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SUMMARY OF WORKSHOP

28. THE PERFECTLY IDEAL ACCELEROMETER

Dr. Ernst Stuhlinger, Teledyne Brown Engineering

ABSTRACT

This summary paper gives a condensed version of the results and conclusions that developed during the Workshop. Upper limits of residual accelerations that can be tolerated during materials processes, presented as "acceptable" and as "desirable" limits, are shown. Designs and capabilities of various accelerometers, and their inherent problems, are compared. Results of acceleration measurements on Spacelab flights are summarized, and expected acceleration levels on the Space Station under various conditions are estimated.

Our workshop consisted of four main sessions, a panel discussion, a summary session, and a joint dinner with speech. The titles of the main sessions reflect the problem areas that were to be addressed at the workshop: 1) desired acceleration and frequency limitations of disturbances; 2) residual acceleration levels measured on spacecraft; 3) accelerometer systems; and 4) the Space Station acceleration environment.

We heard two and one half days of presentations, discussions, and debates about a subject that is not new, but has moved into the limelight for spaceplanners during the past one or two years. It is the question of determining to what degree of weightlessness our materials processing experiments in space should be, and will be, exposed during orbital flight.

Fifteen years ago, when we began considering materials processing experiments in space, we talked glibly about zero-g. We prepared experiments for Skylab, but we did not even think of measuring the degree of weightlessness our spacecraft would offer. As the years went by, studies were made about the level of residual accelerations our experiments could tolerate, and also about the acceleration environment to which these experiments would be exposed. Our vernacular changed from zero-g to micro-g. Then, acceleration measurements were made on rockets and on Spacelabs, and our vernacular changed promptly from micro-g to milli-g. We then felt the urge to organize a workshop that would help us shed some light on a problem area that proved to be more important and more complex than most of us had previously thought.

How low should the low-acceleration environment for space processing of materials be, and how can we measure and characterize the residual levels of acceleration that prevail during our materials experiments in space?

The first session was originally planned to address effects that residual accelerations will have on materials processes under near weightlessness. Although much study work has been done during past years to clarify this subject, we still have only a poor understanding of the exact mechanism by which residual accelerative forces produce lattice defects or otherwise imperfect crystals. Robert J. Naumann, NASA/MSFC, reviewed the various sources of low-level accelerations on spacecraft. Steady accelerations, as produced by gravity gradients and by atmospheric drag, are of greater influence than accelerative forces of higher frequencies as they are generated by running machinery or by transient motions of masses onboard the spacecraft. Based on theoretical studies in which movements of particles or volume elements due to convection or diffusion were compared with movements caused by accelerative forces, diagrams were drawn that showed for various crystal growth processes those critical accelerations as functions of frequency above which homogeneous crystals would not be expected to grow without developing lattice defects.

Figure 1 shows this function in a "desirable" and an "acceptable" version for the most sensitive processes presently envisioned for space experiments.

It is obvious that these diagrams cannot claim to be more than very broad, qualitative guidelines for the planners of space experiments. They badly need confirmation, or improvement, by further studies, and by systematic experiments in the laboratory and in space. It is even not quite clear how these experiments should be interpreted. If, for example, a vibration existed that is caused by two sinusoidal excitation functions with closely spaced frequencies, $f(1) \approx f(2)$, each with a peak acceleration of $a(o)$, should the resulting vibration be entered into the diagram of Figure 1 as two points at $f(1); a(o)$ and $f(2); a(0)$, or as one point at $f(1) + f(2) /2; 2a(o)$? In the first case, the two points may fall below the critical curve, and would be judged acceptable; in the second case, the one point may fall above the line, and the vibration would be judged inacceptable.

Ken Demel, JSC, expressed his concern even more drastically: "If you had a bad acceleration event of a few seconds duration, you could dissolve it into a million monochromatic sinusoidal oscillations, each with a little different frequency, but with a real tiny acceleration. Each would have its own point in the diagram, and each point would lie way below the critical curve. Would that be a true representation of what we want to know?"

Lively discussions developed around this question of how to define critical acceleration levels, how to measure them, and how to formulate specifications for spacecraft designers.

Proposals were made to measure and plot the power spectrum density, rather than acceleration of the acceleration environment. However, a power spectrum density diagram would not show those features either that are considered decisive in the growth of homogeneous crystals. It is quite obvious that a simple acceleration versus frequency plot, as shown in Figure 1, can certainly not provide more than qual-

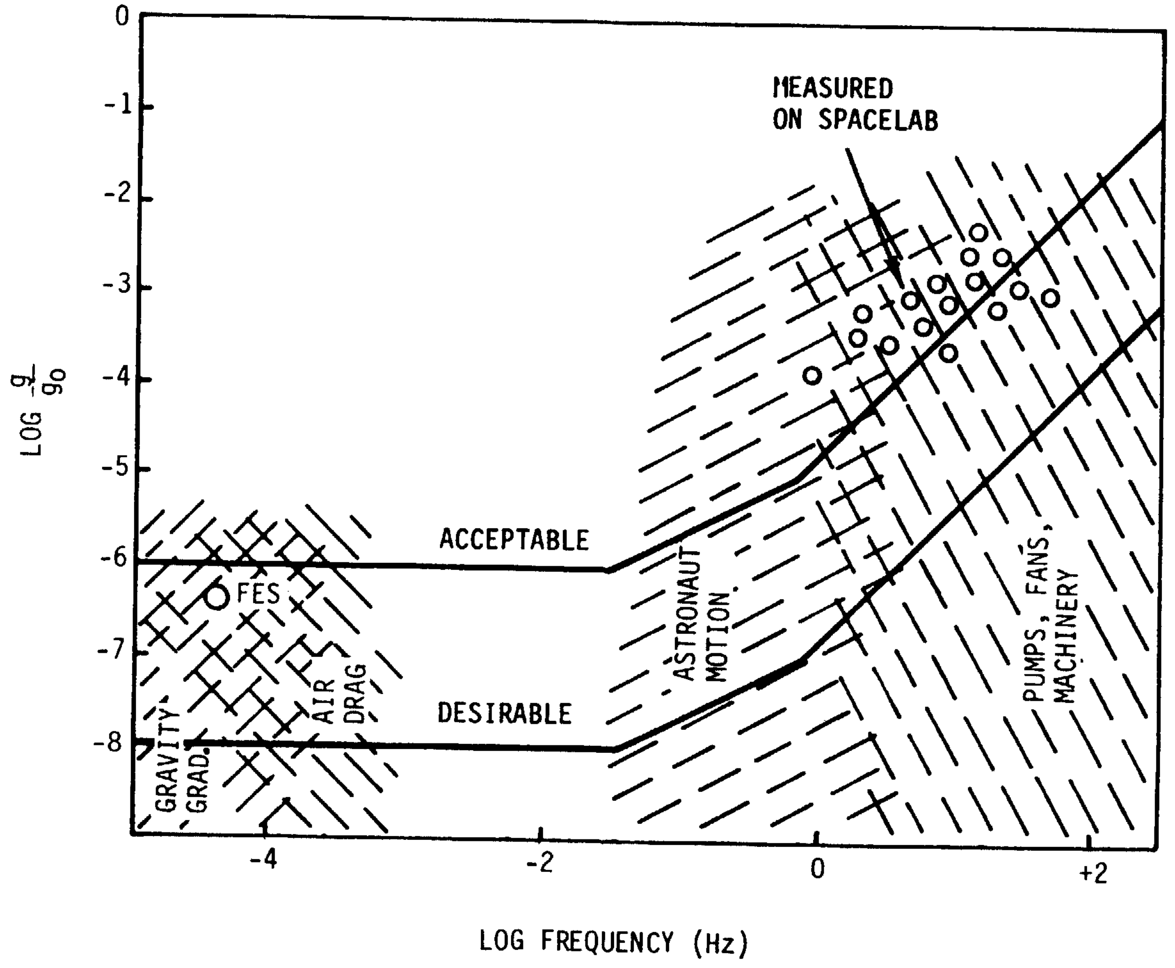


FIGURE 1. PROPOSED ACCELERATION LIMITS

itative guidelines for designers; but in view of the broad uncertainties that still prevail in the question of acceptable levels of residual accelerations, this way of presentation may at present be the most helpful one for Space Station designers. In Dr. Naumann's words, "we set requirements as best as we could." The degree of uncertainty may be illustrated by this remark from the audience: "What does gravity have to do with space processing? We don't really know!" -- a remark that would not have been subscribed by all the attendees, though.

Naumann suggested that the most relevant quantity that would characterize the quality of the acceleration environment would probably be the "moving window average" of the acceleration, as described in Paper No. 19 in these Proceedings.

The most dangerous accelerations affecting materials processes are produced by steady and slowly varying forces, such as gravity gradients, and atmospheric drag. Expected accelerations caused by these forces are shown in Figures 2a, 2b, and 3.

Gravity gradient accelerations can be minimized by placing the sensitive experiments close to the line of the center of gravity on the Space Station, not more than about 0.3 m apart for 10E-7 g.

Deceleration of the Space Station by atmospheric drag forces can be compensated by a continuously working thruster system whose thrust level is controlled according to the drag. With electrothermal thrusters using waste products (water) as propellant, a yearly mass consumption on the order of 10 to 20 tons, and an average electric power of about 5 kWe, would be sufficient to compensate aerodynamic drag forces on a continuous basis. This scheme would also make re-boost maneuvers unnecessary.

Another group of accelerating forces is caused by running machinery, such as fans, pumps, compressors, and alternators, and by functions that include the rapid motion of mechanical parts, such as valves and switches. The frequency spectrum of these disturbances covers a range approximately from 1 to 100 Hz, with acceleration peaks

DISTANCE FROM CG (m)	ACCELERATION (10^{-6} g_0)	
	VERTICAL	LATERAL
R	A_V	A_L
1	0.375	0.125
2	0.75	0.25
4	1.50	0.50
8	3.00	1.00
16	6.00	2.00
32	12.00	4.00
64	24.00	8.00
ORBIT ALTITUDE: 270 n.mi., 500 km		

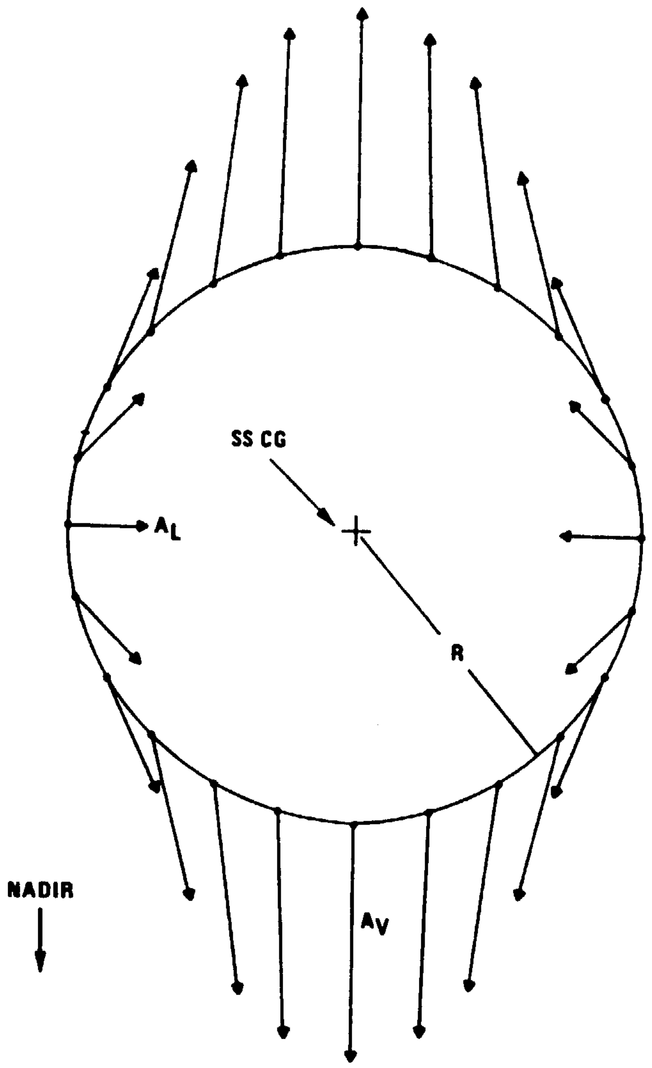
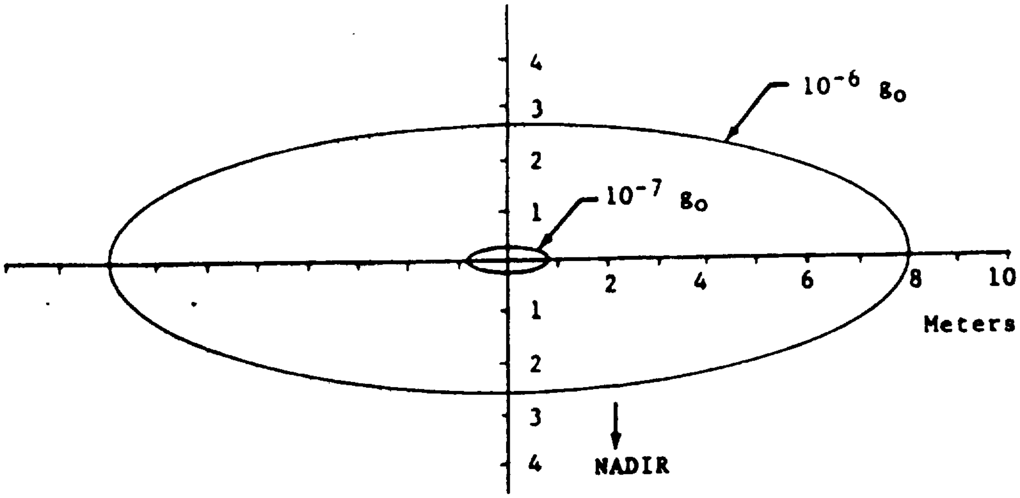


FIGURE 2a. GRAVITY-GRADIENT VECTORS ON A CIRCLE AROUND CENTER OF GRAVITY ON AN ORBITING SPACECRAFT IN A PLANE PERPENDICULAR TO FLIGHT DIRECTION



CONTOURS OF CONSTANT GRAVITY GRAIDENT ACCELERATION IN A PLANE PERPENDICULAR TO THE PATH OF THE SPACECRAFT'S CENTER OF GRAVITY (450 km ORBIT)

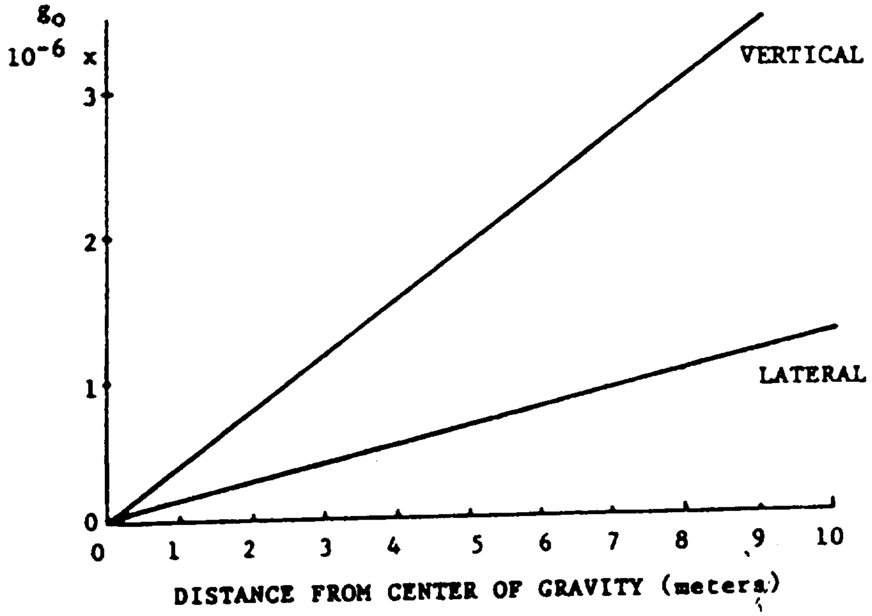


FIGURE 2b. GRAVITY GRADIENT ACCELERATION IN RADIAL AND LATERAL DIRECTION AS A FUNCTION OF DISTANCE FROM THE CG (450 km ORBIT)

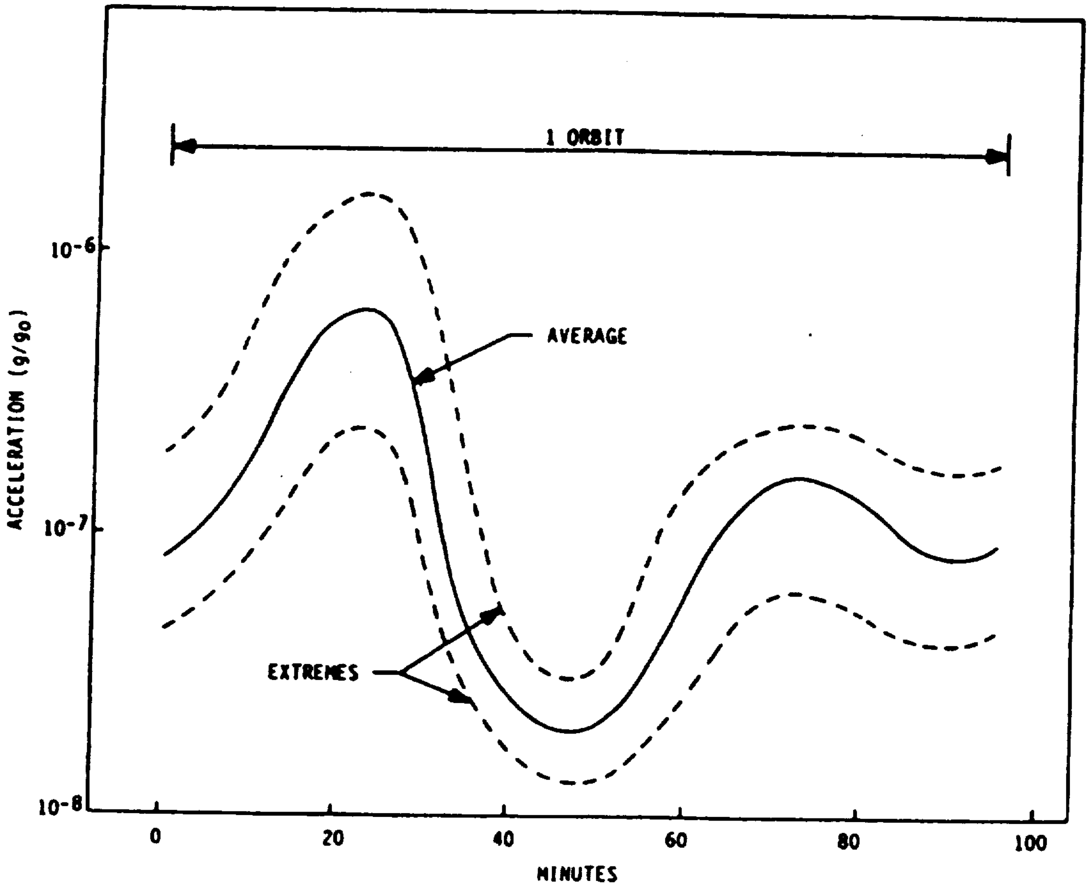


FIGURE 3. DECELERATION OF SPACE STATION CAUSED BY ATMOSPHERIC DRAG

Variations of deceleration result from changes of aspect angle, day-night cycles, and varying solar activity.

up to about 5 x 10E-3 g. It is likely that materials processing experiments can be protected against most of these disturbances by proper shockmounts and other vibration-isolating systems.

A further potentially dangerous group of disturbances falls between these two regions. Caused by the movement of masses onboard the Station (motion of astronauts; docking and undocking of spacecraft; transfer of propellants, waste materials, and freight; change of experimental set-ups), accelerative forces in this group may reach 2 x 10E-2 g with frequency spectra covering a wide range from about 10E-3 to 10 Hz. It may be necessary to avoid such mass movements entirely by proper timelining of activities while high-sensitivity materials processing experiments are underway.

Several acceleration measurements were made on Shuttle flights, particularly by West German investigators, and also on ballistic flights (SPAR Project). They typically show a frequency spectrum reaching from about 1 Hz to 100 Hz, with peak accelerations up to about 2x10E-3 g (Figures 4 and 5)*. Some of the more prominent frequencies could be attributed to specific sources (fans, pumps); shock-like accelerations were obviously caused by astronaut activities (operation of sled; opening and closing of rack drawers). Below a frequency of about 0.5 Hz, the recorded data were not good enough to allow a meaningful analysis.

These measurements were taken on the ground, with the Spacelab suspended on ropes. It is believed that the results are representative of the acceleration environment in flight, except for the effects of air drag and gravity gradient.

Trying to determine a steady-state or slowly varying acceleration component on the order of 10E-5 to 10E-6 within this very lively acceleration environment by analyzing a recorded accelerometer readout as shown in Figures 4 and 5 would seem almost hopeless.

Naumann and co-workers (Papers 4 and 6) tried to determine the quasi-steady state acceleration during a Spacelab flight by analyzing the movie picture record of a crystal floating within a solution. The

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*D. Eilers and W. Knabe, Technical Report PRV-TB-12/80
ERNO Raumfahrttechnik, Bremen, BRD, 12/15-80.

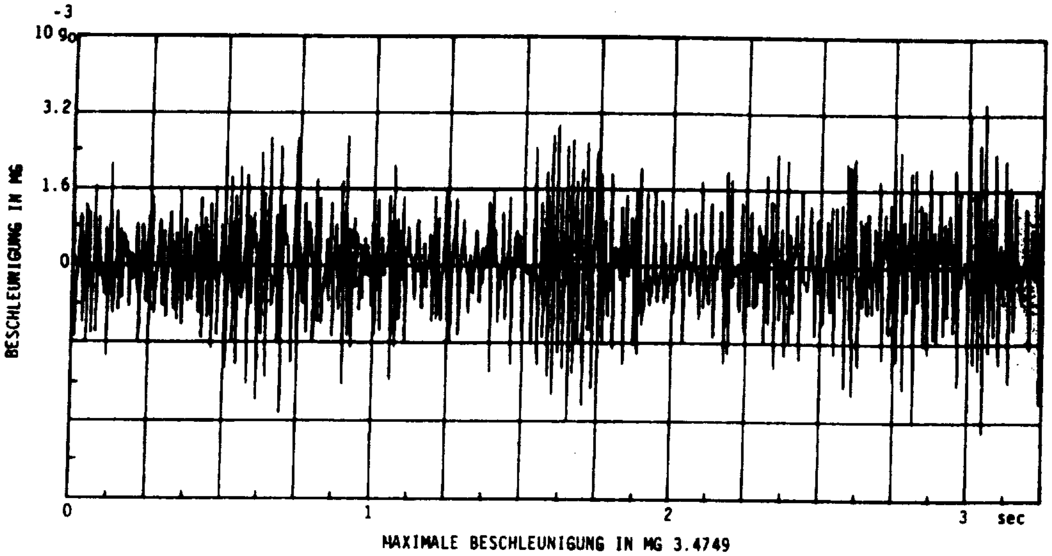

Abb. 3-1-15: Step A4 MP 1y
Spacelab aktiv, Storpegel am Control Center Rack

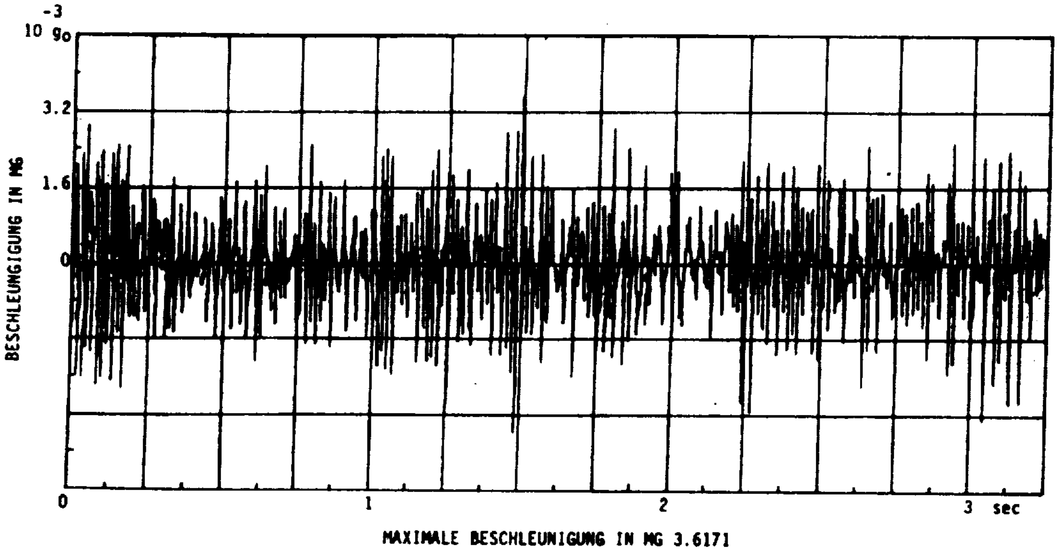

Abb. 3-1-16: Step A4 MP 1Sy
Spacelab aktiv, Storpegel am Control Center Rack

FIGURE 4

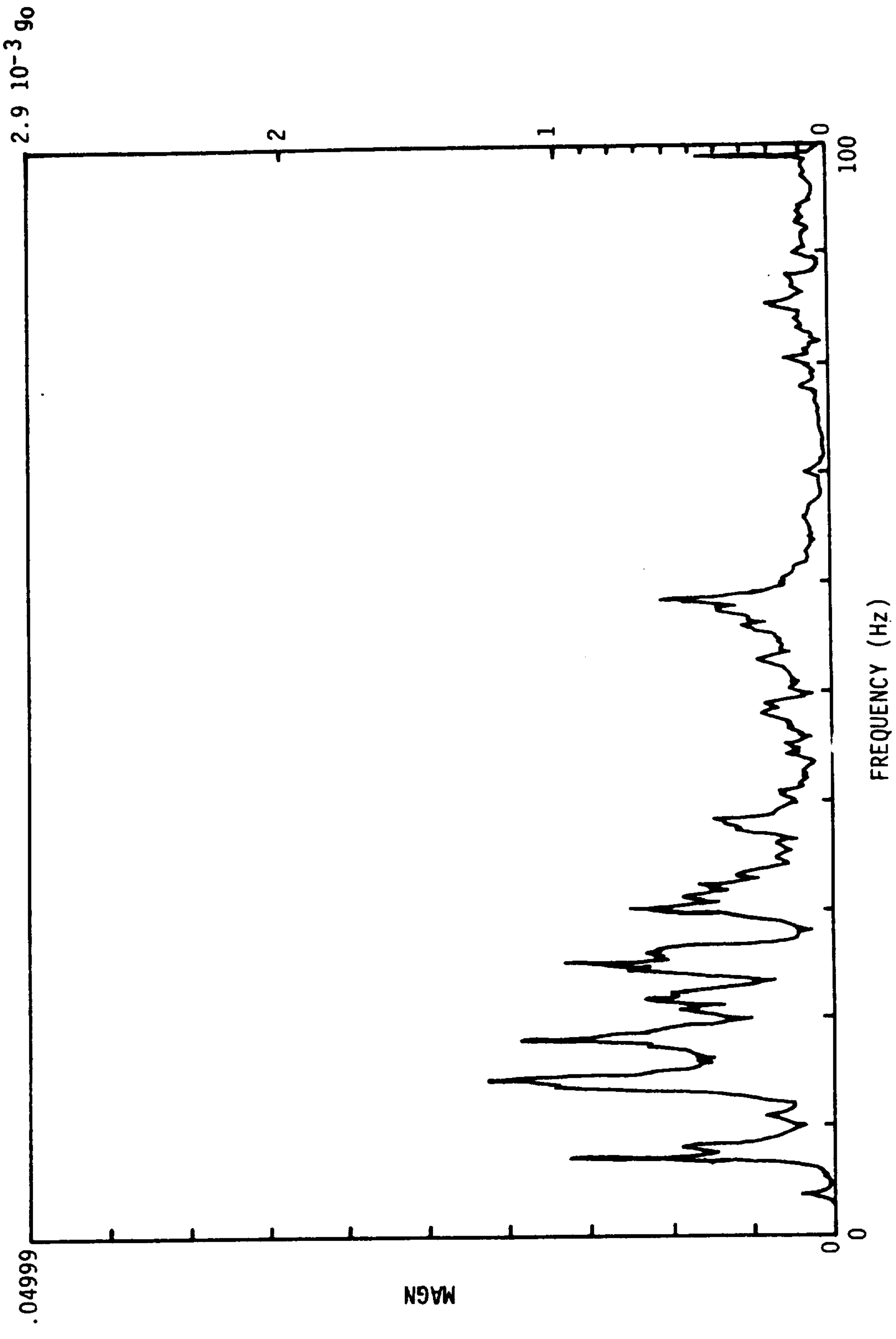

Abb. 3.2-2: Synthetisches Spektrum aus Step A4 MP 1Sy/Step B14 MP 1Su
Spacelab aktiv, plus Simulation von Handhabungsstoßen

FIGURE 5

result, shown in Figure 1 as FES, agrees with expected values. However, since a number of those factors that influenced this measurement are not well known, only limited importance can be attributed to this observation. On the other hand, experiments like this may still offer the best method to determine low-level, quasi-steady state accelerations onboard a spacecraft in the presence of accelerations of higher levels and higher frequencies.

A number of presentations (Papers #14 to 20) describe existing or planned accelerometers; most of them have impressive capabilities regarding sensitivity, frequency response, and accuracy. Among the accelerometers presented or at least brought up during discussions were accelerometer systems developed by Bell Aerospace Textron, Payload Systems, Inc., Honeywell, Inc., University of Maryland, Teledyne Geotech, Applied Technology Associates, Inc., Sundstrand Data Control, Inc., Systron Donner, and NASA/Lewis Research Center.

It became obvious that several types of accelerometers either are, or soon will be available that will be able to measure the acceleration environment that is of interest in materials processing experiments. However, several remaining problems were pointed out during the Workshop; they should be given careful attention.

First, it will be difficult to obtain an accurate record of very low steady or near-steady accelerations against the background of a very restless environment as illustrated in Figure 4. Second, in view of the great sensitivity of some materials processes even to disturbances as short as a fraction of a second, it is hard to imagine how the huge amount of acceleration data accruing over the length of an experiment (hours, and even days or weeks) can be recorded, transmitted to the ground, stored, analyzed, and correlated with materials processing samples, within a reasonable volume of effort. Third, a proper way to correlate specific acceleration events with particular crystal lattice defects or other inhomogeneities has not yet been established. Fourth, in order to obtain a complete picture of the acceleration environment, one should determine the accelerations in three translational and three rotational coordinates at the location of each of the sensitive experiments. This requirement alone will considerably increase the amount of data to be handled. Fifth, the cost of some of the commercially available accelerometers is high, on the order of $300,000 -- each.

The "ideal accelerometer" as conjectured by space planners -- which, naturally, will never exist in reality -- would measure accelerations over an acceleration range from about 10E-9 to 1 g, and over a frequency range from zero to about 100 Hz. It would be strictly linear over both these ranges, and it would measure continuously three translational and three rotational components of the acceleration (Figures 6 and 7). It would provide continuous records on tape of all these accelerations as functions of time.

It would also provide, through an appropriate filter system, continuous readouts of these accelerations in a number of different frequency regimes, such as 0 to 10E-3 Hz; 10E-3 Hz to 0.1 Hz; 0.1 to 1 Hz; 1 to 10 Hz; and 10 to 100 Hz, all as functions of time.

The system would also provide, through a proper network and on a continuous basis, for each coordinate the average acceleration during a specified time interval delta t ("moving window average"). Several displays of this average acceleration, each for a different delta t, would be available.

All these data would be stored on tape for later transfer to earth. They would also be put on telemetry links for immediate transmission to ground stations. Visual displays on a real-time basis would be available, at least on an as-wanted basis, for the scientist astronauts onboard the Station.

Each "ideal" accelerometer would produce data for six coordinates, and each of the sensitive experiments would be equipped with at least one accelerometer. The immense volume of data coming from this system, plus the uncertainties regarding interpretation and correlation of acceleration data with respect to crystal growth experiments, repeat-

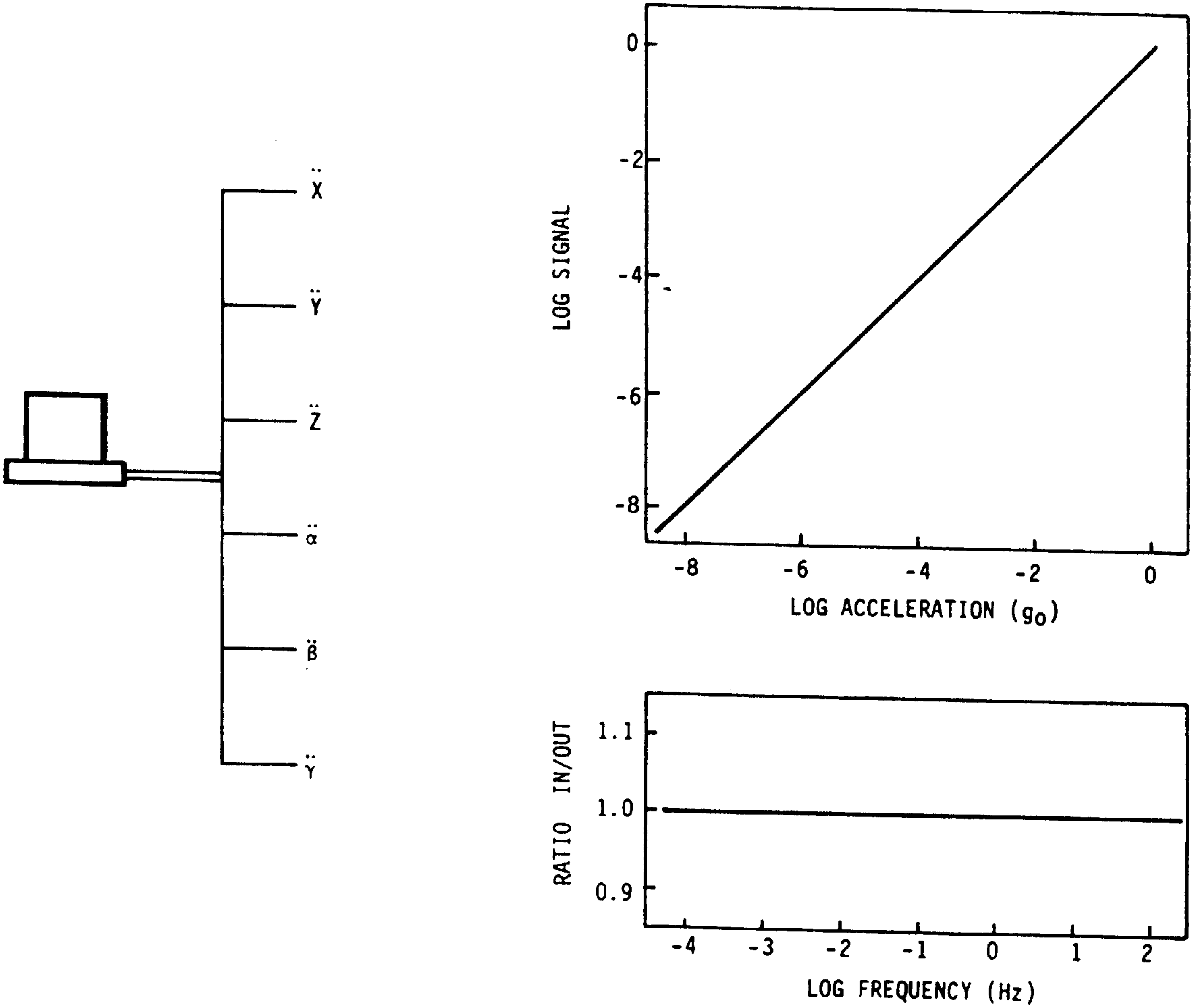

FIGURE 6. THE IDEAL ACCELEROMETER

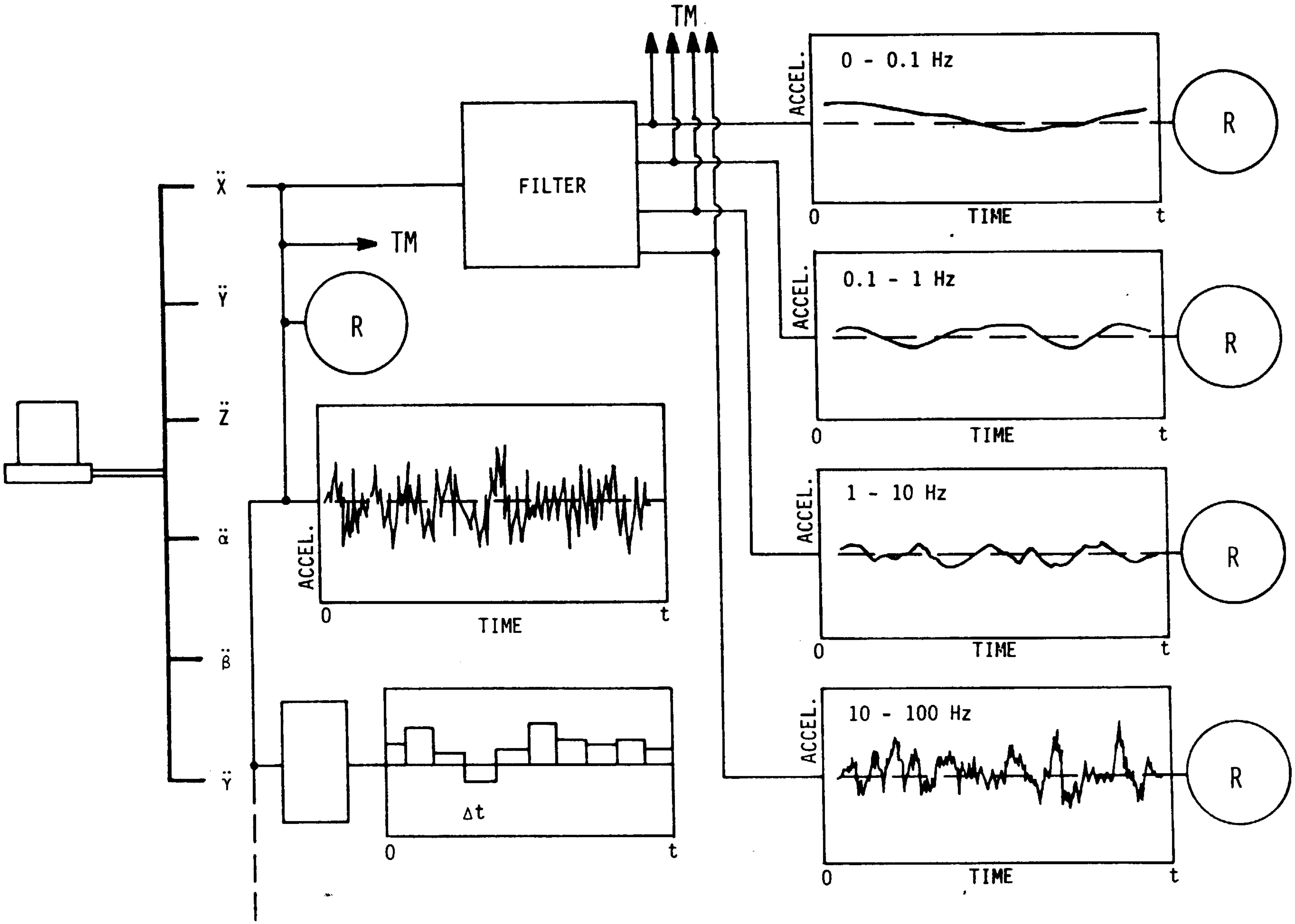

FIGURE 7. IDEAL ACCELEROMETER MEASUREMENTS

edly prompted remarks at the Workshop to the effect that this entire problem area could be avoided by putting the more sensitive materials experiments on free-flying platforms that would operate in conjunction with, but physically separated from the Space Station or the Shuttle. Acceleration levels on a Free Flyer can be expected to remain below 10E-7 g during the total duration of the detached flight. A sketch of a Free Flyer with eight materials processing chambers is shown in Figures 8 and 9.

Throughout the Workshop, the interchange of thoughts between astronauts, scientists, instrument manufacturers, spacecraft engineers, and project planners generated interesting suggestions of great mutual benefit. Among them were the following:

Astronauts' Advice:

Do in space only what cannot be done on the ground. Conduct sample preparations and elaborate evaluations in earth-bound laboratories. Store flight data on tape and transport these to earth.

Do not overburden payload scientists in orbit. Give them enough time to operate, adjust, and repair your instruments. Operational timelines must allow contingencies for unforeseen events.

Familiarize astronaut scientists thoroughly with your instruments and with your research objectives before flight. Once they are in orbit, do not try to guide them on a minute-by-minute basis. They should be prepared to use their own judgement and initiative.

Remember: As soon as a person is in orbit, he -- or she -- is a totally different human being!

Scientists' Concerns:

All the raw data should be stored onboard, and later transferred to earth. Filters, networks, and selection systems compromise the original data, often to the detriment of the value of the experiment.

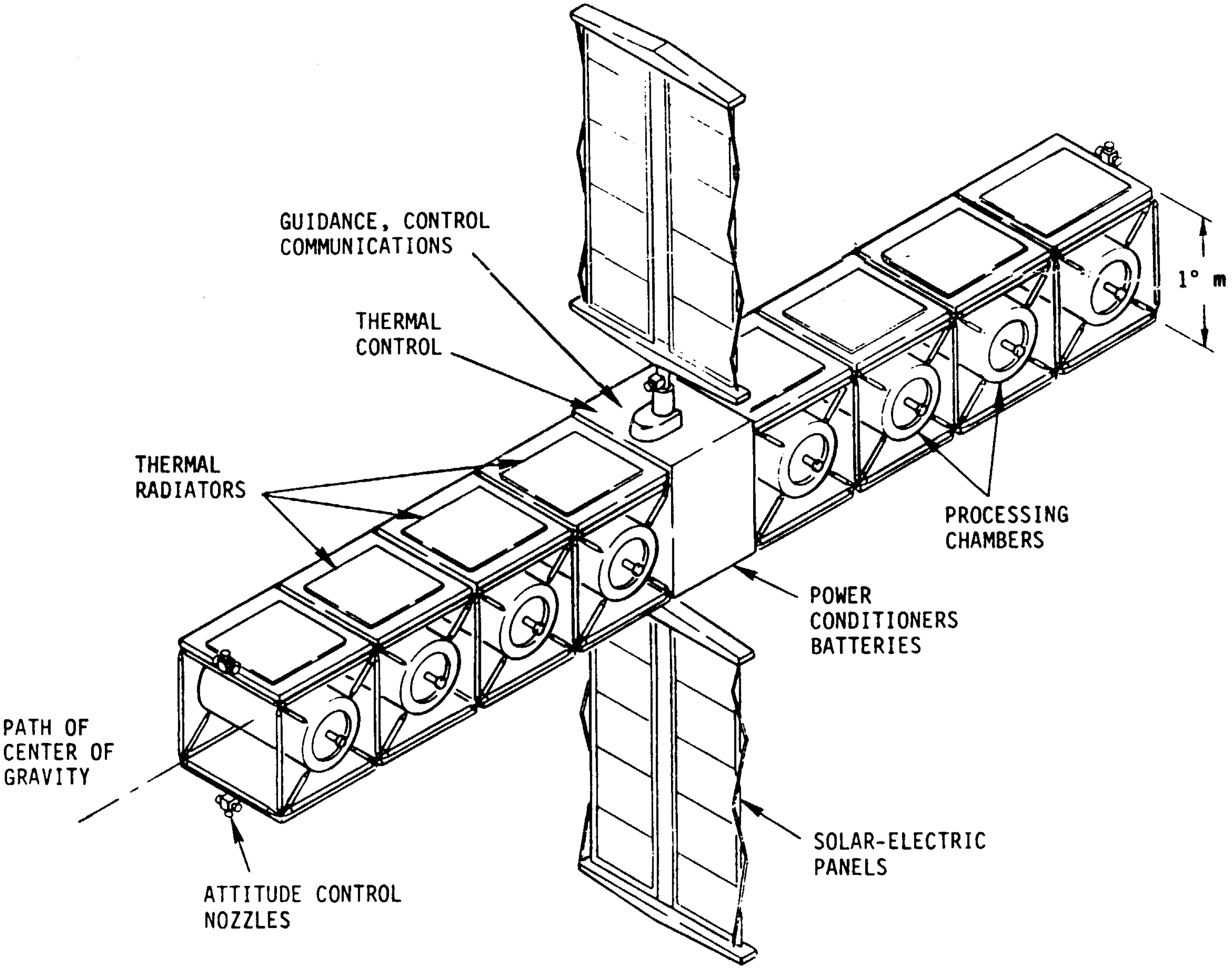

FIGURE 8. FREE FLYER FOR MATERIALS PROCESSING

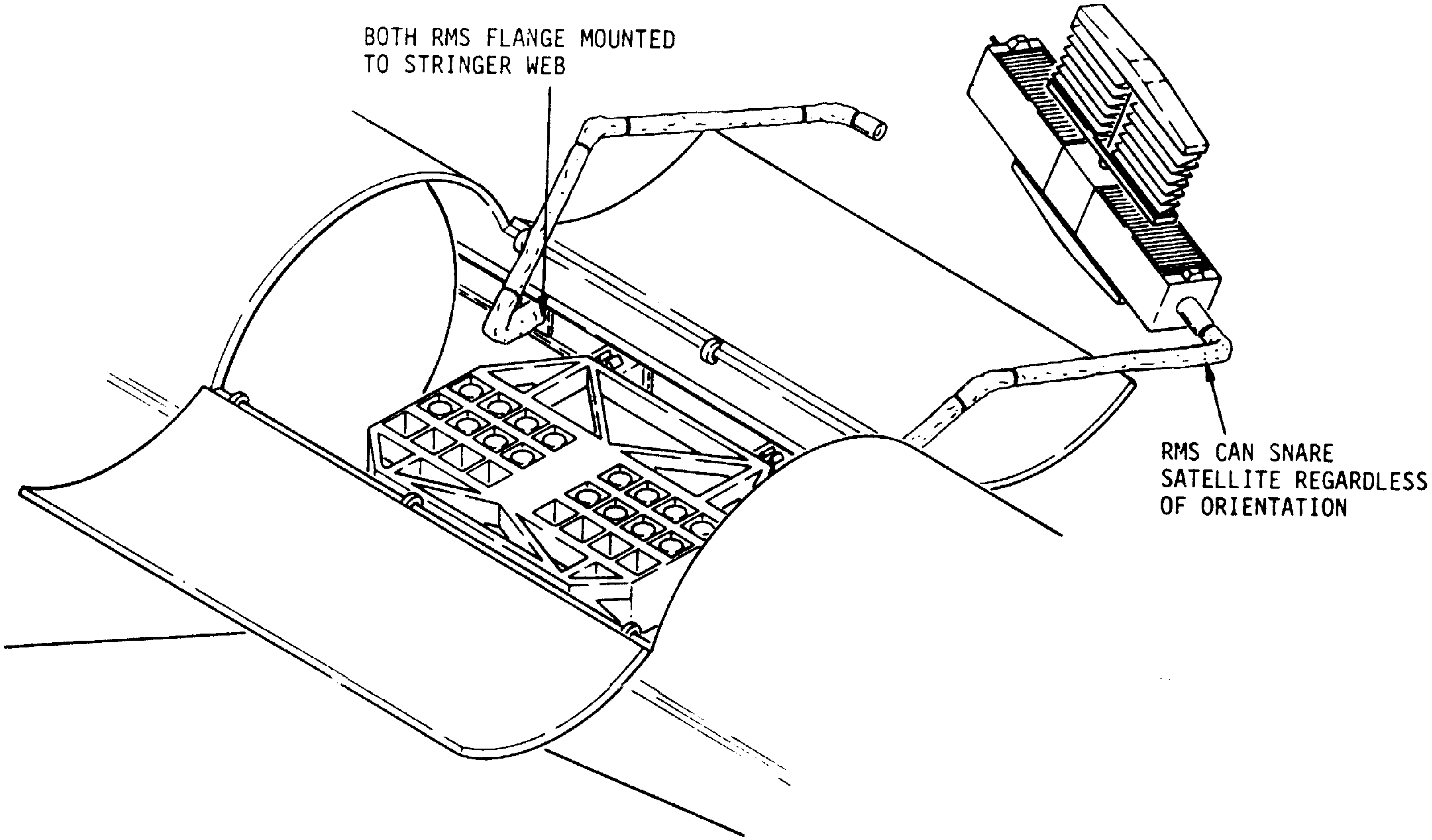

FIGURE 9. SERVICING OF MATERIALS PROCESSING FREE-FLYER ARRAY OF MODULES EXCHANGED SIMULTANEOUSLY

Information on steady, and near-steady accelerations, even in the presence of higher-frequency vibrations, is badly needed.

Scientists need far more time for theoretical and experimental ground work, and for a series of systematic flight expriments, before they can define systems for the manufacturing of materials in space.

Designers' Pleas:

The Space Station is for users. They should define what they need.

Specifications for the residual acceleration levels that can be tolerated by the experimenters are badly needed. Requirements as to the upper limits of acceptable acceleration and frequency levels should be established.

Advice to Designers:

Atmospheric drag compensation by continuously operating thrusters may be necessary. Design studies for such systems should be made.

Structural damping systems, and shock mounts for materials processing chambers, may be needed to provide some protection against accelerative forces.

The Space Station should be designed for acceleration-sensitive experiments. Moving systems, such as fans, pumps, compressors, bearings, hinges, latches, valves, switches, drawers, and doors, shold produce as little of a disturbance as possible.

The Space Station should always be oriented in such a way that the long axis of the Lab Module is parallel to the line along which the center of gravity moves. That line should coincide as closely as possible with the line along which the sensitive materials processing experiments are located within the Lab Module.

Remember: The Space Station must be designed for users!

Several more guidelines for Space Station designers and users, and for space program managers, resulted from discussions during the Workshop. They included the following:

Far more flight experiments are badly needed, perhaps including systematic investigations under different levels of acceleration. Such experiments could be carried out with centrifuges, or with tethers, onboard a Shuttle or the Space Station, or on a free-flying platform with a controllable thruster system.

More analysis and modeling of Space Station dynamics is needed.

Free Flyers, operating in conjunction with, but detached from the Shuttle or Space Station, would provide a long-term acceleration environment of less than 10E-7 g. The use of such spacecraft for automated or remotely controlled materials processing experiments would eliminate all problems caused by residual accelerations above that level.

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