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Interpreting the International Space Station Microgravity Environment

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The International Space Station (ISS) serves as a platform for microgravity research for the foreseeable future. A microgravity environment is one in which the effects of gravity are drastically reduced which then allows physical experiments to be conducted without the overpowering effects of gravity. A physical environment with very low-levels of acceleration and vibration has been accomplished by both the free fall associated with orbital flight and the design of the International Space Station. The International Space Station design has been driven by a long-standing, high-level requirement for a microgravity mode of operation. The Space Acceleration Measurement System has been in operation for nearly four years on the ISS measuring the microgravity environment in support of principal investigators and to characterize the ISS microgravity environment. The Principal Investigator Microgravity Services project functions as a detective to ascertain the source of disturbances seen in the ISS microgravity environment to allow correlation between that environment and experimental data. Payload developers need to predict the microgravity environment that will be imposed upon an experiment and ensure that the science and engineering requirements will be met. The Principal Investigator Microgravity Services project is developing an interactive tool to predict the microgravity environment at science payloads based on user defined operational scenarios. These operations (predictions and post-analyses) allow a researcher to examine the microgravity acceleration levels expected to exist when their experiment is operated and then receive an analysis of the environment which existed during their experiment operations. Presented in this paper will be descriptions of the environment predictive tool and an investigation into a previously unknown disturbance in the ISS microgravity environment.

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Nomenclature

C&T	=	Communication and Tracking
CMG	=	Control Moment Gyroscopes
DAC	=	Design Analysis Cycle
EL	=	elevation angle
g	=	nominal gravitational acceleration at the Earth's surface (~ 9.8 m/s^2)
GMT	=	Greenwich Mean Time
GN&C	=	Guidance Navigation and Control
ISS	=	International Space Station
LVLH	=	local vertical / local horizontal vehicle attitude
MAC	=	Microgravity Analysis Cycle
MAMS	=	Microgravity Acceleration Measurement System
MER	=	Mission Evaluation Room
NIRA	=	Non-Isolated Rack Assessment
ODRC	=	Operational Data Reduction Complex
OSS	=	Orbital Acceleration Research Experiment Sensor System
OTOH	=	One-Third Octave Histogram
PIMS	=	Principal Investigator Microgravity Services
rms	=	root-mean-square
SAMS	=	Space Acceleration Measurement System
TDRS	=	Tracking and Data Relay Satellite
XEL	=	cross elevation angle
XPOP	=	X-axis perpendicular to orbital plane

I. Background

A. Microgravity environment

The microgravity environment of an orbiting spacecraft such as the International Space Station (ISS) is not simply "zero G" as is popularly assumed. Although not ideal, the closest to "zero G" on the ISS would be experienced by an article floating in mid-air at the center of mass of the ISS. Any other article attached to the vehicle will experience vibrations (accelerations) from a variety of sources, such as pumps, fans, ISS attitude control, atmospheric drag, gravity gradient, and others. These disturbances are transmitted mechanically through the vehicle structure and acoustically through the air in the habitable modules. The spectrum of vibrations which may disturb physical science experiments is comprised of a variety of frequencies from steady to 300 Hz. The magnitude of these vibrations varies with frequency, ranging from $1x10^{-5}$ m/s^2 at low-frequencies to $1x10^{-1}$ m/s^2 at higher frequencies. Since the lower acceleration levels are approximately one-millionth of Earth's 1-g (~ 9.8 m/s^2), this environment is referred to as "microgravity."

The ISS program established requirements[1] that specify the allowable levels of acceleration at payload sites within the habitable modules where crew-tended experiments reside. These requirements are in four categories: duration, vibratory, quasi-steady, and transient. In summary, the duration of microgravity mode operations will be at least 180 days per year, the vibratory levels will be below the curve shown in Figure 1, the quasi-steady levels will be less than $1x10^{-5}$ m/s^2, and the transient disturbances will be below specified levels. All components of the ISS vehicle and the payloads are subject to these requirements. References 1 and 2 should be consulted for specific details on these requirements and their treatment by the ISS program.

B. Characterization of the microgravity environment

1. Microgravity acceleration measurement systems

The Space Acceleration Measurement System (SAMS) and the Orbital Acceleration Research Experiment measured the microgravity environment on over twenty Shuttle missions from 1991 to 2003. Mission reports were written by the Principal Investigator Microgravity Services (PIMS) project to summarize the microgravity environment for each of these missions.[4] A SAMS unit also measured the environment of Russia's Mir space station from October 1994 to January 1998 with reports written to document the analyses of that environment.[4] PIMS has also performed specific analyses in response to requests from science investigators, mission cadre, and others.

The SAMS was re-designed for operation on the ISS and is comprised of a control unit and remote triaxial sensors which measure the environment in the vibratory regime from 0.01 Hz to 300 Hz. Also on-board the ISS is the Microgravity Acceleration Measurement System (MAMS) which is comprised of two triaxial sensors, one for the vibratory regime and one for the quasi-steady regime below 0.01 Hz. The MAMS and SAMS units began measuring the environment on the ISS in May and June 2001, respectively, and both units have continued to the present. Several increment-based reports have been written by PIMS to characterize the environment for that time period. [5-9]

2. Analysis of acceleration data

The PIMS analysts work as detectives as they attempt to correlate the features seen in the acceleration data to events that occur on-board the vehicle, whether the Shuttle, Mir, or the ISS. Many sources of data are consulted, such as vehicle subsystem data and status reports, the operations timeline, experiment operational data from science teams, and notes taken during PIMS control center operations. PIMS analysts also consult with real-time operations cadre in both the Mission Control Center and the Payload Operations Control Center and long-term operations cadre in the Mission Evaluation Room (MER) about details of the vehicle and subsystems operations. These sources of data are examined for clues as to what may have caused a particular characteristic in the acceleration data. Several recent instances of 'detective work' are illustrated in this paper to illustrate this process. A similar process may be needed for science teams when analyzing the results of their science experiment operations.

3. Data displays

The PIMS team employs several methods of processed acceleration data display, the choice of a particular method is determined by what information is desired to be extracted from the data. Reference 10 describes these methods in detail, only a few of which are used in this paper.

In brief, a spectrogram is a three-dimensional data plot with time represented on the abscissa, frequency represented on the ordinate, and acceleration spectral magnitude represented by color.

In brief, a One-Third Octave Histogram (OTOH) data plot indicates the root-mean-square (rms) levels in one-third-octave frequency intervals over the time span covered by the data. Calculating rms levels for each frequency interval every 100 seconds (as specified in the ISS requirements) and combining these levels in a histogram allows the spread of the levels from the minimum to the maximum to be graphically displayed.

II. Recent Analyses of ISS microgravity environment

A. Quasi-steady regime

The quasi-steady regime is comprised of accelerations with frequency content below 0.01 Hz and magnitudes expected to be on the order of 2 μg or less. These low-frequency accelerations are associated with phenomena related to the orbital rate, primarily aerodynamic drag. However, gravity gradient and rotational effects may dominate in this regime, depending on various conditions and an experiment's location relative to the vehicle's center of mass. Other sources of acceleration to consider in this regime are venting of air or water from the spacecraft and appendage movement such as solar arrays, Space Station Remote Manipulator System and communication antennas.

1. Ku-Band Antenna

The Ku-band antenna system is used to transmit payload science data and television from the ISS. The ISS Ku-band system uses the Tracking and Data Relay Satellite (TDRS) constellation for uplink and downlink. The Ku-band antenna is located on the end of a boom arm attached to the Z1 truss. The antenna is positioned during satellite tracking using two gimbals, an elevation (EL) gimbal and a cross elevation (XEL) gimbal with the pointing angle represented by data items EL and XEL, respectively. This antenna interfaces with the Guidance Navigation and Control (GN&C) system which provides data required for open-loop antenna pointing and provides initial pointing vector information for closed-loop, auto-track antenna pointing.

Movement of the antenna by these gimbals is seen in the quasi-steady acceleration data of MAMS. Figure 2 includes eight hours of MAMS data recorded at Greenwich Mean Time (GMT) 30-November-2003, 00:00-08:00 along with Ku-band operations data retrieved from the Operational Data Reduction Complex (ODRC). The plot shows a pattern of 0.2-5.0 ug spikes which are attributable to the Ku-band antenna "open loop slew" mode. In this mode, the antenna is rapidly moved (typically 1-2 minutes in duration) into position to begin tracking a satellite. This figure demonstrates the correlation between the gimbal movements and the spikes in MAMS data. For nearly every spike in the MAMS vector magnitude plot, the Ku-band operations is in "open slew in progress" mode and is accompanied by rapid changes in one or both of the EL and XEL position values. Mean gimbal slew rates calculated from the plot for these time periods vary from 1.5 - 3.0 degrees/sec.

To develop these correlations, PIMS personnel used real-time observations of ISS operations, ODRC data, and interviews with MER staff. With the somewhat random recurrence of the spikes in the MAMS data and the plethora of other 'features' in the MAMS data, the correlation with Ku-band antenna operation was not obvious initially.

2. Progress Fuel Line Purge

As part of a propellant resupply procedure, fuel and oxidizer are transferred from a newly arrived Progress resupply vehicle to ISS storage tanks. During this procedure the line is purged between steps. An example of a fuel line purge can be seen in Figure 3, which has the MAMS Orbital Acceleration Research Experiment Sensor System (OSS) data plotted as an OSS Best Trimmean Filter. This particular propellant purge occurred prior to Progress 10P undocking, at approximately GMT 22-Aug-2003 234/06:07, with a peak acceleration of 3.06 ug occurring in the Y_A-axis at 06:08. A momentum management event, which is used to de-saturate the Control Moment Gyroscopes (CMG), occurs at GMT 06:22.

To develop these correlations, PIMS personnel used the as-run timeline prepared by the MER staff, interviews with MER staff, and ODRC data.

B. Vibratory regime

Vehicle systems comprise the infrastructure needed for the health of the crew, proper operation of the space station according to the timeline, and the maintenance of the vehicle. Equipment for communication, vehicle attitude maintenance, crew life-support, and other functions can produce accelerations that play a major role in shaping the microgravity environment in the vibratory regime.

1. Ku-Band Antenna

A characteristic in the SAMS data that was noticed early in the ISS operations was referred to as a 'swoosh' signature due to its shape in a spectrogram data plot, Figure 4. The characteristics changed slightly over time but due to the lack of a strong indication of its source, investigation of its source was postponed while analysts worked to identify other sources. Some traits started to emerge as the 'swoosh' was observed over time, namely a correlation to ISS attitude and a close tie to the orbital period. The 'swoosh' signature was apparent in the local vertical / local horizontal (LVLH) attitude, but not in the X-axis perpendicular to orbit plane (XPOP) attitude. This was found by observations during control center console duty by PIMS staff. Examining long-term spectrogram plots of SAMS data during LVLH attitude periods, a slight correlation between the 'swoosh' signature and the orbital period was developed. Over the course of time, though, it was found that the 'swoosh' tie to the day/night cycle of the orbital period varied. This led the PIMS staff to realize that the 'swoosh' phenomenon was orbit-related, but not based on the day/night cycle of the Sun and Earth.

About the same time of the initial 'swoosh' investigation, another unknown source was identified and was referred to as the 'picket fence' due to its signature of short, repetitive broad-frequency disturbances that appeared on a spectrogram as a picket fence, Figure 5. The 'picket fence' was observed in spectrograms with the 'swoosh' signature with a weak correlation between the two.

Many systems on the ISS are affected by the orbital cycle, such as the thermal control system, the electrical power system, GN&C, and communication and tracking (C&T). Thermal radiators rotate to be edge-on to the Sun, the photovoltaic arrays are oriented to be perpendicular to the Sun, the orientation of star sensors and CMGs are fixed in space, and antennae track satellites which are themselves fixed in relation to the Earth. Based on this broad range of possible sources, a request was submitted to the MER for an examination by all system engineers of their systems' operations in selected 'swoosh' and 'picket fence' periods of interest. To begin this request, PIMS staff presented the problem to a representative set of MER engineers and discussed the PIMS initial findings and characteristics of the 'swoosh' and 'picket fence' signatures.

As happens in some great detective stories, a lucky break led the PIMS staff to a correlation between the 'swoosh' signature, the 'picket fence,' and Ku-band antenna operations. In the course of a GN&C engineer investigating GN&C data, he noticed a slight correlation with some Ku-band antenna data. Further investigation by PIMS analysts and C&T engineers, it was found the 'swoosh' and 'picket fence' signatures are caused by motion of the Ku-band antenna during its various operations modes.

The spectrogram of Figure 5 shows an instance of the "picket fence" signature just prior to a "swoosh" signature. Correlation with antenna mode information shows that "gimbal motion halted" results in the "picket fence", while auto-tracking in the LVLH attitude gives rise to the smooth "swoosh" signature. The picket fence feature arises from the Ku-band antenna mode during a Loss of Signal period when the antenna system does not have a lock on a TDRS. The antenna is then put into a spiral search mode to find, acquire, and lock onto a TDRS.

The forty-minute spectrogram in Figure 6 shows the composite vibratory spectral signature of the Ku-band antenna between 0 and 40 Hz. The ascending XEL angular rate before 03:45 suggests the XEL gimbal is responsible for the corresponding ascending narrowband ("swoosh") signature in the spectrogram subplot of that figure, while the descending EL gimbal angular rate aligns with the descending narrowband signature. More information on these analyses (and other analyses of the environment during Increments 6-8) will be contained in Reference 9.

While standard operating procedure relies on this communication link, it may be beneficial for some researchers to become more knowledgeable on its vibratory impact. A comprehensive quantitative look at the vibratory environment below 25 Hz was undertaken to serve dual roles: (1) to assist researchers and others who might be interested in this particular aspect of ISS operations and (2) to summarize the station's vibratory environment for a long period of time. This analysis will be included in Reference 9.

III. Microgravity Analysis Cycle

The examples in the previous section illustrate what is presently done to analyze the microgravity environment of the ISS. Researchers and their experiment teams need a method of predicting what the microgravity environment is expected to be before the experiment design is completed. If this is not done, the experiment results may suffer if the microgravity environment disturbs the experiment conditions sufficiently.

The Microgravity Environment Program at NASA Glenn is also involved in microgravity environment prediction, control, and verification for payloads on the ISS and specifically the Fluids and Combustion Facility. The PIMS experience base of on-orbit microgravity environment and the microgravity modeling efforts for the Fluids and Combustion Facility are being leveraged with the use of ISS vehicle models to provide the Microgravity Analysis Cycle (MAC), a microgravity operational planning tool.

Two requirements-based analyses, Design Analysis Cycles (DAC) and Non-Isolated Rack Assessment (NIRA), have been periodically performed during the design and construction of the ISS vehicle.[**] These analyses provide the expected microgravity acceleration levels that will be transferred from the vehicle to the science experiment racks at a time when the ISS assembly is complete and nominal microgravity science operations commence. Payload teams use these data (and other data) to assist in developing design specifications, selecting design solutions (e.g., the need for vibration isolation), and to determine the payload's compliance to requirements.

The DAC and NIRA analyses combine all possible operational modes of disturbers, such as a fan, to envelope a worse-case environment. For example, those analyses use a fan disturbance at low speed and high speed to develop a worse-case scenario. The MAC microgravity operational planning tool, though, allows a user to selectively define specific operational scenarios and activates the disturber accordingly, such as including a fan at a single speed rather than both speeds. In addition, the MAC tool incorporates payload-to-payload disturbances to further assist in payload operational modeling and planning. The MAC is accessed with a browser web page interface[††] through which a user is able to select payload and vehicle disturbers based on operational scenarios and in a matter of minutes, analyze the impact to a specific science payloads' location. Overall levels at the science location, individual disturber levels, and the contribution of disturbers to the overall level are provided to the user. This allows the user to investigate "what-if" scenarios with disturbers or other payloads operational modes modified. The user is able to investigate past, present, and future ISS increments.

IV. Current environment vs. ISS requirement levels

While no formal microgravity mode operations have been conducted to date, the microgravity levels specified in the ISS program requirements[1] provide a 'yardstick' to which the current levels may be compared. Even though the

[**] The DAC and NIRA reports were prepared for ISS Program participants and were, in general, not made publicly available due to the limited usefulness of the reports for general use.

[††] The MAC web site is accessible by registered users of PIMS on-line services. Registration is free. The PIMS team employs user registration for identification of customer database and for customer metrics and feedback. To register, follow the REGISTERED USER link on the PIMS home page at URL:
http://pims.grc.nasa.gov/pims_iss_index.html

conditions specified in the ISS requirements are not met at this stage of ISS construction, the comparison of current environment against the requirement levels gives an indication of how well the ISS vehicle is progressing towards its required levels at the assembly complete stage.

The microgravity environment of an eight-hour period of nominal ISS operations (GMT 16:00-24:00, 1 October 2003) is shown in Figure 7 as a OTOH (see Reference 10 for OTOH details). In Figure 7, the propensity of the environment is below the ISS requirement levels which take effect when the ISS construction is complete (see section I-A). It can be seen that most of the time, the ISS environment (even though not currently operating in a microgravity mode of operation) is near or below the requirement levels. Analyses for the ISS shows an environment very close to the required level at assembly complete.

V. Further study

The PIMS team will continue to analyze the ISS microgravity environment in support of PIs and to characterize the ISS' microgravity environment. Reports will continue to be prepared to summarize the environment. Special analyses will be performed, as required, to support a PI and to investigation phenomena observed in the data.

VI. Summary

The PIMS team continues to serve the needs of customers (past, present, and future) including science teams, the ISS vehicle program office, structural dynamics engineers, sustaining engineering teams, payload developers, astronauts and cosmonauts. When analyzing their science data, investigators should be aware of activities or events relevant to the acceleration environment that took place on the ISS simultaneous with their experiment. This type of information can help with future experiment runs in terms of whether or not certain activities or events have any significant impact on their work. PIMS can assist with this detective work to assemble a description of the microgravity environment which occurred during the experiment's operations. In-depth analyses tailored to specific needs and questions about the microgravity environment should be considered by investigators who might otherwise be operating in the dark with respect to the acceleration effects.

References

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10. Rogers, M. J. B., Hrovat, K., McPherson, K., Moskowitz, M., and Reckart, T., "Acceleration Data Analysis and Presentation Techniques," NASA TM-113173, September 1997.

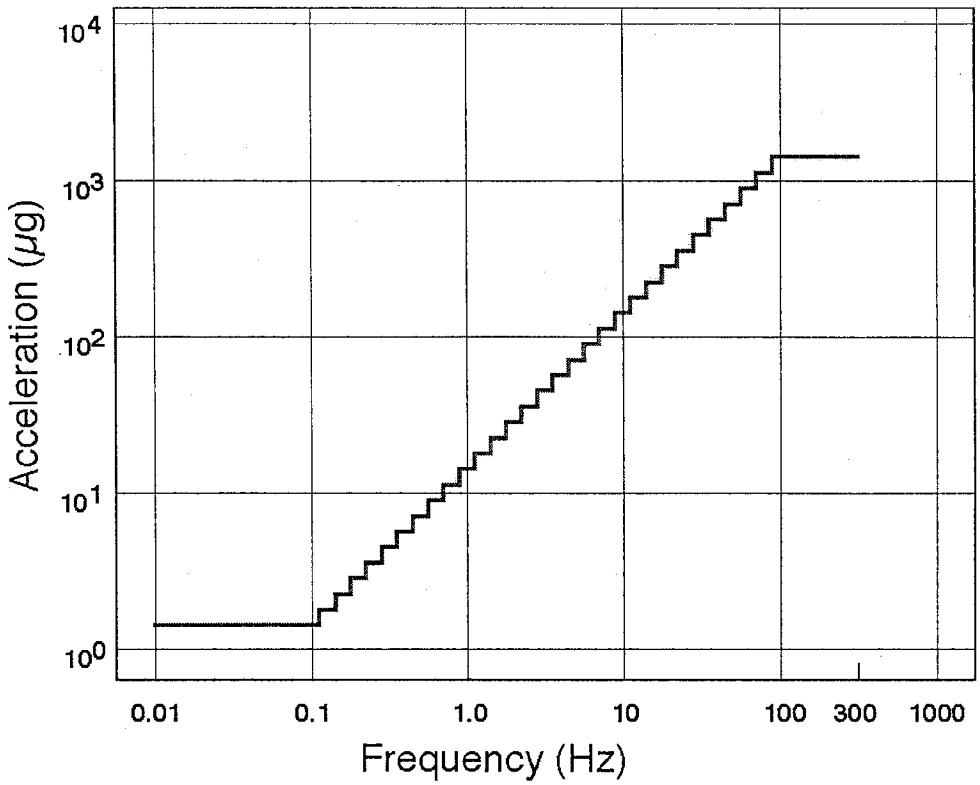

Figure 1. **Maximum rms acceleration levels in one-third-octave frequency intervals according to ISS program requirements (Reference 1).**

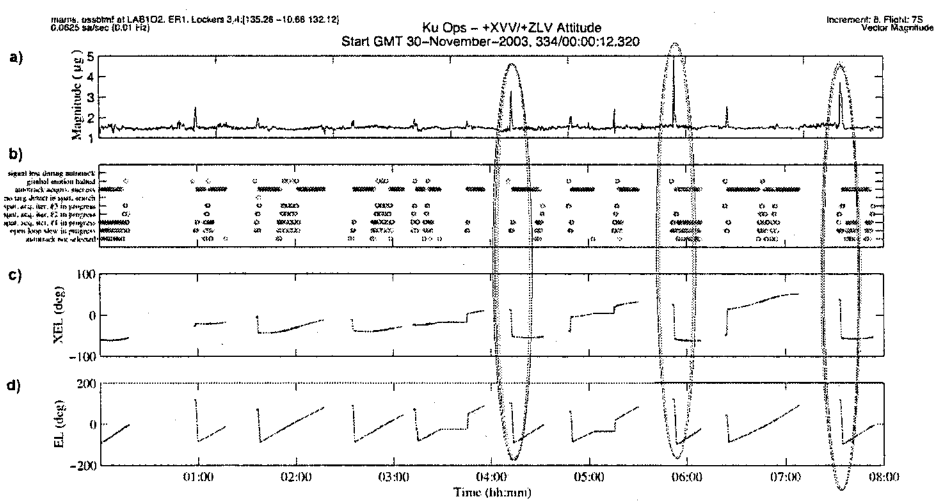

Figure 2. **Data showing correlation between microgravity environment spikes (circled in figure) and Ku-band antenna motion. a) Acceleration data versus time; b) Ku-band antenna discrete data status; c) Ku-band antenna cross elevation pointing angle; and d) Ku-band antenna elevation pointing angle. (GMT 30 November 2003, 00:00-08:00)**

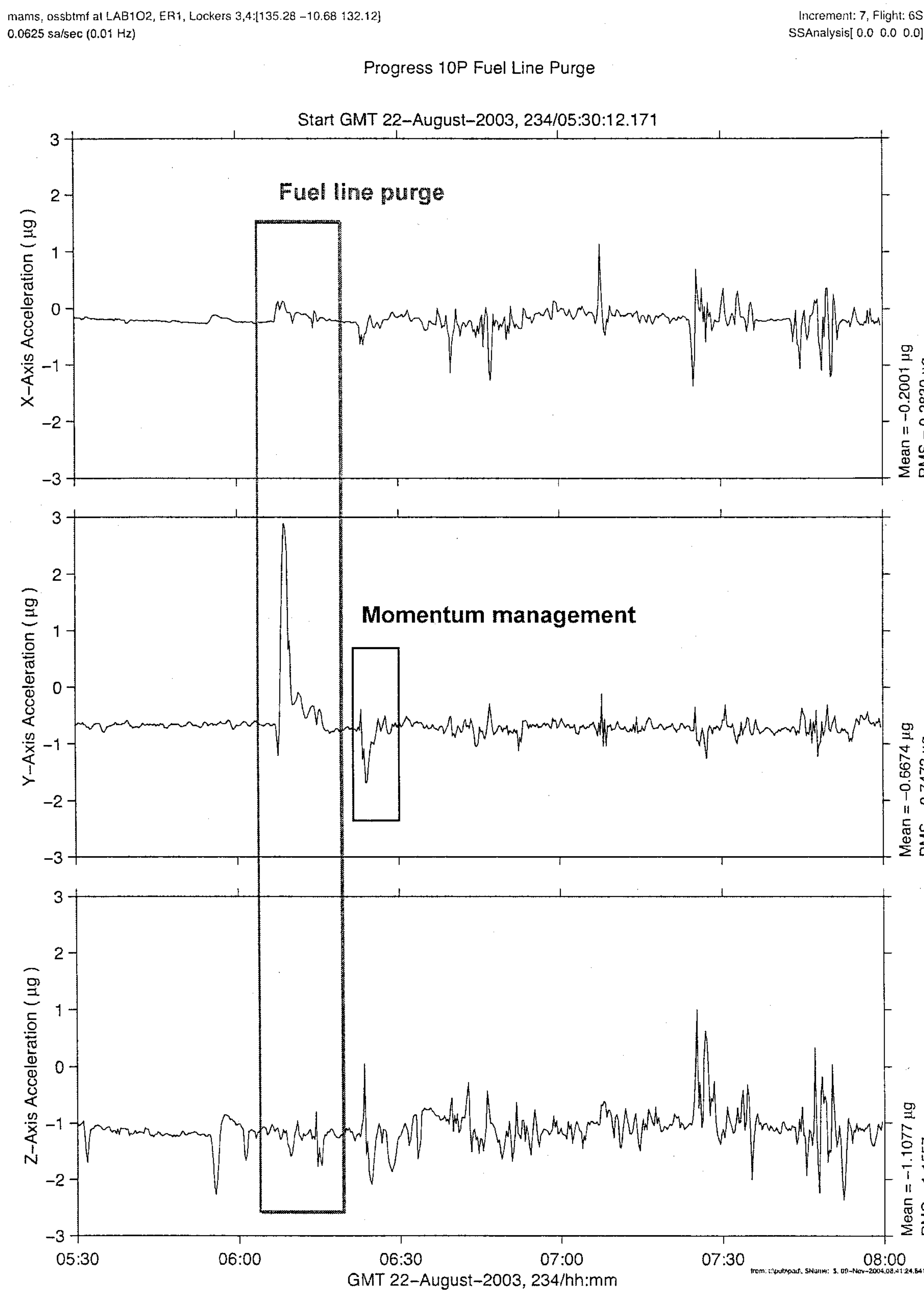

Figure 3. **Time series plot of MAMS acceleration data (GMT 22 August 2003, 05:30-08:00) which encompasses a propellant purge and a corrective momentum management event.**

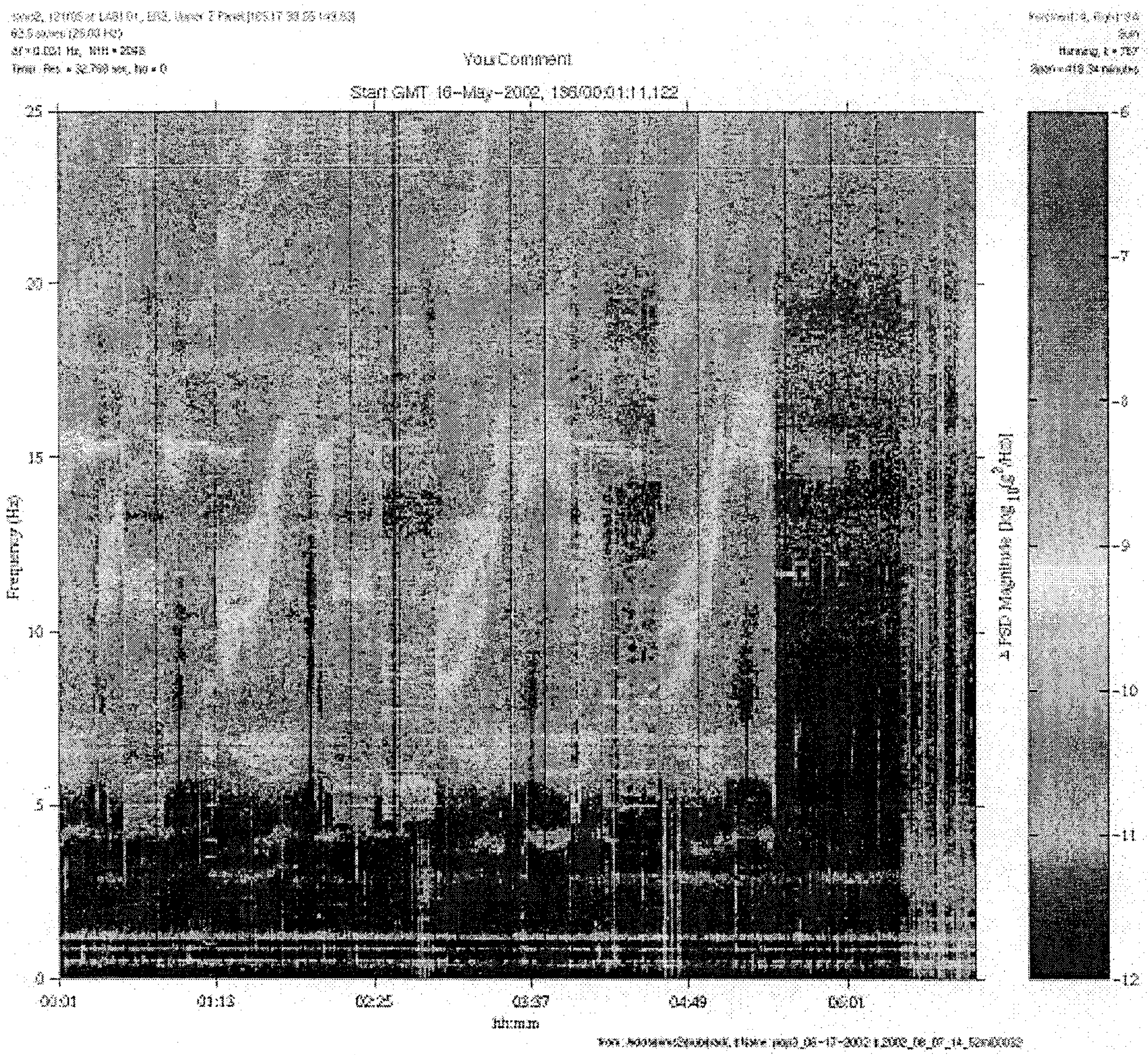

Figure 4. **SAMS microgravity acceleration data in a spectrogram plot which illustrates the typical "swoosh" characteristics (GMT 16 May 2002, 00:01 – 07:10). The multiple, variable-frequency traces between 5 and 25 Hz typify the "swoosh" signature.**

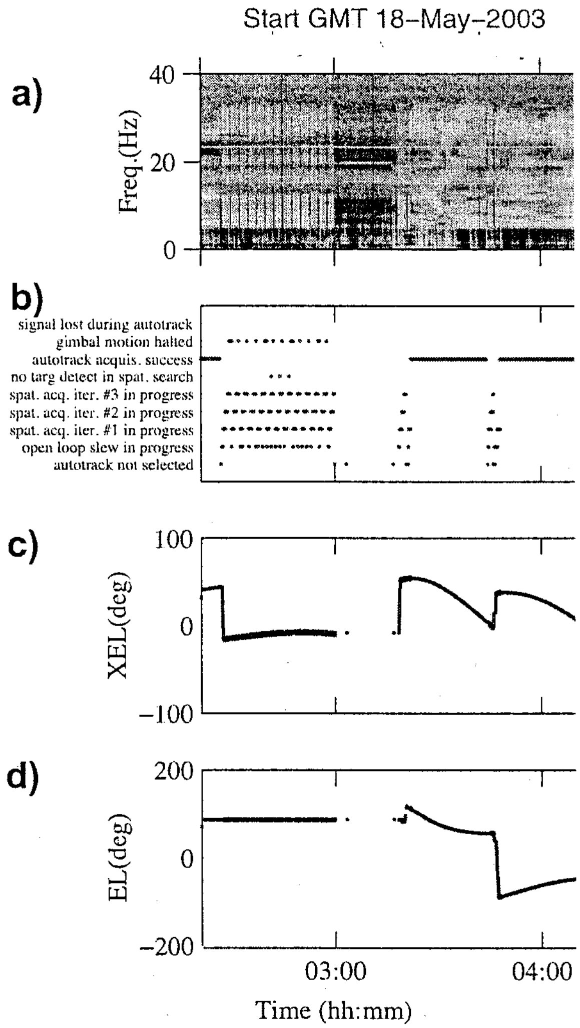

Figure 5. **Data showing correlation between microgravity environment signature and Ku-band antenna motion. a) Spectrogram segment of acceleration data; b) Ku-band antenna discrete data status; c) Ku-band antenna cross elevation pointing angle; and d) Ku-band antenna elevation pointing angle. Correlation is evident between the Ku-band antenna discrete data item *gimbal motion halted* and the "picket fence" feature in the acceleration spectrogram. (GMT 18 May 2003, 02:20-04:10)**

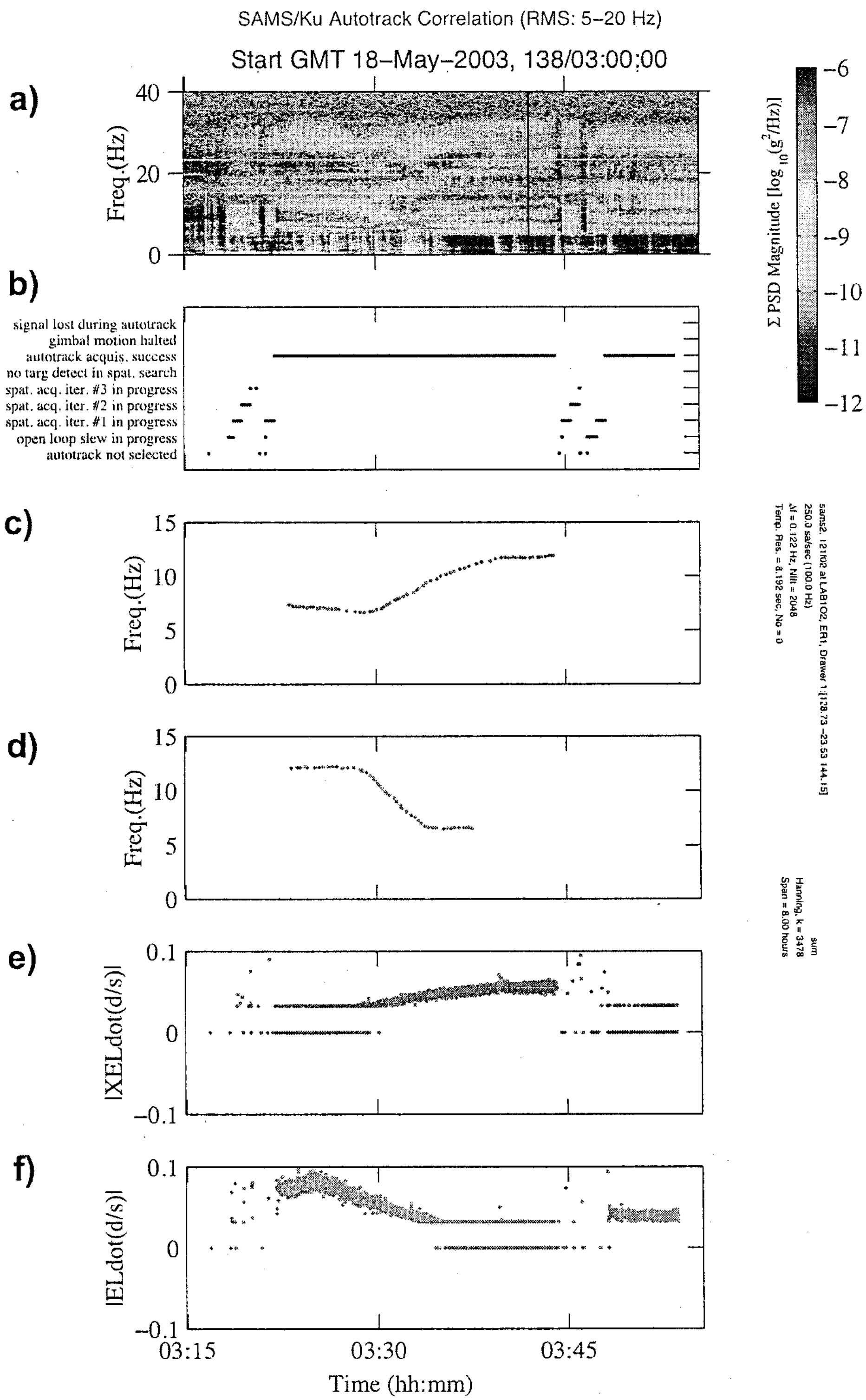

Figure 6. **Data showing correlation between microgravity environment signature and Ku-band antenna motion. a) Spectrogram segment of acceleration data; b) Ku-band antenna discrete data status; c) & d) extracted variable-frequency trace features from spectrogram; and e) & f) Ku-band antenna rate-of-rotation data. (GMT 18 May 2003, 03:15-03:55)**

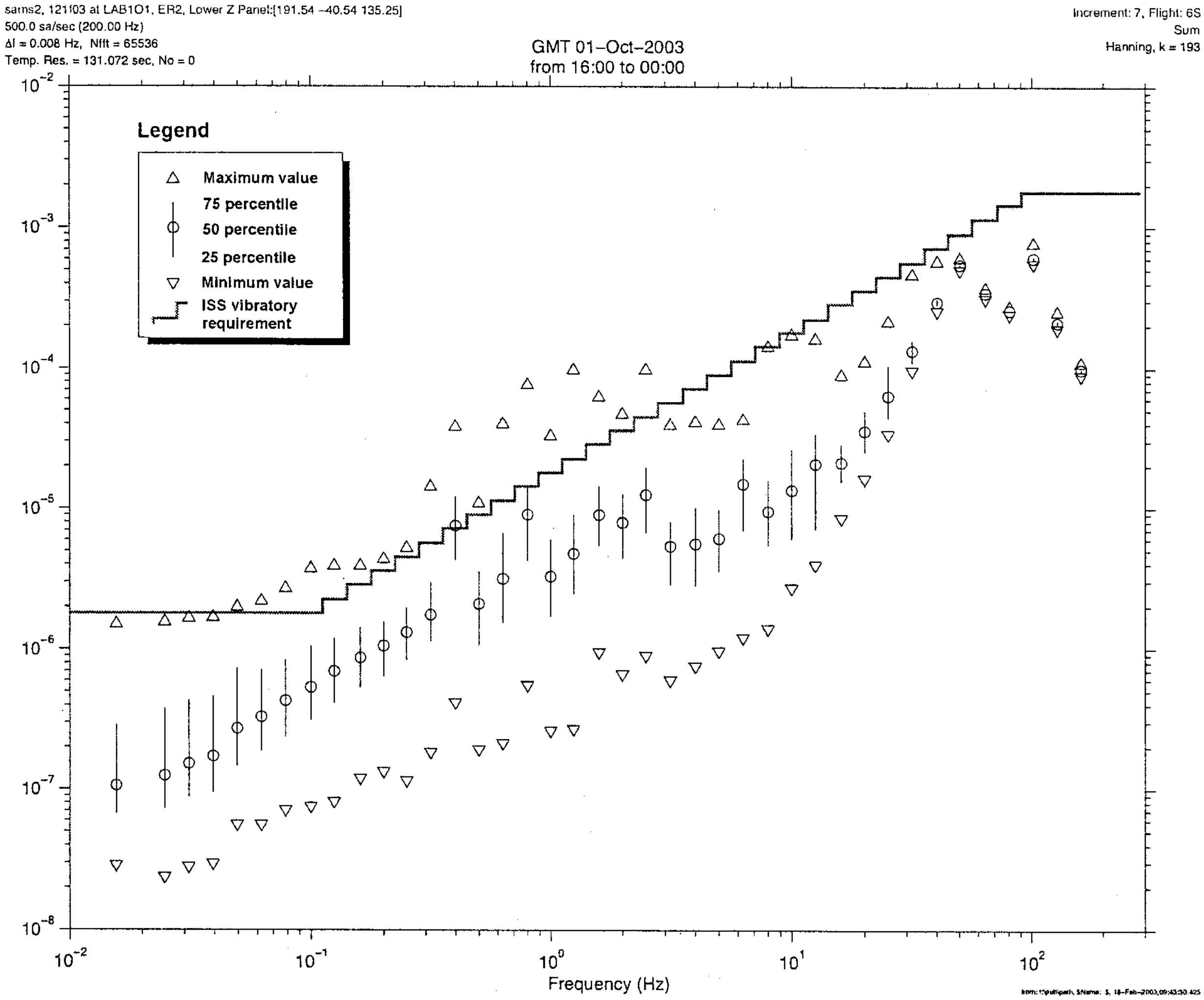

Figure 7. **One-third Octave Histogram plot for 1 October 2003, GMT 16:00-24:00 – This data plot shows the environment levels for an eight hour period calculated as a root-,mean-square values in one-third-octave frequency intervals as dictated by the ISS requirements. It can be seen that this nominal time period has levels below the maximum levels allowed by the requirements**