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SIMULATION OF THE DYNAMIC ENVIRONMENT FOR MISSILE COMPONENT TESTING: DEMONSTRATION

FINAL REPORT

KURNG Y. CHANG

SEPTEMBER 1989

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
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FOR MISSILE COMPONENT TESTING (DEMONSTRATION)

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The problems in defining a realistic test requirement for missile and space vehicle components can be classified into two categories: (1) definition of the test environment representing the expected service condition, and (2) simulation of the desired environment in the test laboratory. Recently, a new 3-Dimensional (3D) test facility was completed at the U.S. Army Harry Diamond Laboratory (HDL) to simulate triaxial vibration input to a test specimen. The vibration test system is designed to support multi-axial vibration tests over the frequency range of 5 to 2000 Hertz. The availability of this 3D test system motivates the development of new methodologies addressing environmental definition and simulation.

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INTRODUCTION

The problems in defining a realistic test requirement for missile and space vehicle components can be classified into two categories: (1) definition of the test environment representing the expected service condition, and (2) simulation of the desired environment in the test laboratory. Recently, a new 3-Dimensional (3D) test facility was completed at the U. S. Army's Harry Diamond Laboratory (HDL) to simulate triaxial vibration input to a test specimen. The vibration test system is designed to support multi-axial vibration tests over the frequency range of 5 to 2000 Hertz. The availability of this 3D test system motivates the development of new methodologies addressing environmental definition and simulation.

The Jet Propulsion Laboratory, sponsored by the U. S. Army Research Office, and in conjunction with the U. S. Army Laboratory Command, Harry Diamond Laboratories, is conducting a research program to investigate some of the fundamental issues of using a three axis excitation system for the qualification of missile components (JPL Task Plan 80-2212). These investigations have two objectives. One is to better understand the physics of the three axis vibration exciter by developing the theory and relating it to methods used for defining test specifications for unidirectional excitation. The second is to develop three dimensional test specifications for several components. This report documents some of the results obtained to date. Specifically, Chapter I discusses the development of three-dimensional random vibration test requirements, Chapter II develops a 3D transportation vibration test requirement for the M732 safe and arm module, and Chapter III develops 3D random vibration test requirements for the Patriot missile fuze. Appendix A provides background on the methodology for determination of dynamic test requirements and Appendix B provides a bibliography of papers and reports relevant to development of 3D vibration test requirements.

CHAPTER I

DEVELOPMENT OF THREE-DIMENSIONAL RANDOM VIBRATION TEST REQUIREMENT

INTRODUCTION

Vibration testing has been widely recognized as a viable means of identifying hardware defects as well as for qualification of hardware design relative to service environments. Traditionally, vibration tests have utilized one-axis at-a-time or one-dimensional (1-D) motion. Using 1-D motion to simulate and to test for the real excitation environment is of questionable validity. "Real world" environments involve three dimensional (3D) motions. In the 1980's, attention has been focused on using random vibration as an effective means for stress screening to improve the quality and reliability of electronic parts. Many standards concerned with vibration testing require such testing to be multi-axial. To meet these requirements, test systems capable of either synchronized or unsynchronized multi-axial vibration motion have been developed. Multi-axial simultaneous shakers have been shown in at least one case to produce more realistic vibration inputs, and to successfully precipitate flaws that had remained hidden with the conventional 1-D shakers, thus contributing to an improvement in overall program cost savings (Reference 1). Stress screen vibration testing is product-dependent and attempts to detect defective parts that might fail in the field environment, rather than to simulate the characteristics of actual field conditions.

Ideally, the laboratory test should duplicate the 3D service environment by duplicating the 3D time histories. However, this duplication is almost never achieved in practice, due mainly to the variability of the service environment and differences between the test and the service installation. Thus, it is intended to simulate the main characteristics of the service environment without undue overtesting or undertesting of hardware. The problem of realistic simulation of field environments can be classified into two categories: (1) definition of the test environment representing the expected service condition, and (2) simulation of the desired environment in the laboratory. Definition of the proper spectrum is one of the most important issues in any test program. In most previous programs the environment has been simulated with only one input axis at-a-time. The test spectrum is selected to envelope the service spectra, and the duration is selected based on an expected service life at that level. This practice typically results in conservative input levels and excessive test time due to serial multi-axial test requirements. Service environments are inherently 3D while environmental simulation by single-axis shakers tend to be rectilinear. Although all exciters exhibit some degree of cross-coupling, it cannot be consistently predicted nor controlled. Thus shakers either do not reproduce the proper dynamic coupling of the service environment or they induce cross-coupling in a frequency range and at a level that does not exist in service.

The recently completed HDL 3D-VTS is intended to test various components in 3D controlled environments (Reference 2). The system utilizes specially developed hydrostatic bearings to achieve maximum drive stiffness in each of three translational directions, with minimal cross-coupling between orthogonal directions. Through mechanical constraints, the test platform (TP), which is 19 inches square, can make these translational motions with all rotations constrained.

In random vibration testing operation, the TP oscillates in spatial directions determined by the control spectrum density matrix. This control matrix, Gxyz, contains 9 (3 X 3) terms for each frequency across the spectrum:

$$Gxyz = \begin{vmatrix} Gxx & Gxy & Gxz \\ Gyx & Gyy & Gyz \\ Gzx & Gzy & Gzz \end{vmatrix} \qquad (1)$$

Where Gxyz - control spectrum matrix
Gxx - Auto spectrum in x axis
Gxy - Cross spectrum between the x axis and y axis. etc.

The terms specified in Equation (1) are controlled by a real-time digital vibration control system within the following test tolerances.

Parameter	Frequency Range (Hz)	Tolerance
PSD amplitude	5-500	+/- 3 dB
	500-2000	+/- 6 dB
grms acceleration	5-2000	+/- 15%

The availability of this 3-D shaker system motives the development of new methodologies addressing environmental definition and simulation including the translating of 1-D test levels used in current vibration tests into equivalent 3D test levels.

DEVELOPMENT OF 3D TEST SPECTRUM MATRIX

If the field vibration environment can be described in terms of the 3D spectrum matrix at the interface point(s) of the hardware, and if this matrix can be reproduced in the testing laboratory, a reasonable simulation of the field environment will result. The determination of the entire spectrum matrix at the interface point(s) is required.

In the Gxyz control matrix, the three diagonal terms are defined as auto spectral or power spectral density (PSD) functions. The power spectral density function is the conventional method used to describe a 1-D random vibration environment. The PSD at any given frequency value represents the power per unit bandwidth centered at that frequency. A description of the detail information and methodology used for developing the test vibration environment is provided in Appendix A. Traditionally, the PSD test specifications have been developed from the field measurements in each of three mutually perpendicular axes. To account for variations in environmental parameters, various enveloping procedures, or an average value plus one or two standard deviations, are employed. Finally, the PSD envelopes are replaced with a series of straight line segments connected at break points to simplify the definition of the amplitude-frequency parameters of the laboratory test specification.

The six off-diagonal terms of Equation (1) are defined as the cross spectral density functions. Cross-spectral density is a complex mathematical expression whose physical significance is considered analogous to the cross-correlation function. In practice, it is difficult and sometimes impossible, to produce a reasonable cross-spectrum for test requirements from field measurements due to one or more of the following factors:

a) Little cross-spectrum data is currently available from field measurements.

b) No acceptable way has been found to summarize or condense the variations of complex values by means of average or envelope procedures.

c) The cross-coupling effects between two corresponding directions are not explicitly defined.

Therefore, when applying the cross-spectral density information to physical problems, it is convenient to use complex polar notation such that:

$$Gxy(f) = |Gxy(f)| \exp[\, j\theta xy(f)] \qquad (2)$$

$$Gyx(f) = Gxy^*(f) = |Gxy(f)| \exp[-j\theta xy(f)] \qquad (3)$$

Where $|Gxy(f)|$ denotes the cross spectral density magnitude, $\theta xy(f)$ is the phase angle, and * represents the complex conjugate. It is often desirable to normalize the cross spectral density magnitude using the coherence function:

$$\gamma_{xy}^2(f) = \frac{|Gxy(f)|^2}{Gxx\ Gyy} \qquad (4)$$

Since $|Gxy(f)|^2 \leq Gxx\ Gyy$, the coherence function can vary between zero and unity. Combining Equations (2) and (4):

$$Gxy(f) = \gamma xy(f) \sqrt{Gxx\ Gyy}\ \exp[\, j\theta xy(f)] \qquad (5)$$

The introduction of the coherence function to replace the cross spectral density provides the following advantages:

a) Quantitative determination of the coupling effects between two directions.

b) An averaging procedure can be applied to account for the variation of the coherence function.

c) A simple curve, or even a constant value in a given frequency range may be used to describe the coherence function without losing generality.

d) Characteristic values obtained from previous measurements may be applied to similar environments.

To summarize, when the three power spectral density (PSD) terms are specified in the 3D test matrix, the cross-spectrum terms can be computed by using Equation (5), since they are dependent on the two other parameters, the coherence function and the phase angle. For natural random environments, no determistic pattern could be found to describe the phase relationship for each frequency point. Generally, a set of statistically independent random variables with uniform distribution is used to represent the phase angles in the frequency domain. Nevertheless, the coherence function can be determined from field measurements of actual or similar hardware in similar mission environments and generalized as a function of hardware/mission type. For example, measurements of transport vehicles shows that the coherence function is quite high in the lower frequency range (0.8 to 0.9) but drops off with increasing frequency (Reference 3). The diminishing coherence at the higher frequencies probably results from the contributions of extraneous signal noise and the low pass filtering characteristics of the vehicle structural response. The coherence function can usually be approximated for transport vehicles by a constant value near unity up to a prescribed frequency, f1, followed by a linear reduction to zero at a higher prescribed frequency, f2.

EVALUATION OF 3D TEST REQUIREMENT

Digital control systems offer attractive advantages for laboratory random vibration testing for both single- and multiple-axial cases. The control theory for these systems has been presented in previously published papers (References 4 and 5) and will not be discussed in this report. The control specification for a laboratory random vibration test is in terms of the auto and cross spectrum. Since the shakers are operated in the time domain, the desired spectrum matrix as defined in the previous section must be capable of being converted into three independent random signals. References 4 and 5 also illustrate how a vector of random signals with a specified spectrum matrix could be represented by a vector of independent white noise sources coupled through a lower triangular transfer matrix. This time domain randomization method is particularly suitable to solve for cross-coupled systems with a partially coherent relationship.

Equation (5) states that the cross-spectrum of the 3D test requirements is specified in terms of auto-spectrum, coherence function and phase angle. The phase angle represents the phase shift between two excitation directions at the frequency f, e.g., $\theta xy(f) = \theta y(f) - \theta x(f)$. For a system with three orthogonal directions (3D space), three phase angles at each frequency point go through a complete cycle and they must sum to zero, i.e.,

$$\theta xy(f) + \theta yz(f) + \theta zx(f) = 0 \qquad (6)$$

Therefore, two independent, randomly varying phase angles are chosen and the third one is determined such that the sum of the three phase angles equates to zero.

For the auto-spectrum, the value for each of the three orthogonal directions is specified individually. The required PSD value usually represents the combination of multiple events rather than a single case, and is the upper envelope of the worst case. In order to convert this into a random signal which can be physically realized, some constraints must be imposed on the values of the three coherence functions. For example, suppose $\gamma xy=1$ and $\gamma yz=1$, but $\gamma xz=0$, (i.e., the x axis is completely coherent with respect to the y axis, and the y axis is completely coherent with respect to the Z axis, but the X axis is incoherent with respect to the Z axis). This is clearly impossible. Based on the results presented in Reference 6, it was found that at each frequency point there is a requirement that the coherence values satisfy the following relationship.

$$1 \geq \gamma xy^2 + \gamma yz^2 + \gamma zx^2 - 2\,\gamma xy\,\gamma yz\,\gamma zx \qquad (7)$$

As far as we have found to date, these are the only mathematical restrictions on the spectrum matrix.

In the case where all three shakers are driven by one random signal the test platform motion can be in only one direction. Thus the magnitude of the coherence between each pair of shaker signals is 1.0 and the test is physically a 1-D test. Conversely, if the input signals are unrelated (i.e., the coherence is 0.0), the direction of motion changes continuously and there's no preferred direction of excitation. Any value of coherence greater than zero between two input axes represents some amount of directionality in the test (i.e., preferred direction of excitation is other than either of the two input axes. The 3D random input at each frequency could be represented by an arbitrarily oriented ellipsoid. Taking zero coherence between the shakers, the input will be an ellipsoid shape with the ellipsoid axes aligned with the shaker axes. Coherence is the only way to reorient and reshape the ellipsoid of the 3D random input to some other space direction (coherent direction) and make the vibration amplitude in that direction larger than the values in the direction of the shaker axes. For a 3D random vibration test, too large of a coherence relative to the field environments will result in an overtest in the coherent direction and an undertest in other perpendicular directions. Therefore, the simulation of the 3D random vibration test is dependent on the definition of the coherence function. In order to truly simulate the actual field environment, test data should always be used along with empirical adjustments to define the coherence between test axes. Finally, three independent random time signals representing the defined 3D test matrix must be able to be synthesized. The physical characteristics of the simulated time histories should be compared with the field environment to evaluate their similarity.

CONCLUSIONS AND RECOMMENDATIONS

The application of multi-axial random vibration to excite test articles provides a more realistic test simulation and significant test time savings can be achieved. The completion of the HDL 3D-VTS has broadened the multi-axial vibration test capability and provides a better simulation of field and/or service environments. Generally, the 3D test requirements for random vibration tests must be defined in terms of the auto-spectrum and cross-spectrum for each of three orthogonal axes. By utilizing the coherence function relationship for cross-correlation effects, the test requirement can be simply defined and provides a more realistic environmental simulation. This methodology was initially developed for defining 3D test requirements to simulate transportation environments, but it is applicable to simulation of other environments and could be employed in a similar fashion to develop laboratory test requirements based on field data. However, further investigations will be needed to demonstrate the role the coherence function plays between the various input axes and to study the important factors which affect damage during 3D random excitation.

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CHAPTER II

3D TRANSPORTATION VIBRATION TEST REQUIREMENT FOR M732

SAFE AND ARM MODULE

INTRODUCTION

Missile and artillery components such as electronic-mechanical fuzes have traditionally been tested with 1-D sinusoidal and random vibration environments in the laboratory to simulate transport environments. A long test time is required to sequentially test in three orthogonal axes and inconsistent test failures between swept sine vibration tests and "equivalent" random vibration tests have resulted (References 1 and 2). Also, road transport tests of such components show less physical damage than the laboratory tests. These results provide evidence that laboratory tests do not adequately simulate the real field cargo transport environment and thus have posed a question as to the validity of the current laboratory simulation test approach.

A primary objective for this task has been to develop an equivalent 3D input spectrum to better simulate the cargo field transportation environment for the M732 safe and arm (S & A) module lot acceptance testing. The 3D test criteria will be established based on the methodology developed in Chapter I by utilizing the coherence function relationship for cross-coupling of three input axes. Verification of the developed 3D test criteria is another phase of the program plan and will be performed at HDL 3D-VTS later.

M732 S AND A MODULE

The M732 S & A module, as illustrated in Figure 1, is a pillbox sized (2" diameter, 3/4" high) watch spring type of mechanism used as part of a proximate fuze to provide a time delay to arm the device when the projectile is fired. The module is located near the artillery fuze base just above the barrier booster cup assembly as shown in Figure 2. The time delay is accomplished by the number of turns of the rotor, which is damped according to the square of its velocity by means of a gear train and runaway escape mechanism. The turns to arm (TTA) is the most important factor and is a standard measurement used for evaluation of the functional integrity of the S and A modules; it indicates the number of turns the spin motor completes before the fuze snaps into the armed position. The criteria for acceptance is within the limits of 25 to 38 revolutions of the module when spun at 2500 rpm.

Originally the modules were lot acceptance tested per MIL-STD 331A, Method 119/procedure II. MIL-STD regulations require that the fuze material be subjected to standardized tests to simulate the vibration environment that may be encountered during shipping from its point of manufacture to its destination in the field. MS 331-119 calls for a logarithmically swept sine test from 5 Hz to 500 Hz and back to 5 Hz as shown in figure 3. Two such cycles per fuze axis are required in procedure II with the shaker vibration direction consecutively parallel to each of three mutually perpendicular fuze orientations, for a total of 6 hours testing. Acceleration amplitudes for MS 331-119 are shown in figure 4. The level increases from 1.5 g at 5 Hz to 2.5 g at 11 Hz, constant at 2.5 g to 37 Hz, increases to 5.0 g at 52 Hz, then constant at 5.0 g to 500 Hz (Reference 1). This specification was established approximately 20 years ago (using old-fashioned analog filtering shock spectra techniques). The test level was basically established by truck transportation environments (both on and off the road), but the specification also covered airplanes, ship, etc. It was intended to cover all transportation and vibration (T/V) environments.

In an effort to shorten the test time and to achieve a more realistic simulation, a random vibration test requirement was developed and proposed to replace the sine-swept test requirements. The random vibration test environment was justified as being both less costly to perform and more meaningful in its replication of the shipping environment than the swept-sine test. A proposed test schedule has been developed including test levels, frequency ranges, and test durations. The test level was an approximate fit to the combined truck-rail shipping and fixed-wing transport vibration environments, with its power spectral density (PSD) set at 1.5×10^{-2} g^2/Hz. This PSD curve, illustrated with its test tolerances in Figure 5, commences at 5 Hz, slopes upward to 10 Hz (at shaker displacement limitations), then is a constant level out to 500 Hz, which corresponds to 2.8 g_{rms} overall value (Reference 2). Two hours have been selected as the duration for the random vibration test.

Random vibration tests performed on the S & A modules do not produce results equivalent to those obtained from the swept-sine tests (References 1 & 2). Two separate road tests were conducted to validate the results of the random vibration laboratory testing. The S & A modules were placed in the cutout of a holding block, installation was done the same way as for laboratory testing, and clamped to the transport floor. There was one test of 255 miles over the U.S. Army Aberdeen Proving Ground (APG) Munson road test course in a two-wheeled trailer, and a second test of 5200 miles in a truck-carryall van, over asphalt and over hard-packed medium-rough to rough dirt surfaces. The results of the road tests have shown that the laboratory tests (sine and random) were a significant overtest compared to the damage potential of the actual logistical shipping environment (Reference 2).

Nevertheless, the random vibration laboratory test environment selected more closely simulates the actual vibration loads on the test articles. These laboratory tests have provided some pertinent data on the M732 S & A module failure mechanisms. They are summarized below.

- Chips or flakes were formed when the fuze was exposed to low level vibration. These flakes were "ground up" into debris after prolonged excitation, causing the arming failure or damage.

- Physical damage such as S & A module surface deterioration and other indications of wear, even when determined quantitatively, is not an adequate (precise) criterion for damage equivalence.

- The effect of the excitation direction on arming failures were inexplicable. Although the uniaxial (Z-axis) vibration causes greater visually apparent damage such as surface wear than results of the the cross-axial (X-Y plane) excitation, laboratory vibration testing excitation axis could not be correlated with arming failures observed.

- Arming failures of the modules may occur when the modules are vibrated in any axial orientation. Rotation of the excitation direction from one axis to another has not been demonstrated to increase failures and may actually reduce potential problems by dislodging debris or particles that would otherwise have impeded arming.

- Vibration testing at elevated amplitudes produced significant arming failures after short testing durations.

- Long duration vibration testing did not produce a noticeable difference in post-vibration TTA readings.

Reproducing the same type and extent of physical damage and debris of the fuzes in the laboratory as found after the road tests do not result in identical post-damage spin-arming times (TTA's). Sufficient similarities exist, however, to allow the formulation of more realistic laboratory test schedules. The test environments must be selected on considerations that supplement those of the "equivalence" factors mentioned above. Emphasis should be placed on simulating the actual vibration levels and durations of high-level damage-causing events in the transportation environment.

TRUCK TRANSPORTATION VIBRATION ENVIRONMENTS

Based on the above results obtained from previous laboratory and road tests, it was required to redefine the M732 S & A modules laboratory test schedules. Ammunition components such as S and A modules are usually shipped as packaged hardware (a sleeve press fit into a cutout in the shipping container) secured to the transport cargo floor. Ideally one would like the laboratory test performed on the test article to be identical to what the article will experience in service. "Real" transportation environments involve three dimensional motions with 6 degrees-of-freedom. For the current HDL 3D-vibration test system (VTS), three translational motions in three mutually perpendicular directions can be controlled and simulated (i.e., rotations are constrained). Extensive effort was expended to obtain and to examine the existing transportation measurements in all three orthogonal directions (i.e., vertical, longitudinal, and transverse). Field measurements to define the transportation environments for all types of military vehicles have been conducted by APG and measured data are presented in various published documents (References 3 and 4). APG data along with other transportation data were evaluated in this investigation. The definition of the test requirement had to take into account the fact that random vibration environments for each transport vehicle have unique characteristics, but that large variations in the measurement levels were observed even for similar vehicles under similar operational conditions. Specific transport modes, vehicles, and distances that will be used for shipment of ordnance equipment cannot be predicted with any certainty. The largest percentage of all ammunition shipments will probably be carried by trucks for most surface transport and cargo ships will be used extensively in overseas shipment. Because of its benign, low-level vibration environment, cargo ship transports may be disregarded in determining test levels. However, in order to cover all possible transport modes and vehicles and to account for variations, an envelope of upper limits to represent the worst-case condition for each excitation axis must be made. The enveloped PSD curves in the 5 to 500 Hz frequency range for each of the three orthogonal measurement axes are presented in Figure 6. The enveloping of field measurements is extremely conservative compared to any one set of measured transport environments, increasing overall Grms vibration levels by as much as 40 percent in some cases. The data utilized for establishing these envelope spectra were derived from base frame measurements of trucks and two-wheeled trailers operating at various speeds over different courses ranging from paved highway to off road conditions.

Based on the measured data as discussed above, the proposed transportation vibration test spectrum for the secured ammunition cargo is presented in Figure 7. The auto-spectrum as shown for each of the three mutually perpendicular axes represents a simple, smooth vibration level which does not envelope all resonant peaks. This specification was based on consideration of the probable conservatisms in the derivation process, i.e., the undefined effects of impedance mismatch between laboratory testing and field transport; and the probable penalties due to an unnecessarily conservative specification. Also, vibration at frequencies above 500 Hz is not generally considered harmful to any ammunition. For the M732 S & A module specifically, its design, construction, and previous test results make it highly unlikely that vibration is a significant concern above about 300 Hz. Since this has not been demonstrated conclusively, however, it is recommended that the test specification be extended to 500 Hz. As can be seen from figure 7, the vertical acceleration is the highest and the highest PSD values are at lower frequencies and approach 0.1 g^2/Hz. An overall value of 1.9 Grms should be used to control vertical vibration testing, with a slightly lower value for the transverse and longitudinal directions. In comparison with other published transportation vibration inputs (References 5 and 6), these proposed vibration levels are considerably higher in the lower and higher frequency ranges as illustrated in figure 8 (vertical only shown). However, these two previously defined curves shown in figure 8 are most suitable for large common carriers such as large conventional trucks and flatbed transport vehicles. Nevertheless, as demonstrated in the same figure, the proposed test requirements are lower than other mission/field environmental measurements (Reference 7) in which typical tactical vehicles are used. The high vibration level in the lower frequency is primarily due to significant differences in truck size and design as well as the differences in rough road conditions. The vibration levels shown at frequencies between 200 to 500 Hz are probably due to wheel/axle coupling excitation, and the level is generally independent of direction. Similar conclusions are also presented in a recent publication (Reference 7). Overall, the proposed test requirement is comparable to existing transport test requirements (MIL-STD-810D) and, in terms of severity, is bounded by the existing requirements.

The definition of the vibration test duration should be based on total shipping mileages of expected transportation of the S & A modules over various road conditions, especially rough road travel distance. An investigation into the distance that ammunition might be transported as loose packaged, stored cargo was presented in References 3 and 6. The implication of these two reports is that the controlling vibration environment for ammunition surface shipment is that of the truck and possibly the two-wheeled trailer. The maximum transport distance that need be considered is no greater than 5000 miles with the last 500 miles for a typical mission/field transportation by truck or two-wheeled trailer. Although both trucks and two-wheeled trailers are utilized for mission/field transport, the vibration levels on the trailer are normally higher and thus should be used to represent the composite wheeled transportation environment. Two hours are estimated to represent the maximum travel time and distance by trailer for the ammunition to reach the using unit. (50 miles or approximately 10 to 15% of the mission/field distance are "rough" road conditions with an average trailer travel speed of 25 miles per hour). Therefore, two hours test time is proposed, which is also specified by MIL-STD-810D and is identical to current HDL laboratory test practices. One may infer from this selection that a 1-hour laboratory test with the proposed spectrum is equivalent to 2500 miles of road travel compared to the MIL-STD-810D of one hour of testing for 1000 miles.

3D T/V TEST REQUIREMENT FOR M732 S & A MODULE

The proposed vibration test levels described in the previous section represent the three diagonal terms of the 3D input test control matrix as described in Reference 3. For complete definition of the 3D test requirement, the remaining six cross-spectrum terms in the input matrix are expressed in terms of three coherence functions and three corresponding phase angles. Based on the recent APG field measurements (Reference 8), figure 9 shows typical phase angle plots obtained from one of the APG truck test runs. These phase relationships appear to follow no general pattern. They can best be described as independently random in their physical nature. Thus, it is proposed that three random phase angles in the defined frequency range be used in the 3D testing. (Note that two sets of independent pseudo-random numbers are needed for the definition of phase angles and the third phase angle is defined such that the sum of all the phase angles at any given frequency is zero.)

Figures 10a and 10b show typical coherence functions at the truck base frame reduced from the same test run as above. Similar results were observed from the other APG truck test run. As expected, a high correlation between each input axis can be observed. An approximate average value of 0.75 over the entire frequency range (5 to 500 Hz) may be used to describe all three coherence functions from field measurement data. However, the coherence value determines the amount of the directionality in the 3D testing. High coherence requires that the physical orientation of the test article must be controlled both in use and on the shaker platform (i.e., the S & A module must always be physically oriented in the same direction in shipment). Since the S & A module is packaged and can be placed in almost any orientation during transport, a more generalized coherence value should be specified. Zero coherence, which represents no control in direction, and the enveloped vibration amplitude of all three directions (i.e., vertical vibration level for all three directions) are proposed for testing of the M732 S & A Modules. The phase angle for this test condition is not important as the coherence value becomes very small or zero between the three input axes. This specification requires no control on the orientation of the test specimen. The S & A module can be mounted on either vertical or horizontal plane of the test fixture on the shaker's platform without consideration to its orientation relative to the direction of the shaker axes. The test module will be excited to the same vibration levels in any direction including the three principal shaker axes. Figure 11 shows the 3D input time histories of the proposed test specification and Figure 12 displays the resultant values in the three dimensional space. A data point in the coordinate plane as plotted in this figure represents the projective view of the resultant vector of the three input amplitudes at any instant time. As can be seen, a spherical shape, more or less, with no preferred direction of excitation is demonstrated.

CONCLUSIONS AND RECOMMENDATIONS

A new acceleration spectral density requirement to simulate truck transportation environments has been presented herein (Figure 7) and is proposed for use as a general truck transportation vibration requirement for 1-D laboratory testing of ammunition components. Furthermore, the coherence function relationship to account for cross-correlation effects is applied to develop a preliminary 3D T/V test requirement for the M732 S & A module. The enveloped (vertical) vibration level along with three random phase angles and zero coherence value from 5 to 500 Hz for two hours test time is proposed for the module 3D testing. This preliminary test criteria was established theoretically based on the available field measurement data and should be verified by laboratory test experimentally. Damage equivalency should be determined by a comparison of the test results with those obtained from the M732 S & A modules field transportation. It is also recommended that at later date, the methodology for defining 3D random vibration test requirements be refined by evaluation of HDL 3D-VTS test results and that test requirements for the M732 S & A modules be refined.

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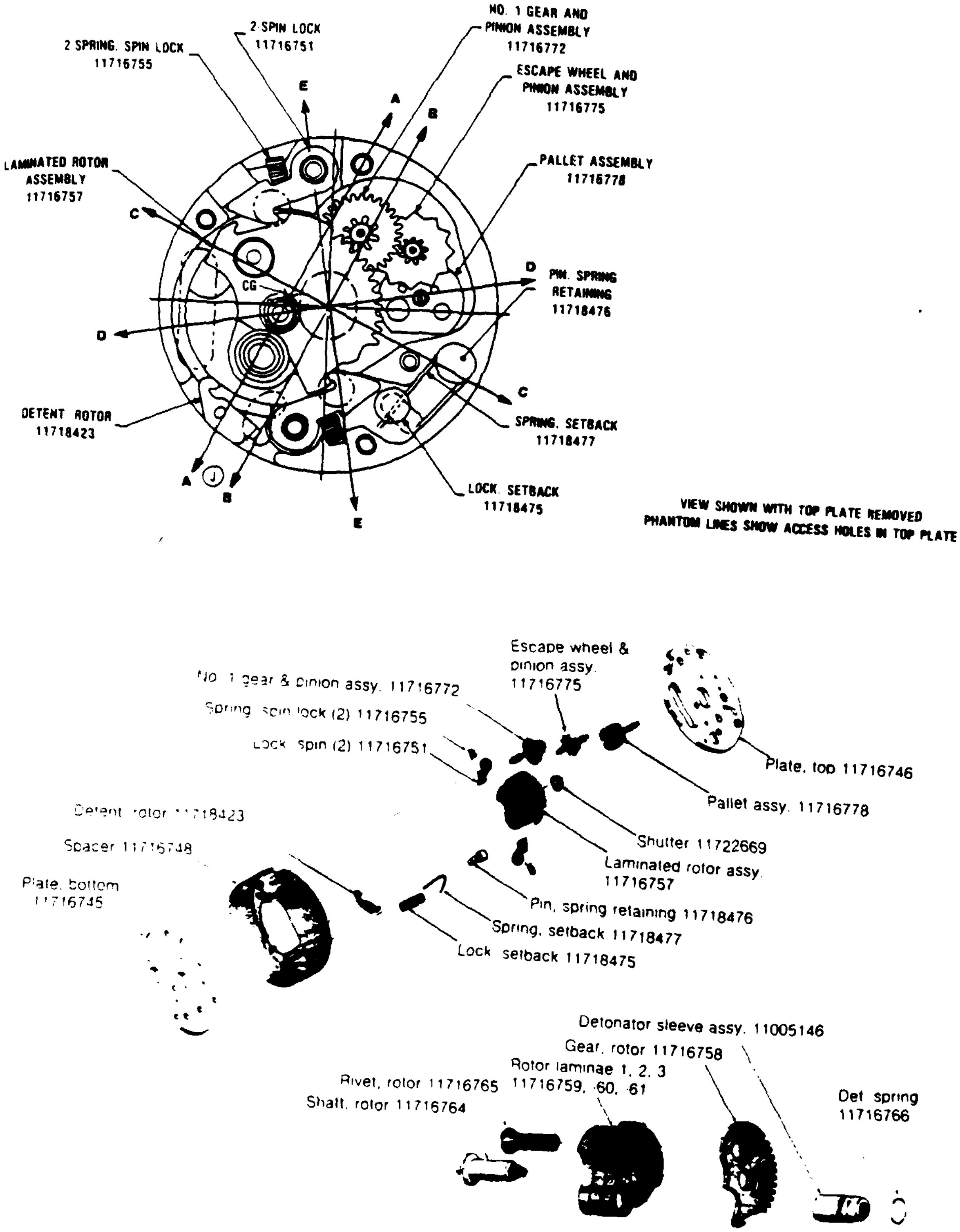

Figure 1. M732 fuze S&A module—exploded view

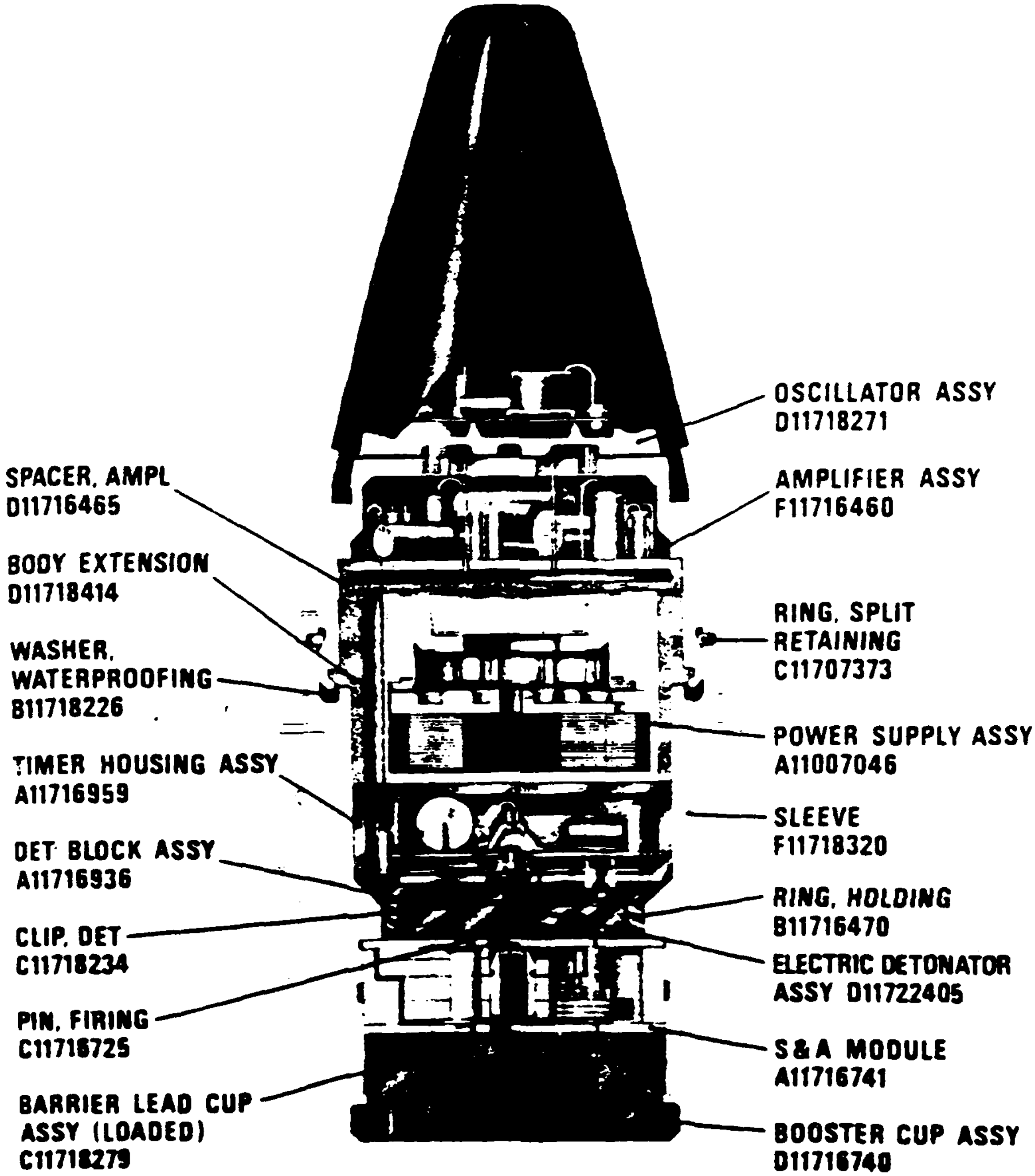

Figure 2. M732 Fuze - cutaway view showing S&A module

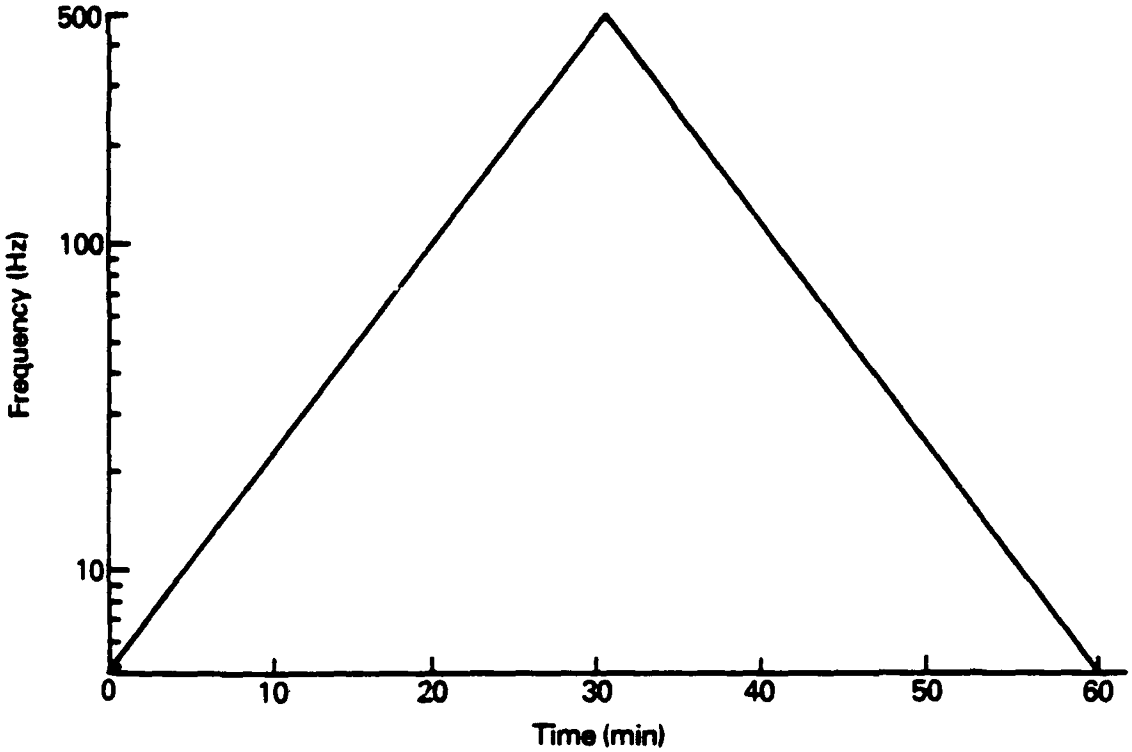

Figure 3. MIL-STD 331, Method 119, transportation vibration sinusoidal sweep cycle

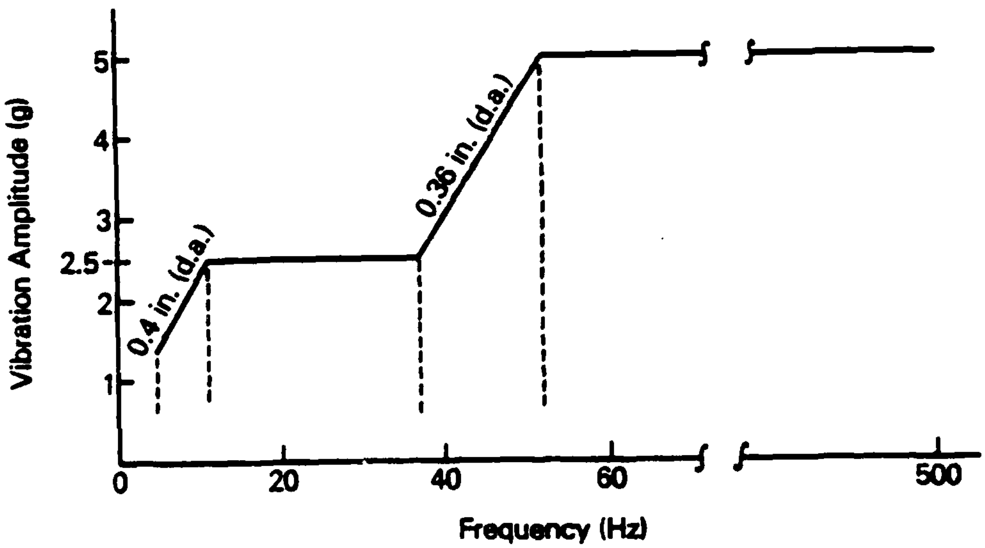

Figure 4. MIL-STD 331, Method 119, transportation vibration sinusoidal sweep spectrum.

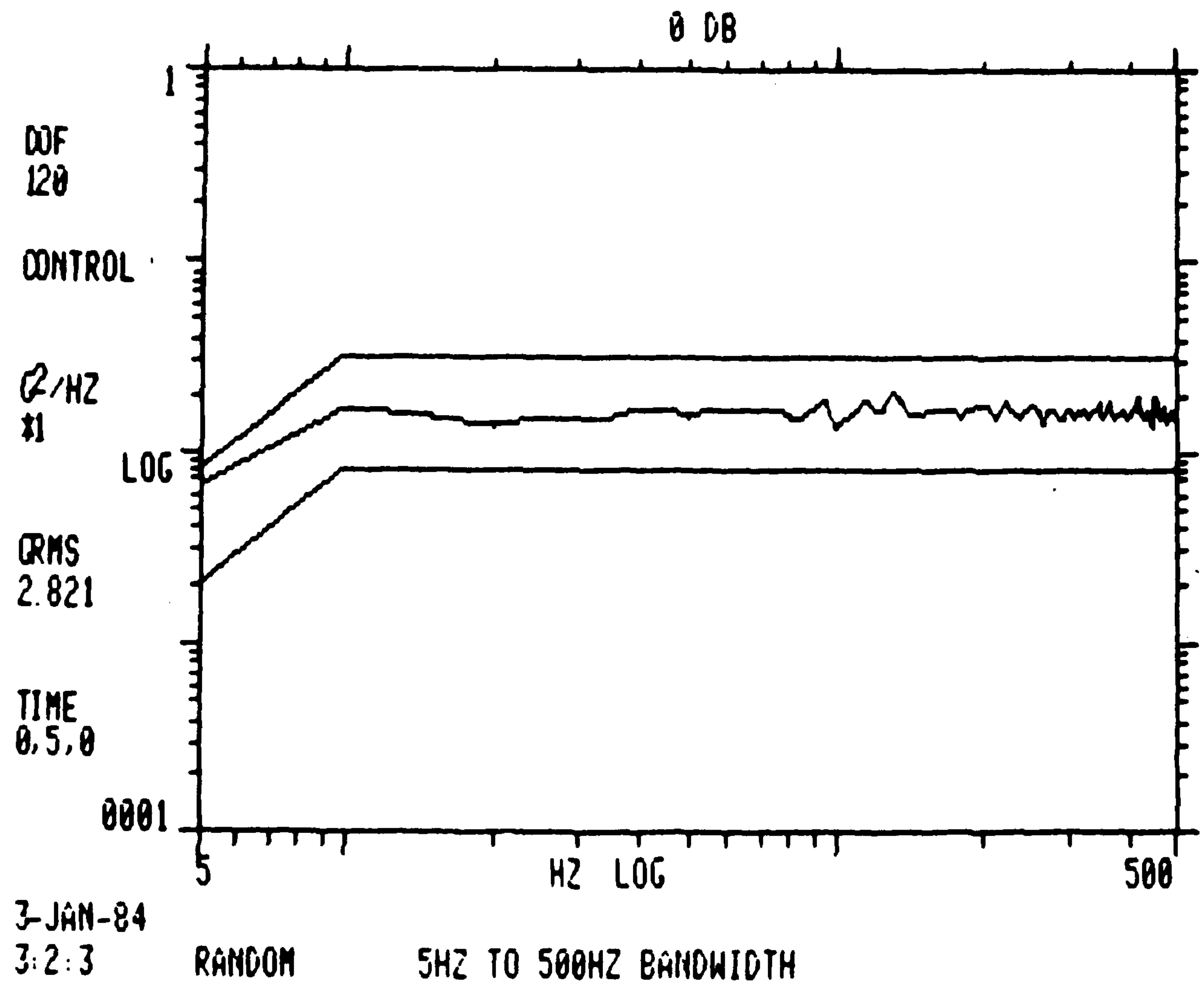

Figure 5. Random Vibration 2.8 Grms Test Spectrum

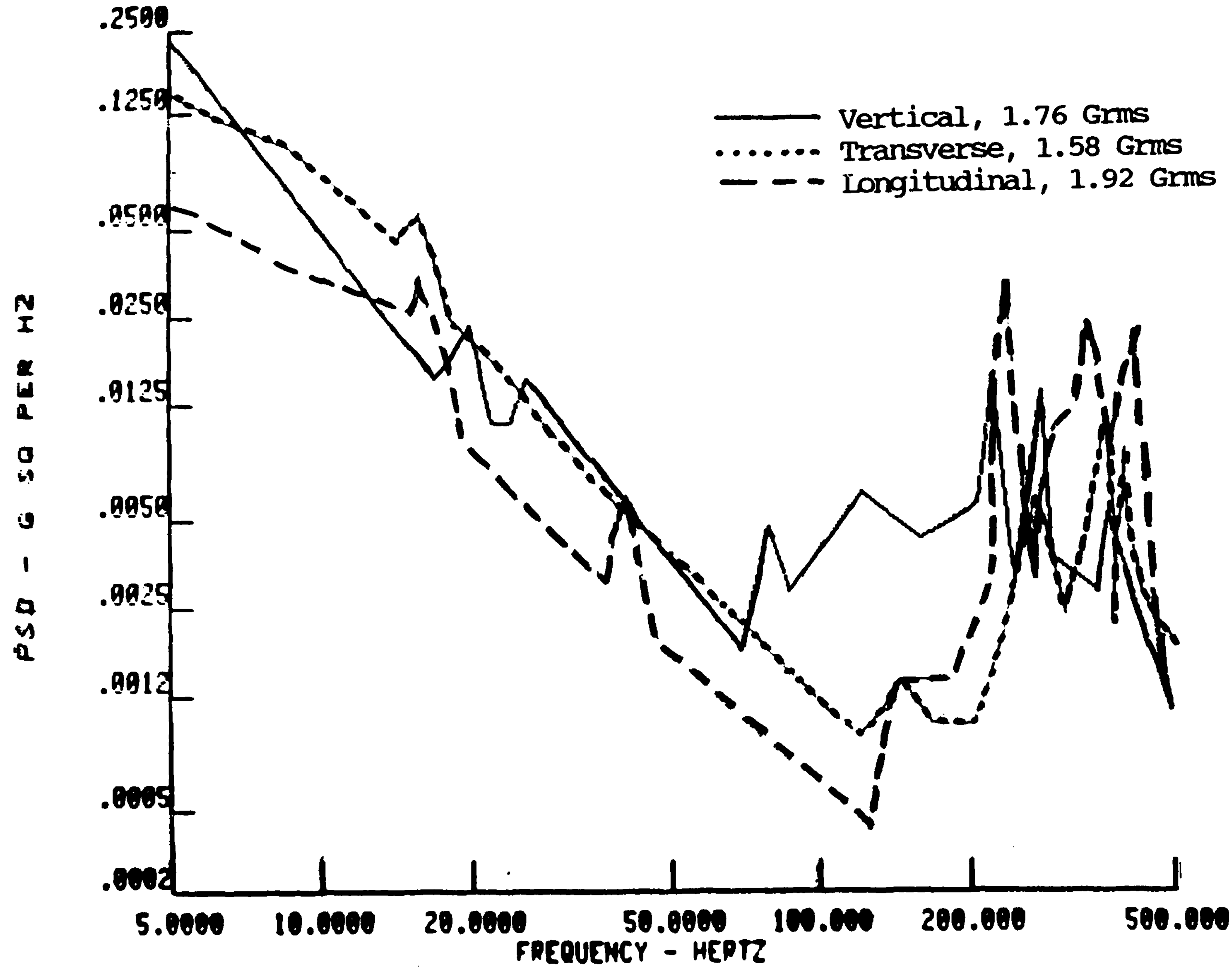

Figure 6. Composite Wheeled Vehicle Vibration Environment

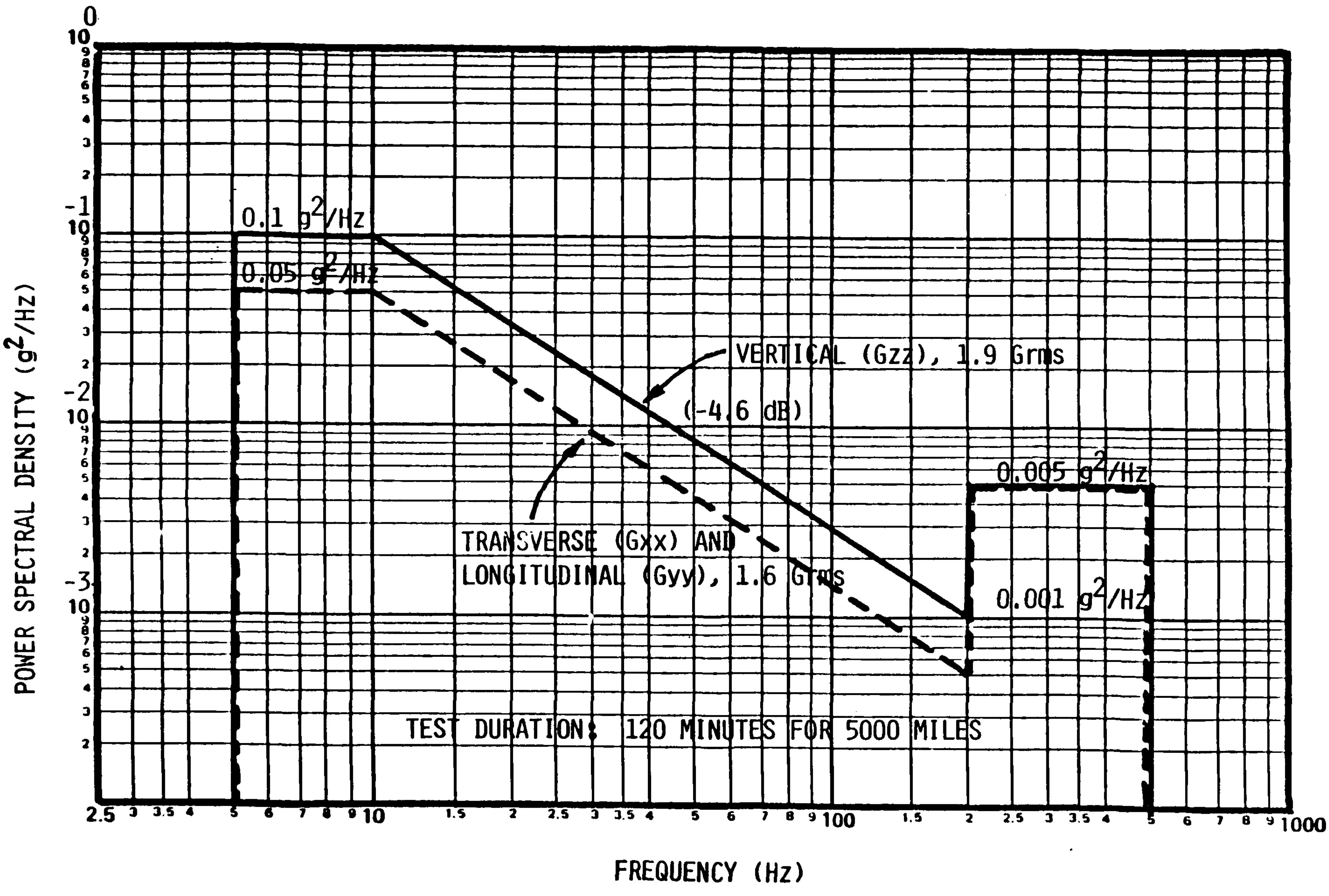

Figure 7. Proposed Transportation Vibration Requirements (Random Vibration Test Spectra)

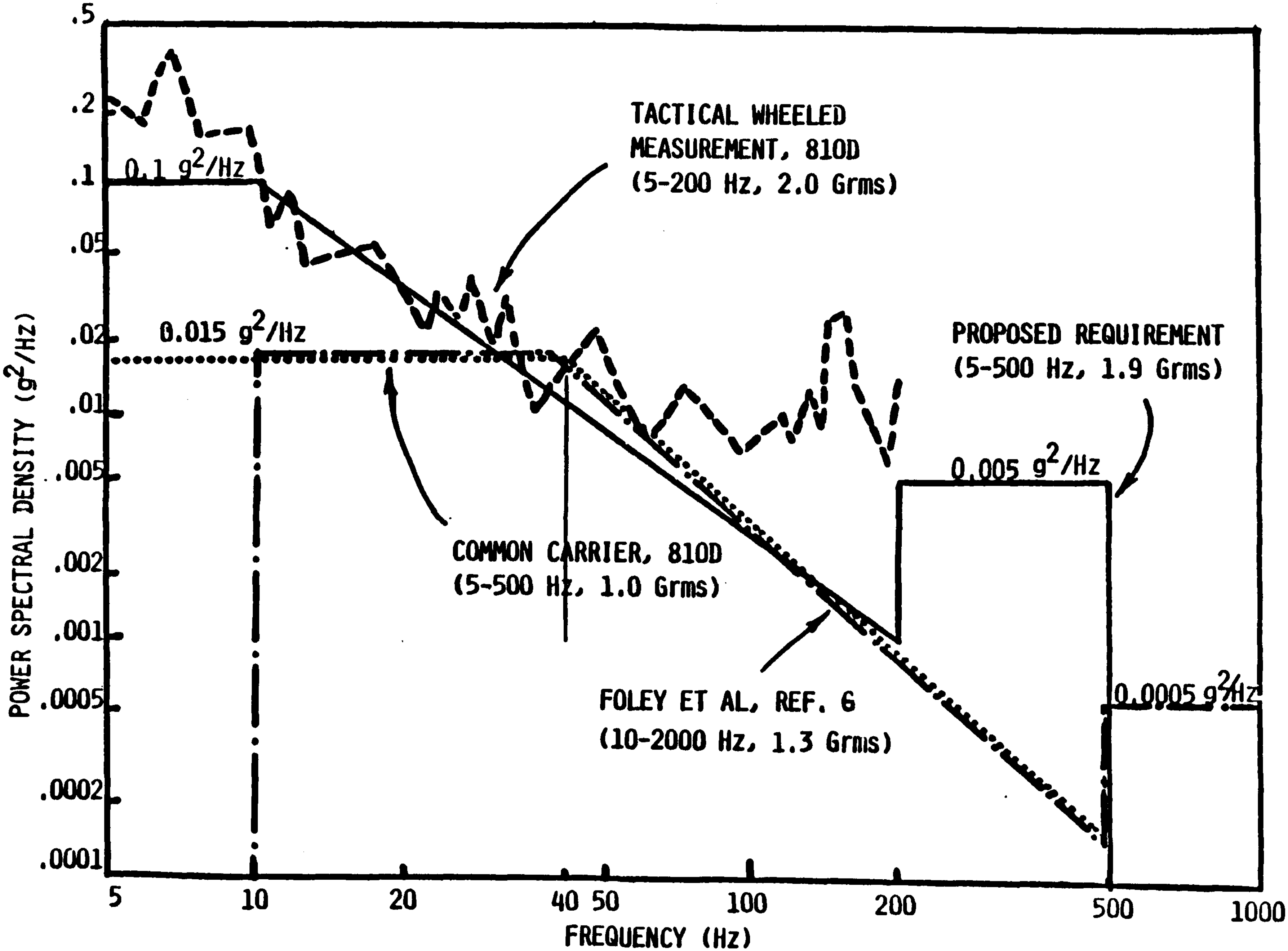

Figure 8. Comparison of Transportation Vibration Levels (Vertical Direction only)

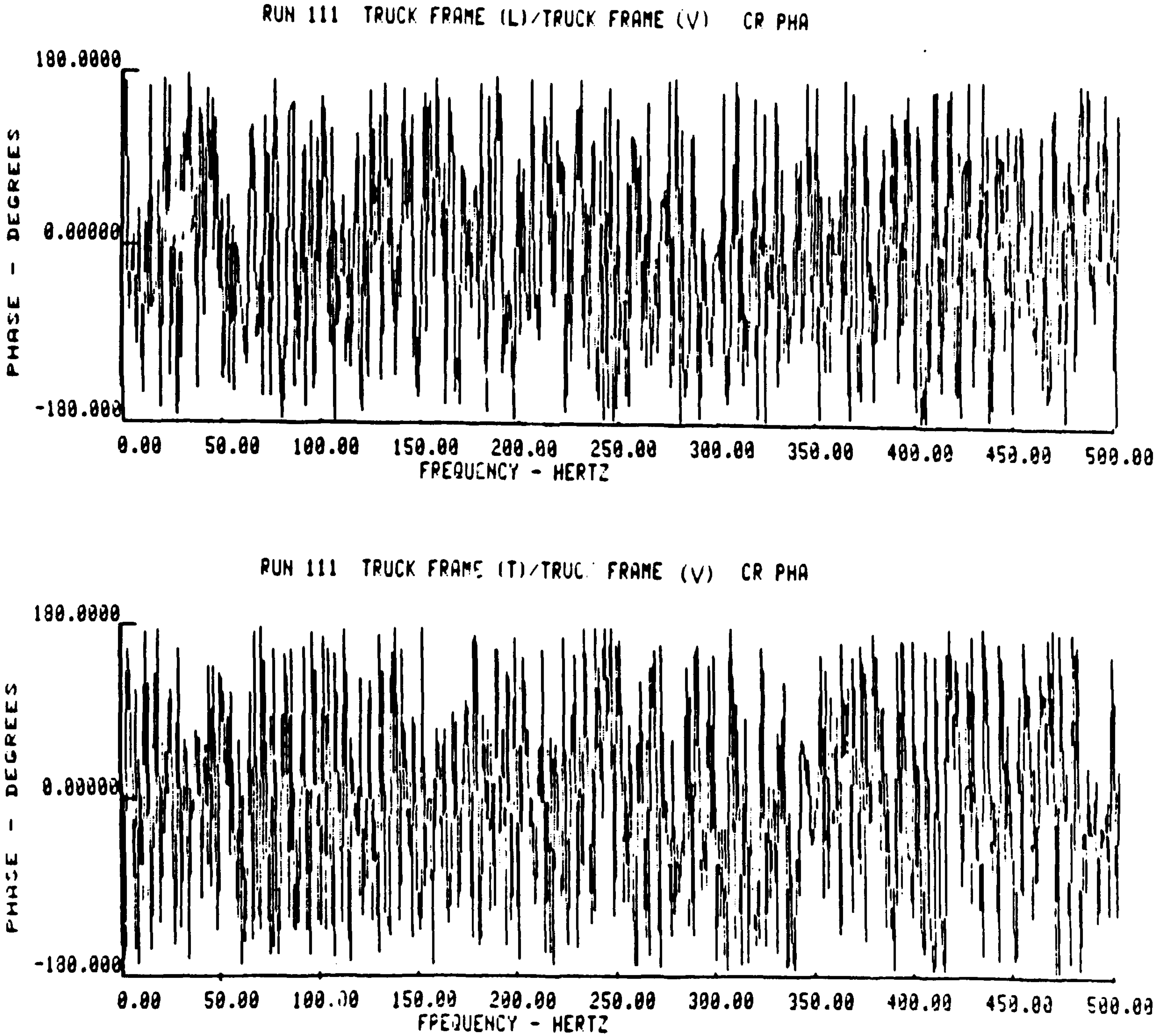

Figure 9. Cross-spectrum Phase Angles of Transport Vibration Environment

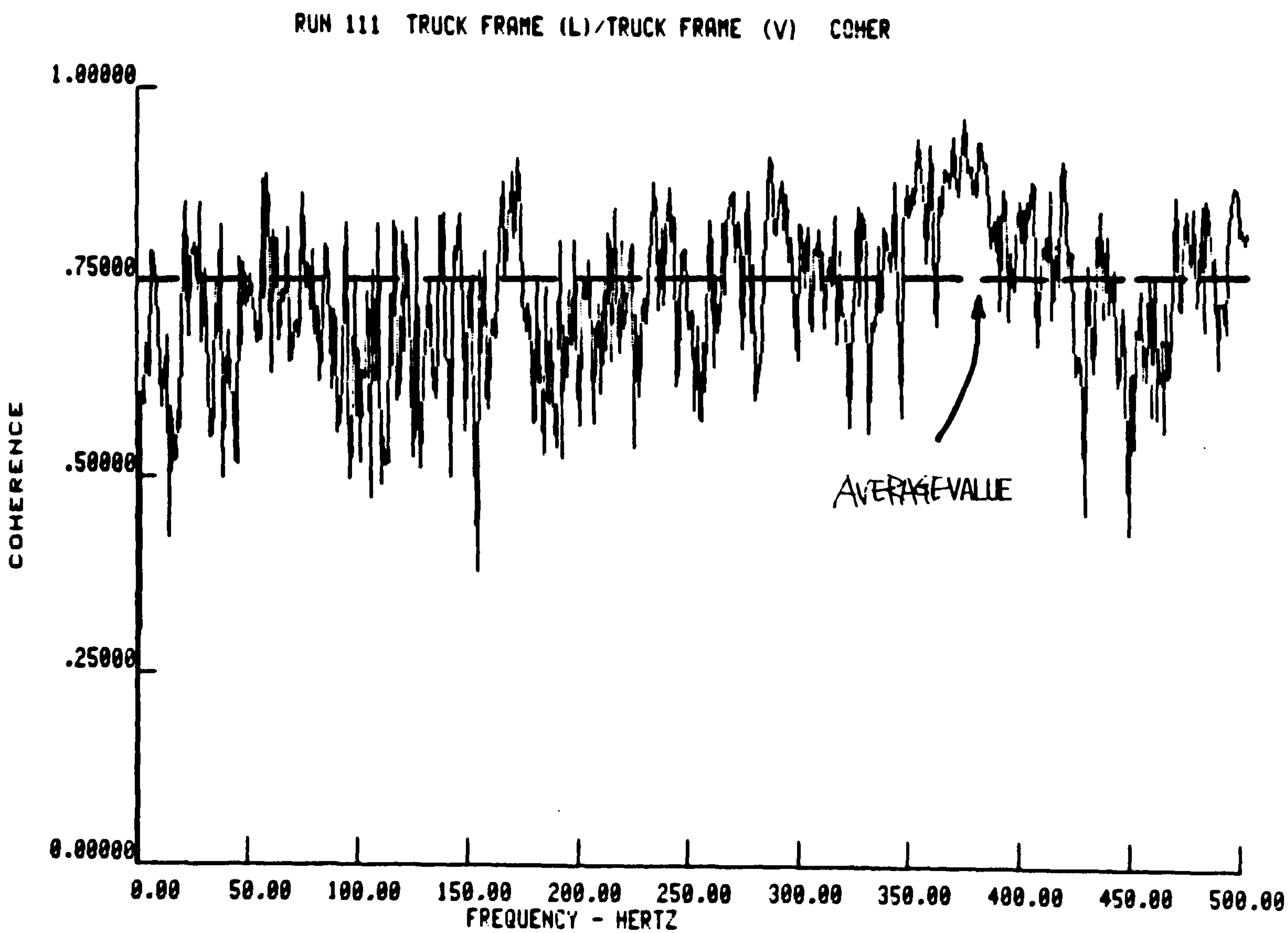

Figure 10a. Coherence Function of Truck Transport Vibration Environment

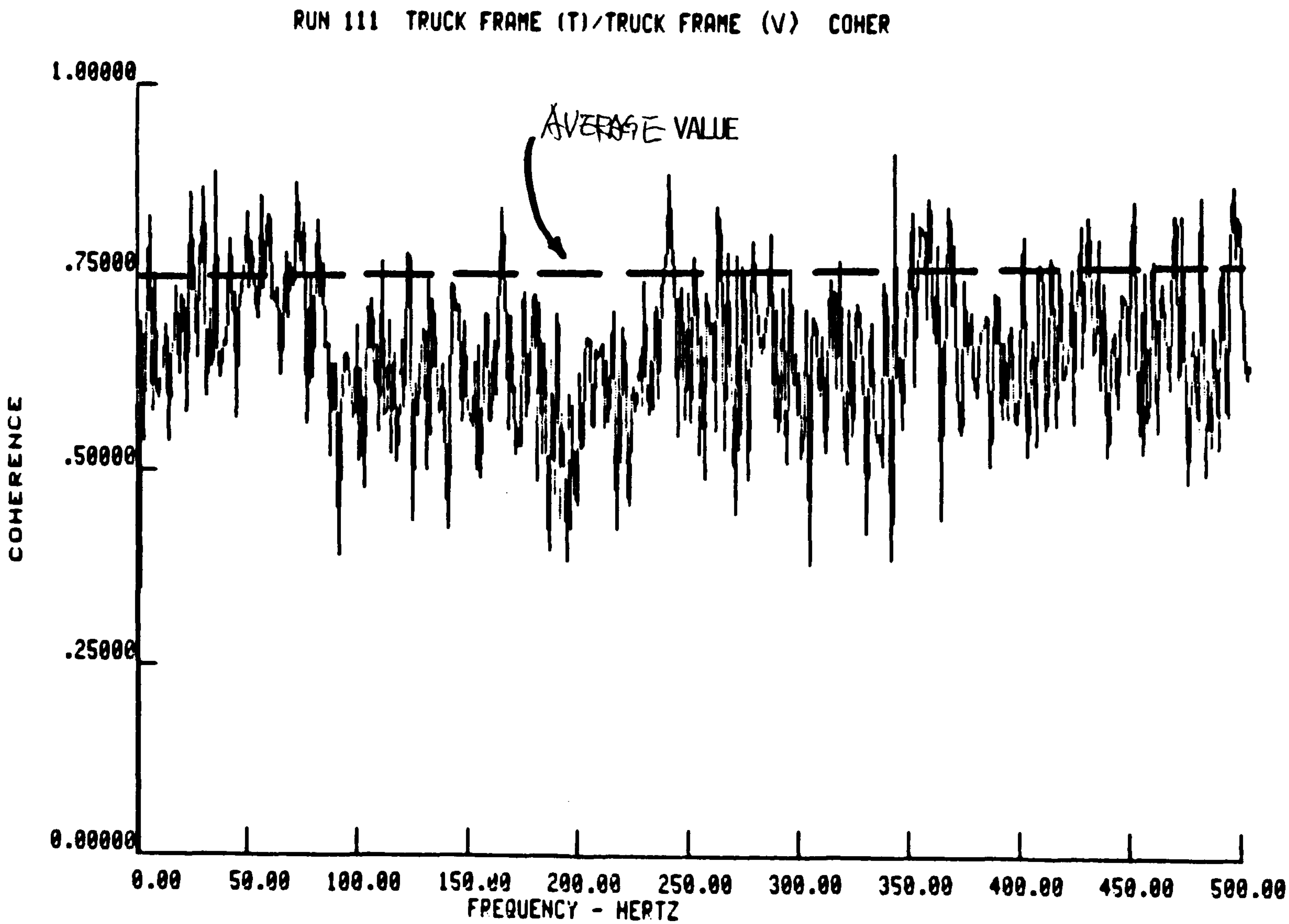

Figure 10b. Coherence Function of Truck Transport Vibration Environment

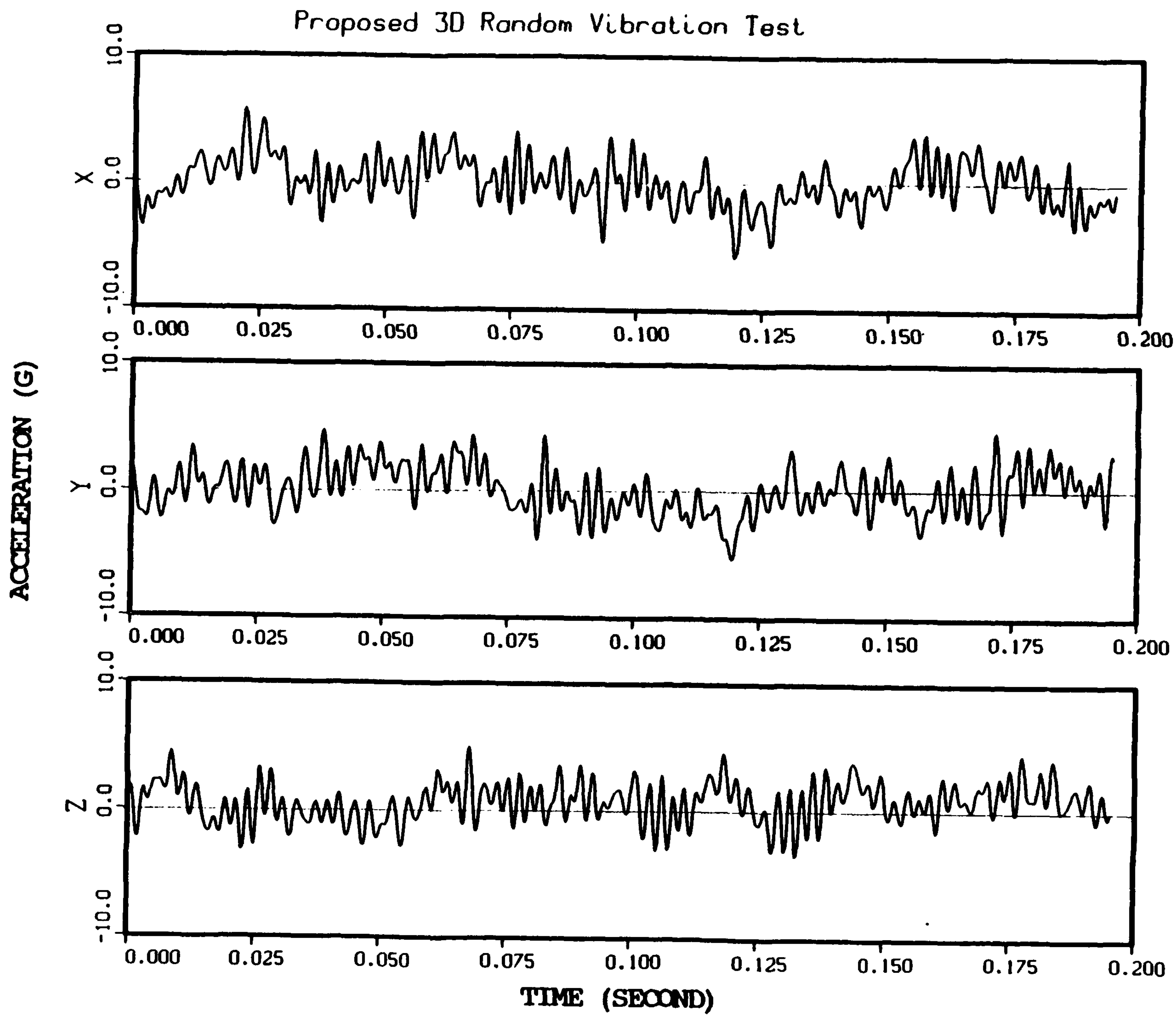

Figure 11. 3D Time Histories of Proposed 732 S&A Module Transportation Vibration Test Requirement

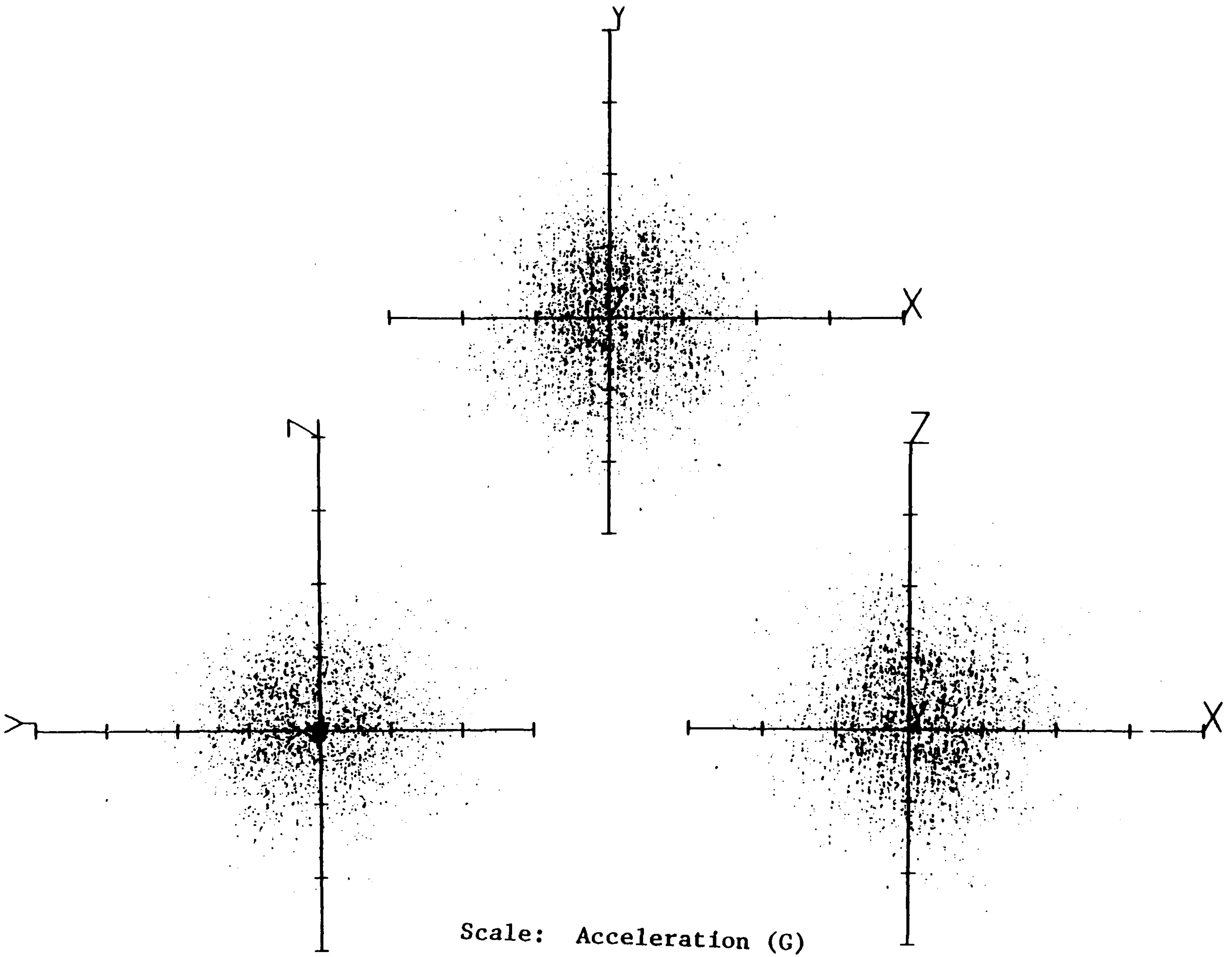

Figure 12. Projected Views of 732 S&A Module Vibration Test Environment

CHAPTER III

3D RANDOM VIBRATION TEST REQUIREMENTS FOR PATRIOT MISSILE FUZE

INTRODUCTION

PATRIOT missile fuzes are normally exposed to sinusoidal and random vibration environments in the test laboratory utilizing one-axis at-a-time or uniaxial motion. "Real world" environments involve three dimensional (3D) motions. Development of a 3D test requirement identical to the actual service environment for the PATRIOT fuzes, and implementation of qualification and acceptance testing using the HDL 3D VTS will eliminate the overtest and undertest potential of 1-D vibration and resulting laboratory or field failures. Literature on the transportation and flight environment of the missile fuze including specifications, test reports and related articles were reviewed and were used to derive the 3D random vibration test requirements for the PATRIOT missile fuze. This chapter documents the results of this effort.

PATRIOT MISSILE FUZE AND MISSILE TRANSPORTER

The guided PATRIOT Missile, formerly the Surface-to-Air Missile Development (SAM-D), is used in the mobility air defense system. Each missile is installed in a ballasted canister to form one missile round. Each missile round weights about 3750 pounds. The Missile canister is a welded aluminum structure fabricated from flat sheet stock for the skin shell, with riveted steel main frames. Each missile is supported on an internal aluminum nylatron covered rail system that conforms to the missile contour. Four external shock isolation frames with skids provide shock mitigation, and provide fittings for tiedown attachments. Two canisters are stacked together by means of the vertical tiedown bolts. Two or four canisters (1 or 2 stack configurations) are usually tied down to the modified M270A1 semi-trailer (4-wheel, 12-ton low-bed trailer) for shipping. An M819 truck tractor/wrecker has been used to tow the modified M270A1 trailer. This wrecker is a 5-ton 6-wheel truck that has one driving front axle and two driving rear axles. Figure 1 shows the overall configuration of the guided missile transporter (GMT) with 4 missile payloads on it.

A guided PATRIOT missile consists of four sections; namely, a slip-cast fuzed silica radome, a guidance section, a warhead section, and an insert propulsion and control section. Figure 2 shows the missile forebody sections including the warhead and missile fuze. The PATRIOT missile fuze is located inside the warhead shell as identified in the figure. The fuze assembly, as illustrated in Figure 3, is a cylindrically shaped box (approximately a foot in diameter with four inches depth and weighs about 18 pounds) with four aluminum tab-like attachment structures mounted to the side of the fuze box assembly. These four tabs support the fuze on the missile warhead canister and are attached with 3/8-inch bolts at the reinforced bosses. The missile fuze contains electronic parts, mostly of unpotted construction and is used as an arm initiator.

The transportation vibration (T/V) requirements currently prescribed for the fuze are a 15 minute logarithmic sinusoidal sweep from 12.9 Hz to 500 Hz and back to 12.9 Hz repeated four (4) times (a total of one hour test time). The levels of vibration are as follows (Reference 1):

$\pm$8.5 g pk from 12.9 Hz to 14.9 Hz
$\pm$5.0 g pk from 14.9 Hz to 44 Hz
$\pm$2.0 g pk from 44 Hz to 100 Hz
$\pm$1.5 g pk from 100 Hz to 500 Hz

The test article is subjected to these sine vibration levels in each of three orthogonal directions. This requirement was intended to cover a variety of modes of transportation such as rail transport (humping of freight cars), trucks, aircraft, and the transportation of the assembled PATRIOT missile in the field.

For flight vibration (F/V), random vibrations with different vibration spectrum levels for the longitudinal and lateral axes were specified (Reference 1). Figures 4a and 4b give the random vibration test levels and durations.

The above two test requirements currently prescribed for the PATRIOT missile fuze were derived from the PATRIOT system requirements, missile warhead section requirements, advanced development flight data and directly from fuze development specification MI-CP-15035803. Especially the flight (random) vibration requirements, imposed on the fuze contractor through the fuze specification MIL-F-60966 (Reference 2), are envelopes of MIL-CP-15035803. This has resulted in vibration levels that may significantly exceed the flight environment and thus overtest the fuze. For obvious reasons, there is a desire to investigate the environment that the fuze will actually experience, and if possible, substitute a more realistic equivalent 3D random vibration test environment. The situation with respect to the PATRIOT is considerably different than for the M732 Safe and Arm module in that no standard military specification exists and the HDL-3D shaker can be used without an attempt to match prior test specifications.

DYNAMIC CHARACTERISTICS OF THE PATRIOT MISSILE FUZE

Numerous laboratory tests have been performed on the PATRIOT missile fuzes (References 3, 4). A swept sine test from 20 Hz to 2500 Hz at 2 g constant amplitude with 1 octave per minute sweeprate was conducted at Bendix Corp. The fuze assembly was directly mounted on the shaker table for vertical (Roll) axial testing. Several triaxial miniature accelerometers were mounted on various components inside the fuze to measure the responses. Also, at Raytheon Corp., the fuze was mounted in the missile body (warhead shell) and the assembly attached to the test fixture and the shaker table. A random vibration test profile was imposed in this configuration. The assembly was excited for four (4) minutes in each of the vertical, transverse, and longitudinal axes. The same test was later on conducted at HDL as fuze acceptance tests. The purposes of these tests were to assess fuze module response levels to the Limited Environmental Tests (LET), and to compare those response levels to the individual component/module test levels. All test results were used to evaluate the significant dynamic characteristics of the fuze assembly and to provide information needed to define an appropriate random vibration test environment for the HDL 3D shaker system. Table 1 presents the comparison of the sine sweep and the random vibration test response data for three different locations inside the fuze box. The results show that the lowest resonant mode of the fuze assembly is in the vertical direction, between frequencies 350 to 400 Hz. The other resonant frequencies are much higher, approximately 600, 920 and 1200 Hz. Overall, the fuze assembly is quite "rigid" relative to the missile canister body. However, potential failure mechanisms cannot be deduced from these test results.

T/V FOR PATRIOT MISSILE FUZE

Vibration loading on the missile round due to logistics ground transportation was considered during the early stages of the missile development program. References 5, 6, 7 and 8 present the results of actual road tests of the PATRIOT missile/canister in the vertical one, two, and four-stack configurations for the tractor/trailer transportation. The tests were conducted over the rough terrain road course as well as improved and unimproved roads at various speeds ranging from 5 to 50 mph. The purposes of these tests were to verify the capability of the missile transporter, and to confirm that the missile responses were within specification, as well as to establish critical speeds of missile transportation for the various road course obstacles. Piezoresistive type accelerometers with a frequency response range of 0 to 250 Hz were installed and monitored during road testing to calibrate the shocks induced on the missile, the canister and the trailer bed. In the test reports, the data presented were tabulized peak acceleration responses and frequencies. No PSDs were analyzed. Although samples of the acceleration time history and shock spectra were included for some test runs, they are not applicable for defining the PATRIOT missile fuze transportation environment. Other transportation testing of the entire PATRIOT air defense system was later conducted at the U. S. Army Aberdeen Proving Ground (APG) (Reference 9). This test was to demonstrate the capability of the missile system vehicles and to determine the physical performance characteristics as well as to provide environmental test data. Two different types of transportation modes were measured in these road tests. One was the missile canisters with the missile insert mounted on the semi-trailer, and towed by a standard M818, 5-ton tractor/wrecker as previously described. Another mode of transport was the missile canisters installed on a launching station (a special design semi-trailer) towed by an M818. Strain gage type accelerometers were installed on the missile, canisters, and semi-trailer bed in all test runs. The root mean square (RMS) and the peak acceleration amplitude and also the power spectral density (PSD) were analyzed.

Comparing the vibration levels of the two transport modes, it is seen that the acceleration response data at the missile body from the guided missile transporter is higher than those from the launching station. Those differences are probably due to different transport trailer and missile canister mounting conditions. Also, the guided missile transporter is normally operated at slightly higher speeds (up to 40 mph) than the launching station (less than 35 mph).

Not all the PSD data from the field measurements are included in the APG report. Only the most severe PSD plots for some locations on the launching station are presented. (Efforts were made to obtain additional PSD data from APG but were not successful). Aberdeen test reports yield response data for the vertical axis only at missile station 153.6, which is in proximity of the fuze. However, the longitudinal axis measurement channel at this station was inoperative and the report fails to indicate whether these accelerometers were mounted on the actual fuze or the missile structure. Additional data on road transportation environments would be required in order to define an appropriate random 3D environment. Effort was extended to examine the existing transportation measurements obtained from road tests of a similar transporter recorded in all three directions (i.e., vertical, longitudinal, and transverse). Field measurements to define the actual transportation vibration environments for secured cargo transportation in various military ground vehicles have been performed by APG in various test programs (Reference 10). In this reference, a M127, 12-ton semi-trailer, as illustrated in Figure 5, was tested and operated at its critical speed on the APG Munson test courses. This trailer is similar to the one used for the PATRIOT missile transportation. The composite test data measured at the trailer bed frame for all different test courses is shown in Figure 6. Using this information as a basis, the proposed T/V test requirement at the missile transport bed is given in Figure 7. (It must be noted that the transmission characteristics (e.g., transfer function) of the missile and the canister should be considered to modify the trailer bed test environment for derivation of the final 3D random vibration test requirements for the missile fuze). In the figure, vibration levels for all three directions are identical for most of the frequency range except at frequencies above 200 Hz. In this frequency range the vertical vibration is negligible. The test duration is chosen to be 1 hour for 1000 miles travel distance, which is based on the 810D (Reference 11) specification for larger common carriers.

For complete definition of the 3D test requirement, the three coherence functions and three phase angles must also be defined as described in Chapter I. The three phase angles are normally specified as random for all random vibration testing. The coherence function, however, has to be defined from actual field measurements. No cross-coupling information relating to the APG test data of the 12-ton semi-trailer exists. Figure 8 gives estimated coherence values for PATRIOT missile fuze testing based on JPL test data (Reference 12) obtained on a trailer used to transport spacecraft. As described previously, the coherence function is quite high for ground transportation in the lower frequency range but does drop off with increasing frequency as a result of the contributions from extraneous noise. The correlation between the two cross axes (X and Y) is due to wheel/axle coupling excitation and is independent of road conditions. The 3D time histories simulating the above proposed test requirements are shown in Figure 9 and the projected views of the resultant values in Figure 10 (10 thousand data points for 2 second period). The directivity of the ellipsoid shape which represents the 3D random vibration excitation of the PATRIOT missile fuze is quite noticeable in this display.

F/V FOR PATRIOT MISSILE FUZE

Flight measurement data at various missile locations during the SAM-D flight test program of missile CTV-1 through 10 have been documented in References 13 and 14. Five key missile locations; namely, MS143 (nose ring), MS153 (PCU ring), MS 179 (TM base), MS 295 (control ring) and MS 304 (battery mounting ring) were instrumented to measure accelerations in the longitudinal and radial directions. Figure 11 illustrates these missile locations. However, only three channels were acquired via telemetry to a ground station during each of ten CTV flights (i.e., total of 30 measurements for 10 flights) and any one particular location was measured on no more than three flights. Miniature piezoelectric accelerometers were used for measuring both shock and vibration environments during missile launch and flight operation, which created problems in presetting the dynamic range. The result of this compromise was that the flight vibration level was very close to the instrumentation noise floor when measurement ranges were set for the ignition transient. Thus, it is difficult to identify the intensity of each vibration source separately. (Definition of the missile shock environment is not within the scope of the present task.) Therefore, the flight data have been evaluated with the objective of establishing a suitable upper bound vibration environment for missile fuze flight testing. The problem of the signal to noise ratio mentioned above is largely circumvented because the vibration periods of concern are those which place an upper bound on the vibration environment. During periods of vibration which were selected for analysis, the signal is well above the noise level.

The vibration environment during flight is produced by a number of sources which were identified during the development phase of the SAM-D program (Reference 15). These sources are:

1. Aerodynamics - Turbulent boundary layer, base pressure fluctuations, cross flow due to maneuvers.
2. Rocket motor.
3. Motor pump.

The rocket motor was shown to be a very weak source of vibration for the warhead, guidance, and nose sections. This fact is confirmed by the CTV flight data. The vibration level during the non-maneuvering portions of motor burn are less than the noise floor of the measurement system.

The vibration induced by aerodynamics is dependent on the missile angle of attack as well as flight trajectory, altitude and missile maneuvers. Based on the conclusions given in Reference 13, for the worst tactical flight condition the dynamic pressure could be increased by a factor of 1.2 to 1.8

in comparison with all the CTV flight tests. Therefore, it is concluded that the tactical vibration levels will possibly exceed the flight test levels by the ratio of the maximum possible dynamic pressure to maximum dynamic pressure achieved in flight test. This ratio amounts to increasing the flight test vibration levels by a factor of approximately 6 dB. However, such a factor is not necessary for the narrow band frequency output of the motor pump. This pump has a characteristic frequency varying between 1200 and 1500 Hz in response to control demand, and not as a function of dynamic pressure. The maximum output of the pump is, therefore, not expected to exceed the values measured during CTV flights. Although the pump output is not, strictly speaking, a constant frequency, constant amplitude source, its "almost periodic" nature is superimposed on the wide band random aerodynamic sources. References 14 and 15 contain a collection of missile CTV flight shock and vibration data which have been processed by Martin Marietta Corporation (MMC). Copies of the raw data tapes were also made available to HDL and JPL for data processing and analysis to obtain additional information for defining a 3D testing environment for the missile fuzes. These data have been processed in various manners. Selected time segments of the data were processed to obtain PSD spectra of acceleration and, in some cases, the peak acceleration amplitude distribution associated with the spectra. These data segments were selected from each of the 10 CTV data tapes. Root mean square acceleration data were also processed for longer time segments from data tapes for CTV's 4, 7, 8, and 9. Some overall root mean square accelerations and 1/3 octave band acceleration plots were also reduced by JPL for verification.

The MMC vibration data analysis employed short time averages to determine the acceleration spectral densities. This approach has been discussed in References 16 and 17. The execution of this type of data analysis requires considerable judgment. Problems are encountered because the flight data is not strictly a random process and there are an insufficient number of samples at each flight condition to be statistically significant. The low flight sample size prevents ensemble averaging and computer and cost limitations prevent considering the flight as a whole. Nevertheless, from a practical engineering standpoint, a suitable definition of the flight environment may be developed. For simplicity, the time variance of the data during flight and from flight to flight is covered by enveloping a composite of the PSD spectra. During the enveloping process, the tendency is to broaden the peaks which appear in the spectrum. This conservatism allows for small changes in the resonant frequencies of missile hardware which will occur from flight to flight and assembly to assembly. The enveloping process is illustrated in Figure 12 where a typical composite of the acceleration spectral density of two time periods from CTV 10 are shown. In the later time sample, the low frequencies have a higher spectral density, while the pump frequency is dominant in the earlier time period. The envelopes of these two spectra are represented by the solid dark line in the figure. The grms level of the envelope spectra is higher than the RMS level of either actual spectra. Nevertheless, the envelope data does not represent a conservative estimate of the flight environment because worst case conditions did not exist during the CTV flight program. It is necessary to extrapolate the CTV data to worst case tactical conditions as explained earlier.

The following summarizes the results related to the CTV flight data evaluation. A typical RMS acceleration time history representing one of the CTV flights is shown in Figure 13. As can be seen from the data, the mean value was quite high at the beginning of the test flight due to transient shock. Figure 14 shows the short period PSD value within the first ten seconds and Figure 15 shows the longer time PSD value for the next 90 seconds. The results indicate that the general shape of the vibration spectra does change significantly for various time periods. The transient period which represents the missile flight shock environment was not considered in the present evaluation. Based on the short time averaged PSD, the envelope of all CTV flight data for both longitudinal and radial directions at missile station MS153 are given in Figure 16. The proposed flight vibration levels, which include a factor of 3.0, or 10 dB, above the maximum enveloped data (except in the frequency range between 1200 to 1500 where a factor of 1.5 was used), are presented in Figure 17. (The 10 dB margin is composed of 6dB for the tactical flight difference from the CTV flight as discussed earlier and another 4 dB to account for flight-to-flight variations). The results suggest that the previously specified flight acceptance vibration requirements, as compared with the proposed levels in Figure 18, are significantly more severe especially in the lower frequency range, and should be altered to reflect the actual flight measurements. (For qualification testing, an additional 3-4dB increase should be applied to the proposed flight level for design verification. This margin assures that even with the worst combination of test tolerances, repeat tests and variations in hardware parts, material and manufacturing, the flight integrity of the missile fuse will not be jeopardized).

For 3D test specifications, the coherence functions are best obtained from actual measurements. Figure 19 shows typical cross-coupling data at the missile body location where two direction measurements exist. Based on the available measurements, the proposed coherence function for XZ and YZ directions (longitudinal vs. lateral) is shown in Figure 20. High coherence (0.9) is expected in the lower frequency range (frequencies up to 200 Hz) but coherence drops off with increasing frequency. At the frequency range between 1200 Hz to 1500 Hz, the high coherence is due to a single source, the pump operation. No measurements were made on the cross-coupling of two lateral axes. Based on the assumption that the missile is symmetrical in the lateral axes (i.e., full correlation for X and Y axes), a value of 0.9 was assigned over the entire frequency range (20 to 2000 Hz). Figure 21 shows the simulated 3D time histories of the proposed test requirements for the Patriot missile fuze. Figure 22 demonstrates the resultant value plots in the 3D space.

For flight hardware, it has been suggested that the vibration test levels and duration must be closely related to the anticipated service environmental levels and durations (Reference 17). However, under normal conditions, the maximum flight environment upon which the ground test levels are based will be encountered only during a few flights and only for very short time periods. Based on the test flight data, the maximum vibration levels occur for brief periods and the environment for most of the flight is less than one half the maximum RMS level. From this it is concluded that test times longer than flight times seem to provide an unnecessary conservatism. However, the selection of a suitable test time is somewhat arbitrary; in fact the current SAM-D specification of 8 minutes along each of 3 axes is completely arbitrary. It is recommended that the test duration be established no more than the maximum flight time along each axis. Two (2) minutes test time is proposed for the PATRIOT missile fuze flight vibration testing.

CONCLUSIONS AND RECOMMENDATIONS

The preliminary 3D random vibration test requirements for the PATRIOT missile fuze for transportation and flight operation were derived separately and presented herein. The derivation process involved analyzing, enveloping interpreting and adjusting the field data. This process is complex and requires the exercise of many engineering judgments. The intent has been to make judgments which result in conservative vibration test levels. In the extreme, this can lead to overly conservative test levels and can cause unnecessary laboratory failures of flight worthy hardware. The opposite extreme is to pass unworthy hardware which results in mission failures. Also, these 3D test criteria, especially higher coherence values, were established theoretically based on the available field data and, therefore, should be verified by HDL 3D-VTS experimentally. In future 3D vibration test planning for the PATRIOT missile fuze, further investigation is recommended to determine the role the coherence function plays between the input axes and to study the effects of varying the lengths of the axes of the 3D excitation ellipsoid on damage potential.

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Table 1. Resonant Frequency of PATRIOT Missile Fuze

		X-AXIS			Y-AXIS			Z-AXIS		
TEST DESCRIPTION	SOURCE	FREQUENCY	Gmax	Psd	FREQUENCY	Gmax	Psd	FREQUENCY	Gmax	Psd
ACCELEROMETER-1										
Sine Sweep	HDL	920	5		370	15		370	22	
Random	LET	920		.001	370		.0015	370		.275
Random	HDL	920		.400	370		.90	370		6.000
Random max	LET	575		.030	1125		.007			
Random max	HDL	500		2.00	1200		1.00			
ACCELEROMETER-2										
Sine Sweep	HDL	370	4		370	6		370	30	
Random	LET	370		.015	370		.030	370		.030
Random	HDL	370		2.25	370		.125	370		3.000
Random max	LET	1225		.020	525		.040			
Random max	HDL				525		.300			
ACCELEROMETER-3										
Sine Sweep	HDL	600	12		920	12		370	22	
Random	LET	600		.0015	920		.00015	370		.120
Random	HDL	600		.007	920		.040	370		4.000
Random max	LET	1175		.140	400		.035			
Random max	HDL	1175		.125	370		.500			

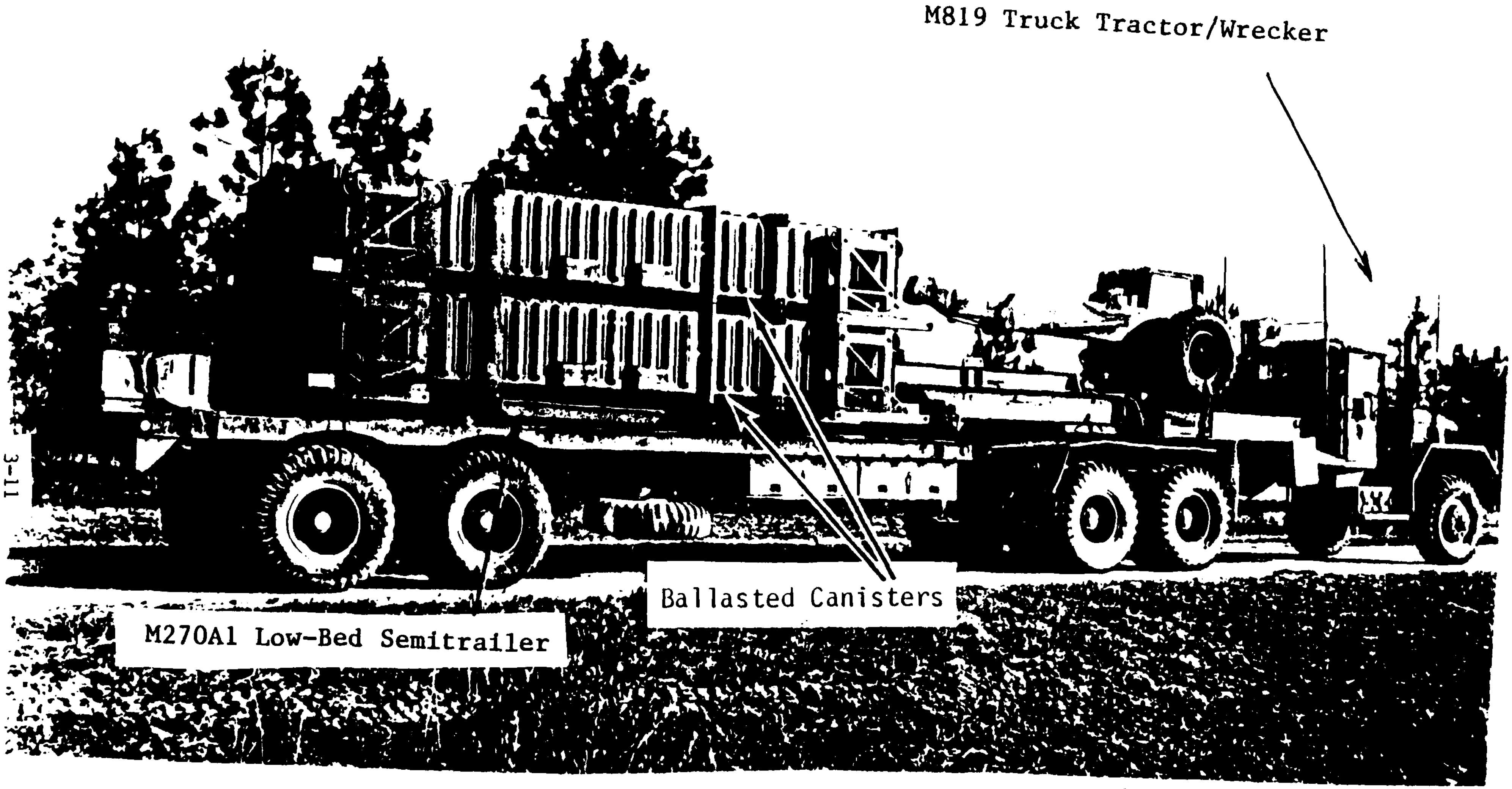


Figure 1. Guided Missile Transporter with Payload in Place

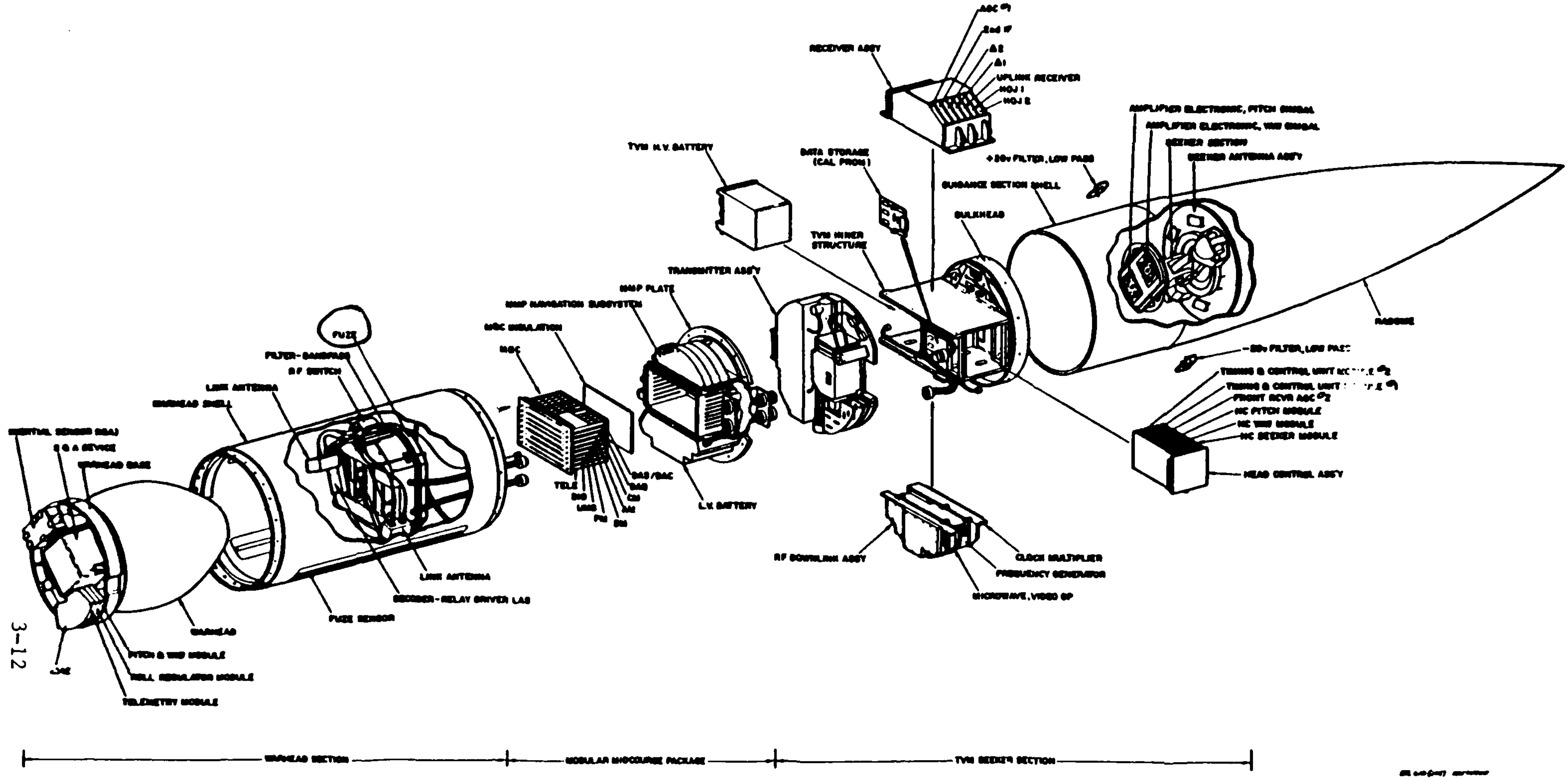


Figure 2. PATRIOT Missile/Forebody & Seeker Sections

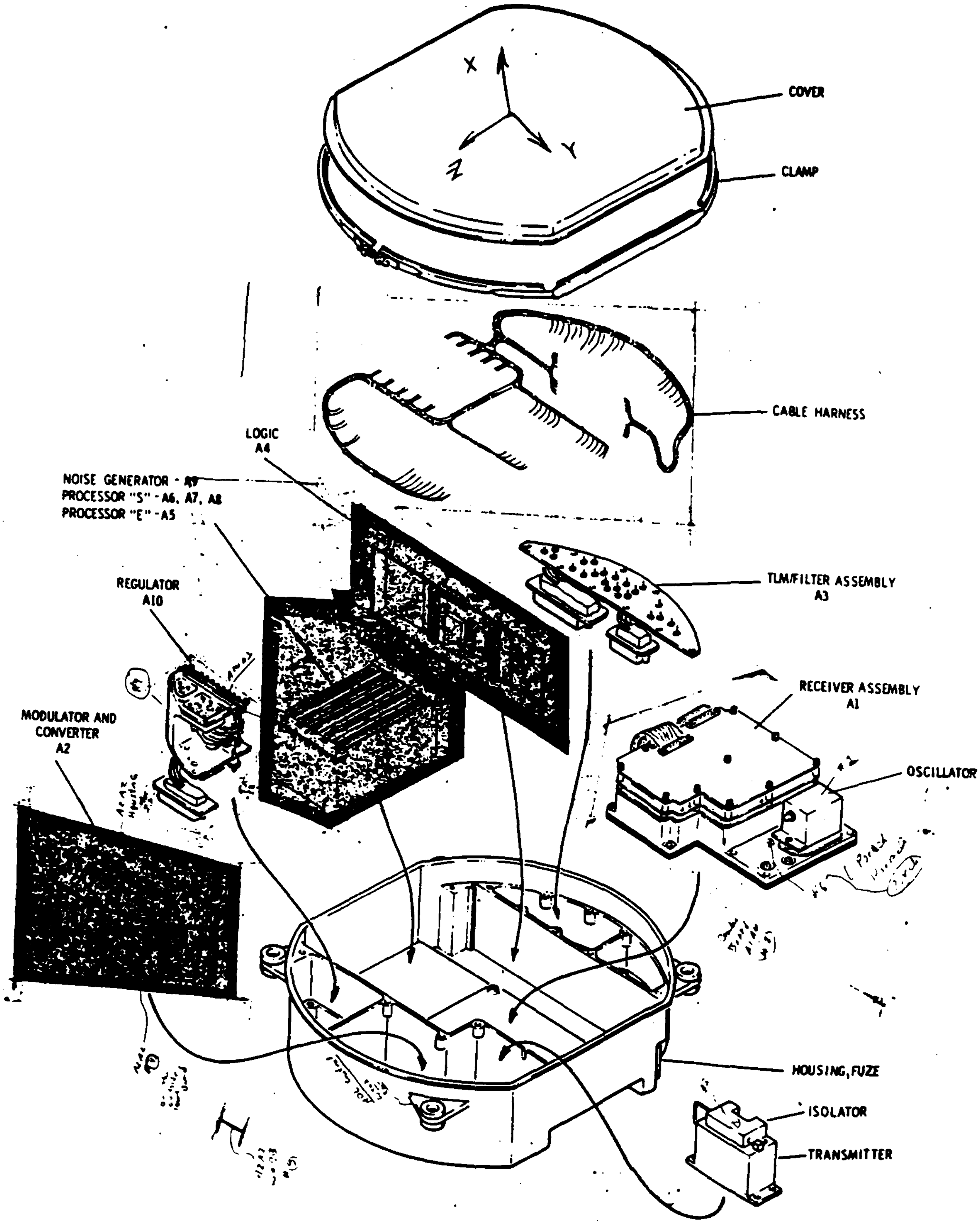
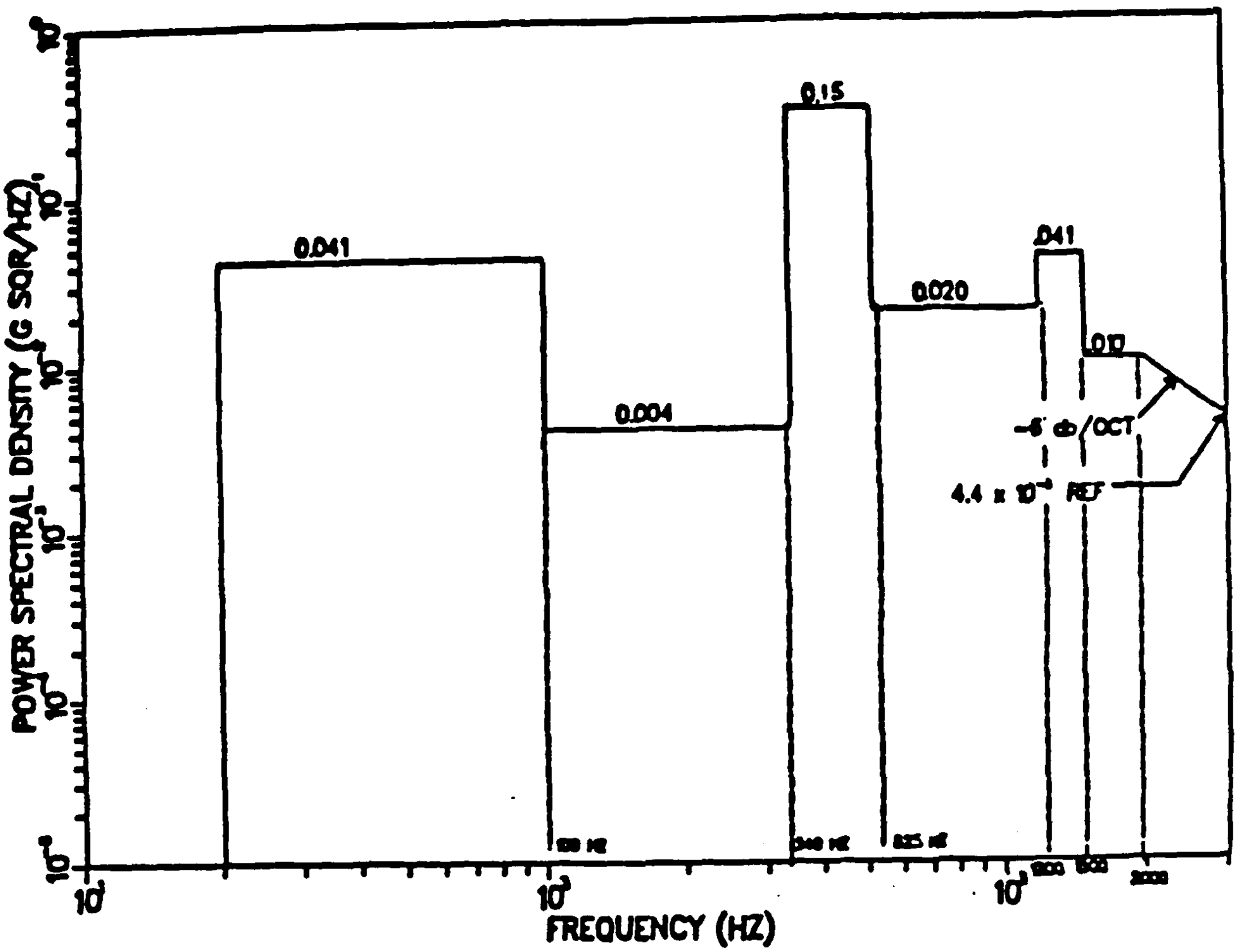


Figure 3. Overview of PATRIOT Missile Fuze

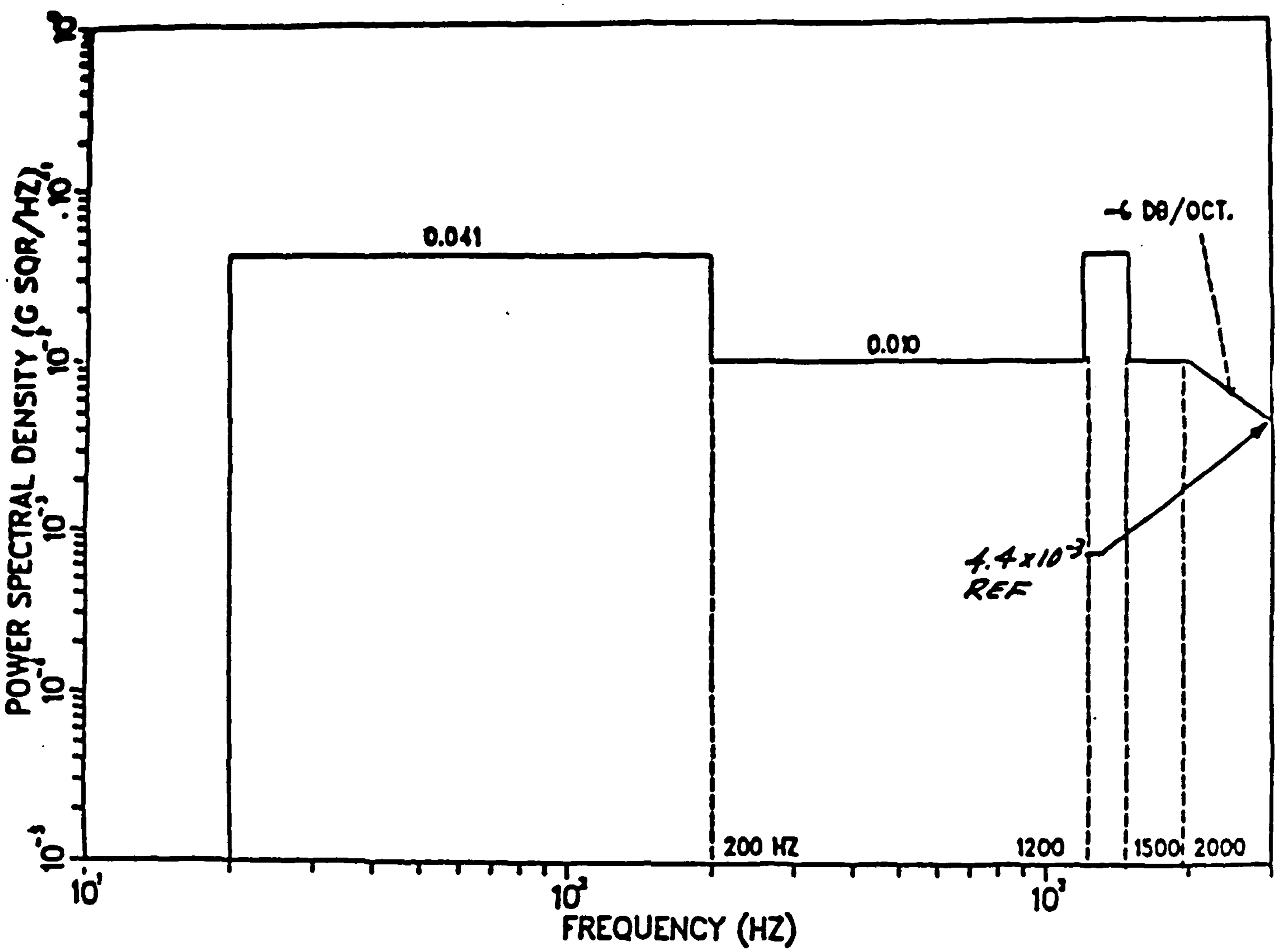


G RMS = 8.33 ±0.83 G's

Duration: 8 minutes or 8 minutes each per split-band

Tolerance on amplitude, freq. and duration see MIL-F-60966

Figure 4a. Flight Vibration Profile - Roll Axis



G RMS = 6.43 ±0.64 G's: G RMS 20 - 2K Hz = 5.89: G RMS 2K - 3K Hz = 2.58

Duration: 8 minutes or 8 minutes each per split-band

Tolerances on amplitude, freq. & duration: MIL-F-60966

Figure 4b. Flight Vibration Profile - Pitch and Yaw Axes

Figure 5. M127, 12-ton Semi-Trailer With Dummy Cargo Load

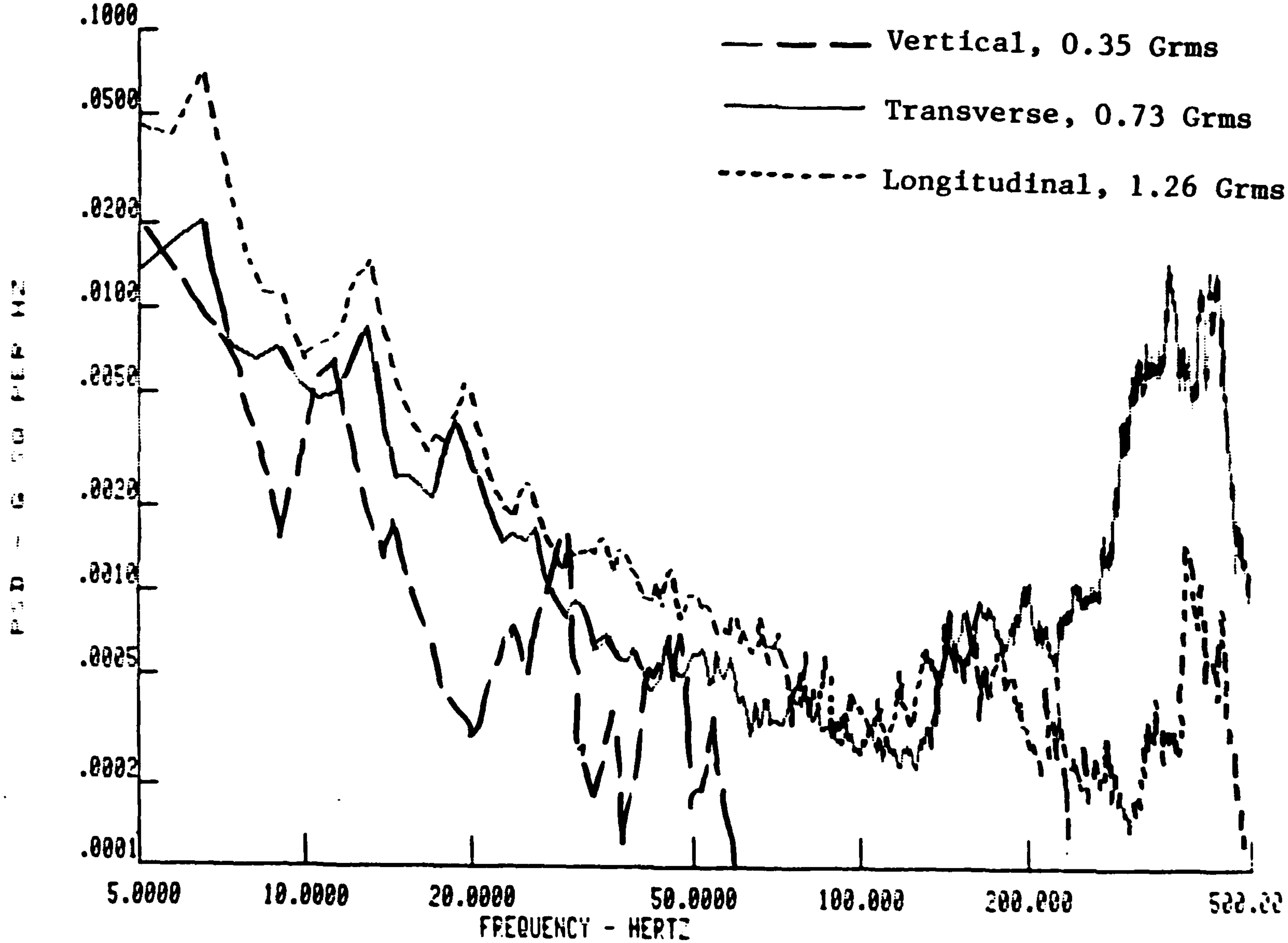


Figure 6. 12 Ton, Semi-Trailer Composite Vibration Environment

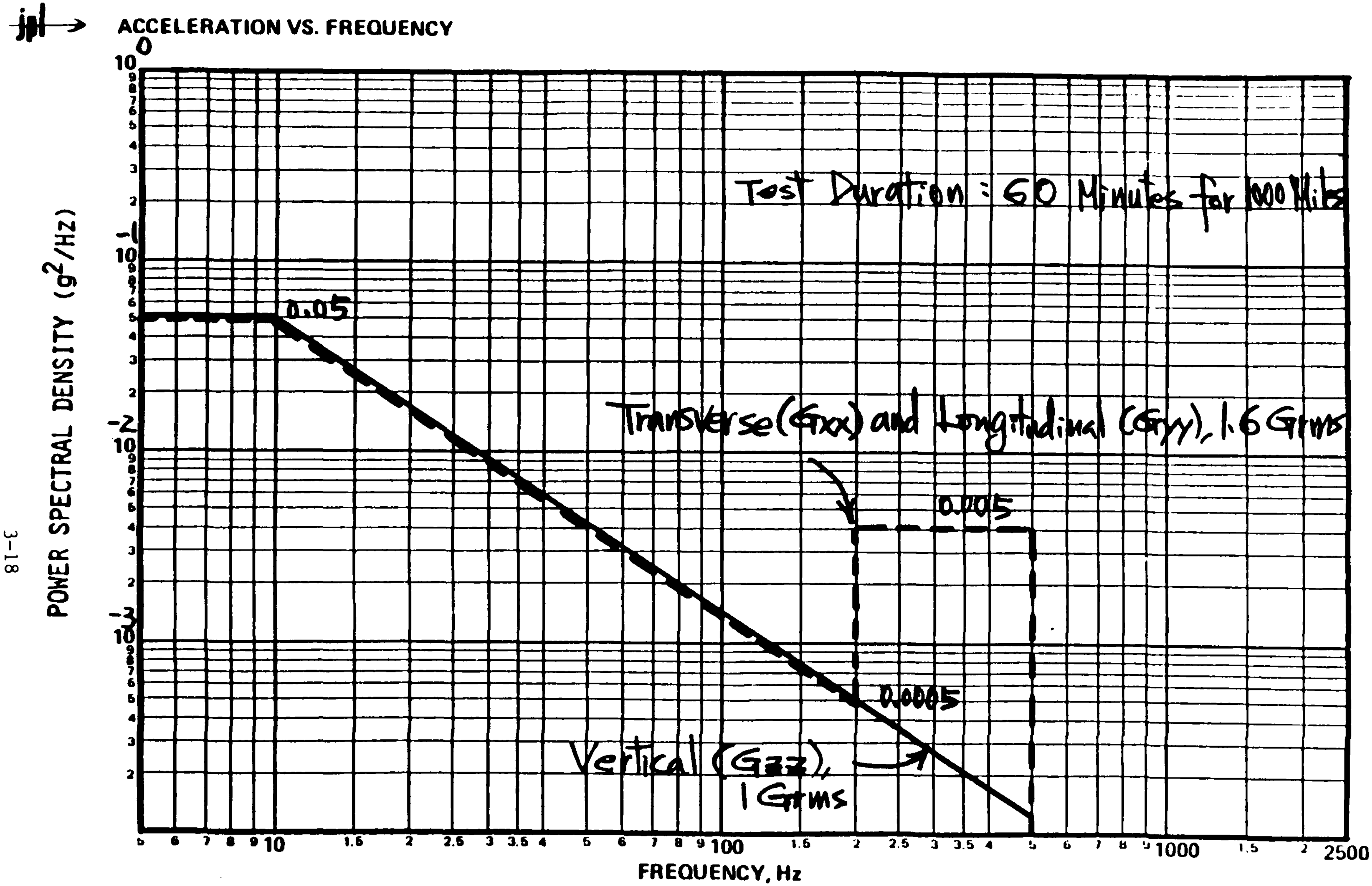


Figure 7. Proposed Transportation Vibration Test Requirement For PATRIOT Missile Fuze at Transporter base

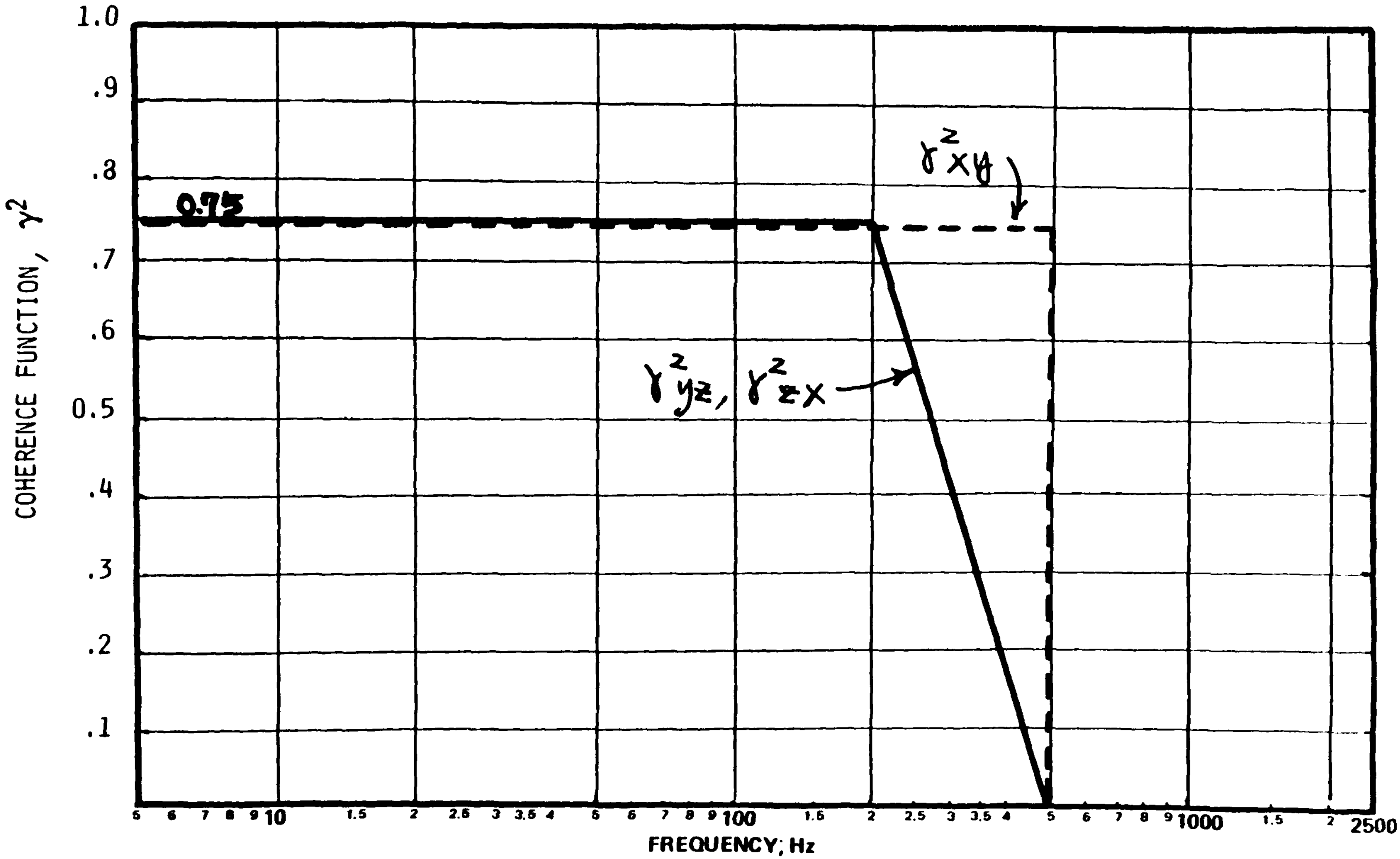


Figure 8. Proposed Coherence Functions (Transportation Environment) For PATRIOT Missile Fuze at Transporter base.

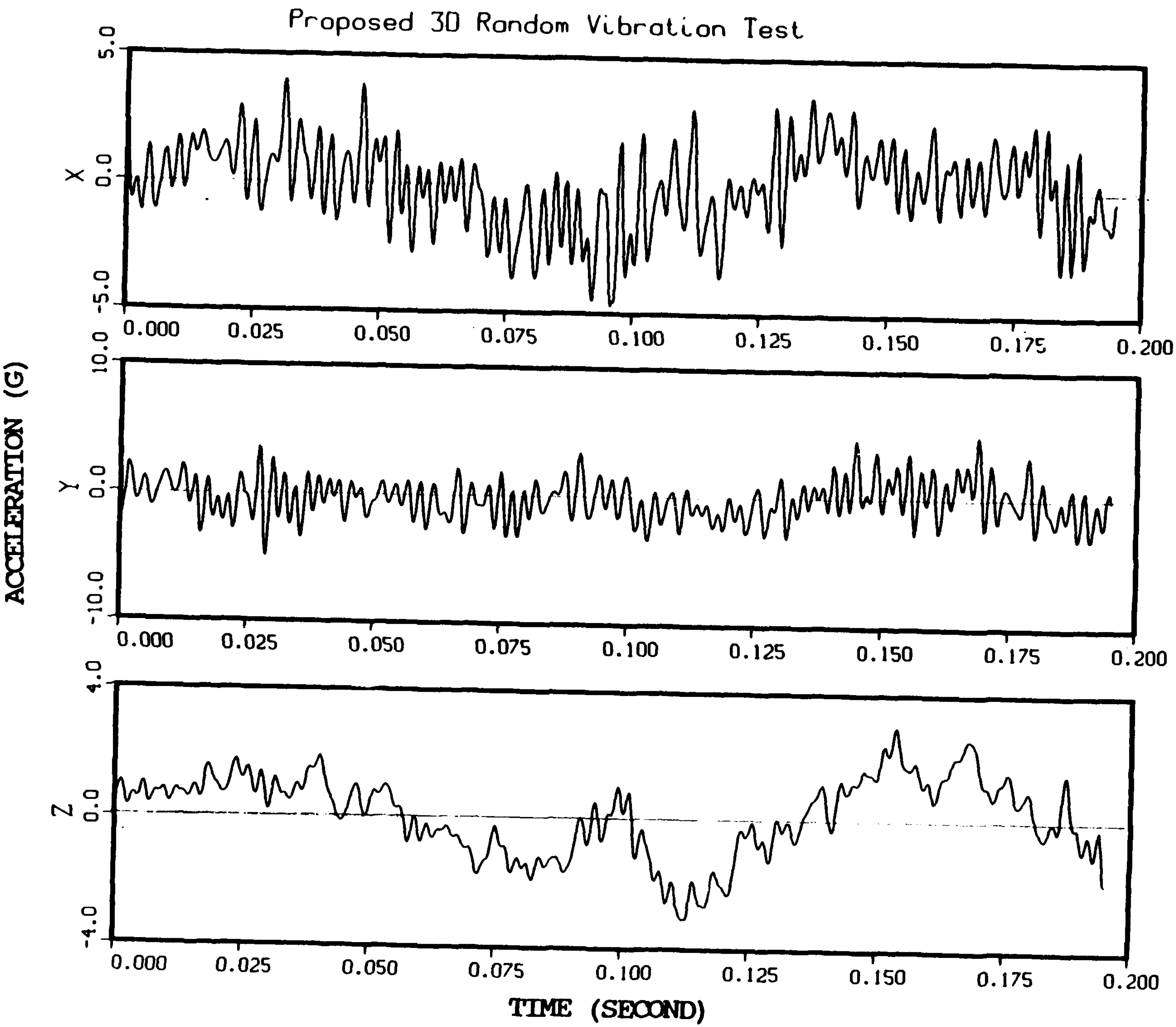
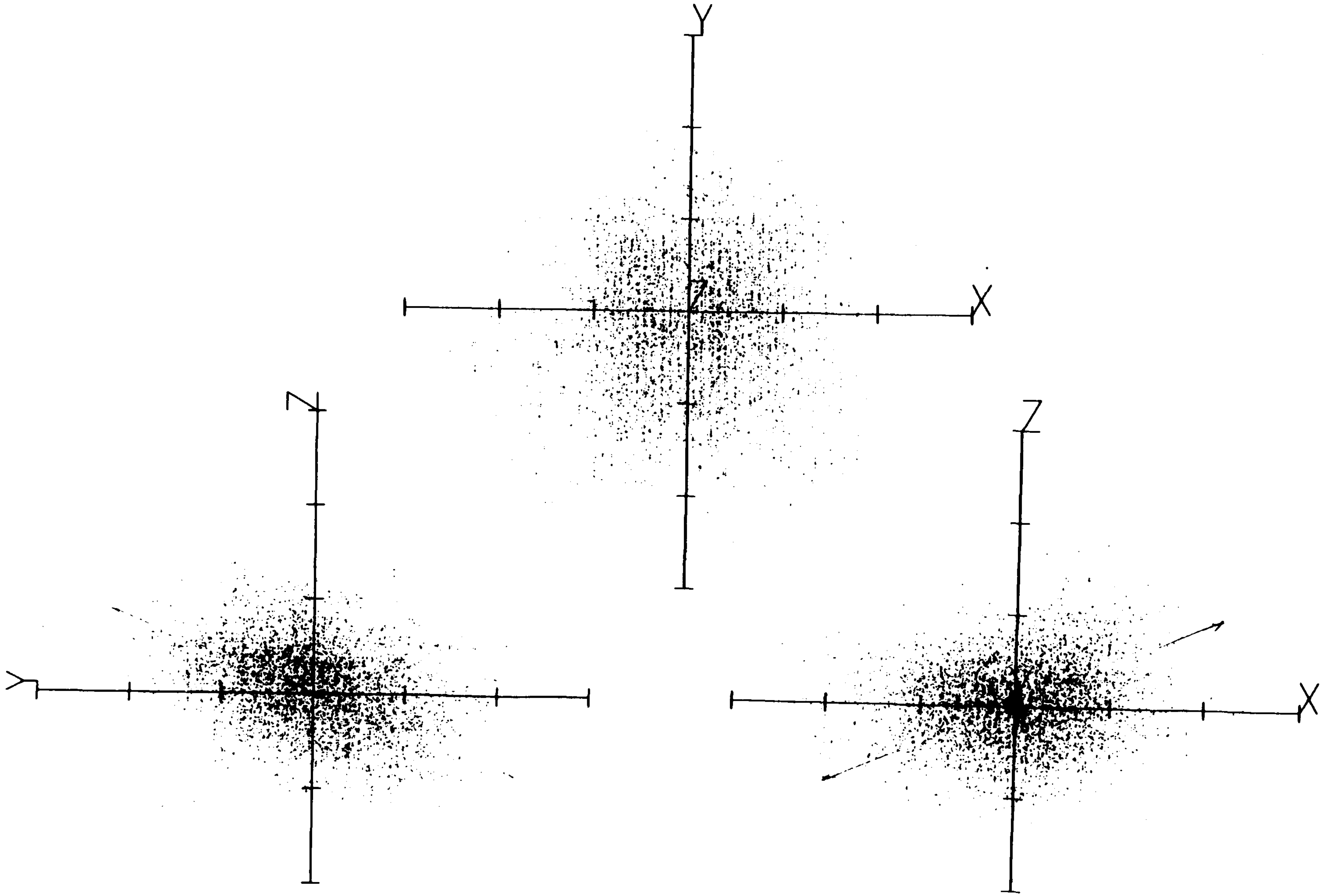


Figure 9. 3D Time Histories of Proposed Transportation Vibration Test for PATRIOT Missile Fuze



Scale: Acceleration (G)

Figure 10. Projected Views of PATRIOT Missile Fuze Transportation Vibration Test Environment

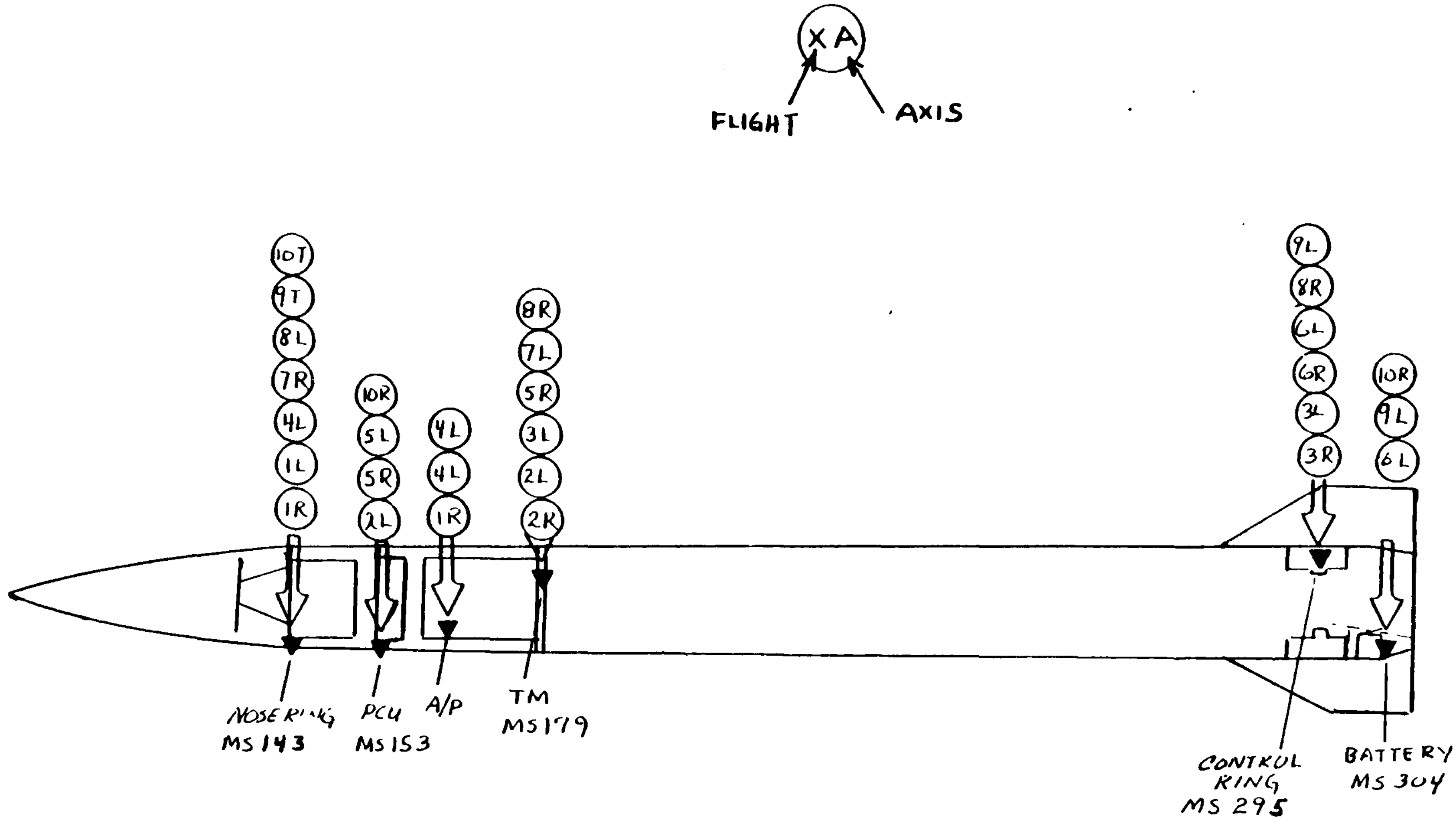


Figure 11. SAM-D Measurement Locations

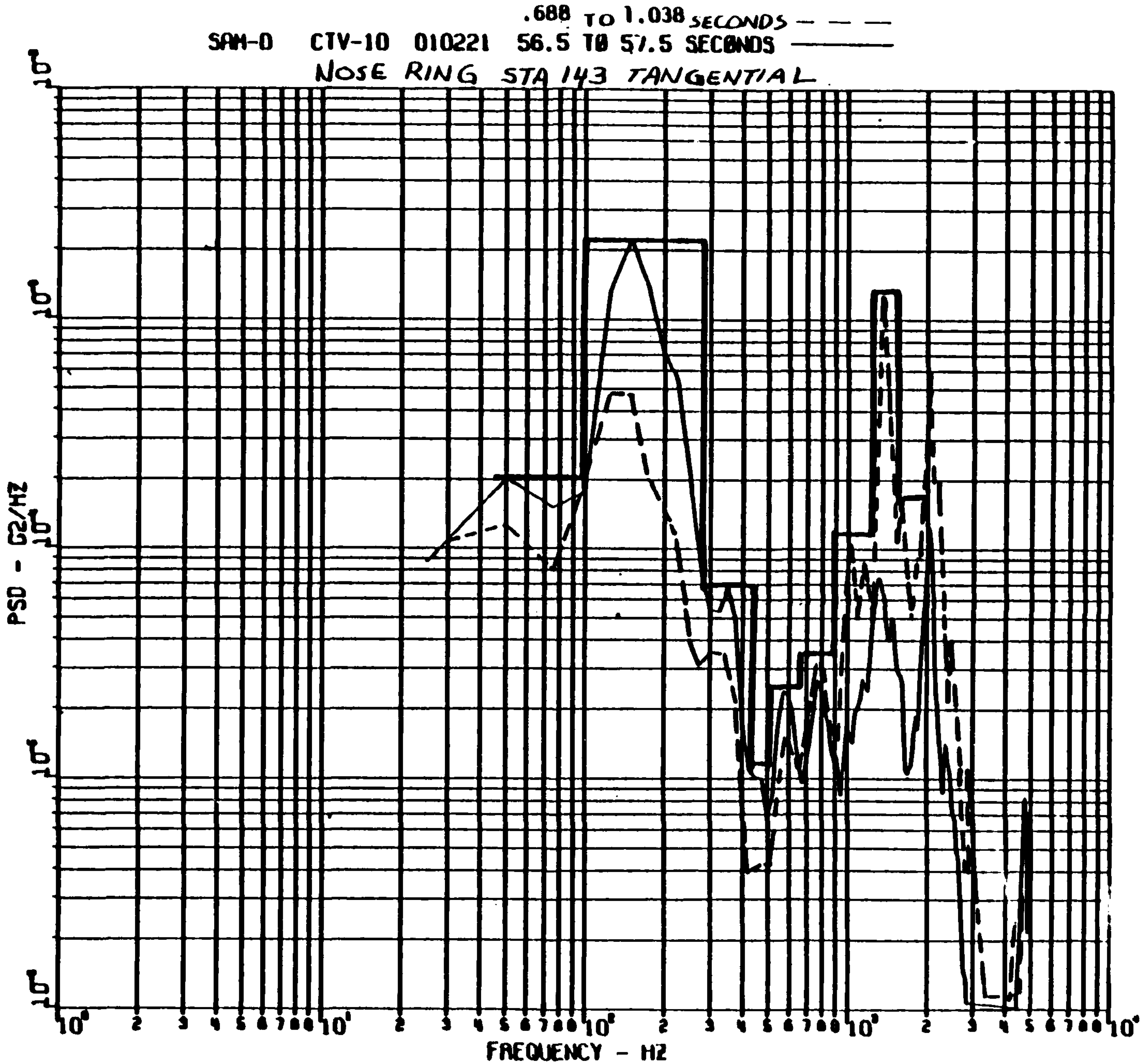


Figure 12. Envelope of Acceleration Spectral Density Spectra

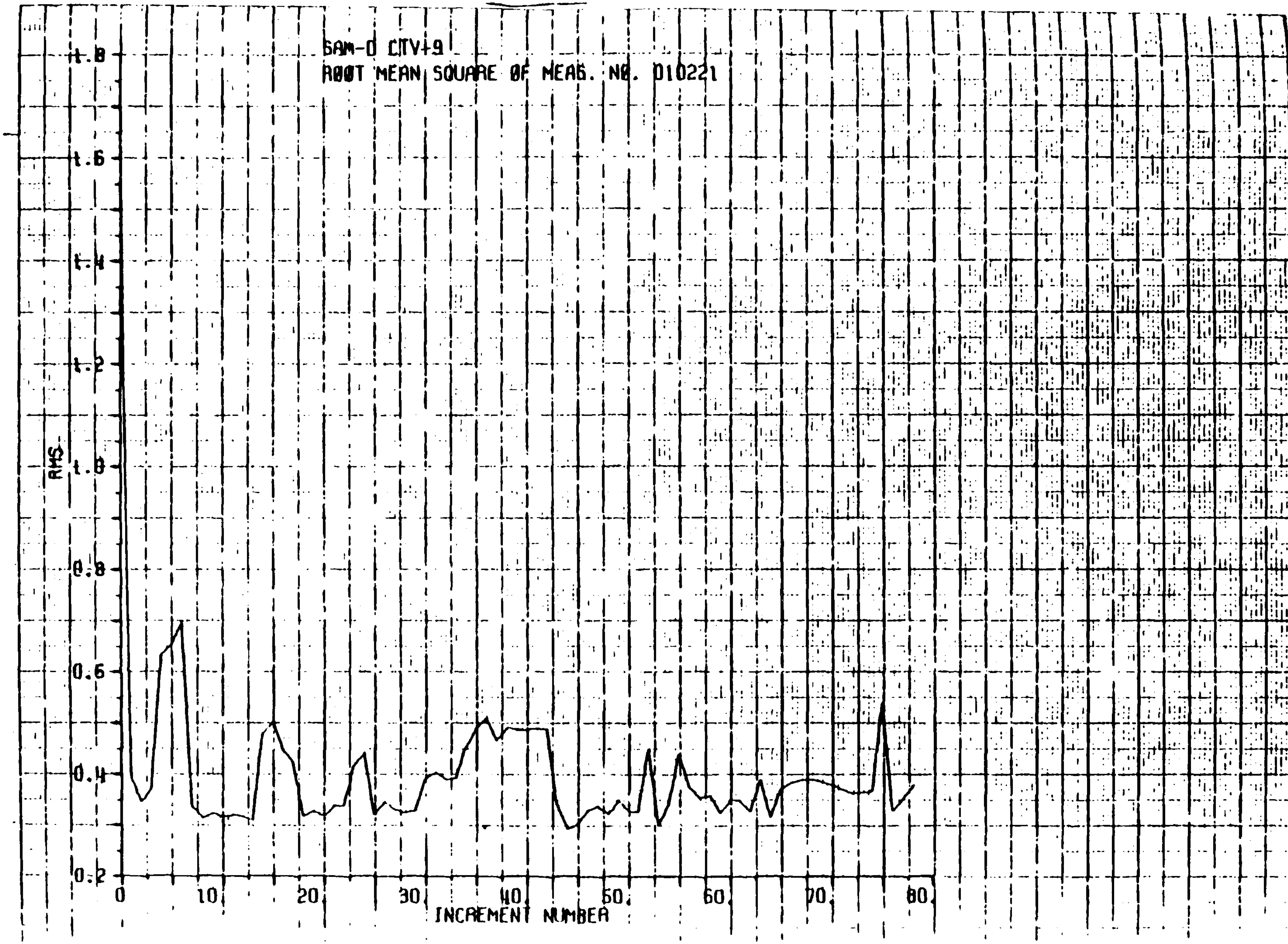


Figure 13. Root Mean Square of CTV-9 Flight

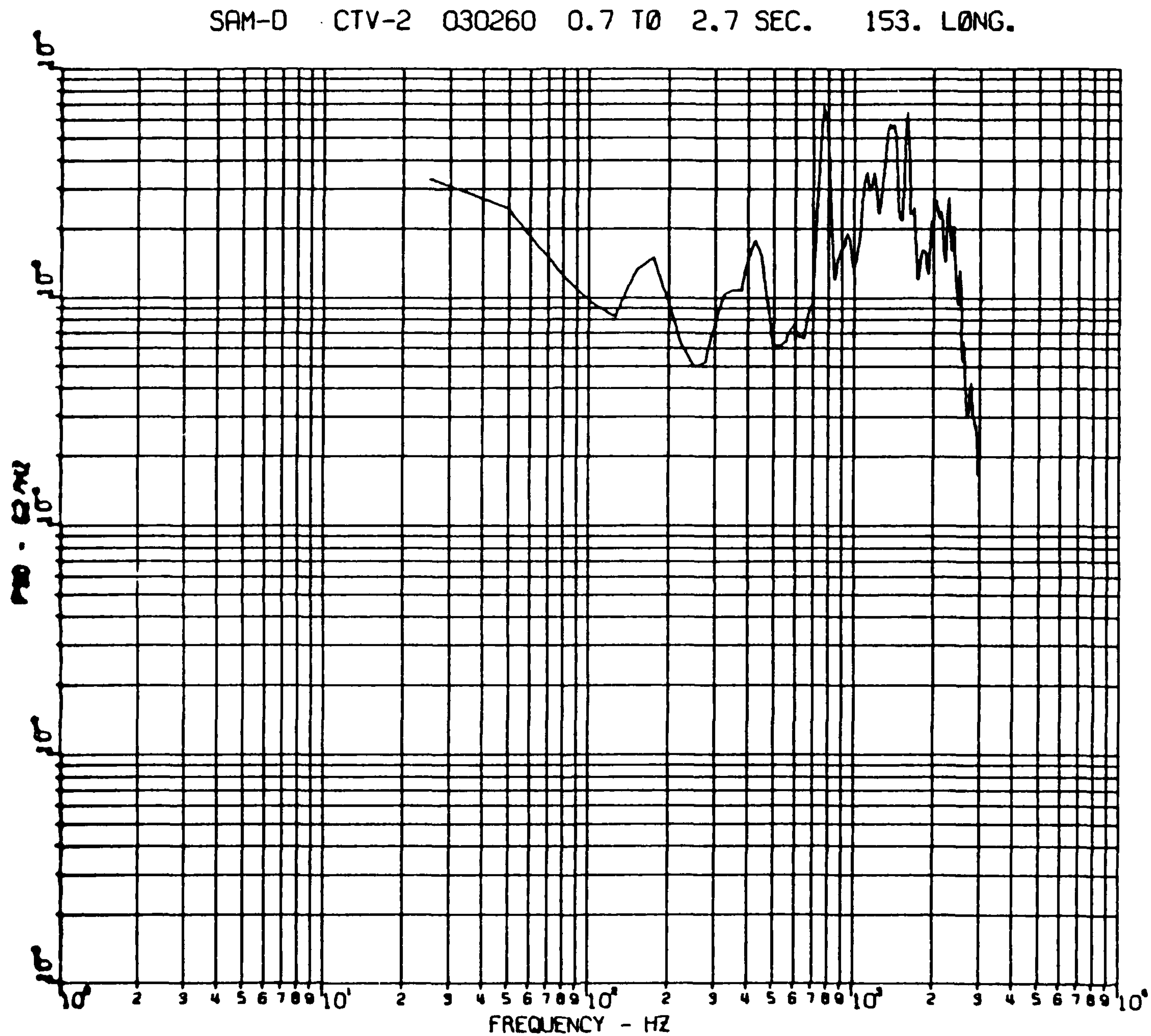


Figure 14. Short Period PSD of CTV-2 Flight

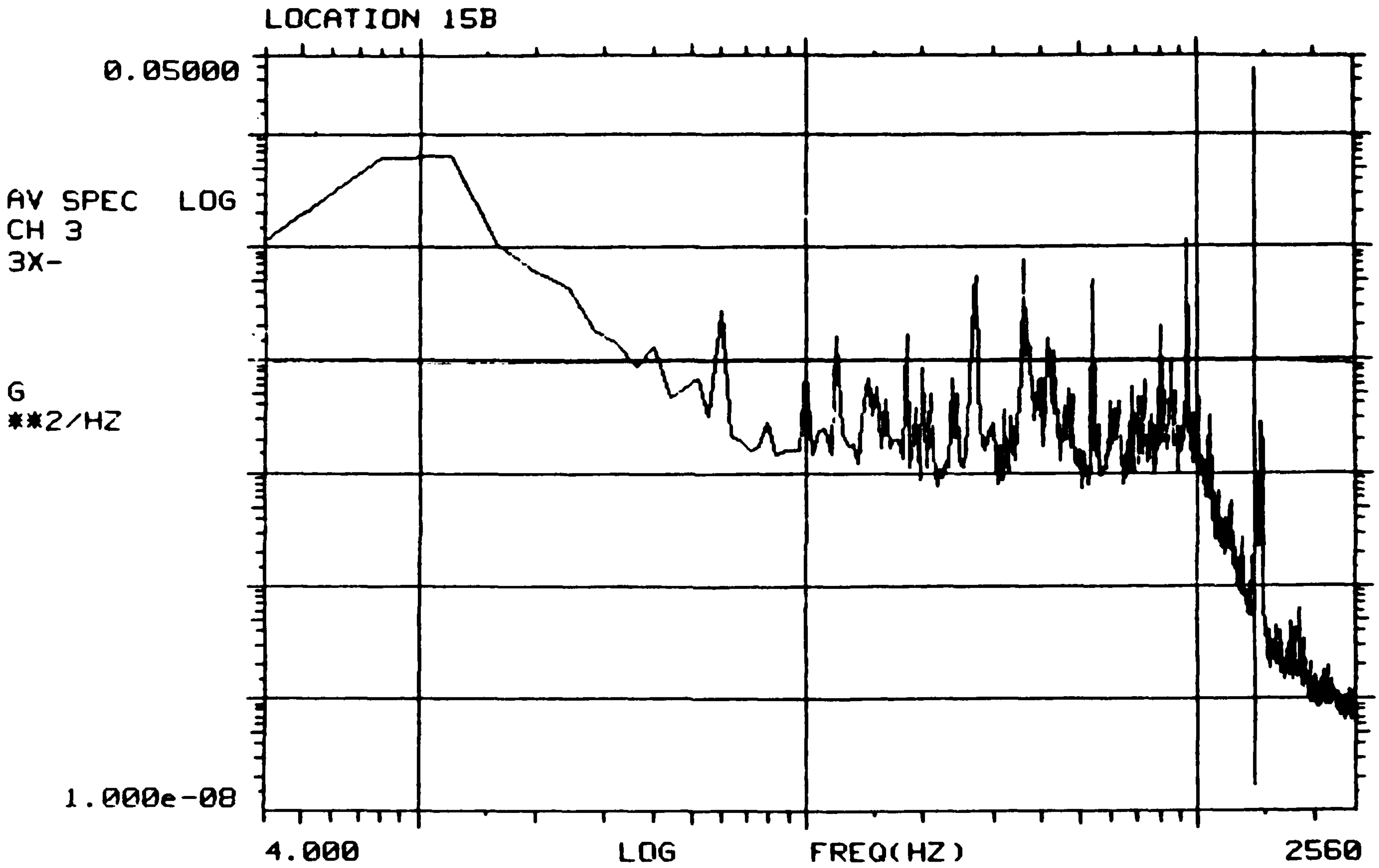


Figure 15. Long Period PSD of CTV-2 Flight

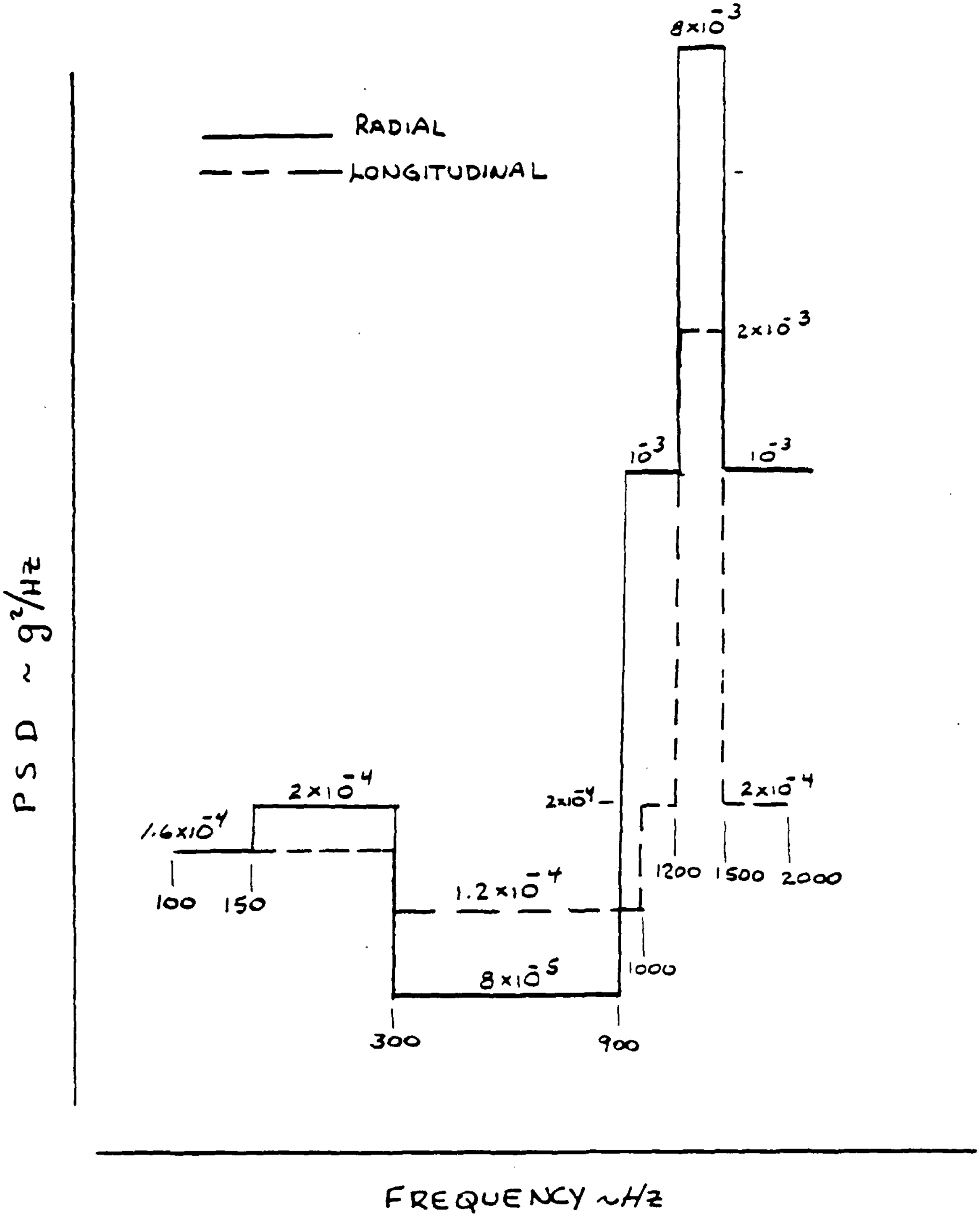


Figure 16. STA 153 Enveloped CTV Flight Data

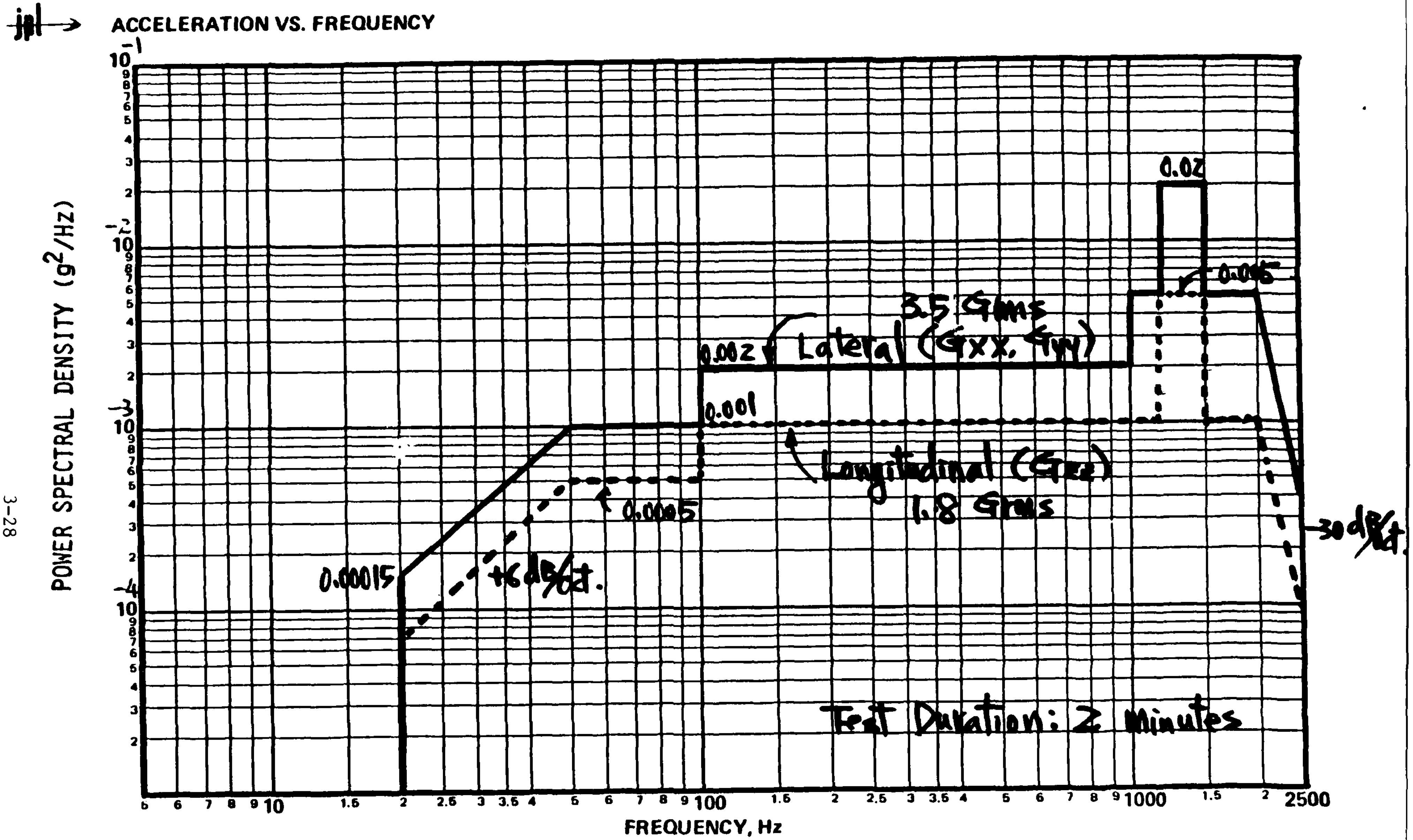


Figure 17. Proposed Flight Vibration Test Requirement For PATRIOT Missile Fuse

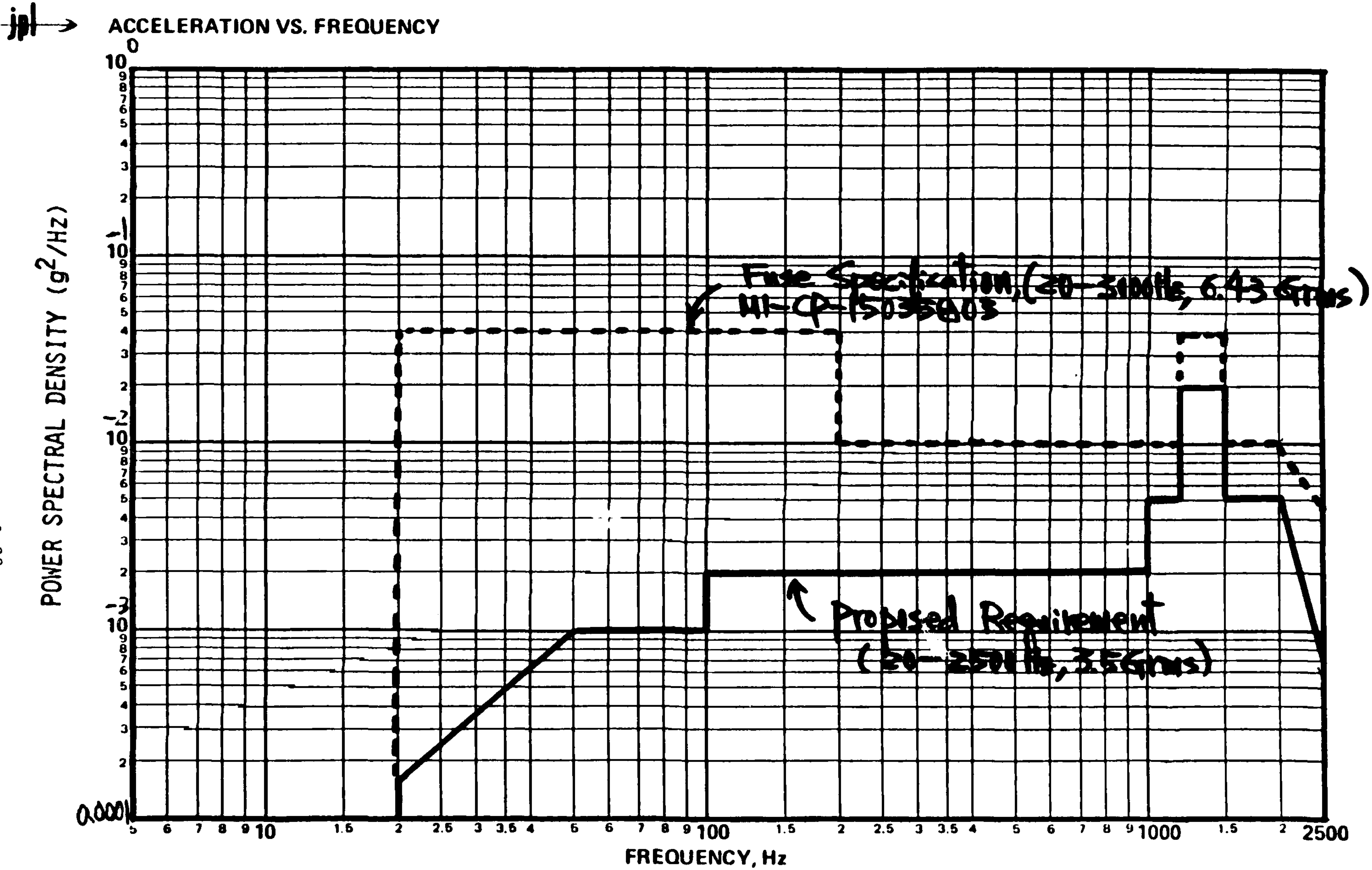


Figure 18. Comparison of Proposed Flight Vibration Levels With Specification

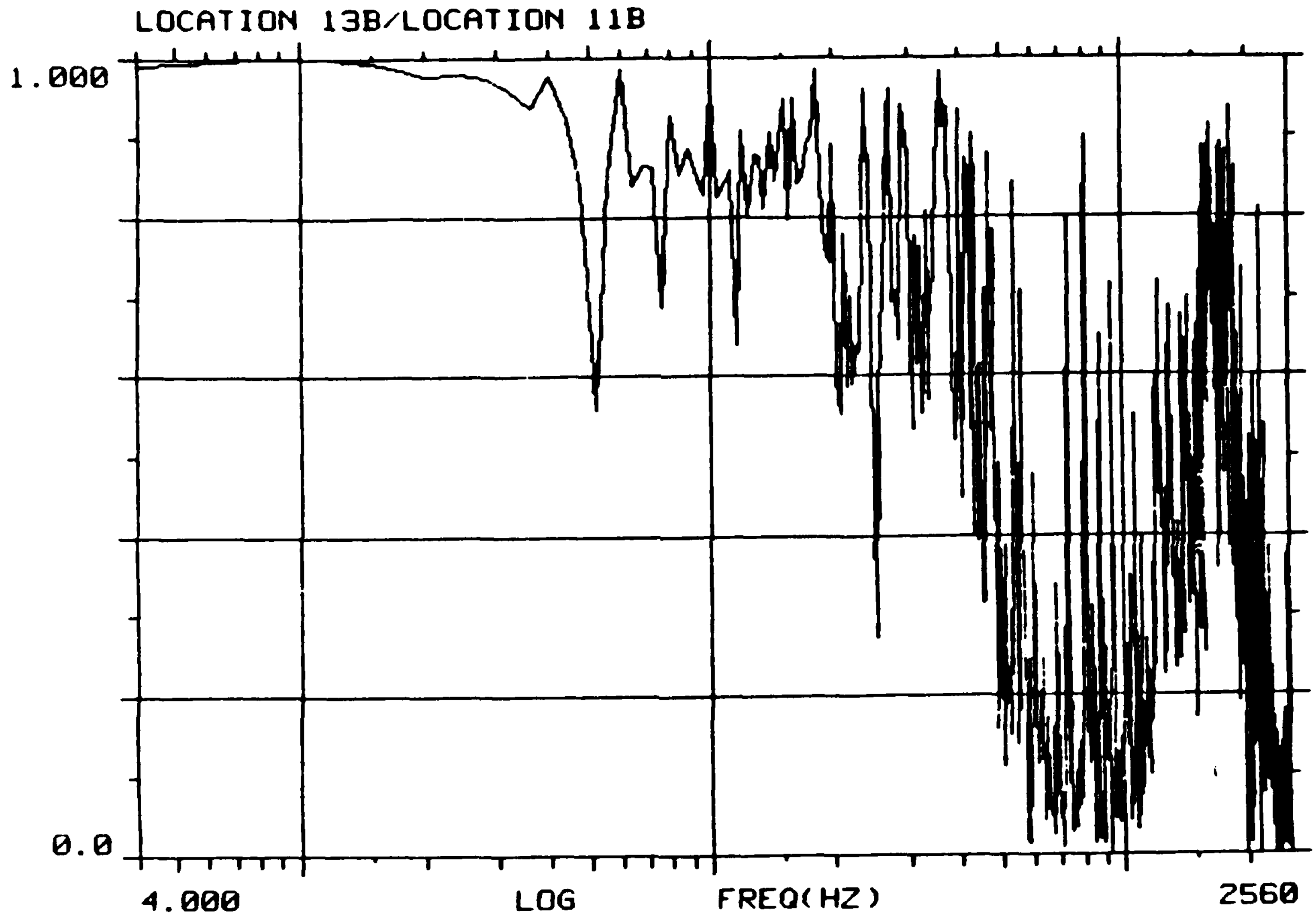


Figure 19. Coherence Function of PATRIOT Missile Flight Vibration Environment

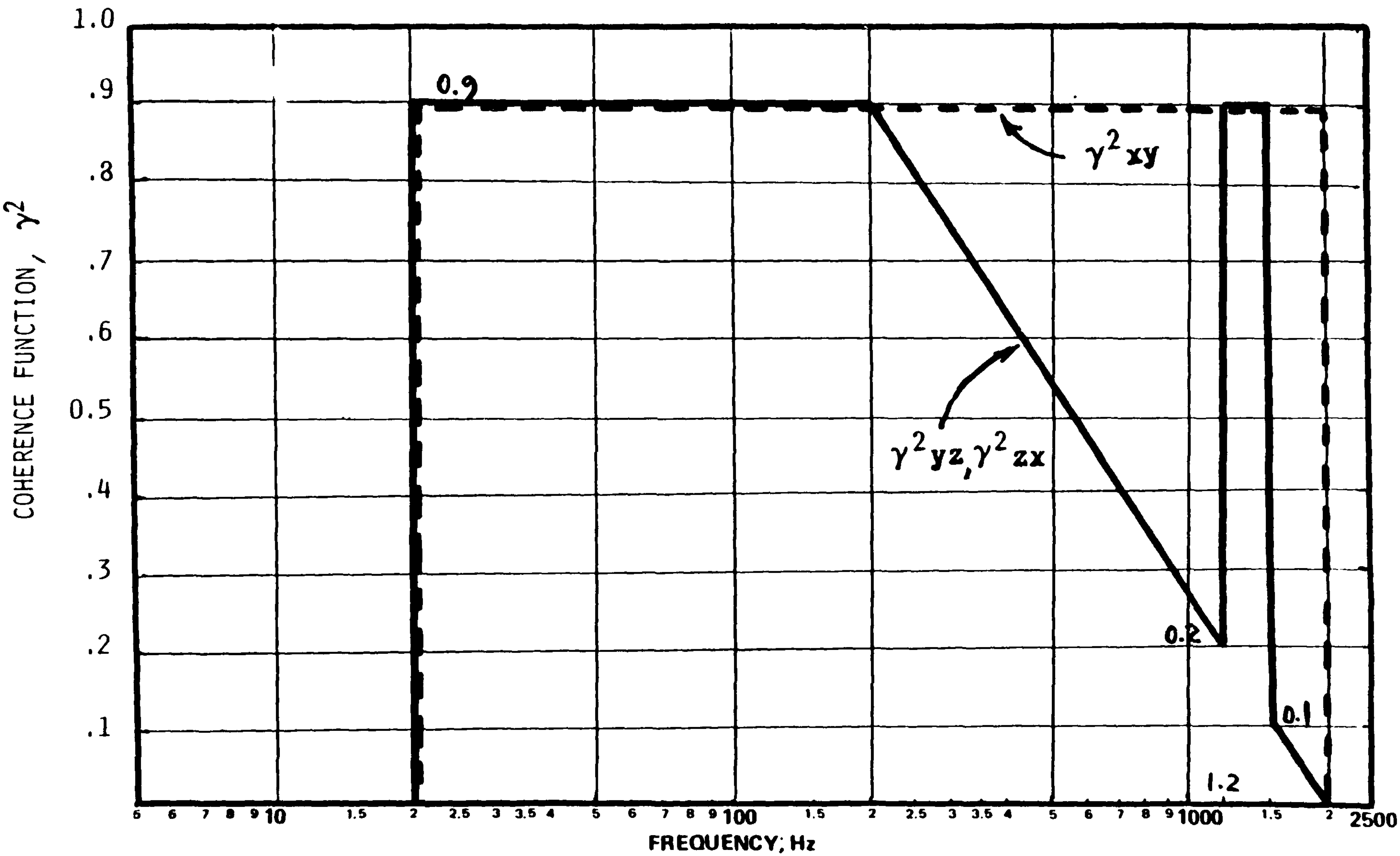


Figure 20. Proposed Coherence Functions (Flight Environment) For PATRIOT Missile Fuse

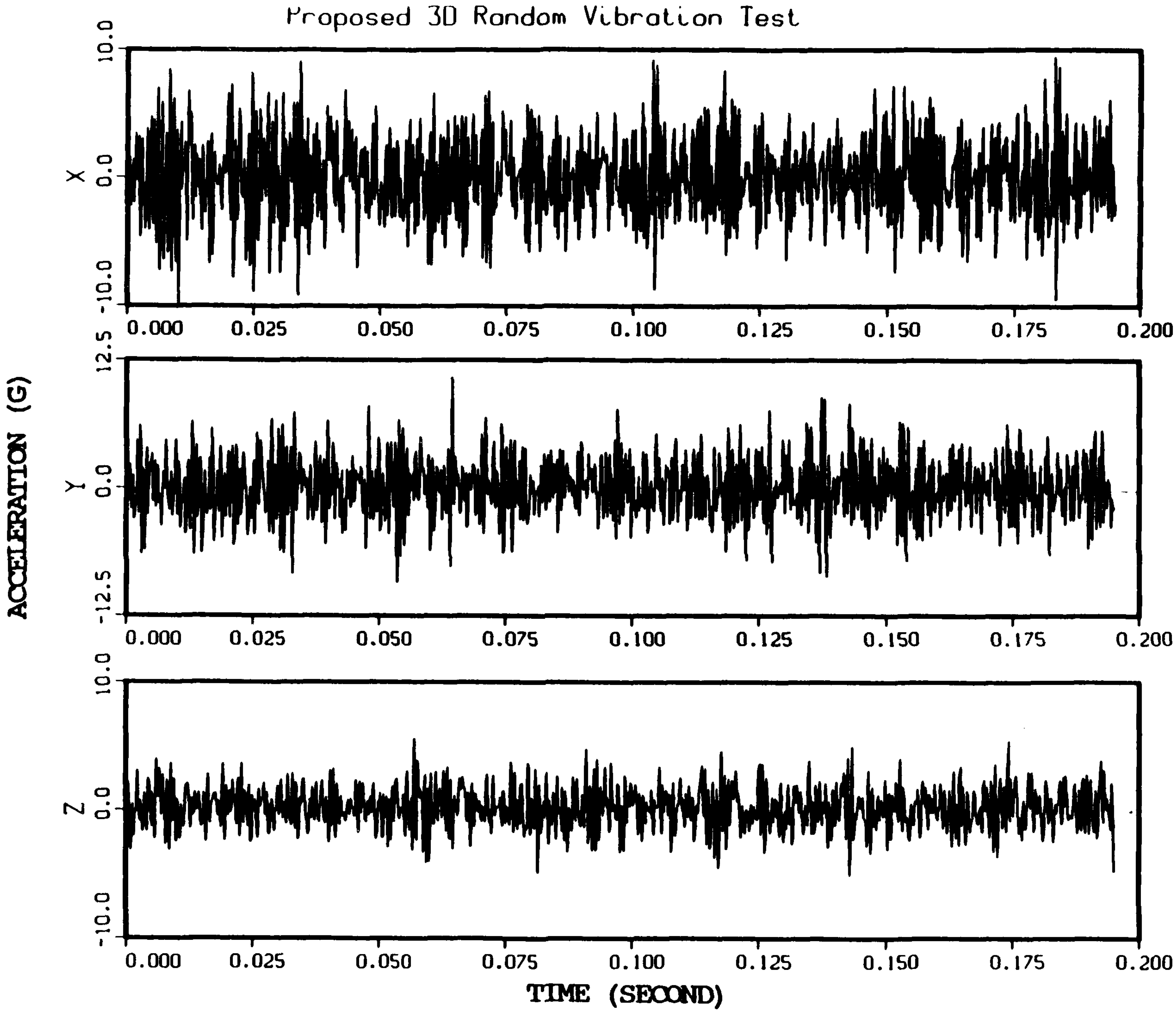
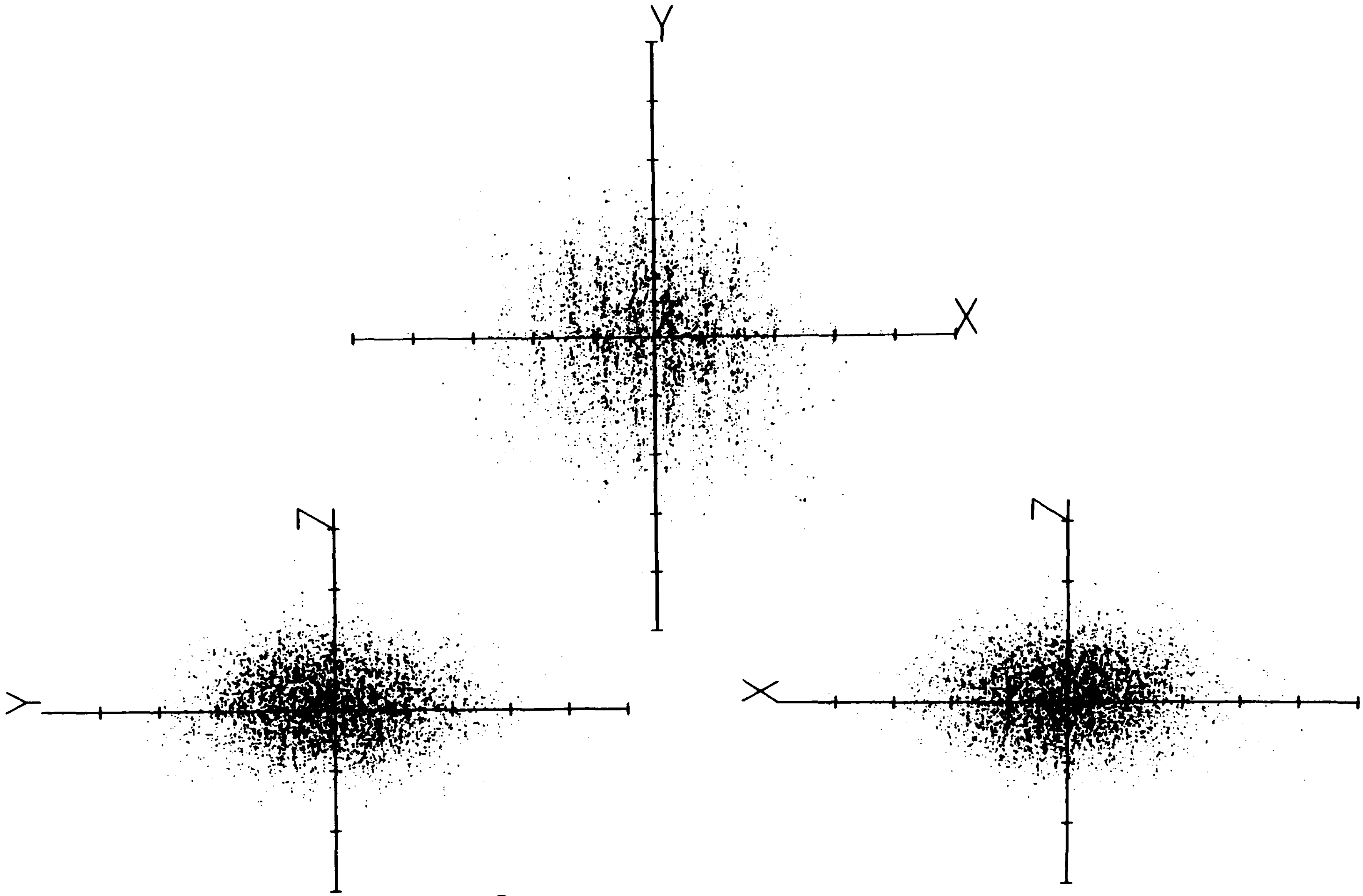


Figure 21. 3D Time Histories of Proposed Flight Vibration Test Requirement for PATRIOT Missile Fuze



Scale: Acceleration (G)

Figure 22. Projected Views of PATRIOT Missile Fuze Flight Vibration Test Environment

APPENDIX A

DETERMINATION OF DYNAMIC TEST REQUIREMENTS

SUMMARY

The proper dynamic test requirements for electronic-mechanical hardware are intended to envelope the maximum vibration environments during the expected service condition. The environmental test is to simulate the environment by reproducing the essential deterministic and/or statistical characteristics of that defined environment. Random waveforms with approximately Gaussian distribution are generally selected to represent these service environments in a test laboratory. The vibration test levels are based on response measurements made during ground tests or service and/or analysis as appropriate. Where sufficient ground and field data are available, the maximum predicted environment is typically derived from the mean value plus 2 times the standard deviation, as determined through statistical analysis procedures. The test duration of the maximum environments is typically defined as the total period during service when the vibration amplitude is greater than one-half the peak amplitude. Where insufficient test data are available, a conservative envelope of the extrapolated data obtained from previous similar service conditions or ground tests must be applied to account for the variability of the environment and uncertainty in the prediction. The final "smooth" spectral representation for the maximum predicted environment must also be greater than the minimum screening level which efficiently reveals workmanship defects in the test hardware. Three mutually perpendicular axes are normally excited to fully test the hardware.

A-1 INTRODUCTION

Vibration testing should be viewed as a verification process to qualify the design and/or to reveal latent defects in the hardware. A possible approach to achieve these objectives would be to simulate the service profile as closely as possible to detect defects and with a known margin to qualify the design. This is based on the rationale that exposure to the service environment would reveal all and only those failures that would otherwise occur in the field. However, an effective testing process may not be dependent on matching an environmental test program to specific service profiles.

In this appendix, current industry practice for tailoring the test requirements is presented. Considerations are presented for tailoring to achieve the optimal environmental test for the test objectives. These considerations are based on analysis of the defect type, hardware anatomy, and program needs.

A-2 VIBRATION TEST CURRENT PRACTICE

The dynamic test environment is intended to envelope the maximum vibration environments during ground transportation and handling, launch and flight. The service environment consists of transients (including low frequency and high frequency), sine vibration for rotating machinery, acoustics, random vibration and quasi-steady flight acceleration.

The selection of an appropriate vibration test environment is essentially limited to three practical possibilities: (1) transient time histories; (2) sinusoidal, either fixed or swept frequency; (3) random with approximately Gaussian distribution. The circumstances in which the selection of a particular waveform may be made are described below.

If the basic approach to the selection of test environments is to simulate the service environment or environmental effects, then the selected waveform should reproduce the essential deterministic and/or statistical characteristics of that environment. It might appear that the first option listed above would be the immediate choice in this case. However, for a number of reasons, it is believed that the apparent advantages of this method of achieving the desired waveform are largely illusory and that this approach is suitable only in very special circumstances. If the time history is not to be reproduced, then the major waveform characteristics which must be reproduced are (1) the variation of intensity with frequency and (2) the statistical characteristics of either the instantaneous or peak values of the waveform in terms of the probability density function. In view of the above two conditions, it can be said that fixed frequency sinusoidal waveforms rarely reproduce the desired characteristics of the service environment. On the other hand, it has been found that the waveform characteristics of a random noise signal with Gaussian or normally distributed amplitudes and appropriate spectral shaping will generally reproduce the essential characteristics of the service environment, which leads to the selection of the third option above. A number of tests, such as quality assurance or proof-of-workmanship, tests have purposes which are only indirectly related to the service environment and for which, the waveform may be selected arbitrarily to best suit the purpose of the test. The objective here is to select a waveform which will efficiently reveal defects in the test article while avoiding unrealistic damage.

The adequacy of the waveform selected can best be judged after the fact, based on the subsequent failure history in equipment so tested. However, it has been observed that the waveforms consisting of random vibration with Gaussian or normally distributed amplitudes do appear to be relatively more efficient in revealing hardware defects in assembled equipment.

A-3 DEVELOPMENT OF RANDOM VIBRATION TEST REQUIREMENTS

The random vibration environmental test parameters which must be specified are: (1) vibration magnitudes, such as vibration levels and frequency range; (2) test duration and test orientation; (3) test accuracy (tolerances). Each of these conditions can generally be specified independently, although the simulation characteristics of the test are affected by interrelationships between these parameters. Also, before development of a specification, a study of the test hardware should be performed to

a. determine the dynamic hardware characteristics to establish the potential effectiveness of the vibration testing.

b. ascertain the upper acceleration level which, if exceeded, could cause hardware degradation, and

c. identify the vibration level which is sufficient to reveal hardware specific defects. A structure is not normally significantly stressed except at its resonant frequency modes. For effective testing, one must produce adequate excitation at the location of the defect.

A-3.1 Vibration Amplitude

The vibration test level is intended to simulate the maximum service environment. It is necessary to determine a test level which will provide high confidence that the hardware will perform satisfactorily in its mission environment when installed in the complete system. The usual approach, assuming that vibration data on the actual or a similar hardware system in its service environment is not available, is based on the determination of the transfer or frequency response function between the specified forcing function input locations and the hardware attachments, either by analysis or by test of a structural model of the complete system. Multiplication of this frequency response curve by the specified input would presumably then yield an accurate estimate of the average hardware environment. The test environment is then derived by adding a margin to the predicted environment to account for various uncertainties. However, test levels obtained in this manner would undoubtedly vary with frequency in a very complex fashion, thus leading to very complicated tests. Second, the dissimilarities between the real equipment and either a laboratory test model or an analytical model would render the fine detail of the frequency response curves essentially meaningless. Furthermore, it is likely that the high end of the frequency range would be attenuated to an unrealistically low level when the real environment is considered. The most difficult judgement to make will be with respect to the several large peaks in the derived test levels which reflect the resonant modes of the entire structure. It requires a degree of engineering judgment to select a test level which does not necessarily envelop these peaks in both amplitude and frequency. Yet consideration of the probable inaccuracies in the derivation process, i.e., the unknown effects of impedance mismatch between test hardware and equipment assembly; the very significant differences between installation of the test hardware in a very rigid vibration fixture and the relatively flexible assembly; and the probable penalties due to unnecessary conservatism; requires selection of a test level based on smoothing or averaging of the transfer functions, rather than enveloping.

When it is not possible to determine or reasonably predict the service environment, selection of the vibration test level may be made in one of two ways. First, test levels which previously have proven satisfactory for similar equipment or for similar use may be used again. The accuracy of the extrapolations is heavily dependent upon the quantity and quality of the reference data, and upon the similarity of the reference equipment system to the new system. Alternatively, general military specifications such as MIL-STD-810D could be consulted. These specifications usually contain several alternative test procedures, each of which may be conducted at one of several levels for a given duration.

For the acceptance test, the vibration levels are typically set equal to or greater than a "smooth" spectral representation of the maximum predicted environment as defined above. However, the level must be greater than the minimum screening level which effectively reveals workmanship defects in the test hardware. For the qualification test, the vibration level normally exceeds the acceptance vibration level by a factor of safety which assures that, even with the worst combination of test tolerances, repeated tests and variations in hardware parts, material, and manufacturing, the integrity of the equipment will not be jeopardized by the acceptance tests.

<u>A-3.2 Test Duration</u>

The test duration discussed below and the test amplitude discussed in the previous section are very closely interrelated. Two criteria are typically used to establish test durations: (1) duration based on simulation of service life, and (2) duration which will uncover a satisfactory fraction of total latent defects.

The duration of the service vibration environments is typically defined as the total period during service when the vibration amplitude is greater than one-half the peak amplitude. Test duration based on operational life may be very straightforward, such as in the case of rocket and Shuttle launch, where simulation of the complete vibration exposure amounts to a few minutes test duration. On the other hand, direct simulation of vibration exposures which may last for hundreds of hours over a wide range of intensities is impractical. In this case, a test duration must be derived which, based on some acceptable model for damage accumulation is equivalent to the service environment. This derivation would logically lead to a test duration at the maximum expected intensity which is equivalent to the integration of the cumulative effects of varying durations at varying intensities up to and including the maximum expected intensity. If the test duration so derived is still impractically long, then the duration of an accelerated test conducted at an intensity greater than expected in service may be derived using the same model for damage accumulation. Damage accumulation models are most commonly based on material fatigue characteristics. An approximate rule of thumb relating duration and intensity based on fatigue accumulation considerations is that a 3 dB increase in intensity (doubling of spectral density) is equivalent to a factor of ten in reduction of duration (Reference 1).

Laboratory experience in vibration testing seems to indicate that, for a given vibration intensity, most failures that are going to occur will occur in the first few minutes of test, regardless of the type of vibration environment. This experience is substantiated by the results presented in Reference 2. In this development study program, it was found that essentially all workmanship failures occurred during the first ten (10) minutes of vibration. This is consistent with findings of other related studies (References 3 and 4). The foregoing seems to be counter to the cumulative fatigue damage theory. However, if one postulates that most failures in vibration tests are initiated by an imperfection of some kind which causes severe stress concentration, then failure is due more to exceeding the ultimate strength rather than the sloping portion of the typical material endurance curves to which cumulative damage is applicable.

There are also other types of failures typical in complex electromechanical equipment which do not conform to fatigue accumulation type models, such as wear or abrasion failures or excessive displacement related failures. Complex structures also sometimes respond nonlinearily with excitation levels. These deviations of actual failure mechanisms from fatigue damage failure models can result in accelerated tests which may be either overly conservative, causing test failures which would not occur in the service environment, or nonconservative, failing to detect latent flaws that would later be precipitated in the service environment. Therefore, if practical, accelerated testing is best employed only on hardware whose failure mechanisms are well understood and where hardware test failure rates and failure mechanisms can be correlated with field failure data.

A-3.3 Axes of Vibration Test

In some cases, vibration in one axis can be effective for detecting workmanship and design defects, provided that the equipment has a distinct preferred response axis. However, in many cases, the observed failure distributions strongly suggest that certain failure modes are much more effectively excited by vibration in directions other than the axis of highest response. If the most severe axis for all probable failure modes cannot be easily selected, then vibration testing in three mutually perpendiular axes should be performed. This approach is conservative. However, the conservatism is probably less penalizing than that engendered by misguided attempts to solve the problem by exciting in only one direction while increasing the test levels. Of course 3D vibration testing has the potential to eliminate both the undertest and overtest concerns of one, two, or three axis testing applied separately and to reduce test time - both actual test time and time required to change shaker axes.

A-3.4 Test Tolerances

The justifications that are often cited for specification of test parameters with rather small allowable variations are the need for repeatability of tests coupled with quality control requirements. However, experience shows that even on the very tight specifications, the variability of test results still persists, suggesting that the major variability in the results is due to parameters which have not been either identified or controlled and which probably cannot be controlled even if identified. Furthermore, there is little reason to expect that the variability in the service environment, upon which test levels are based, will be any less than those which are observed during test. In fact, there is good reason to expect considerably greater variation. Thus, while reasonable effort to maintain a certain accuracy in test conditions is necessary, it is suggested that only that precision essential to the purpose of the test be specified. Considerations which should enter into the definition of tolerances for those vibration parameters are discussed below.

A-3.4.1 Vibration Amplitude

It is common practice to specify a tolerance of ±3 dB (+100, -50 percent on spectral density) across the frequency range or alternatively, to specify ±1.5 dB (+40, -30 percent) below 500 Hz and ±3 dB above 500 Hz. The latter practice recognizes the relatively easier task of achieving the required values at lower frequencies. Compared to the typical ±10 percent tolerance on sinusoidal amplitude, these are generous tolerances which probably reflect early random vibration test experience when the equalization process was carried out manually. However, for large test articles, fixture resonances in the higher frequencies (generally above 1000 Hz) makes these tolerances difficult or impossible to achieve and compromises are often necessary.

An additional requirement that the overall rms acceleration be maintained within a certain tolerance, say ±10 percent, is often included. Presumably this prevents unscrupulous testers from running the test 3 dB low across the whole frequency band.

A-3.4.2 Frequency Range

A typical specification tolerance for vibration frequency is 1/2 Hz below 20 Hz or ±2 percent. Perhaps it would be more logical to specify 25 Hz as the cutoff so that no step in the tolerance occurred (Reference 1). In any case, frequency in vibration testing is, like duration, more an independent variable than a controllable dependent variable. It is important to specify the accuracy with which it is measured. The specification of a tolerance does not appear to be particularly meaningful.

A-3.4.3 Test Duration

A typical specification tolerance for test duration is ± 1%. Time is, in a sense, the independent variable of the test. Nevertheless, it should be permitted a reasonable specified variability. It is quite easy to control accurately yet is probably relatively unimportant to the overall test objectives. First, the derivation of the nominal test duration, as mentioned in section A-3.2, is probably the most arbitrary test parameter. Second, the shape of a typical fatigue curve is such that a 3 dB change in amplitude is equivalent to a factor of ten in time. Thus the efforts often made to set up an exact test time may be well meaning and satisfy specifications but hardly contribute to the overall value of the test program.

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APPENDIX B
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