Comparison tools for assessing the microgravity environment of space missions, carriers and conditions

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ABSTRACT

The microgravity environment of the NASA Shuttles and Russia's Mir space station have been measured by specially designed accelerometer systems. The need for comparisons between different missions, vehicles, conditions, etc. has been addressed by the two new processes described in this paper.

The Principal Component Spectral Analysis (PCSA) and Quasi-steady Three-dimensional Histogram (QTH) techniques provide the means to describe the microgravity acceleration environment of a long time span of data on a single plot. As described in this paper, the PCSA and QTH techniques allow both the range and the median of the microgravity environment to be represented graphically on a single page. A variety of operating conditions may be made evident by using PCSA or QTH plots. The PCSA plot can help to distinquish between equipment operating full time or part time, as well as show the variability of the magnitude and/or frequency of an acceleration source. A QTH plot summarizes the magnitude and orientation of the low-frequency acceleration vector. This type of plot can show the microgravity effects of attitude, altitude, venting, etc.

Keywords: microgravity, acceleration, Shuttle mission, Mir space station, histogram, power spectral density

1. INTRODUCTION

The NASA Lewis Research Center (LeRC), Cleveland, Ohio, manages several accelerometer projects for measuring the microgravity environment of the NASA Shuttle missions, Russia's Mir space station, free flyers, and, in the near future, the International Space Station. These measurements and the subsequent analyses are performed to support principal investigators performing scientific experiments on these carriers.

The LeRC accelerometers that have flown on twenty-one Shuttle missions since 1991 are the Space Acceleration Measurement System (SAMS)[1] and the Orbital Acceleration Research Experiment (OARE)[2]. One SAMS unit has been used on the Mir space station since it was installed in September 1994. The SAMS measures the vibratory and transient acceleration environment from 0.01 Hz up to 100 Hz with a set of three distributed triaxial sensor heads. The OARE measures the quasi-steady environment below about 1 Hz with a single triaxial sensor located near the Shuttle's center of mass.

The data sets from these instruments are analyzed by the NASA LeRC Principal Investigator Microgravity Services (PIMS) project and the results are provided to interested principal investigators associated with the microgravity experiments of a mission. A number of standard formats for data display have been developed to graphically display the data acquired from these missions. Standard formats include: acceleration vs. time, power spectral density (PSD) vs. frequency, and spectrograms (PSD vs. frequency vs. time)[3, 4]. The particular technique used for an analysis depends on the type of information desired, the quantity of data considered, and the requester's needs. For the wide variety of microgravity experiments, the operation times range from minutes to weeks, and Shuttle missions are typically one to two weeks long. The analysis of acceleration data using the above mentioned standard techniques can result in many pages of plots, particularly for long-duration experiments or missions.

There has been a need to produce a meaningful, single-page summary of a mission, carrier, or time period so that comparisons may be made with another mission, carrier, or time period. The Principal Component Spectral Analysis (PCSA)

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and the Quasi-steady Three-dimensional Histogram (QTH) techniques were developed by the PIMS project to fulfill this need. As this paper shows, the PCSA and QTH techniques allow both the range and the median of the microgravity environment to be displayed on a single page for an entire mission, time period, or condition of interest. These plots may then be compared in order to determine the unique characteristics of each condition of interest.

The PCSA plot is based upon the frequency distribution of the vibrational energy, and is normally used for an acceleration data set containing frequencies above the lowest natural frequencies of the vehicle (e.g. SAMS data). The QTH plot is based upon the direction and magnitude of the acceleration vector and is normally used for acceleration data sets with frequency content less than 0.1 Hz (e.g. OARE data).

Various operating conditions are made evident by using PCSA or QTH plots. Equipment operating either full or part time (with sufficient magnitude to be considered a disturbance) may be evident. A source's magnitude and/or frequency variability may be evident by how it appears on a PCSA plot. Both the PCSA and the QTH plots can show the amount of variability of the microgravity environment.

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2. PRINCIPAL COMPONENT SPECTRAL ANALYSIS

2.1 PCSA methodology

The source of microgravity acceleration data for a PCSA plot is a sampled data set produced by an accelerometer system such as SAMS. The time frame to be analyzed is first divided into successive equal-duration time intervals. The duration of an interval is chosen based upon the desired frequency resolution, which is given by

$$\Delta f = 1/(\Delta t_i), \qquad (1)$$

where Δf is the frequency resolution (in Hertz) and Δt_i is the length of time (in seconds) in each of the intervals. The PSD (inset of figure 1) for each interval is then computed.

The next step in the PCSA processing is to determine the significant spectral peaks in each of the PSDs from all of the successive time intervals. For the purpose of this discussion, a significant spectral peak (figure 1) is defined to be a PSD magnitude value that is a local maximum, at least as high as any other magnitude point within a specified frequency range. The frequency range is usually specified by a number of frequency resolution intervals (a neighborhood) on either side of a data point. Typical values for this neighborhood for SAMS data analyses are 0.05 - 0.10 Hz.

The magnitude and frequency of the significant spectral peaks are extracted from the individual PSDs and stored as intermediate results. From these sets of magnitude vs. frequency values, a two-dimensional histogram is calculated by quantizing the values to desired resolutions, and assigning a count for each magnitude/frequency bin.

The two-dimensional histogram calculation yields a matrix containing the number of points falling within each magnitude/frequency bin. The raw results from the histogram analysis are dependent upon the total time period analyzed (e.g. 1 hour or 10 days). A larger time period would be expected to result in a higher number of coincidences in any given bin. In order to counteract this time dependence, a normalization procedure is implemented by which the number of occurrences in any given bin are divided by the total number of periods analyzed for the plot. By doing this, a measure of the percentage of time is achieved by the following equation:

$$t_p = \frac{p}{M} \times 100\,\%, \qquad (2)$$

where t_p is the percentage of time, p is the number of points falling within any given bin, and M is the total number of time periods analyzed for the plot. This data set is then imaged with a color or gray scale on a semi-log plot as shown in figure 2. This figure illustrates a PCSA plot for the SAMS data from the STS-78 mission which had the Life and Microgravity Spacelab (LMS) as the primary payload. Features of this data plot will be discussed in the next section.

2.2 PCSA interpretation

Correlation of the PCSA plots with known mission events (e.g. Ku-band antenna dither, water pumps, compressors, etc.) has led to a method by which the characteristics of a PCSA plot are related to mission activities and equipment operation. The basic interpretation of the plot's data is that the gray shading higher up the scale (i.e. towards lighter shades of gray) indicate that a magnitude/frequency combination occurred more often than that combination with a gray shading lower on the scale (i.e. towards black). The band of medium grays indicates the propensity of the microgravity environment to be in that region for much of the time included in the plot. This is illustrated in figure 2 where, for example, the tendency is for the environment below 1 Hz to be around 10^{-9} g^2/Hz.

An individual set of significant spectral peak points extracted from a PSD indicate the upper levels of the microgravity environment for the time period of that particular PSD. This upper level of the microgravity environment is of interest to the vast majority of principal investigators for their analysis of the microgravity environment. For a PCSA plot, the range of the microgravity environment's upper level is bounded by the upper and lower edges of the gray bands. Thus a single PCSA plot shows the range of the microgravity environment for the time period of interest.

2.3 Mission characteristics

The PCSA plot of SAMS data from the STS-78 mission (figure 2) will be used to show some of the characteristics discernible with the PCSA technique. Individual disturbances may be identified by certain characteristic shapes in a PCSA plot. The STS-78 Shuttle mission's primary payload was the LMS suite of experiments in the Spacelab module.

The STS-78 mission had a single shift crew where all seven crew members were on the same daily wake/sleep cycle. This mode of operation produced two distinct microgravity environment characteristics. During the crew active time, equipment operation and crew motion contributed towards higher acceleration levels, as compared with times for which the crew members were resting or sleeping. These crew active periods contributed to the higher magnitude disturbances (annotated in figure 2) between 10^{-7} and 10^{-6} g^2/Hz from about 8 to 21 Hz. Similarly, crew rest periods (reduced equipment operation and lack of crew motion) contributed to the lower microgravity levels between 10^{-9} and 10^{-7} g^2/Hz in the same frequency band.

The Ku-band antenna on the Shuttle dithers at a controlled 17 Hz frequency to prevent mechanical stiction as it slews to track communications satellites. This fixed vibration rate produces the thin vertical line at 17 Hz in the PCSA plot. The white area (representing very few histogram 'hits') below the 17 Hz thin vertical line indicates that the vibration at 17 Hz did not drop below $2x10^{-6}$ g^2/Hz for any appreciable time during the mission. The conclusion drawn from this data is that the Ku-band antenna is operating for most, if not all of the mission, as it normally does during a Shuttle mission.

The vehicle and payload structural vibration mode frequencies are seen in a PCSA plot as the broad magnitude peaks in the lower frequency regions below about 10 Hz. The Shuttle and the Spacelab module combine to produce a unique set of peaks for each mission at frequencies below 10 Hz.

The two large "humps" in the LMS PCSA plot at around 22 and 23 Hz were caused by the two refrigerator/freezers[5] located in the Spacelab module. Each refrigerator/freezer operates with a motorized compressor/evaporator with a rotational speed and operating duty cycle which vary according to the load, power supply, and temperature characteristics. This produces a vibration which varies in magnitude, frequency, and duration. This results in a PCSA signature which does not occur in a tightly controlled frequency band. For these two refrigerator/freezers, the vibrations produced by the motor/compressors were slightly different and they cycled on and off at independent times during the course of the mission. Thus, there are times when the environment around 22 and 23 Hz was not dominated by the vibrations from one or both of these refrigerator/freezers. This results in histogram 'hits' below the 10^{-5} g^2/Hz level in that frequency range, as opposed to the white area at 17 Hz from the nearly constant dither of the Ku-band antenna.

2.4 PCSA comparison

There have been many situations when a scientist has asked the PIMS project to prepare a comparison of a period of time from one mission with a period of time from either the same or a different mission. Such a comparison is not reasonable to perform by using standard PSD plots because the microgravity acceleration environment is so dynamic. Comparison of long-duration PSDs is hindered by the non-stationary nature of the acceleration environment. Spectral averaging techniques intended to suppress spurious peaks and accentuate significant spectral contributions obscure the spectrum where brief, transitory contributions occur. Selecting data from a "representative" time is another complicating factor when trying to utilize standard PSD plots to illustrate the general microgravity environment.

A PCSA plot allows the user to make a visual comparison between missions, carriers (e.g. the Spacelab module and the Shuttle's middeck), time periods within a mission (e.g. crew active and crew sleep) and mission conditions (e.g. different Shuttle attitudes, different levels of crew activity, etc.). Timing information has been removed by the processing to arrive at a PCSA plot, but this technique provides the desired comparison with respect to the overall magnitude levels and trends.

3. QUASI-STEADY THREE-DIMENSIONAL HISTOGRAM

3.1 QTH methodology

The source of microgravity acceleration data for a QTH plot is a sampled data set produced by a low frequency accelerometer system, such as the OARE. The raw OARE data are acceleration measurements digitized at a rate of 10 samples per second for each of the X, Y, and Z axes. Prior to its use in QTH plots, the data are transformed from the OARE coordinate system to the Shuttle body coordinate system[3] and a trimmean filter is applied to the data[2]. The trimmean filter is used to gain a better estimate of the quasi-steady acceleration levels. This filtering procedure ranks the collected data in order of increasing magnitude, measures the deviation of the distribution from a normal distribution, and deletes (trims) an adaptively-determined amount of the data from the high and/or low ends of the distribution. The mean of the remaining data is calculated and this value is assigned to the initial time of the interval analyzed[2]. For this paper, the filter was applied to 50 seconds (500 sampled data points) of OARE data in order to generate a data point every 25 seconds. The filtered OARE data for the STS-62 mission (which contained the Second United States Microgravity Payload (USMP-2) payload[6]) are plotted as acceleration vs. time in figure 3.

From these sets of three-axis (X, Y, Z) magnitude values, three two-dimensional histograms are formed by plotting pairs of the three-axis data points (i.e. X-Y, X-Z, Y-Z) in three scatter diagrams. These three diagrams provide front, side, and top volumetric slices of the acceleration vector. The histogram is calculated by quantizing the magnitudes to a desired resolution (typically 0.05 μg) and assigning a count for an occurrence in each bin. A color is then assigned based on the number of occurrences that fall within each bin.

The two-dimensional histogram calculation yields a matrix of the number of points falling within each histogram bin. Therefore, the raw results of the histogram analysis are dependent on the total time period analyzed (e.g. 1 hour, or 10 days). A larger time period would be expected to result in a higher number of coincidences in any given bin. In order to counteract this time dependence, a normalization procedure is implemented by which the number of occurrences in each bin is divided by the total number of periods analyzed for the plot. By doing this, a measure of the percentage of time is achieved by utilizing equation 3.

$$t_p = \frac{p}{N} \times 100\ \%, \tag{3}$$

where t_p is the percentage of time, p is the number of points falling within a bin, and N is the number of data points included in the QTH plot analysis.

This data set is then imaged as the three scatter plots in figure 4. A single QTH data point should be viewed as the tip of an acceleration vector which represents the local quasi-steady acceleration environment at the location of interest. The location of the data point in the QTH gives a relative indication of the quasi-steady acceleration vector magnitude and direction. The gray or color scale value indicates the percentage of time which the vector magnitude and direction occurred within the total time of the plot.

The OARE data from a mission may be transformed to represent the quasi-steady acceleration environment at different locations on the Shuttle by utilizing the Shuttle state vector data. The transformed OARE data may then be used to prepare a QTH plot for a specific experiment location or any other position of interest within the vehicle.

3.2 QTH interpretation

The QTH plot of the STS-62 mission will be used to show some of the characteristics discernible with this analysis technique. Correlation of the QTH plots with known mission events (e.g. vehicle attitude, vehicle altitude, water dumps) has led to the interpretation of the QTH plot characteristics relative to mission activities and vehicle equipment operation. The basic interpretation of the plot's data is that the grays higher up the scale (i.e. towards light gray) indicate that the acceleration vector fell into that bin more often than those bins with a gray lower on the scale (i.e. towards black). The lighter gray areas indicate the propensity of the microgravity environment to be in that region for most of the time of the data included in the plot. This is illustrated in figure 4, where the tendency for the quasi-steady acceleration vector was to be near the regions identified as A, B and C. These three regions are due to the three principal attitudes[3] of the Shuttle for that mission.

One primary attitude was with the Shuttle tail toward Earth and the cargo bay in the direction of flight, which resulted in the tendency for the acceleration vector to be near $(X_b, Y_b, Z_b) = (-0.7, 0.1, -0.5)$ μg, identified in figure 4 as (A). Another primary attitude was with the cargo bay toward Earth and the right wing in the direction of flight, which resulted in the tendency for the acceleration vector to be near (-0.7, 0.1, 0.2) μg, identified in figure 4 as (B). Another primary attitude was with the tail toward Earth and the belly in the direction of flight, which resulted in the tendency for the acceleration vector to be near (0.1, 0.1, 0.6) μg, identified in figure 4 as (C). The predominant direction of the quasi-steady acceleration may be seen where the gray area is lightest.

During part of the STS-62 mission, the Shuttle operated with the cargo bay toward Earth and the right wing in the direction of flight in an elliptical orbit with altitudes of 105 nautical miles (perigee) and 138 nautical miles (apogee). This type of orbit appears in the STS-62 QTH plot as the linear trace extending in the Y_b-axis direction, identified in figure 4 as (D). The increased atmospheric drag at the lower altitudes increased the acceleration levels in the axis directed into the velocity vector (the Y_b axis in this case).

The general range of the quasi-steady microgravity environment for the data included in a QTH plot is bounded by the non-white areas in the plot. A QTH plot shows the propensity of the quasi-steady acceleration vector direction and magnitude over the time period included in the plot.

3.3 QTH comparison

Comparisons of the quasi-steady acceleration levels using plots of acceleration vs. time are not adequate because the microgravity quasi-steady acceleration levels slowly change over time and the overall conditions are not readily apparent. QTH plots allow the user to make a visual comparison between missions, carriers, time periods of a given mission, and conditions (i.e. attitudes, crew activity, etc.) by showing the long-duration variability in the quasi-steady acceleration environment in a single plot.

4. FUTURE UTILIZATION

The PCSA and QTH plots are useful during the analysis of the vast quantity of data which has been received from the operations of accelerometer systems on Shuttle missions and the Mir space station. Even more so, these techniques will be useful for analyzing the data from the accelerometer systems on the International Space Station.

These techniques may also be used as a calculation in an automatic data interpretation system under development by PIMS for use during the International Space Station operations. Processing the mission data using PCSA and QTH techniques will allow an automatic system to recognize the mission activities which have been described in this paper.

5. CONCLUSIONS

The PCSA and QTH plots provide tools by which comparisons can be made for different sets of microgravity acceleration data. These techniques, as well as others, have been employed during the analysis of acceleration data from microgravity science missions in order to derive concise, meaningful information in support of microgravity science experiments.

6. REFERENCES

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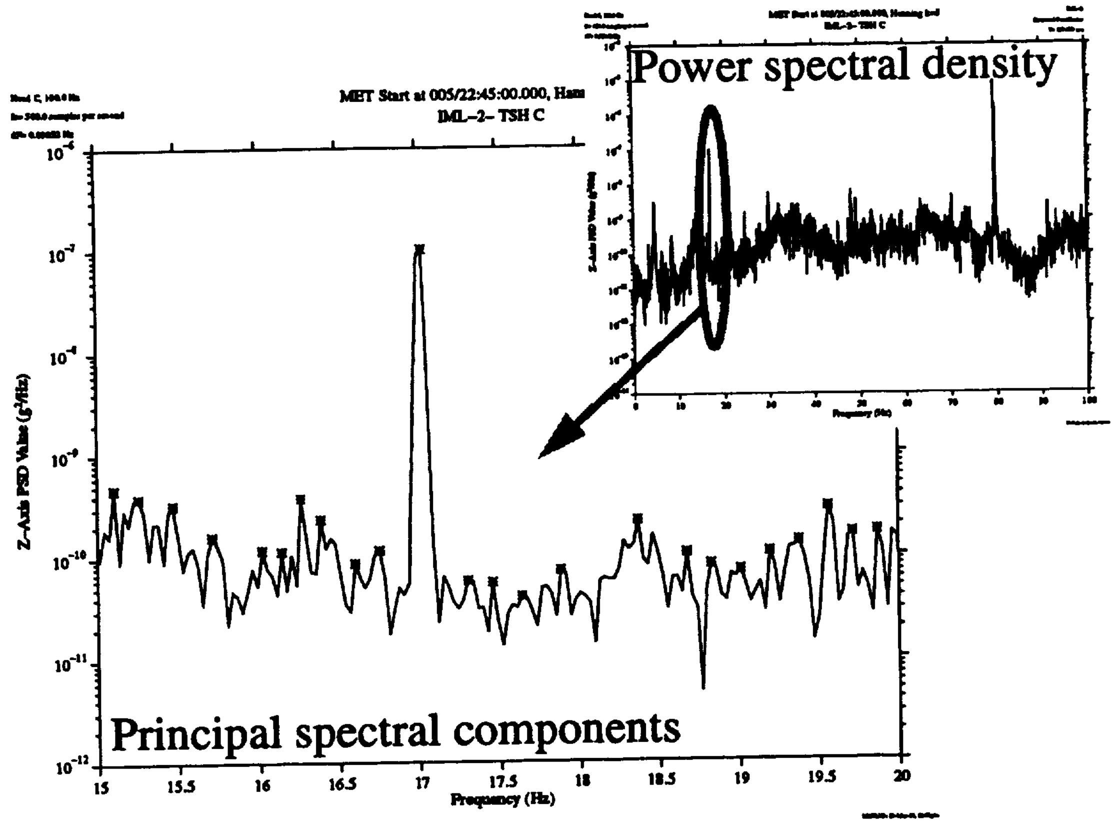

Figure 1: Extraction of significant spectral peaks from power spectral density plot.

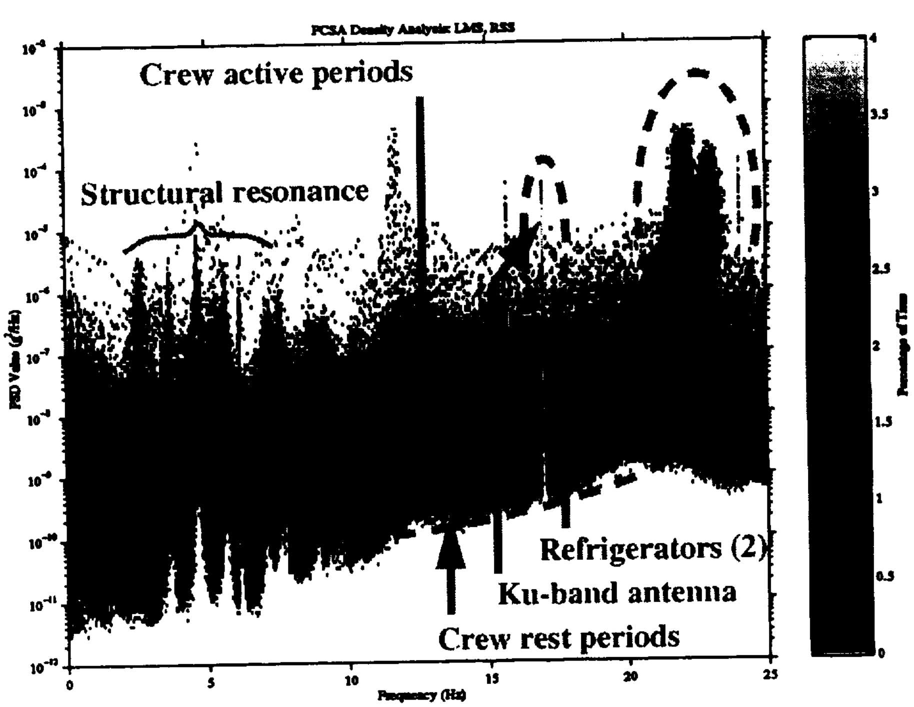

Figure 2: Principal Component Spectral Analysis plot of SAMS data for STS-78.

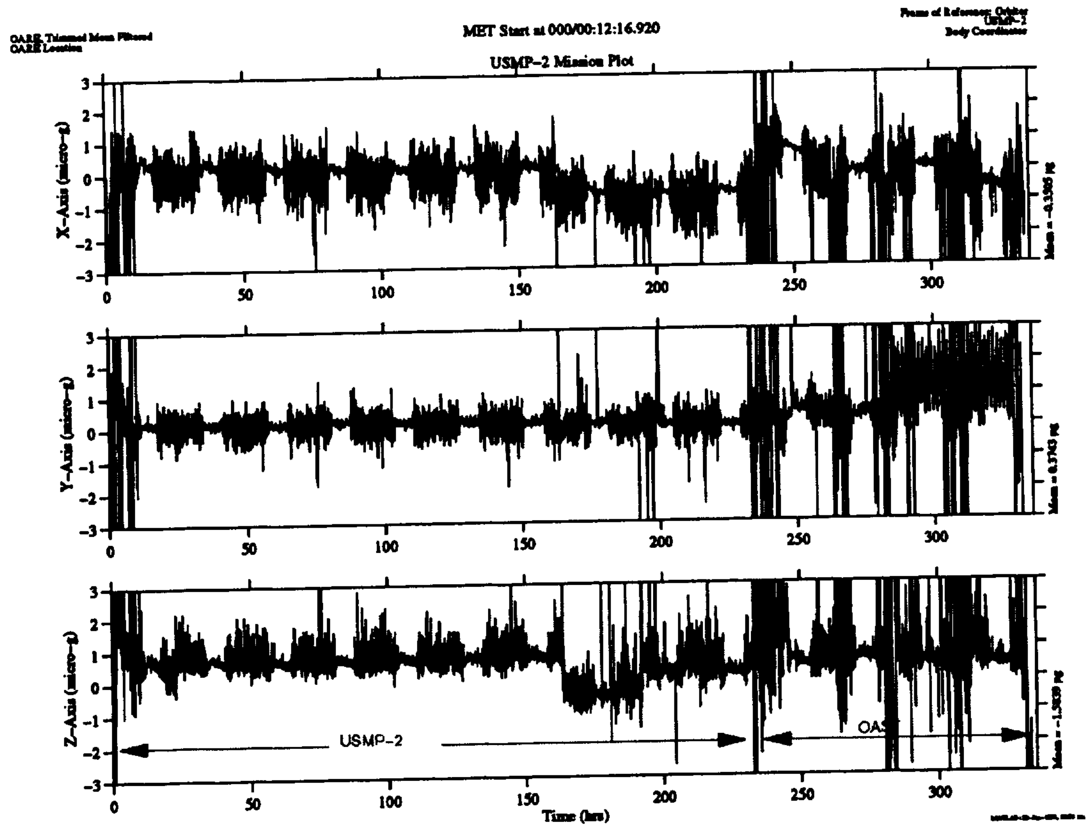

Figure 3: OARE sampled data set in acceleration vs. time for STS-62.

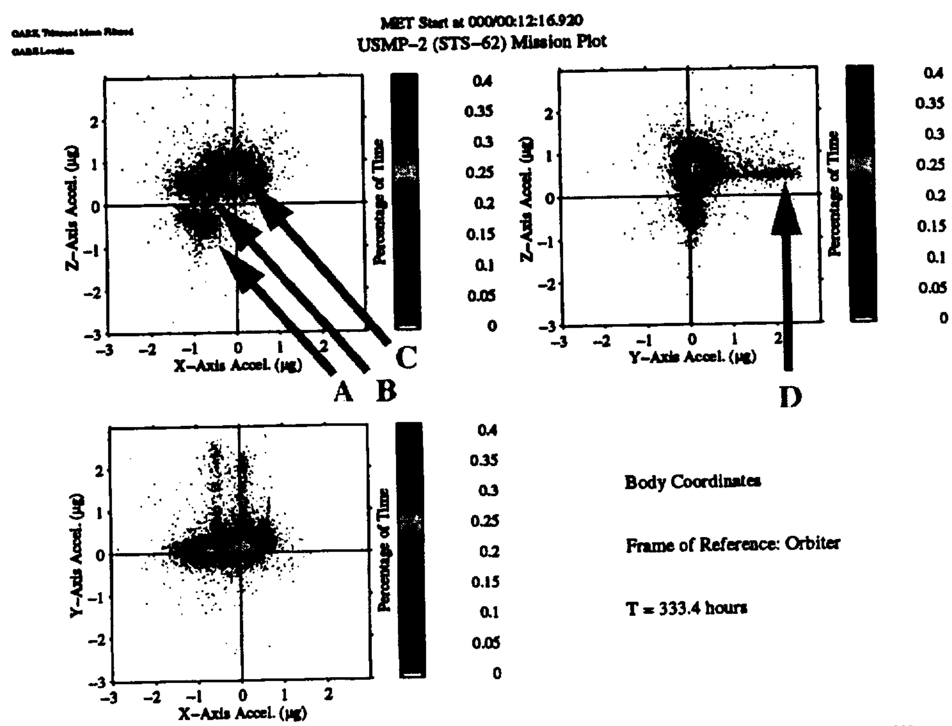

Figure 4: Quasi-steady Three-dimensional Histogram plot of OARE data for STS-62.