B. STS-40 PAPERS PREPARED BY PI

A COMPARISON OF LOW-GRAVITY MEASUREMENTS ON-BOARD COLUMBIA DURING STS-40

M. J. B. Rogers
Center for Microgravity and Materials Research
University of Alabama in Huntsville
Huntsville, Alabama 35899 USA

C. R. Baugher
Acceleration Characterization and Analysis Project
NASA Marshall Space Flight Center
MSFC, Alabama 35812 USA

R. C. Blanchard
OARE Project Technologist
NASA Langley Research Center
Hampton, Virginia USA

R. DeLombard
SAMS Project Manager
NASA Lewis Research Center
Cleveland, Ohio USA

W. W. Durgin
Aerospace Engineering
Worcester Polytechnic Institute
Worcester, Massachusetts USA

D. H. Matthiesen
Case Western Reserve Univ.
NASA Lewis Research Center
Cleveland, Ohio USA

W. Neupert
Code 680
NASA Goddard Space Flight Ctr.
Greenbelt, Maryland USA

P. Roussel
European Space Agency
Keplerlaan 1
Noordwijk, The Netherlands

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Abstract

The first NASA Spacelab Life Sciences mission (SLS-1) flew 5 June to 14 June 1991 on the orbiter Columbia (STS-40). The purpose of the mission was to investigate the human body's adaptation to the low-gravity conditions of space flight and the body's readjustment after the mission to the 1 g environment of earth. In addition to the life sciences experiments manifested for the Spacelab module, a variety of experiments in other scientific disciplines flew in the Spacelab and in Get Away Special (GAS) Canisters on the GAS Bridge Assembly. Several principal investigators designed and flew specialized accelerometer systems to better assess the results of their experiments by means of a low-gravity environment characterization. This was also the first flight of the NASA Microgravity Science and Applications Division (MSAD) sponsored Space Acceleration Measurement System (SAMS) and the first flight of the NASA Orbiter Experiments Office (OEX) sponsored Orbital Acceleration Research Experiment accelerometer (OARE). We present a brief introduction to seven STS-40 accelerometer systems and discuss and compare the resulting data. During crew sleep periods, acceleration magnitudes in the 10^{-6} to 10^{-5} g range were recorded in the Spacelab module and on the GAS Bridge Assembly. Magnitudes increased to the 10^{-4} g level during periods of nominal crew activity. Vernier thruster firings caused acceleration shifts on the order of 10^{-4} g and primary thruster firings caused accelerations as great as 10^{-2} g. Frequency domain analysis revealed typical excitation of Orbiter and Spacelab structural modes at 3.5, 4.7, 5.2, 6.2, 7, and 17 Hz.

1. Introduction

The first NASA Spacelab Life Sciences mission (SLS-1) flew 5 June to 14 June 1991 on the orbiter Columbia (mission STS-40). The purpose of the mission was to investigate the human body's adaptation to the low-gravity conditions of space flight and the body's readjustment after the mission to the 1 g environment of earth. In addition to the life sciences experiments manifested for the Spacelab module, a variety of experiments in other scientific disciplines flew in the Spacelab and in Get Away Special (GAS) Canisters on the GAS Bridge Assembly. Several principal investigators designed and flew accelerometer systems to characterize the low-gravity environment. This was done to better assess the results of their experiments. This was also the first flight of the MSAD-sponsored SAMS and the first flight of the OEX-sponsored OARE. This paper presents a brief introduction to seven accelerometer systems which measured and recorded acceleration levels during STS-40 and discusses the resulting data.

2. Accelerometer Systems

The STS-40 accelerometer systems to be discussed are listed in Table 1. Two of the systems flew in support of individual crystal growth experiments - the Worcester Polytechnic Institute (WPI) Fluid Behavior and Zeolite Crystal Growth Experiments, and the GTE Gallium Arsenide Crystal Growth Experiment.[1,2] The NASA Goddard Orbiter Stability Experiment (OSE) was designed to characterize Orbiter g-jitter by measuring angular accelerations using sun sensors. The ESA Solid State Micro-Accelerometer (SSMA) recorded data as part of a component performance testing procedure. The OARE system, a space accelerometer package with on-orbit calibration capabilities, was designed to measure and record the Orbiter aerodynamic acceleration environment from the free molecule flow regime through the rarefied-flow transition into the hypersonic continuum regime.[3,4] The OEX High Resolution Acceleration Package (HiRAP) was also designed to measure low frequency aerodynamic accelerations with the goal of determining Orbiter re-entry aerodynamic flight performance characteristics.[5-14] SAMS flew in support of the Solid Surface Combustion Experiment (SSCE). SAMS was designed to support multiple experiments and multiple missions; it is scheduled to fly on all Orbiter missions which include MSAD-sponsored low-gravity experiments. The resulting data base is expected to contribute to the characterization of the low-gravity environment of Orbiters.[15-17] The locations of the GAS Bridge Assembly and of the SAMS units in the Spacelab are shown in Figs. 1 and 2.

2.1 GTE Gallium Arsenide Crystal Growth Experiment

The GTE experiment was designed to study the effect of reduced gravity on the growth of gallium arsenide (GaAs) semiconductor material.[1] The experiment was located in GAS Canister G-052 and was oriented with the accelerometer x- and y-axes parallel to those of the Orbiter and with the z-axes anti-parallel. The GTE triaxial sensor accelerometer was developed and tested prior to the STS-40 flight on a NASA KC-135 Microgravity Research Aircraft.[2] On STS-40, a Sundstrand QA-2000 sensor was aligned with the crystal growth axis (x-axis) and two QA-1400 sensors were used in the y- and z-directions. The measurement range for the system was 1×10^{-5} to 1×10^{-2} g and the data were lowpass filtered at 16 Hz with a 3 dB/decade rolloff. A Tattletale IV microcomputer was used for data processing and storage, allowing 155 kilobytes of memory per axis.

A specialized data processing technique was developed to reduce memory requirements. For a two second period, 100 measurements were made and initially stored. For each two second block of data, a least squares fit to the data was computed and the slope and intercept of the fit were recorded. Two other statistics were recorded - the standard deviation of the 100 samples and the value of the point with the largest deviation from the intercept value. Upon calculation and storage of these values, the 100 data points were discarded and the next two seconds of data were recorded. At five minute intervals, absolute time, relative time, microcomputer temperature, and accelerometer temperature were recorded.

2.2 WPI Fluid Behavior and Zeolite Crystal Growth Experiments

The WPI accelerometer system flew on STS-40 in conjunction with zeolite crystal growth and fluid behavior experiments in GAS Canister G-408. The zeolite crystal growth experiment involved nucleation and subsequent growth from solution. It was hypothesized that the mass transfer and, thus, the growth rate would be functions of the g-jitter environment. The fluid behavior experiment involved measurements of quantity and heat and mass transfer in the re-establishment of equilibrium. It was expected that these processes as well as transfer of additional liquid to the test vessels would also be affected by the g-jitter environment.

The accelerometer system was flown to assess the performance of these experiments as a function of the acceleration environment. The system consists of three piezoelectric sensors and a system for analog signal processing, digital sampling, and storage of data. Accelerometer axes were aligned with the roll, pitch, and yaw axes of the Orbiter. A low frequency data cutoff of approximately 0.8 Hz was established by the a.c. nature of the piezoelectric elements. The high frequency cutoff was set at 10 Hz using a lowpass filter associated with the signal amplifiers. Each of the three channels was monitored by positive and negative peak detectors which were read at a rate of 1 Hz. The greatest magnitude value for each one second window for each channel was stored together with sign. For the data presented here, the magnitude of the acceleration vector (root sum of squares of the three axes) is used. Resolution of the system was 10 μg, and full scale was 20,000 μg.

2.3 NASA/GSFC Orbiter Stability Experiment

The primary objective of the Orbiter Stability Experiment (OSE) was to obtain a characterization of the Orbiter's spectrum of high frequency angular motions. The OSE measures angular accelerations directly with sun sensors by observing changes in the orientation of the Orbiter in pitch and roll relative to the Sun. The OSE detected the Orbiter's motion by measuring the direction of incoming sunlight with two precision Lockheed Intermediate Sun Sensors (LISS) provided by the Lockheed Missiles and Space Co. SPARCS Office, White Sands Missile Range, NM, under contract to the Wallops Flight Facility of the NASA Goddard Space Flight Center.

The system can measure angular changes as small as 0.25 arc sec, the level set by data digitization. Electronics noise is about 0.2 arc sec RMS for the most sensitive pitch and roll channels. The OSE recorded the position of the Sun relative to the Orbiter during the sunlit portions of orbits 34, 35, and 39, for a total duration of three hours. It was necessary for the OSE sensors to be oriented toward the Sun within two degrees before observations could be made, and the Orbiter was held in a $-z_0$ solar inertial attitude with a deadband of 0.1 arc degree during observations. The sensors were mounted to the top plate of GAS Canister G-507 and aligned to the GAS Bridge within 1 arc min in pitch and 7 arc min in roll.

The two LISS were oriented to provide signals of opposite polarity for Orbiter pointing deviation as a means of discriminating against unintended electrical noise pickup. The analog signals from the sensor were passed through an 11 Hz lowpass filter with 12 dB/octave rolloff, amplified, and sampled at a rate of 58 Hz for each of four (two pitch and two roll) data channels. The data stream was recorded on a Lockheed 4200 tape recorder for playback after the mission. The instrument was operated both with and without a solar input to determine the level of internal electronic noise.

2.4 ESA Solid State Micro-Accelerometer

The primary objective of the Solid State Micro-Accelerometer experiment (SSMA) was to test a new type of highly sensitive accelerometer in low-g to characterize performance in the absence of the 1 g environment of Earth. The system was also designed to provide an engineering test demonstration of the sensors to prove suitability for applications on future flights. The SSMA was located in GAS Canister G-021. Each accelerometer unit included a small proof mass (15 micro-gram) and supporting silicon springs fabricated from mono-crystalline silicon and combined on a hybrid substrate with the analog readout electronics. The micro-structure and associated micro-electronics were sealed and mounted in a standard, 14 pin dual-in-line electronics package as an integral unit. The accelerometers were designed to operate within the acceleration range ±80 milli-g with a sensitivity of 125 volts/g and a frequency range from d.c. to 100 Hz.

Twelve accelerometers (among which were two dummy units) were mounted in a three axis array on a one axis vibrating table designed to provide variable calibration signals during flight. Four accelerometers were oriented with their sensitive axis parallel to the vibration axis of the table and to the Orbiter pitch axis (y-axis), 3 parallel to the Orbiter roll axis (x-axis), and 3 parallel to the Orbiter z-axis. The array configuration was chosen to assess the transverse effects of the accelerometers and to compensate, at the processing level, for external disturbances. The SSMA experiment consisted of 51 measurement sequences: 31 with excitations from 1 μg to 40 milli-g at rates between 0.1 and 50 Hz (sinusoidal); 12 without excitation; and 8 self-test sequences.

The Data Acquisition System was designed to sample, digitize, and store in a Mass Memory Unit the signals of the 12 accelerometers; the thermistor readings of accelerometer temperature; the displacement transducer signals from the vibrating table; the temperature and voltage outputs from the Data Acquisition System; the temperature, pressure, and voltages from the battery; and the signals from a Real Time Clock and an Advanced Real Time Clock. To minimize the amount of stored data and to avoid aliasing effects, the accelerometers and displacement transducer signals were sampled at 16 times the excitation frequency and filtered through a digital signal processor with a cut-off frequency of 4 times the excitation and a rolloff of -80 dB.

2.5 Orbital Acceleration Research Experiment

The Orbital Acceleration Research Experiment (OARE) is a triaxial electrostatic accelerometer package with complete on-orbit calibration capabilities.[3,4] The OARE consists of three orthogonal, electrostatically suspended proof mass sensors, a full in-flight calibration station, and a microprocessor which is used for in-flight experiment control, processing, and storage of flight data. The experiment system is designed to measure low frequency (<5 Hz), low-level acceleration (nano-g sensitivity), and is principally directed at characterizing the Orbiter's aerodynamic behavior in the rarefied-flow flight regime. The OARE system is mounted as a payload on the floor of the cargo bay on a keel bridge spanning bay 11.

2.6 High Resolution Acceleration Package

The High Resolution Acceleration Package (HiRAP) consists of a set of three orthogonal, pendulous, gas-damped accelerometers, each with a resolution of 1 μg and a measurement range of approximately ±8000 μg. The HiRAP is designed to measure high-altitude aerodynamic acceleration on the Orbiter vehicle during atmospheric re-entry. The HiRAP is mounted in a wing box of the cargo bay, such that the orthogonal HiRAP axes are aligned with the Orbiter body axes. Data are collected at 112 Hz, and two lowpass filters at 20 Hz and 2 Hz are applied. The HiRAP absolute accuracy over its twelve flights since 1983, after in-flight calibration, is 3 to 7 μg. [5-14]

2.7 Space Acceleration Measurement System

The Space Acceleration Measurement System was developed to monitor and measure the low-g environment of Orbiters in support of MSAD-sponsored science payloads.[15-17] Resulting data are used by microgravity investigators in assessing the influence of acceleration on flight experiments. On STS-40, SAMS was manifested to support the Solid Surface Combustion Experiment (SSCE). SAMS consists of three remote triaxial sensor heads, connecting cables, and a controlling data acquisition unit with a digital data recording system using optical disks with 200 megabyte storage capacity per side. With the availability of crew access to change the disks, data storage capacity is essentially unlimited. On STS-40, three triaxial sets of Sundstrand QA-2000 sensors recorded data at 25 samples per second with a 5 Hz lowpass filter applied (140 dB/decade rolloff). The SAMS control electronics and data recording package was mounted in the Spacelab in SMIDEX Rack 5. The three triaxial sensor heads were mounted 1) on the Spacelab floor on the base of the Body Restraint System, 2) on the connector bracket panel of the SMIDEX in Rack 5, and 3) on the SSCE in Rack 7, see Fig. 2. The orientations of the SAMS heads with respect to the Orbiter coordinate system are given in Table 2.

3. Results

The accelerometer systems flown during STS-40 recorded data during a variety of time periods. There is some overlap, however, early in the mission and especially during crew sleep periods. A comparison of the results from these periods provides an indication of the low-g environment at various locations.

3.1 GTE Gallium Arsenide Crystal Growth Experiment

According to the pre-flight mission plan, the GTE experiment was to be activated at MET 02/10:35. The accelerometer system was to start recording data 4 hours, 55 minutes later. Crystal growth was scheduled to begin at the same time as data recording. These times were selected to coincide with a crew sleep period, to reduce the effects of crew related g-jitter. While the exact time of experiment activation was not recorded, examination of the data indicates that the full five hours of crystal growth and accelerometer data recording did take place during a quiescent period.

Several general comments can be made about the GTE accelerometer data during STS-40. Details have been presented previously.[1] The z-axis experienced the greatest variation and the x-axis was the most quiet. The lesser quality of the accelerometer sensors used for the y- and z-axes is apparent; the increased temperature dependence of these sensors was manifested as larger drifts due to temperature variations.

The data collected indicate that a relatively quiet acceleration environment existed for the GTE crystal growth experiment run. A total of 541 significant acceleration variations were recorded on the three axes. Events were considered significant when a relative change of at least $1x10^{-5}$ g occurred. For variations of 10^{-4} g or larger only 28 events were detected, with none in the most sensitive experiment axis (x-axis). The largest difference in average acceleration during the five hour crystal growth period was $2.5x10^{-4}$ g.

3.2 WPI Fluid Behavior and Zeolite Crystal Growth Experiments

The GAS relay for this experiment package was activated at MET 00/10:47. The times indicated on Fig. 3 are relative to that MET. The total run time for the experiment was approximately 71 hours and acceleration data were continuously collected during that time. Fig. 3 shows a two hour record beginning at experiment start plus four hours and illustrates two basic types of acceleration environment present during the experiment operation. Type A data were defined by pairs of acceleration pulses occurring approximately every 2 minutes with magnitudes of 5 to 7 milli-g. This type of event is present during the entire 71 hours. Type B accelerations have magnitudes on the order of 2 to 3 milli-g occurring at intervals of 10.1 seconds.

The Type A accelerations resulted from an electromechanical relay used to control the oven heating system for the zeolite crystal growth experiment. The period was approximately 2.0 minutes early in the experiment and became 1.9 minutes near the end of the experiment because decreasing payload temperature resulted in faster heat loss from the oven. Similarly, the duty cycle increased from 17 to 18 seconds over the course of the experiment because lower battery voltage necessitated greater heating times.

The Type B accelerations resulted from relays in a power conservation system. Whenever precision temperature and pressure readings were required from the fluid behavior system, the analog circuits were energized and de-energized at approximately 10 second intervals.

Between these events, accelerations on the order of 100 to 200 μg were recorded. Thus, the self-induced acceleration of the experiment package greatly exceeded the Orbiter accelerations whenever electromechanical devices were in operation.

3.3 NASA/GSFC Orbiter Stability Experiment

The OSE was operated for a total of three hours on STS-40: MET 01/23:56 - 02/02:01 and 02/07:26 - 02/08:21. Only data from the first two hour interval have been processed to date. That interval included two periods of solar observation separated by about 30 min in the Earth's shadow. During this period, the offset of the Orbiter's $-z_0$-axis from the solar direction as the vehicle moved in its deadband about its pitch axis (+y-axis) produced a signal reminiscent of a rectified sine wave. Atmospheric drag forces typically rotated the Orbiter against one side of the deadband. The motions of the Orbiter about its roll axis (+x-axis) were less regular in frequency.

The objective of the OSE was to record high frequency g-jitter in the Orbiter bay that might be superimposed on the expected larger scale motion of the Orbiter within its deadband. An initial scan of the first sunlit interval of observation indicates that any g-jitter must have been at or below the limit of detectability (0.25 - 0.5 arc sec). A typical example of the signal output for pitch channel A during an interval including an assumed thruster firing (which reversed the angular motion of the Orbiter) is shown in Fig. 4.

Power spectral densities were calculated for periods of interest. The reversal of Orbiter motion due to a thruster firing at the extremes of its deadband is smooth. No detailed correlation of the data has yet been made, however, and it is not clear to what extent the smooth reversal of attitude is the result of a sequence of thruster firings or reflects a low frequency response by the Orbiter to a single firing. In any case, no angular vibrations at frequencies above about 1 Hz attributable to a vernier thruster firing are detectable with the present instrument.

3.4 ESA Solid State Micro-Accelerometer

The GAS relay for G-021 was activated at MET 00/10:37. The SSMA sequences started 4 hours, 33 minutes later during the first crew sleep period. From post-flight data analysis, no significant differences were found between the on-ground and the in-space performance of these new accelerometers. The measured noise of the devices was 0.1 μg RMS (0.6 μg/Hz). The success of the SSMA experiment demonstrates that the new type of accelerometers based on silicon technology are suitable and adequate for low-gravity applications.

The SSMA also provided measurements of the dynamic environment, mainly during the experiment sequences for which the vibrating table was not excited and when the amplitude of induced accelerations was below 100 μg. The amplitudes of the micro-dynamic disturbances observed during the experiment were on average below 10 to 50 μg with the exception of some peak events correlated with Orbiter thruster firings. It was clear, after processing, that the relatively large signals observed in the time domain were essentially due to strong disturbances at specific frequencies. Fig. 5 shows data from Experiment Sequence No. 5. In the time domain, the 1 Hz/6 μg calibration signal is clearly visible together with two strong external perturbations. Frequency modes of 3.7 Hz and 4.7 Hz dominate the frequency domain representations of this time period.

Other frequency modes related to the vibrating table, Orbiter structural modes, and the Orbiter Ku band antenna (17 Hz) were observed in sequences of SSMA data. Within the low frequency observation band (d.c. - 1 Hz), the acceleration levels are very low. Long periods of quiet environment in low frequency regimes can be found in between successive Orbiter thruster firing events. The 4.7 Hz signal, observed consistently in the frequency domain, could also be clearly discerned in the time domain associated with strong events such as thruster firings.

3.5 Orbital Acceleration Research Experiment

Because of its sensitivity, the OARE instrument detects aerodynamic behavior of the Orbiter while in low-Earth orbit. A typical sleep period (MET 07/16 - 07/18) was examined on STS-40. The results of the examination for the spacecraft y-axis are shown in Fig. 6. During the flight, a "trimmed-mean" filter was applied to the data which were stored aboard the Shuttle in the OARE data storage system.[3,4] An acceleration model which includes aerodynamic, gravity gradient, and rotational effects was constructed and compared with flight data. Comparison of the model to the flight data shows the instrument to be sensitive to all major expected low frequency acceleration phenomena in the y-axis. Variation of atmospheric drag among orbits was on the order of $\pm 2 \times 10^{-7}$ g. Some erratic instrument bias persists in the x- and z-axes. In these axes, the OARE data can be made to match a comprehensive atmospheric-aerodynamic model by making arbitrary bias adjustments.

3.6 High Resolution Acceleration Package

On STS-40, HiRAP data were recorded during ascent, orbit, and re-entry. During re-entry, aerodynamic control surfaces used for Orbiter attitude and control require hydraulic power. This power is provided by a set of three auxiliary power units (APU). The exhaust gas ports for these pulsed turbines are located on the top of the Orbiter just in front and to the sides of the vertical tail. The exhaust jets of gas produce accelerations in the Orbiter negative z-direction. These APU accelerations were measured and recorded by HiRAP.

Fig. 7 shows the HiRAP z-axis re-entry acceleration measurements for STS-40. The APU signals become evident at two times during Orbiter descent: just before the deorbit burn and just before the onset of atmospheric drag. The 112 Hz HiRAP data have been averaged over one second intervals to permit characterization of the acceleration changes. The time history of this data segment shows a shift at the ignition of the first APU, a sensor saturation during deorbit burn, a second shift at the ignition of the second and third APU, and the onset of atmospheric drag. The scattered points are the averaged thruster induced acceleration spikes.

In the region surrounding the first APU transition, a measurement of the data shift represents a bias of about 15 μg. Data from the second and third APU transition show a shift of about 32 μg. It is at the second APU transition region that an in-flight HiRAP calibration is performed. This 32 μg shift is incorporated in the calibration aerodynamic signal. The shifts in the z-axis acceleration signal are consistent with shifts found in prior HiRAP mission data.[5-14]

3.7 Space Acceleration Measurement System

The SAMS units collected data for approximately 7 days during STS-40: MET 01/00:57 - 08/01:38. SAMS was powered down twice during this time to allow operation of the Rotating Dome Experiment. Initial processing of the SAMS data as reported in the ACAP Early Summary Report[17] includes calculation and plotting of 10-second means and 1-second RMS for 2-hour periods and frequency domain representations of composite magnitude spectra in color spectrogram form. Data correction for bias and temperature variations used both Sundstrand supplied information and information derived from mission data. Detailed analysis of specific segments of the STS-40 SAMS data has focused on periods of thruster firings. Fig. 8 shows an example of a visual correlation of thruster firing occurrences with 1-second mean SAMS data during a period of otherwise low-level activity. Resulting accelerations (vector magnitude) reached 10^{-2} g. Variations in thruster-related acceleration result from the different combinations of jets fired and different pulse strength and firing duration. Fig. 9 shows a detailed example of one axis of SAMS data during a vernier thruster firing. Note that the effect of the firing is an overall linear shift of the vehicle, reflected in a shift of the mean acceleration.

In general, the acceleration environment measured by SAMS during STS-40 is summarized as follows. During sleep periods, acceleration magnitudes were in the 5 μg range. During periods of crew activity, magnitudes ranged from tens to hundreds of μg. As seen in previous studies of Orbiter acceleration environment,[18-21] spectral representations of SAMS data were dominated by specific Orbiter and Spacelab structural modes, most notable are the 3.5, 4.7, 5.2, 6.2, and 7 Hz modes. The three modes >5 Hz are modulated by the 5 Hz lowpass filter applied to the data.

4. Discussion

The accelerometers which flew on STS-40 provided data in the frequency range up to 100 Hz (ESA SSMA), but most were restricted to an upper bound of about 10 Hz. This limited the contribution of higher frequency vibration and noise to the measured data, making the STS-40 data some of the "quietest" acceleration data collected on an Orbiter mission. During crew sleep periods, acceleration magnitudes in the 10^{-6} to 10^{-5} g range were recorded in the Spacelab module and on the GAS Bridge Assembly. The acceleration magnitudes increased to the 10^{-4} g level during periods of nominal crew activity. Vernier thruster firings caused acceleration shifts on the order of 10^{-4} g and primary thruster firings caused accelerations as great as 10^{-2} g. The WPI accelerometer system recorded a number of acceleration events in the milli-g range which were identified as experiment related. The OSE accelerometer system measured no angular vibrations with frequencies greater than 1 Hz during a period of vernier firings. This is attributed to the g-jitter levels being below the instrument's limit of detectability. The HiRAP data show variations on the order of 10^{-5} g during APU firings during Orbiter re-entry. This is consistent with data collected during previous flights of HiRAP, but cannot be compared with other STS-40 accelerometer data because of the data collection time. OARE measured low frequency accelerations consistent with a model of atmospheric and aerodynamic effects.

Frequency domain analysis was applied to OSE, SAMS, and SSMA data. The SAMS and SSMA data show the typical excitation of Orbiter and Spacelab structural modes that is expected in accelerometer data. The most common of these modes in the STS-40 data are those at 3.5, 4.7, 5.2, 6.2, and 7 Hz. The SSMA, recording data at a higher sampling rate than other instruments on STS-40, also measured the 17 Hz Ku-band antenna dither and Orbiter structural mode. The fact that the 4.7 Hz Spacelab mode was recorded by the SSMA on the GAS Bridge

Assembly leads us to reevaluate our understanding of how accelerations propagate across loosely coupled structures. Further analysis of this phenomenon is required. Before drawing any conclusions about the Orbiter low-g environment, however, one must keep in mind that the environment monitored by SSMA was that of the accelerometer head linked to the cargo bay through the vibrating table, the GAS canister, and the GAS Bridge Assembly.

The flight of the seven accelerometer systems discussed here made STS-40 the best instrumented low-g Orbiter flight to date. The analysis to date has greatly fortified our knowledge of the typical acceleration environment of a manned Orbiter in low-Earth orbit. Further work, specifically additional frequency domain analysis, comparisons of thruster firing times with accelerometer data, and comparisons of data from accelerometers in the Spacelab and on the Gas Bridge Assembly, will greatly increase our understanding of the propagation of accelerations throughout and across structures of the Spacelab and Orbiter.

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Acknowledgements

There is a very large group of people without whom this paper would not have been possible. These are the teams responsible for the development and flight of the accelerometer systems and the post-flight analysis of the accelerometer data. This includes the SAMS project team at NASA LeRC and the ACAP project team at NASA MSFC who are involved in the development and flight of SAMS and the analysis of SAMS data, respectively. Continuing support by NASA Headquarters for the SAMS and ACAP projects is greatly appreciated.

Technical development of the OSE was carried out by J. Houston, K. J. Meese, W. S. Money, T. B. Plummer, and F. P. Russo, all of the NASA Goddard Laboratory for Astronomy and Solar Physics. Project coordination was provided by N. F. Barthelme and S. P. Olden of Goddard's Special Payloads Division.

The SSMA units were manufactured by Centre Suisse pour Electronique et Microtechnique. The manufacturer of the measurement support system and the overall prime contractor for the payload was Compagnie Industrielle Radioelectrique.

Special thanks to Lynne Carver of the CMMR for formatting the majority of the figures. Walt Roark of Sverdrup Technology/ACAP Project provided Fig. 8.

Figure Captions

Fig. 1. General locations of the Spacelab Module and GAS Bridge Assembly on Columbia during STS-40.

Fig. 2. General locations of SAMS units in the Spacelab Module during STS-40: on the base of the Body Restraint System (BRS), on the connector bracket panel of the SMIDEX in Rack 5, and on the SSCE in Rack 7.

Fig. 3. Peak acceleration magnitude versus time recorded by the WPI accelerometer system. Note Type A accelerations resulting from an electromechanical relay and Type B accelerations resulting from power conservation system relays. Time is from initiation of experiment operations.

Fig. 4. Output of the OSE high sensitivity pitch channel during an interval when vernier thrusters were active. Pitch offset is the angle between the solar direction and the optical axis of a sun sensor. Time is from initiation of experiment operations.

Fig. 5. Time history (a) and frequency domain representation (b) of SSMA y-axis data during Experiment Sequence 5. Note the 1 Hz / 6 μg calibration signal and structural frequency modes of 3.7 and 4.7 Hz.

Fig. 6. OARE y-axis flight data compared with calculated atmospheric-aerodynamic model. Time is in MET.

Fig. 7. HiRAP z-axis (1.0 sec mean) uncalibrated reentry data. Time is in GMT.

Fig. 8. Overlay of thruster firing occurrences with 1-second mean SAMS data during a period of low-level activity. Solid circles denote firings of vernier thrusters; open circles denote firings of primary thrusters.

Fig. 9. Y-axis SAMS data during a period of vernier thruster firings. Note that the resultant linear shift of the vehicle is reflected in a shift of the mean acceleration in the time domain (a) and an increased d.c. component in the frequency domain (b).

Table 1. STS-40 Accelerometer Systems

Accelerometer System/Experiment	Investigator / Contact Person	Organization/Affiliation
Fluid Behavior and Zeolite Crystal Growth Experiments	William W. Durgin	Worcester Polytechnic Institute
Gallium Arsenide Crystal Growth	David H. Matthiesen	Case Western Reserve University / NASA LeRC
Orbiter Stability Experiment	Werner Neupert	NASA GSFC
OARE	Robert C. Blanchard	NASA LaRC
HiRAP	Robert C. Blanchard	NASA LaRC
Solid State Micro-Accelerometer	Philippe Roussel	ESA
SAMS	Richard DeLombard	NASA LeRC

Table 2. Orientation of SAMS with respect to the Orbiter on STS-40.

Sensor Head	SAMS Orientation With Respect to Orbiter		
	Xo	**Yo**	**Zo**
Spacelab floor	Ys	-Zs	-Xs
Rack 5	-Ys*	-Xs*	-Zs*
Rack 7	-Ys	-Xs	-Zs

*with -28.9° rotation about Ys

AIAA 93-0833
Low Gravity Environment On-board Columbia During STS-40

M. J. B. Rogers
Center for Microgravity and Materials Research
University of Alabama in Huntsville, Huntsville, Alabama 35899 USA

C. R. Baugher
Acceleration Characterization and Analysis Project
NASA Marshall Space Flight Center, MSFC, Alabama 35812 USA

R. C. Blanchard
OARE Project Technologist,
NASA Langley Research Center, Hampton, Virginia USA

R. DeLombard
SAMS Project Manager
NASA Lewis Research Center, Cleveland, Ohio USA

W. W. Durgin
Aerospace Engineering
Worcester Polytechnic Institute, Worcester, Massachusetts USA

D. H. Matthiesen
Case Western Reserve University
NASA Lewis Research Center, Cleveland, Ohio USA

W. Neupert
Code 680
NASA Goddard Space Flight Center, Greenbelt, Maryland USA

P. Roussel
European Space Agency
Keplerlaan 1, Noordwijk, The Netherlands

31st Aerospace Sciences Meeting & Exhibit

January 11-14, 1993 / Reno, NV

AIAA-93-0833

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M. J. B. Rogers
Center for Microgravity and Materials Research
University of Alabama in Huntsville
Huntsville, Alabama 35899 USA

C. R. Baugher
Acceleration Characterization and Analysis Project
NASA Marshall Space Flight Center
MSFC, Alabama 35812 USA

R. C. Blanchard
OARE Project Technologist
NASA Langley Research Center
Hampton, Virginia USA

R. DeLombard
SAMS Project Manager
NASA Lewis Research Center
Cleveland, Ohio USA

W. W. Durgin
Aerospace Engineering
Worcester Polytechnic Institute
Worcester, Massachusetts USA

D. H. Matthiesen
Case Western Reserve Univ.
NASA Lewis Research Center
Cleveland, Ohio USA

W. Neupert
Code 680
NASA Goddard Space Flight Ctr.
Greenbelt, Maryland USA

P. Roussel
European Space Agency
Keplerlaan 1, Noordwijk
The Netherlands

Abstract

The first NASA Spacelab Life Sciences mission (SLS-1) flew 5 June to 14 June 1991 on the orbiter Columbia (STS-40). The purpose of the mission was to investigate the human body's adaptation to the low gravity conditions of space flight and the body's readjustment after the mission to the 1 g environment of earth. In addition to the life sciences experiments manifested for the Spacelab module, a variety of experiments in other scientific disciplines flew in the Spacelab and in Get Away Special (GAS) Canisters on the GAS Bridge Assembly. Several principal investigators designed and flew specialized accelerometer systems to characterize the low gravity environment. This was done to better assess the results of their experiments. This was also the first flight of the NASA Microgravity Science and Applications Division (MSAD) sponsored Space Acceleration Measurement System (SAMS) and the first flight of the NASA Orbiter Experiments Office (OEX) sponsored Orbital Acceleration Research Experiment accelerometer (OARE). We present a brief introduction to seven STS-40 accelerometer systems and discuss and compare the resulting data.

1. Introduction

The first NASA Spacelab Life Sciences mission (SLS-1) flew 5 June to 14 June 1991 on the orbiter Columbia (mission STS-40). The purpose of the mission was to investigate the human body's adaptation to the low gravity conditions of space flight and the body's readjustment after the mission to the 1 g environment of earth. In addition to the life sciences experiments manifested for the Spacelab module, a variety of experiments in other scientific disciplines flew in the Spacelab and in Get Away Special (GAS) Canisters on the GAS Bridge Assembly. To better assess the results of the various experiments, several principal investigators designed and flew accelerometer systems. This was also the first flight of the MSAD-sponsored SAMS and the first flight of the OEX-sponsored OARE. In the following section, we introduce seven accelerometer systems which measured and recorded acceleration levels during STS-40 and discuss the resulting data.

2. Accelerometer Systems, Data, and Results

The STS-40 accelerometer systems to be discussed are listed in Table 1.

Table 1. STS-40 Accelerometer Systems

Accelerometer System/Experiment	Investigator / Contact Person	Organization/ Affiliation
Fluid Behavior and Zeolite Crystal Growth Experiments	William W. Durgin	Worcester Polytechnic Institute
Gallium Arsenide Crystal Growth	David H. Matthiesen	Case Western Reserve Univ.
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Solid State Micro-Accelerometer	Philippe Roussel	ESA
SAMS	Richard DeLombard	NASA LeRC

2.1 GTE Gallium Arsenide Crystal Growth Experiment

The GTE experiment was designed to study the effect of reduced gravity on the growth of gallium arsenide semiconductor material.[1] The experiment was located in GAS Canister G-052 and was oriented with the accelerometer x- and y-axes parallel to those of the Orbiter and with the z-axes anti-parallel. A Sundstrand QA-2000 sensor was aligned with the crystal growth axis (x-axis) and QA-1400 sensors were used in the y- and z-directions. The measurement range for the system was 1×10^{-5}

clear to what extent the smooth reversal of attitude is the result of a sequence of thruster firings or reflects a low frequency response by the Orbiter to a single firing. In any case, no angular vibration at frequencies above about 1 Hz attributable to a vernier thruster firing is detectable with the present instrument.

2.4 ESA Solid State Micro-Accelerometer

The primary objective of the Solid State Micro-Accelerometer experiment (SSMA) was to test a new type of highly sensitive accelerometer in low-g to characterize the instrument performance. The system was designed to provide an engineering test demonstration of the sensors to prove suitability for applications on future flights. The SSMA was located in GAS Canister G-021. Twelve accelerometers (including two dummy units) were mounted in a three axis array on a one axis vibrating table designed to provide variable calibration signals during flight. Four accelerometers were oriented with their sensitive axis parallel to the vibration axis of the table and to the Orbiter y-axis, three parallel to the Orbiter x-axis, and three parallel to the Orbiter z-axis. Each accelerometer unit included a small proof mass (15 micro-gram) and supporting silicon springs fabricated from mono-crystalline silicon and combined on a hybrid substrate with analog readout electronics. The micro-structure and associated micro-electronics were sealed and mounted in a standard, 14 pin dual-in-line electronics package as an integral unit.

The SSMA was designed to operate in the range ±8 milli-g with a sensitivity of 125 volts/g and a frequency range of d.c. to

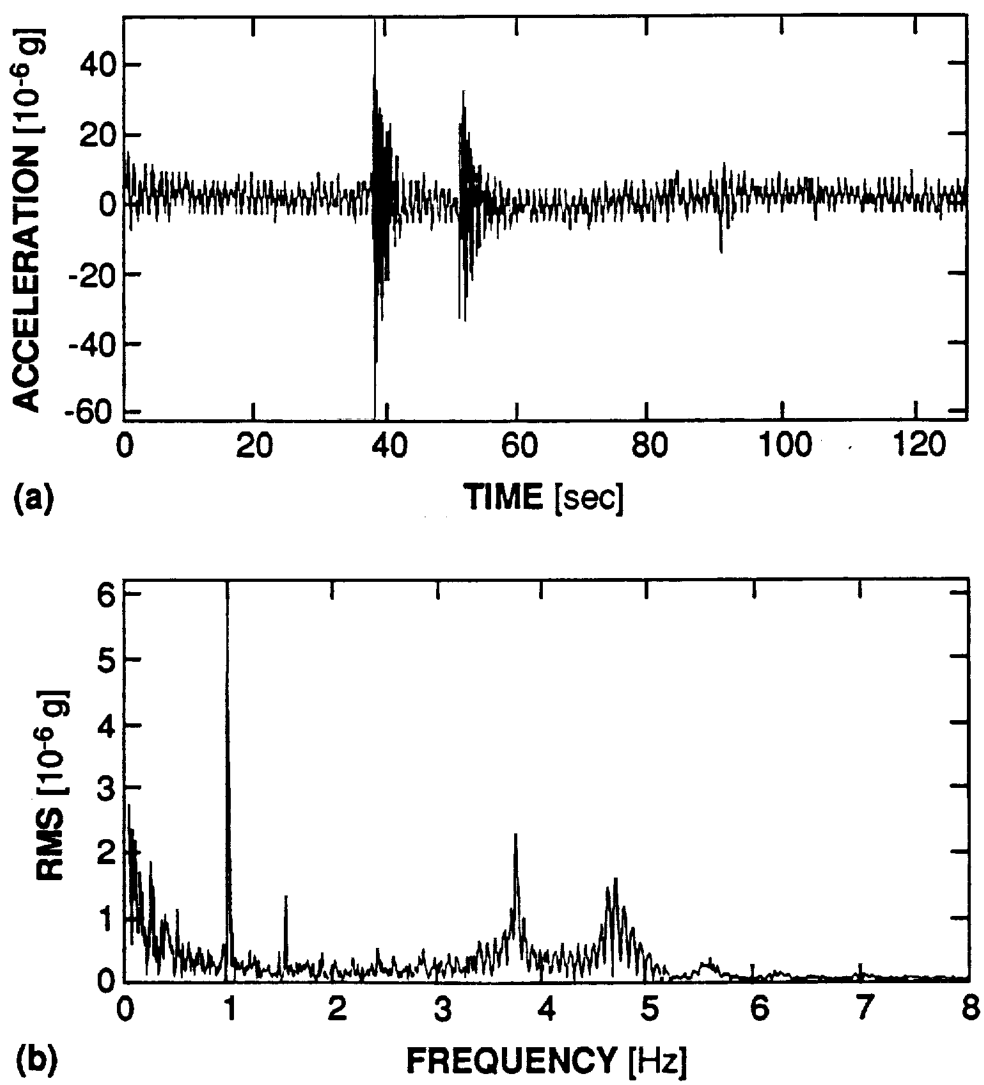

Fig. 1. Time history (a) and frequency domain representation (b) of SSMA y-axis data during Experiment Sequence 5. Note the 1 Hz/6 µg calibration signal and structural frequency modes of 3.7 and 4.7 Hz. Data were sampled at 16 Hz and a 4 Hz cutoff was applied in processing.

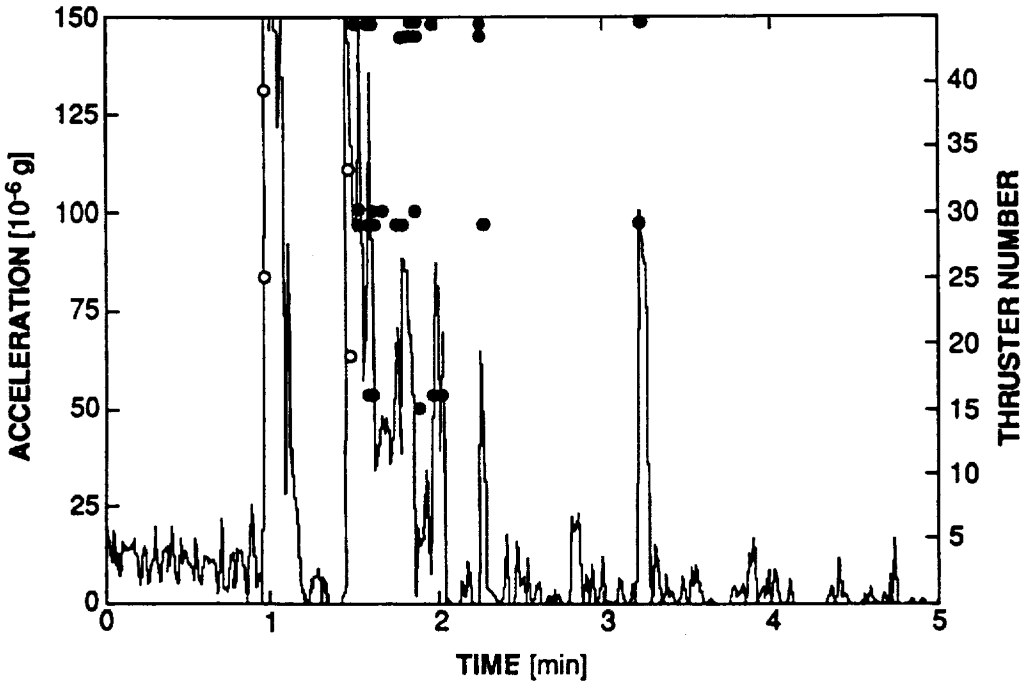

Fig. 3. Overlay of thruster firing occurrences and 1-second mean SAMS data. Solid circles denote vernier thruster firings, open circles denote primary thruster firings.

Variation of atmospheric drag among orbits was on the order of $\pm 2\times10^{-7}$ g. Some erratic instrument bias persists in the x- and z-axes. In these axes, the OARE data can be made to match a comprehensive atmospheric-aerodynamic model by making arbitrary bias adjustments.

2.6 High Resolution Acceleration Package

The High Resolution Acceleration Package (HiRAP) consists of a set of three orthogonal, pendulous, gas-damped accelerometers, each with a resolution of 1 μg and a measurement range of approximately ±8000 μg. HiRAP is designed to measure high-altitude aerodynamic acceleration on the Orbiter vehicle during atmospheric re-entry. The HiRAP is mounted in a wing box of the cargo bay, such that the orthogonal HiRAP axes are aligned with the Orbiter body axes. Data are collected at 112 Hz, and two lowpass filters at 20 Hz and 2 Hz are applied. HiRAP absolute accuracy over its twelve flights since 1983, after in-flight calibration, is in the range 3 to 7 μg.[4-13]

During re-entry, aerodynamic control surfaces used for Orbiter attitude and control require hydraulic power. This power is provided by a set of three auxiliary power units (APU). The exhaust gas ports for these pulsed turbines are located on the top of the Orbiter just in front and to the sides of the vertical tail. The exhaust jets of gas produce accelerations in the Orbiter negative z-direction. These APU accelerations were measured and recorded by HiRAP.

The APU signals become evident at two times during Orbiter descent: just before the deorbit burn and just before the onset of atmospheric drag. The 112 Hz HiRAP data were averaged over one second intervals to permit characterization of the acceleration changes. A time history of this period shows a shift at the ignition of the first APU, a sensor saturation during deorbit burn, a second shift at the ignition of the second and third APU, and the onset of dominant atmospheric drag.

Around the first APU transition, a measurement of the data shift shows a bias of about 15 μg. Data from the second and third APU transitions show a shift of about 32 μg. It is at the second APU transition region that an in-flight HiRAP calibration is performed. This 32 μg shift is incorporated in the calibration aerodynamic signal. The shifts in the z-axis acceleration signal are consistent with the shifts found in prior HiRAP missions.

2.7 Space Acceleration Measurement System

The Space Acceleration Measurement System was developed to monitor and measure the low-g environment of MSAD-sponsored science payloads on the Orbiter.[14,15] SAMS consists of three remote triaxial sensor heads, connecting cables, and a controlling data acquisition unit with a digital data recording system using optical disks with 200 megabyte storage capacity per side. With crew access to change the disks, the data storage capacity is essentially unlimited. On STS-40, three triaxial sets of Sundstrand QA-2000 sensors recorded data at 25 samples per second with a 5 Hz lowpass filter applied (140 dB/decade rolloff). The SAMS control electronics and data recording package was mounted in the Spacelab in SMIDEX Rack 5; SAMS was manifested to support the Solid Surface Combus-

SAMS, and SSMA data. The SAMS and SSMA data show typical excitation of Orbiter and Spacelab structural modes. The most common of these modes in the STS-40 data are those at 3.5, 4.7, 5.2, 6.2, and 7 Hz. The SSMA, recording data at a higher sampling rate than other instruments on STS-40, also measured the 17 Hz Ku-band antenna dither and Orbiter structural mode. The fact that the 4.7 Hz Spacelab mode was recorded by the SSMA on the GAS Bridge Assembly leads us to reevaluate our understanding of how vibrations propagate across loosely coupled structures. Further analysis of this phenomenon is required.

The flight of the seven accelerometer systems discussed here made STS-40 the best instrumented low-g Orbiter flight to date. The analysis has increased our knowledge of the typical acceleration environment of a manned Orbiter in low-Earth orbit. Further work, specifically additional frequency domain analysis, comparisons of thruster firing times with accelerometer data, and comparisons of data from accelerometers in the Spacelab and on the Gas Bridge Assembly, will greatly enhance our understanding of the propagation of accelerations throughout and across structures of the Spacelab and Orbiter.

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NOTES

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. 4	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle: Acceleration Studies		5. Report Date: April 15, 1993
		6. Performing Organization Code
7. Author(s): Ms. Melissa Rogers		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address: Center for Microgravity and Materials Research, The University of Alabama in Huntsville, Huntsville, AL 35899		11. Contract or Grant No.: NAS8-38609, D.O.29
		13. Type of Report and Period Covered: Final
12. Sponsoring Agency Name and Address: George C. Marshall Space Flight Center, National Aeronautics & Space Administration, Marshall Space Flight Center, AL 35812		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Work was performed under NASA Contract NAS8-38609, Delivery Order 29 to support the NASA MSFC Acceleration Characterization and Analysis Project (ACAP). Four tasks (Analysis Development, Analysis Research, Analysis Documentation, and Acceleration Analysis) were addressed by parallel projects: 1) assessment of data access and processing needs of low-gravity investigators; 2) analysis, development, and implementation of acceleration data processing software; and 3) analysis of the acceleration environment of Orbiters. Work in particular was concentrated on the preparation for and implementation of near real-time SAMS data analysis during the USMP-1 mission. Addition data analysis and investigator contact involved the USML-1, USML-2. and USMP-2 missions. User support documents and case specific software documentation and tutorials were developed. Information and results were presented to microgravity users through participation in MGMG meetings and preparation and submittal of technical papers. The potential for future work exists: ACAP computer facilities need to be fully implemented and networked, data resources must be cataloged and accessible, future microgravity missions must be coordinated, and continued Orbiter characterization is necessary.

17. Key Words (Suggested by Author(s)): Microgravity, Residual Acceleration		18. Distribution Statement: UNCLASSIFIED UNLIMITED	
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price

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