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LOW-G MEASUREMENTS BY NASA

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INTRODUCTION

Some aspects of low-g environment during flight of a spacecraft have been of interest since the beginnings of manned spaceflight. Virtually all engineers and scientists involved in spaceflight during the sixties and early seventies assumed that acceleration was reduced to zero once Earth orbit had been achieved. Hence, the term "zero-g" is still heard occasionally, although we are much more enlightened now and know that "zero-g" is only theoretical.

Studies of the effects of astronaut crew motion on spacecraft stabilization and control systems were conducted in the early 1960's. A flight experiment to assess the characteristics of astronaut crew motion disturbances was conducted on the second manned Skylab mission in August 1973. Although the Skylab was not instrumented with low-g accelerometers, forces exerted by the astronauts were determined and acceleration levels were inferred [1]. The flights of materials processing experiments on aircraft in parabolic maneuvers and on suborbital rockets brought low-g accelerometer instrumentation into use to provide experiment investigators a record of the acceleration environment; this, in turn, provided a means of correlating experiments results with residual accelerations.

The following topics provide residual examples of data which have been collected and analyzed over a period exceeding twelve years. Acceleration information from flights of KC-135 aircraft, Spacelab, and the Materials Science Laboratory are included, along with other low-g acceleration data. Some discussion of the challenges associated with the data collection and analysis is also given.

CHALLENGES

Handling of low-g data is definitely not straightforward. One of the challenges in obtaining useful low-g data is that the signal is extremely small when measuring, say, one-millionth of normal Earth gravity or 10^{-6} g. Even at 100 times greater levels (10^{-4} g), we are still measuring a very small signal, i.e., 1/10,000th of g. These tiny signals can easily be masked by ordinary electronic noise and the data user may be misled into believing he has accelerometer data when he may actually have nothing but a useless record of electronic noise. Therefore, it is very important to have quieting circuits built into the electronics and to assure that the signal-to-noise ratio is greater than 1.0 for the end application.

Another challenge in handling low-g data is that the accelerations can be self-induced. At times, the microgravity scientist or engineer overlooks the subtle, but influential accelerations induced by fans, pumps, etc., internal to the experiment apparatus, while at the same time levying stringent acceleration limits on equipment provided by others. Obviously, the key here is to stress objectivity in flight equipment selections, regardless of the source of the equipment, so that minimal accelerations occur at the low-g critical sites.

Another area which requires attention in assessing low-g data is the shifts in accelerometer calibration which occur with these sensitive instruments; these shifts require corrections to the amplitude offset bias which occurs in the low-g data.

Attention must also be paid to the variety of different axes systems which are in use by different sectors of the aerospace and scientific community. Occasionally, axes assignments are casually made for convenience of a single organization. More frequently, axes assignments are made formally, based upon either technical logic or tradition. Overall, several different axes assignments are typically used, e.g., for payload layout, for flight operations, for experiment-unique considerations, etc. The informed user or processor of low-g acceleration data should benefit from the learning adventure of the authors that X-axis data from someone else are not necessarily X-axis data in the axes system you are using.

Another challenge is the enormity of the data, i.e., for each sample per second on one axis we obtain one-half a million data points on a typical shuttle mission. A common, workable method for handling this large amount of low-g data is yet to be devised.

The single greatest challenge in working with low-g data is the difficulty in correlating mission events (which are known to cause accelerations) with the notable features of the low-g data in a cause-and-effect relationship. In the vast majority of cases, we observe an apparent lack of correlation, even though a cause-and-effect phenomena is known or probable. In the preponderance of cases, we routinely observe unusual accelerations, then search for causes, and then cannot positively or even remotely identify the cause or causes. For example, a mysterious 17 Hz acceleration seems to occur on most Shuttle missions for which we have data, but no one has yet come close to positively identifying the cause for this acceleration. In other cases, we know an acceleration-inducing event occurred, but this event is not reflected in the data, for reasons not readily obvious. After some effort some of these reasons become known, but others remain a mystery.

In grappling with these difficulties, we have pursued the data analyses up to now only to a very limited extent, primarily since many of the low-g data users have not as yet determined the specific use to which the data will be put. They know fundamentally that if the residual accelerations, however low, can possibly have significant or even profound effects on the low-g experimental results, then these residual accelerations should be characterized via low-g measurements during the experiment. However, the specific application of the low-g data for an investigator such as a metallurgist or crytallographer may require that the investigator be capable of readily assimilating low-g data, converting it to meaningful effects on fluid dynamics, converting that in turn to concentration gradients, and that to effects at the solid-liquid interface. This series of events certainly is not at all straightforward and beyond the time or resources available to many of the low-g investigators or frequently beyond their experience base. Therefore, until the need for fully analyzed low-g data becomes more prevalent, only limited resources will be invested in this complex activity.

VARIETY IN THE FORMS OF DATA PRESENTATION

Low-g data have been presented in a wide variety of narrative, graphic, and tabular forms. Various degrees of detail and processing were included. Analyses such as filtering, inverse filtering, RMS accelerations, power spectral density and shock spectra were used with no standardized approach. In the case of Spacelab, a summary table of ranges of acceleration levels and frequency content was given.

LOW-G ACCELERATION MEASUREMENTS IN A GROUND LABORATORY

We have stated that experiments conducted in low gravity can be adversely affected by accelerations which are "self-inflicted," i.e., accelerations caused by equipment within the experiment apparatus such as pumps, fans, acoustic levitators, camera mechanisms, coolant flow, and vent ports. For two of the MSFC suborbital SPAR low-g payloads, special tests were performed prior to flight to measure these self-induced accelerations. These payloads included furnaces and levitators which contained components suspected of generating undesired accelerations. Figure 1 shows a sample of one of the higher level power spectral density plots acquired from low-g acceleration readings during one of these simulated flight functional tests of the experiment payload; the payload was suspended on an overhead crane to avoid the damping of accelerations which would occur if the payload rested on a solid support such as a laboratory floor [2].

LOW-G ACCELERATION MEASUREMENTS DURING PARABOLIC AIRCRAFT FLIGHT

Short periods of low-g can be obtained during parabolic flight in aircraft. NASA has frequently utilized a KC-135 aircraft, among others, to conduct low-g experiments. Many parabolas are executed during a typical flight, resulting in alternating periods of low-g and high-g as well as some one-g periods when level flight is needed to reset or repair experiments between runs. Figure 2 provides a sample of acceleration versus time as four parabolas are flown.

Digitized data from a Sunstrand Model 303T15 accelerometer, tabulated in Table 1, provides a more quantitative history for a similar KC-135 flight. Accelerations from 1 to 10 milli-g are recorded in the separate axes during a period of low acceleration levels which lasted up to 20 sec.

LOW-G ACCELERATION MEASUREMENTS DURING SUBORBITAL FLIGHT

A Low-Gravity Accelerometer System (LGAS) was flown as a piggyback item on a suborbital mission, October 4, 1974, to demonstrate the feasibility of measuring low-g accelerations during free fall of a rocket payload; the LGAS had been developed at MSFC using Singer-Kearfott C70-2412 sensors. Figure 3 indicates the successful demonstrated flight results which provided a time history of low-g accelerations in each of three orthogonal axes [3]. Figure 4 provides similar data for one axis during the SPAR X suborbital flight on June 17, 1983. SPAR operated much as an unmanned "FREE FLYER" and, thus, provided one of the very best low-g environments of any carrier to date. Measurements on SPAR payloads I through IV are reported in Reference 4.

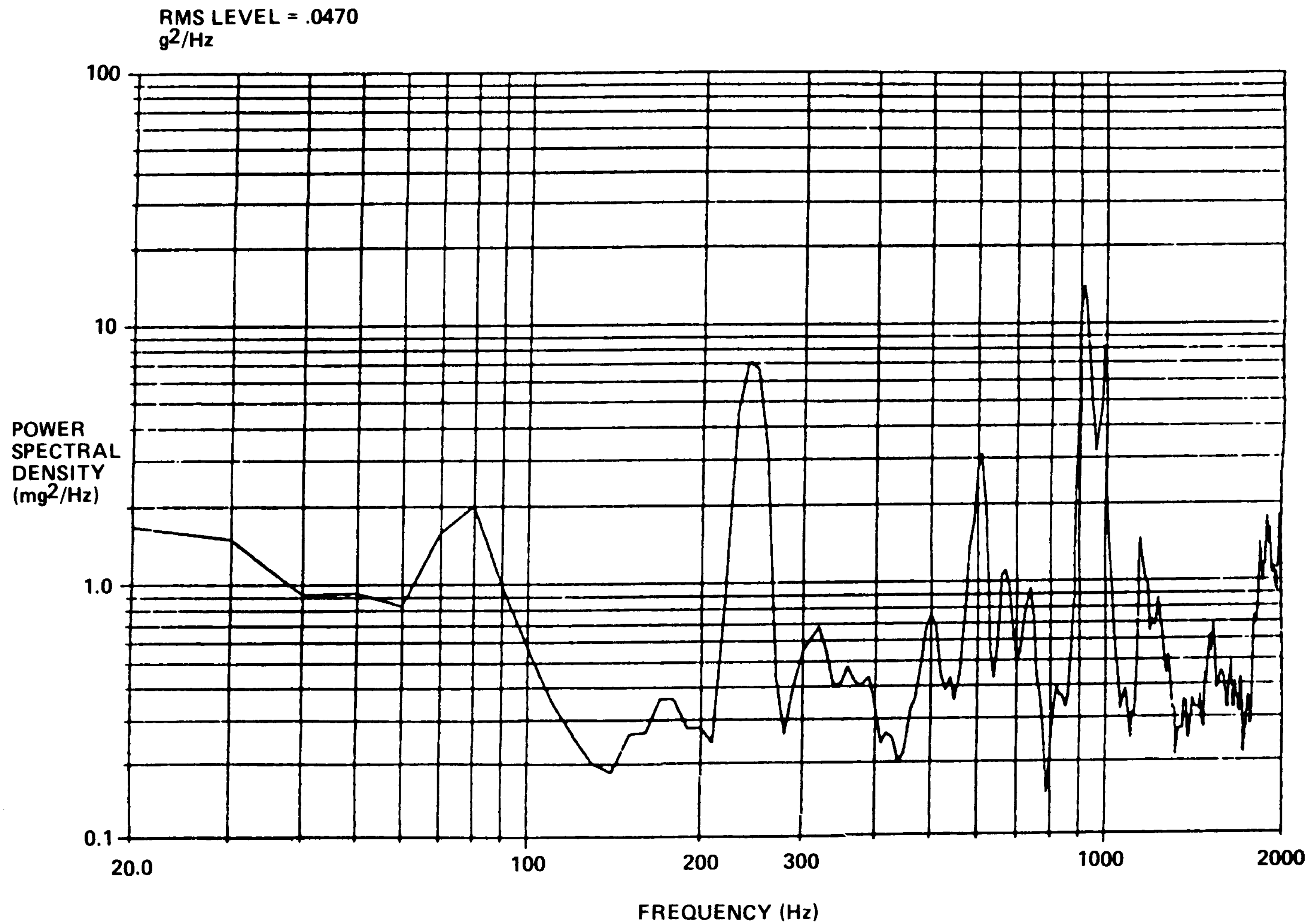

Figure 1. Self-induced accelerations in SPAR payload ground test.

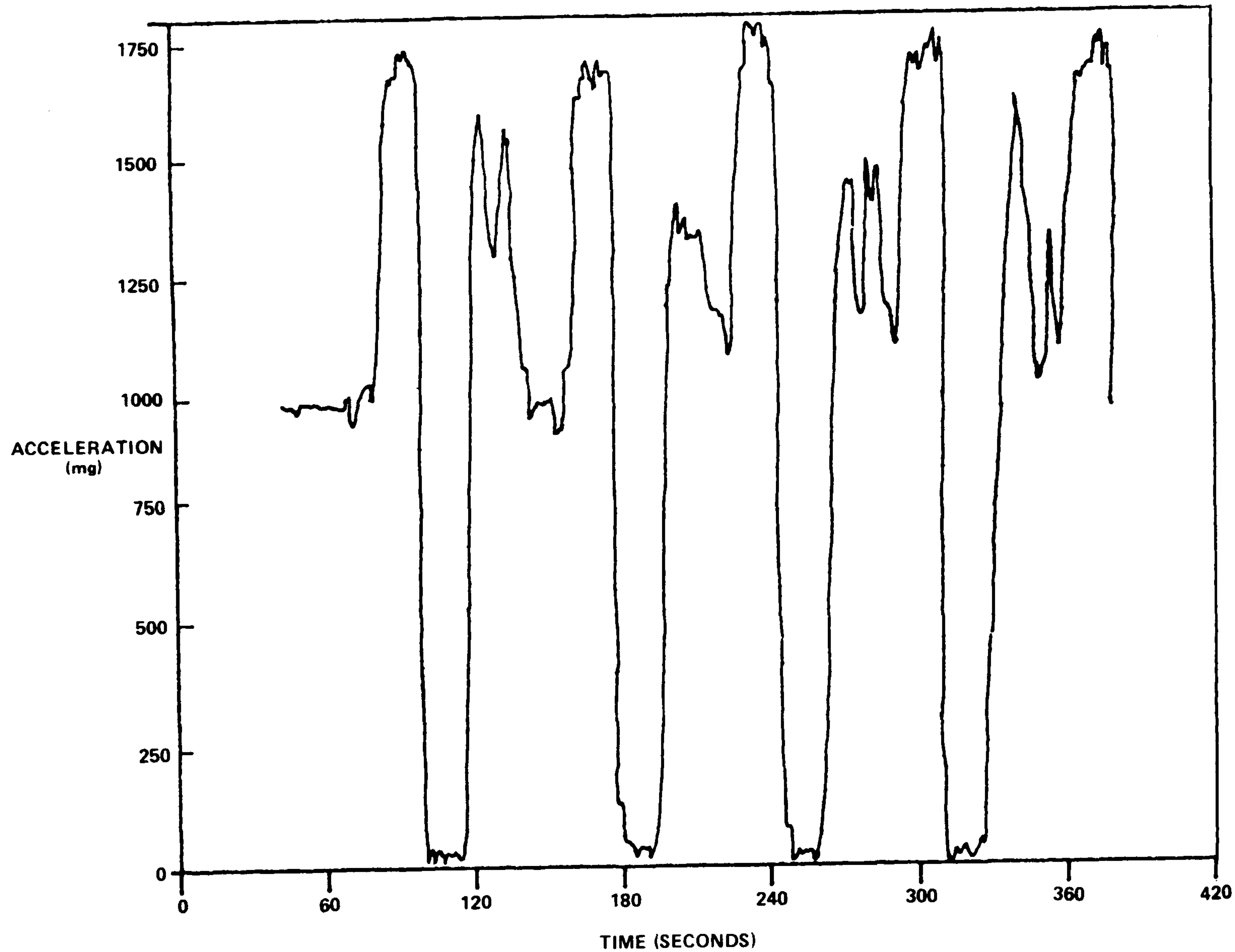

Figure 2. Raw data from KC-135 flight.

TABLE 1. RAW DIGITIZED DATA FROM KC-135 FLIGHT

TIME	X AXIS (mg)	Y AXIS (mg)	Z AXIS (mg)
20 SEC	+ 122	+1,742	+ 58
21 SEC	+ 129	+1,748	+ 39
22 SEC	+ 132	+1,715	+ 18
23 SEC	+ 134	+1,646	+ 28
24 SEC	+ 135	+1,564	+ 43
25 SEC	+ 75	+1,028	+ 33
26 SEC	+ 21	+ 449	+ 10
27 SEC	− 2	+ 269	+ 2
28 SEC	− 11	+ 160	+ 11
29 SEC	− 11	+ 73	+ 18
30 SEC	− 10	+ 51	+ 16
31 SEC	− 9	+ 28	+ 5
32 SEC	− 10	− 2	− 1
33 SEC	− 8	− 2	− 3
34 SEC	− 8	+ 5	+ 2
35 SEC	− 7	+ 5	+ 8
36 SEC	− 7	+ 4	+ 10
37 SEC	− 7	+ 7	+ 6
38 SEC	− 8	+ 10	0
39 SEC	− 8	− 6	− 2
40 SEC	− 9	− 9	0
41 SEC	− 10	− 8	+ 4
42 SEC	− 10	− 4	+ 8
43 SEC	− 12	+ 10	+ 5
44 SEC	− 13	+ 9	0
45 SEC	− 16	− 10	− 2
46 SEC	− 14	− 6	0
47 SEC	− 19	+ 35	+ 8
48 SEC	− 17	+ 71	+ 6
49 SEC	− 22	+ 209	+ 4
50 SEC	− 22	+ 416	+ 4

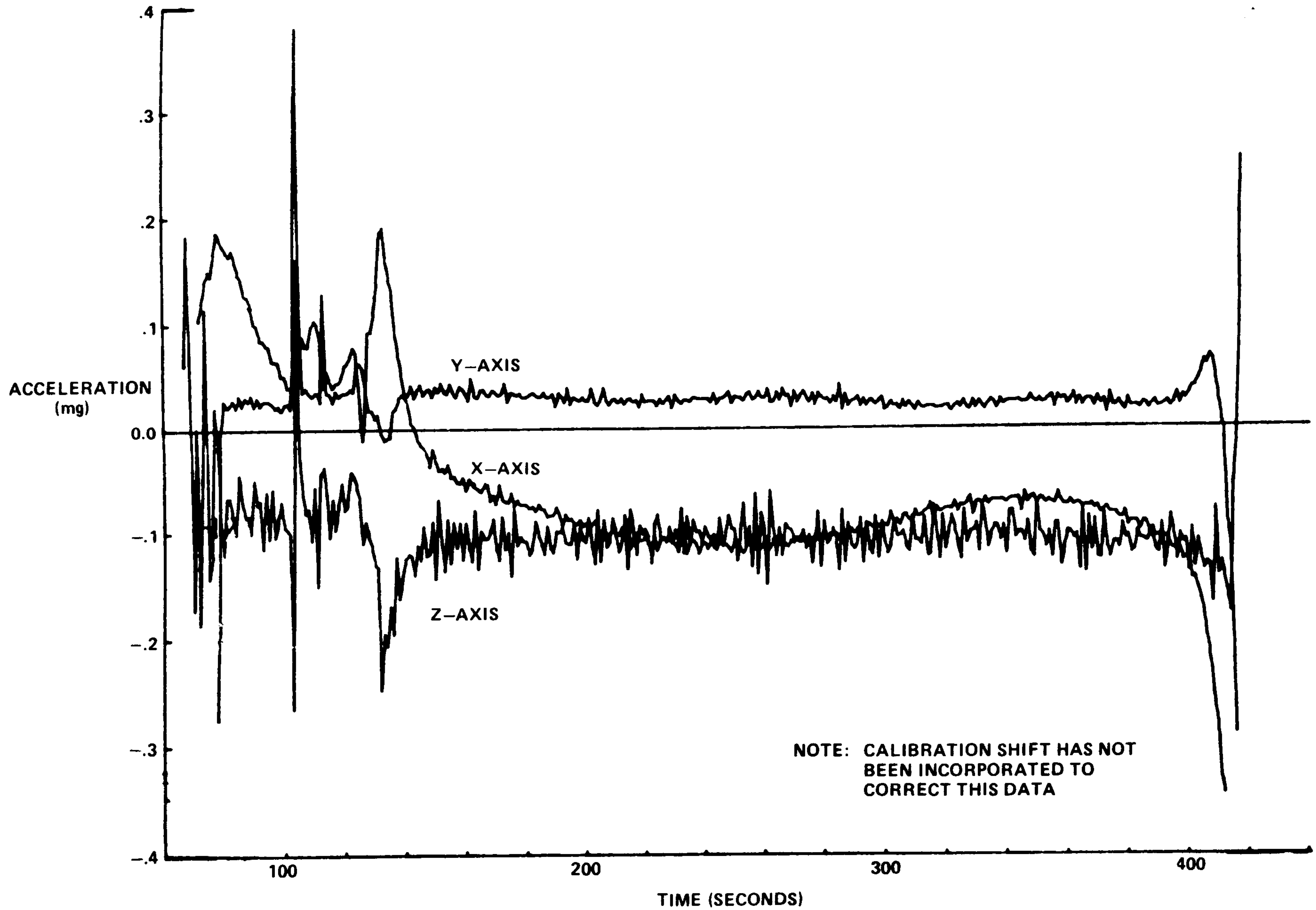

Figure 3. Suborbital accelerations during demonstration flight.

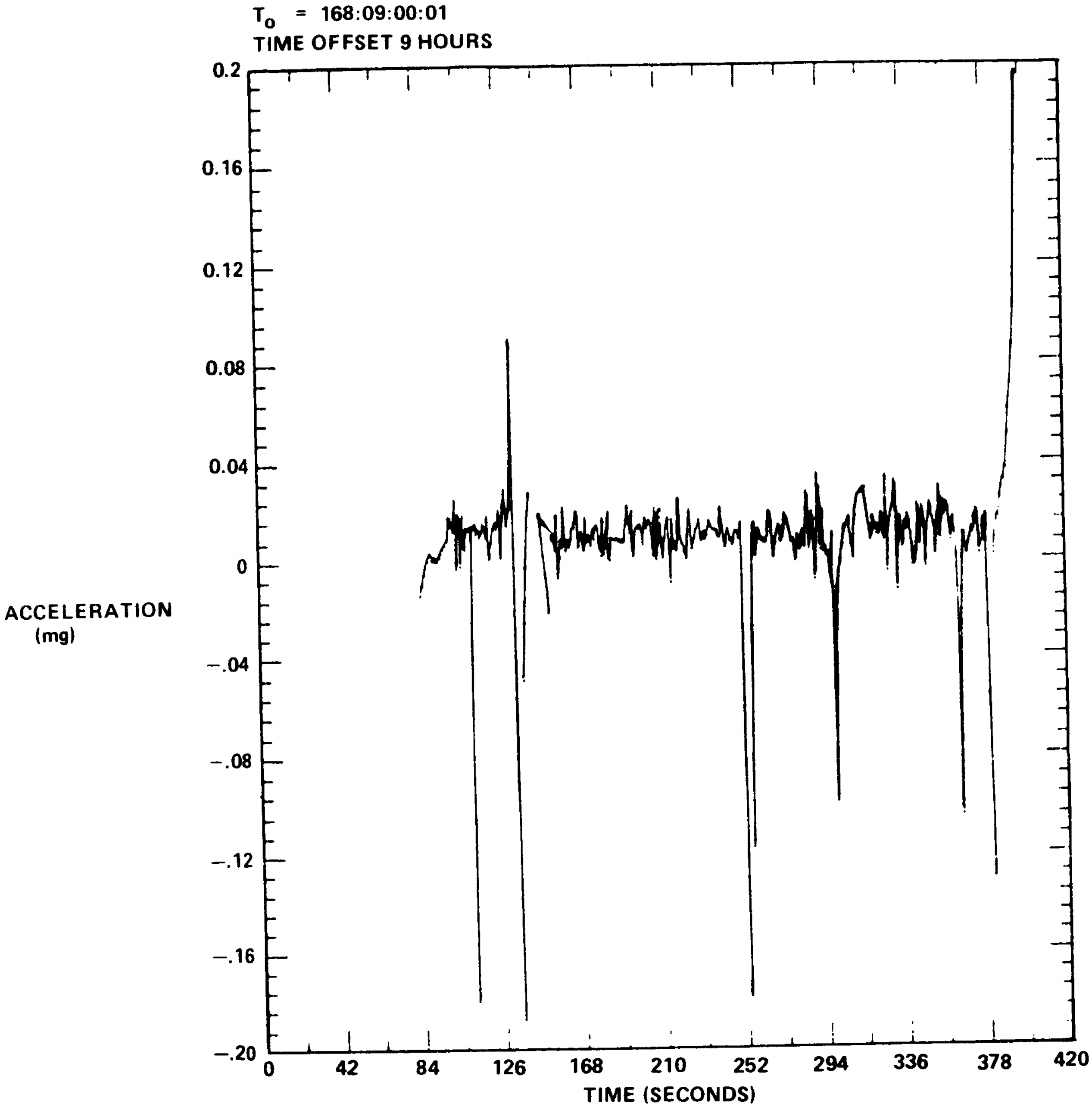

Figure 4. Suborbital acceleration during SPAR X "FREE FLYER" mission.

LOW-G ACCELERATION MEASUREMENTS IN THE STS ORBITER MIDDECK

Small low-g experiments are conducted in the Orbiter Middeck area on many Shuttle Transportation System (STS) missions. To provide some indication of the low-g environment, a Micro-g Acceleration Measurement System (M-GAMS) was initially utilized during the STS-3 mission in March 1982. The M-GAMS includes a two-axis capability provided by SA-100 sensors from Columbia Research Laboratories. Figure 5 provides a narrative characterization of the acceleration readings obtained during the Electrophoresis Equipment Verification Test on that STS mission [5]. Figure 6 contains similar information plotted as a function of time [6]. Note that much of the actual low-g data is marked by background electronic noise. The noise has a magnitude of 1 bit or 10^{-4} g and occurs in both the positive and negative direction. Therefore, we only know that the g-levels were below the false signals caused by the electronic noise.

LOW-G MEASUREMENTS IN THE MATERIALS EXPERIMENT ASSEMBLY OF STS-7

The Materials Experiment Assembly (MEA) is a carrier for microgravity experiments in the STS Orbiter Bay. The MEA contains a Low-g Accelerometer System (LGAS) which is very similar to the one described above for use during suborbital SPAR flights. Figure 7 displays a low-g time history during MEA experiments when an STS thruster firing is known to have occurred. The data obtained from the LGAS are in the form of an integrated average of the accelerations during each one-second interval in each axis. Notice that the acceleration caused by the thruster firing is masked by the one-second averaging and the induced acceleration cannot be observed in this data [7]. However, recent investigations have determined that the very low frequency vibrations and DC accelerations are more detrimental to low-g experiments, in general, and therefore an event such as a rapid thruster firing may not be of as much interest as previously thought.

LOW-G ACCELERATION MEASUREMENTS ON SPACELAB 1

The flight of Spacelab 1 occurred in November-December 1983 and was instrumented with 14 Systron-Donner linear accelerometers. Each accelerometer had a sensitivity of 10 micro-g and a bandwidth of 30 Hz. Data were recorded at the rate of 80 samples per second. One example of data taken during a time when the crew activity was constrained to a cough test is shown in Figure 8 [8]. The acceleration peaks were less than one milli-g and, in fact, the time history shown is very comparable to "quiet time" periods.

- TYPICALLY THE ACCELERATION READINGS WERE LESS THAN 2.5 MILLI-G IN ONE AXIS AND LESS THAN 1.25 MILLI-G IN AN ORTHOGONAL AXIS. (THE THIRD AXIS WAS NOT MEASURED).

- MAXIMUM ACCELERATION READINGS OCCURRED DURING A PERIOD OF LESS THAN TWO HOURS.
  - 137 ACCELERATION EVENTS
  - EACH EVENT WAS $\geq$ 38 MILLI-G
  - DAMPING OF EACH EVENT WITHIN 3-4 SECONDS
  - FREQUENCY CHARACTERISTICS: 10 TO 25 HZ

Figure 5. Accelerations observed on STS-3 in the orbiter middeck.

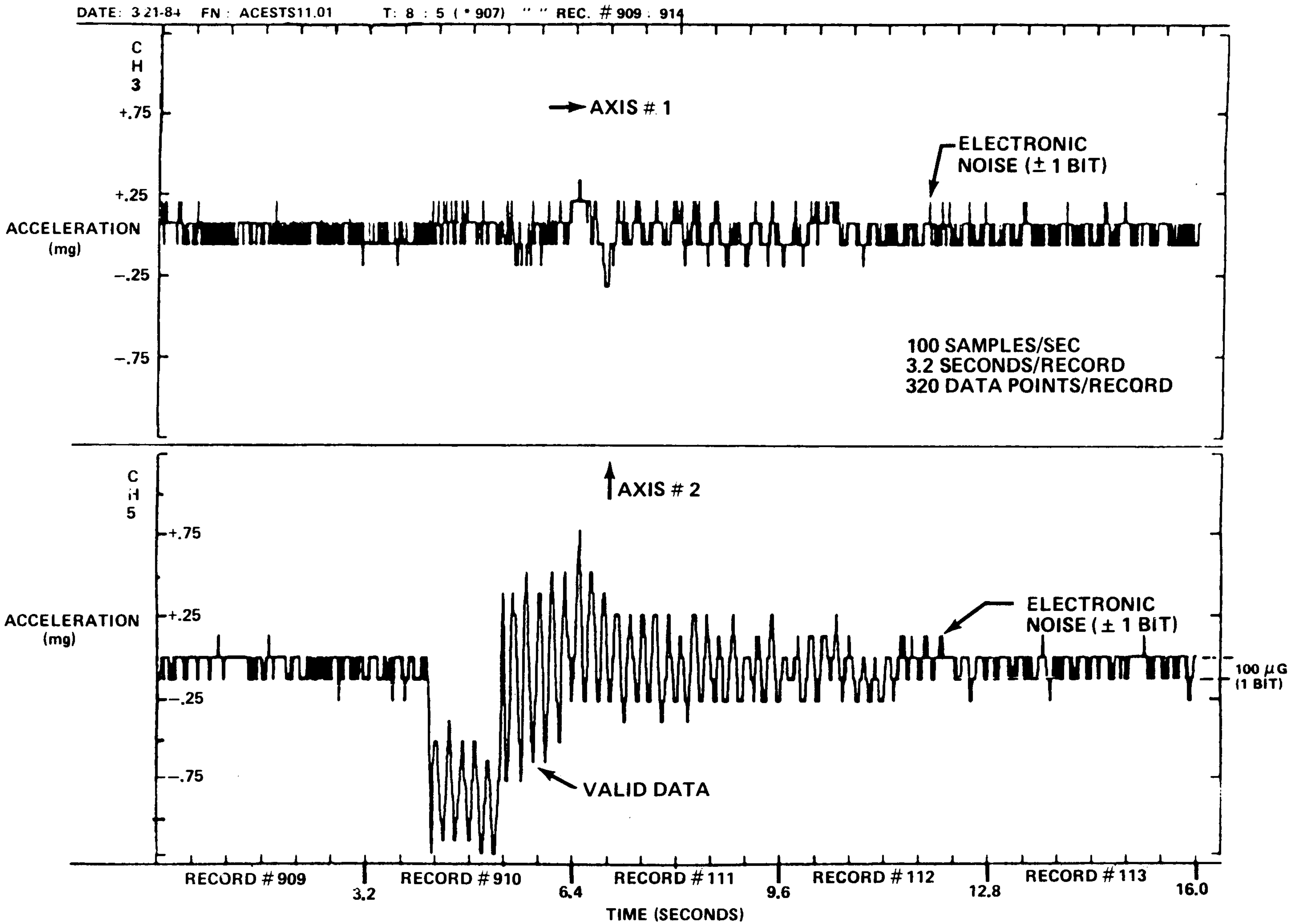

Figure 6. Sample acceleration data from STS-11 middeck (Aces experiment).

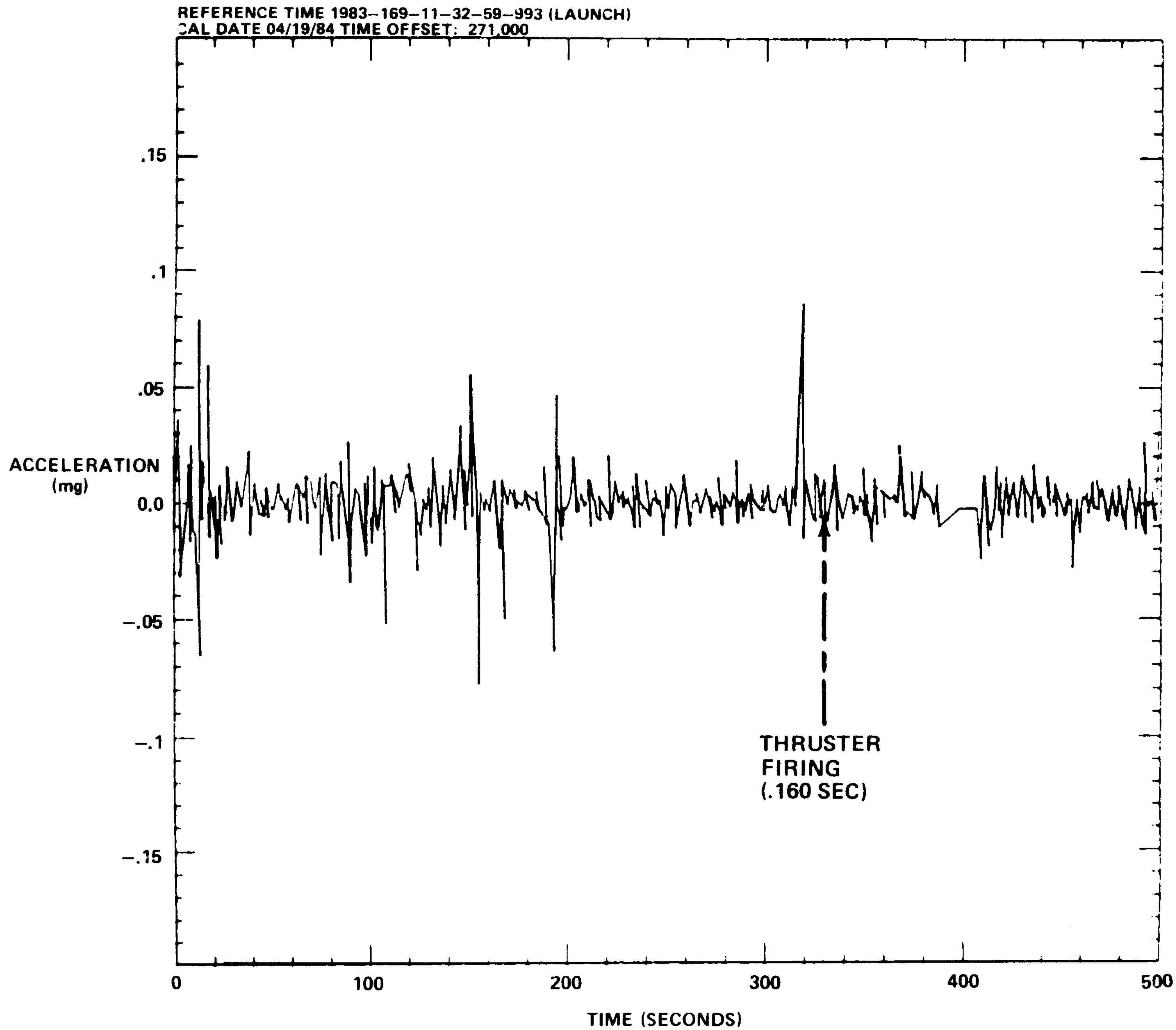

Figure 7. Raw data from STS-7 MEA experiments (average acceleration at 1 sec intervals).

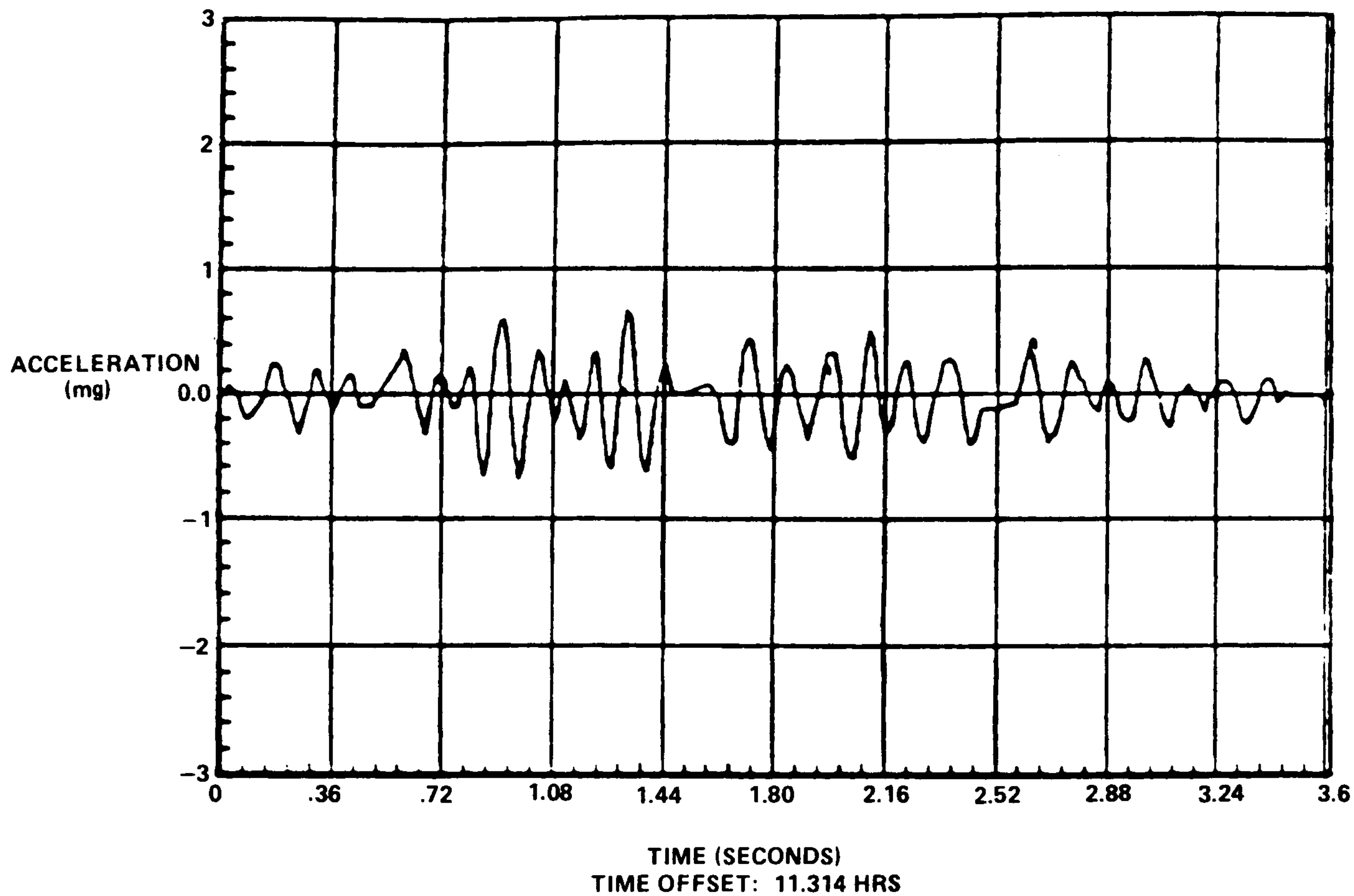

Figure 8. Crew-induced acceleration on Spacelab 1 (via "cough test").

Figure 9 shows the shock spectra for the acceleration history shown in the previous figure. The shock spectra are derived by using the acceleration time history as a forcing function to drive a massless spring (with natural frequency Omega and damping which gives an amplification factor of 20). The frequency is varied from 0 to 100 Hz and the peak acceleration response of the spring at each frequency determines the shock spectrum amplitude. The maximum value at 10 Hz shown on this figure is 5.6 milli-g.

Table 2 recaps the acceleration levels and the frequencies at which they occur on both the Spacelab module and pallet. During the quiet time, the acceleration ranged from 0.25 to 0.65 milli-g in the module and from 0.13 to 0.45 milli-g on the pallet. Frequencies ranged from 8 to 40 Hz.

During the "cough test," accelerations ranged from 0.2 milli-g on the pallet to 2.8 milli-g in the Z direction in the module. Frequencies ranged from 8 to 11 Hz. For the crew's "push off" test, the accelerations occurred in the X-direction for a Y-direction pushoff at 0.1 milli-g and the largest acceleration also occurred (with a Y-direction pushoff) in the Z-direction at 2.4 milli-g.

Lower level (111 Newtons) vernier thruster firings of the Orbital Rate Control System produced 0.3 to 1.0 milli-g while higher level (3870 Newtons) primary thrusters produced up to 29 milli-g. A Spacelab disturbance attributed to sudden release of tunnel trunnion frictional forces produced 2.4 to 12.0 milli-g. Note that the accelerations experienced out on the pallet were significantly attenuated as compared to those inside the Spacelab Module which were very close to the acceleration source.

LOW-G ACCELERATION MEASUREMENTS ON SAFE

On the OAST I Solar Array Flight Experiment (SAFE), the base of the solar array was instrumented with Sunstrand model QA1101 accelerometers measuring parallel to the axes of the STS Orbiter.

Figure 10 shows a time history of the low-g data taken at the base of the SAFE, taken in the X-direction over a 100 sec period. A "steady state" amplitude bias of about 0.35 milli-g is apparent in this data, but the cause is not identified in available records. It is probably a calibration shift, which would have been removed in more refined versions of the data. In an attempt to reproduce some of the SAFE data, we learned that all the processed data had been deleted from the computer tape library and only the original analog date tapes remain. Thus, to reproduce data for this flight would require a complete repeat of the entire post-flight data processing operation, at considerable additional cost. This highlights the fact that data are not stored indefinitely in all their forms, primarily due to data storage capacity limitations [9].

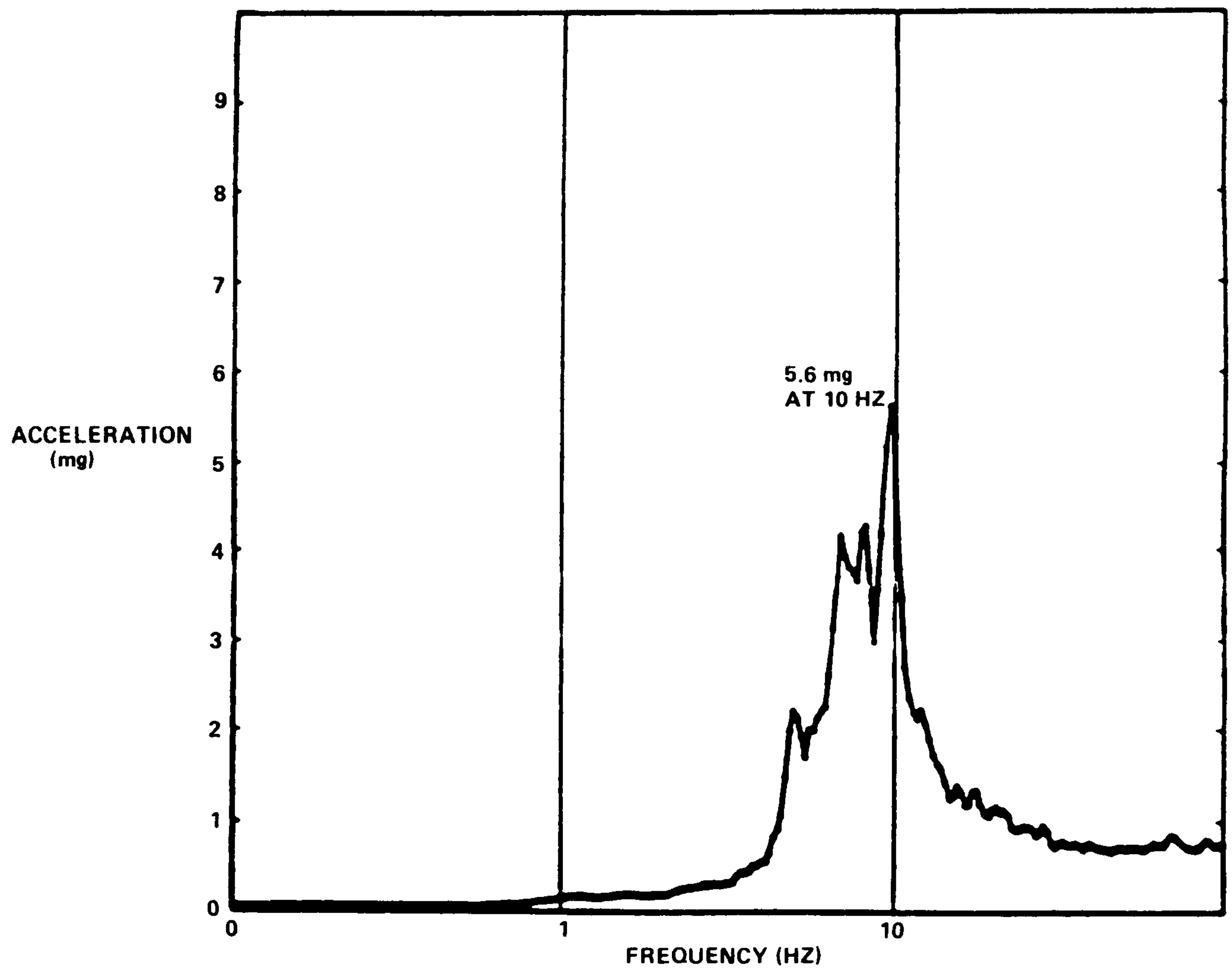

Figure 9. Shock spectra from Spacelab 1 crew-induced acceleration (via "cough test").

TABLE 2. PEAK ACCELERATIONS FROM SPACELAB 1

	MODULE			PALLET		
	X–DIRECTION	Y–DIRECTION	Z–DIRECTION	X–DIRECTION	Y–DIRECTION	Z–DIRECTION
"QUIET TIME" 11.18–11.23 HRS AMPLITUDE (mg) FREQUENCY (Hz)	0.35 – 0.4 20 –35	0.25 22 – 40	0.5 – 0.65 17 – 40	0.13 – 0.25 22	0.2 – 0.45 22	0.13–0.25 8 – 16
COUGH TEST 11.314 – 11.315 HRS AMPLITUDE (mg) FREQUENCY (Hz)	1.0 10	1.0 11	2.8 9	0.2 10	0.3 8	0.7 10
X–PUSH–OFF 11.340 – 11.355 HRS AMPLITUDE (mg) FREQUENCY (Hz)	2.8 12	3.0 21	2.5 9	0.6 12	1.0 6	1.2 8
Y–PUSH–OFF 11.375 – 11.385 HRS. AMPLITUDE (mg) FREQUENCY (Hz)	0.1 16	1.0 21	2.4 8	0.3 18	0.5 15	0.5 8
Z PUSH–OFF 11.404–11.406 HRS. AMPLITUDE (mg) FREQUENCY (Hz)	1.1 12	1.0 20	1.7 16	0.7 15	1.1 17	1.0 9
VERNIER THRUSTER FIRING 202050–202110 SEC. (111 NEWTONS) AMPLITUDE (mg) FREQUENCY (Hz)	0.3 – 0.5 17	0.3 – 0.6 25	0.5 – 1.0 18	NOT AVAILABLE	NOT AVAILABLE	NOT AVAILABLE
PRIMARY THRUSTER FIRING 188.870–188.930 HRS. (3,870 NEWTONS) AMPLITUDE (mg) FREQUENCY (Hz)	25 – 29 9	20 – 29 9	2.5 – 2.9 9	10 – 15 8	10–15 16	20 – 29 16
TUNNEL TRUNNION DISTURBANCE 188.431 – 188.435 HRS. AMPLITUDE (mg) FREQUENCY (Hz)	12 13	6.0 20	9.0 15	2.5 12	2.4 25	3.0 12

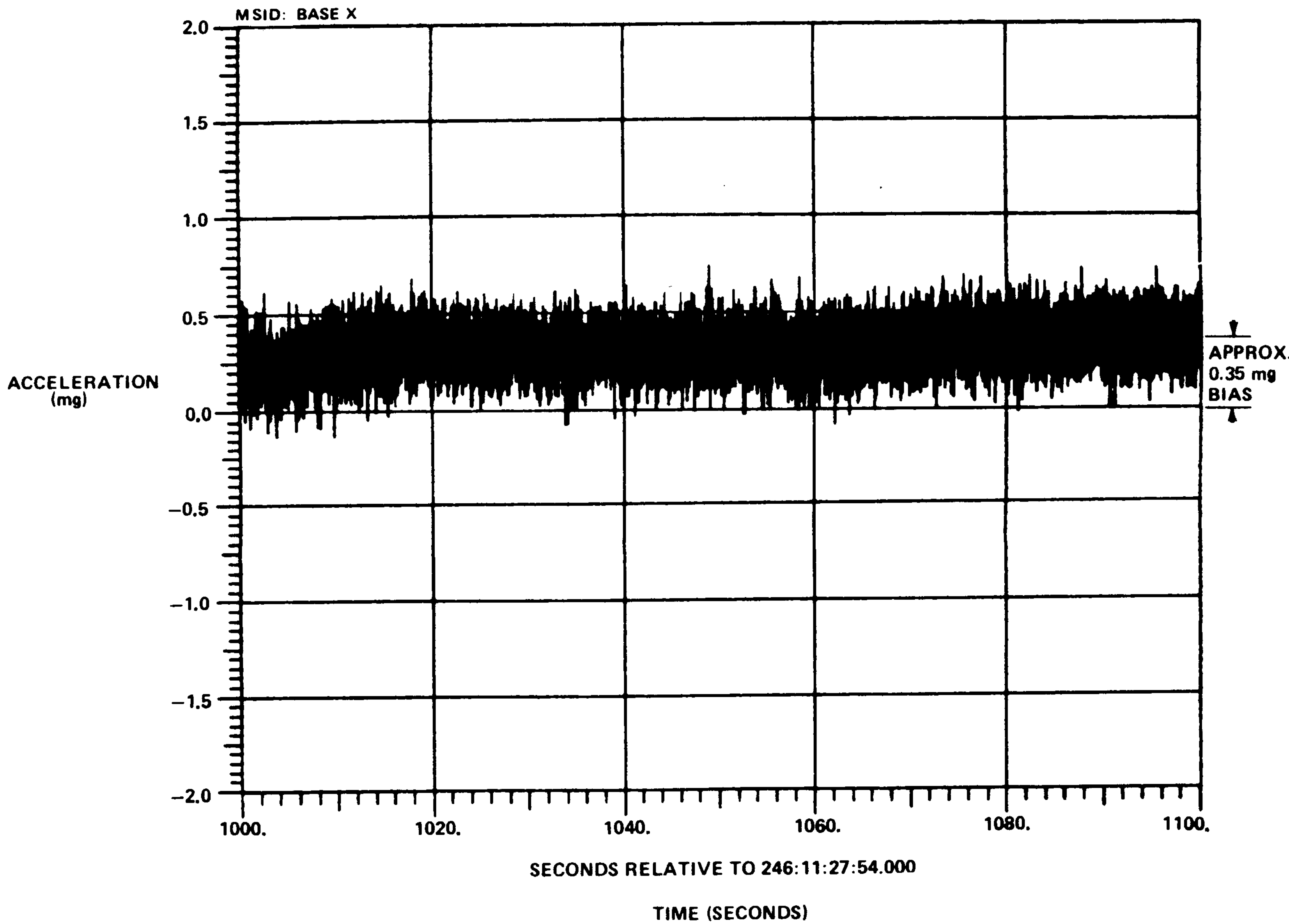

Figure 10. Raw data from solar array flight experiment.

LOW-G ACCELERATIONS MEASUREMENT ON SPACELAB 3

The flight of Spacelab 3 on STS-51B in April-May 1985 carried the Fluids Experiment System (FES). The experiment was mounted on a 135 kg optical bench which was, in turn, mounted on the double rack inside the manned Spacelab module. A package of Bell Miniature Electrostatic Accelerometers (MESA) was mounted on the optical bench. For experiment purposes, measuring axes of the X and Z accelerometers were rotated 65.7 deg clockwise (facing the FES rack) from the X- and Z-operational axes of the Orbiter. The resolution of the accelerometers is 1 micro-g and the bandwidth is 50 Hz. Data were recorded at 300 samples per second. We have included several samples of low-g data from this experiment as it, perhaps, has been the subject of more analyses at MSFC than any other. Table 3 shows the form of data as it is received in real time at the MSFC Huntsville Operations Support Center. Average and peak-g levels are given for each axis in units of micro-g for 1-sec and 60-sec time intervals. The notes at the bottom of Table 3 are recorded by the person monitoring the data.

RAW DATA AND POWER SPECIAL DENSITY FROM SPACELAB 3

Figures 11 and 12 deal with a 14-sec time slice of data taken during the Spacelab 3 mission when the FES was not active, but the accelerometers were functioning. An unidentified disturbance occurs at about 5 sec into the interval and damps out in about 3 sec. A power spectral density for the entire time period shows dominant frequencies of 5.8 Hz, 17.2 Hz, 34 Hz, and 138 Hz. A band-pass filter was applied to this data and the results are discussed next.

FILTERED DATA AND POWER SPECTRAL DENSITY (PSD) PLOTS FROM SPACELAB 3

The frequency spectrum was filtered to display the 0 to 7.5 Hz acceleration time history shown in Figure 13. The effect of the same unidentified disturbance is clearly visible in this figure. In Figure 14, the PSD plot shows that this filtered sample is almost entirely made up of the 5.8 Hz oscillation.

ACCELERATION "CALIBRATION" DURING SPACELAB 3

During Spacelab 3 we were concerned with the higher-than-expected low-g readings. To aid in identifying the source(s) of the accelerations, we requested that all flight crewmen leave the Spacelab module and remain as motionless as practical in the Orbiter. We then had one crewman re-enter Spacelab and perform routine experiment tasks, so we could attempt to correlate his actions with low-g readings. Figure 15 gives a record of specific activity of the one crewman. A video tape record of these actions was made in real time during the mission. After the mission, the tape was viewed and the tabulation of activity and timing were made. This record was used to correlate events with spikes in the accelerometer data for the same time period.

TABLE 3. TYPICAL FORMAT FOR REALTIME ACCELERATION DATA FROM SPACELAB 3 (FES EXPERIMENT)

NOTE: DATA DISPLAYED ARE NOT TRUE AVERAGE OR PEAK VALUES SINCE ONLY EVERY 30TH DATA POINT IS USED IN CALCULATIONS. ALSO NEGATIVE PEAK VALUES WERE NOT CALCULATED CORRECTLY.

PB HRMGMT 123:06:21:46
MET 4:13:25:19
GMT 124:05:27:37

	G–LEVEL (E–6G'S)	
	1 – SEC PERIOD	60 – SEC PERIOD
X AVERAGE	–2179	– 801
Y AVERAGE	–1212	–1226
Z AVERAGE	–1913	–1517
X PEAK	1100	91000
Y PEAK	60	12700
Z PEAK	–680	11500

NOTES:

TAPE 22:44 → 4/13 25:19 LODEWIJK VAN DEN BERG AT OCP & THAGGARD IS AT MID–MODULE

4/13:27:03	L.V. CLOSED LH OB DOOR (& THEN REOPENS IT TO ALLOW RH DOOR TO CLOSE)
4/13:27:05	L.V. CLOSED RH OB DOOR
4/13:27:06	L.V. CLOSED LH OB DOOR

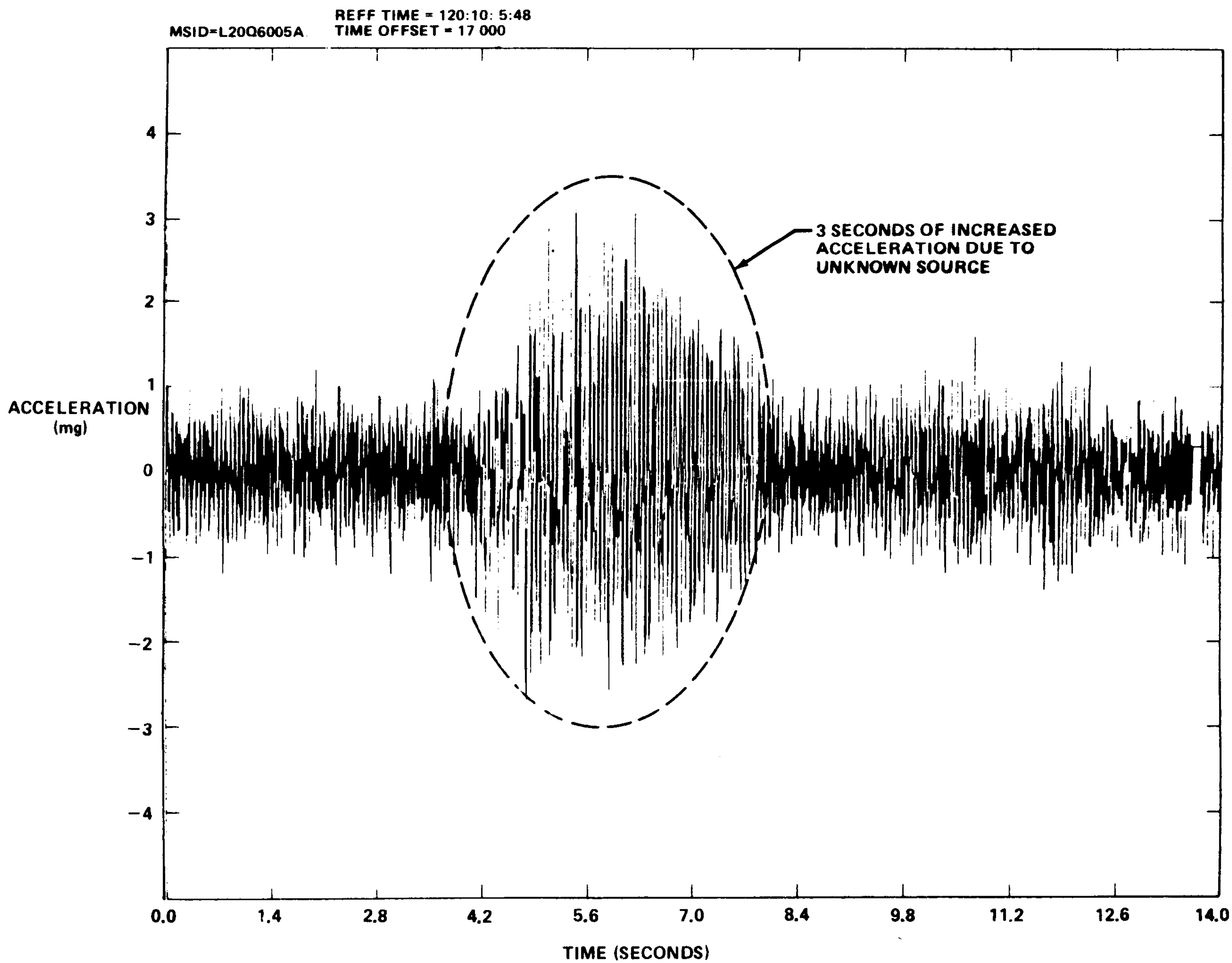

Figure 11. Raw data from Spacelab 3.

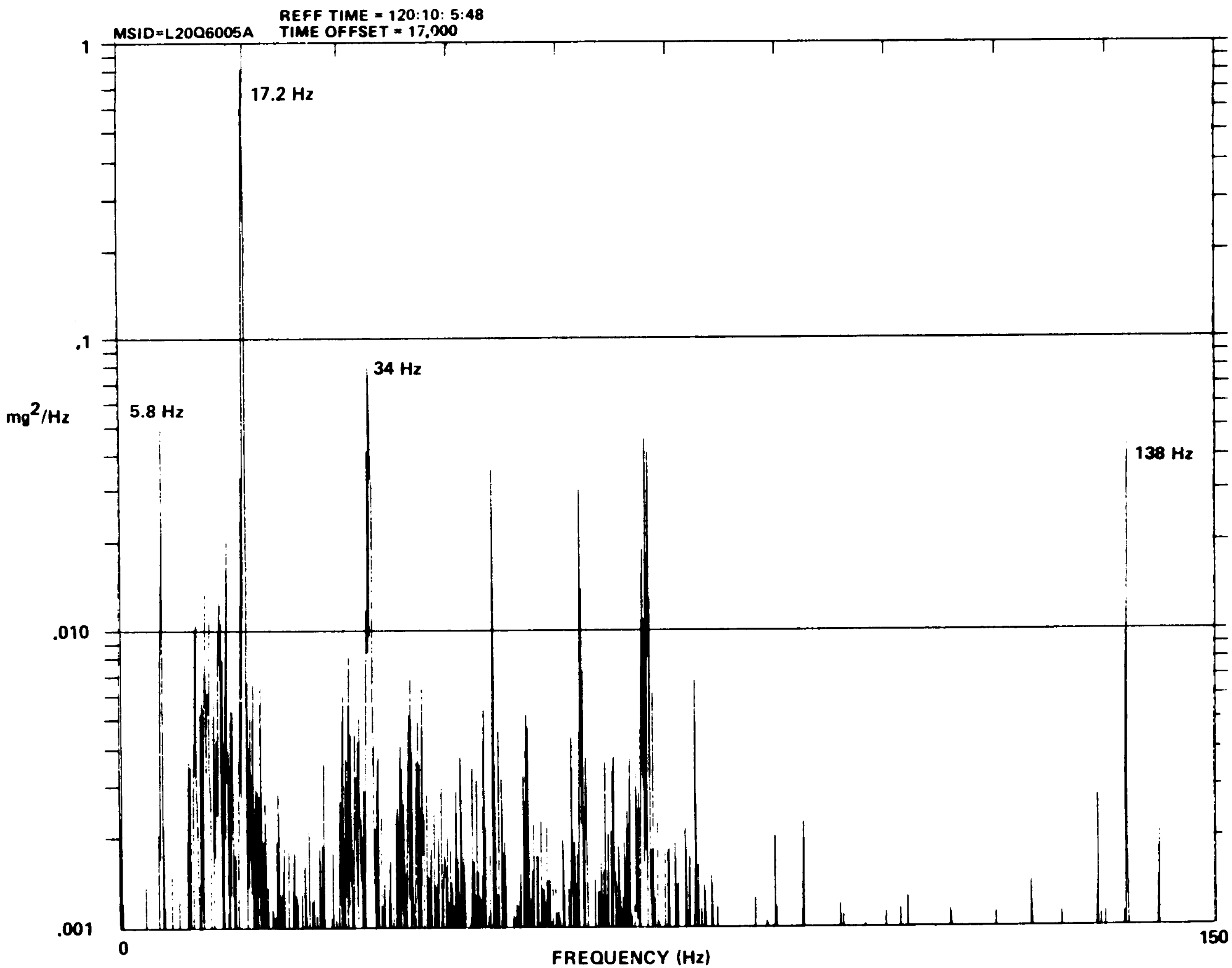

Figure 12. Power spectral density from Spacelab 3 (raw data).

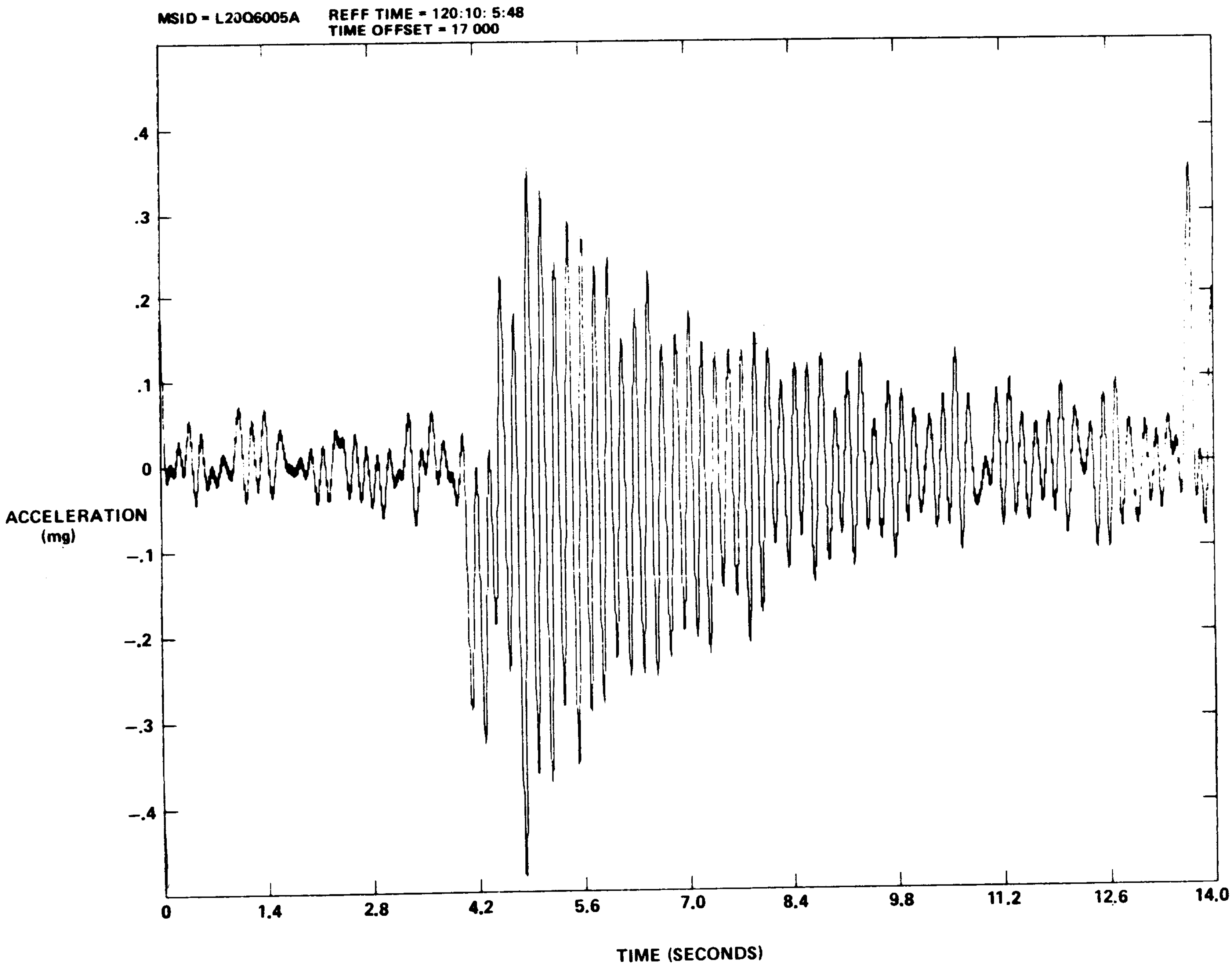

Figure 13. Filtered data from Spacelab 3 (0 to 7.5 Hz bandpass).

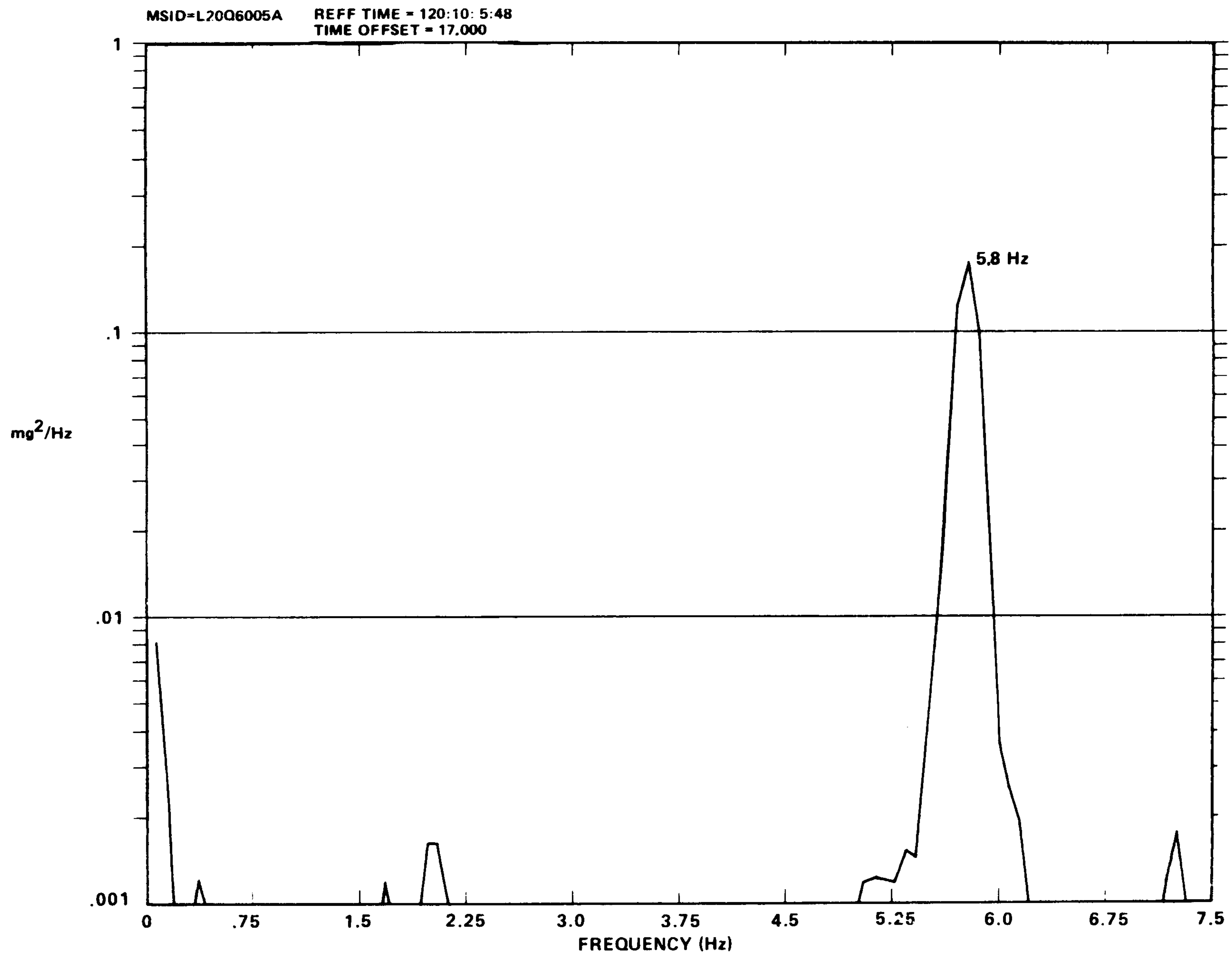

Figure 14. Power spectral density from Spacelab 3 (filtered data: 0 to 7.5 Hz bandpass).

REMOVE CREWMEN FROM SL–3 THEN:

TAPE INDICATOR READING		
0:30:21	START VCG ROTATION	
0:35:13	HOLOGRAM TAKEN	
0:36:49	PUSH OFF FROM FES	
0:37:02	UNLATCH FES DOORS	
0:37:10	OPEN FES DOORS	
0:37:56	ENTER FES	~ 5 MINUTES
0:38:20	RE–ENTER BENCH	
0:42:27	CLOSE FES DOORS	
0:42:50	PUSH OFF FROM FES	
0:43:25	PUSH OFF FROM FES	
0:44:40	OPEN PREHEAT DOOR	
0:45:11	CLOSE PREHEAT DOOR	
0:49:40	RE–ENTERING CREW MEMBER	

START	MET	05:13:31:48	TAPE	0:17:33
END	MET	05:14:06:14	TAPE	0:51:55

Figure 15. Acceleration calibration during Spacelab 3 (FES experiment).

ACCELERATION PEAKS WITH LATCH OPENINGS

Figure 16 shows the distinct peaks in "self-inflicted" acceleration which occurred as the latches on the FES Optical Bench doors were opened. The background acceleration is fairly steady, with peaks slightly greater than 1 milli-g. The peaks at latch openings range from about 4 to 8 milli-g.

ACCELERATION CHANGE WITH CHANGE IN DOOR POSITION

Figure 17 shows a much longer time period (1600 sec). For the first 750 sec, the Optical Bench doors were in the closed position. For the next 300 sec, the doors were in the open position and then, for the remaining interval, the doors were again in the closed position. The acceleration level shows a marked decrease in amplitude while the doors were open. The exact cause of this phenomenon has not been determined, but the effect of configuration alteration is clear.

LOW-G ACCELERATION MEASUREMENTS ON SPACELAB 2

Spacelab 2 was flown on STS-51F in July-August 1985. Similar to Spacelab 1, it was instrumented with Systron-Donner linear accelerometers and data were accumulated over periods of varied activity. Two examples of the Spacelab 2 data are included here.

CREW-INDUCED ACCELERATION ON SPACELAB 2

Figure 18 shows the acceleration history resulting from crew pushoff from one wall of the module. Only small disturbances appear in the particular axis shown. Wider ranges of acceleration occur when all axes are considered, as was indicated previously for Spacelab 1. Shock spectra were generated for the Spacelab 2 data. The shock spectra from the pushoff data just shown is presented in Figure 19. The peak response is 6.5 milli-g at 17.4 Hz.

ORBITAL MANEUVERING SYSTEM BURN DURING SPACELAB 2

An example of the relatively large accelerations due to firing of the Orbital Maneuvering System (OMS) thrusters is shown in Figure 20. The initial shock of the thruster produces peaks of 30 milli-g. After about 3.5 sec, a near steady level of -12 to -14 milli-g is reached. Figure 21 shows the shock spectra for this OMS burn with a peak of 235 milli-g at 5.58 Hz [10]. The measuring direction for this example is the Z axis of the orbiter which is perpendicular to the wing plane. Accelerations along the long axis of the orbiter due to the OMS thruster are on the order of 50 milli-g.

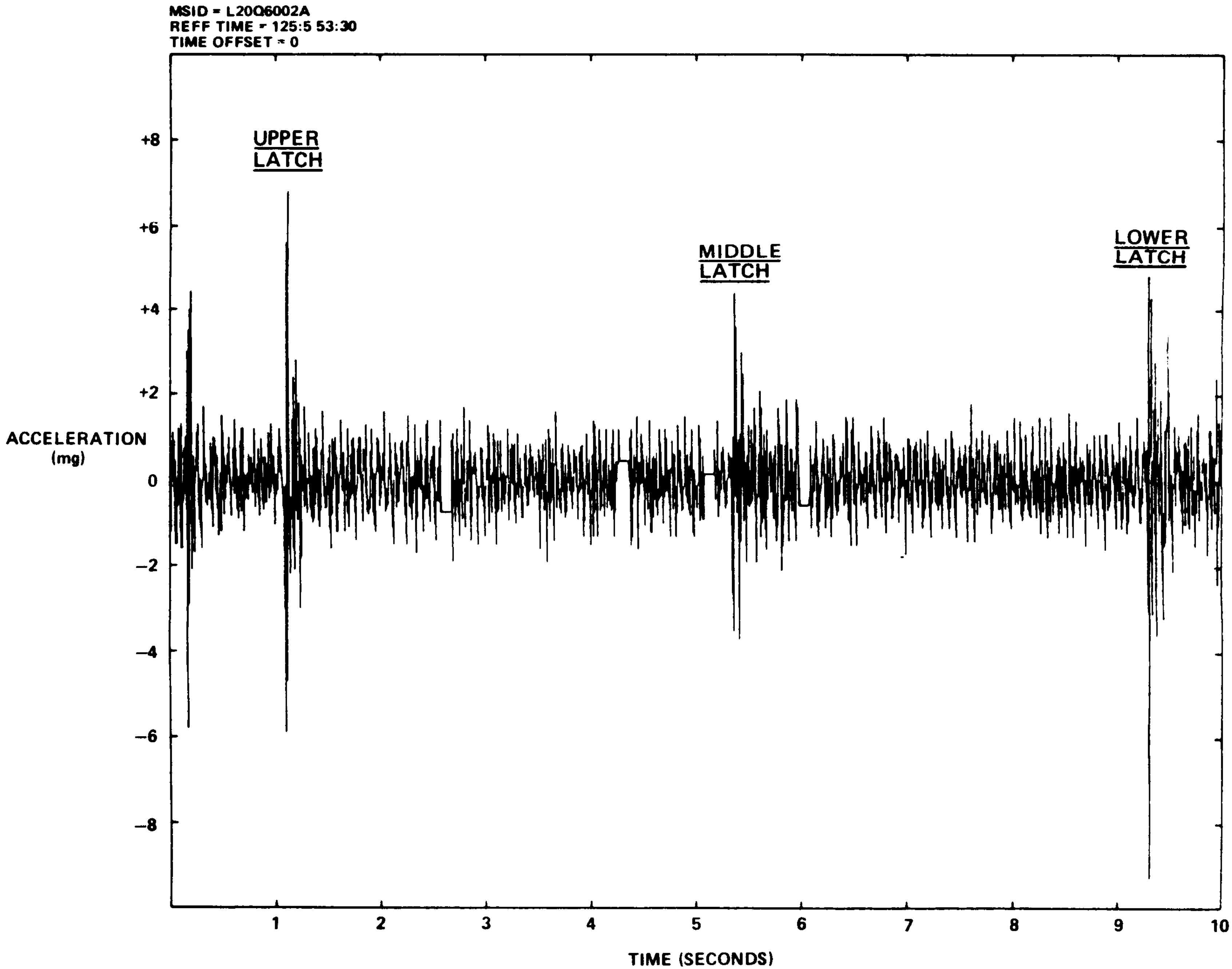

Figure 16. Acceleration peaks with latch openings, Spacelab 3.

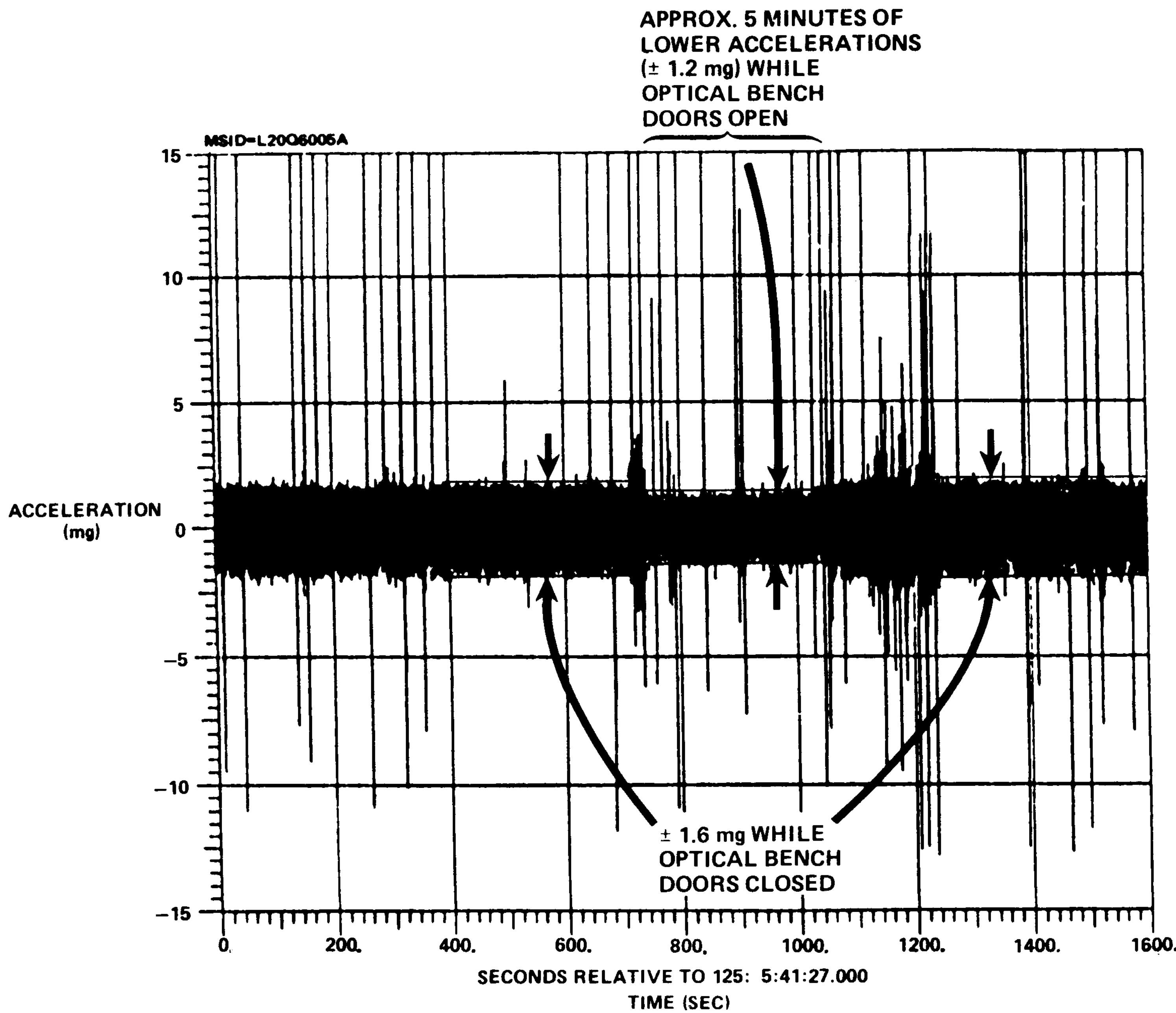

Figure 17. Acceleration change with configuration modification.

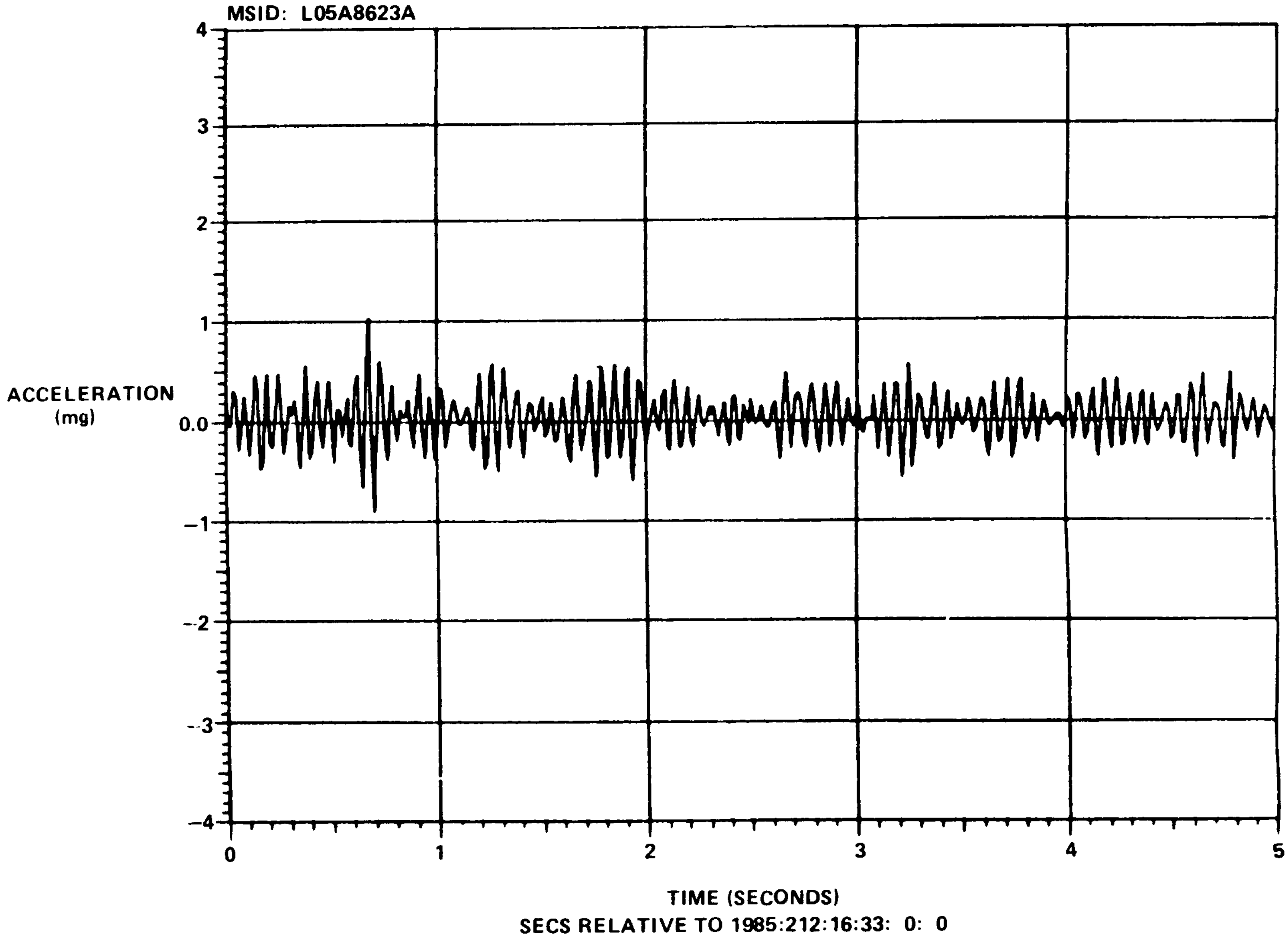

Figure 18. Crew induced acceleration on Spacelab 2 (via pushoff from wall).

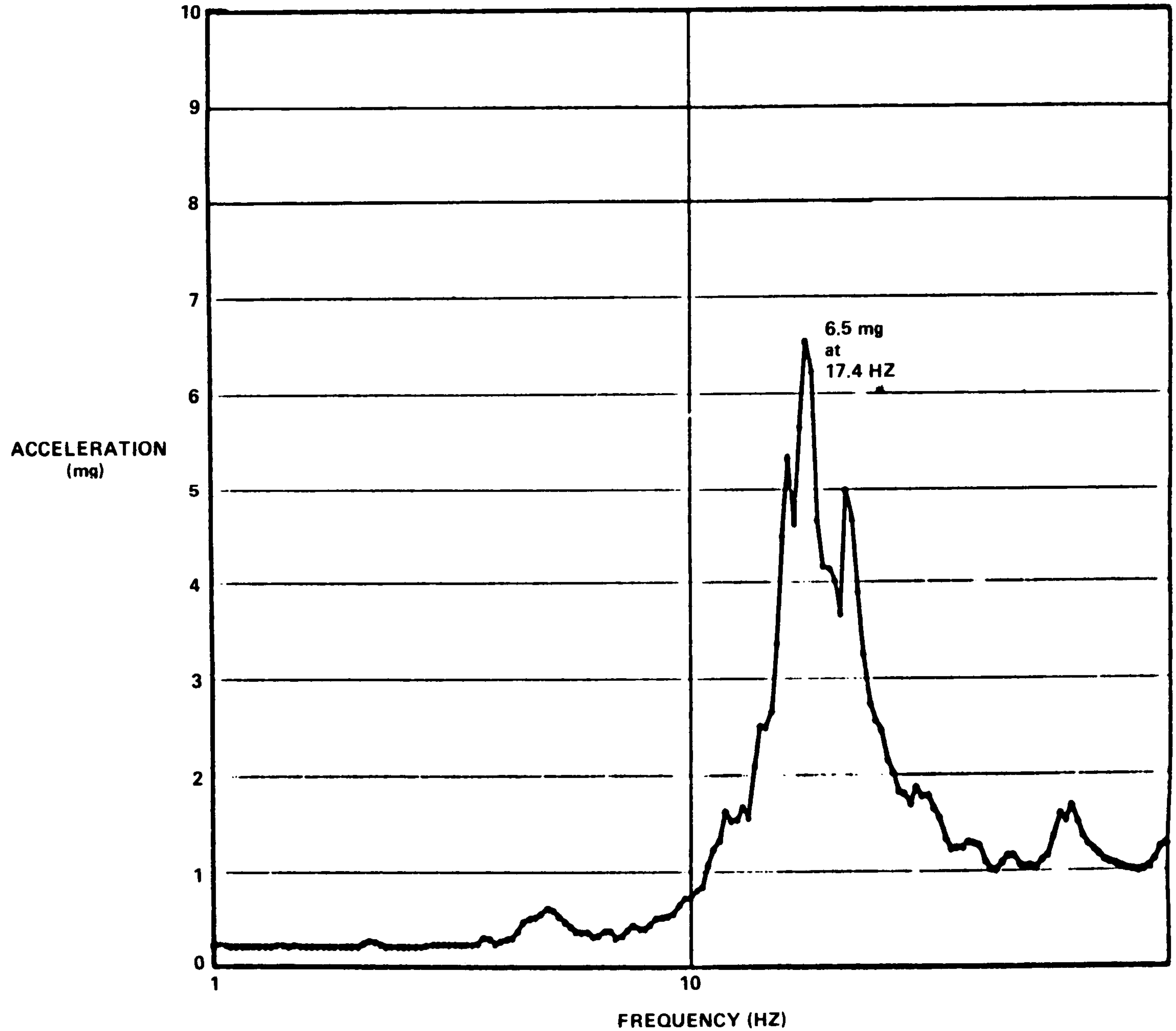

Figure 19. Shock spectra from Spacelab 2 crew-induced acceleration (via pushoff from wall).

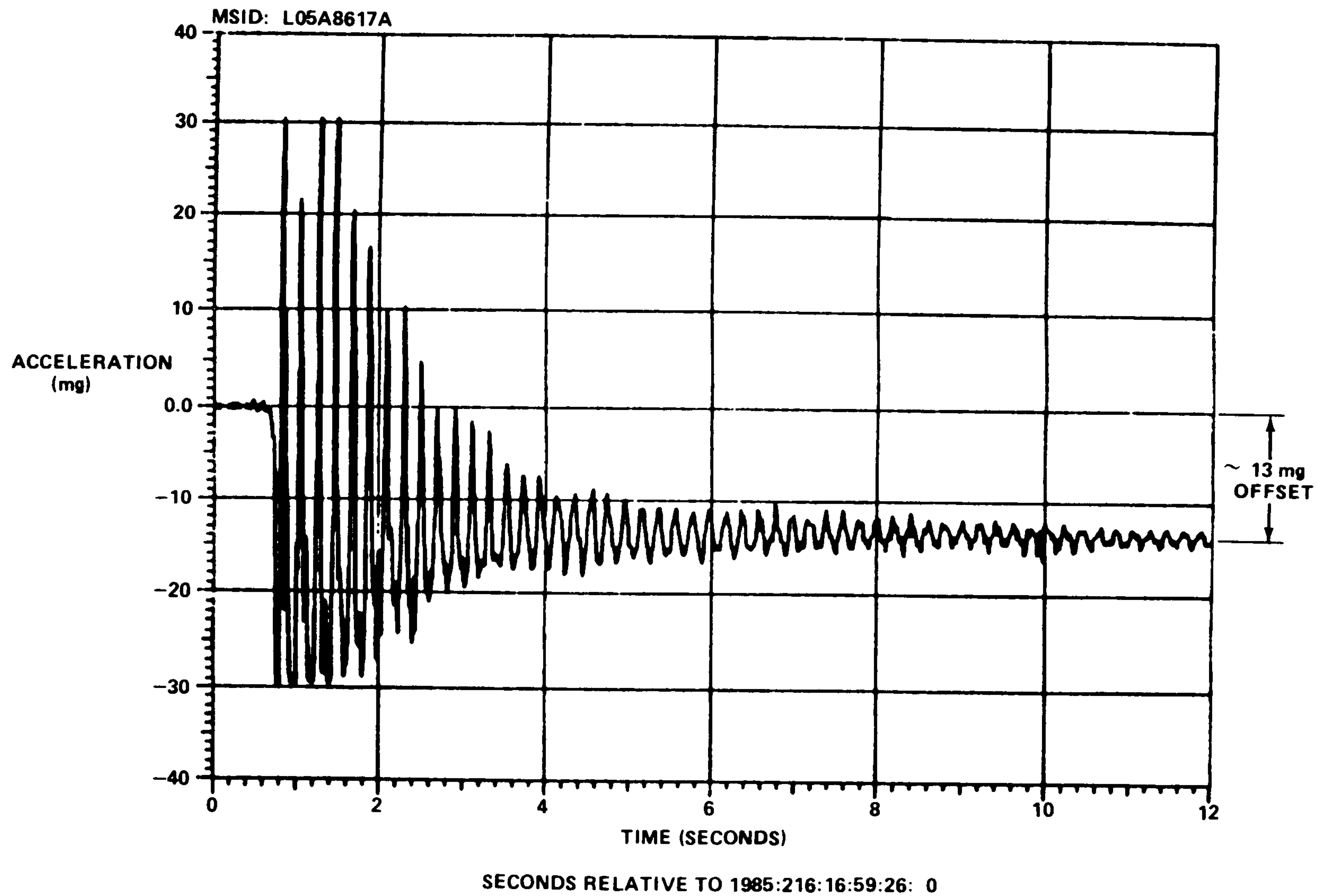

Figure 20. Raw data from Spacelab 2 OMS burn.

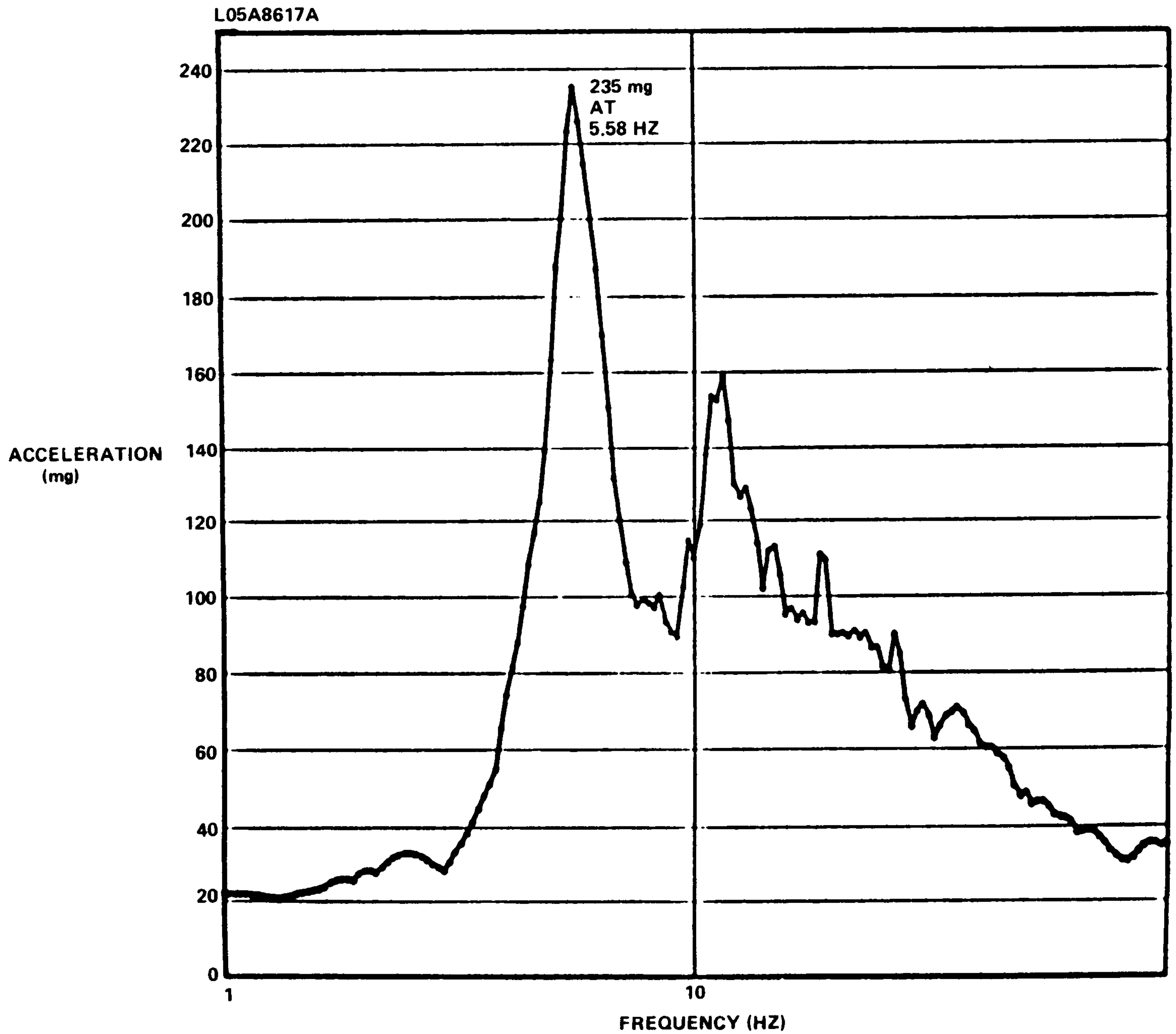

Figure 21. Shock spectra from Spacelab 2 OMS burn.

LOW-G ACCELERATION MEASUREMENTS ON MATERIALS SCIENCE LABORATORY

The Materials Science Laboratory 2 (MSL 2) was carried aboard STS-61C in January 1986. It was instrumented with two Bell Aerospace Model No. 6471-300001 accelerometers with a range of ± 0.512 milli-g, an accuracy of ± 5 percent, and frequency response of 0.01 to 20 Hz. The data were collected at a rate of 125 samples per second.

This accelerometer data system was obtained from the cancelled Advanced Gimbal System (AGS) project and the range was not wide enough to accommodate peak data during periods of vigorous activity. However, much useful data were collected. Some examples follow.

ACCELERATION INDUCED BY TREADMILL USAGE BY FLIGHT CREWMAN ON MSL 2

Figure 22 shows a 5-sec time history of the acceleration environment during treadmill usage by a flight crewman on MSL 2. (Figure 23 shows a flight crewman using a treadmill on another STS flight). During the vigorous MSL 2 treadmill activity, the data peaks were frequently clipped by the limited range of the system. The rolloff of the frequency response of the accelerometer is such, however, that the higher frequency data are not clipped. Thus, by using "inverse filtering," the data can be reamplified and the output expressed in the correct wider range than that originally recorded. The sample shown in Figure 22 was prior to inverse filtering. Figure 24 shows the same data after it is adjusted by this inverse filter procedure. Several peaks of more than 1 milli-g appear here [11].

LOW-G ACCELERATION MEASUREMENTS FROM THE HIGH RESOLUTION ACCELERATION PACKAGE (HIRAP)

The HIRAP is a separate associated major subassembly of the Aerodynamic Coefficient Identification Package (ACIP). It is mounted on the Orbiter ACIP mounting shelf. The ACIP contains linear and angular accelerometers used to collect aerodynamic and flight dynamic data during shuttle ascent, orbit and re-entry flight for spacecraft design and operational considerations. The angular accelerometers are in a Systron-Donner model 5612 triaxial assembly using model 4595 single axis angular accelerometers. The linear instrument is a Bendix GSD triaxial linear accelerometer. The HIRAP uses three orthogonally mounted, gas damped, Bell Aerospace Model X1 linear accelerometers. The HIRAP instruments are better than those in the ACIP for characterizing the low-g environment. They have 1 micro-g resolution and a range of ± 8.0 milli-g and an accuracy of better than 0.125 percent. The frequency response is limited, however, by low-pass filters at 2 Hz and 20 Hz. Inverse filtering can be used as previously mentioned to adjust the output [12]. One example of HIRAP data from this reference is shown in Figure 25. It shows a relatively long period of 2000 sec consisting initially of a quiet period, then a period of primary (3870 Newtons) thruster firings and finally a period of vernier (111 Newtons) thruster firings of the Orbital Rate Control System. The relative magnitudes of acceleration in the different periods is readily apparent. To date, the emphasis on analysis of HIRAP data has

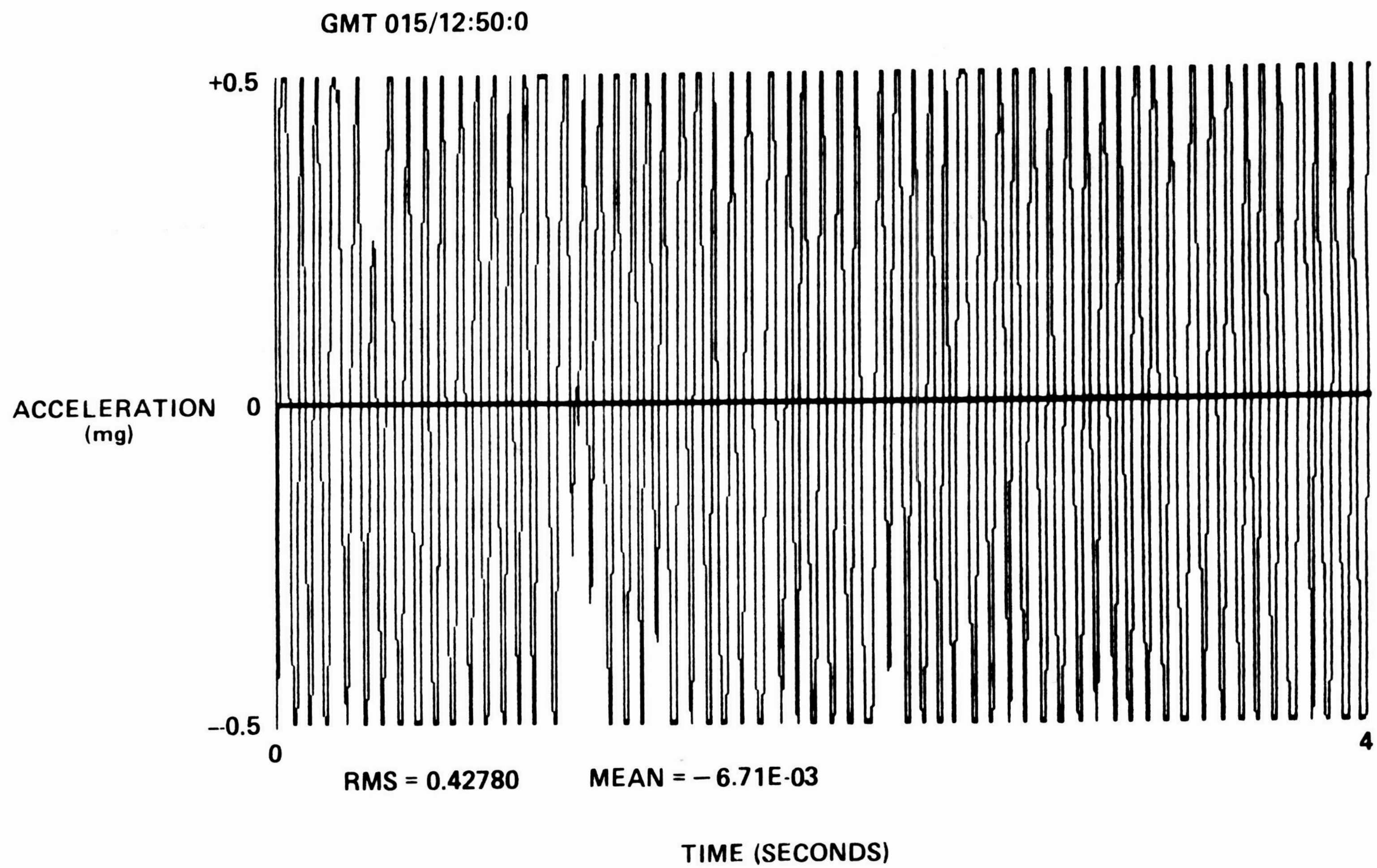

Figure 22. Acceleration induced by treadmill on MSL-2 (in-flight filtered data).

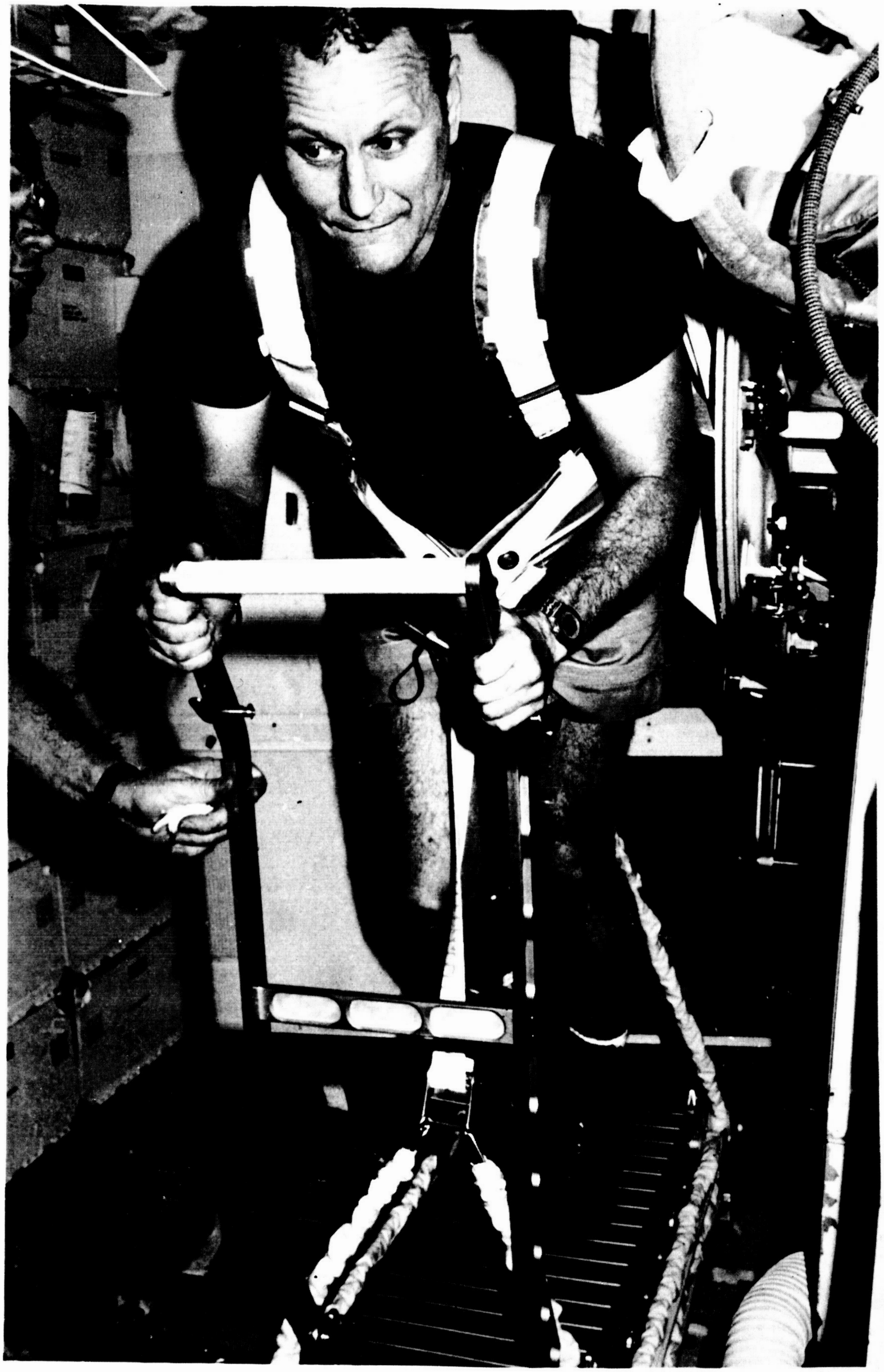

Figure 23. Flight crewman exercising on treadmill.

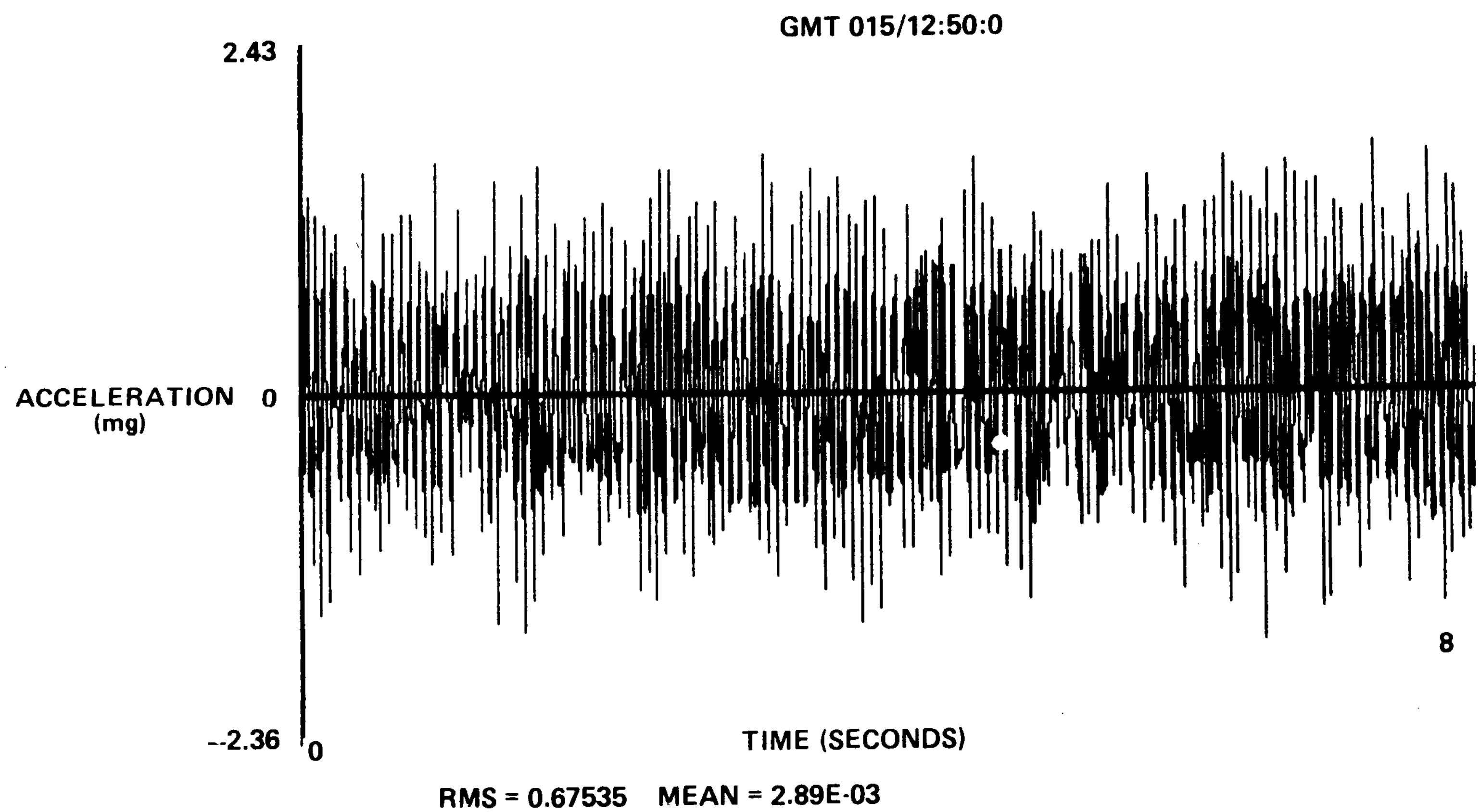

Figure 24. Acceleration induced by treadmill on MSL-2 (post-flight inverse filtered data).

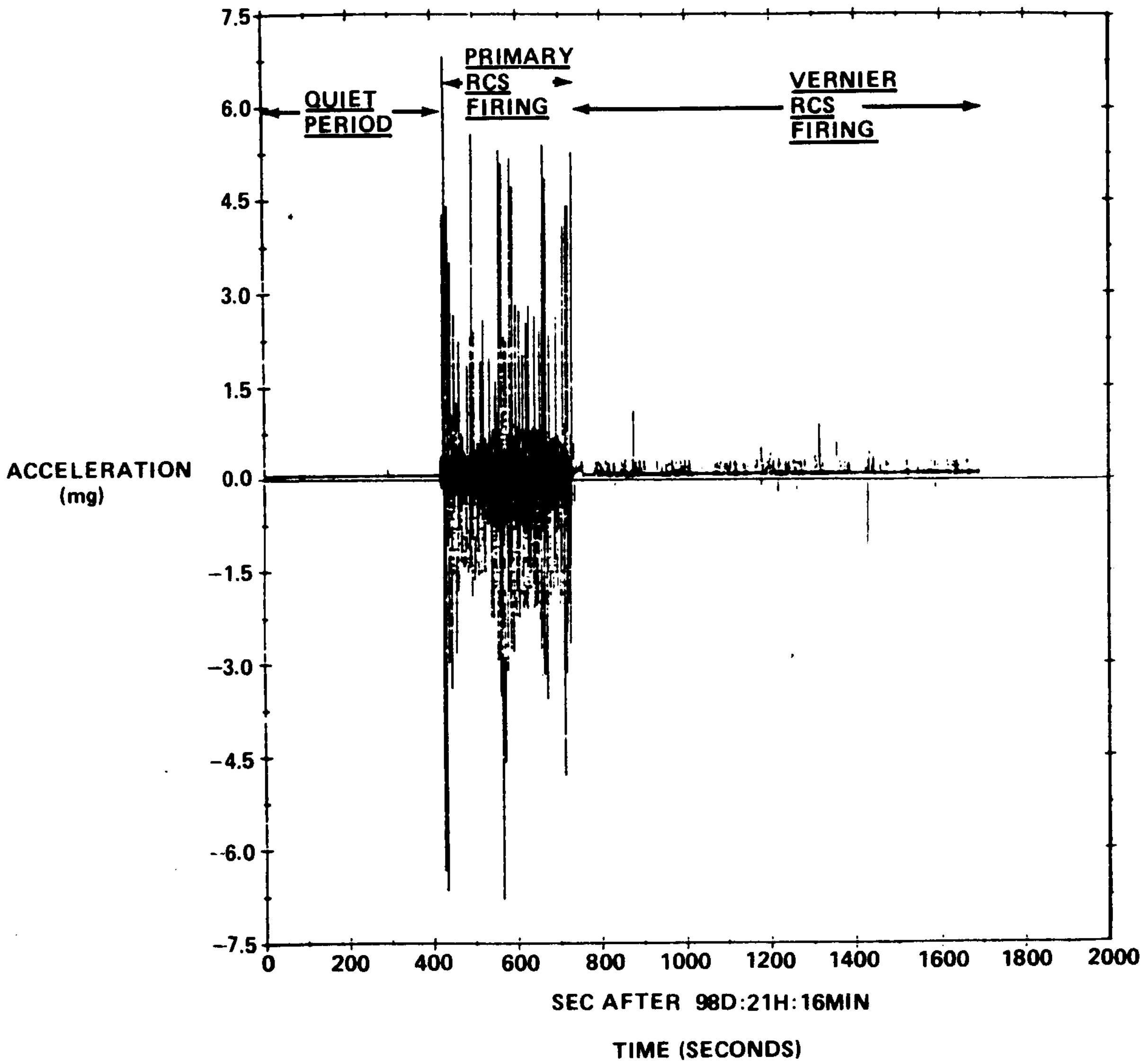

Figure 25. Acceleration change with rate control system (RCS) firings (from HIRAP).

been on its use in deriving the aerodynamic forces exerted on the Orbiter in the early stages of re-entry, but it appears that the HIRAP can contribute to the analysis of the on-orbit low-g environment as well. Reference 13 gives a list of ACIP and HIRAP data available and also some examples of the data available from some missions.

CONCLUSIONS

Perhaps the most significant message from this summary of 12 years of low-g data is highlighted by our choice of units in which to present the bulk of the material, i.e., milli-g rather than micro-g. We had initially hoped for 10^{-6} g maximum, but decided to request a more achievable 10^{-5} g on STS missions. Instead, we were promised 10^{-4} g maximum, but actually were provided 10^{-3} g of jitter. So we "lost" three orders of magnitude. (The extent to which this can be improved on Space Station is yet to be shown.) So on low-g carriers thus far, we typically have been using a "milli-g" environment; micro-g will be a future goal.

One other significant problem is that detailed records of mission events (particularly crew activity, but also mechanical events and activity) are difficult to obtain and very difficult to correlate with acceleration data.

A problem which surfaced during preparation of this paper is that all the processed forms of data cannot be stored indefinitely. Thus, prompt analysis and reduction of data to encompass the significant information and storage of that information is essential.

RECOMMENDATIONS

More systematic data acquisition and reduction techniques are needed for low-g data. Previous efforts have been highly individualized and relatively ineffective.

The body of well-qualified scientists which need low-g is composed mostly of metallurgists, crystallographers, or physicists who are expert in their fields of specialty, but who may not be adept at: (1) taking low-g data and converting that to the effects on fluid dynamics; (2) converting that, in turn, to effects of concentration gradients; and, (3) transforming that into an understanding of the effects on crystal microstructure. Therefore, low-g users need to strategize their specific use of low-g data very early in their experiment planning, so that the low-g data can be smoothly integrated into the in-flight and post-flight experiment analyses — not overlooked, as is prevalent today.

The volume of low-g data is massive and the extent of analysis of the data is still limited. However, interest in the results is growing and NASA has created an STS Orbiter Environment Panel to gather information on all aspects of the on-orbit environment into a central data base; the Orbiter Motion Subpanel (which was originally chaired by one of the authors and is currently chaired by the other) is charged with gathering the low-g data for the above panel. Continued effort will be applied by the Orbiter Motion Subpanel to characterize and understand the low-g environment on the STS Orbiter and take measures to improve the environment for the many investigators who need a more quiescent acceleration environment for acceptable experiment results. Obviously, these same types of measures should be diligently incorporated into the Space Station planning, design, and operation. It is of utmost importance that acceleration levels on Space Station be held to a minimum and that characterizing and understanding those residual accelerations be a standard real-time Space Station task.

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APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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16. ABSTRACT

NASA has utilized low-g accelerometers on a variety of flights for over 12 years. These flights have included aircraft parabolas, suborbital trajectories, and orbital missions. This large quantity of data has undergone only limited in-depth analyses. Examples of data in many forms and results of analyses such as power spectral densities and shock spectra are given for a wide variety of missions. Accelerometers used to acquire the data are also identified.

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