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SIMULATION OF SHUTTLE LAUNCH G FORCES AND ACOUSTIC LOADS USING THE NASA AMES RESEARCH CENTER 20G CENTRIFUGE

T. L. Shaw, J. M. Corliss, D. P. Gundo, G. M. Mulenburg

NASA Ames Research Center

G. A. Breit and J. B. Griffith

Bionetics Corporation

INTRODUCTION

The high cost and long times required to develop research packages for space flight can often be offset by using ground test techniques. This paper describes a space shuttle launch and reentry simulation using the NASA Ames Research Center's 20G centrifuge facility. The combined G-forces and acoustic environment during shuttle launch and landing were simulated to evaluate the effect on a payload of laboratory rats. The launch G force and acoustic profiles are matched to actual shuttle launch data to produce the required G-forces and acoustic spectrum in the centrifuge test cab where the rats were caged on a free-swinging platform. For reentry, only G force is simulated as the aero-acoustic noise is insignificant compared to that during launch.

The shuttle G-force profiles of launch and landing are achieved by programming the centrifuge drive computer to continuously adjust centrifuge rotational speed to obtain the correct launch and landing G forces. The shuttle launch acoustic environment is simulated using a high-power, low-frequency audio system. Accelerometer data from STS-56 and microphone data from STS-1 through STS-5 are used as baselines for the simulations. This paper provides a description of the test setup and the results of the simulation with recommendations for follow-on simulations.

REQUIREMENTS

The two major simulation requirements were to subject a group of laboratory rats to an accurate re-creation of: 1) the principal acceleration component at a given location on the payload; and 2) the matching acoustic environment of the shuttle mid-deck, simultaneously. In addition, video tape recordings and temperature data were required. The rats were housed in simulated shuttle Animal Enclosure Modules (AEMsim). Reentry simulation occurred 9 days after launch. During the 9 day interim period the animals were housed in an animal holding room.

G Force Requirements

The orientation and coordinate system for the shuttle and the AEMsims carried in the middeck is shown in Figure 1. The principal acceleration component is in the nose to tail (G_x) direction during launch and in the floor to ceiling (G_Z) direction during reentry. The G forces to be simulated were from crew cabin accelerometer data taken during the STS-56 mission (Figures 2 and 3). Within a cab of the 20G Centrifuge, two simulated AEMsims were mounted on the swing platform as show in Figure 4. It was desired to develop a centrifuge rotation rate profile which accurately (±1%) simulated the principal acceleration at a fixed point on the AEMsims.

Acoustic Requirements

The objective of the acoustic testing was to provide a sound environment representative of the space shuttle mid-deck during launch. Microphone data from shuttle missions STS-1 through STS-5 were used to develop sound pressure level spectra for the lift-off and aeronoise portions of launch. The graphs represent the maximum sound pressure level experienced during these three portions of launch.

METHODS

The NASA Ames Research Center's 20G centrifuge consists of a truss work arm approximately 56 feet long, supported on a vertical shaft at the center. Cab enclosures are situated at both ends of the rotating arm, each centered 25 feet from the rotational axis. In addition a short radius cab is located near the center. Two AEMsims were mounted side-by-side on a balanced free-swinging platform (arm length 14 in) positioned at the center of one end cab.

The resultant G force, G_R, provided by the centrifuge is the vector sum of the centripetal force due to centrifuge rotation about its central axis (G_C), and Earth's gravity (g). This is the acceleration acting on the swing platform. Because is assumed perpendicular to the floor of the swing platform, the orientation of the AEMsims on the platform was changed from launch ($G_R = G_X$) to reentry ($G_R = -G_Z$) to account for the difference in principal acceleration direction between the two shuttle profiles.

Centrifuge G Profile Development

To provide the correct G profile to the animals in the AEMsims, a computer-generated rotational velocity profile for the centrifuge was created based upon STS-56 crew cabin accelerometer data (Figures 2 and 3). All profile development was performed using routines developed in the C language on a 33 MHz i486-based microcomputer. The data were spline interpolated to 10 Hz required for the drive command software. Accelerations less than one g were truncated at 1.01g for the simulation. The desired resultant g data was then translated to centrifuge velocity command voltages and the drive computer software data file generated.

A mathematical model was developed to predict the rpm/resultant g relationship, taking into account the pitch angle of the swing platform. As an approximation, the top surface of the swing platform is assumed to align itself perpendicular to the direction of the local resultant acceleration vector G_R. A numerical root finding algorithm was employed to determine a hypothetical set of angle data for each rate for a range of rotation rates. Given the radial position on the swing platform assembly at which the acceleration was to be modeled, a hypothetical resultant acceleration versus rotation rate data set was generated. To create a simple expression for rotation rate as a function of desired acceleration, this data set was fit to a two parameter model. The model is based on the relationship between rotation rate and the resultant acceleration present at a fixed radius on the centrifuge. This approximation expression allowed calculation of the centrifuge rotation rate necessary to generate a desired resultant acceleration at the measurement site on the swing platform.

Instrumentation

The resultant acceleration was measured using ±5g Systron Donner 4855 accelerometers which have voltage outputs proportional to acceleration. The voltage signals were passed through an L&M Electronics optical isolation amplifier with unity gain. The signals were then routed through the Centrifuge slip rings and through a patch panel to the data acquisition computer, a video panel meter and a digital voltmeter display. The temperature inside the AEM simulation unit was also recorded via the same routing scheme using a Newport RTD-805/N gas and air temperature probe. The RTD signal was sent through a Newport INFCR Infinity C Programmable Digital RTD Controller and converted to a voltage before being sent through the Centrifuge slip rings. The data acquisition computer was a Hewlett Packard 486/66 with a National Instruments AT-MIO-64F-5 Multifunction I/O board. A data logger program written in National Instruments LabWindows software was used to acquire the acceleration and temperature signals. The data logger provided user selection of the required number of channels, sampling rate, and averaging.

The video camera was mounted to provide a view of one of the cages throughout each run of the Centrifuge. The video signal was routed through slip rings to a video panel meter. The video panel meter combined digital displays of the accelerometer and temperature signals along with the video signal. From the video panel meter these signals were then sent through a video cassette recorder (VCR) and displayed on a video monitor to allow for viewing and recording. This information was saved on 1/2 inch VHS tape using the VCR. A block diagram representation of the accelerometer, temperature and video signal pathways is shown in Figure 5.

Development of Acoustic Timeline for Launch

Since no two shuttle launches are identical, the data from missions STS-1 through STS-5 were averaged to provide a representative acoustic spectrum. Figures 6 and 7 show plots of the microphone data for the lift-off and aeronoise portions for the five launches, as well as the average spectra used for the simulation. The lift-off portion of launch has the higher overall level, 107.6 dB, as compared to the aeronoise portion of launch at 102.6 dB. While both spectra have strong low-frequency components, the aeronoise spectrum has stronger components in the high-frequency regime indicative of aerodynamic noise during high-velocity flight.

After developing the representative acoustic spectra for lift-off and aeronoise, it was necessary to determine how these spectra should be allocated along the launch timeline. For the simulation, the duration of a shuttle launch was defined to be 524 seconds. The launch timeline follows the basic sequence of events listed below (times are approximate).

Table 1: Launch Timeline

TIME (secs)	EVENT
0	Lift-off start
100	Solid Rocket Booster Burnout
120	Solid Rocket Booster Separation
450	3-g Throttle back
514	First Main Engine Shut-down
524	End of launch

The basic philosophy for the simulation is to apply the lift-off acoustic spectrum from Lift-off Start to SRB Burnout (t=0 secs to 100 secs), and to apply the aeronoise spectrum from SRB Separation to the First SSME Shut-down (t=120 secs to 514 secs). Throughout an actual launch the overall sound pressure level varies with throttle changes, velocity changes, and other variable conditions. For the 20G Centrifuge simulation, the maximum 107.6 dB lift-off level and 102.6 dB aeronoise level is held constant throughout the respective portions of the launch. This is primarily because the supplied microphone data does not contain any time history data applicable to the shuttle mid-deck. Taking all of these factors into account, an acoustic timeline for launch was developed for the simulation and is shown in Figure 8.

Acoustic Equipment

A high power, low frequency sound system was designed and installed to reproduce the lift-off and aeronoise acoustic spectrums. The primary components of the acoustic system are shown in Table 2. The Hewlett-Packard analyzer, Rane equalizers, and QSC amplifier were located in the control room of the 20G centrifuge facility. The Electro-Voice speaker and B&K microphone were located in the centrifuge test cab in close proximity to the AEMsims.

Table 2: Primary Acoustic Equipment

Hewlett-Packard 35665A Dual-Channel Dynamic Signal Analyzer
Rane GE30 Interpolating Constant-Q Graphic Equalizer (1/3 Octave)
Rane MPE-28 Programmable Equalizer
QSC 1700 Power Amplifier (325 Watts/channel)
Electro-Voice TL3512 Very-Low-Frequency Speaker System
B&K 1/2" Microphone with Power Supply and Pre-Amp
University Sound DWS-100 Wireless Microphone System

The Hewlett-Packard analyzer generated a pink noise signal which was conditioned by the two Rane equalizers and QSC amplifier to produced the required acoustic spectrum inside the centrifuge test cab. The programmable equalizer was pre-programmed with seven spectra which were designed and timed throughout the launch simulation to compensate for changes in the acoustic response of the test cab. These changes in the test cab's acoustic response were due to the varying angle of the swing platform as the G-forces changed. The acoustic spectra inside the test cab was monitored in real time with the Hewlett-Packard signal analyzer. The set-up of the acoustic system is diagrammed in Figure 9.

RESULTS

G Force Results

Representative plots of acceleration data for launch and reentry simulations are shown in Figures 10 and 11 respectively with corresponding STS-56 profiles overlaid. The greatest percentage error occurred at the peaks of acceleration, particularly at the higher levels of acceleration - end of launch, and at where the rate of change of acceleration is greatest - beginning of launch (Figure 10). The average percentage error for the last plateau of the launch profile was calculated to be 0.77%. Error present in the reentry simulations were less than for launch (Figure 11).

Acoustic Results

The acoustic data recorded during the test included: 1) the overall dB level inside the centrifuge test cab; and 2) the acoustic spectrum for the lift-off and aeronoise portions of launch.

Overall dB Levels

The overall dB level inside the centrifuge test cab during each test was continuously recorded from the display of the HP 35665A signal analyzer by video camera. This data was later recorded from the video tape into spreadsheet format and is plotted in Figure 12. The overall dB level for each test was held very closely to the test requirements. For the lift-off portion of launch the maximum difference between the as-tested sound pressure level and the test requirement was 1.3 dB t=10 seconds. For the aeronoise portion of launch the maximum difference between the as-tested sound pressure level and the test requirement was 1.0 dB from t=185 seconds to t=190 seconds.

Frequency Spectra

Traces of the acoustic frequency spectra were recorded from the HP 35665A signal analyzer. For each test group, the data from individual time intervals was averaged for both the lift-off and aeronoise portions of launch. The resultant averaged spectra for lift-off and aeronoise are shown in Figures 13 and 14 respectively. The as-tested acoustic spectra closely matched the test requirements and repeated very well between test groups. For both the lift-off and aeronoise spectra the largest deviation from the test requirements occurred at a frequency of 63 Hz. For lift-off the maximum deviation was 4.0 dB and for aeronoise the maximum deviation was 3.2 dB. Note that these deviations are only at one specific frequency band, and that the overall sound pressure level in the centrifuge test cab was consistent with the test requirements.

RECOMMENDATIONS

Development of the centrifuge rotation profiles required mathematical modeling of the relationship between rotation rate and resultant acceleration at a fixed point on the swing platform.

Although this approach yielded satisfactory results, it was nevertheless subject to assumptions about the underlying mechanics. A closed-loop control system utilizing feedback from an accelerometer mounted on the swing platform would bypass the necessity to rely on such approximations, allowing for direct simulation of a desired acceleration profile.

Adding vibration to the simulation would significantly increase the realism. This was investigated for this study, but due to schedule and budget constraints, it was not feasible to include. Single axis vibration, especially during launch simulation, could provide important additional information.

LIST OF FIGURES

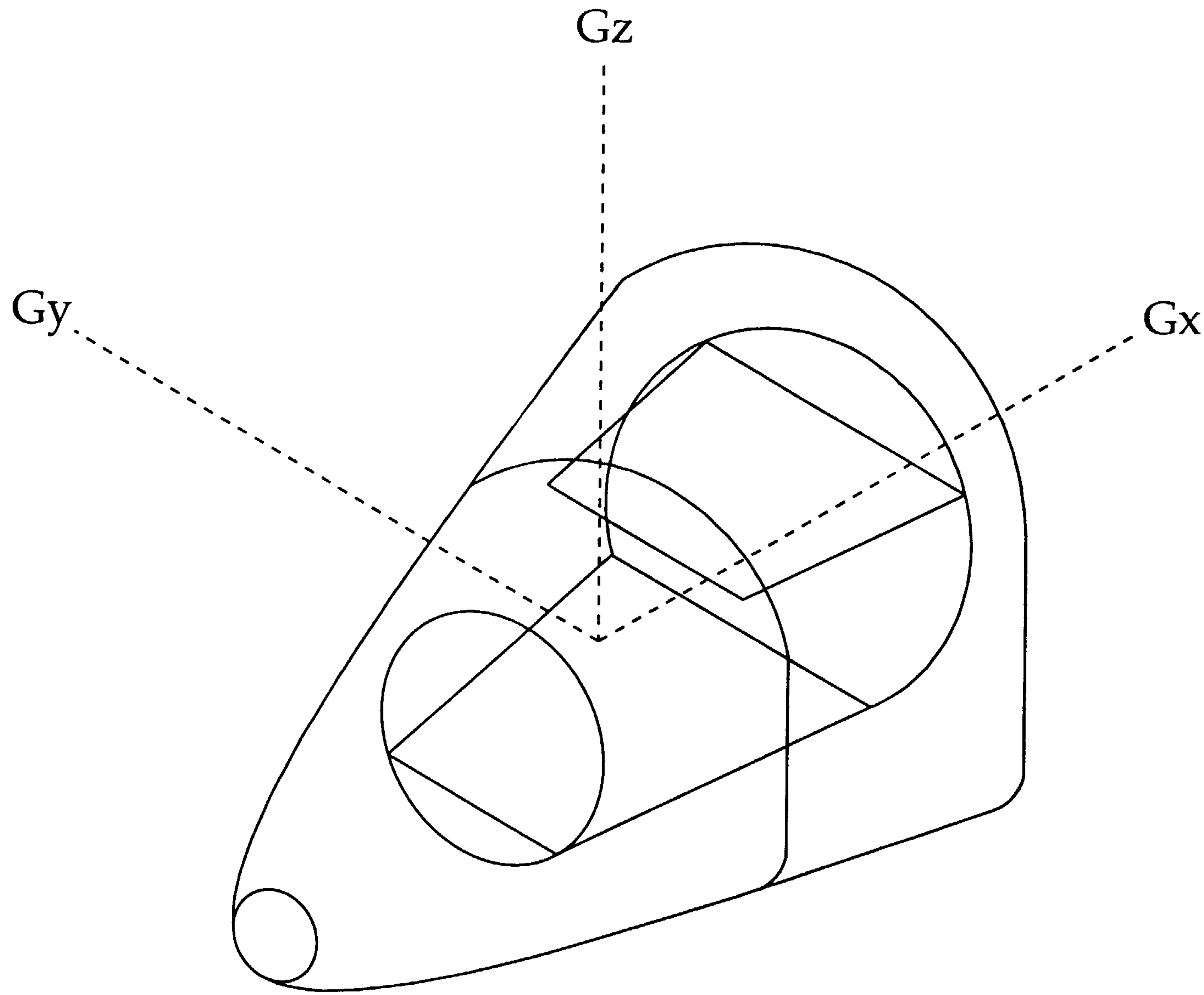


Figure 1: STS Axes Orientation

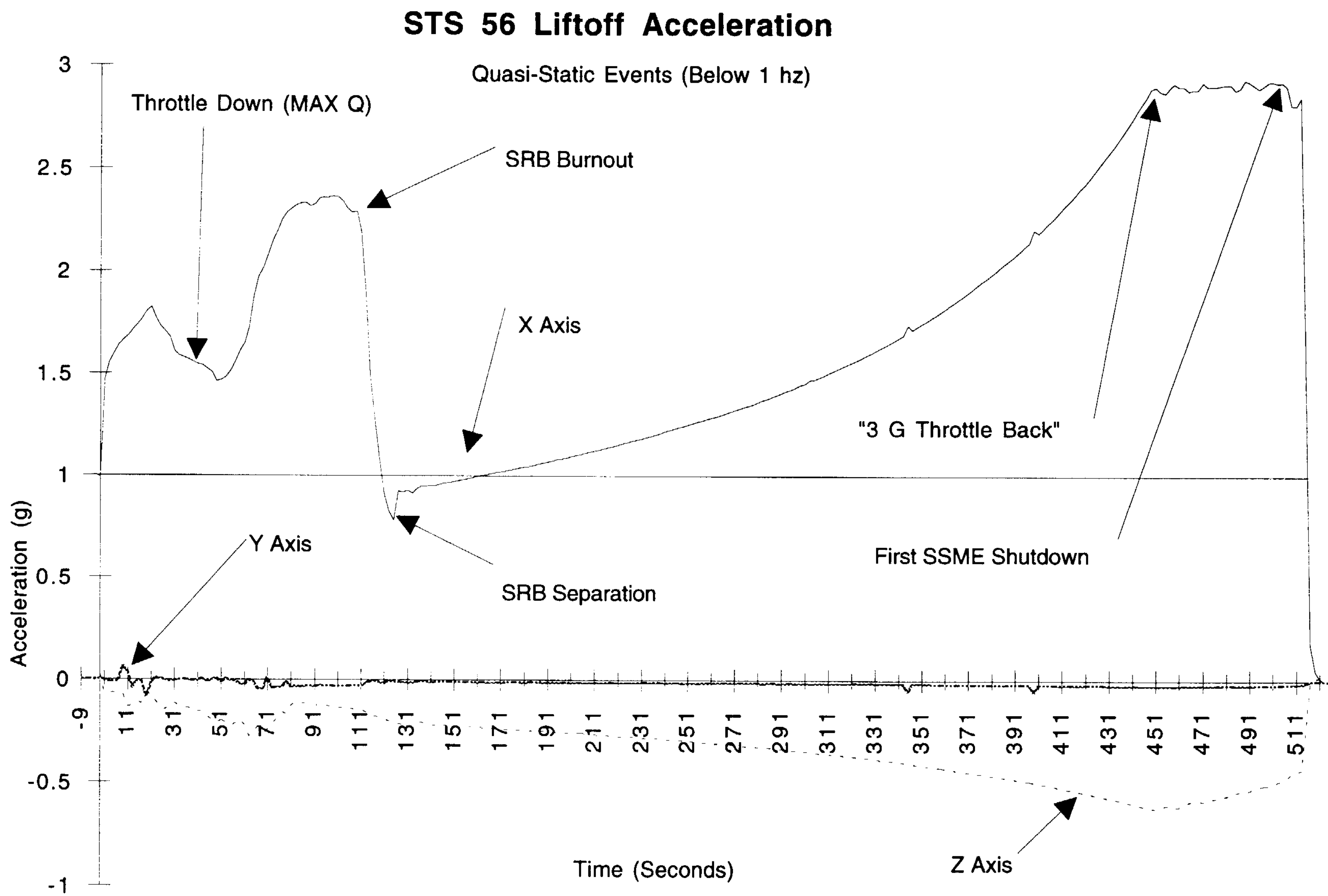


Figure 2: STS-56 Crew Cabin Acceleration During Launch

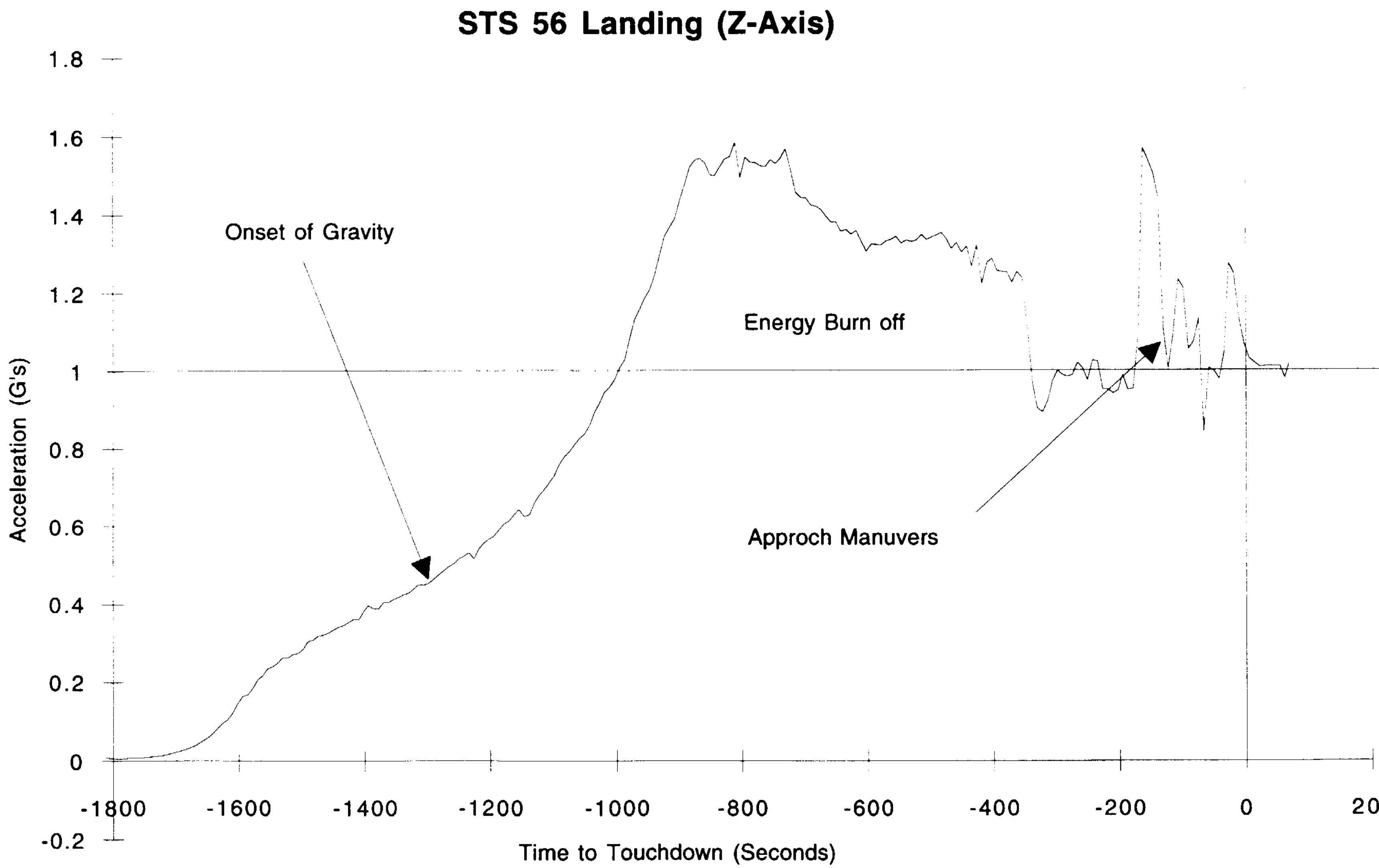


Figure 3: STS-56 Crew Cabin Acceleration During Reentry

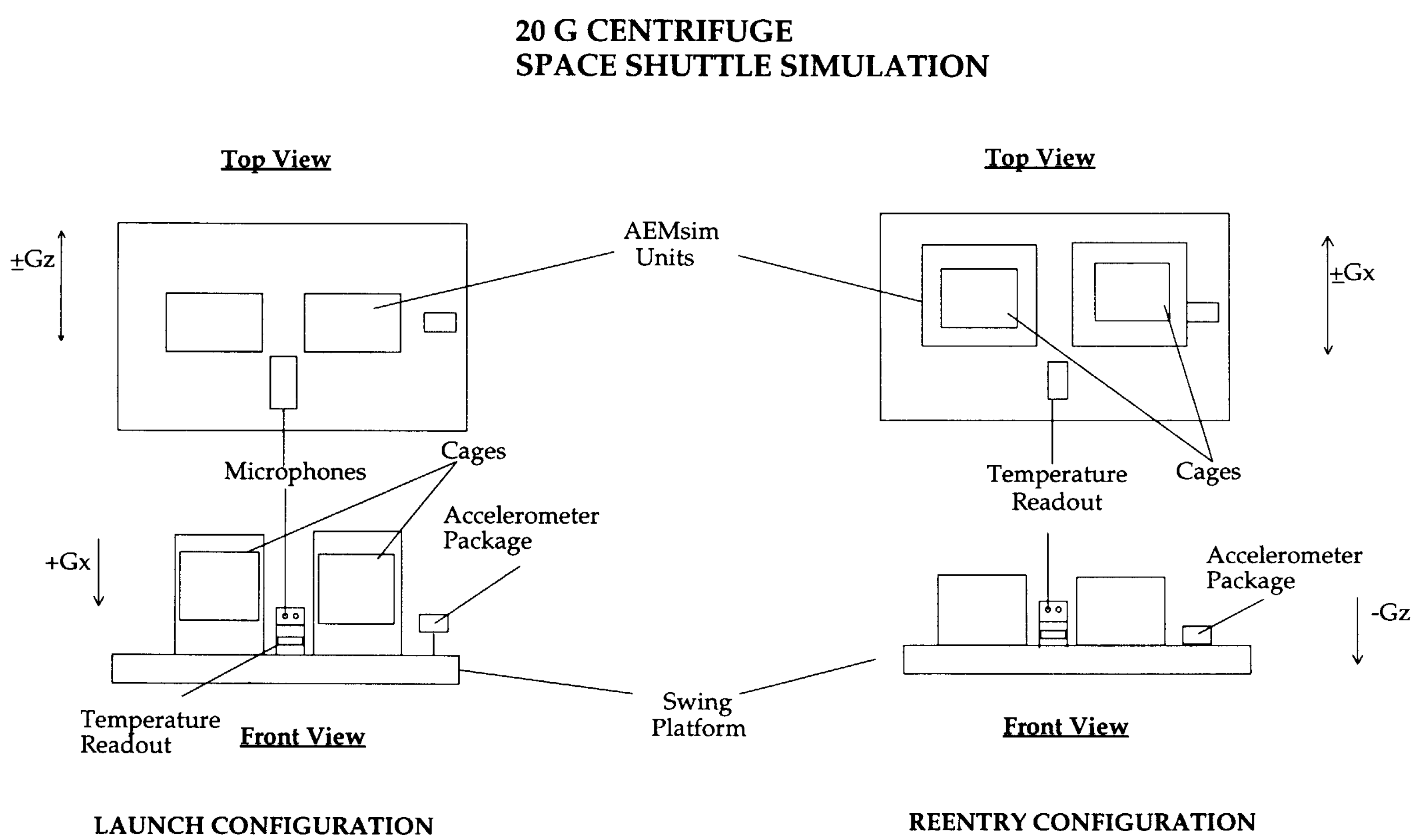


Figure 4: Simulated Animal Enclosure Modules Launch and Reentry Configurations

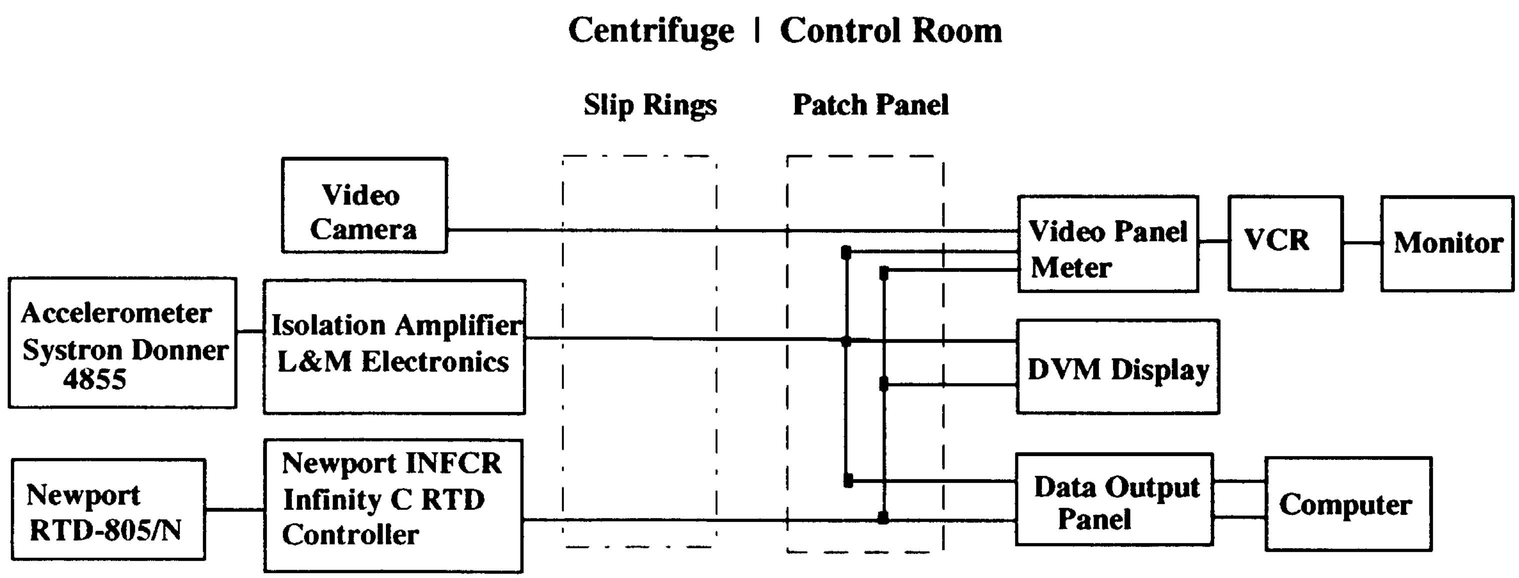


Figure 5: Block Diagram of Data Acquisition System

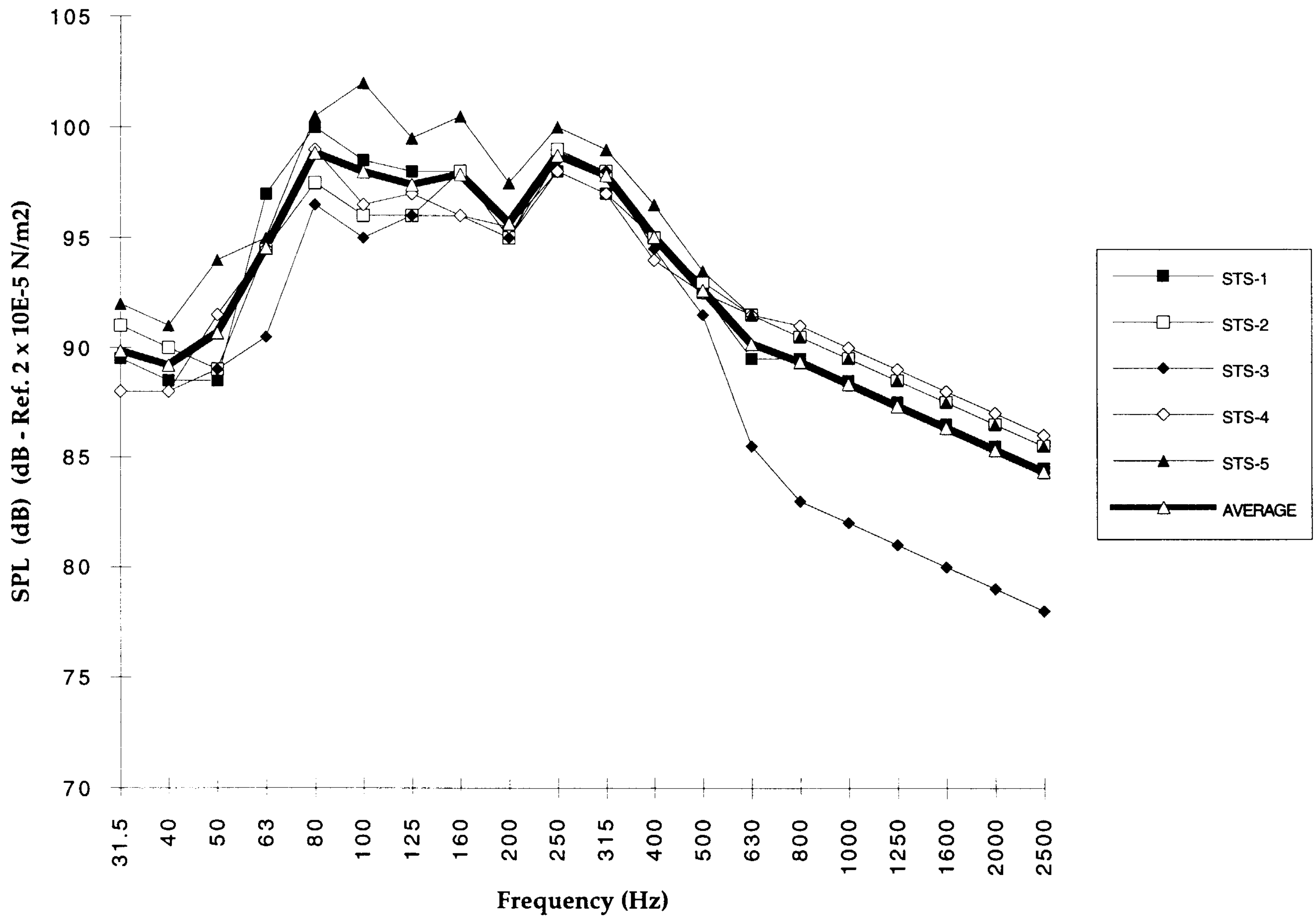


Figure 6: Lift-Off Acoustic Spectra

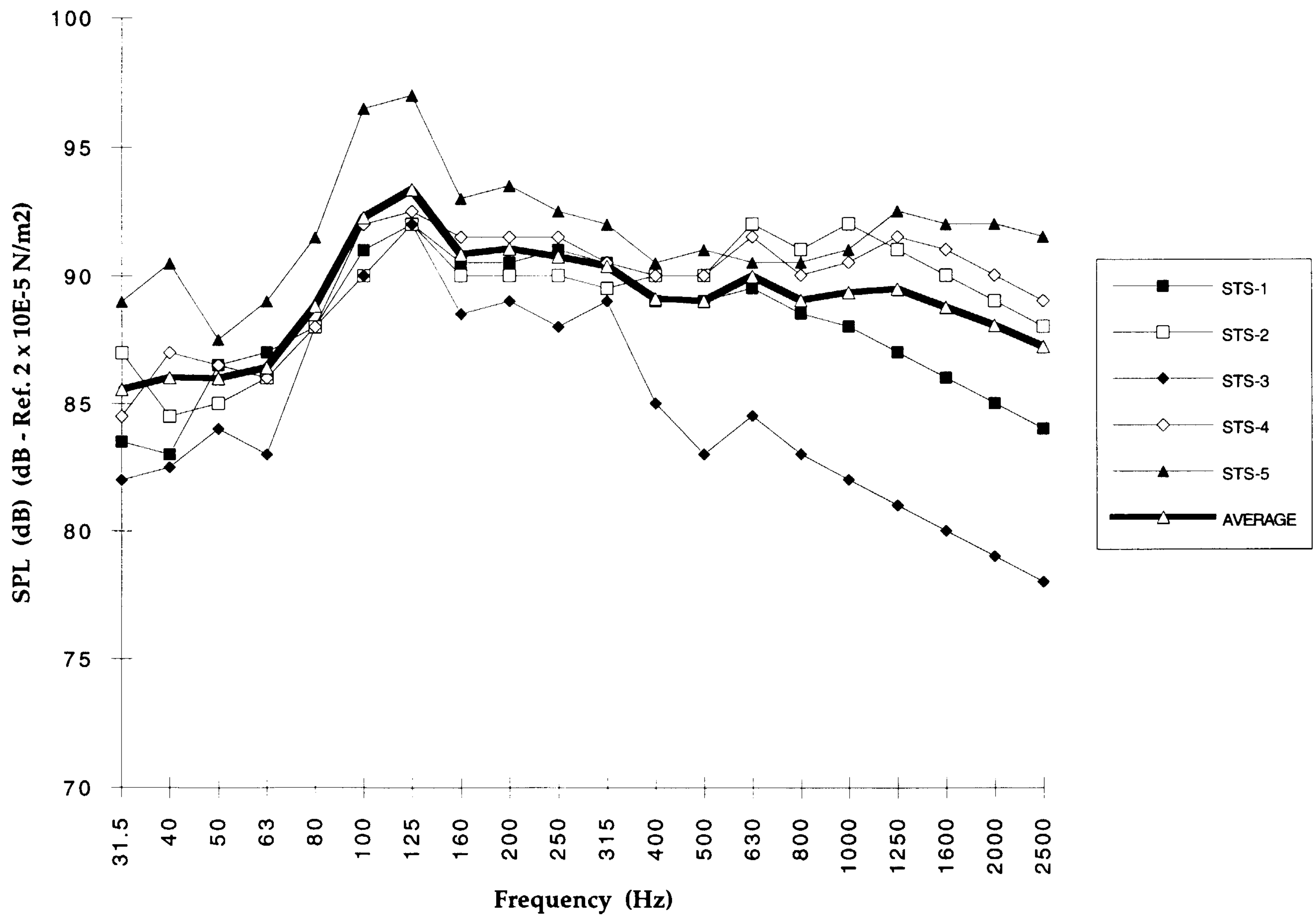
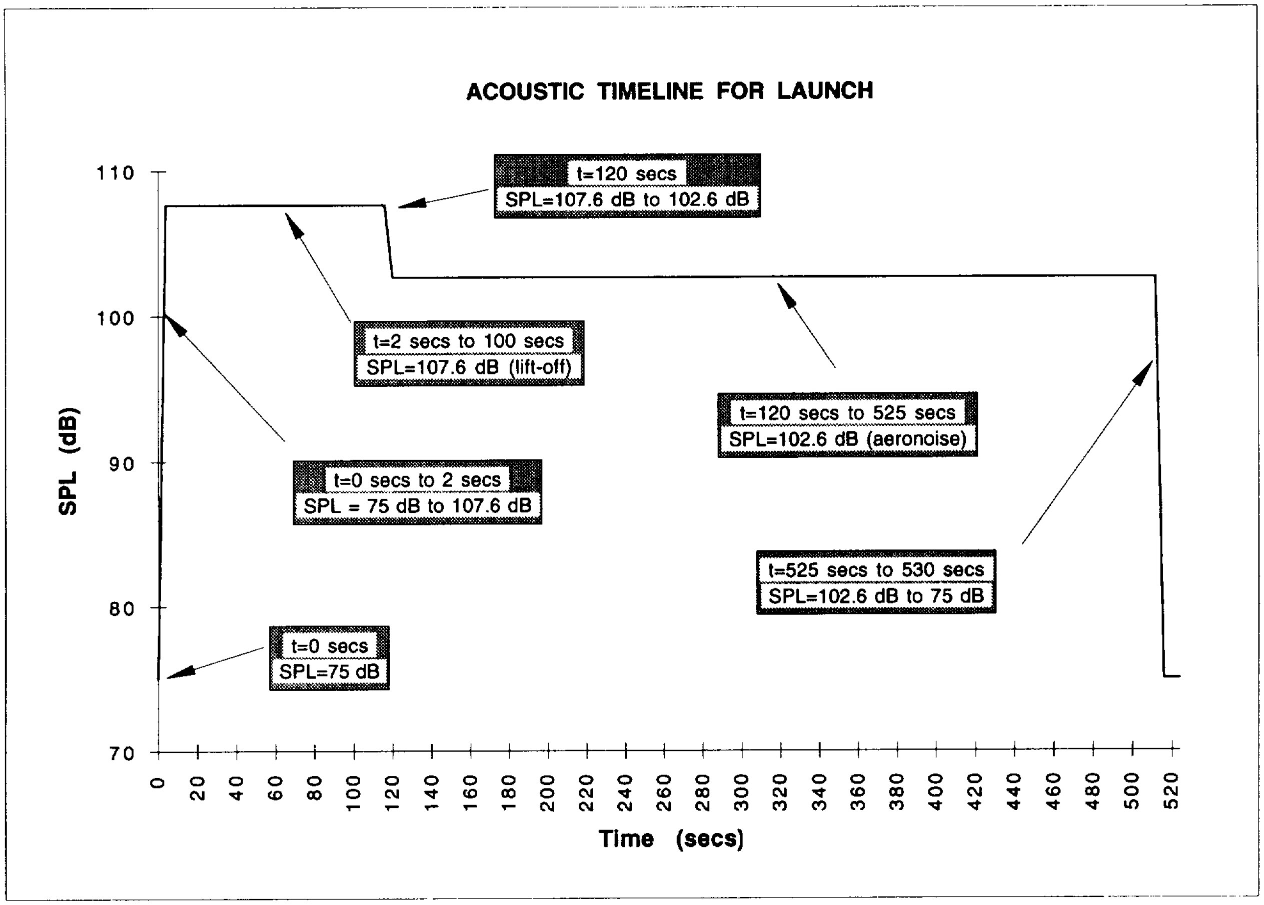


Figure 7: Aeronoise Acoustic Spectra



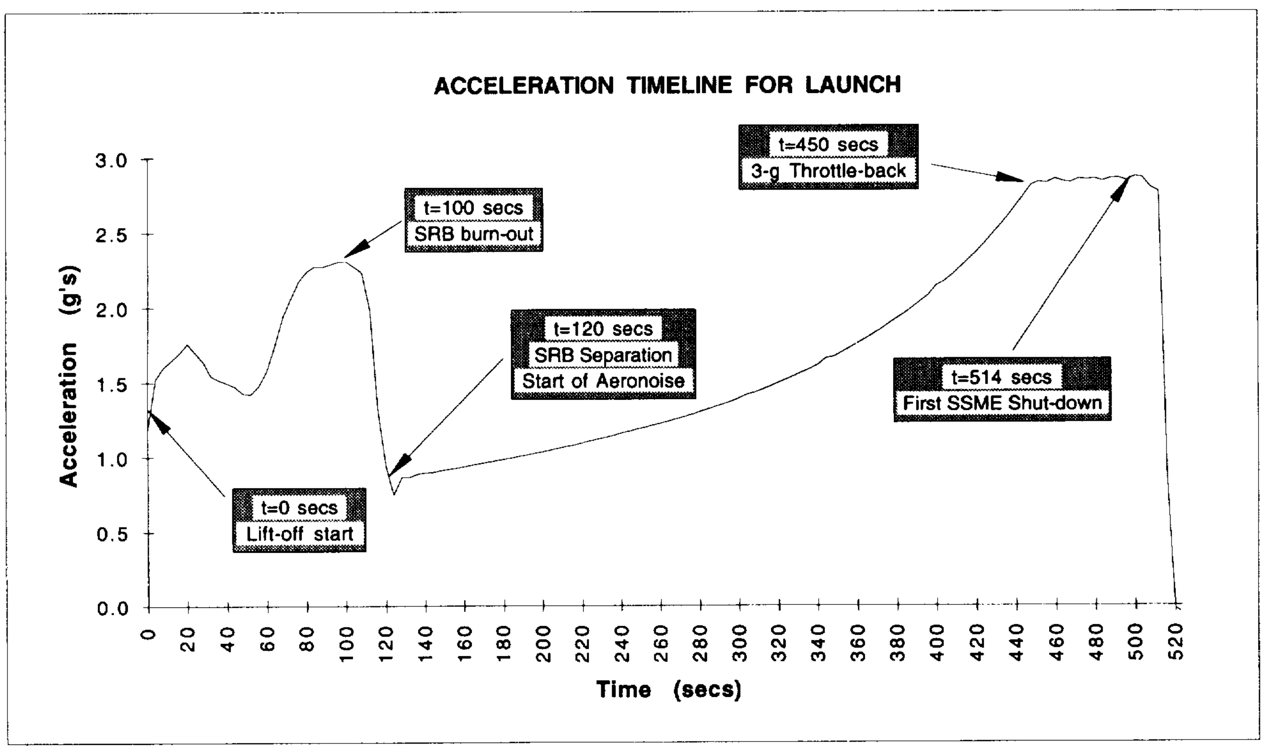


Figure 8: Acoustic Timeline for Launch

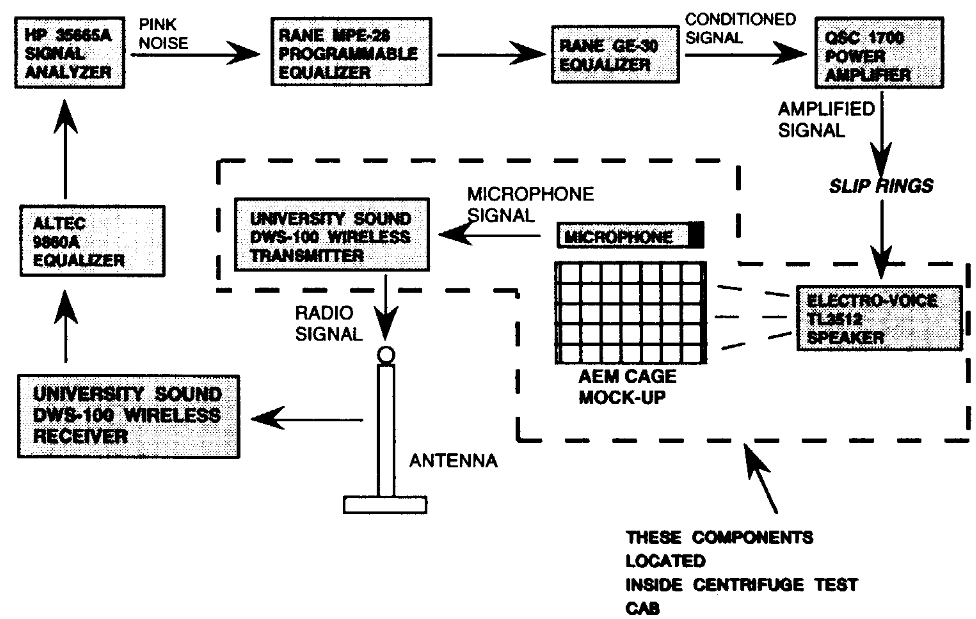


Figure 9: Acoustic System Set-up

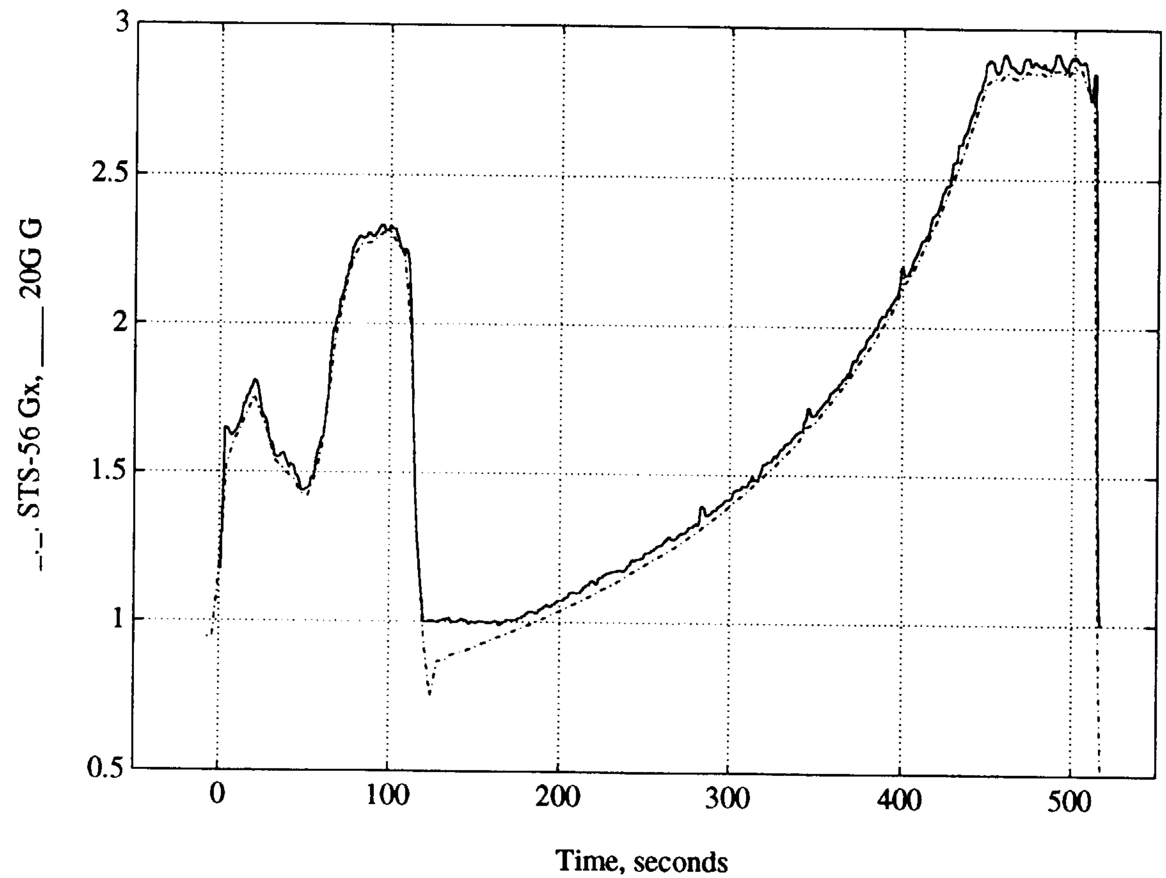


Figure 10: Launch Simulation Acceleration and STS-56 Launch Profiles

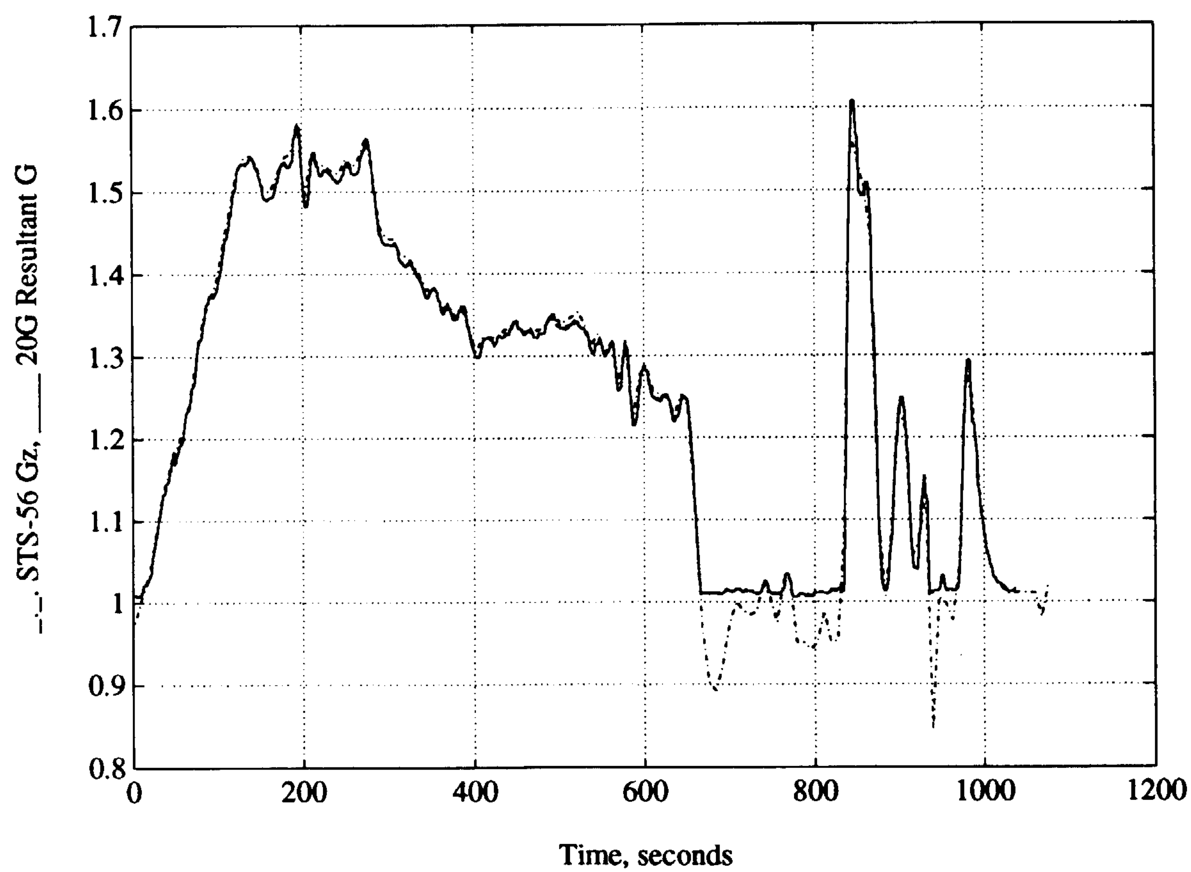


Figure 11: Reentry Simulation Acceleration and STS-56 Reentry Profiles

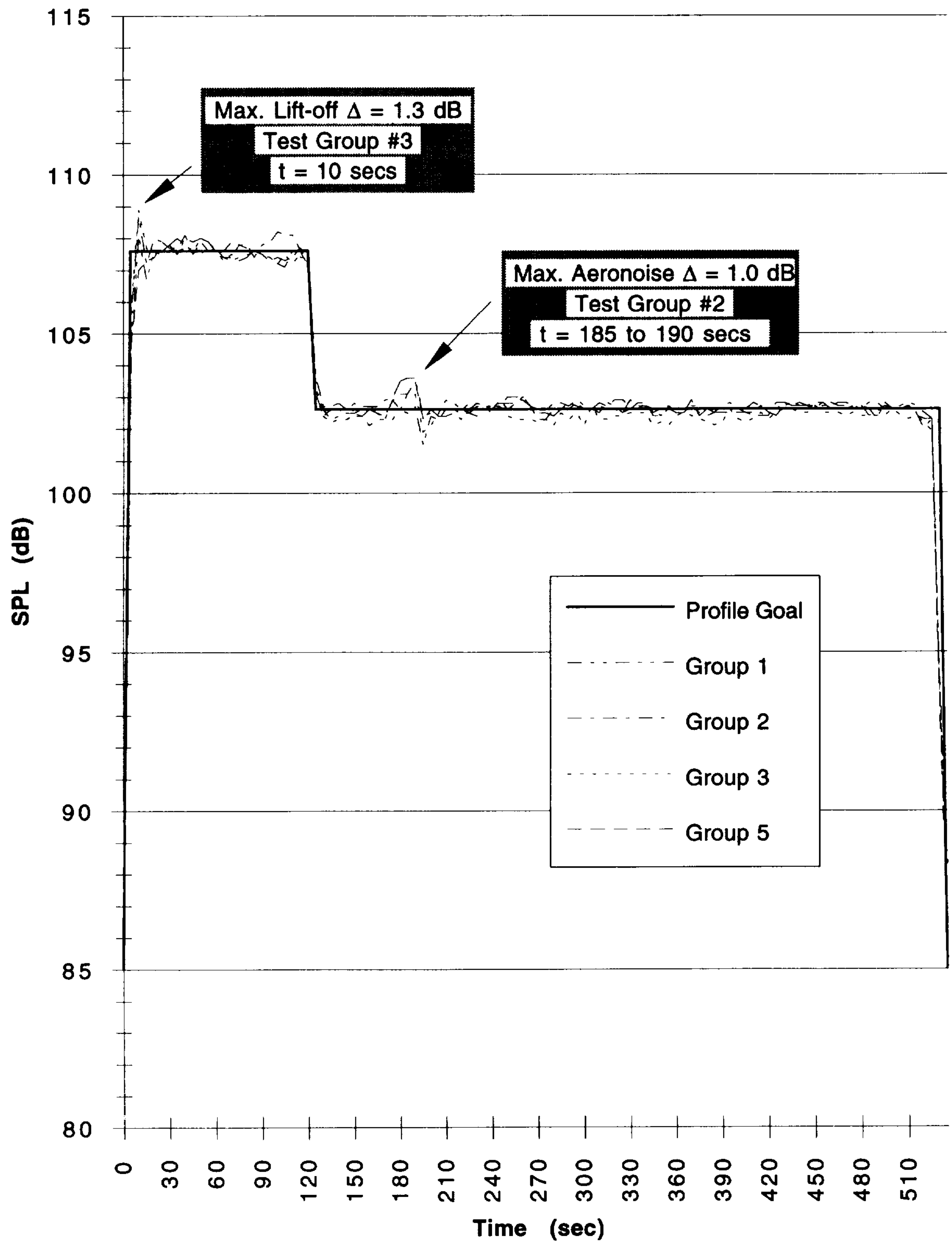


Figure 12: As-tested Overall dB Levels

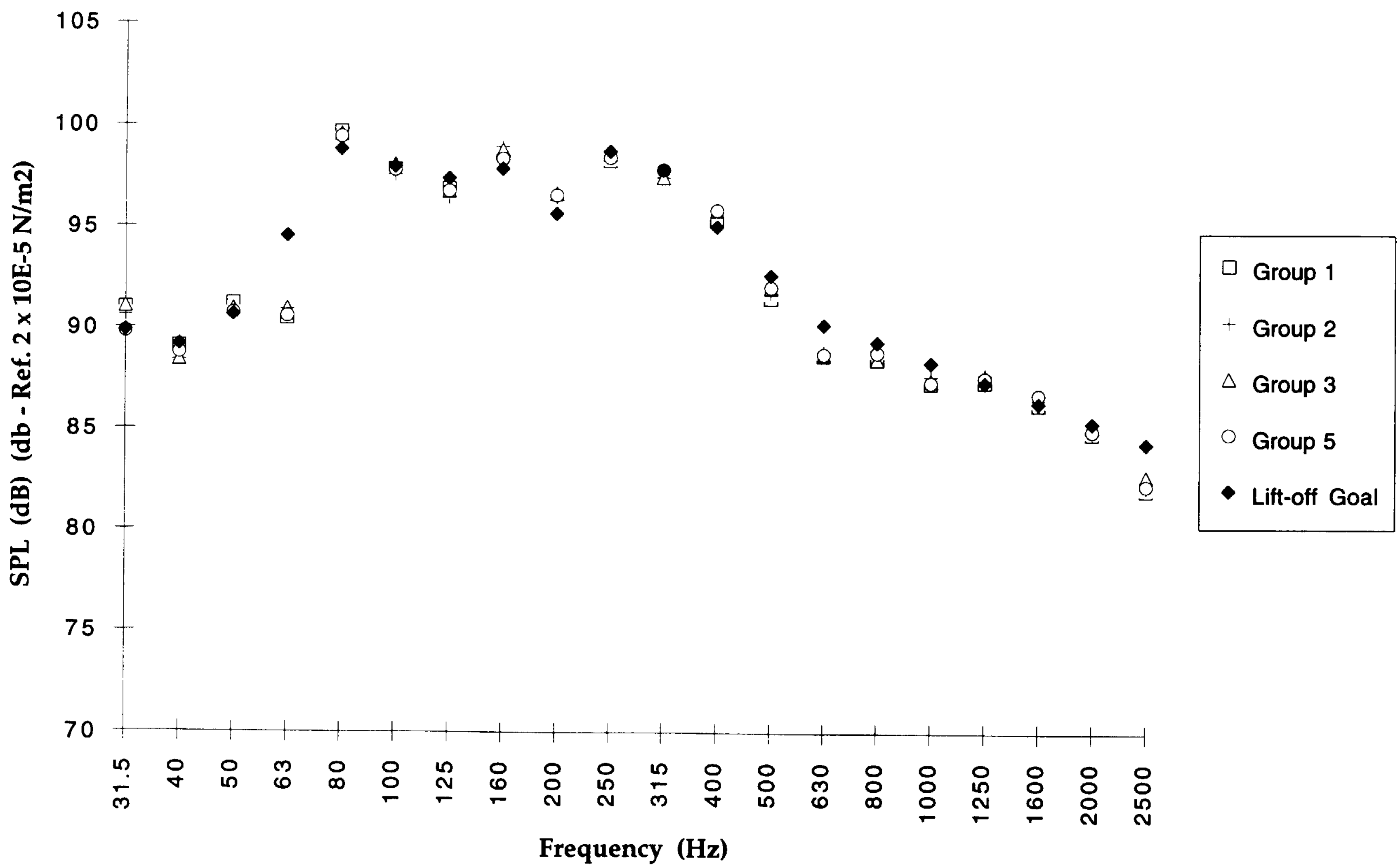


Figure 13: Summary of As-Tested Lift-Off Spectra

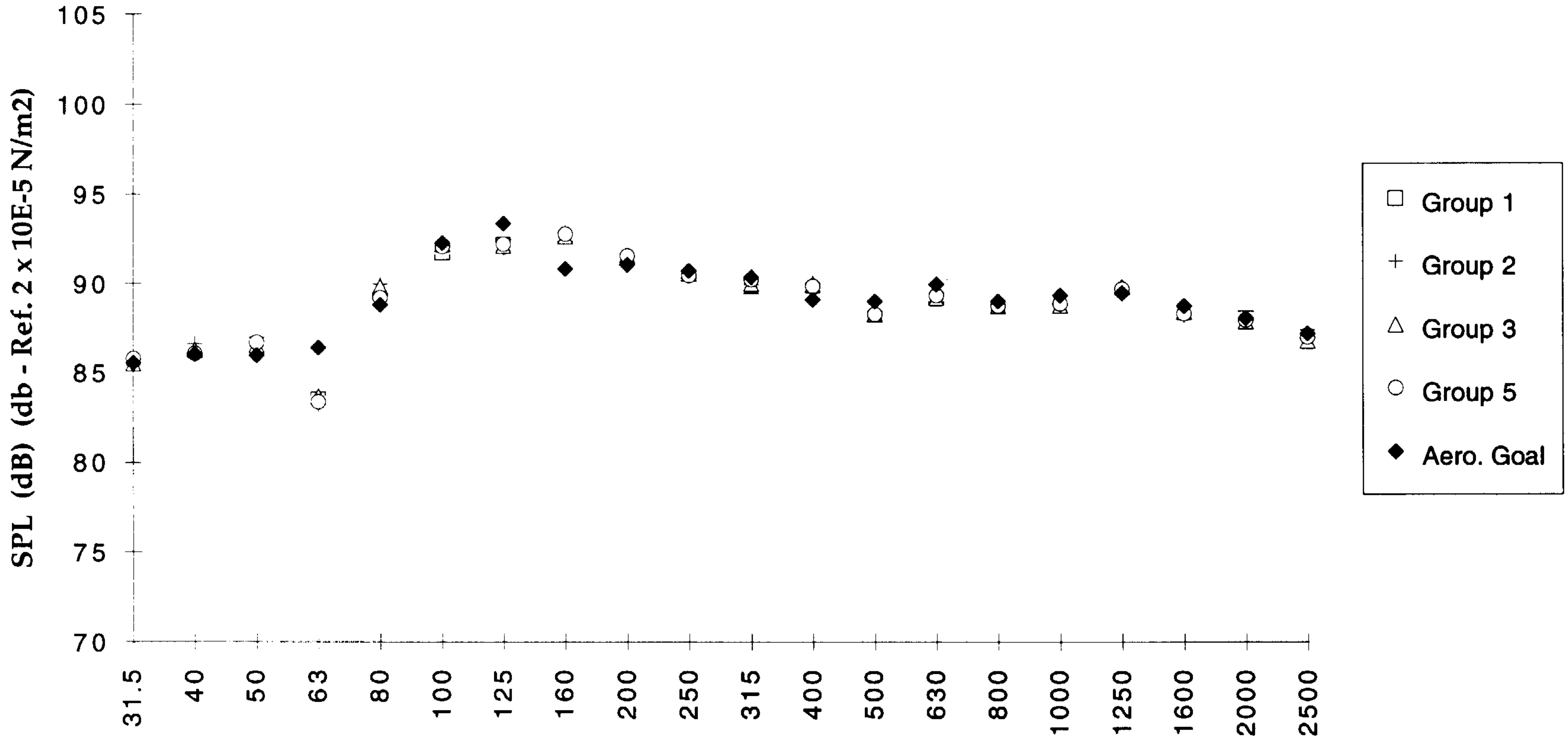


Figure 14: Summary of As-Tested Aeronoise Spectra