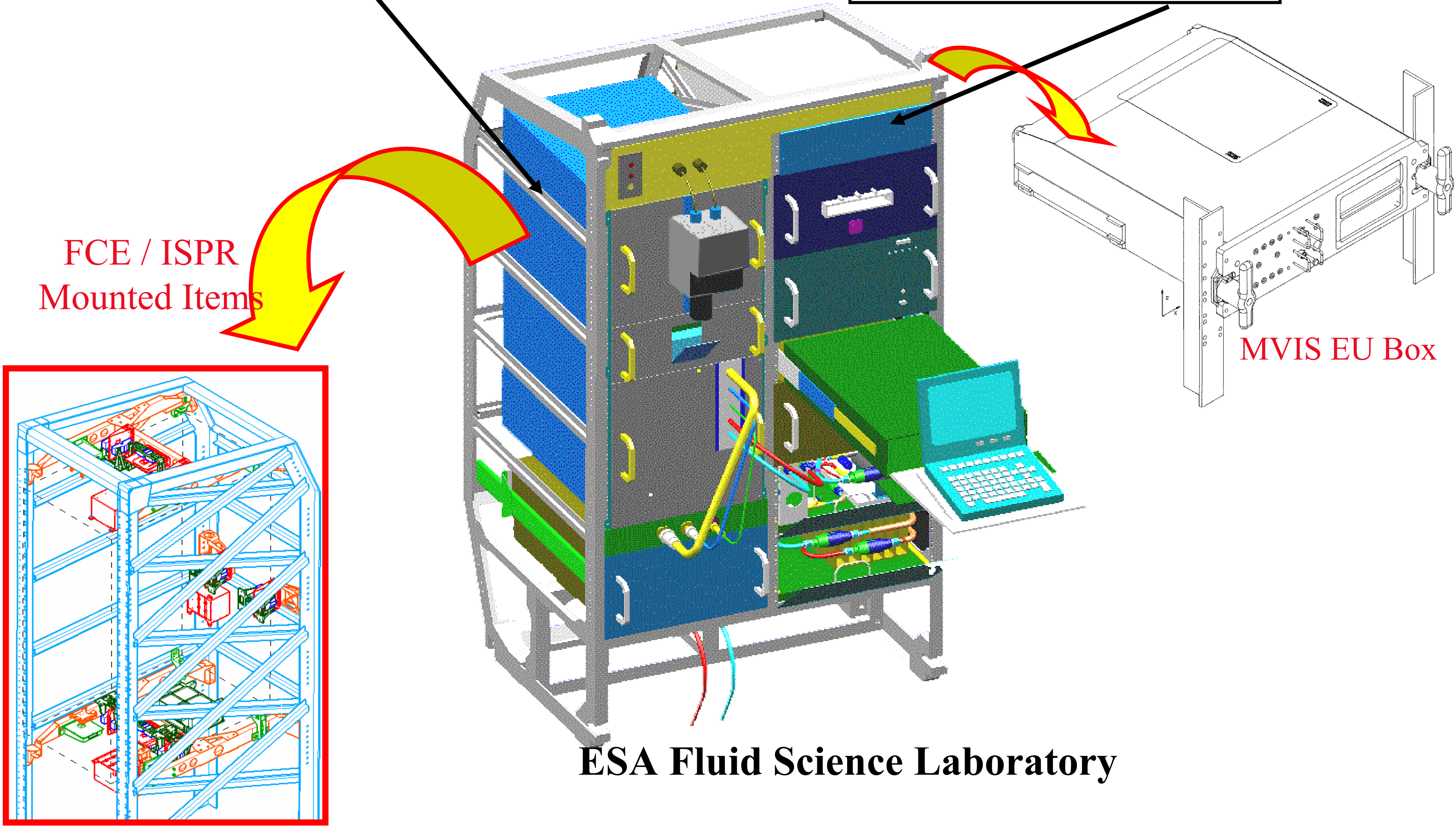
## Two Isolation Support Systems

| | |
|---|---|
| MIMBU | - Microgravity-vibration Isolation Mount Base Unit to support ATEN,PROSPECT,SURD and other science hardware |
| MVIS | -Microgravity Vibration Isolation Subsystem for the ESA Fluid Science Laboratory |

# The Effect of G-Jitter on Fluid Based Experiments

**Fluid Core Element (FCE)**

**MVIS Electronic Unit**



FCE / ISPR Mounted Items

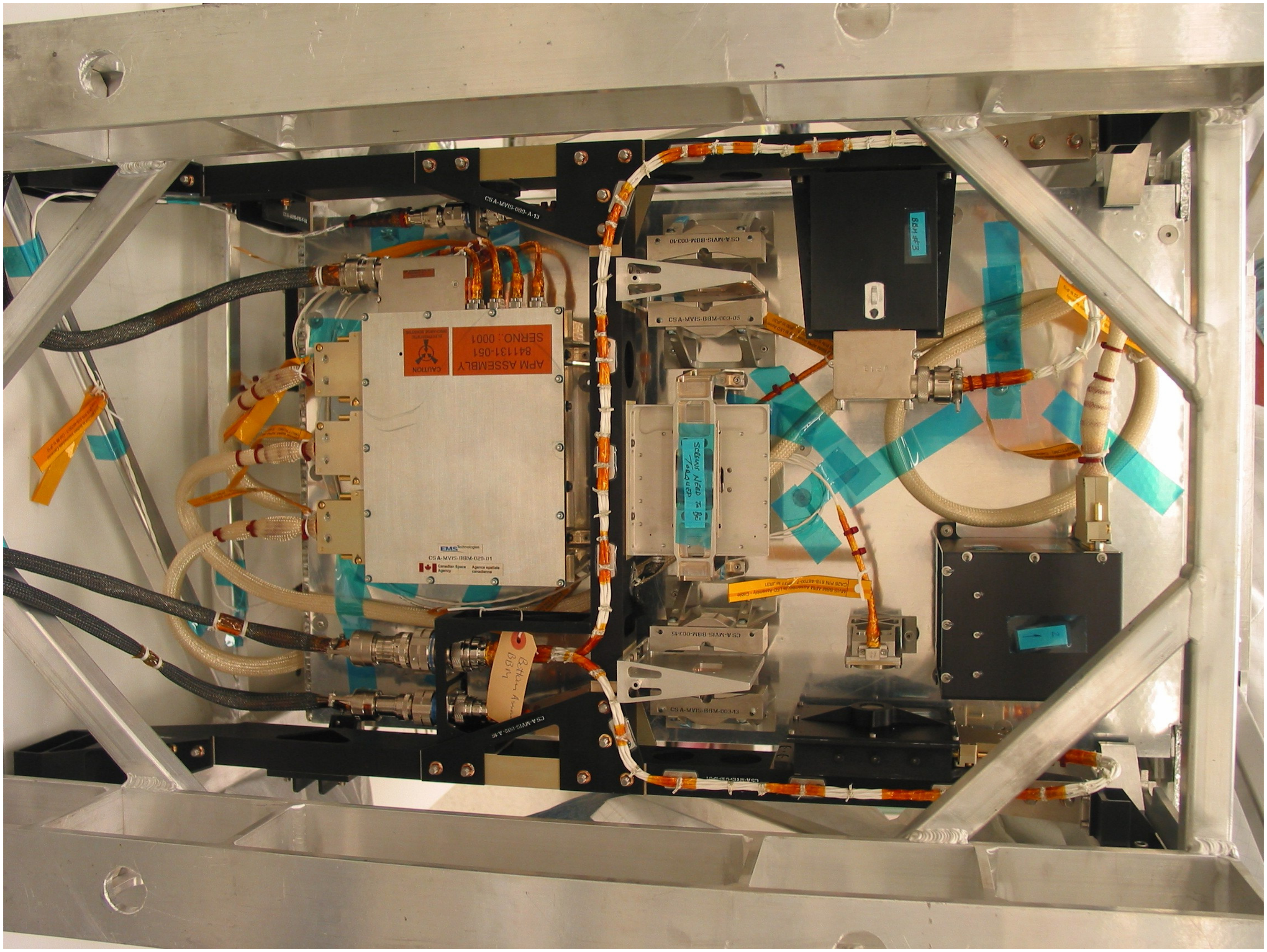
MVIS EU Box

**ESA Fluid Science Laboratory**

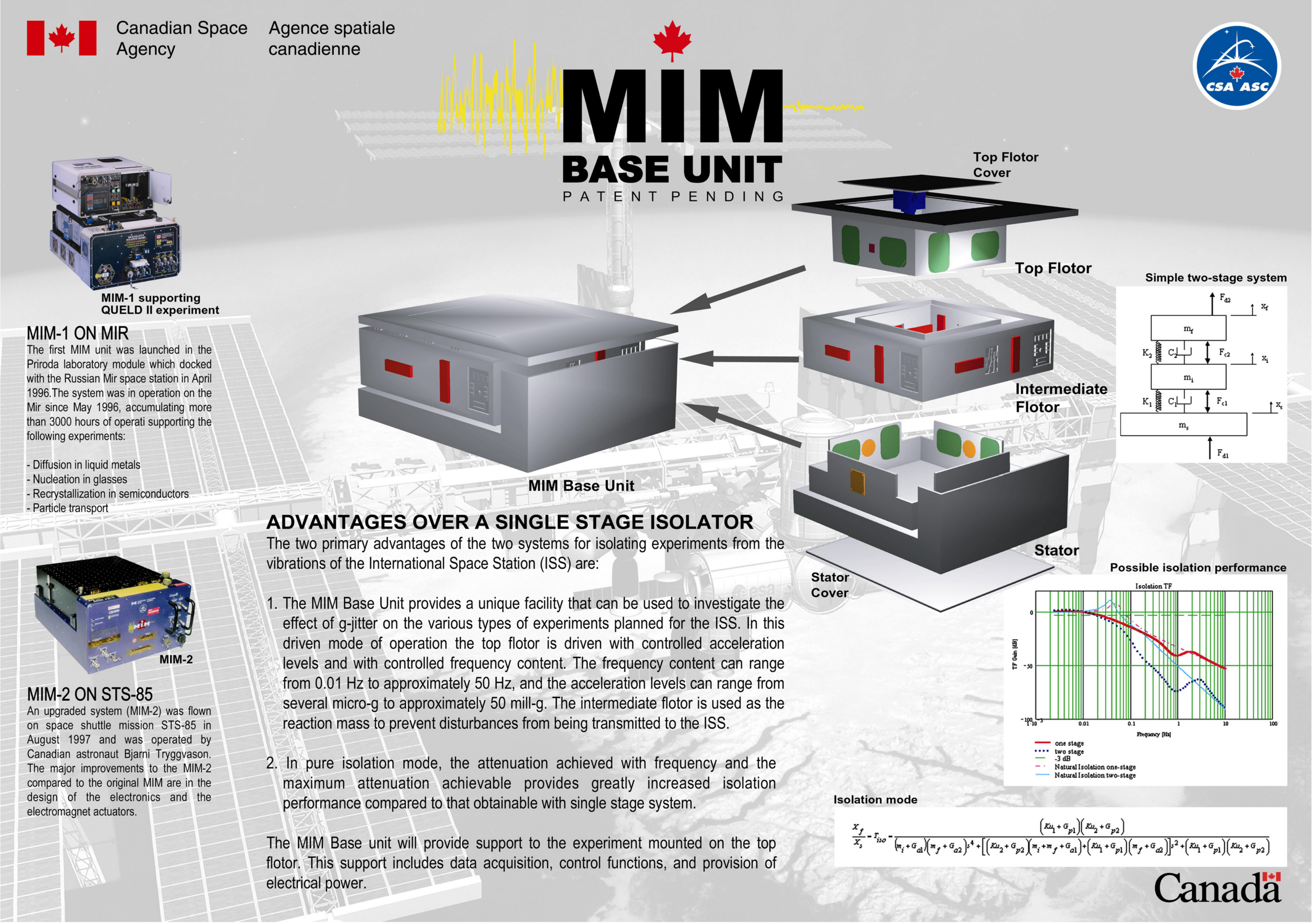
**MVIS**

# MVIS Engineering Model

# MVIS Engineering Model



# MIM Base Unit



Canadian Space Agency | Agence spatiale canadienne

## MIM BASE UNIT

PATENT PENDING

MIM-1 supporting QUELD II experiment

### MIM-1 ON MIR

The first MIM unit was launched in the Priroda laboratory module which docked with the Russian Mir space station in April 1996.The system was in operation on the Mir since May 1996, accumulating more than 3000 hours of operati supporting the following experiments:

- Diffusion in liquid metals
- Nucleation in glasses
- Recrystallization in semiconductors
- Particle transport

MIM-2

### MIM-2 ON STS-85

An upgraded system (MIM-2) was flown on space shuttle mission STS-85 in August 1997 and was operated by Canadian astronaut Bjarni Tryggvason. The major improvements to the MIM-2 compared to the original MIM are in the design of the electronics and the electromagnet actuators.

MIM Base Unit

### ADVANTAGES OVER A SINGLE STAGE ISOLATOR

The two primary advantages of the two systems for isolating experiments from the vibrations of the International Space Station (ISS) are:

1. The MIM Base Unit provides a unique facility that can be used to investigate the effect of g-jitter on the various types of experiments planned for the ISS. In this driven mode of operation the top flotor is driven with controlled acceleration levels and with controlled frequency content. The frequency content can range from 0.01 Hz to approximately 50 Hz, and the acceleration levels can range from several micro-g to approximately 50 mill-g. The intermediate flotor is used as the reaction mass to prevent disturbances from being transmitted to the ISS.

2. In pure isolation mode, the attenuation achieved with frequency and the maximum attenuation achievable provides greatly increased isolation performance compared to that obtainable with single stage system.

The MIM Base unit will provide support to the experiment mounted on the top flotor. This support includes data acquisition, control functions, and provision of electrical power.

Simple two-stage system

Possible isolation performance

Isolation mode

$$\frac{X_f}{X_s} = T_{iso} = \frac{\left(Ku_1 + G_{p1}\right)\left(Ku_2 + G_{p2}\right)}{\left(m_i + G_{a1}\right)\left(m_f + G_{a2}\right)s^4 + \left[\left(Ku_2 + G_{p2}\right)\left(m_i + m_f + G_{a1}\right) + \left(Ku_1 + G_{p1}\right)\left(m_f + G_{a2}\right)\right]s^2 + \left(Ku_1 + G_{p1}\right)\left(Ku_2 + G_{p2}\right)}$$

Canada

# The Effect of G-Jitter on Fluid Based Experiments