



Microgravity Environment on the International Space Station

Richard DeLombard
Glenn Research Center, Cleveland, Ohio

Kenneth Hrovat and Eric Kelly
ZIN Technologies, Inc., Brook Park, Ohio

Kevin McPherson
Glenn Research Center, Cleveland, Ohio

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Richard DeLombard
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Kenneth Hrovat and Eric Kelly
ZIN Technologies, Inc.
Brook Park, Ohio 44142

Kevin McPherson
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

ABSTRACT

The International Space Station is being assembled on-orbit to serve as a research platform for the next twenty years. A primary feature of this research platform will be its microgravity environment – an environment in which the effects of gravity are drastically reduced. A physical environment with very low-levels of acceleration and vibration has been accomplished by both the free fall associated with orbital flight and the design of the International Space Station. The International Space Station design has been driven by a long-standing, high-level requirement for a microgravity mode of operation.

Various types of data are gathered when science experiments are conducted, with common variables being temperature, pressure, voltage, and power. The acceleration levels experienced during operation should be factored into the analysis of the experiment results of most microgravity experiments. To this end, the NASA Fundamental Microgravity Research in the Physical Sciences program has had the Space Acceleration Measurement System recording the acceleration levels to support microgravity researchers for over twelve years of Shuttle missions, three years on Mir, and now nearly three years of International Space Station operations.

The Fundamental Microgravity Research in the Physical Sciences program also supports the Principal Investigator Microgravity Services project to assist the principal investigators with their analysis of the acceleration (microgravity) environment. The Principal

Investigator Microgravity Services project provides cataloged data, periodic analysis summary reports, specialized reports for experiment teams, and real-time data in a variety of user-defined formats. Characterization of the various microgravity carriers (e.g. Shuttle and International Space Station) is also accomplished for the experiment teams.

In the future, the Principal Investigator Microgravity Services project will provide a detailed predictive analysis of the microgravity environment for particular payloads in specified locations. This will assist greatly in the operational payload planning process. In addition, a neural-network-based system is planned which will automatically interpret the environment in real-time and present the results to users in an easily understood format.

Presented in this paper will be a short description of how microgravity disturbances may affect some experiment classes, a snapshot of the microgravity environment, and a view into how well the space station is expected to meet the user requirements.

ABBREVIATIONS AND ACRONYMS

ARIS	Active Rack Isolation System
ICE	ISS Characterization Experiment
ISS	International Space Station
MAMS	Microgravity Acceleration Measurement System
NASA	National Aeronautics and Space Administration
PIMS	Principal Investigator Microgravity Services
SAMS	Space Acceleration Measurement System
SOFBALL	Structures of Flameballs at Low Lewis Numbers
STS	Space Transportation System

INTRODUCTION

Many common, gravity-related phenomena are taken for granted, such as a helium balloon rising, bubbles rising in a pot of boiling water, the flat surface of a cup of coffee, and a stone sinking in a pond. Buoyancy and sedimentation occur due to the stratification effect of gravity on materials of different densities. The phenomena of many physical science experiments are adversely affected by buoyancy and sedimentation. Consequently, some science experiments are routinely placed in a microgravity environment where such gravitational effects are drastically reduced.

The apparent removal of the dominant 1-g force in a microgravity environment results in weaker forces, such as surface tension, becoming significant. While the drastic reduction of the 1-g effects is desirable to make weak forces more observable, mechanical vibrations from outside sources become significant and undesirable disturbances. Even though these disturbances are low in magnitude, they can be comparable to forces being investigated, such as surface tension. Therefore, the mechanical disturbances to which microgravity experiments are exposed need to be measured and considered in the analysis of the science data.

NOT JUST GRAVITY

Gravitational force is not the only force that is desirable to eliminate or reduce by conducting an experiment in a microgravity environment. Disturbances to experiments on the ISS may be caused by other forces, such as vibrations (e.g. pumps and fans), steady forces (e.g. atmospheric drag), and transient phenomena (e.g. valve operation). The magnitude of these forces range from 0.01-g (briefly for a thruster jet) to below one-millionth of 1-g (prolonged for atmospheric drag in orbit).

The impact of these disturbances are many and varied. Vibrations can cause non-linear effects in fluids, especially in fluids with mixtures of different density components, such as gas bubbles in a liquid. Mechanical vibrations may introduce significant energy into a cryogenic sample. Steady or nearly-steady (so called quasi-steady), low-level accelerations can cause sedimentation and/or convection in fluids with vastly different densities such as in a molten semiconductor compound in a furnace.

EFFECTS ON EXPERIMENTS

Only a few experiments are satisfied with an acceleration environment where only the gravitational force has been drastically reduced. Many of these are biological experiments where the time constants of change are hours, days, or weeks in which the integrated effects of 1-g dominates the integrated effects of the smaller forces.

Effects occur when unbalanced forces cause motion, quite often in experiments involving fluids, which are involved in nearly every microgravity science experiment. Fluids exist in microgravity experiments in the form of liquids (e.g. silicone oils and semiconductor melts), gases (e.g. hot combustion products), critical fluids (e.g. liquid helium), and granular solids.

Detrimental effects of fluid motion caused by external accelerations may appear to be due to scientific phenomena. Acceleration-driven convective flow in the Surface-Tension Driven Convection Experiment would have drastically reduced the science return.¹ During experiment operations on Space Transportation System (STS) -50, external-sourced vibrations were observed to cause drastic effects in the fluid sample chamber.

Knowledge of the acceleration environment is critically important for most microgravity experiments, whether the knowledge is from predictive analyses or from real-time measurements of the actual environment.

The microgravity environment requirements for classes of microgravity science payloads were collected to reaffirm the need for the ISS programmatic microgravity environment requirements.²

ACCELERATION AS A PARAMETER

Experiment and/or facility design incorporates parameter measurement (e.g. pressure and temperature) into the design of the experiment in unique methods according to the requirements of the experiment. In some cases, the design of such diagnostics is an engineering and scientific pursuit of its own.

Measurement of the acceleration environment for NASA microgravity space experiments was assigned to the NASA Glenn Research Center in 1986. Coupled with that measurement task is the analysis and dissemination of those data, thereby relieving the experiment teams of those specialized functions.

Some researchers measure the acceleration environment of their ground laboratories in order to better understand their experimental results when the experiment has been operated in a microgravity

environment. Examples of ground laboratory disturbance sources include elevator operations, air conditioning equipment, automobile and truck traffic, and laboratory personnel. Air conditioning equipment operation may be a large contributor to the acceleration environment of a ground laboratory due to the initial starting transients and the continuous vibrations of compressors as well as the disturbances from flowing room air.

Some researchers have used a controlled shaking of their experiment chamber to investigate the susceptibility of their experiment to vibrations. These results may lead to constraints on the design and operation of the experiment.

SUSCEPTIBILITY VERSUS ENVIRONMENT

The susceptibility of an experiment to acceleration inputs help to determine its acceleration environment requirements. If the experiment has a resonant frequency determined by its mechanical design, its susceptibility for disturbance by an acceleration is high at that frequency. Precautions must be taken to avoid mechanical resonance frequencies of the experiment chamber close to the frequencies of disturbance source frequencies. Such a problem came about during operations of the Fourth United States Microgravity Payload, one of two major payloads on STS-87. During the mission, vibrations from the thermal subsystem fans within one of the four experiments was found to interfere with the adjacent experiment, the Confined Helium Experiment. Real-time analysis during the mission resulted in compensation applied to the data from the affected experiment to counter the energy input from the vibrations.^{3,4}

On the other hand, if an experiment is found to be susceptible to disturbances, it may not be possible to compensate the experimental data nor modify the design of the experiment or disturbance source. In some cases, an operational remedy may be needed where the experiment is operated when the disturbance source is not present. The Structures of Flameballs at Low Lewis Numbers (SOFBALL) combustion experiment was found to be very susceptible to acceleration disturbances from Shuttle thrusters firing during the STS-94 mission. After this was discovered, the researcher requested that thruster jets be inhibited during future experiment operations of SOFBALL.⁵ Figure 1 shows the effect of thruster firings had on the thermal radiation levels. The remedy in this case was possible because the SOFBALL

experiment operations were short (< 2 minutes) since the Shuttle operational requirements would not allow longer time periods with inhibited thrusters.

VIBRATION ISOLATION

Early in the development stages of the ISS, requirements were introduced into the ISS program to ensure a quiet microgravity environment for extended periods of time. Figure 2 summarizes these requirements which are contained in ISS program documentation.⁶ Even though the ISS components and major elements have been designed, analyzed, and tested to meet these requirements, an active isolation mechanism was required at payload locations to reduce the disturbances to a level below that of the requirements. The Active Rack Isolation System (ARIS) provides mechanical isolation between an entire ISS payload rack and the rest of the ISS vehicle so that minimal vibrations are transmitted from the vehicle to the experiment payloads on that rack.⁷

There are other isolation systems designed for payload-level, experiment-chamber isolation. A vibration isolation system of this nature may be optimized for the experiment apparatus structural dynamics and the experiment phenomena's dynamics. Such systems may also provide an experiment with a programmed amount of vibration for sensitivity studies or for pre-mixing materials for an experiment.

ISS ENVIRONMENT

The Principal Investigator Microgravity Services (PIMS) project has developed standard methods of presenting the results of microgravity acceleration data. Assistance in understanding these data plots is available from PIMS increment reports and other products.^{8,9,10,11} In many of the vibratory regime plots, the levels from the ISS requirements document⁶ are shown for comparison with the actual or predicted environment. For explanations of the ISS environment to date, consult the PIMS increment reports.^{11,12,13,14}

The ISS operations have been designed in accordance with the long-standing requirements on acceleration levels at payload locations. During microgravity operational intervals of 30 days minimum, the ISS will be operated so the payload locations will encounter an acceleration environment at or below the levels specified in the requirement.⁶ All components of the ISS, including payloads, are subject to these requirements, the

only exceptions are some crew actions and safety contingencies.

The Boeing Company, the ISS prime contractor, is performing formal analyses to show that the ISS will meet the microgravity environment requirements. Results from current analyses show that the ISS will meet most of the microgravity environment requirements when the ISS assembly is complete.^{15, 16, 17} The results show an exceedance in the quasi-steady regime where only 14 rack locations (16 are required) are in compliance.¹⁵

The ARIS ISS Characterization Experiment (ARIS-ICE) tests were conducted on the ISS from June 2001 to June 2002 and again through November 2002. The results demonstrated that the ARIS system will be effective in reducing the transmission of vibrations from the ISS to payloads in ARIS-equipped racks (Figure 3).⁷

The Space Acceleration Measurement System (SAMS) data from the ISS indicates a trend that the environment will meet requirements when the assembly is complete and microgravity operational conditions are imposed. The data included in the analysis of Figure 4 represents a relatively quiet period of ISS operations although the ISS is not yet operated in a strict microgravity mode of operation. This plot shows the environment to be below the required levels across most of the spectrum for the vast majority of the time.

The Microgravity Acceleration Measurement System (MAMS) data from the ISS indicates that the quasi-steady environment will not meet the formal requirements either by the number of racks and/or acceleration levels. Utilizing MAMS quasi-steady data, a PIMS analysis estimated the acceleration levels for each payload rack location for the ISS configuration at Assembly Complete, Figure 5. This shows that no racks (as opposed to the 16 specified by the requirements) will have the required quasi-steady levels. However, for most of the racks, the numeric deviation of the perpendicular components with respect to the requirements approaches the accuracy of the MAMS data. Additionally, no attempt was made to adjust for the difference in drag effects or ISS principal axis offset at Assembly Complete. These factors can affect the outcome of the analysis significantly.

The ISS Program has periodically prepared an analysis of the vibratory acceleration environment of the ISS non-isolated racks. This is the environment seen by a payload mounted in the laboratory module, but outside of an ARIS rack. Preliminary results from the Non-

Isolated Rack Assessment predict, at Assembly Complete, the levels shown in Figure 6.¹⁸ These levels are shown with the ISS vibratory requirement levels as a comparison, but it must be noted that the ISS is not required to meet these levels outside of the ARIS racks. As explained earlier, the ARIS will reduce the non-isolated rack levels for the payloads mounted in ARIS-equipped racks.

These various analyses will be updated as the ISS is constructed further and the microgravity environment changes accordingly. Measured data will continue to be compared with analyses.

The PIMS ISS environment analyses to date have primarily concentrated on identifying the source of the disturbances seen in the measured data. These disturbances include vehicle docking, reboost, subsystem equipment, payload equipment, crew actions (e.g. exercise and extra-vehicular activity), venting, and vehicle orbital attitude. Many of these disturbances will not be present during microgravity mode operations by definition of that operational mode. These analyses will result in an understanding of the environment (in particular, the sources of disturbance) in preparation for ISS payload support during microgravity mode operations after ISS Assembly Complete.

MICROGRAVITY ENVIRONMENT INTERPRETATION

The PIMS project offers educational opportunities to principal investigators and their team members to better understand the microgravity environment and its influence on their experiment. The Microgravity Environment Interpretation Tutorial⁸ is offered annually at the NASA Glenn Research Center with no registration fee for this three day tutorial. The participants acquire a better understanding of the microgravity environment and are therefore better prepared for conducting their experiments in a microgravity environment or supporting those who do.

The PIMS project analyzes acceleration data from the SAMS and the MAMS instruments on-board the ISS in order that the microgravity environment may be understood and possibly correlated with science experiment results. A real-time computer system receives the SAMS and MAMS data streams and processes standard data plots which are made available for all users on the World Wide Web.¹⁹ The PIMS analysis results are published in periodic reports of the microgravity environment for the ISS increments.^{11, 12,}

^{13, 14} Events during the operation of the ISS are included in these analyses, such as vehicle docking, extra-vehicular activity, reboost operations, and experiment operations.

For measurements during experiment operations, the SAMS and PIMS projects can help plan the acquisition of appropriate acceleration data. If necessary, arrangements may be made to install a SAMS sensor on or near an experiment, PIMS can then provide standard and custom analyses of the measured data for the PI team.

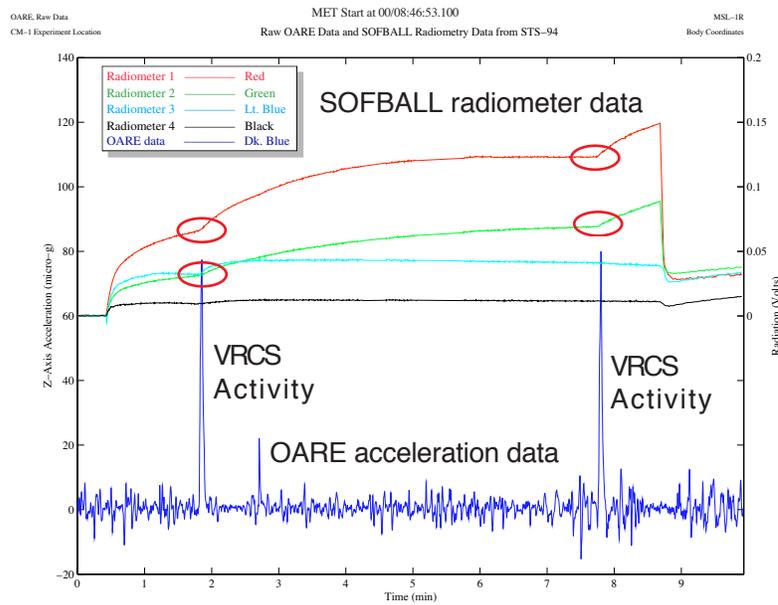
SUMMARY

The ISS microgravity environment appears to be on-course for levels as required and planned for microgravity science experiment operations on the ISS.

The PIMS, SAMS, and MAMS teams are chartered to support the microgravity environment needs of the PI teams. For current and/or future support, contact PIMS now.

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MEIT 2002 Figure 13-4: Raw OARE Data and SOFBALL Radiometry Data from STS-94 (MSL-1R)

Figure 1: SOFBALL radiometer data affected by thruster firings. Ovals indicate changes in radiometer data as a result of the accelerations experienced from the Orbiter's Vernier Reaction Control System (VRCS) thrusters firing.⁵

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
- $g \leq 10 \mu g\text{-sec}$ per axis (integrated over 10 sec)

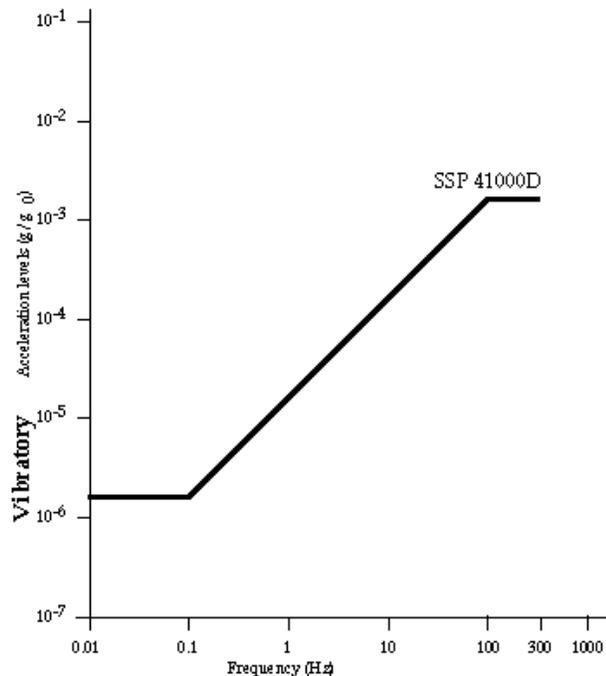


Figure 2: ISS microgravity requirements summarized from ISS program documentation. The microgravity operations will be during 30 day (minimum) intervals with a total of 180 days per year.⁶

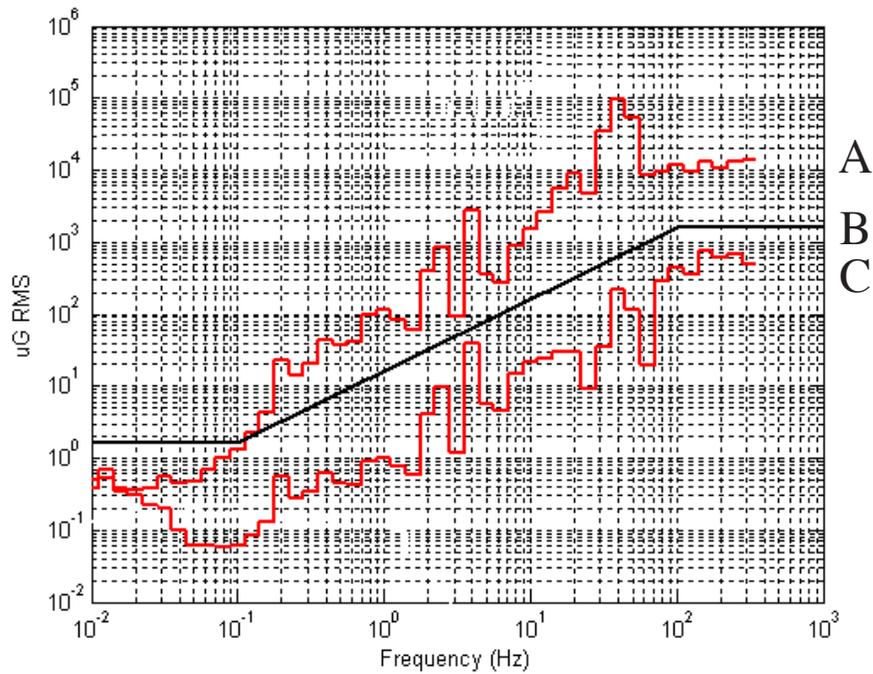


Figure 3: Typical measured acceleration levels during ARIS-ICE operations. Line A is the vehicle off-board environment. Line B is the ISS programmatic requirement level for the vibratory regime. Line C is the environment on-board an ARIS rack. ARIS reduces the off-board levels to on-board levels which are lower than the required environment levels. (ARIS-ICE data processed by The Boeing Company.¹⁶)

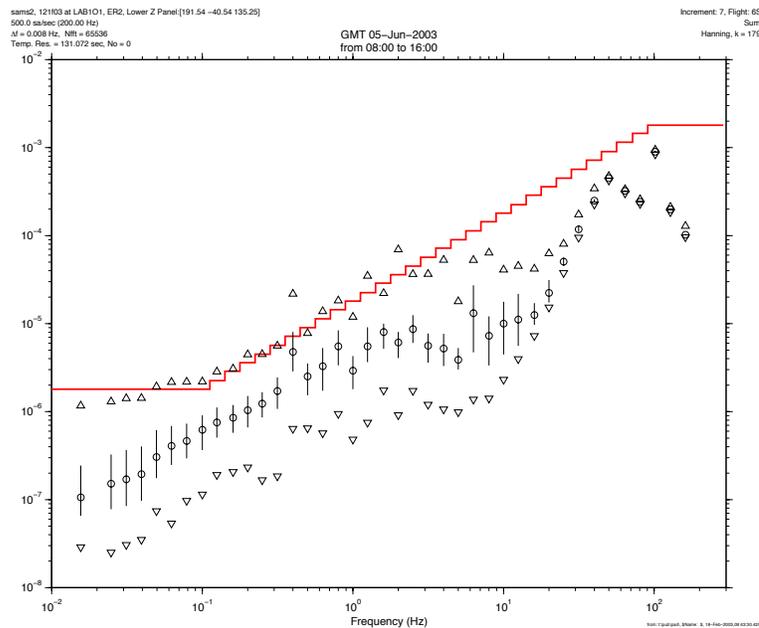
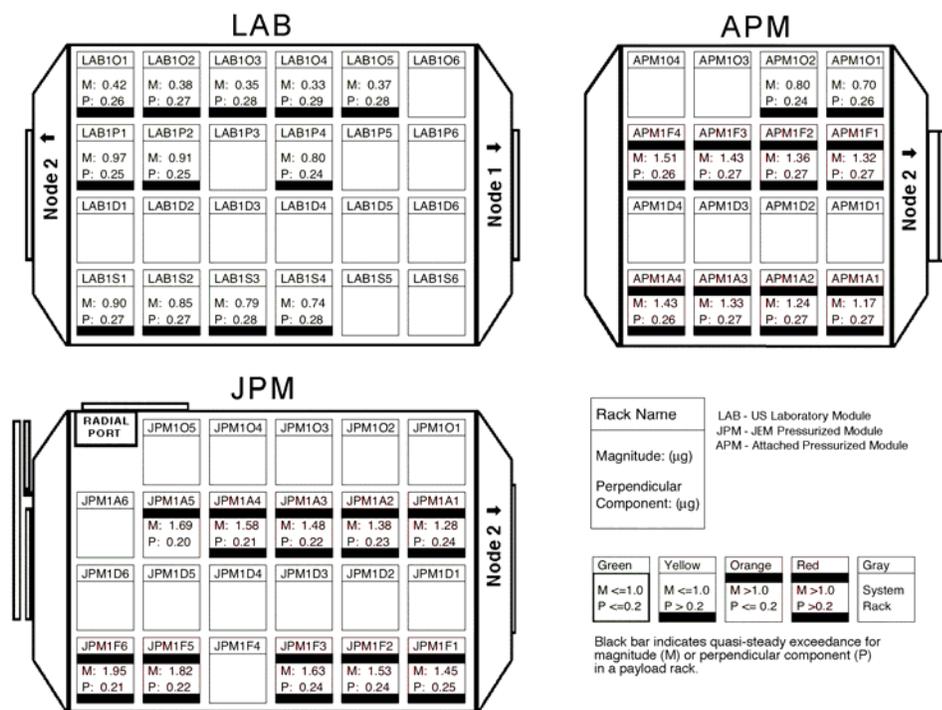


Figure 4: One-third-octave quartile plot of ISS vibratory environment during nominal crew activities on June 5, 2003. The upper symbol in each one-third octave is the maximum value, the vertical line indicates 25 to 75 percentile, and the lower symbol is the minimum value. The circle indicates the median of the data for each one-third octave band. The ISS vibratory requirement level is shown for comparison. (SAMS data processed by PIMS.)



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Figure 5: Quasi-steady acceleration levels predicted for Assembly Complete in the U.S. Laboratory module, Destiny. The black bar in the rack location graphic denotes exceedance of the requirement for either magnitude or the perpendicular component. (PIMS analysis of MAMS data.)

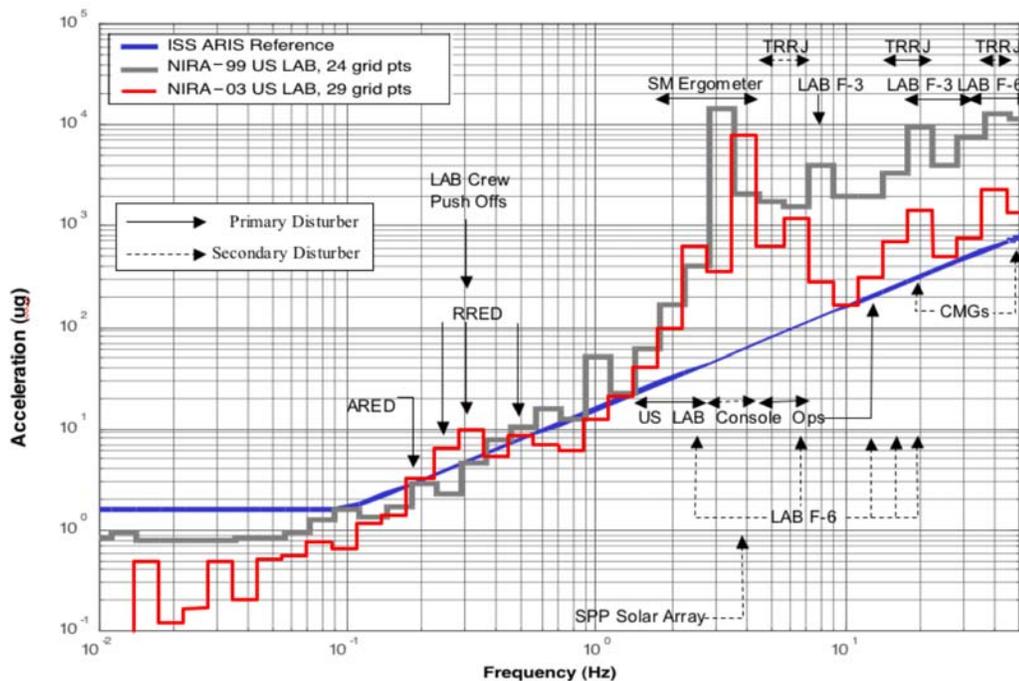


Figure 6: Preliminary assessment of vibratory environment of a non-isolated rack in the ISS Destiny laboratory module.¹⁸

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