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Requirements and Development of an Acceleration Measurement System for International Space Station Microgravity Science Payloads

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ABSTRACT

The International Space Station is being developed by NASA and international partners as a versatile user platform to allow long term on-orbit investigations of a variety of scientific and technology arenas. In particular, scientific studies are planned within a research class known as microgravity science in areas such as biotechnology, combustion, fluid physics, and materials sciences. An acceleration measurement system is in development to aid such research conducted in the on-orbit conditions of apparent weightlessness. This system provides a general purpose acceleration measurement capability in support of these payloads and investigators. Such capability allows for systematic study of scientific phenomena by obtaining information regarding the local accelerations present during experiment operations.

Preparations for implementing this flight measurement system involves two distinct stages: requirements development prior to initiating the design activity, and the design activity itself. This paper defines the requirements definition approach taken, provides an overview of the results of the requirements phase, and outlines the initial design considerations being addressed for this measurement system. Some preliminary engineering approaches are also described.

ACRONYMS

A/D	Analog-to-Digital (conversion)
CU	SAMS-II Control Unit
ESRD	Experiment Support Requirements Document
GOE	SAMS-II Ground Operations Equipment
ISS	International Space Station
OARE	Orbital Acceleration Research Experiment
PI	Principal Investigator
PIMS	Principal Investigator Microgravity Services
RTS	Remote Triaxial Sensor
RTS-EE	RTS Electronics Enclosure
RTS-SE	RTS Sensor Enclosure
SAMS	Space Acceleration Measurement System
SAMS-II	Second generation SAMS for ISS

INTRODUCTION

A project has been initiated to provide an acceleration measurement system for the International Space Station (ISS). Typical of such aerospace projects, a systematic approach is being taken to provide this capability. Generally, aerospace projects proceed through a series of phases to develop a new system. These planning phases encompass development of requirements, the design process, and the operational phase. Further, these three general categories may decomposed into a variety of subelements. One such decomposition is shown in table 1 below.

table 1: Project Planning Methodology

Requirements Development	**Design Implementation**	**Operations**
needs definition	design tradeoffs	enter service
requirements definition	design solutions	operate
requirements decomposition	detailed engineering	decommission
	system development/ buildup	
	system verification	

In this table, time passage proceeds from left to right. It is imperative to establish a reasonable set of requirements for a system prior to its development and operation. A system to acquire acceleration data aboard the ISS is required to satisfy a need of the microgravity science community to enhance the results of on-orbit research. The results of the process in use by the Space Acceleration Measurement System-II (SAMS-II) project is described in this paper, beginning with the requirements development process.

MICROGRAVITY SCIENCE

Early in the manned space flight program, scientific experimentation was conducted to take advantage of the unique qualities of orbital conditions. (ref. 1) A fundamental condition occurring as a spacecraft orbits the earth is that it maintains an apparent condition of weightlessness. The spacecraft falls towards the earth at generally the same rate that it is being forced outward from the earth due to its forward motion. An equilibrium condition exists, which has become known as being in microgravity. A simplified viewpoint to understand this concept is to visualize a cannon firing a ball atop a tall mountain. (figure 1)

Once fired, the cannonball falls to earth. As the cannonball is shot at successively faster velocities, it travels farther before landing. Eventually, when shot at the proper velocity, the ball achieves a state of continuous free-fall around the earth. This results in a steady-state condition of free-fall known as an orbit. So, the term microgravity does not represent a fixed magnitude, but rather this condition of equilibrium. (ref. 2)

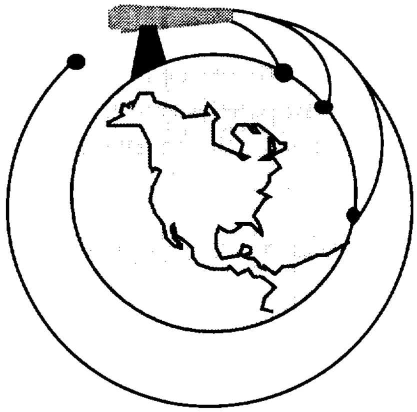

figure 1
Isaac Newton's Cannonball "Thought Experiment"

MEASUREMENT OF ON-ORBIT ACCELERATION

As initial scientific experiments were being conducted and their results analyzed, the accuracy and reproducibility of microgravity research results were called into question. One of the key parameters affecting the outcome, in fact the reason for conducting the science while in orbit, was not being measured. The actual acceleration environment present during the experimentation was unknown. Residual accelerations existed and were known to be time varying due to changing conditions such as the orbital altitude and vehicle attitude affecting vehicle drag, spacecraft equipment operations, and crewmember activity. In some cases it was possible that an experiment apparatus may have generated excitations which were detrimental to the purpose of the investigation. Thus, the assumption of having a quiescent acceleration condition ironically might be violated as a result of operating the experiment.

At first, independent measurement devices were developed to support individual experiments. As the microgravity science research program matured, a realization was reached that a general purpose measurement system could better satisfy the needs of the science community and reduce duplication of efforts and resources. The requirement for a common source of acceleration measurement was formulated from this realization.

PREVIOUS SYSTEMS

To satisfy the desire for a general purpose measurement system, a series of instruments known as SAMS, the Space Acceleration Measurement System, were developed at the NASA Lewis Research Center in the late 1980s. (ref. 3) These instruments have flown over sixteen times, successfully supporting microgravity science experiments conducted aboard the NASA space shuttle from 1991 into 1997. One SAMS instrument has been modified and is aboard the Russian space station Mir, acquiring acceleration data supporting cooperative microgravity research activities on that vehicle. (ref. 4) SAMS instruments acquire acceleration data over the frequency range of 0-100 Hz. Another instrument, originally developed to conduct shuttle aerodynamic drag research in low earth orbit, is being successfully used to complement SAMS in the 0-0.01 Hz low-frequency regime with higher accuracy measurements. The Orbital Aerodynamic Research Experiment (OARE) instrument has flown ten times, specifically supporting seven microgravity missions. (ref. 5, 6) Other systems were developed to fulfill unique acceleration measurement needs that general purpose instruments could not fulfill.

REQUIREMENTS DEVELOPMENT

The call for a general purpose acceleration measurement system has again been made as NASA and the science community prepare to enter a new era in space-based research using the ISS. In a document discussing the future of microgravity research, the National Research Council stated the following challenge:

> "The g-level must be measured accurately, locally, frequently, and synchronously with every experiment." (ref. 7)

A number of fundamental operational differences are anticipated to occur while conducting experiments in a long-duration orbiting facility such as ISS as opposed to those in a relatively short flight-duration platform such as the shuttle. Technology improvements made since SAMS was developed result in a desire to provide a second generation system for the ISS. The SAMS-II project sets out to improve upon those operational areas that SAMS and OARE were found through experience to be lacking while, at the same time, leverage the positive feedback from the performances of SAMS, OARE, and other successful shuttle-based instruments.

SAMS-II must adapt to and work within a significantly different vehicle than the shuttle, and do so for a considerably longer timeframe. Experience gained from the long period of operation of the SAMS unit aboard Mir continues to provide some insight to potential SAMS-II approaches for operation on the ISS.

The fundamental requirements set forth for development of the SAMS-II instrument are formulated from a compilation of user requirements in the science disciplines being supported. Microgravity science disciplines of biotechnology, combustion, fluid physics, low temperature microgravity physics, and materials science have specified their peculiar acceleration measurement and data analysis requirements. These discipline-specific requirements are combined into a parent set of system requirements for SAMS-II known as the Experiment Support Requirements Document (ESRD). A summary of the ESRD requirements are provided in table 2.

Of course, factors other than these end-user requirements also influence the design and development plans for the SAMS-II. Other requirements encompass vehicle interfaces, differing vehicle capabilities than offered by the shuttle, unknowns on the likely environment measurement conditions, likelihood of higher amplitude wideband vibratory energy sources being present, more payloads being supported, a more "laboratory-type" setting, and more crew time being available for long duration research. Of special significance to the development of SAMS-II is the likely increase in maturity of the ISS science investigator. The maturing science community continues to progress from requiring just being in low gravity, to specifying a specific environment, to further refinements which require measurement and verification that the proper test conditions were obtained, to an eventual situation where a user requires environments which are not yet attainable.

table 2: SAMS-II Experiment Support Requirements

1.0 Acquire acceleration data	**2.0 Allocate control to the users**	**3.0 Provide data to users**
1.1 measure accelerations with an accuracy and resolution better than the acceleration environment envelope of the ISS program	2.1 principal investigator control of parameters	3.1 supply information in a selectable format
1.2 acquire the acceleration data with correlated time information	2.2 on-orbit crew control of parameters	3.2 supply information within a selectable amount of time
1.3 measure acceleration with selectable frequency range		
1.4 measure acceleration in, on and/or near the experiment sample/ chamber/ apparatus		

As a complement to the planned measurements of the acceleration environment, the Principal Investigator Microgravity Services (PIMS) project fulfills the responsibility of assisting the microgravity science community in pre-mission planning by characterizing the likely acceleration environment based on previous results and the planned mission profiles. The PIMS organization also responds to requests to describe the environment of a vehicle in support of initial scientific feasibility studies and concepts, and aids in the planning for future research aboard a particular on-orbit platform. The PIMS project is also responsible for maintaining the ESRD based on evolving user requirement inputs.

The SAMS-II project has taken these user design requirements and created a conceptual solution capable of meeting the goals set forth in the ESRD. SAMS-II is providing small triaxial sensors which are located at or near the point of research. These remote sensors measure the vibratory responses at the interface to the science investigation. A globally accessible control unit allows central control of the remote sensors and will provide a means of data collection for the sensors. This control unit also provides a means to measure quasi-steady acceleration amplitudes and responses. The SAMS-II also is developing a ground operations capability to enable command and control of the on-orbit system. Communications between the sensors, control unit, and ground equipment rely on ISS network capabilities.

Additionally, detailed requirements are decomposed further into categories such as acquisition parameters, structural and thermal environments, network communications, data analysis capabilities, safety, reliability, maintainability, and crew availability. Acquisition parameters, for example, may be further decomposed into subcategories such as frequency range, amplitude range and accuracy, and timestamp availability and accuracy, just to name a few.

Once the requirements are decomposed to a level which allows a design to be formulated, a combination of requirements and the conceptual approach are used to develop a preliminary design solution. This design then leads to subsystem evaluations of performance and feasibility. Such evaluations are referred to as proof-of-concept tests.

As the requirements process transitions into the design process, estimates of resource requirements are made and are allocated to the various system elements. In the case of SAMS-II, allocations of functionality between the control unit and sensor hardware are made, along with estimations of required resources such as power, cooling, weight, volume, and network bandwidth. All of these elements ultimately will be provided as part of the ISS capability, which of course, is based on a design also currently in progress. Table 3 lists some of the key allocations of the SAMS-II on-orbit hardware elements.

table 3: SAMS-II On-Orbit Hardware Allocations

	Control Unit	RTS Electronics Enclosure (each)	RTS Sensor Enclosure (each)
Volume	0.065 m^3 (4000 cu-in)	0.00761 m^3 (465 cu-in)	0.00288 m^3 (176 cu-in)
Weight	46 Kg (101 lbs)	5.0 Kg (11.0 lbs)	1.5 Kg (3.3 lbs)
Power	350 W (@ 28 VDC)	32 W (@ 28 VDC)	powered from -EE
Cooling	350 W (water @ 43°C)	25 W (interface @ 45°C)	3.5 W (interface @ 45°C)
Bandwidth	800 Kbits/sec	160 Kbits/sec	80 Kbits/sec

DESIGN IMPLEMENTATION

As outlined conceptually in the requirements section above, the SAMS-II consists of three basic hardware elements: a number of on-orbit measurement instruments, a centralized on-orbit data acquisition and control system, and a ground operations system. For SAMS-II these are defined as a series of Remote Triaxial Sensor (RTS) systems, a Control Unit (CU), and the Ground Operations Equipment (GOE). These elements are interconnected by the ISS networking system as shown in figure 2.

CONTROL UNIT

The SAMS-II on-orbit hardware consists of a relatively straightforward client-server embedded system architecture. The Control Unit (CU) serves as the server, and provides the backbone to the SAMS-II on-orbit interface and data analysis capability. Primary hardware elements of the CU are commercially available. Custom modification and packaging of some elements is necessary to ensure launch vibration load and on-orbit environment survivability. Where practical, industrial or military-grade components are used to increase system reliability. The CU provides the common mass storage site for acquired data from multiple sensor locations. This mass storage can be either on a hard-drive unit or on a removable media magneto-optical drive unit for return to earth at a later date. Many of the functions which are now conducted in a post-processing fashion on SAMS data are anticipated to be requested in near-real-time aboard the ISS, and are incorporated in the SAMS-II CU hardware and software. The CU executes commonly requested data analysis functions such as root-mean-square, peak, and average value calculations, as well as more processor intensive computations of frequency spectra and waterfall-type plots. The CU has the capability to provide a threshold flag indicator to on-orbit user payloads, allowing a degree of automation and autonomy of operation, if the user so desires. Such a flag indicates, for example, that the acceleration environment is above or below a preset value.

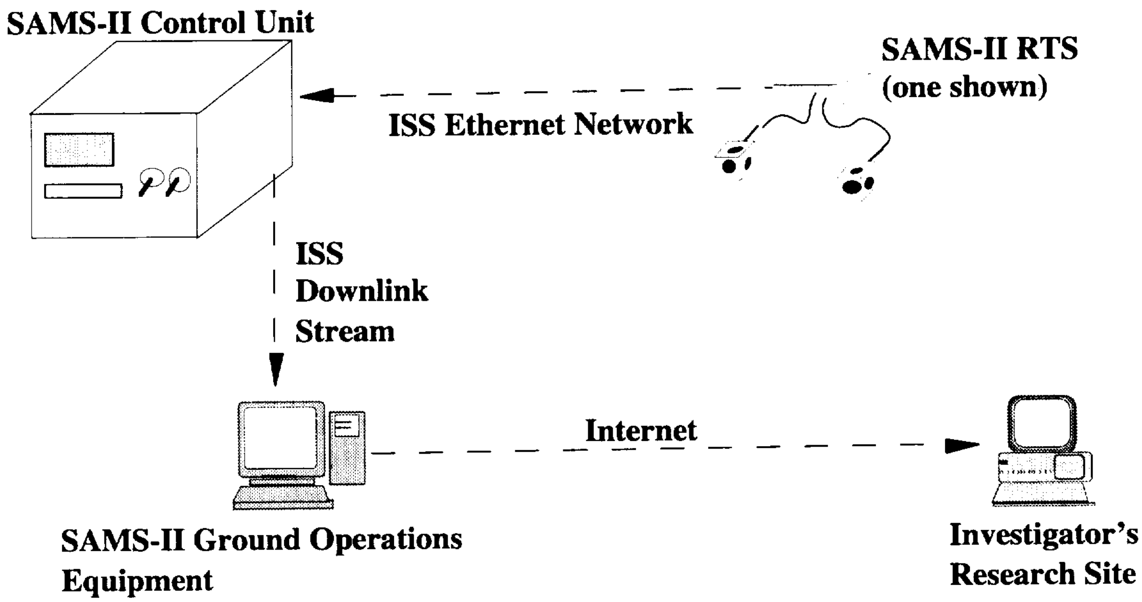

figure 2: SAMS-II System Block Diagram

Also, as a result of system partitioning, a quasi-steady measurement capability is being provided as a single point sensor subsystem within the CU. Quasi-steady measurements can be transformed from a measurement location to an experiment location by knowing the rigid-body rotation rates of the vehicle and the moment-arm separations of the measurement, center-of-rotation, and the experiment location. Once again, the processing capability of the CU enables this on-orbit functionality.

GROUND OPERATIONS EQUIPMENT

The Ground Operations Equipment (GOE) provides the gateway to a science user, who is known as a Principal Investigator (PI). The PI is provided with the tools to command a particular sensor configuration for appropriate data acquisition setups of frequency range and data processing. A portion of the CU storage and on-board processing capability is allocated to each PI. The user is also allocated a portion of the ISS downlink bandwidth to acquire the acceleration data in near-real-time. There is sufficient versatility in the operational approach to permit a PI to either analyze the acceleration data on-orbit or do so once data is received at the home research site following downlink and transmission.

REMOTE TRIAXIAL SENSOR

All the capabilities for data analysis and communications hinge on the acquisition of a good measurement. The key element of the SAMS-II ultimately is the Remote Triaxial Sensor (RTS) system. The RTS is responsible for acquiring an accurate measurement and communicating that measurement in an acceptable format to the user. The SAMS-II RTS must provide the user versatile frequency selectable ranges up through 300 Hz, and must measure across an expected amplitude range from over 10,000 μg to less than 1 μg. The sensor must be as non-intrusive as practicable to the system being measured.

Size constraints force the RTS system to be divided into two hardware elements. User desires dictate that the sensor measurement device be as small as possible. Toward this end, the RTS Sensor Enclosure (-SE) was developed with the minimum level of hardware to ensure a quality measurement, while the RTS Electronics Enclosure (-EE) was created to provide intermediate interface capability to the control unit and to provide initial, low-level data compensation and processing to the acquired acceleration data from the RTS-SE.

The RTS-SE contains the primary hardware necessary to ensure an accurate and complete measurement of the broadband microgravity environment. Three orthogonally mounted commercially available servo-type sensors are configured so that their measurement axes intersect in a coincident point. These sensors thus form a purely translational triaxial acceleration measurement configuration. Each axis has an independent signal conditioning board dedicated to the conversion of the analog current signal into a digital data stream. To enable this, the A/D board contains a current-to-voltage conversion circuit, selectable gain circuitry, an anti-aliasing filter, and a 24 bit delta-sigma analog-to-digital converter. Each A/D board communicates to the RTS-EE via an input/output board. This board transmits the digital acceleration data and the analog temperature signals from each sensor to the RTS-EE for processing. Table 4 lists some of the pertinent characteristics of the RTS-SE, while figure 3 provides a two-view cutaway of the -SE subsystem.

table 4: RTS Sensor Enclosure Performance

sample rates	programmable, 62.5, 125, 250, 500, 1000 Hz
frequency ranges (passband)	0- 23.44 Hz, -46.88, -93.75, -187.5, -375 Hz
amplitude range	0.1 μg - 0.1 g, 24 bit Δ-Σ A/D conversion
temperature range	10-35°C (nominal), 0-45°C (min/max)
output characteristic	digital triaxial acceleration data, analog temperature signals

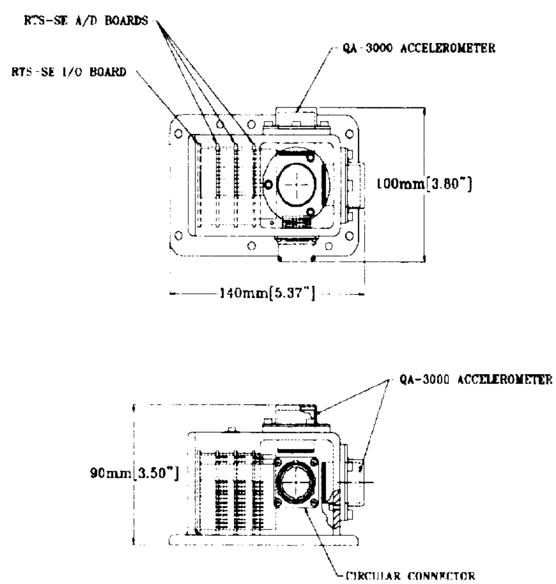

figure 3: RTS Sensor Enclosure

The RTS-EE acts as the intermediate interface between two RTS-SE measurement units and the higher level functions provided by the Control Unit. The RTS-EE acquires the analog temperature signals, conditions and digitizes them with a 16 bit analog-to-digital converter and merges the results with the digital acceleration data from the -SE and appropriate temperature calibration coefficients to provide temperature compensated triaxial acceleration data. This data is converted to engineering units via programmable scale factor calibration values. An optional adjustment for alignment corrections or axes rotations is also available. Table 5 lists key performance features of the -EE.

table 5: RTS Electronics Enclosure Performance

software control	remote-boot based (from Control Unit)
sensor enclosures supported	two, simultaneous sampling
health monitoring	16 channel, 16 bit A/D conversion, sampled 10/sec
processing capability	temperature compensation alignment corrections engineering unit conversion
output characteristics	temperature compensated digital triaxial acceleration data
output format	10BaseT Ethernet

The RTS-EE is comprised of two hardware elements: the power conversion assemblies are located within approximately one third of the -EE, while the computational power of the RTS-EE is provided via a PC/104 format card stack. The PC/104 stack consists of commercial-off-the-shelf cards and custom designed interface cards. The commercial cards include a central processor unit card, an Ethernet network card, and the analog-to-digital converter card used for accelerometer temperature measurements. This A/D board is also used to measure various health monitoring points within the RTS-EE such as power converter voltages and component interface temperatures. Due to the lack of natural convection cooling on-orbit, the PC/104 boards consuming the most electrical power require cooling modifications. These boards are sandwiched between thermally conducting, electrically isolating material and are provided with a thermal conduction path to the base of the RTS-EE. The power components are mounted to heat sink plates which are in direct thermal contact with the RTS-EE baseplate. This RTS-EE baseplate is generally expected to be mounted to a water cooled cold-plate in its nominal on-orbit operating condition. Figure 4 provides an exploded isometric view of the RTS-EE showing the PC/104 card stack installation.

OPERATIONS

The operational aspect of the SAMS-II design must await the completion of key elements of the International Space Station and the research payloads and facilities which the SAMS-II hardware will support. These elements are expected to become available in the early twenty-first century, at which time the SAMS-II hardware will be launched, undergo on-orbit checkout, and begin day-to-day operations. Further detail to the operational plans and methods will continue to evolve as the SAMS-II design matures and the capabilities of the ISS become more defined.

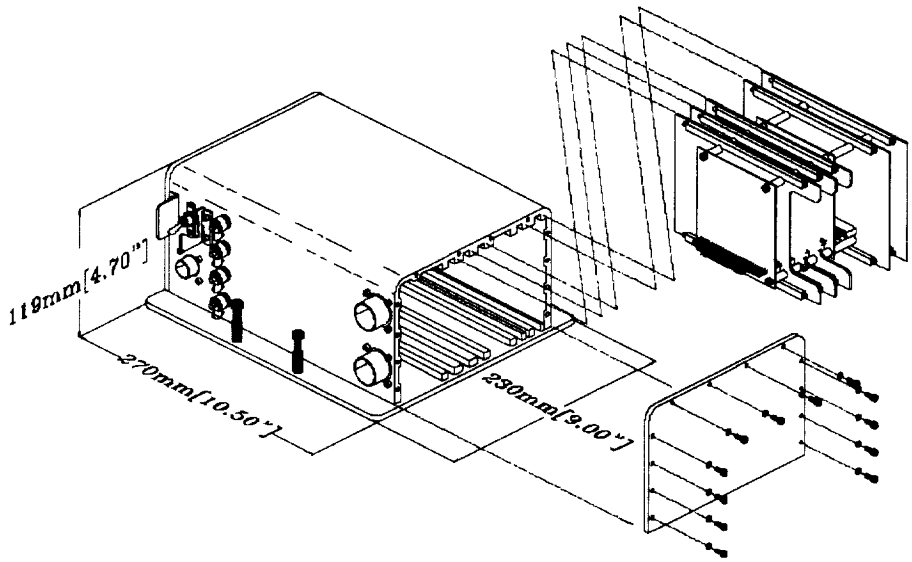

figure 4: RTS Electronics Enclosure

SUMMARY

A process of requirements identification has been completed, and a system is in development to acquire acceleration data for microgravity science payloads and facilities aboard the International Space Station. The second generation Space Acceleration Measurement System (SAMS-II) hardware design contains specific elements focused on maintaining flexibility of operation and allowing systematic upgrades as technology improves over the operational lifetime of the system.

REFERENCES

1. Petrash, D. A., Nussle, et. al.; Effect of Acceleration Disturbances Encountered in MA-7 Spacecraft on the Liquid-Vapor Interface, NASA TN D-1577, 1963.
2. A Microgravity Investigator's Guide, NASA Microgravity Science and Applications Division, 1994.
3. DeLombard, R., Finley, et. al.; Development of and Flight Results from the Space Acceleration Measurement System (SAMS), NASA TM-105652 (AIAA 92-0354), 1992.
4. DeLombard, R. and Rogers; Quick Look Report of Acceleration Measurements on Mir Space Station During Mir-16, NASA TM-106835, 1995.
5. Blanchard, R. C., Nicholson, et. al.; Orbital Acceleration Research Experiment: Calibration Measurements, Journal of Spacecraft and Rockets, Vol. 32, No. 4, pp. 619-626, 1995.
6. Wagar, W. O., Lugasy, et. al.; A Plan for Orbital Acceleration Research Experiment Operations on STS-73 (USML-2), AIAA 95-0689, 1995.
7. Toward a Microgravity Research Strategy, Space Studies Board, National Research Council, 1992.

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