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p. 17**REVIEW OF EUROPEAN MICROGRAVITY MEASUREMENTS****H. Hamacher**

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ABSTRACT

European efforts to characterizing the microgravity (11g) environment within a space laboratory began in the late seventies with the design of the First Spacelab Mission SL-1. Its Material Science Double Rack was the first payload element to carry its own tri-axial acceleration sensor package. Even though incapable for any frequency analysis, the data provided a wealth of novel information for optimal experiment and hardware design and operation for missions to come. Theoretical investigations under ESA contract demonstrated the significance of the detailed knowledge of μg data for a thorough experiment analysis. They especially revealed the high sensitivity of numerous phenomena to low frequency acceleration. Accordingly, the payloads of the Spacelab missions D-1 and D-2 were furnished with state-of-the-art detection systems to ensure frequency analysis between 0.1 and 100 Hz. The Microgravity Measurement Assembly (MMA) of D-2 was a centralized system comprising fixed installed as well as mobile tri-axial packages allowing real-time data processing and transmission to ground. ESA's free flyer EURECA carried a system for continuous measurement over the entire mission. All EURECA subsystems and experiment facilities had to meet tough requirements defining the upper acceleration limits. In a French / Russian cooperation, CNES developed a microgravity detection system for analyzing the Mir space station μg -environment for the first time. An approach to get access to low frequency acceleration between 0 and 0.02 Hz will be realized by QSAM (Quasi-steady Acceleration Measurement) on IML-2, complementary to the NASA system Spacelab Acceleration Measurement System SAMS. A second flight of QSAM is planned for the Russian free flyer FOTON.

INTRODUCTION

Experimentation under microgravity has been a focal point in Europe's space utilization since the late seventies when NASA and ESA agreed to develop Spacelab and to fly it in a first joint Mission SL-1 in 1983. About two-thirds of the European experiments carried out in SL-1 were investigations in materials science and fluid physics which made use of the greatly reduced level of gravitation. Even more microgravity experiments were performed in the Spacelab missions with European involvement which followed SL-1. The German Spacelab missions D-1 and D-2 (1985 and 1993, respectively) were especially dedicated to microgravity experimentation. ESA designed the unmanned free flier EURECA

(European Retrievable Carrier) which was launched by the Space Shuttle in 1992 to stay in a 500 km orbit for about a year. EURECA-1 carried a nearly 100% microgravity payload. European scientists also participate with microgravity experiments in the IML flights, USML and USMP. They also contribute μg -experiments to the Russian space station Mir and other flight opportunities like the free flying capsule FOTON.

Almost all European microgravity investigations have been accompanied by efforts to measure the residual acceleration occurring during the experiment's running time. It started with a single measuring device within the Materials Science Double Rack (MSDR) of SL-1. In contrast to that, the payload of D-2, brought into orbit a decade later, was equipped with the centralized Microgravity Measurement Assembly (MMA) which comprises fixed installed as well as mobile sensors packages. It allowed to transmit real time acceleration data to ground during the mission enabling the experimenters to judge whether the experimental conditions have been met or not. This is the concept ESA anticipates to apply on Columbus.

It was recognized very soon that microgravity analysis must be guided by the needs of the physical phenomena to be investigated. Like NASA, ESA supported studies to analyze the susceptibility of the physical phenomena to residual acceleration [1-5]. Chief results were sensitivity curves indicating the level of continuous sinusoidal acceleration which is tolerated by an experiment versus frequency. Examples are shown in Fig. 1. The investigations yielded the following results:

1. Experiments are only sensitive to accelerations within a limited bandwidth. A range between 0 (d.c.) and 100 Hz is regarded to cover the requirements for all Spacelab type experiments.
2. The tolerated acceleration is lowest at low frequencies and increases towards higher frequencies.

These results have been applied for the definition of measurement and characterization requirements which usually consist of the following steps:

i) On-board Measurement

The *low frequency range* is characterized by low level acceleration typically $< 10^{-6}$ g, (Fig. 1). It requires

- (i) sensor sensitivity better than 10^{-7} g
- (ii) in-orbit calibration and sufficient zero point stability between the calibrations.

Since the low frequency range is usually below the spacecraft's fundamental frequency f_f , a single point measurement is sufficient to determine the entire low frequency field from rigid body dynamics. To characterize the *high frequency regime*, ranging from the vicinity of the fundamental frequency to the upper limit, local measurements as close to the experiments as possible are indispensable.

ii) Modeling

Microgravity characterization cannot be accomplished by measurement alone. Some locations within the spacecraft might not be accessible, e.g. a materials sample within a furnace. In such cases the

mechanical transfer function between the location of the perturbing force and the sample has to be known to calculate the acceleration at the location of interest from the on-board measurements.

The microgravity activities in Europe either directed by ESA or by national agencies aim to contribute to these tasks. In the following, some of the activities are described in more detail.

I. MICROGRAVITY MEASUREMENT ACTIVITIES

A. Spacelab

SL-1 Mission (1983): The Material Science Double Rack (MSDR) was one of the first payload elements to be equipped with an accelerometer package for monitoring the microgravity environment [6]. Even though operated in a peak detection mode to reduce the amount of data, the system provided valuable data for scientists as well as for design and system engineers. These early data revealed the order of magnitude of residual acceleration attainable in Spacelab experiment rack. Some results were truly unique. Owing to the fact that the Space Shuttle in its early (verification) flights was equipped with extensive auxiliary measurement devices, it was possible to correlate the data of the MSDR sensor to these measurement results. As an example, a stick-slip event, monitored by a strain gauge at the flange connecting the Transfer Tunnel with the Spacelab module, could be correlated to a sharp spike in the μg -recording within the MSDR as shown in Fig. 2. This occurrence is an example of a stochastic event which cannot be explained in nowadays Spacelab missions. SL-1 also gave the first valuable experience on how to correlate acceleration data to the disturbing sources. It turned out that continuous onboard video recordings are indispensable means for microgravity data interpretation.

D-1 Mission (1985): Each microgravity payload element of that mission carried at least one accelerometer [7,8]. High frequency signal sampling ensured frequency sufficient for all experiments and, in combination with extensive onboard video recordings, data correlation to perturbations for many events. It gave some novel insights into Spacelab's in-orbit dynamics and the spectral composition of its acceleration (Fig. 3). The achievements effectively forwarded our knowledge to improve experiment hardware design and operation. It demonstrated Spacelab's excellent capability as a carrier for microgravity payloads.

D-2 Mission: Despite these accomplishments, D-1 also indicated difficulties in the analysis of data measured by different autonomous systems especially if, for example, exact time correlation is required. Various investigations, such as transfer function measurements for structural dynamics experiments, call for precise time correlation and accuracy of the data. It was for this and some other fundamental reasons that Spacelab D-2 was equipped with a centralized system, the Microgravity Measurement Assembly

(MMA) [9]. It comprises six triaxial sensors, four of which permanently mounted in experiment racks and two mobile sensor packages which allowed investigation of the acceleration across the entire Spacelab module (Fig. 4). The MMA makes use of a new generation of small size micro-mechanical accelerometers developed by CSEM (Centre Suisse d'Electronique et de Microtechnique S.A.), Switzerland, under ESA contract [10]. This development is aimed at a miniaturization of the sensor to allow its installation as closely to the experiment as possible. The key element is an electromechanical silicon chip as shown in Fig. 5. A movable plate, suspended by flexure bars, deflects from its neutral position under the action of acceleration applied perpendicular to the plate. This deflection is transformed to an electrical signal by measuring the change in capacitance between the plate and the electrodes placed on either side of the housing walls. The chip itself has a dimension of 7 mm x 3.6 mm x 1.4 mm. Its resonance frequency is 700 Hz near critical damping. Another novel feature of the MMA was real-time data transfer capability to ground. During the mission, processed μg data were available for the experimenters in the Payload Operations Control Center in Oberpfaffenhofen, Germany to judge whether the experimental condition had been met. This principle is intended by ESA to be applied on Columbus for interactive experimentation. The MMA also comprised an impulse hammer to measure the structural transfer function under microgravity conditions [11]. The D-2 μg characterization program also included acceleration measurements on ground on the integrated Spacelab prior the mission during the Mission Sequence Test. The intention was to investigate to what extent the spacecraft in-orbit vibration behavior can be predicted from ground measurements.

The lower detection limit of the MMA was 0.1 Hz which excluded the measurement of low frequency acceleration. For that reason a calculation program has been applied to estimate the main contributions by atmospheric drag, gravity gradient (tidal) and rotational acceleration (Fig. 6) [12]. An instrument (QSAM: Quasi-steady Acceleration Measurement) is under development for the IML-2 mission allowing access to the low frequency range between 0 and 0.02 Hz. Continuous zero-offset elimination is achieved by periodic signal modulation. This is achieved by flipping the sensor sensitive axis every 10 sec [13].

B. EURECA

This automated platform allowed to perform long lasting microgravity experiments in its first mission EURECA-1 (Fig. 7). To minimize the orbit decay during the eleven month flight the carrier was flown in a 500 km orbit which ensured a level of drag acceleration in or below the 10^{-6}g range. An upper limit of residual acceleration was defined between 0 and 1000 Hz as shown in Fig. 8. Various design features had been determined to minimize EURECA's residual acceleration level in the low frequency as well as in the high frequency range. For the first time in microgravity experimentation, all subsystems

and experiment facilities had to meet stringent requirements which defined maximum acceleration limits at their interfaces. This had to be verified by analysis and test. The platform itself was equipped with a Microgravity Measurement System (MMS) which allowed continuous measurement over the entire mission duration with a bandwidth between 0 and 5 Hz [14]. Figure 9 shows a plot of the acceleration which occurred during a thruster firing. Preliminary data are given in [15].

C. Russian Missions

European scientists also participate with microgravity experiments on Russian flight opportunities like the space station Mir and the free flying capsule FOTON. In a French / Russian cooperation, CNES developed and provided the technology experiment "Microaccelerometre" which was especially dedicated to characterize the residual acceleration. It was the first systematic effort to analyze the Mir μg - environment. Measurements were taken at some 80 locations across the station during characteristic operation phases like working and sleeping periods, orbit maintenance and docking maneuvers. The bandwidth was between 0.1 and 400 Hz [16].

The German Space Agency DARA anticipates to fly a QSAM-type measurement system on the free flying capsule FOTON in 1995. This carrier is expected to provide a very low μg -level. All experiment facilities provided by DARA for the EuroMir Mission 1995 will also be equipped with accelerometer packages.

II. STUDIES

Quite a number of studies have been performed or are under way dealing with modeling, prediction and measures to prevent or to reduce residual acceleration. A great number of the studies supported by ESA are related to the Columbus microgravity environment. As an example, an active suspension system (Microgravity Isolation Mount, MGIM) has been designed under ESA contract to isolate sensitive experiment facilities from the vibrating spacecraft structure. Other studies deal with systematic identification of the perturbation sources and their reduction, and the computational modeling to predict the broad band vibration response spectra [11, 17].

III. OUTLOOK

The European activities in the field of microgravity measurement were always characterized by close cooperation with international partners. Microgravity data of Spacelab Missions are extensively exchanged between NASA and ESA. The upcoming Spacelab Mission IML-2 (Second International Microgravity Laboratory) is an excellent demonstration of the intensive international cooperation in this field. Scientists from the United States, Japan and Europe participate in that mission to measure the

residual acceleration and to test novel sensor systems and means to isolate vibrations. NASA's Space Acceleration Measurement System SAMS and the European QSAM are complementary instruments for characterizing the residual acceleration of the entire Spacelab. A great deal of these fruitful collaborations has been initiated by the Microgravity Measurement Group (MGMG) an international advisory group established and organized by NASA. It is our pleasure to acknowledge the outstanding contribution of Gary Martin of NASA Headquarters and Charles R. Baugher of NASA Marshall Space Flight Center.

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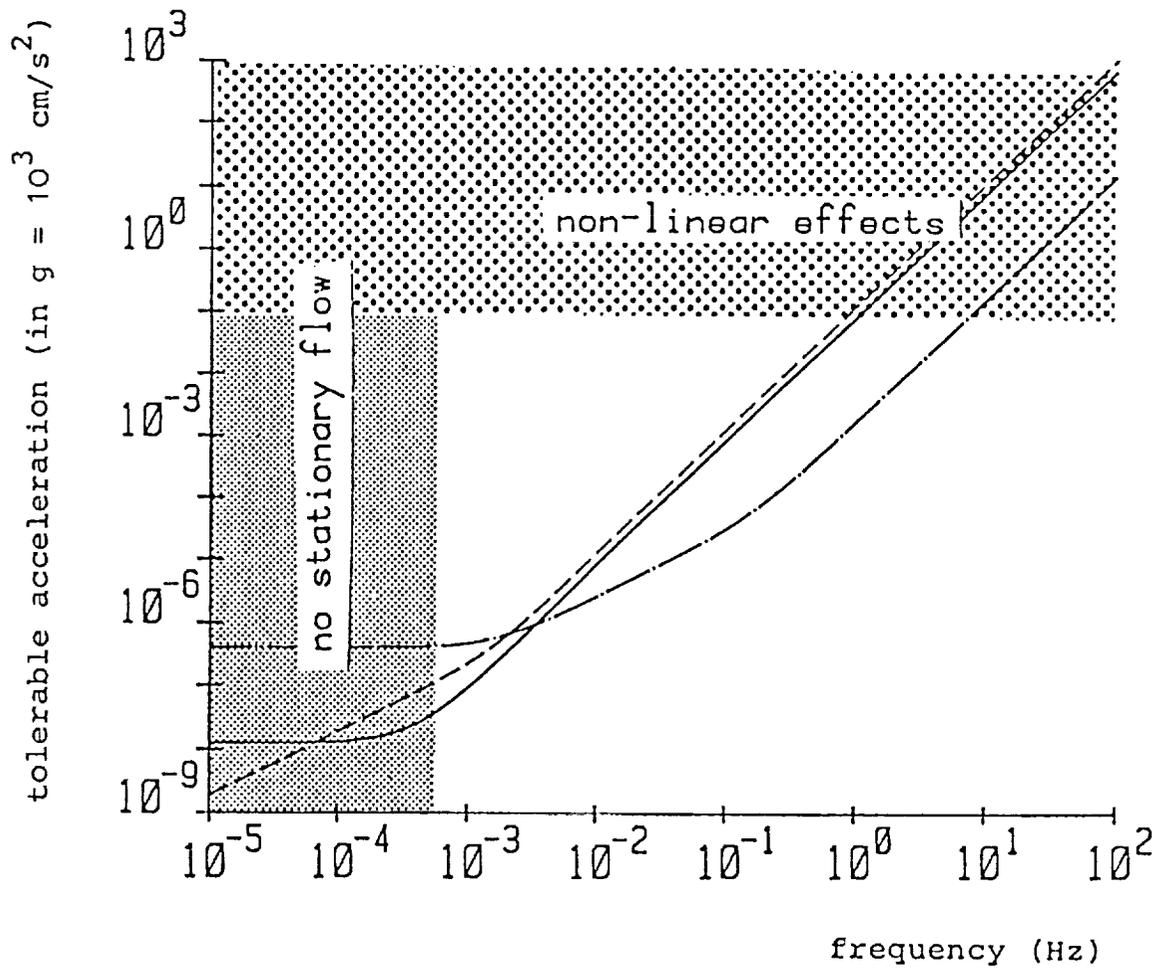


Figure 1 The tolerable residual acceleration in
 _____ a fluid physics experiment involving a temperature gradient,
 - - - - - a crystal growth experiment by the THM method,
 - · - · - an experiment on thermodiffusion; [1]

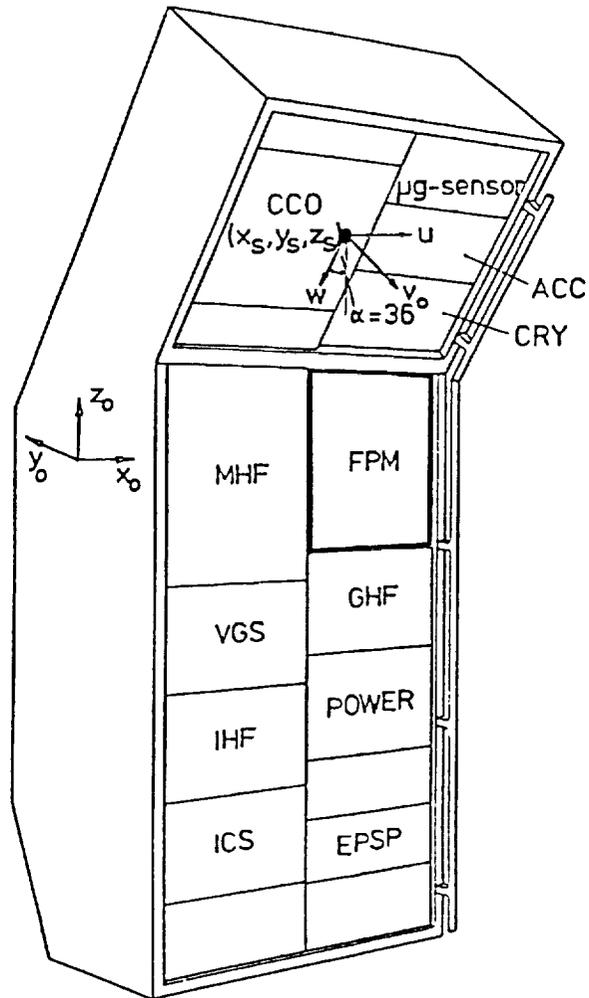


Figure 2 Material Science Double Rack (MSDR) and coordinate system of the μg -sensor of SL1.

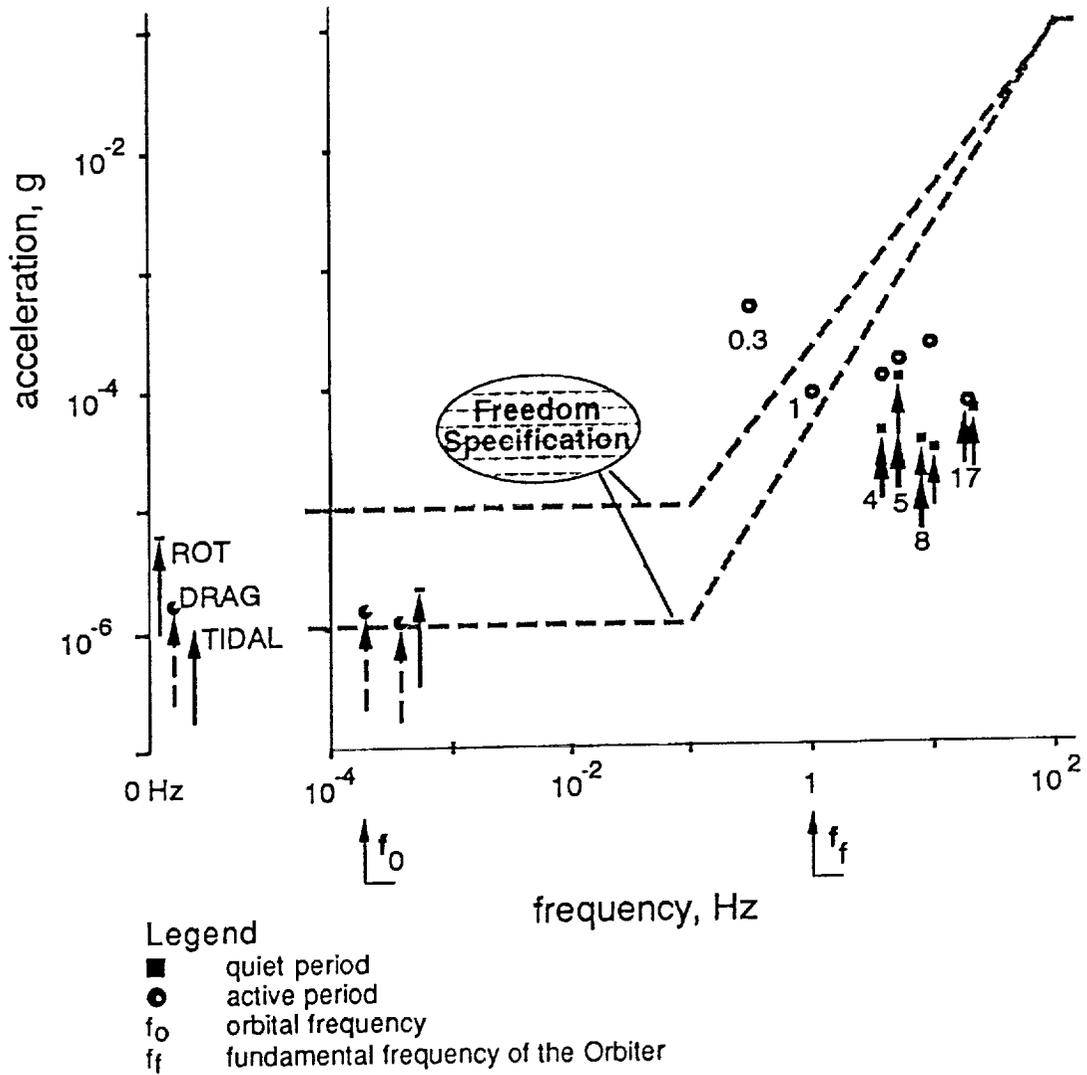


Figure 3 Spectral composition of the Spacelab's acceleration (D-1 mission) compared to the space station.

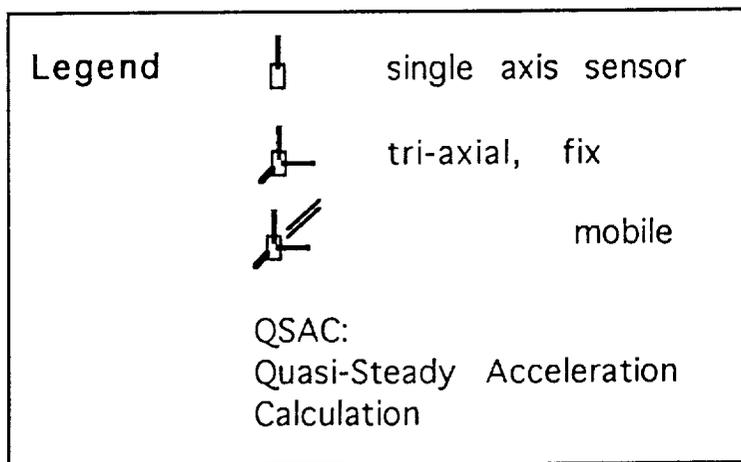
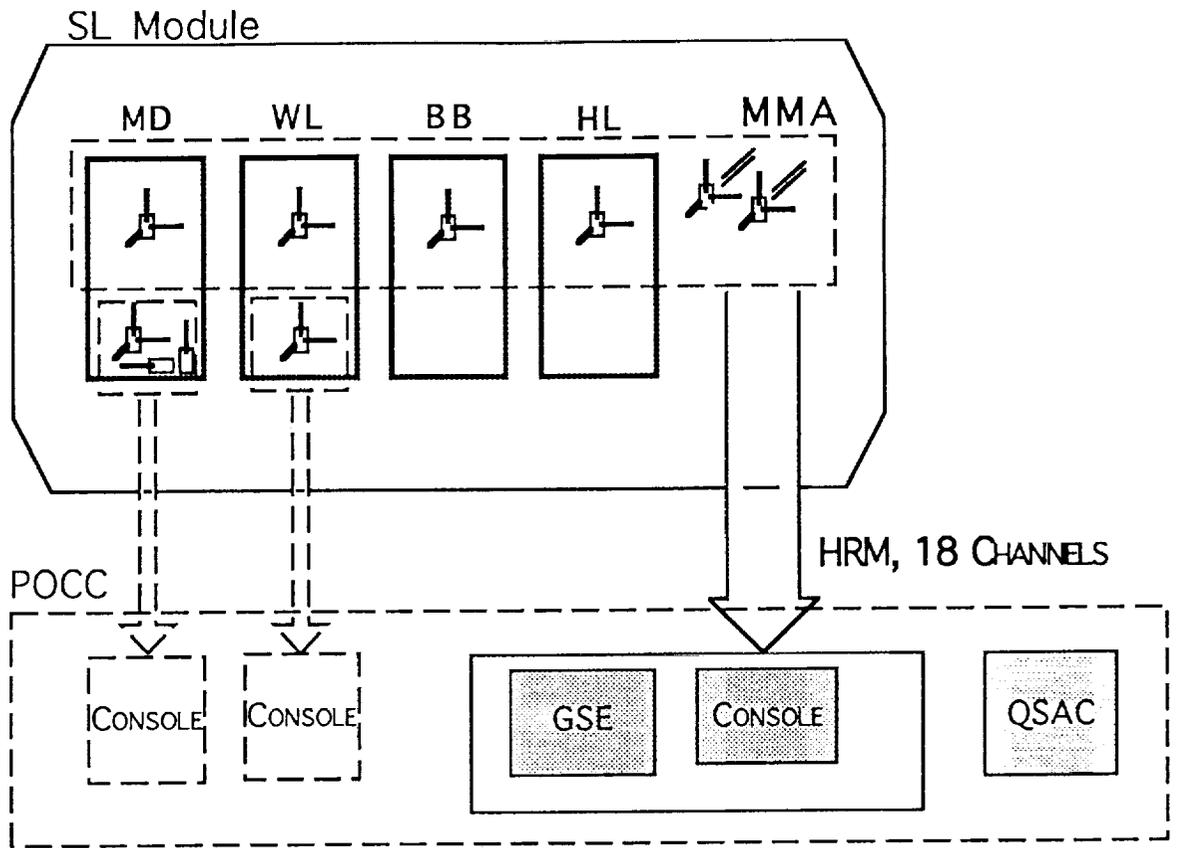


Figure 4 MMA sensor location and data transmission.

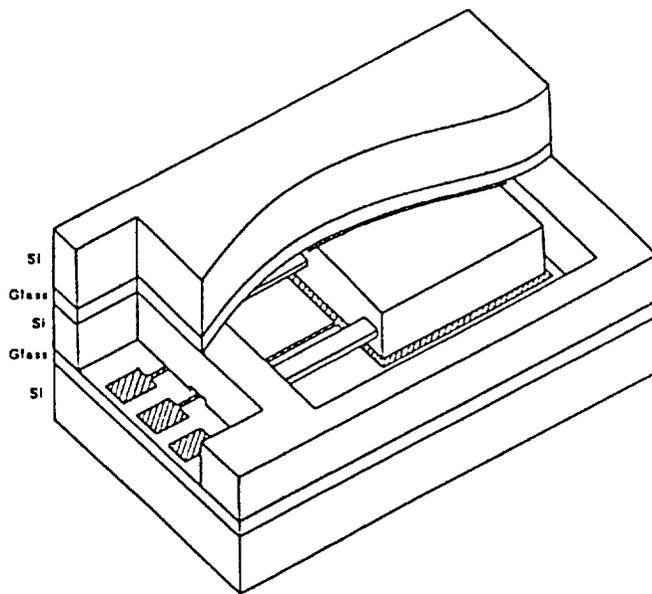


Figure 5 The CSEM accelerometer applied to the MMA. The top plates have been partially cut away to show the spring-mass system and the fixed electrodes.

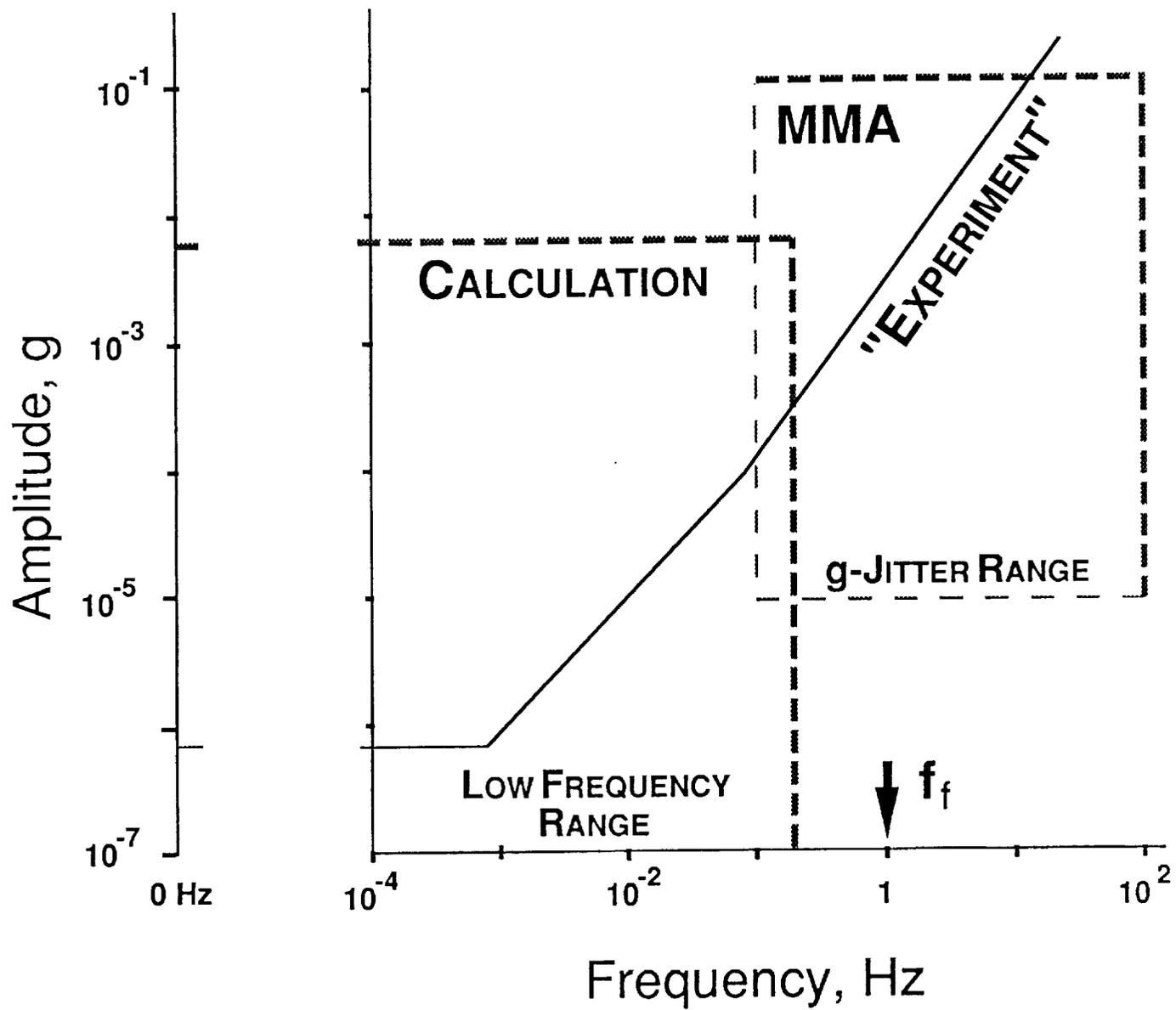


Figure 6 Detection Range of the MMA and low frequency range to be calculated.

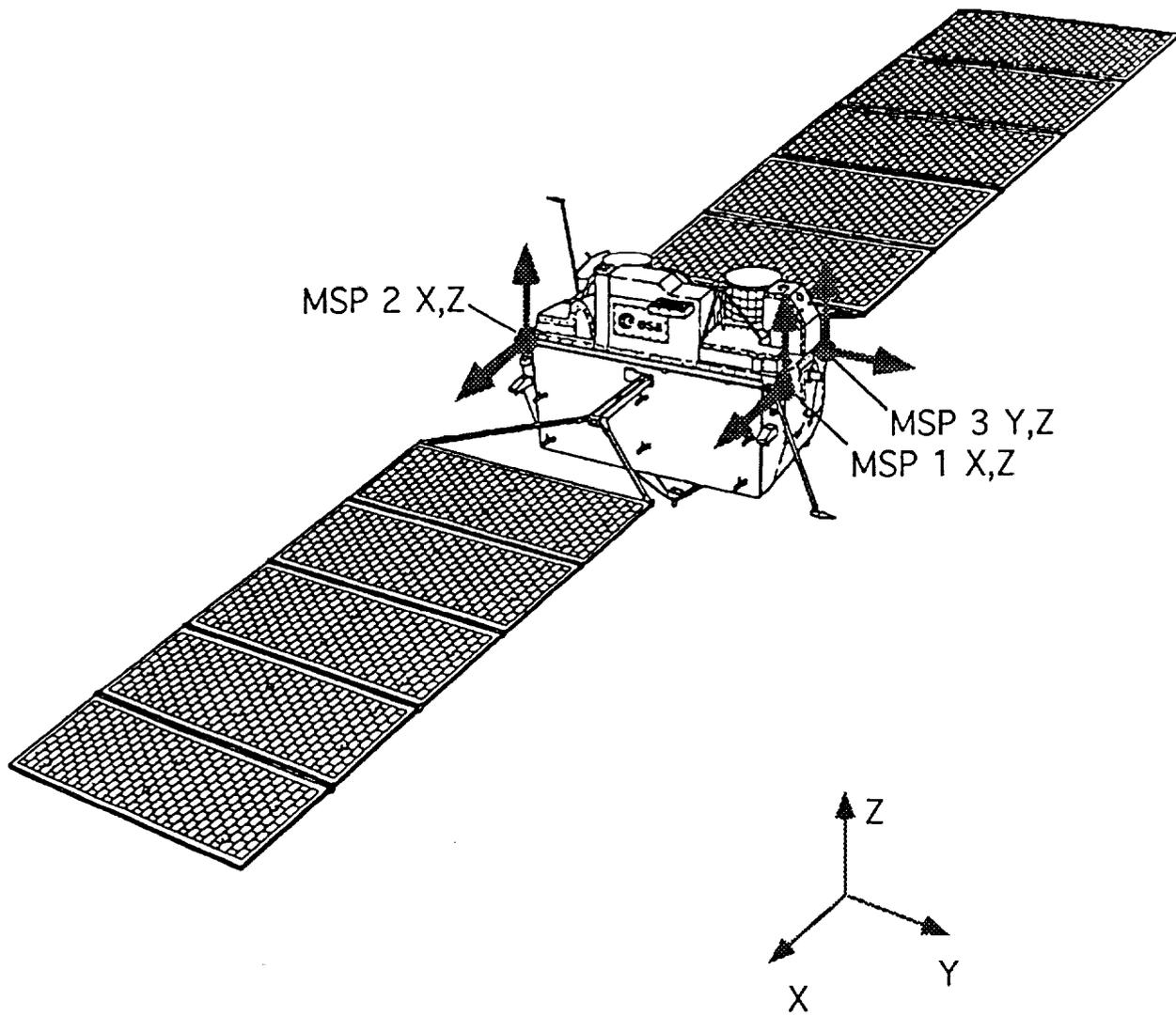


Figure 7 EURECA configuration and MMS sensor location and orientation of sensitive axes.

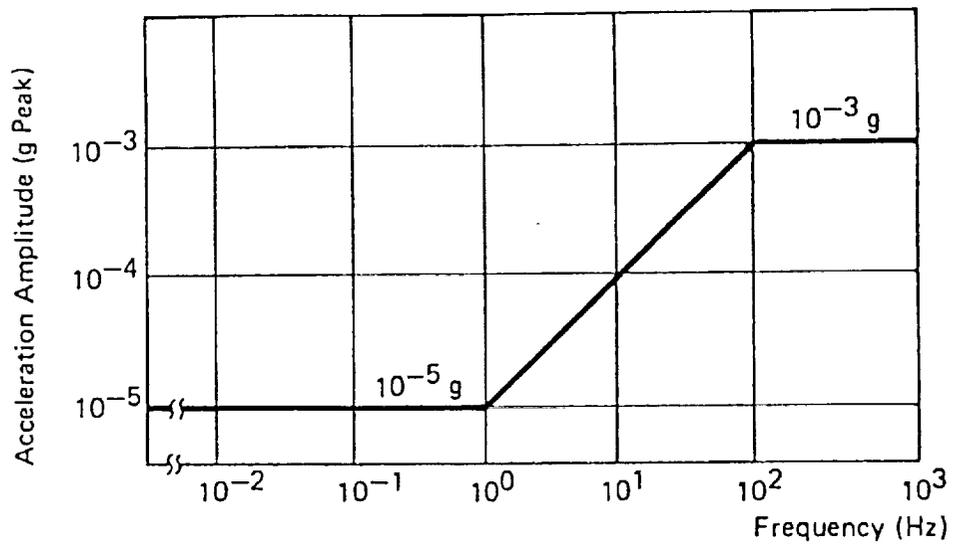


Figure 8 EURECA microgravity environment design specification [14].

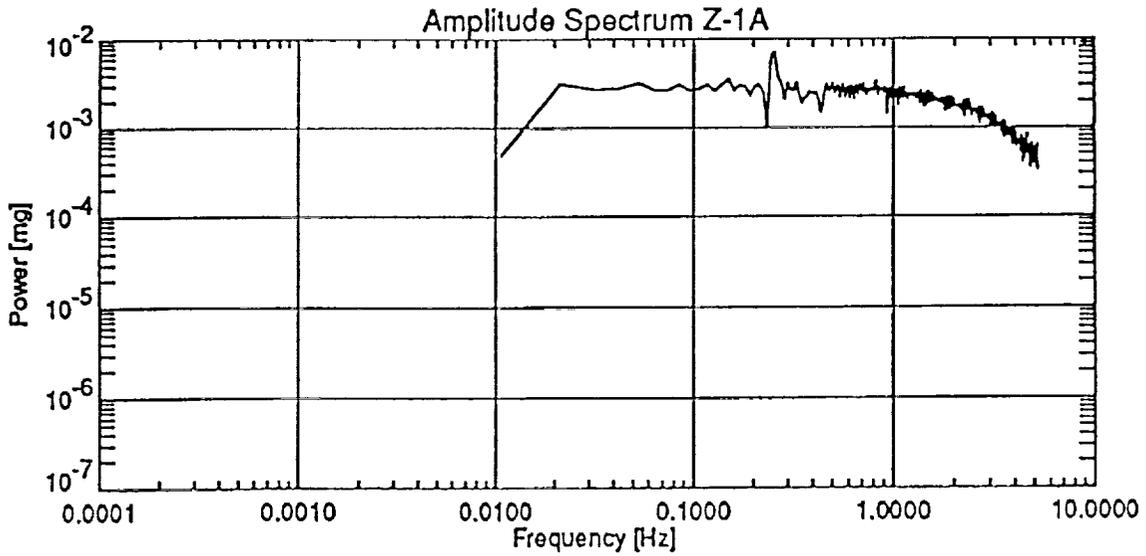
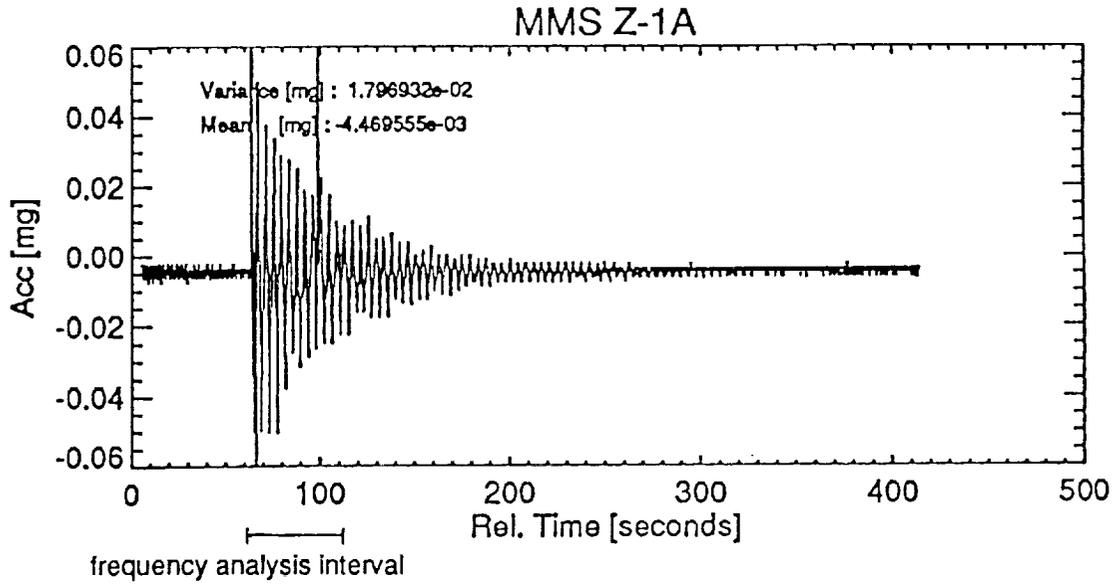


Figure 9 EURECA acceleration during a hydrazine thruster firing.

Discussion

Comment: (Dr. Bonnie Dunbar) *When we take the measurements during a flight on crew activity it is probably going to be helpful to interview the crew afterwards about their approach to it and I can give you some insights to it on D-1 versus USML-1. First of all, going back to D-1 and to Spacelab-1. Spacelab-1 was a 10 day flight. D-1 was a 7 day flight. D-1 also had a mix of disciplines. We did have the vestibular sled on that flight and we had the SPARS palette in the back which required Earth pointing. So the mission attitude was split about half and half, between the gravity gradient attitude and the other half bay to the Earth attitude and that rotation occurred at least once a day. And although the crew were sensitive to the microgravity experiments needs (environment wise) there wasn't an understanding of the relationship (of the experiment response) to the (acceleration) magnitude, so as I recall being on the mission, we operated in a laboratory environment but we weren't aware that closing locker doors for instance put in spikes into the structure that actually ran through. On USML-1 mission, we were much more aware of that environment particularly because of the results of D-1 and we were particularly sensitive to things like that; for example in areas where we had drawers that were sticking we simply did not close those lockers during particular experiments. So the results that you see may indicate different values for what is called crew activity because of that sensitization.*

Question : *The question I have deals with EURECA which was a solar inertial platform and as such had a rotational residual g vector even though it might be very small. My question is, what kind of effect did that have on your directional solidification experiment or do you have that correlation yet ?*

Answer: Yes. We have to calculate the effect of the rotating vector, but all the details have still to be worked out. The rotation of the residual vector introduces a low frequency acceleration that is very important to experiments sensitive to that range and most experiments are sensitive to low frequency accelerations.

