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Uncertainty Analysis of an Accelerometer DAQ System

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Uncertainty Analysis of an Accelerometer DAQ System

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Abstract

An uncertainty analysis was performed on two very similar piezoresistive (PR) accelerometer-type data acquisition (DAQ) systems typical of those in the "Shock Lab" in Building 860, Area I, and the "Mechanical Shock Lab" or "Actuator," Building 6570, in Tech Area III. Components included in the analysis were Endevco Model 7270A PR-type accelerometers (most often used), connecting cables, Dynamics Model 7600A and 8000 signal conditioner/amplifiers, DSP digitizers, and IBM compatible PC systems. The analysis was performed assuming the data have been validated and issues, such as faulty transducers, cables, and other "major" potential problems, have been resolved. This analysis can be easily modified for other PR type transducers. Results from the analysis show that, excluding systematic uncertainties caused by accelerometer mounting methods, the uncertainty of the entire DAQ system used in typical accelerometer measurements is about ± 5 per cent (95 per cent confidence) or ± 8 per cent (99 per cent confidence). Most of that uncertainty is because of the Endevco accelerometer; little of the uncertainty is because of the remainder of the DAQ system.

Acknowledgements

The author thanks several individuals for their assistance with this report: Tim Miller for numerous discussions on the Dynamics signal conditioning systems, cabling, and review of the report, Vesta Bateman and Dan Gregory for discussions about transducers, Lloyd Swanson for photographs, Ron Coleman, Fred Brown and Luis Abeyta for discussions about the Area III systems, and Dave Davis and Steve Heffelfinger for reviewing the manuscript.

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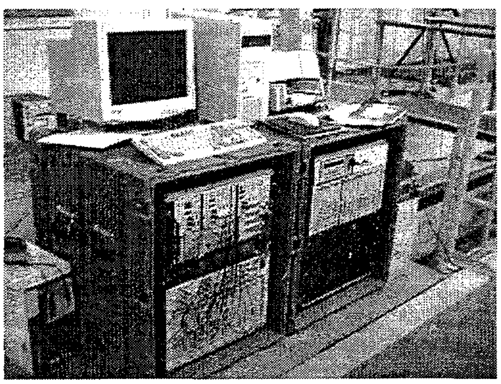
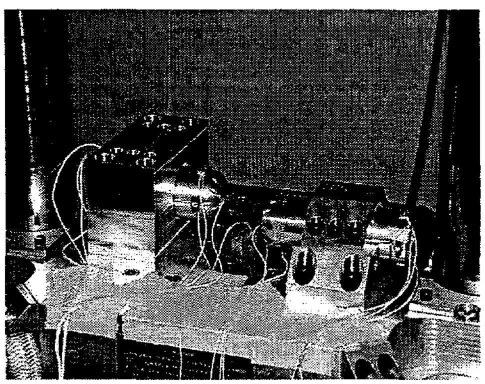
1 Executive Summary

An uncertainty analysis was performed on two very similar piezoresistive (PR) accelerometer-type data acquisition (DAQ) systems used in Center 9100. These measurement systems are typical of those in experiments performed in Sandia's Technical Area III (TAIII) Albuquerque Full-Scale Experimental Complex (AFSEC), Department 9134, and Solid Mechanics Engineering Department 9126. Specifically DAQ systems used in the "Shock Lab" in Building 860, Area I, and the "Portable MIC" DAQ system used in the "Mechanical Shock Lab," Building 6570, in Tech Area III were analyzed. Components included in the analysis were Endevco Model 7270A PR-type accelerometers (most often used), connecting cables, Dynamics Model 7600A and 8000 signal conditioner/amplifiers, DSP digitizers, and PC systems. The analysis was performed assuming the data have been validated and issues, such as faulty transducers, cables, and other "major" potential problems have been resolved. This analysis can be easily modified for other transducers.



"Portable MIC" DAQ System



Building 860 Shock Lab Test Specimen

Results from the analysis show that, excluding systematic uncertainties caused by accelerometer mounting methods, the uncertainty of the entire DAQ system used in typical accelerometer measurements is about ± 5 per cent (95 per cent confidence) or ± 8 per cent (99 per cent confidence). Most of that uncertainty is because of the Endevco accelerometer; little of the uncertainty is because of the remainder of the DAQ system.

Systematic uncertainties caused by installation effects vary from experiment to experiment. In some installations in the Mechanical Shock lab (Building 6570), the test unit cannot be disturbed. Therefore, an accelerometer is screwed into an aluminum block that is then glued onto the test unit. The accelerometer measures its own acceleration, not the acceleration of the test unit. If properly mounted, the difference between the two accelerations is small, but not always. For example, if a relatively large accelerometer is mounted on a relatively small test unit, one can affect the response of the test unit causing an error. Consequently, the total measurement uncertainty will be larger. It is, therefore, important to quantify the uncertainties caused by installation effects or ensure they are negligible. Because uncertainties owing to installation effects can vary, they are not addressed here and are not included in the uncertainties listed above. For most "well designed" experiments, this type of uncertainty (systematic) is probably negligible but should be checked (see Section 8 for more discussion).

2 Acronyms and Abbreviations

AC	alternating current
AFSEC	Albuquerque Full-Scale Experimental Complex
ANSI	American National Standards Institute
ASME	The American Society of Mechanical Engineers
CAL	calibration
CAP	Certification Augmentation Program
cmrr	common mode rejection ratio
DAQ	data acquisition
DC	direct current
ESCC	Experimental and Systems Certification Capabilities
IEEE	International Electrical and Electronic Engineers
ISO	International Standards Organization
lsb	least significant bit
MIC	mobile instrumentation container
MIU	mobile interface unit
NIST	National Institute of Standards and Technology
PE	piezoelectric
PR	piezoresistive
PTC	performance test code
rms	root mean square
RSS	root sum square
rti	relative to input
rto	relative to output
TAIII	Technical Area III
TC	thermocouple
VCO	voltage control oscillator

3 Introduction

This uncertainty analysis is of a typical accelerometer and data acquisition system (DAQ system) used in Sandia's Technical Area III Full-Scale Experimental Complex (AFSEC), Department 9134 - i.e., the "portable MIC" used in Building 6570, the Mechanical Shock Lab - and the system used in Solid Mechanics Engineering Department 9126 - i.e., the Shock Lab in Building 860. Equipment analyzed is typical of that used during 1999.

This information can be used when providing experimental data to customers, be they systems-level personnel trying to understand the behavior of their system or an analyst trying to obtain experimental data to compare with model predictions. One cannot hope to use experimental data to compare with model predictions to a known uncertainty if the experimental data uncertainties are not quantified.

This analysis is part of a larger study to analyze and document the uncertainties and errors present in typical experiments performed using DAQ equipment (accelerometers, pressure gages, strain gages, thermocouples, etc.) in Center 9100. A thermocouple uncertainty analysis was completed in 1999 (Nakos, 1999).

This project began under the support of the Experimental and Systems Certification Capabilities (ESCC) Program, continued under the Certification Augmentation Program (CAP), and is now supported by AFSEC, that support is gratefully acknowledged.

4 Uncertainty Analysis Methods

There are a number of methods that can be used for the determination of measurement uncertainty. A summary of the various uncertainty analysis methods is provided in Dieck, 1997. The American Society of Mechanical Engineers (ASME's) earlier performance test Code PTC 19.1-1985 (ASME, 1985) has been revised and was replaced by PTC 19.1-1998 (ASME, 1998). In ASME, 1985 and ASME, 1998, uncertainties were separated into two types: "bias" or "systematic" uncertainties (B) and "random" or "precision" uncertainties (S). Systematic uncertainties are often, but not always, constant for the duration of the experiment. Random errors are not constant and are characterized via the standard deviation of the random measurements, thus, the abbreviation 'S.' In ASME, 1985, the total uncertainty was expressed in two ways, depending on the "coverage" desired. First, the "additive" method:

$$U_{ADD} = \pm[(B) + (t_{95}S_x)], \qquad \textbf{(1)}$$

where B is the bias or systematic uncertainty of the result, S_x is the random uncertainty or precision of the result, and t_{95} is "Student's t" at 95 per cent for the appropriate degrees of freedom (DOF). This method provides about 99 per cent "coverage." "Coverage" here does not mean "confidence" because a statistical term (S_x) was combined with a non statistical term (B) (Dieck, 1997).

The second choice was the root-sum-square (RSS) method (ASME, 1985) and has a 95 per cent confidence level:

$$U_{RSS} = \pm[(B)^2 + (t_{95}S_x)^2]^{1/2} \qquad \textbf{(2)}$$

A third method, adopted by the International Standards Organization (ISO, 1993) and the National Standards Institute (ANSI, 1997), separates uncertainty types into Type A and Type B. Type A sources are derived from statistical methods, whereas Type B sources are not. The method of calculating total uncertainty in this model is as follows:

$$U_{ISO} = \pm K[(U_A)^2 + (U_B)^2]^{1/2}, \qquad \textbf{(3)}$$

where U_A and U_B are the Type A and B uncertainties (both at 1σ confidence levels); and K is a "coverage factor" used to obtain a level of confidence. K normally varies between 2 (for 95 per cent) and 3 (for 99 per cent).

Coleman and Steele, 1995 provide a comparison of the uncertainty methods available, and the National Institute of Standards and Technology's (NIST's) method of estimating uncertainty is provided in Taylor and Kuyatt, 1994.

The new ASME PTC 19.1-1998 (ASME, 1998) uncertainty methodology is defined as follows:

$$U_{95} = \pm [(B)^2 + (2*S_x)^2]^{1/2} \qquad \textbf{(4)}$$

and provides a 95 per cent confidence level.

Because we are involved with "engineering sciences" in Engineering Sciences Center 9100 the ASME model recommended in Equation 4 is the most relevant and so will be used in this analysis.

In Equation 4 above individual S_{xi} that make up S_x are provided as one standard deviation value and B_i as individual 2σ values. In practical terms manufacturer's specifications most often do not specify uncertainty types as systematic or random or with any kind of confidence level - e.g., 95 per cent or 99 per cent. As a result, the practitioner has the problem of trying to determine how to combine uncertainty values with incomplete information. If it is crucial to determine more about the uncertainties listed, it is best to call the manufacturer. Most often the uncertainties listed are maximum values, so it is reasonable to assume there are three standard deviations. In these cases there is a need to adjust the listed uncertainties to a 1σ value for random uncertainties or 2σ value for systematic uncertainties, then use Equation 4 to find the total uncertainty.

An alternative used in Taylor, 1988 arose because of the way manufacturers provide data on "accuracies," "errors," or "uncertainty" estimates. As noted above, most manufacturers do not specify uncertainty sources as systematic or random, nor do they provide confidence levels - i.e., ±3 sigma [± 99 per cent] or ± 2 sigma [± 95 per cent] errors. Often "accuracies" or "errors" are provided as a maximum value or a percentage of the reading or a percentage of full scale. As a result, a rigorous uncertainty analysis - i.e., knowing the error to ± 95 per cent or ± 99 per cent confidence level - is often not possible.

According to Taylor, 1988 because the uncertainties provided by the manufacturers are often the maximum values possible, there is no need to use an additional coverage factor, and the total uncertainty may be expressed as:

$$U_{max} = \pm[B + R], \tag{5}$$

where R is the RSS of the "random" or "precision" uncertainties. 'R' is used rather than 'S' so as not to imply that in this case, the random uncertainty is one standard deviation (it is often three standard deviations). 'B' is the maximum total systematic uncertainty. Use of Taylor's Equation 5 provides an upper bound (conservative) value for the error and is not the same as Equation 3.

In all of the methods described above, the total systematic uncertainty B and total random uncertainty S_x are found using the RSS method:

$$B = (B_1^2 + B_2^2 + B_3^2 + \ldots)^{1/2} \tag{6}$$

$$S_x = (S_1^2 + S_2^2 + S_3^2 + \ldots)^{1/2,} \tag{7}$$

where B_1, B_2, B_3 and S_1, S_2, S_3 are the individual uncertainty sources.

It is sometimes difficult to determine which type of uncertainty source (systematic or random) one is faced with. One way to determine if a source is systematic or random is to ask the question: Can I eliminate or reduce this error? (Taylor, 1988) If the answer is yes, the uncertainty is systematic; if the answer is no, the uncertainty type is random. Another way to tell is if the uncertainty always skews the data in the same direction - i.e., + or –. If so, then it is systematic. A third way is to ask if the uncertainty is constant for the duration of the experiment or if it contributes to data scatter. If constant, it is a systematic uncertainty; if it contributes to data scatter, it is random. A fourth way is to see if the uncertainty was statistically determined; if so, it is random. Typical types of systematic uncertainties are sensitivity, non linearity, and gain. Less commonly discussed systematic uncertainties are those that result from the sensor design - i.e., TC type - and coupling with the environment. Typical types of random errors are noise and frequency response errors from the sensor and DAQ system. Taylor, 1988 provides valuable information on how to effectively interpret the manufacturer's specifications.

"Uncertainties" and "errors" are used to convey specific ideas. When making a measurement, one never knows what the "true" value is. The "error" is the difference between the true value and the measured value. "Uncertainty" means that your measurement is uncertain; you can only say that the true value is within some uncertainty interval. More precise definitions of "error" and "uncertainty" are provided in ASME, 1998.

In summary, the method outlined in ASME PTC 19.1-1998 and expressed in Equation 4 above will be used in the analysis below to estimate the uncertainty for a 95 per cent confidence

level. For a 99 per cent confidence level, the methodology provided in ASME, 1998, Appendix B, the ISO method, will be used and is shown in Equation 3 with K = 3.0.

5 Literature Review

An analysis similar to the one below, but less detailed, was performed on accelerometer measurements for the Defense High-Level Waste Transportation Cask (Madsen et.al., 1987). Results were not reported as 95 per cent or 99 per cent confidence. Uncertainties were presented as in Table 1 which follows:

Table 1 – Reported Uncertainty from Madsen et.al., 1987	
Uncertainty Source	**Value** (assumed to be 99% values)
1) Transducer calibration and response	± 10%
2) Data acquisition noise levels	± 3%
3) Data acquisition bridge conditioning excitation voltage – human error	± 2%
4) Data acquisition, VCO, analog tape machine, analog tape reproducer	± 1%
5) Post processing, analog-to-digital conversion, filtering, plotting data interpretation – human error	± 10%
6) Estimated total uncertainty (RSS method)	± 14.6% or ± 15%

It is evident from the above that the major portion of the uncertainty is from the transducer. The data acquisition system adds a small amount as compared with the transducer and post processing. There is also a substantial uncertainty because of "post processing, …, and human errors."

Ammerman et.al., 1991 discussed an evaluation of accelerometers and strain gages. Although an uncertainty analysis was not provided, the authors evaluated the results of multiple accelerometers measuring the same value. Some results are as follows:

1) One cannot depend on the results of a single transducer – use multiple transducers where possible.
2) There can be as much as a 10 per cent deviation between transducers (this is consistent with the results in Table 1, (15 per cent uncertainty).
3) The choice of a transducer is important.

6 System Description

Figure 1 shows a schematic of the entire DAQ system. It consists of the following components:

1) Endevco Series 7270A-20K piezoresistive accelerometer
2) Connecting cable - e.g., Alpha cable 2468, or Mercury cable MW# 7122.
3) Dynamics Model 7600A or 8000 power supply and amplifier

4) Dynamics filters (Bessel)
5) DSP Technology, Inc., TRAQ digitizing system
6) IBM compatible PC with data analysis software - e.g., post processing filters.

The three individual components of the Dynamics Model 8000 system (power supply, amplifier, and filters) are treated separately because specifications for those components are discussed separately in the Dynamics Manual.

Figure 1 also serves as the summary for the analysis.

7 Assumptions

Assumptions used in the uncertainty analysis are as follows:
1) The input signal from the test item is within the range of 0-20,000 g.
2) The input signal from the test item is at the frequency 10 kHz.
3) The experiment's duration is so short that there are no changes in temperature; therefore, drift is negligible. The temperature is assumed to be +75°F.
4) The excitation is 10v.
5) Full-scale output is ±10v.
6) Cable lengths are 50 ft or less.
7) Mounting method errors/uncertainties are negligible (see Section 8 for further information on this subject).

8 Uncertainty Analysis

8.1 Endevco Series 7270A-20K piezoresistive accelerometer

Figures 2a and 2b provide specifications on the accelerometer. Model 7270AM6 (Figure 2b) is the same as Model 7270A (Figure 2a) except that Model 7270AM6 has an added isolator developed at Sandia (by Vesta Bateman).

8.1.1 *Sensitivity*

Figure 1 under the accelerometer summarizes the individual error/uncertainty sources for the Model 7270A. The first item of concern is the sensitivity. From Figure 2a for the Model 7270A-20K accelerometer, the sensitivity is specified as 10 ±5 microvolts/g (minimum to maximum sensitivity). This range is clearly too large (300% variation) to use without further calibration. Typical sensitivities from Sandia's calibration laboratory have accuracies of ± 3 per cent. This type of uncertainty is a systematic uncertainty (B) because it can be reduced with better and better calibrations (up to a point).

8.1.2 *Frequency response*

This is listed as ± 5 per cent maximum, ref. 100 Hz. The note says "Frequency response should deviate by less than ± 5% from DC to indicated frequency based on analysis. Measurement uncertainties above 10kHz prevents stating ± 5% as a specification limit for all but the 7270-2K."

For the Model 7270A-20K (20,000-g range), the specification is ± 5 per cent from dc up to 50 kHz. Based on the footnote, the ± 5 per cent specification applies only for data frequencies up to10 kHz, not 50 kHz. This difference is likely owing to the difficulty of calibrating accelerometers at high frequencies, as stated in the quote, and based on a personal conversation[1]. Therefore, for the 0 to 20,000-g range accelerometer, the frequency response is only known to ± 5 per cent for 0-10kHz, not 50kHz. One should contact Endevco for the frequency response specification above 10kHz. This error type is considered to be a random uncertainty (S).

8.1.3 *Mounted resonance frequency*

The mounted resonance frequency for this accelerometer is typically 350 kHz, with a minimum of 220 kHz. This causes no additional uncertainty because the frequency response specification includes any amplitude error caused by damping. For a small damping ratio (e.g., 0.01-0.10), the amplitude can be affected to values down to 0.1 times the resonant frequency (see Wright, 1995, Page 71, Figure 2.37) or in this case down to a minimum of 22 kHz. However, because we are assuming a signal of 10 kHz, the amplitude would not be affected by the damping. In addition, the damping ratio of this type of accelerometer may be much larger than 0.01-0.1.

8.1.4 *Non linearity & hysteresis*

From Figure 2a this error is listed as "± 2% of reading, maximum, to full range, up to acceleration corresponding to the recommended range. Measurement uncertainties prevent stating this as a specification limit above 10,000g." This source is also a systematic uncertainty (B).

8.1.5 *Transverse sensitivity*

This is because the accelerometer is sensitive to inputs from the transverse direction, up to a maximum of 5 per cent (± 5 per cent). This error type is considered to be a systematic uncertainty (B) because it can potentially be reduced.

8.1.6 *Zero measure and output (max)*

This is listed as ± 100 mv maximum in Figure 2a. It is assumed that this is an offset or bias that can be adjusted to zero before the test begins. This would be a systematic uncertainty if non-zero.

8.1.7 *Zero shift owing to half sine acceleration causing 200-mV output (or 150,000 g, whichever is smaller)*

This is stated as 0.5 mV max. At 20,000 g and a sensitivity of 10 microvolts/g, the output is 200 mv. Therefore, the zero shift owing to half sine acceleration is 0.25 per cent maximum 0.5/200). It will be assumed that this uncertainty cannot be removed before testing begins. This error type is a random uncertainty (S).

[1] Personal conversation with Dan Gregory, August 17, 1998.

8.1.8 *Zero shift owing to mounting torque (0 to 8 lbf-in., 0-9 nm)*
This is stated as ± 2 mV max. This is also called "base strain sensitivity" and refers to strain introduced into an accelerometer by bolting down the accelerometer to the test item. This could introduce a base strain sensitivity error ± 2 mV max. At 20,000 g and a sensitivity of 10 microvolts/g, the output is 200 mv. Therefore, the base strain sensitivity is 1 per cent maximum (2/200). It will be assumed that this uncertainty is zeroed out before testing begins. This uncertainty type would be a systematic uncertainty (B).

8.1.9 *Thermal zero shift*
This is listed as ± 50 mv max and applies from –30 to +150°F (-34 to +66°C) with a +75°F (+24°C) reference. Because the experiment is performed at a constant temperature and we assume the system is zeroed before beginning, this uncertainty is zero. This is a systematic uncertainty.

8.1.10 *Thermal sensitivity shift (from 0 °F and +150 °F)*
This refers to the fact that the sensitivity can vary or shift, depending on the temperature, based on an initial temperature of +75°F. From Figure 2a this uncertainty is listed as ± 10 per cent maximum. Because the initial temperature was assumed to be +75°F and the test is performed at a constant temperature, this uncertainty source is zero in this case. This would be a systematic uncertainty.

Summary for Endevco Series 7270A-20K accelerometer:

Systematic uncertainties:
1) Sensitivity: ± 3%
2) Non linearity and hysteresis: ± 2%
3) Transverse sensitivity: ± 5%

Random uncertainties:
1) Frequency response: ± 5%
2) Zero shift owing to half sine acceleration: ± 0.25%

As can be seen, there is a sizable uncertainty associated with the transducer. These are assumed to be the maximum uncertainties - i.e., 99 per cent - not 95 per cent uncertainties.

8.2 Connecting cable - e.g., Alpha cable 2468 or Mercury cable MW# 7122.

There are several potential uncertainties related to cabling:
1) Excitation voltage reduction owing to lead wire resistance
2) Output signal attenuation through lead wires
3) Frequency response of typical cabling

8.2.1 *Lead wire resistance:*
If not accounted for, typical lead wire resistances can cause a reduction in the excitation voltage at the bridge. For example, at the rocket rail in Area III near the south end of the 10,000-foot

sled track, there could be 200 ft of lead wire on each leg, or 400 ft total. With a resistance of 28 ohms/1000 ft, typical of Alpha Cable 2468, 200 ft of lead wires amounts to about 5.6 ohms or 10.2 ohms total. At the Mechanical Shock Facility there could be 50 foot on each leg or 1.4 ohms each. Typical input resistances of Endevco Model 7270A accelerometers is 550 ohms. So with 2.8 ohms in series with the 550 ohms, the excitation could be reduced by about 0.5 per cent (2.8/552.8). This would be a systematic uncertainty.

The MIDAS system has a six-wire capability that allows automatic bridge voltage reading at the bridge. The MIC system has no such capability, so we have to manually read the voltage at the bridge. As a result, there is no uncertainty caused by the lead wires related to the excitation voltage, other than reading the voltage (addressed below).

8.2.2 *Output signal:*
A typical input impedance value for the Model 7600A is 25 meg ohms shunted by 500 picofarads; and for the Model 8000, 50 meg ohms shunted by 500 picofarads. Because the input impedance (25 or 50 meg ohms) is so large as compared with a 2.8-ohm lead wire resistance (2.8/25,000,000 or 0.00001 per cent), the lead wire resistance has negligible effect on the output signal. This would be a systematic uncertainty.

8.2.3 *Cable frequency response:*
The frequency response of some typical lead cabling has been checked by Mike Arviso (Arviso, 1994). Mercury MW-7122 field cable was characterized, the cable that will be used in the Mobile Interface Units (MIUs) in Tech Area III. A cable length of 50 to 1000 ft in 50 ft increments was checked via a H-P 3585B Spectrum Analyzer from DC to a frequency that reached beyond the –0.5 dB point. Results for short cabling are good: At 50 ft the –0.5-dB point is at a frequency of 858 kHz, well beyond our normal signal frequencies. However, for long cable lengths the frequency response is not as good: At 500 ft the –0.5 dB-point is at 85 kHz, an order of magnitude lower. Results for cable lengths of 50-1,000 ft are provided in Appendix A (Arviso, 1994). Because I am assuming the signal is at a maximum of 10 kHz and cable lengths are 50 ft or less, the resulting cable attenuation is assumed to be negligible. However, for experiments with long cable lengths and high signal frequencies, cable frequency response should be checked.

Summary for Connecting Cable:

<u>Systematic uncertainties:</u> negligible

<u>Random uncertainties:</u> negligible

8.3 Dynamics Model 7600A or 8000 power supply, amplifier, and filters
Refer to Figure 3 for specifications for the Dynamics Model 8000 power supply, amplifier, and filters. Tech Area III operations - e.g., the Mechanical Shock capability using the "Portable MIC" DAQ system - use Model 8000 systems (constant voltage, high-voltage output), whereas the Shock Lab in Building 860 uses the Model 7600A systems (constant voltage, standard output). The MIUs use Model 8000 systems.

8.3.1 *Power supply – Model 8000*

8.3.1.1 Resolution

This is shown on Figure 3. It will be assumed that we are using the "constant voltage, high voltage option" power supply (second column).[2] The resolution is stated as 0.120V. Assuming the excitation is 10v, the resolution corresponds to an error of 1.2 per cent (0.120/10). This is considered to be a random uncertainty (S).

Tim Miller (1998)[2] had 24 Model 8000 power supplies checked, and all of them met or exceeded the 1.2 per cent uncertainty, in fact, all were less than 0.6 per cent. I will use the ±1.2 per cent value to be conservative.

8.3.1.2 Line regulation

This is specified as 0.005 per cent or 300 microvolts, whichever is greater for ± 10 per cent line variations. At 10v, 0.005 per cent is 0.0005v or 500 microvolts. Therefore, the 0.005 per cent (± 0.005 per cent) specification is largest. This is considered to be a random uncertainty (S).

8.3.1.3 Load regulation

This is specified as "300 microvolts plus 100 microvolts/ohm of lead resistance to 5 ohm independent of the excitation voltage. Sense current is 100 microamps. The output does not overvoltage with the sense leads disconnected. Local sense may be selected on the bridge completion card." We will use the 2.8-ohm lead resistance calculated above, so the load regulation error is as follows:

300 microvolts + 100 microvolts/ohm x 2.8 ohms = 580 microvolts.

At 10-vdc input, the error is 0.006 per cent (± 0.006 per cent). This can be considered a systematic uncertainty.

8.3.1.4 Noise

Figure 3 states the noise is 300 microvolts peak-to-peak from 0.1 Hz to 20 kHz. Since our assumption is that the signal is at 10kHz, the uncertainty is:

300 microvolts/10,000,000 microvolt excitation = 0.003 per cent (± 0.003 per cent)

This is a random uncertainty.

8.3.1.5 Stability

Stability is stated as 0.01 per cent or 1 millivolt per 8 hours after 30-minute warm up. Because this is a short duration experiment, this uncertainty source is negligible. This would be a systematic uncertainty.

[2] Personal conversation with Tim Miller, August 17, 1999.

8.3.1.6 Temperature coefficient

This error is stated as 0.005 per cent /°C or 200 microvolts/°C, whichever is greater. This also does not apply because of the short test duration, which occurs at constant temperature. This is a systematic uncertainty.

8.4 Summary for Dynamics Model 8000 power supply:

Systematic uncertainties:

1) Load regulation: ± 0.006 per cent

Random uncertainties:

1) Resolution: ± 1.2 per cent
2) Line regulation: ± 0.005 per cent
3) Noise: ± 0.003 per cent

As can be seen, there are very small uncertainties associated with the power supply except for the resolution (±1.2 per cent), which is surprisingly high compared with the Model 7600A resolution (0.085 per cent, see below).

8.5 Power supply – Model 7600A

8.5.1 *Resolution*

This is shown on Figure 4. It will be assumed that we are using the "constant voltage, standard voltage option" power supply (first column).[3] The resolution is stated as "setability of 8.5 mV." Assuming the excitation is 10 v, the resolution corresponds to an error of 0.085 per cent. This is a random uncertainty. Note that this specification is much better than that for the Model 8000 system, which had a resolution of 0.060V or 60 mV.

8.5.2 *Line regulation*

This is specified as 0.005 per cent or 150 microvolts, whichever is greater for ± 10 per cent line variations. At 10 v, 0.005 per cent is 0.0005v or 500 microvolts. Therefore, the 0.005 per cent (± 0.005 per cent) specification is largest. This is a random uncertainty.

8.5.3 *Load regulation*

This is specified as "150 microvolts plus 100 microvolts/ohm of lead resistance to 5 ohm independent of the excitation voltage. Sense current is 100 microamps. The output does not overvoltage with the sense leads disconnected. Local sense may be selected on the bridge completion card." Assuming the lead resistance is 2.8 ohms, the load regulation error is as follows:

150 microvolts + 100 microvolts/ohm x 2.8 ohms = 430 microvolts.

At 10 vdc input, the error is 0.004 per cent (± 0.004 per cent). This is a systematic uncertainty.

[3] Personal conversation with Fred Brown, August 18, 1999.

8.5.4 *Noise*
Figure 4 states the noise is 150 microvolts peak-to-peak from 0.1 Hz to 20 kHz. Since our assumption is that the signal is below 10kHz, the uncertainty is:

150 microvolts/10,000,000 microvolt excitation = 0.0015 per cent (±0.0015 per cent)
This is a random uncertainty.

8.5.5 *Stability*
Stability is stated as 0.01 per cent or 500 microvolts per 8 hours after 30 minute warm up. Because this is a short duration experiment, this uncertainty source is negligible. This would be a systematic uncertainty.

8.5.6 *Temperature coefficient*
This error is stated as 0.005 per cent /°C or 100 microvolts/°C, whichever is greater. This also does not apply because of the short test duration, which occurs at constant temperature. This is a systematic uncertainty.

Summary for Dynamics Model 7600A power supply:

Systematic uncertainties:
1) Load regulation: ± 0.004 per cent

Random uncertainties:
1) Resolution: ± 0.085 per cent
2) Line regulation: ± 0.005 per cent
3) Noise: ± 0.0015 per cent

As can be seen, there is a very small uncertainty/error associated with the Model 7600 power supply. It is interesting to note that for the Model 8000 power supply which uses the high output, the resolution uncertainty is much greater (120 mv) than for the Model 7600A, which uses the standard output (8.5 mv). If the total uncertainty had to be lowered, use of the Model 7600A would be a consideration.

8.6 Amplifier – Model 8000

8.6.1 *AC Characteristics:*
1a) Frequency response, 100-kHz bandwidth
This is shown on Figure 3. It will be assumed that we are using the 100-kHz bandwidth model. The response is stated as "±1% from DC to 10 kHz, ±1 dB from 10kHz to 50 kHz and –3dB above 100 kHz for gains of 1000 or less." Because we are in the 10 kHz or less regime, the error is ±1 per cent. However, if we were in the 10-50 kHz range, the error is ±1dB, not ±1 per cent. +1dB in error is +12.2 per cent, and –1dB in error is about –10.9 per cent. Care should be taken to operate the Dynamics amplifiers well within their range, or large uncertainties will result. This is considered to be a random uncertainty.

1b) Frequency response, 500-kHz bandwidth

The response is stated as "± 1 per cent from DC to 50 kHz, ±1 dB from 50kHz to 200 kHz and –3dB above 500 kHz for gains of 1000 or less, and –3dB above 20 kHz for gains of 1000 or greater." Because we are in the 10 kHz or less regime, the error is ± 1 per cent. However, if we were above 20 kHz with high gains - i.e., >1000 - the error would be as high as –3dB, or 29.3 per cent. Again, care should be taken when operating the Dynamics amplifiers in applications with high gains or high frequencies. This is considered to be a random uncertainty. This bandwidth will not be used in this example; it was included for completeness.

8.6.2 *Settling time*

This is specified as "less than 25 microsec to 0.1 per cent of the final value" – the amplifier responds to the peak (final) value in less than 25 μsec. This is a random uncertainty. For a 10-kHz sine wave signal, that goes from peak-to-peak in half cycle, the time from peak-to-peak is 50 μsec. So the uncertainty would be less than 0.1 per cent (I will use 0.1 per cent to be conservative). It would be beneficial to check this specification for signals greater than about 20 kHz (25 μsec rise time).

8.6.3 *Overload recovery time*

This is specified as "less than 50 microsec to 5% of full scale for any overload up to 10 times full-scale input not exceeding ± 20 v DC or peak AC." It will be assumed that there is no overload, so this does not apply. This is a systematic uncertainty.

8.6.4 *Slew rate*

Figure 3 states the slew rate is "3.77v/microsec 20v peak-to-peak to 60kHz." This means that the amplifier cannot follow an input signal that changes faster than 3.77 v/microsec. For an accelerometer of nominal sensitivity, 10 microvolts/g (10v excitation), the maximum output of the accelerometer (input of amplifier) with a gain of 1 is about 0.2v. Assuming a gain of 100, the maximum output is 20v. Therefore, using a maximum input of 20v peak-to-peak and a slew rate of 3.77 v/microsec, the amplifier can follow a signal as fast as about 190 kHz. The other specification - i.e., 20v p-p to 60 kHz - implies a slew rate of 1.2 v/microsec., about one third of the other value (3.77). (I assume the slew rate drops from 3.77 to 1.2 as the frequency and signal size increase.) For large voltage changes between 60 and 190 kHz, there may be some unintended filtering, and for frequencies above 190 kHz, the amplifier acts as a filter. Since our assumption is that the signal is below 10kHz, this slew rate specification causes no additional uncertainty. This would be a random uncertainty.

8.6.5 *Noise*

Noise is stated "RTI" or "relative to input" for various bandwidths plus 200 microvolts "RTO" or "relative to output." Assuming we use the 10-kHz bandwidth, the noise is 5 microvolts rms (root-mean-square) plus 200 microvolts "RTO" or "relative to output." Assuming we have a maximum output of 0.2v without any gain and we want ±10V output, then the gain should be 50 (10/0.2). Therefore, the noise is as follows:

5 x 50 + 200 = 450 microvolts rms. Peak noise is desired, so multiply by 1.414 so the noise level is 635 microvolts. For 10-v full-scale output, this is 0.006 per cent. This is a random uncertainty.

DC Characteristics:

8.6.6 *Constant temperature drift*

This error is stated as "±2 microvolts RTI, ±200 microvolts RTO plus ±200 microvolts/volt of output. Offset per 8 hours after a half-hour warmup." This does not apply because of the short test duration. This is a random uncertainty.

8.6.7 *Temperature coefficient of drift*

This is specified as ±0.5 microvolts/°C RTI plus ±150 microvolts/v/°C of output offset. This also does not apply because of the short test duration, which occurs at constant temperature. This is a random uncertainty.

8.6.8 *Gain accuracy*

This is specified as ±0.1 per cent. This is a systematic uncertainty. Based on checks of 24 Model 8000 Dynamics amplifiers (Tim Miller, personal conversation, August 17, 1999), the gain accuracy was less than ± 0.1 per cent for low gains, but for high gains - e.g., 200, 500, 1000, 2000 - the gain inaccuracies increased, the highest being 3.6 per cent. Care should be taken with use of high gains. I will assume low gains are used, so the ± 0.1 per cent value applies.

8.6.9 *Gain stability*

This is stated as ±0.005 per cent/200 hours and ±0.005 per cent/°C. Because of the short duration test at constant temperature, this does not apply. This is a random uncertainty.

8.6.10 *Linearity*

This is specified as ±0.005 per cent at DC. This is a systematic uncertainty.

8.6.11 *Zero adjustment*

This is specified as follows: "Recessed front panel control provides ± 100 microvolts RTI of zero adjustment. RTO is set by output of zero controls." This is considered as a systematic uncertainty. Assume a gain of 50 and a full-scale output of 10v:

$\pm 100 \times 50 = 5000\ \mu V = 0.05$ per cent.

8.6.12 *Common mode noise rejection*

The common mode rejection ratio (CMRR) is specified for four gains (1000, 100, 10, 1). For an assumed gain of 50 (see above: uncertainty #5, noise), the CMRR would be between 86 and 106 dB for a zero ohm line unbalance (assume small line unbalances for an accelerometer). On a semi-log plot the CMRR is about 100 for a gain of 50.

CMRR = $20 \log (e_o/e_i * \text{gain})$, or $e_o/e_i * \text{gain} = \log^{-1} (-100/20) \approx 1.0 \times 10^{-5}$

For a 10-v common mode voltage and gain of 50: $e_o = 0.005$v or 0.05 per cent based on a 10-v output. This is a random uncertainty.

8.7 Summary for Dynamics Model 8000 Amplifier:

Systematic uncertainties:
1) Gain accuracy: ± 0.1 per cent
2) Linearity: ± 0.005 per cent
3) Zero adjustment: ± 0.05 per cent

Random uncertainties:
1) Frequency response: ± 1.0 per cent
2) Settling time: ± 0.1 per cent
3) Noise: ± 0.006 per cent
4) CMRR: ± 0.05 per cent

As can be seen, the amplifier uncertainty/error is relatively small as compared with the uncertainty of the accelerometer.

8.8 Amplifier – Model 7600A

AC Characteristics:

8.8.1 *Frequency response, 100-kHz bandwidth*

This is shown on Figure 4. The Model 7600A only has the 100-kHz bandwidth option. The response is stated as "±1% from DC to 10 kHz, ±1 dB from 10 to 50 kHz and –3dB above 100 kHz." Because we are in the 10 kHz or less regime, the error is ± 1 per cent. This is a random uncertainty.

8.8.2 *Settling time*

This is specified as "less than 25 microsec to 0.1% of the final value." This is a random uncertainty.

8.8.3 *Overload recovery time*

This is specified as "less than 50 microsec to 5% of full scale for any overload up to 10 times full-scale input not exceeding ± 20 v DC or peak AC." It will be assumed that there is no overload, so this does not apply. This is a systematic uncertainty.

8.8.4 *Slew rate*

Figure 3 states the slew rate is "3.7v/microsec 20v peak-to-peak to 60kHz." This is essentially the same specification for the Model 8000 system, so I'll assume the uncertainty is also negligible because the signal is 10 kHz (see above). This is a random uncertainty.

8.8.5 *Noise*

Noise is stated "RTI" or "relative to input" for various bandwidths plus 200 microvolts "RTO" or "relative to output." This is the same specification as the Model 8000 unit except there is no entry for the 500-kHz bandwidth, so we will use the same uncertainty as above, 0.006 per cent. This is a random uncertainty.

DC Characteristics:

8.8.6 *Constant temperature zero drift*

This error is stated as "±2 microvolts RTI, ±200 microvolts RTO plus ±200 microvolts/volt of output. Offset per 8 hours after a half hour warmup." This does not apply because of the short test duration. This is a random uncertainty.

8.8.7 *Temperature coefficient of drift*

This is specified as ±0.5 microvolts/°C RTI plus ±100 microvolts/v/°C of output offset. This also does not apply because of the short test duration. This is a random uncertainty.

8.8.8 *Gain accuracy*

This is specified as "±0.1% in calibrate position of the CAL switch." This is a systematic uncertainty.

8.8.9 *Gain stability*

This is stated as ±0.005 per cent /200 hours and ±0.005 per cent /°C. Because of the short duration test at constant temperature, this is negligible. This is a random uncertainty.

8.8.10 *Linearity*

This is specified as ±0.005 per cent of full scale at DC. This is a systematic uncertainty.

8.8.11 *Zero adjustment*

This is specified as follows: "±100 microvolts RTI of zero adjustment. RTO is set by output of zero controls." This is a systematic uncertainty and the same as for the Model 8000 system; therefore, the uncertainty is 0.05 per cent.

8.8.12 *Common mode noise rejection*

This specification is essentially the same as for the Model 8000 system, so has the same uncertainty, 0.05 per cent. This is a random uncertainty.

Summary for Dynamics Model 7600A Amplifier:

<u>Systematic uncertainties:</u>

1) Gain accuracy: ±0.1 per cent
2) Linearity: ±0.005 per cent
3) Zero adjustment: ±0.05 per cent

<u>Random uncertainties:</u>

1) Frequency response: ±1.0 per cent
2) Settling time: ±0.1 per cent
3) Noise: ±0.006 per cent
4) CMRR: ±0.05 per cent

As can be seen, the amplifier uncertainty for the Model 7600A is relatively small as compared with the uncertainty of the accelerometer, similar to the Model 8000.

8.9 Dynamics filters – Portable MIC and MIU

Anti aliasing, 6-pole Bessel filters are used in the MIU systems and portable MIC. As can be seen in Figure 3, there are a number of filters that can be used with the Dynamics Model 8000 system. Bessel and Butterworth filters are available with 2-6 poles and cutoff frequencies of 1-Hz to 30-kHz. The most prevalent filters in AFSEC equipment are 5-, 20-, and 50-kHz, 6-pole Bessel Filters. As with any filter caution should be exercised when measuring frequencies close to the –3dB point - e.g., when a 10-kHz filter is specified, the –3dB point is at 10-kHz, or about 30 per cent down from the flat portion of the response curve. Frequency response plots for virtually all of the AFSEC Dynamics filters are available from Tim Miller, Department 9134.

Some filters - e.g., Butterworth - have some "ripple" or "ringing" in the "flat" amplitude portion and if it exists, should be added as an additional uncertainty. However, it is assumed that for Bessel filters in the flat amplitude response portion, there is negligible "ripple" - i.e., no variations about the mean amplitude.

Summary for Dynamics Model 8000 Filter:

<u>Systematic uncertainties:</u> negligible

<u>Random uncertainties:</u> negligible

8.10 DSP Technologies "TRAQ" Digitizer Model 2860

Figure 5 shows the specifications for the Model 2860 TRAQ Digitizer module. Specifications that contribute to the uncertainty of the digitizer are listed below.

8.10.1 *Resolution*
For the Model 2860 the resolution is quoted as 12 bits/channel. The resolution error is calculated as follows:

Resolution error = (Full-scale output)/2^n , where n = # bits (=12).

Therefore, for this case Resolution error = $20/2^{12}$ = 0.0048v. For ±10 v output, this is about 0.00048 or 0.048 per cent. For only a 1 volt output, this increases to 0.48 per cent. The implication is that one should be careful to set the full-scale output correctly, or the resolution error will be higher than expected. This is a systematic uncertainty.

8.10.2 *Bandwidth (frequency response)*
For the Model 2860 the -0.5 dB point is at 500 kHz, and the –3 dB point is at about 1 MHz. The –0.5dB point corresponds to about –5.6 per cent error at 500 kHz. According to Stein, 1997 for faithful reproduction of the amplitude to –1 dB or –10 per cent in a first order system, one needs to be at 0.5*f or an octave lower than 'f', where 'f' is the frequency at the –3.0dB point. Therefore, for –10 per cent amplitude error, one cannot be any higher than 0.5*1MHz, or 500kHz. Comparing this with the Model 2860 specification (-0.5 dB or –5.6 per cent @ 500 kHz), it seems that the Model 2860 has a higher roll-off as compared with a first order system.

The manufacturer did not have useful information on the roll-off. However, the –3-dB frequency is much higher than the Dynamics amplifier roll-off.

For a first order system, one can estimate the error at 10-kHz signal frequency (Stein, 1997). At 10-kHz the error is less than -0.005 per cent. The digitizers have at least a first order roll-off. Because the first order system uncertainty is so small, it will be assumed negligible. This would be a random uncertainty.

8.10.3 *Common Mode Rejection Ratio (CMRR)*
The CMRR [dc – 100 Hz] specification is 72 dB. Because the Dynamics amplifier is upstream of the digitizer, the CMRR of the Dynamics amplifier applies, as listed above. No additional uncertainty (from CMRR) is included by the digitizer. This is a random uncertainty.

8.10.4 *Gain Error*
This is stated as ± 0.1 per cent and is a systematic uncertainty.

8.10.5 *Offset Error*
This is stated as ± 0.1 per cent of full-scale and is a systematic uncertainty.

8.10.6 *Integral and Differential Non linearity*
Integral non linearity is stated as ± 0.5 "LSB" (least significant bit). From above, ± 1 LSB was 0.048 per cent for ± 10V output. For ±0.5 LSB, the uncertainty is 0.024 per cent. Differential non linearity is stated as ± 1.0 LSB From above, ±1 LSB was 0.048 per cent for ± 10V output.

The IEEE, 1996 defines integral non linearity as the "maximum non-linearity (deviation) over the specified operating range of a system, usually expressed as a percentage of the maximum of the specified range." Differential non linearity is defined by IEEE as "the percentage departure of the slope of the plot of output versus input from the slope of the reference line."

The most relevant uncertainty specification in this case is the integral non linearity because we are interested in the output linearity (integral), rather than the non linearity, of the slope (differential). Therefore, we will use the 0.024 per cent uncertainty value.

8.10.7 *Channel-Channel Skew*
This is the maximum difference in time that could occur when sampling channels. For example, if ten channels were sampled at a specified time, the times could be different by a maximum of the channel-channel skew, 100 nanosecond or 100×10^{-9} sec. This specification would be used to present the uncertainty in time.

Summary for DSP Model 2860 TRAQ Digitizer:
<u>Systematic uncertainties:</u>
1) Resolution: ± 0.048 per cent
2) Gain error: ± 0.1 per cent
3) Offset error: ± 0.1 per cent
4) Integral non-linearity: ±0.024 per cent

Random uncertainties:
1) Bandwidth (frequency response): negligible at 10kHz signal.
2) CMRR: N/A.

8.11 IBM compatible PC and Data Post processing
A properly functioning PC does not add any additional uncertainty to the signal.

Once the data are in digital format, a large amount of data analysis can be performed on the data - e.g., differentiation, integration, fast Fourier transform, filtering, etc. I will not attempt to cover all those possibilities in this uncertainty analysis. When developing the "Data Viewer" for use in AFSEC experiments, Tim Miller validated and documented (Miller, 1998) the following functions:
a) Butterworth filter
b) Chebyshev filter
c) Bessel filter
d) Decimation
e) Integration

For this analysis I'll assume there are no additional uncertainties added to the data when post processing takes place, but this should be checked for each case. For example, Madsen et.al., 1987 assumed the uncertainties owing to "post-processing, analog-to-digital conversion, filtering, plotting data, and interpretation – human error," to be ± 10 per cent. This would substantially increase the total uncertainty.

8.12 Uncertainty Summary for Entire System:

The method used to find the uncertainty of the entire system is to add the individual uncertainties using the RSS method. First, I'll summarize all the systematic and random uncertainties:

a) Summary for Endevco Series 7270A-20K accelerometer:

Systematic uncertainties:
1) Sensitivity: ± 3 per cent
2) Non-linearity & hysteresis: ± 2 per cent
3) Transverse sensitivity: ± 5 per cent

Random uncertainties:
1) Frequency response: ± 5 per cent
2) Zero shift due to half sine acceleration: ± 0.25 per cent

b) Summary for Connecting Cable:
Systematic uncertainties: negligible

Random uncertainties: negligible

c) Summary for Dynamics Model 8000 power supply:

<u>Systematic uncertainties:</u>
1) Load regulation: ± 0.006 per cent

<u>Random uncertainties:</u>
1) Resolution: ± 1.2 per cent
2) Line regulation: ± 0.005 per cent
3) Noise: ± 0.003 per cent

d) Summary for Dynamics Model 7600A power supply:

<u>Systematic uncertainties:</u>
1) Load regulation: ± 0.004 per cent

<u>Random uncertainties:</u>
1) Resolution: ± 0.085 per cent
2) Line regulation: ± 0.005 per cent
3) Noise: ± 0.0015 per cent

e) Summary for Dynamics Model 8000 or Model 7600A Amplifiers:

<u>Systematic uncertainties:</u>
1) Gain accuracy: ± 0.1 per cent
2) Linearity: ± 0.005 per cent
3) Zero adjustment: ± 0.05 per cent

<u>Random uncertainties:</u>
1) Frequency response: ± 1.0 per cent
2) Settling time: ± 0.1 per cent
3) Noise: ± 0.006 per cent
4) CMRR: ± 0.05 per cent

f) Summary for DSP Model 2860 TRAQ Digitizer:

<u>Systematic uncertainties:</u>
1) Resolution: ± 0.048 per cent
2) Gain error: ± 0.1 per cent
3) Offset error: ± 0.1 per cent
4) Integral non-linearity: ±0.024 per cent

<u>Random uncertainties:</u>
1) Bandwidth (frequency response): negligible
2) CMRR: N/A

To estimate the overall uncertainty of the entire system, one combines the systematic and random components using Equation 4. When using this method, it becomes clear that only the large terms dominate. In addition, many of the accelerometers specifications have only one significant digit, so it makes no sense to carry other uncertainty sources with much smaller numbers - e.g., 0.005 per cent. Therefore, for the calculations below, only those uncertainty sources with a single significant digit will be used.

As stated earlier, most of the uncertainties provided by manufacturers are maximum values - i.e., 99 per cent confidence or 3σ. Therefore, to use Equation 4 for 95 per cent confidence (2σ), the systematic uncertainties should be reduced by multiplying by two thirds and the random values by one third.

Total Uncertainty for 95 per cent Confidence

A) For the system including the Dynamics Model 8000 amplifier/signal conditioner:

$$B = [(3.0*0.67)^2 + (2.0*0.67)^2 + (5.0*0.67)^2 + (0.1*0.67)^2 + (0.1*0.67)^2 + (0.1*0.67)^2]^{1/2} \approx 4.1\%,$$

and

$$S_x = [(5.0*0.33)^2 + (0.25*0.33)^2 + (1.2*0.33)^2 + (1.0*0.33)^2 + (0.1*0.33)^2]^{1/2} \approx 1.8\%,$$

therefore, using Equation 4:

$$U_{95} = \pm [(B)^2 + (2*S_x)^2]^{1/2} = \pm [(4.1)^2 + (2*1.75)^2]^{1/2} = \pm 5.4\%$$

$U_{95} \approx \pm 5.4\%$ (Dynamics Model 8000 amplifier/signal conditioner)

B) For the system including the Dynamics Model 7600A amplifier/signal conditioner:

B = same as above $\approx 4.1\%$,

and

$$S_x = [(5.0*0.33)^2 + (0.25*0.33)^2 + (1.0*0.33)^2 + (0.1*0.33)^2]^{1/2} \approx 1.7\%;$$

therefore, using Equation 4:

$$U_{95} = \pm [(B)^2 + (2*S_x)^2]^{1/2} = \pm [(4.1)^2 + (3.4)^2]^{1/2} = \pm 5.3\%$$

$U_{95} \approx \pm 5.3$ per cent (Dynamics Model 7600A amplifier/signal conditioner)

Total Uncertainty for 99 per cent Confidence

To obtain an estimate of the total uncertainty with 99 per cent confidence, Equation 3 should be used (ASME, 1998). If Equation 3 is used, the B_i (U_B) and S_{xi} (U_A) used should be 1σ values, and K should be 3 for 99 per cent confidence.

A) For the system including the Dynamics Model 8000 amplifier/signal conditioner:

$U_A = [(3.0*0.33)^2 + (2.0*0.33)^2 + (5.0*0.33)^2 + (0.1*0.33)^2 + (0.1*0.33)^2 + (0.1*0.33)^2]^{1/2} \approx 2.1\%$,

and

$U_B = S_x =$ same as above $\approx \pm\ 1.8\%$;

therefore, using Equation 3 with K as 3.0:

$U_{99} = \pm\ K[U_A{}^2 + U_B{}^2]^{1/2} \approx = \pm\ 3.0\ [2.1^2 + 1.8^2\ ]^{1/2} \approx \pm 8.3\%$.

Therefore:

$U_{99} \approx \pm 8.3$ per cent (Dynamics Model 8000 amplifier/signal conditioner)

Note that this is less than the uncertainty value available from Table 1 (± 15 per cent) but that value included human error not included here.

B) For the system including the Dynamics Model 7600A amplifier/signal conditioner:

$U_A \approx \pm\ 2.1\%$,

and

$U_B = S_x \approx \pm\ 1.7\%$;

therefore, using Equation 3 with K as 3.0:

$U_{99} = \pm\ 3\ [2.1^2 + 1.7^2]^{1/2} \approx \pm 8.1\%$.

therefore:

$U_{99} \approx \pm 8.1$ per cent (Dynamics Model 7600A amplifier/signal conditioner)

8.13 Mounting Method Considerations

Similar to considerations for thermocouples (Nakos, 1999), the method used to mount the transducer onto the test unit can have a profound effect on the overall measurement uncertainty. Walter, 1999, states that one crucial consideration of mounting accelerometers onto a test unit is "impedance or mass loading." The fact that the accelerometer is of finite (but small) mass (Endevco Model 7270A accelerometers weigh 1.5 gm) will have an effect on the response of the test unit. For example, "an 11-gram accelerometer would have a 10% effect at all frequencies on the measured velocity of the structure if the structure responded as a pure 100 gm mass." "Since velocity and acceleration can be related through frequency… for pure masses this same 10 per cent error would also quantify the error in the measured acceleration." (Walter, 1999) In other words, the 11-gm accelerometer would produce a 10 per cent error in acceleration on a 100-gm mass.

The velocity response of the "system" (test unit) is modified by the accelerometer via the following relation:

$$V_s^*/V_s = Z_s/(Z_s + Z_a), \qquad \textbf{(8)}$$

where V_s^* is the modified system response; V_s is the unmodified system response; Z_s is the "mechanical impedance" of the system; and Z_a is the mechanical impedance of the accelerometer (Walter, 1999). For pure masses Z_s and Z_a are the masses of the accelerometer (Z_a) and the test unit (Z_s). Not only can an accelerometer change the amplitude of the response but also its frequency.

Bowers et al., 1991, also discuss the effect of accelerometer mounting methods on the response of test units. Large differences can result because of mounting (stud, adhesive, magnetic, etc.); loose sensors; measurement location; measurement by different people; and multiple measurements by one person. There are numerous other references that discuss this issue and related issues, but I will not discuss them further - e. g., Walter and Nelson, 1979. The important conclusion is that care should be used regarding mounting, or the total uncertainty can be much larger.

9 Conclusions

There is a ± 5 per cent uncertainty (95 per cent confidence level) or ± 8 per cent uncertainty (99 per cent confidence level) associated with either of the accelerometer DAQ systems. Most of the uncertainty comes from the transducer. The conclusion is that the DAQ system is a small uncertainty contributor, and the most effort should be expended to reduce transducer uncertainties. Also as shown in Section 8, if mounting techniques are not carefully considered, the overall system uncertainty can be much larger because the system to be measured will be affected so much that the measurement has changed-sometimes by large amounts.

10 References

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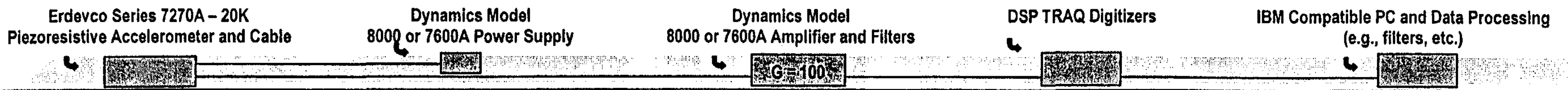
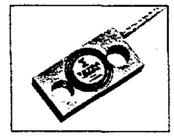
Figure 1. Uncertainty Analysis of Accelerometer Data Acquisition (DAQ) System



Accelerometer Systematic Uncertainties: 1. Sensitivity: ± 3% 2. Nonlinearity & hysterisis: ±2% 3. Transverse sensitivity: ±5% Random Uncertainties: 1. Frequency response: ±5% 2. Zero shift (half-sine): ±0.25% **Connecting Cable** Systematic Uncertainties: negligible Random Uncertainties: negligible	**Model 8000 Power Supply** Systematic Uncertainties: 1. Load regulation: ±0.006% Random Uncertainties: 1. Resolution: ±1.2% 2. Line regulation: ±0.005% 3. Noise: ±0.003% **Model 7600A Power Supply** Systematic Uncertainties: 1. Load regulation: ±0.004% Random Uncertainties: 1. Resolution: ±0.085% 2. Line regulation: ±0.005% 3. Noise: ±0.0015%	**Model 8000 or 7600A Amplifier** Systematic Uncertainties: 1. Gain accuracy: ±0.1% 2. Linearity: ±0.005% 3. Zero adjustment: ±0.05% Random Uncertainties: 1. Frequency response: ±1.0% 2. Settling time: ±0.1% 3. Noise: ±0.006% 4. CMRR: ±0.05% **6-Pole Bessel Filters** Systematic Uncertainties: negligible Random Uncertainties: negligible	**Model 2860 DSP TRAQ Digitizer** Systematic Uncertainties: 1. Resolution: ±0.048% 2. Gain: ±0.1% 3. Offset: ±0.1% 4. Integral non-linearity: ±0.024% Random Uncertainties: 1. Bandwidth (frequency response): negligible at 10 kHz 2. CMRR: N/A.	**PC and Post-processing** Systematic Uncertainties: negligible Random Uncertainties: negligible **Uncertainty of entire system for Model 8000 amplifiers and power supplies:** $B = \pm [(3.0*0.67)^2 + (2.0*0.67)^2 + (5.0*0.67)^2 + (0.1*0.67)^2 + (0.1*0.67)^2 + (0.1*0.67)^2]^{1/2} \approx \pm 4.1\%$, and $S = \pm [(5.0*0.33)^2 + (0.25*0.33)^2 + (1.2*0.33)^2 + (1.0*0.33)^2 + (0.1*0.33)^2]^{1/2} \approx \pm 1.8\%$, Therefore, using Equation 4: $U_{95} = \pm [B^2 + (2*S_X)^2]^{1/2} = \pm [4.1^2 + (3.6)^2]^{1/2} = \pm 5.4\%$ **$U_{95} \approx \pm 5.4\%$** **Similarly, uncertainty of entire system for Model 7600A amplifiers/power supplies: $U_{95} \approx \pm 5.3\%$** Using Equation 3 get 99% uncertainty: **$U_{99} \approx \pm 8.3\%$ (Model 8000)** **$U_{99} \approx \pm 8.1\%$ (Model 7600A)**

Piezoresistive Accelerometer

ENDEVCO MODEL 7270A



Actual size

Model 7270A

- **2000 to 200 000 g Full Scale**
- **High Resonance Frequency**
- **DC Response**
- **Rugged Undamped**

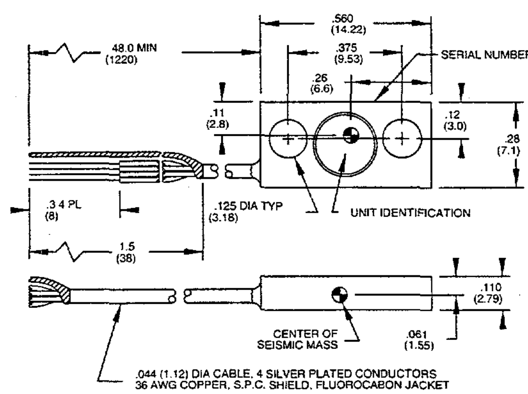
DESCRIPTION

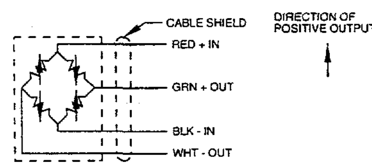
The ENDEVCO® Model 7270A series of piezoresistive accelerometers are rugged un-damped units designed for shock measurements.

ENDEVCO micro-machines the sensing system of the 7270A from a single piece of silicon. This etched silicon chip includes the inertial mass and strain gages arranged in an active four-arm Wheatstone bridge circuit complete with a novel on-chip zero balance network.

The low mass, extremely small size and unique construction of the element blends an exceptionally high resonance frequency with characteristics such as low impedance, high overrange, and zero damping for no phase shift. The high resonance frequency of these sensors permits their survival in the presence of these high frequency components in a shock pulse that could shatter the seismic system of accelerometers having lower resonance.

High resonance frequencies and zero damping also allow the accelerometers to respond accurately to fast rise time, short duration shock motion. With a frequency response extending down to dc or steady state accelerations, these transducers are ideal for measurement of long duration transients.





SCHEMATIC

STANDARD TOLERANCE
INCHES (MILLIMETERS)
.XX = +/- .03 (.X = +/- .8)
.XXX = +/- .010 (.XX = +/- .25)

Model 7270A-XXM4, with integral 1/4-28 mounting stud, is available on special order.

ENDEVCO Model 136 Three-Channel System, Model 4430A or Model 68207 BCAS™ Computer Controlled System are recommended as signal conditioner and power supply.

SPECIFICATIONS

PERFORMANCE CHARACTERISTICS: All values are typical at +75°F (+24°C) and 10 Vdc excitation unless otherwise specified. Calibration data, traceable to the National Institute of Standards (NIST), is supplied.

	Units	7270A-2K	-6K	-20K	-60K	-200K
RANGE [1]	g pk	±2000	±6000	20 000	±60 000	±200 000
SENSITIVITY	µV/g	100 ±50	30 +20/-15	10 ±5	3 +2/-1.5	1 ±0.5
FREQUENCY RESPONSE [2] (±5% max, ref. 100 Hz)	kHz	0 to 10	0 to 20	0 to 50	0 to 100	0 to 150
MOUNTED RESONANCE FREQUENCY	kHz Typ	90	180	350	700	1200
	(Min)	(60)	(120)	(220)	(400)	(800)
NON-LINEARITY AND HYSTERESIS (% of reading, to full range)	% Max	±2, up to acceleration corresponding to the recommended range. Measurement uncertainties prevent stating this as a specification limit above 10 000 g.				
TRANSVERSE SENSITIVITY	% Max	5	5	5	5	5
ZERO MEASURAND OUTPUT	mV Max	±100	±100	±100	±100	±100

ENDEVCO MODEL 7270A

Piezoresistive Accelerometer

SPECIFICATIONS—continued

PERFORMANCE CHARACTERISTICS

	Units	7270A	-6K	-20K	-60K	-200K
ZERO SHIFT DUE TO HALF SINE ACCELERATION CAUSING 200 mV OUTPUT (or 150 000 g, whichever is smaller)	mV Max	0.5	0.5	0.5	0.5	0.5
ZERO SHIFT DUE TO MOUNTING TORQUE (0 TO 8 LBF-IN., 0 TO 0.9 NM)	mV Max	±2	±2	±2	±2	±2
THERMAL ZERO SHIFT [4] From -30°F to +150°F (-34°C to +66°C)	mV Max	±50	±50	±50	±50	±50
THERMAL SENSITIVITY SHIFT From 0°F and +150°F (-18°C and +66°C)	% Max	±10	+10	±10	±10	±10
OVERRANGE LIMIT [2}	9 pk	±10 000	±18 000	±60 000	±180 000	±200 000
WARM-UP TIME	Minutes Max (Seconds) Typ)	2 (15)	2 (15)	2 (15)	2 (15)	2 (15)

ELECTRICAL

EXCITATION	10.0 Vdc, 12 Vdc maximum
INPUT RESISTANCE	550 ±200 ohms
OUTPUT RESISTANCE	550 ±200 ohms
INSULATION RESISTANCE	100 megohms minimum at 100 Vdc; between sensor, cable shield and case

PHYSICAL

CASE, MATERIAL	Stainless Steel (17-4 PH CRES)
ELECTRICAL, CONNECTIONS	Integral cable, 4 conductor No. 36 AWG Teflon® insulated leads, braided shield, flourocarbon jacket
IDENTIFICATION	Manufacturer's logo, model number and serial number
MOUNTING/TORQUE [3]	Holes for two 4-40 or M3 mounting screws/8 ±2 lbf-in (0.9 Nm)
WEIGHT	1.5 grams (cable weighs 3.6 grams/meter)

ENVIRONMENTAL

ACCELERATION LIMITS [3] [4]	±200 000 g half sine pulse or three times the recommended range, in any direction, whichever is smaller. Pulse duration should be the greater of 20 microseconds or five periods of the resonance frequency
BASE STRAIN SENSITIVITY (at 250 microstrain)	Typically less than 0.5 mV
TEMPERATURE Operating Storage	-30°F to +150°F (-34°C to +66°C) -65°F to +250°F (-54°C to +121°C)
HUMIDITY	Unaffected. Unit is epoxy sealed
ALTITUDE	Unaffected

CALIBRATION DATA SUPPLIED

SENSITIVITY [5]	μV/g at recommended range or 5000 g, whichever is smaller. Time history at respective g level

ACCESSORIES

EHW265	(2) SIZE - 4 FLAT WASHERS
EH137	(2) 4-40 X 1/4 INCH ALLENOY STEEL, OR EQUIVALENT, SOCKET HEAD CAP SCREWS

OPTIONAL ACCESSORIES

25034	4 CONDUCTOR SHIELDED CABLE
7970	TRIAXIAL MOUNTING BLOCK
EHX268	ACOUSTIC COUPLANT

NOTES

1. The unit will operate to the overrange limit, with slightly degraded linearity. Above the overrange limit, the sensor may fail. IMPORTANT: Frequency content of shocks which exceed the 7270A overrange limits often contain amplitudes above 100 kHz. Insufficient bandwidth in signal conditioning may give lower indicated peak acceleration.
2. Frequency response deviates less than ±5% from dc to indicated frequency based on analysis. Measurement uncertainties above 10 kHz prevent stating ±5% as a specification limit for all but the 7270A-2K.
   NOTE: The sensor chip includes two masses, each with a separate resonance frequency. If these resonances are excited, the transducer output will exhibit a "beat" frequency.
3. Use 8 ±2 lbf-in (0.9 Nm) mounting torque, acoustic couplant and high strength steel screws to ensure intimate contact between accelerometer and mounting surface, to prevent yielding of the screw and loss of preload force due to shocks, particularly those above 100 000 g. Loss of meaningful data and possible damage to the accelerometer can result from using an incorrect value of mounting torque.
   The use of low strength mounting material (such as aluminum) is not recommended. However, if such is the case, epoxy should be used between the transducer and mounting surface. If large transverse shocks are anticipated, the use of liquid threadlocking compounds is recommended to reduce loss of screw preload.
4. Prior to final calibration, each accelerometer is given a shock in its sensitive axis approximately equal to its overrange limit (reference ENDEVCO TP283)
5. Calibrations are performed on Model 2965C Shock Calibrator or Model 2925 POP Shock Calibrator.

NOTE: Tighter specifications available on special order.

ENDEVCO CORPORATION, 30700 RANCHO VIEJO ROAD, SAN JUAN CAPISTRANO, CA 92675 USA (949) 493-8181 fax (949) 661-7231 0298

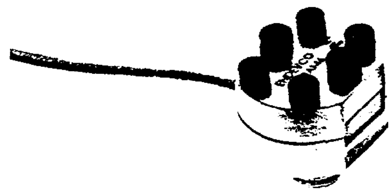
Figure 2B

Piezoresistive Accelerometer

ENDEVCO MODEL 7270AM6

Model 7270AM6

- **Mechanical Filter**
- **6000 to 60 000 g Full Scale**
- **DC Response**
- **Rugged**



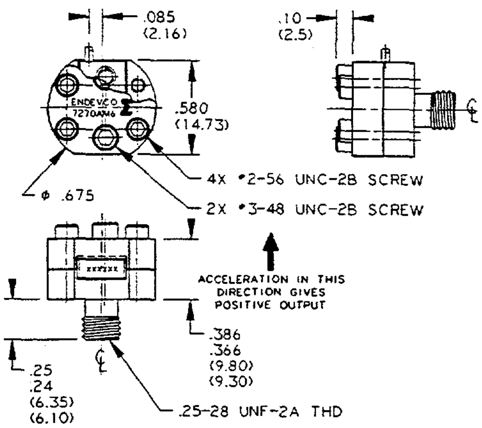
Actual size

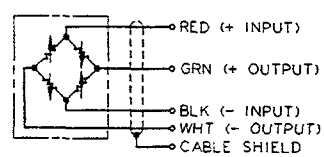
DESCRIPTION

The ENDEVCO® Model 7270AM6 series of piezoresistive accelerometers are rugged units with built-in mechanical filters designed for shock measurements. The mechanical filter assembly is designed to mitigate the high frequency content of a shock pulse in order to protect the accelerometer sensor from high g, high frequency inputs that would otherwise exceed the over-range limits. The Model 7270A-XXM6 is available in ranges of 6000 to 60 000g Full Scale.

Developed by Sandia National Laboratories, the mechanical isolator consists of an aluminum housing lined with two layers of elastomer filter that cushions the Model 7270A Piezoresistive Accelerometer. With the elastomer on both sides of the accelerometer, the response is the same to both positive and negative accelerations. The mechanical filter used in the Model 7270A-XXM6 features a damped output with a linear phase shift. The unit is usable over the frequency range from DC to 10 kHz for the temperature range of -30 to +150°F (-34 to +66°C).

The Endevco Model 136 Three-Channel Signal Conditioner, Model 68207 BCAS Computer Controlled System or Model 4430A Bridge Signal Conditioner are recommended as signal conditioner and power supply.





STANDARD TOLERANCE

INCHES	(MILLIMETERS)
XX = ±.01	X = ±.3
XXX = ±.005	XX = ±.13

U.S. Patents 4,498, 229, 4,605,919 and 4,689,600

SPECIFICATIONS

PERFORMANCE CHARACTERISTICS: All values are typical at +75°F (+24°C) and 10 Vdc excitation unless otherwise stated. Calibration data, traceable to the National Institute of Standards (NIST), is supplied.

	Units	-6KM6	-20KM6	-60KM6
RANGE [1]	g pk	±6000	20 000	±60 000
SENSITIVITY	μV/g	30 +20/-15	10 ±5	3 +2/-1.5
FREQUENCY RESPONSE [2] (±10% max, ref. 100 Hz)	kHz	0 to 10	0 to 10	0 to 10
NON-LINEARITY (% of reading, to full range)	% Max	±2, up to acceleration corresponding to the recommended range. Measurement uncertainties prevent stating this as a specification limit above 10 000 g.		
TRANSVERSE SENSITIVITY	% Typ	5	5	5
ZERO MEASURAND OUTPUT	mV Max	±100	±100	±100

ENDEVCO MODEL 7270AM6

Piezoresistive Accelerometer

SPECIFICATIONS—continued

PERFORMANCE CHARACTERISTICS–continued

	Units	-6KM6	-20KM6	-60KM6
THERMAL ZERO SHIFT From -30°F to +150°F (-34°C to +66°C)	mV Max	±50	±50	±50
THERMAL SENSITIVITY SHIFT From -30°F and +150°F (-34°C and +66°C)	% Max	±10	±10	±10
OVERRANGE LIMIT	g pk	±18 000	±60 000	±100 000
WARM-UP TIME	Minutes Max Seconds (Typ)	2 (15)	2 (15)	2 (15)

ELECTRICAL	
EXCITATION	10.0 Vdc, 12 Vdc maximum
INPUT RESISTANCE	550 ±200 ohms
OUTPUT RESISTANCE	550 ±200 ohms
INSULATION RESISTANCE	100 megohms minimum at 100 Vdc; between sensor, cable shield and case
PHYSICAL	
CASE, MATERIAL	Stainless Steel (17-4 PH CRES)
ELECTRICAL, CONNECTIONS	Integral cable, 4 conductor No. 36 AWG Teflon® insulated leads, braided shield, flourocarbon jacket
IDENTIFICATION	*Manufacturer's logo, model number and serial number*
MOUNTING/TORQUE [1]	75 lbf-in (8.4 Nm)
WEIGHT	8.4 grams excluding cable (cable weighs 3.6 grams/meter)
ENVIRONMENTAL	
ACCELERATION LIMITS	±100 000 g half sine pulse or three times the recommended range, in any direction, whichever is smaller. Pulse duration should be the greater of 20 microseconds or five periods of the resonance frequency
TEMPERATURE Operating Storage	 -30°F to +150°F (-34°C to +66°C) -65°F to +250°F (-54°C to +121°C)
HUMIDITY	Unaffected. Unit is epoxy sealed
ALTITUDE	Unaffected
CALIBRATION DATA SUPPLIED	
SENSITIVITY [5]	µV/g at 5000 g
ACCESSORY	
31290	WRENCH
OPTIONAL ACCESSORIES	
25034	4 CONDUCTOR SHIELDED CABLE
32103	TRI-AXIAL MOUNTING BLOCK

NOTES

1. Removable Loctite should be applied to 10-32 stud before installation. Recommended mounting torque should be applied to bottom half of unit.

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SIGNAL CONDITIONER SPECIFICATIONS (OPTIONAL)

Excitation Power Supply

	Constant Voltage Standard Output	Constant Voltage (High Vol.Option)	Constant Current
Excitation	0.1 to 15V at 100 mA. Short circuit current limited to 160mA.	0.1 to 30V at 75 mA. Short circuit current limited to 160mA.	1 mA to 100 mA. Compliance voltage is 0.1V to 25V at 0 to 100 mA.
Resolution:	0.060V	0.120V	400/uA
Line Regulation	0.005% or 150 uV whichever is greater for ±10% line variations.	0.005% or 300 uV whichever is greater for ±10% line variations.	0.005% or 1.0 uA whichever is greater for ±10% line variations.
Load Regulation	150 uV plus 100 uV/ohm of lead resistance to 5 ohm independent of the excitation voltage. Sense current is less than 100 uA. The output does not overvoltage with the sense leads disconnected. Local sense may be selected on the bridge completion card.	300 uV plus 100 uv/ohm of lead resistance limited to 5 ohm independent of the excitation voltage. Sense current is less than 100 uA. The output does not overvoltage with the sense leads disconnected. Local sense may be selected on the bridge completion card.	Less than 0.005% or 1.0 uA whichever is a greater chance in output current for a 10 to 1 change in compliance voltage.
Output Impedance	0.01 ohm in series with 20 uH	0.01 ohm in series with 20 uH	10 Mohm in parallel with 300 pF.

086759 06/20/86

Noise	150 uV p-p from 0.1 Hz to 20 kHz.	300 uV p-p from 0.1 Hz to 20 kHz.	1 uA p-p from 0.1 Hz to 20 kHz with a 350 ohm bridge.
Stability	0.01% or 500 uV per 8 hours after 30 minute warm-up	0.01% or 1 mV per 8 hours after 30 minute warm-up	0.01% or 1.5 uA per 8 hours after 30 minute warm-up.
Temperature Coefficient	0.005%/C' or 100 uV/C' whichever is greater.	0.005%/C' or 200 uV/'C whichever is greater.	0.005%/C' or 0.5 uA/'C whichever is greater.

Selection of constant voltage or constant current excitation is by an internal switch. The switch position is monitored by the computer. The excitation voltage is controlled by an eight-bit DAC, which is set by the computer.

Excitation Disconnect	A computer controlled relay disconnects the plus excitation from the bridge and connects the plus bridge power to the minus bridge power. A front panel red LED is illuminated when the excitation is off.
Configuration	1, 2, 3, or 4 active arm bridges.
Input wiring	Any input wiring configuration from 2 to 10 wires plus shield.
Bridge Balance	The bridge is balanced by a recessed 20K ohm potentiometer or optionally through the computer controlled RTI offset.
Bridge Balance Indication	A front panel mounted LED indicates the polarity of the output. The LED is red when the output is positive, green when it negative and off when the output is within 1 mV of zero.
Monitor-Local	Front panel mounted pin jacks allows the excitation and amplifier input to be measured.
Monitor-Remote (Optional)	Computer controlled guarded relays switch the amplifier input and excitation to the monitor buss.

AC Characteristics

Frequency Response 100 kHz Bandwdith
±1% from DC to 10 kHz

±1dB from 10 kHz to 50 kHz
-3dB above 100 kHz for gains of 1000 or less

Frequency Response 500 kHz Bandwidth
±1% from DC to 50 kHz
±1dB from 50kHz to 200 kHz
-3dB above 500 kHz for gains less than 1000
-3dB above 20 kHz for gains of 1000 or greater

Settling Time
Less than 25 us to 0.1% of final value.

Overload Recovery Time
Less than 50 us to 5% of full scale for any overload up to 10 times full-scale input not exceeding plus or minus 20VDC or peak AC.

Slew Rate
3.77 V/us 20V p-p to 60 kHz

Noise

RTI	Bandwidth
10 uV rms	500 kHz
5 uV rms	100 kHz
3 uV rms	50 kHz
2 uV rms	10 kHz
4 uV p-p	100 Hz
1 uV p-p	10 Hz

plus 200 uV RTO

DC Characteristics

Constant Temperature Drift
±2 uV RTI, ±200 uV RTO plus ±200 uV/V of output.
offset per 8 hours after 1/2 hour warm up.

Temperature Coefficient of Drift
±0.5 uV/'C RTI plus ±150 uV/V/'C of output offset.

Gain
Computer selected gain steps of 1, 2, 5, 10, 20, 50, 100, 200, 500, 1K, 2K, 5K and 10K. Gains below one and a binary gain sequence are available as options.

Gain Accuracy
±0.1%

Gain Stability
±0.005% /200 hours
±0.005% /'C

Linearity
±0.005% at dc

Zero Adjustment
Recessed front panel control provides ±100 uV RTI of zero adjustment. RTO is set by output zero controls. Automatic input zero adjustment is available as an option.

Common Mode

Common-Mode Rejection Ratio (dc to 60 Hz)

	Line Unbalance	
Gain	0 ohm	350 ohm
1000	126 dB	120 dB
100	106 dB	100 dB
10	86 dB	80 dB
1	66 dB	66 dB

CMRR decreases at a rate of 6 dB/octave above 60 Hz limited to 60 dB at a gain of 1000 up to 100 MHZ.

Common-Mode Level — ±50 Vdc up to 60 Hz decreases at a rate of 6 dB/octave above 1 kHz, limited to 1V p-p.

Common-Mode Overscale — ±75V dc or peak ac without damage.

Common-Mode-Input Impedance — 2000 Mohm shunted by 1.5 pF.

Common-Mode Level (Optional) — ±300 V dc up to 60 Hz decreases at a rate of 6 dB/octave above 1 kHz, limited to 1V p-p.

Waugh Controls

Dynamics Filters

TABLE 1-3 ACCESSORIES

Filter - Installs into Model 8000

```
8010 - XXX - X - X
        |    |   |_____  1 = linear phase or Bessel response
        |    |           2 = Butterworth response
        |    |
        |    |_________  2 = 2 pole low-pass filter
        |                3 = 3 pole low-pass filter
        |                4 = 4 pole low pass filter
        |                6 = 6 pole low pass filter
        |
        |______________  001 = 1 Hz cutoff (-3 dB)
                         003 = 3 Hz
                         010 = 10 Hz
                         030 = 30 Hz
                         100 = 100 Hz
                         300 = 300 Hz
                         01K = 1K Hz
                         03K = 3K Hz
                         10K = 10K Hz
                         30K = 30K Hz
                         XXX = custom range from 1 Hz to 50 KHz.
```

Rack - Holds up to 8 Model 8000

```
7931-X-X
     | |_______________  1 115 Vac Power 47-63 Hz
     |                   2 230 Vac Power 47-63 Hz
     |
     |_________________  1 RS-232C Interface
                         2 IEEE 488 Interface
```

In every system one Model 7931 cabinet must be a master.

Mating Connectors
Part number 086801

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Table 1-3 Leading Particulars

ITEM	CHARACTERISTICS
Identification	Model 7600A
Type	Differential Dc Amplifier Signal Conditioning System
Enclosure	Plugs into 10-channel cabinet, Model 7914R/NR or Single-Channel cabinet, Model 7914D/NR.
Dimensions	
Width	1.75 in. (4.45 cm)
Height	8.75 in. (22.25 cm)
Depth	18 in. (45.72 cm)
Weight	Approximately 7 lb. (3.18 kg)
Power Requirements	
Ac Input	(-1) 100 to 125 Vrms, 47 to 63 Hz (-2) 200 to 250 Vrms, 47 to 63 Hz
Power Consumption	15W maximum
Fuse	Internal in Amplifier
Environment	
Temperature Range	
Operating	+32 to +122 °F (0 to +50 °C)
Storage	-4 to +167 °F (-20 to +70 °C)
Humidity	Up to 90% relative humidity without condensation.

Table 1-2 (Continued)

II SIGNAL CONDITIONER

Excitation Power Supply

	Constant Voltage Standard Output	Constant Voltage (High Volt.Option)	Constant Current
Excitation	0.1 to 15V at 100 mA. Constant current or constant voltage selected by jumpers on bridge completion card. Short circuit current limited to 160 mA.	0.1 to 30V at 75 mA. Constant current or constant voltage selected by jumpers on bridge completion card. Short circuit current limited to 160 mA.	1 mA to 100 mA. Compliance voltage is 0.1V to 15V. At 0 to 75 mA and 0.1V to 13V at 75 to 100 mA. Constant current or constant voltage selected by jumpers on bridge completion card.
Resolution	Recessed front panel control has setability of 8.5 mV.	Recessed front panel control has setability of 17 mV.	Recessed front panel control has setability of 60 uA.
Line Regulation	0.005% or 150 uV whichever is greater for plus or minus 10% line variations.	0.005% or 300 uV whichever is greater for plus or minus 10% line variations.	0.005% or 1.0 uA whichever is greater for plus or minus 10% line variations.
Load Regulation	150 uV plus 100 uV/ohm of lead resistance limited to 5 ohm independent of the excitation voltage. Sense current is less than 100 uA. The output does not overvoltage with the sense leads disconnected. Local sense may be selected on the completion card.	300 uV plus 100 uV/ohm of lead resistance limited to 5 ohm independent of the excitation voltage. Sense current is less than 100 uA. The output does not overvoltage with the sense leads disconnected. Local sense may be selected on the completion card.	Less than 0.005% or 1.0 uA whichever is a greater change in output current for a 10 to 1 change in compliance voltage.

Output Impedance	0.01 ohm in series with 20 uH	0.01 ohm in series with 20 uH	10 Mohm in parallel with 300 pF.
Noise	150 uV p-p from 0.1 Hz to 20 kHz.	300 uV p-p from 0.1 Hz to 20 kHz.	1 uA p-p from 0.1 Hz to 20 kHz with a 350 ohm bridge.
Stability	0.01% or 500 uV per 8 hours after 30 minute warm-up	0.01% or 1 mV per 8 hours after 30 minute warm-up	0.01% or 1.5 uA per 8 hours after 30 minute warm-up
Temperature Coefficient	0.005%/°C or 100 uV/°C whichever is greater.	0.005%/°C or 200 uV/°C whichever is greater.	0.005%/°C or 0.5 uA/°C whichever is greater.

Table 1-2 Performance Characteristics

PARAMETER	CHARACTERISTICS
I. DIFFERENTIAL DC AMPLIFIER	
A. Input	
1. Input Impedance	25 Megohm shunted by 500 pF
2. Source Impedance	Specifications met with up to a source impedance of 1 kohm. (10 kohm operation permitted.)
3. Overscale Input	±30 Vdc, or peak ac without damage.
4. Input Bias Current ...	<2.0 nA at 25 °C <0.5 nA/°C
B. Tape Output (Standard)	
1. Output Capability	±10V at 5 mA, limited to ±15V at 25 mA. Short-circuit protected.
2. Capacitive Loading ...	Up to 0.1 uF, no instability
3. Output Impedance	1.0 ohm in series with 20 uH.
4. Output Level	Adjustable from 0V to ±10V
5. Output Zero Control	
a) Adjustment Range ..	±40 mV
b) Resolution	±0.5 mV
C. Galvo Output (Optional)	
1. Output Capability	±10V at 100 mA limited to ±15V at 150 mA
2. Current Limiting	Adjustable from ±20 mA or ±120 mA
3. Output Impedance	0.5 ohm in series with 5 uH.
4. Output Level	Adjustable from 0V to ±10V
5. Output Zero Control	
a) Adjustment Range ..	-10 Vdc to +10 Vdc
b) Resolution	±1 mV @ 0V, and ±20 mV @ ±10V Output

Table 1-2 (Continued)

D. Outputs (General)

1. Polarity .... Same for Tape and Galvo outputs

2. Isolation .... One output may be shorted with <0.025% effect upon the other

3. Zero Indicator .... LED indicates the tape output zero status:
   (a) Red if output is positive
   (b) Green if output is negative
   (c) Off if output is within 1.0mV of zero.

   (Does not include effects of the Galvo Output Zero Control)

E. Ac

(All ac specifications are independent of gain steps or variable gain settings)

1. Frequency Response .... ±1% (dc to 10 kHz)
   ±1 dB (10 kHz to 50 kHz)
   -3 dB (above 100 kHz)

2. Settling Time .... <25 us to 0.1% of final value

3. Overload Recovery Time .... <50 us to 5% of full scale for any overload up to 10 times full-scale input not exceeding ±20 Vdc or peak ac

4. Slewing Rate .... 3.7 V/us, 20V p-p output to 60 kHz

5. Noise ....

RTI	Bandwith
5.0 uV rms	0.1 Hz to 100 kHz
3.0 uV rms	0.1 Hz to 50 kHz
2.0 uV rms	0.1 Hz to 10 kHz
4.0 uV p-p	0.1 Hz to 100 Hz
1.0 uV p-p	0.1 Hz to 10 Hz
+200 uV rms	RTO

Amplifier

Table 1-2 (Continued)

F. Dc

1. Zero Drift
   (Constant Temp.) .... ±2 uV RTI, ±200 uV RTO
   ±200 uV/V (output offset)/8 hours after 1/2 hour warmup

2. Temperature Coefficient of Drift .... ±0.5 uV/°C RTI, ±100 uV/°C RTO
   ±100 uV/V/°C of output offset

3. Linearity .... ±0.005% of full Scale at dc.

4. Gain Accuracy .... ±0.1% in calibrate position of the CAL switch

5. Gain Stability .... ±0.005%/200 hours, ±0.005%/°C

6. Zero Range .... ±100 uV RTI of zero adjustment
   RTO set by output controls

G. Common-Mode

1. Rejection Ratio ....

Gain	SOURCE IMPEDANCE 0 Ohm	350 Ohm
1000	126 dB	120 dB
100	106 dB	100 dB
10	86 dB	80 dB
1	66 dB	66 dB

For common-mode frequencies from dc to 60 Hz, CMRR decreases at a rate of 6 dB/Octave above 60 Hz.
Limited to 60 dB at a gain of 1000, for frequencies up to 100 MHz.

2. Operating Level ...... ±50 Vdc from dc to 60 Hz.
   Decreases at a rate of 6 dB/octave above 1 kHz.
   Limited to 1V p-p up to 100 MHz.

3. Overscale .... ±75 Vdc or peak ac without damage.

4. Input Impedance ...... 2000 Mohm shunted by 1.5 pF.

Figure 5
DSP Digitizer
Model 2860

TRAQ DIGITIZER MODULE SPECIFICATIONS

SPECIFICATION		2812	2814	2825	2860	2824	UNITS
Number of Channels		8	4	4	4	1	Module
RESOLUTION		12	14	12	12	12	Bits
INPUTS							
Voltage Range				+/-5			Volts
Impedance		100		100	100	100	kOhms
Bandwidth	(0.5dB)	100K	50K	200K	500K	1M	Hz
	(3dB)	200K	100M	250K	1M	2M	Hz
CMRR	(dc-100Hz)	72	80	72	72	72	dB
CMVR				+/- 12			Volts
Protection (dc)				+/- 50			Volts
Type				Differential			
ACCURACY (DC)							
Gain Error				+/- 0.1			%
Offset Error				+/- 0.1			%of FS
Integral Non-Linearity				+/- 0.5			LSB
Differential Non-Linearity				1			LSB
SAMPLING RATE		100K	100K	250K	1M	2M	Hz
APERTURE DELAY				<25			NSec
CHANNEL-CHANNEL SKEW				<100			NSec
POWER REQUIREMENTS							
+24 Volts		0.15	0.25	0.2	0.25	0.1	Amps/Module
+ 6 Volts		1.5	1.7	1.0	1.7	1.0	Amps/Module
- 6 Volts		0.55	0.0	0.0	0.0	0.7	Amps/Module
-24 Volts		0.15	0.27	0.3	0.27	0.1	Amps/Module
Power Consumption		2.4	5.0	4.5	5.0	15.0	Watts/Chan
TEMPERATURE RANGE							
Specifications				10 - 55			Celsius
Storage				-5 - 85			Celsius

Sandia National Laboratories

Albuquerque, New Mexico 87185

date: May 20, 1994

to: Distribution

from: M. Arviso, 6642

subject: Characterization of Field Cabling

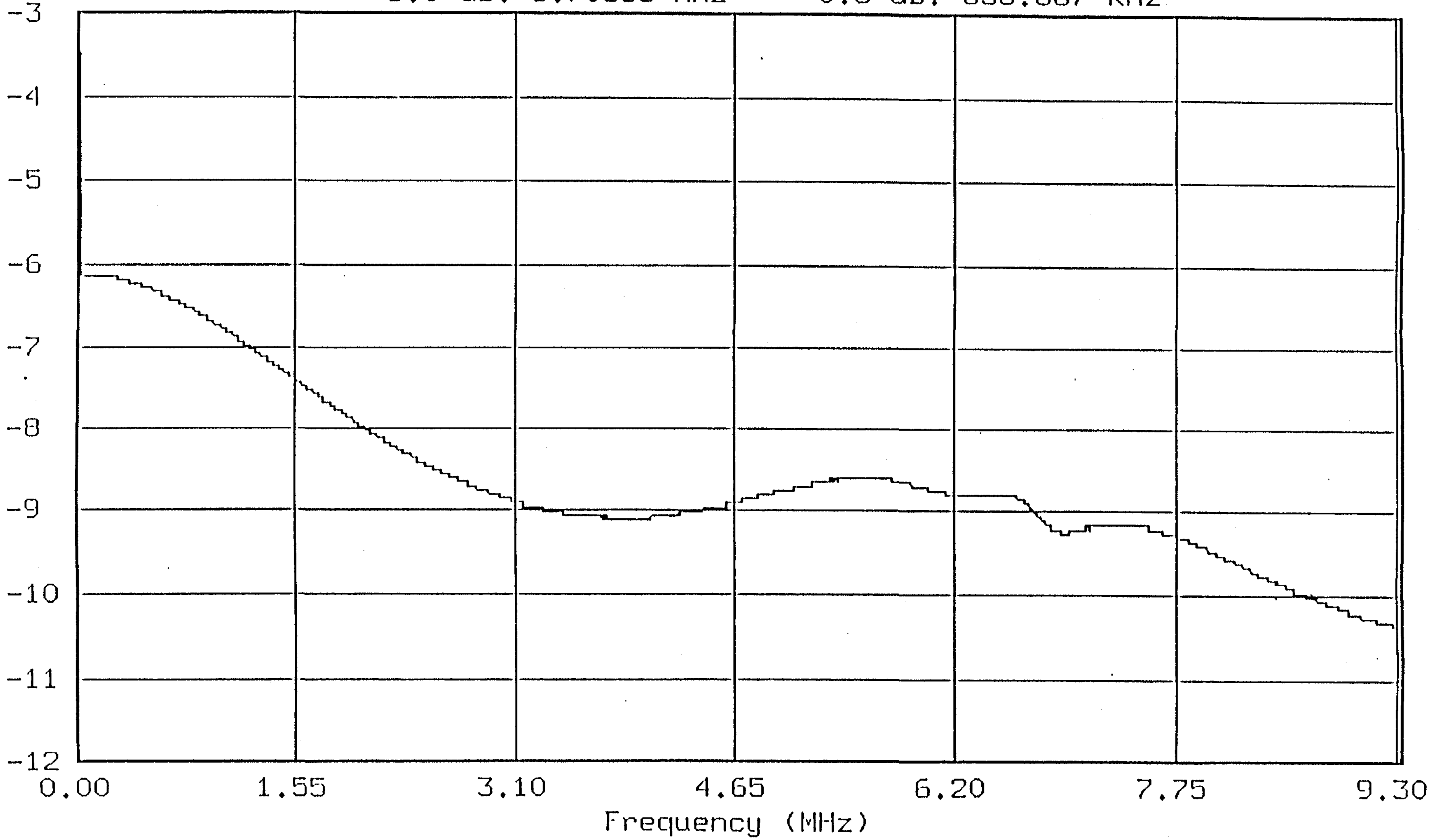
The characterization of the attenuation on the Mercury MW-7122 field cabling has been completed. Cable length was started at 1000 feet and then decremented by 50 feet until a final length of 50 feet was reached. A Hewlett Packard 3585B Spectrum Analyzer was used to insert a signal of varying frequency from DC to a frequency beyond the -0.5 dB point which ranged from 37.4 kilohertz at 1000 feet to 858.7 kilohertz at 50 feet. The cable is a 3 pair individually twisted shielded cable that is color coded per Western Regional Straingage Association Specifications. The weight of this cable is 0.045 pounds/foot. Enclosed are the field cable response plots. If you have any questions or comments, please call me at 5-9157.

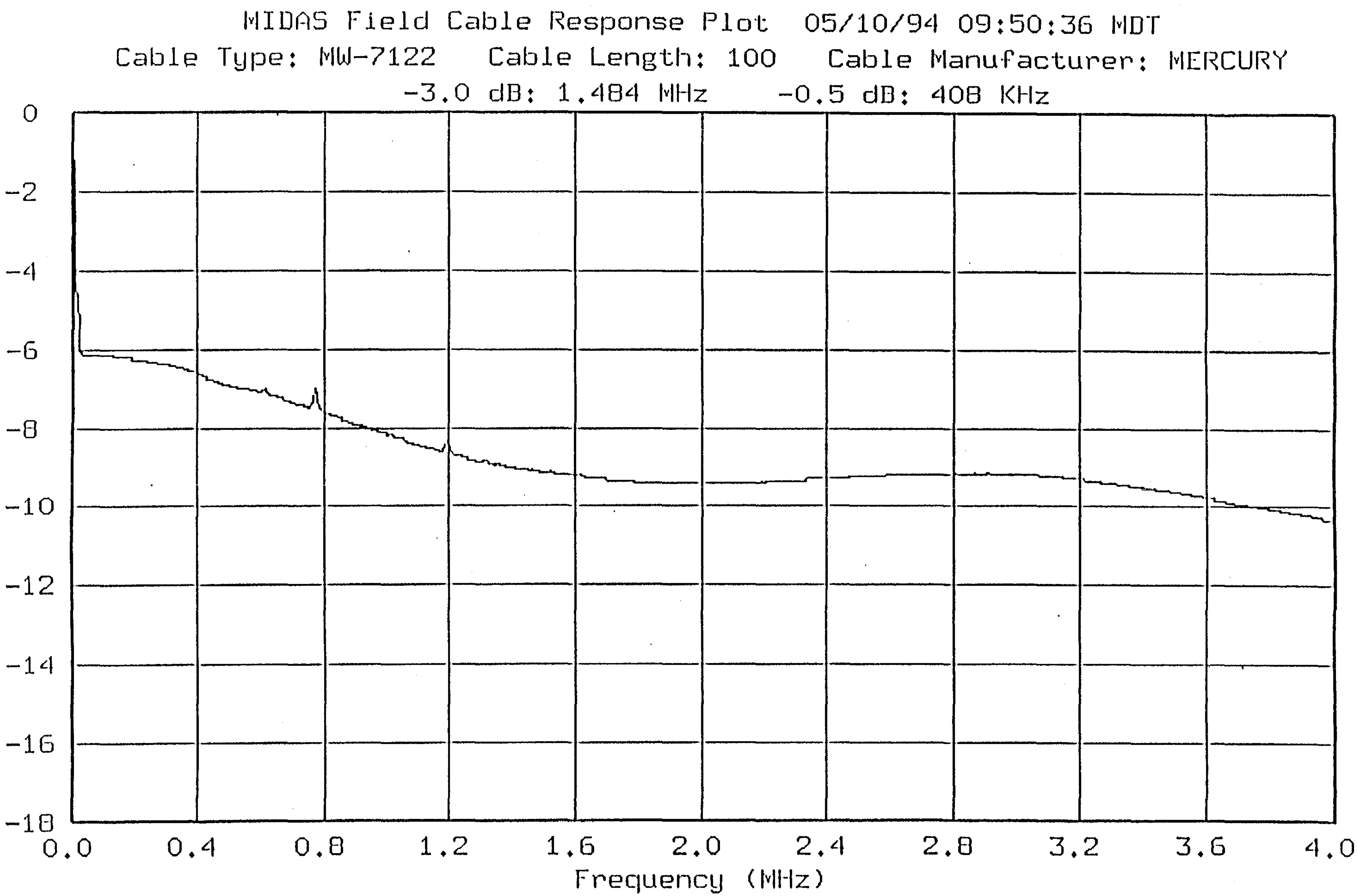
Copy to:
6642 J. G. Bobbe
6642 D. L. Bolton
6642 D. C. Harding
6642 W. McMurtry
6642 J. D. Pierce
6642 W. L. Uncapher
6643 D. R. Stenberg

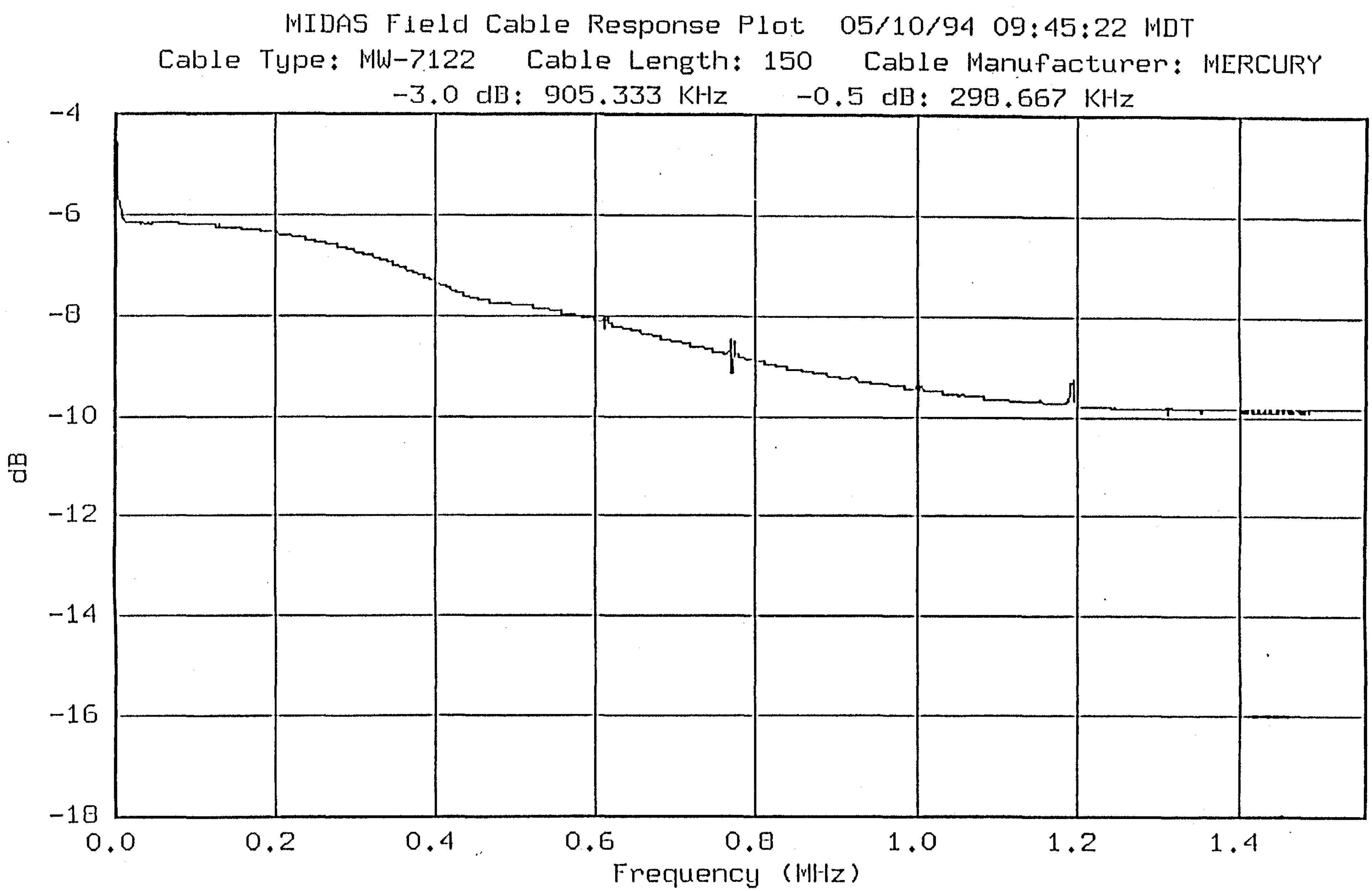
MIDAS Field Cable Response Plot 05/10/94 09:57:51 MDT

Cable Type: MW-7122 Cable Length: 50 Cable Manufacturer: MERCURY

-3.0 dB: 3.70533 MHz -0.5 dB: 858.667 KHz



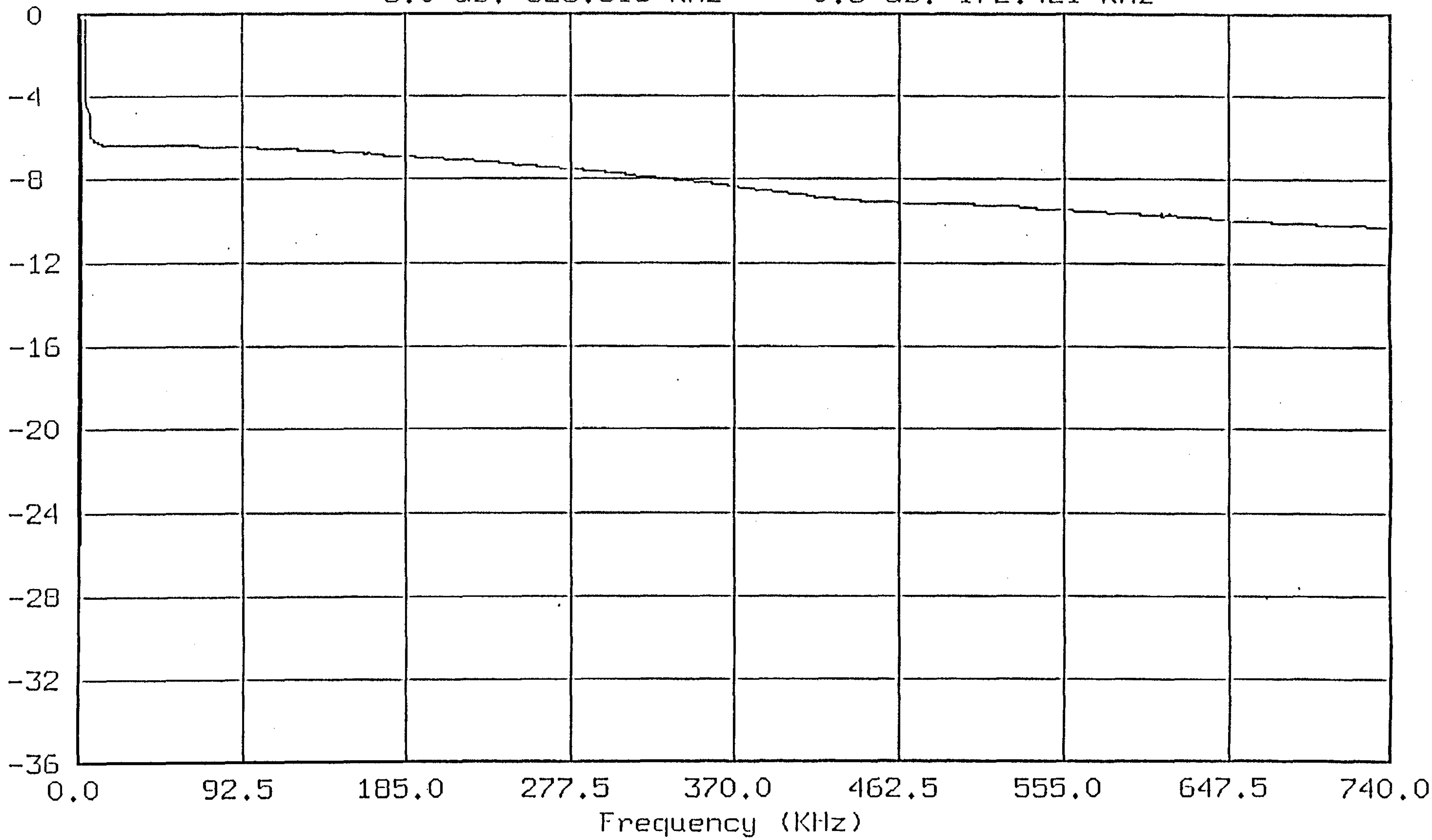

MIDAS Field Cable Response Plot 05/10/94 09:50:36 MDT
Cable Type: MW-7122 Cable Length: 100 Cable Manufacturer: MERCURY
-3.0 dB: 1.484 MHz -0.5 dB: 408 KHz
dB
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
Frequency (MHz)


MIDAS Field Cable Response Plot 05/10/94 09:45:22 MDT
Cable Type: MW-7122 Cable Length: 150 Cable Manufacturer: MERCURY
-3.0 dB: 905.333 KHz -0.5 dB: 298.667 KHz
-4
-6
-8
-10
-12
-14
-16
-18
dB
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Frequency (MHz)

MIDAS Field Cable Response Plot 05/9/94 15:20:05 MDT

Cable Type: MW-7122 Cable Length: 200 Cable Manufacturer: MERCURY

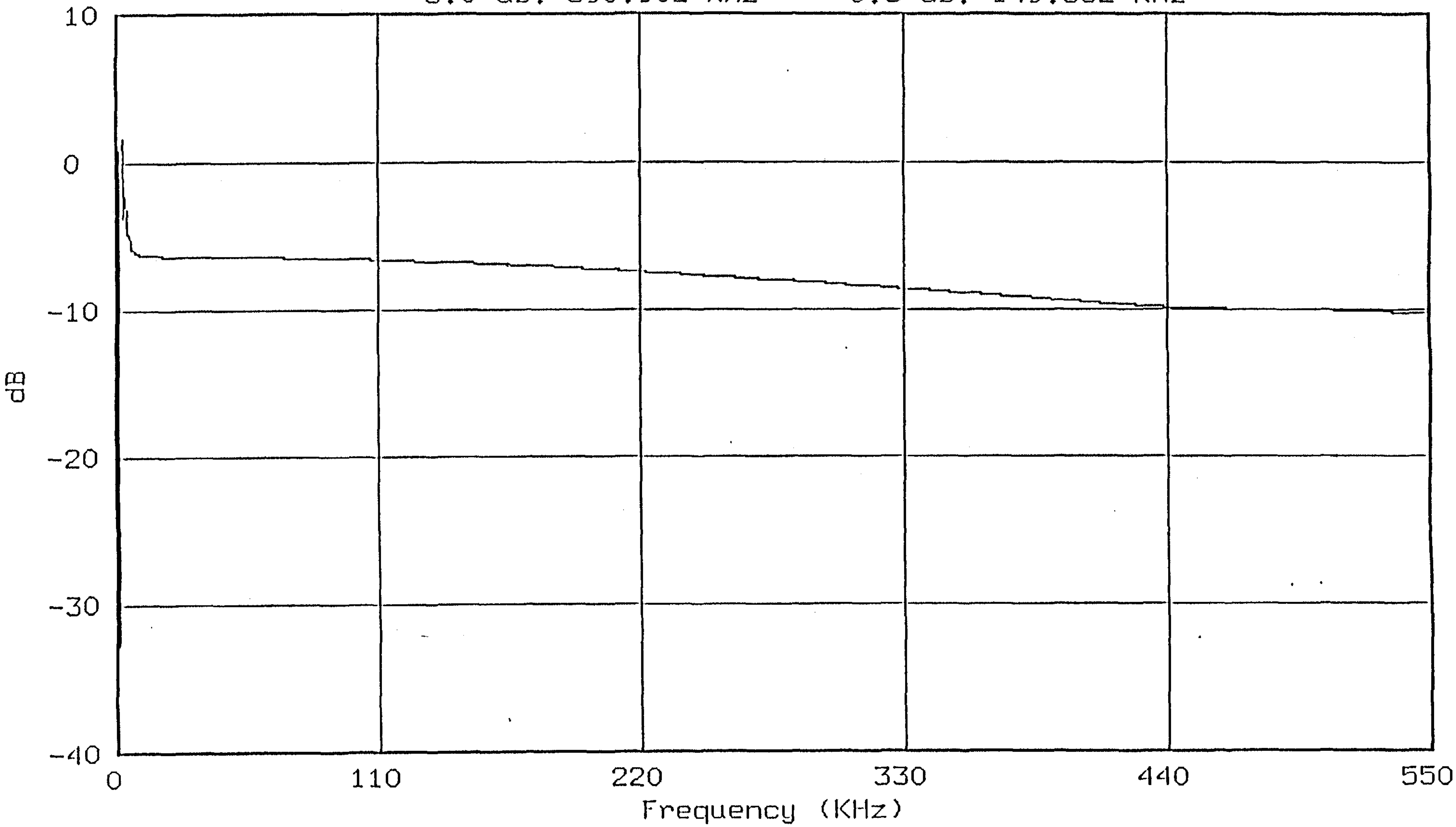
-3.0 dB: 528.316 KHz -0.5 dB: 172.421 KHz



MIDAS Field Cable Response Plot 05/9/94 15:24:43 MDT

Cable Type: MW-7122 Cable Length: 250 Cable Manufacturer: MERCURY

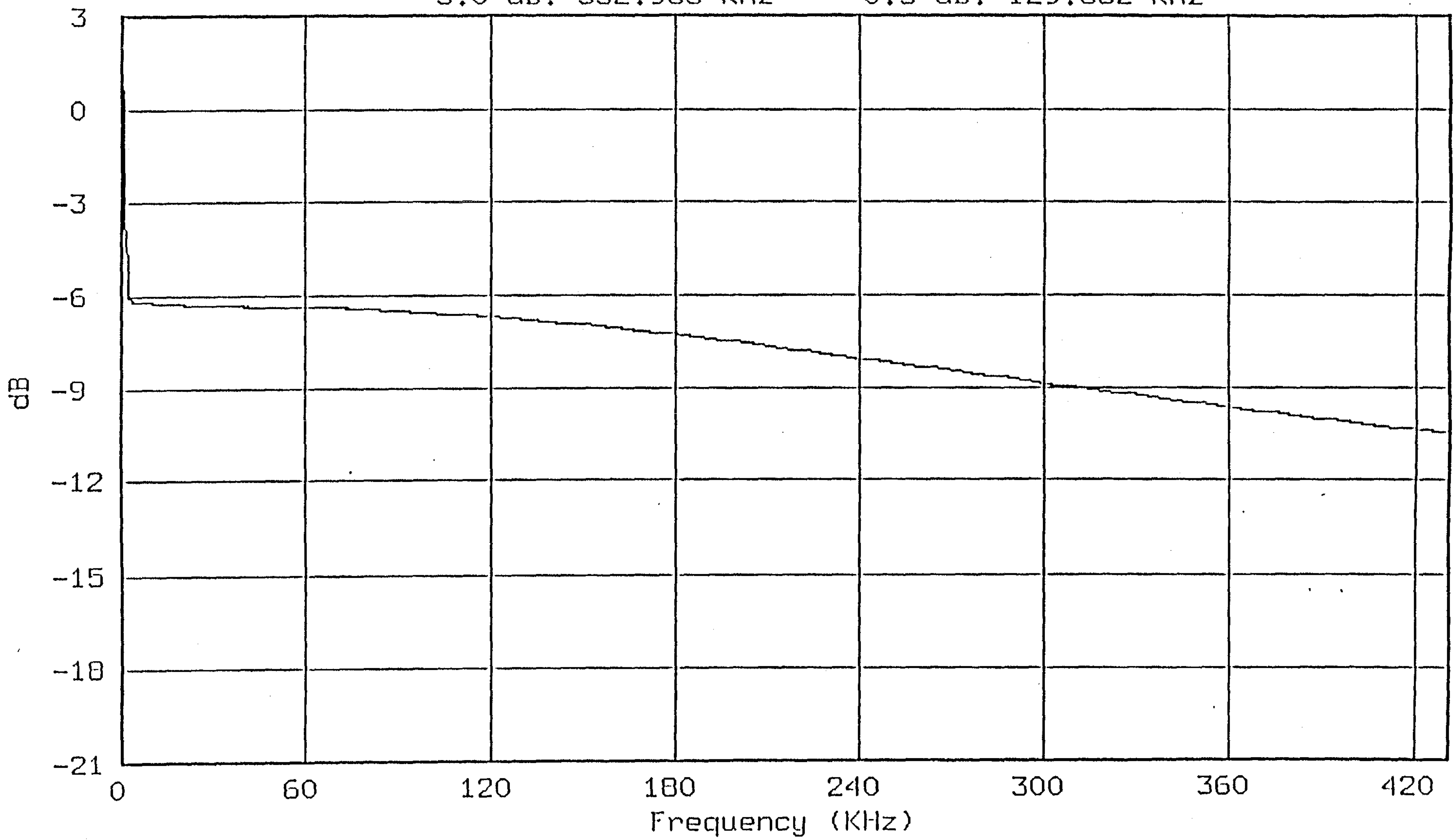
-3.0 dB: 390.902 KHz -0.5 dB: 149.882 KHz



MIDAS Field Cable Response Plot 05/9/94 15:28:57 MDT

Cable Type: MW-7122 Cable Length: 300 Cable Manufacturer: MERCURY

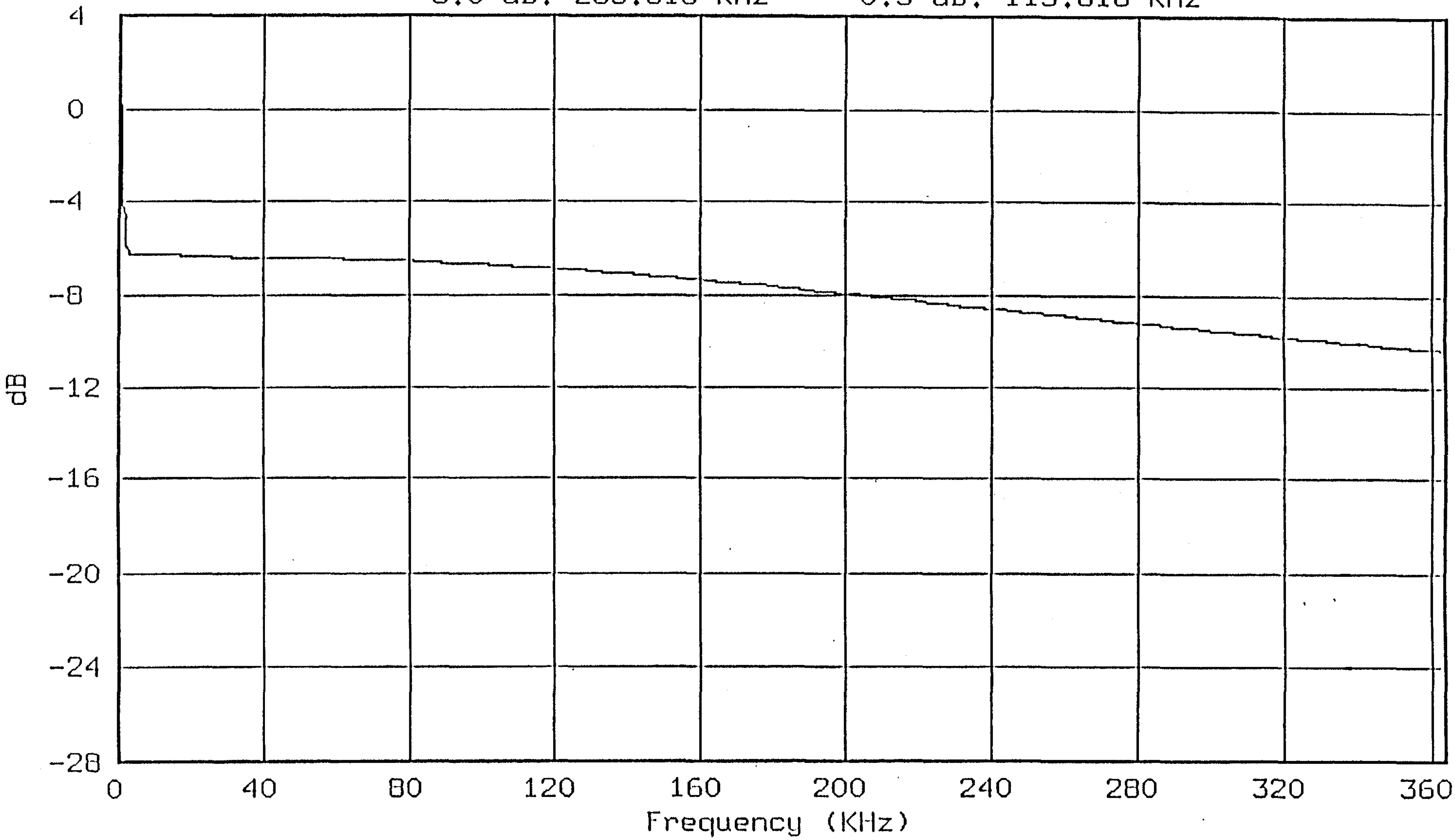
-3.0 dB: 332.985 KHz -0.5 dB: 129.662 KHz



MIDAS Field Cable Response Plot 05/9/94 15:31:53 MDT

Cable Type: MW-7122 Cable Length: 350 Cable Manufacturer: MERCURY

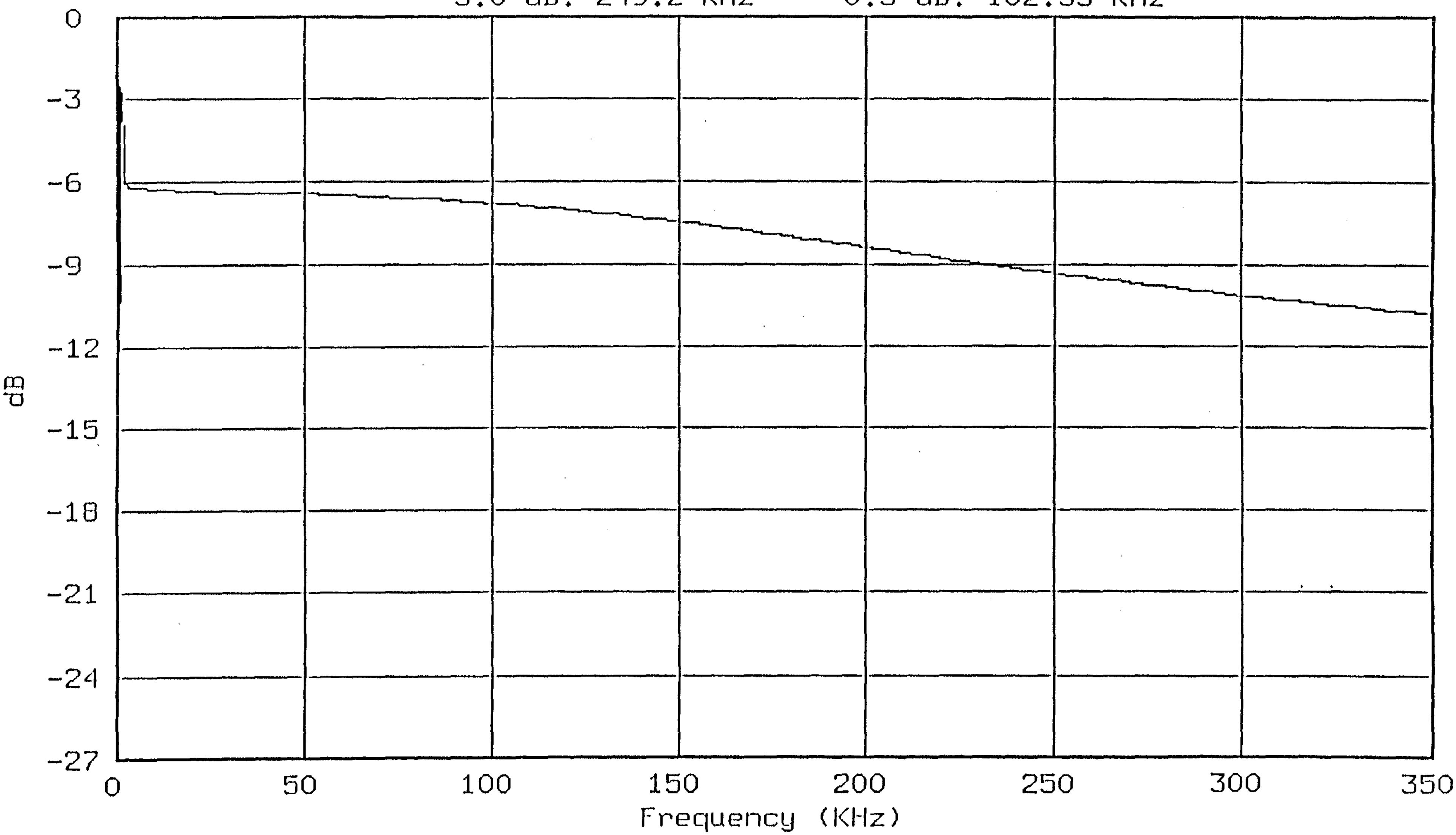
-3.0 dB: 285.818 KHz -0.5 dB: 113.818 KHz



MIDAS Field Cable Response Plot 05/9/94 15:35:07 MDT

Cable Type: MW-7122 Cable Length: 400 Cable Manufacturer: MERCURY

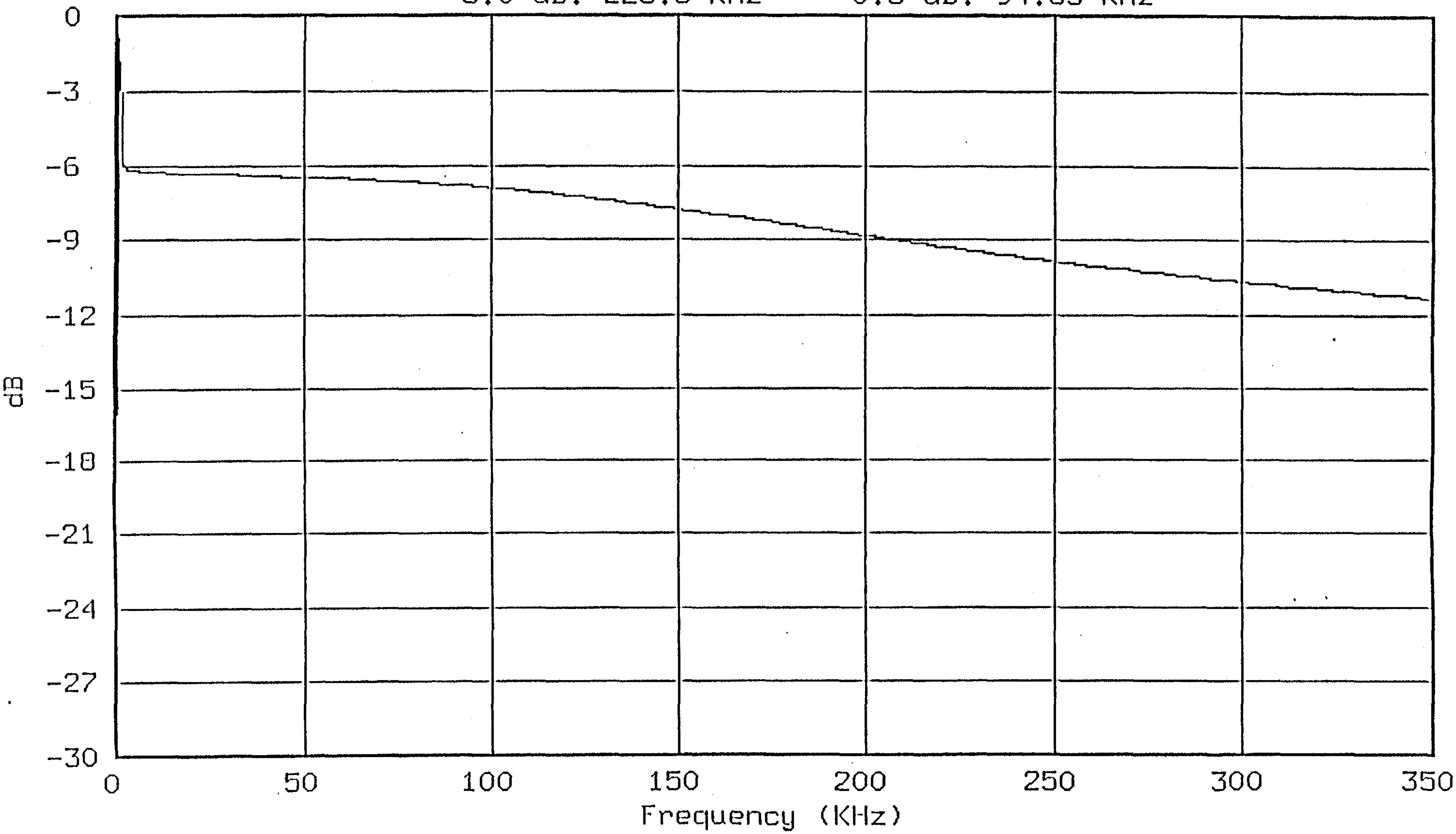
-3.0 dB: 249.2 KHz -0.5 dB: 102.55 KHz

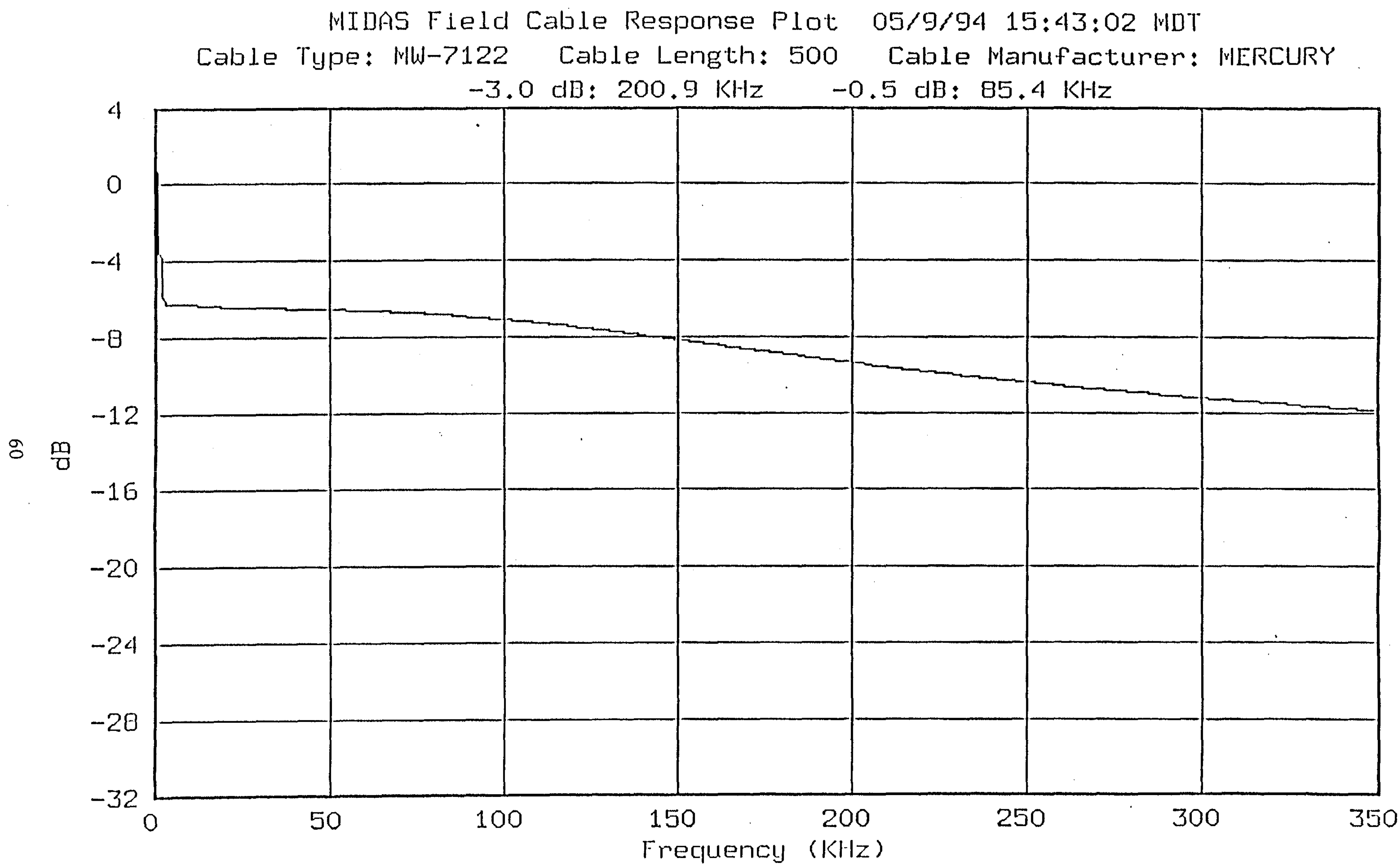


MIDAS Field Cable Response Plot 05/9/94 15:40:08 MDT

Cable Type: MW-7122 Cable Length: 450 Cable Manufacturer: MERCURY

-3.0 dB: 223.3 KHz -0.5 dB: 94.85 KHz

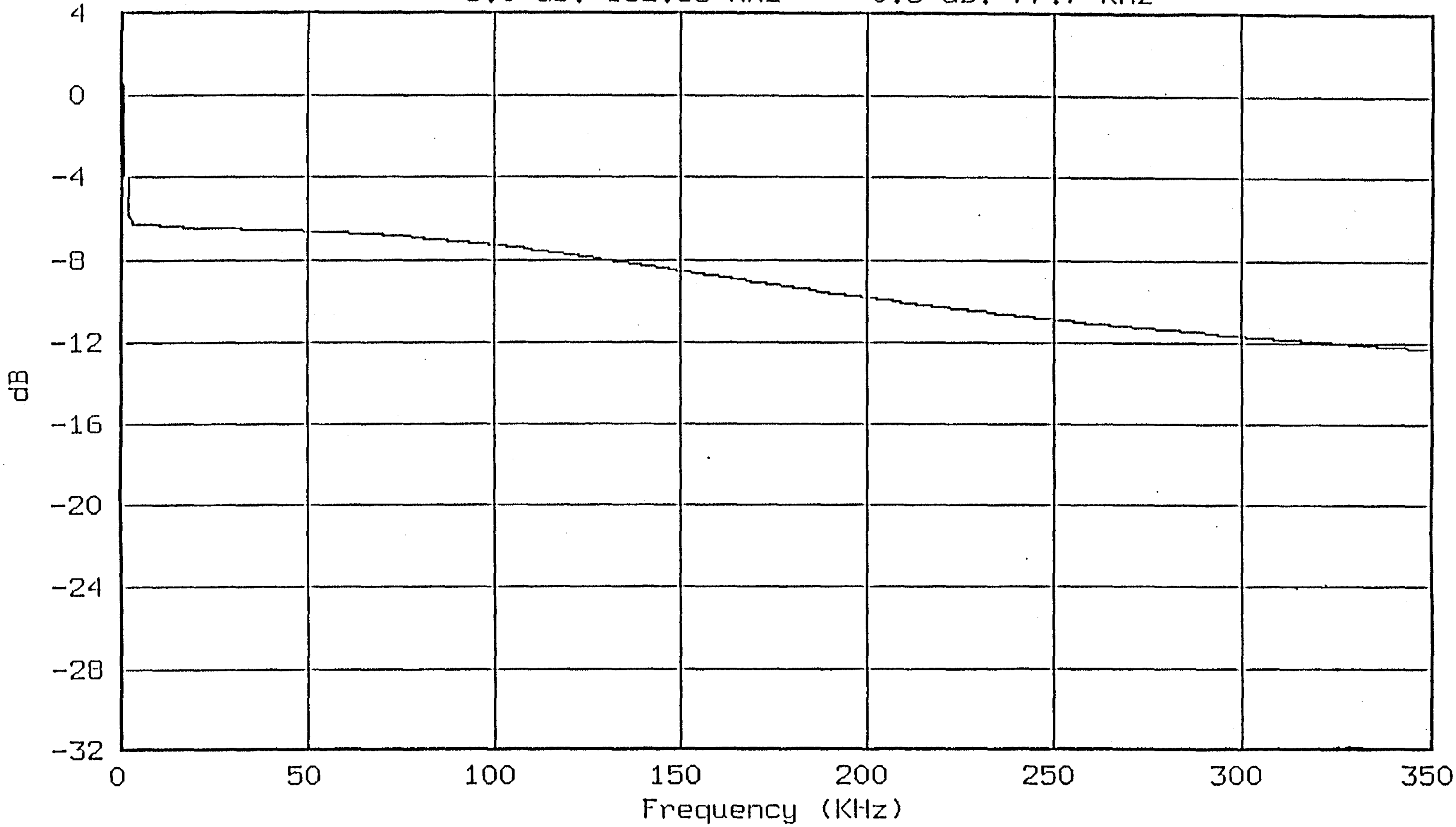



MIDAS Field Cable Response Plot 05/9/94 15:43:02 MDT
Cable Type: MW-7122 Cable Length: 500 Cable Manufacturer: MERCURY
-3.0 dB: 200.9 KHz -0.5 dB: 85.4 KHz
4
0
-4
-8
-12
-16
-20
-24
-28
-32
dB
0
50
100
150
200
250
300
350
Frequency (KHz)

MIDAS Field Cable Response Plot 05/9/94 15:45:29 MDT

Cable Type: MW-7122 Cable Length: 550 Cable Manufacturer: MERCURY

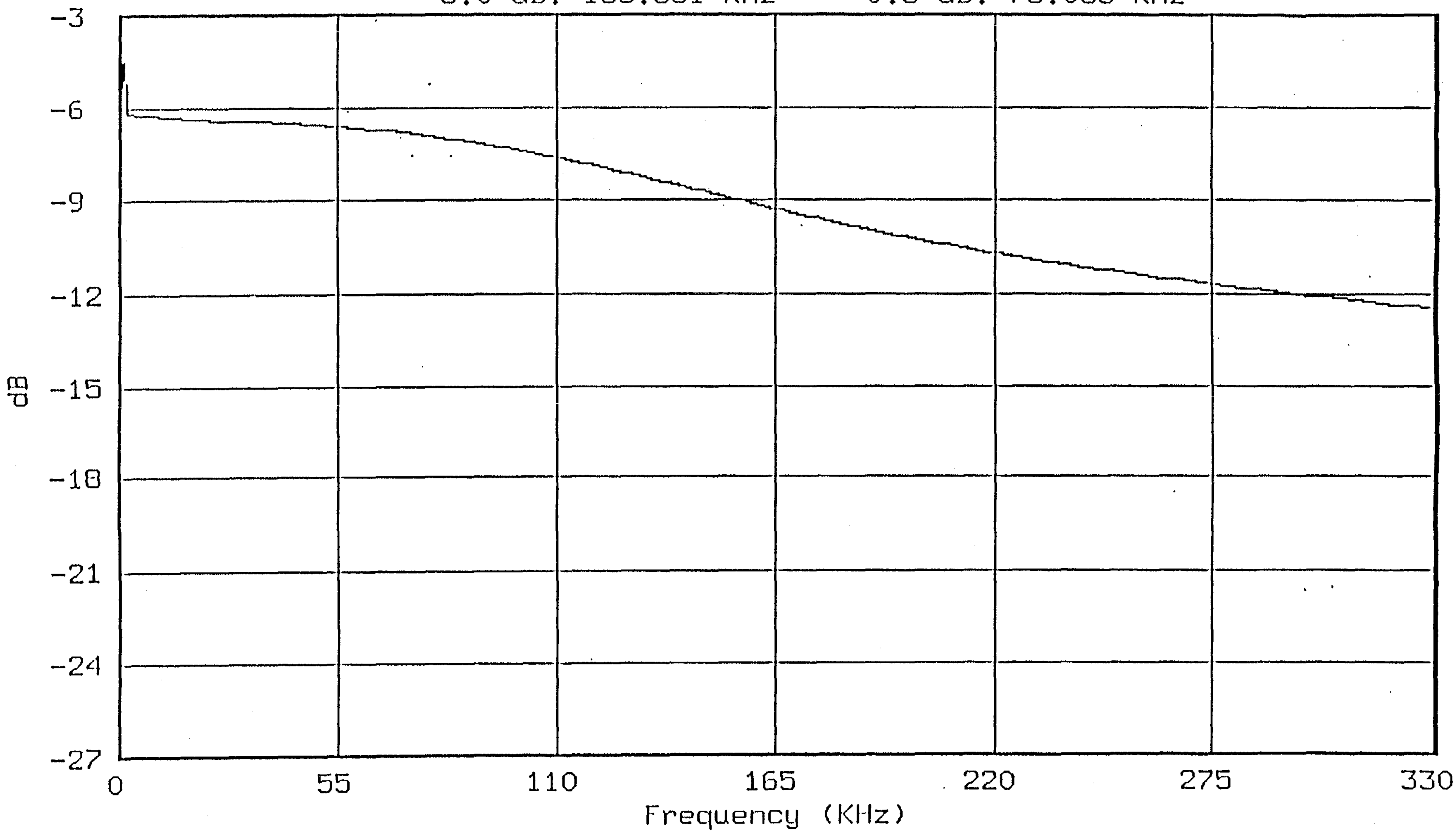
-3.0 dB: 182.35 KHz -0.5 dB: 77.7 KHz



MIDAS Field Cable Response Plot 05/9/94 15:48:07 MDT

Cable Type: MW-7122 Cable Length: 600 Cable Manufacturer: MERCURY

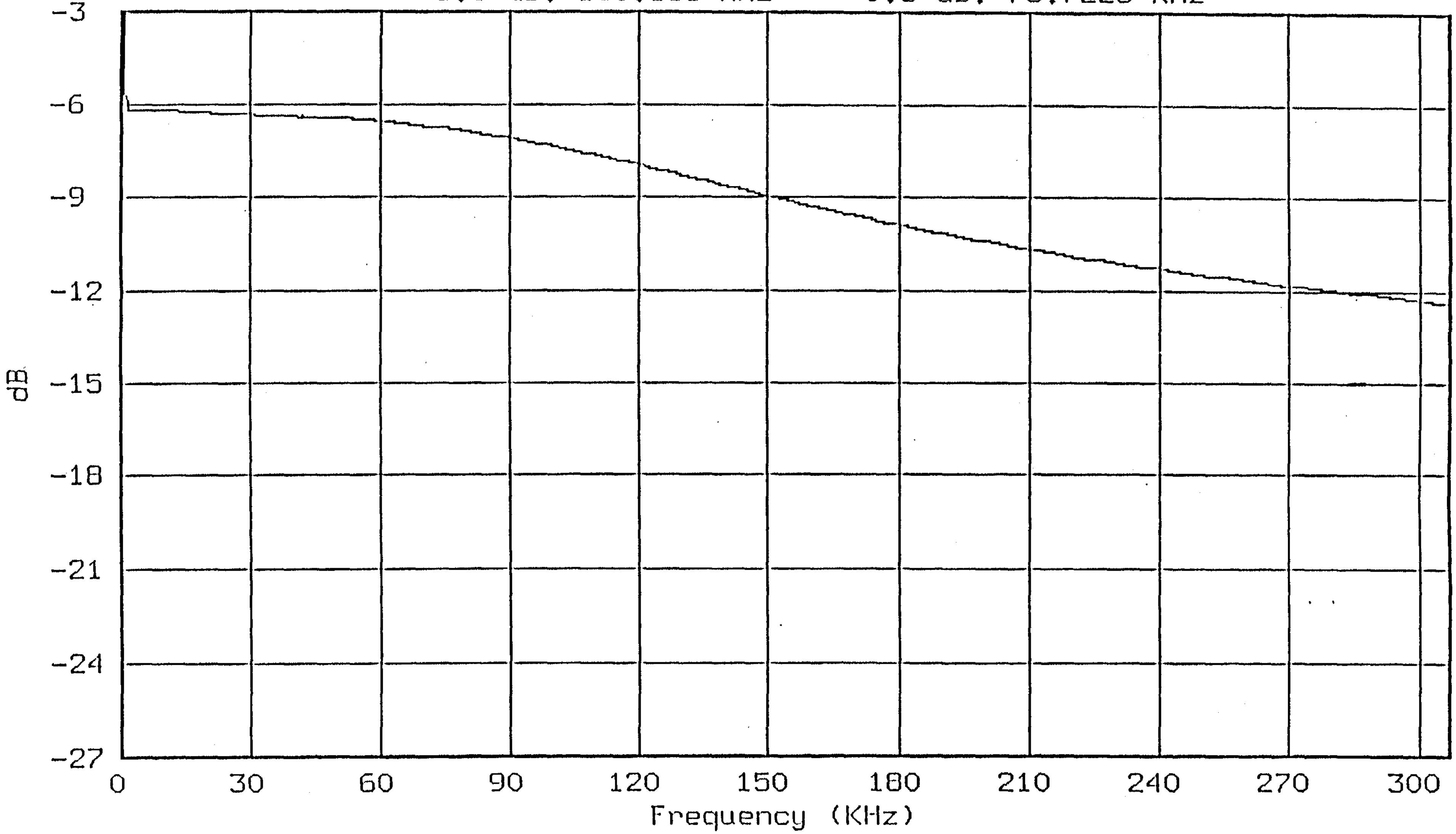
-3.0 dB: 168.661 KHz -0.5 dB: 76.063 KHz



MIDAS Field Cable Response Plot 05/10/94 09:00:48 MDT

Cable Type: MW-7122 Cable Length: 650 Cable Manufacturer: MERCURY

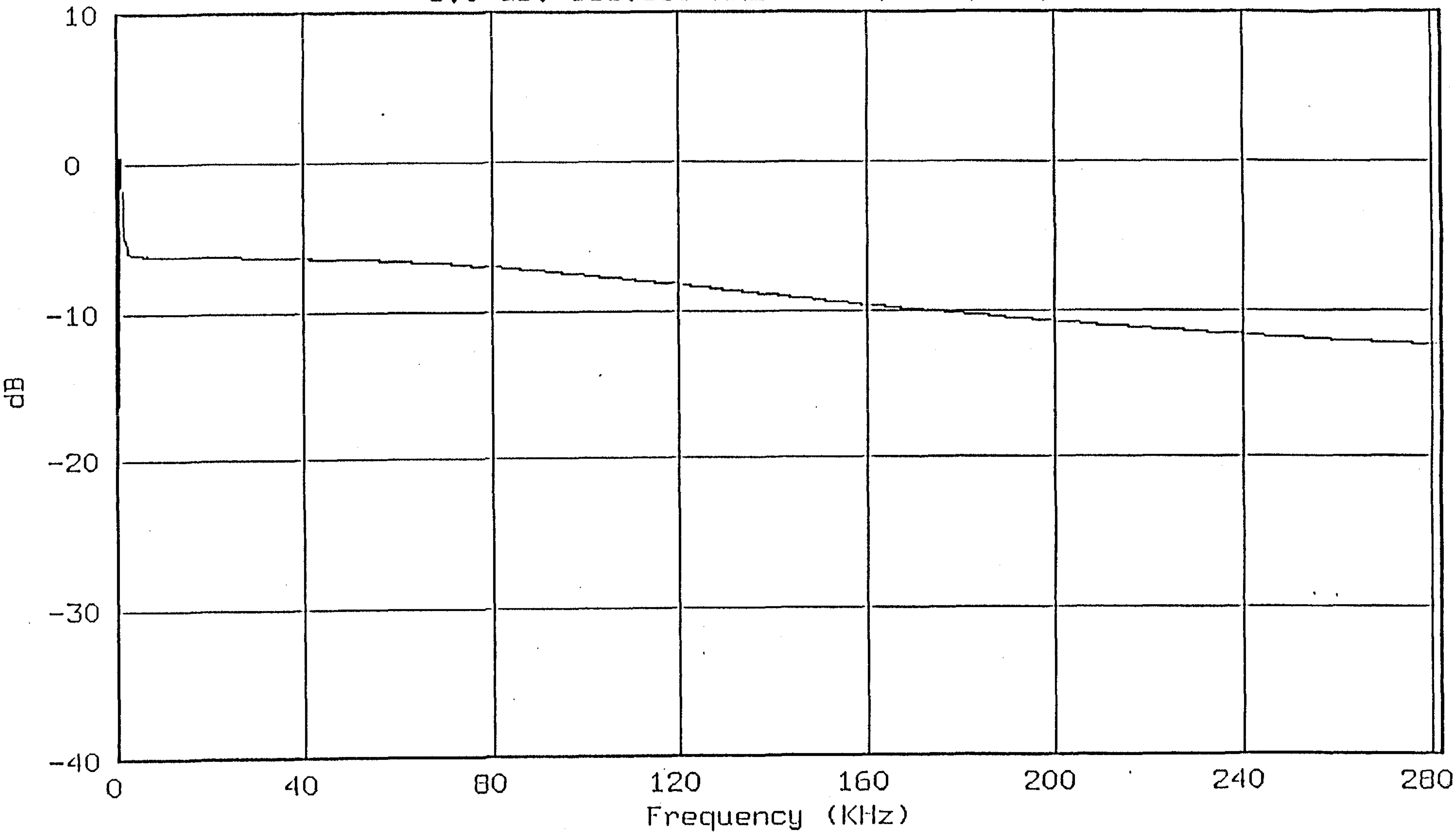
-3.0 dB: 160.336 KHz -0.5 dB: 75.7226 KHz



MIDAS Field Cable Response Plot 05/10/94 09:03:25 MDT

Cable Type: MW-7122   Cable Length: 700   Cable Manufacturer: MERCURY

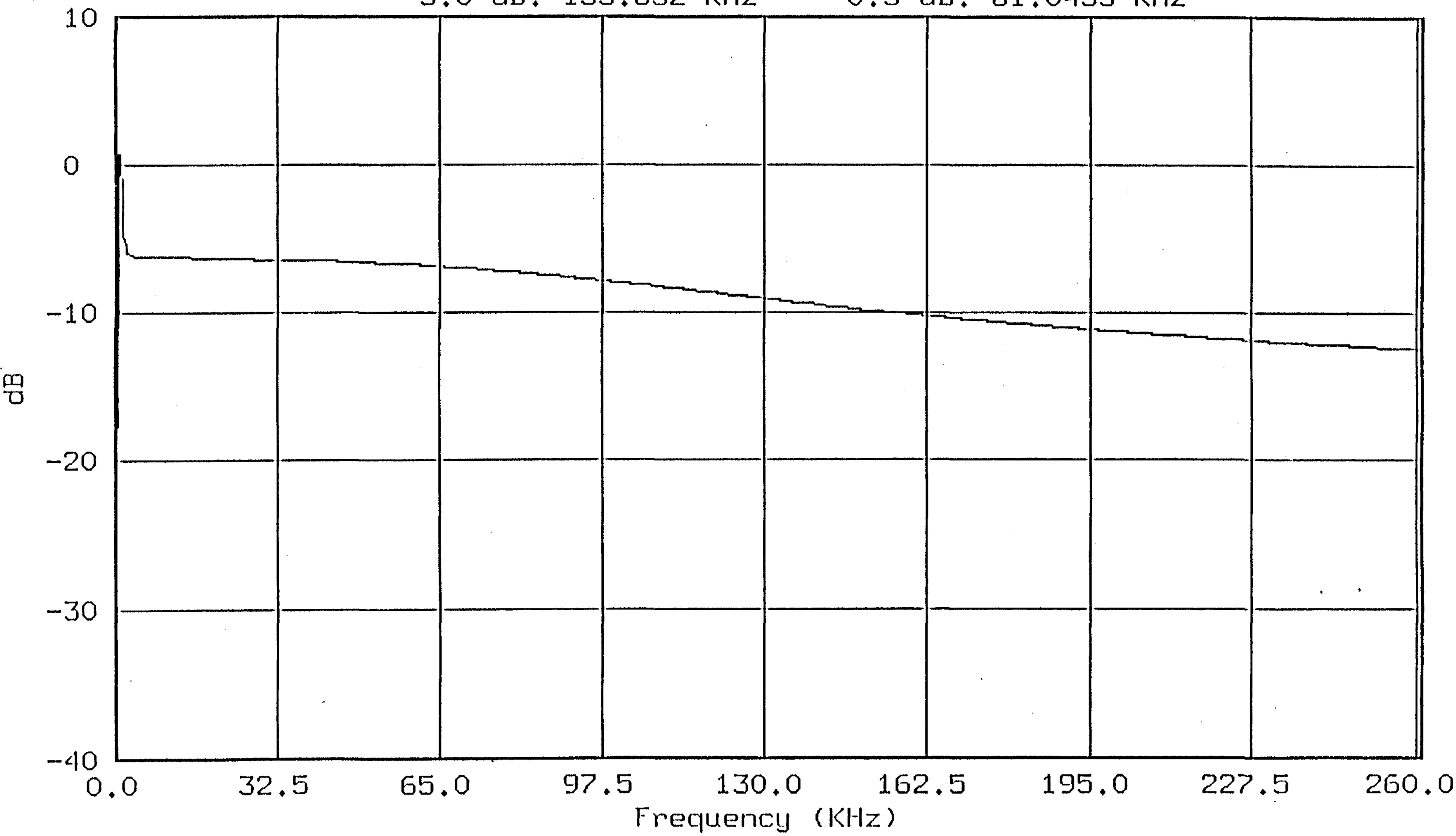
-3.0 dB: 151.369 KHz   -0.5 dB: 71.3154 KHz



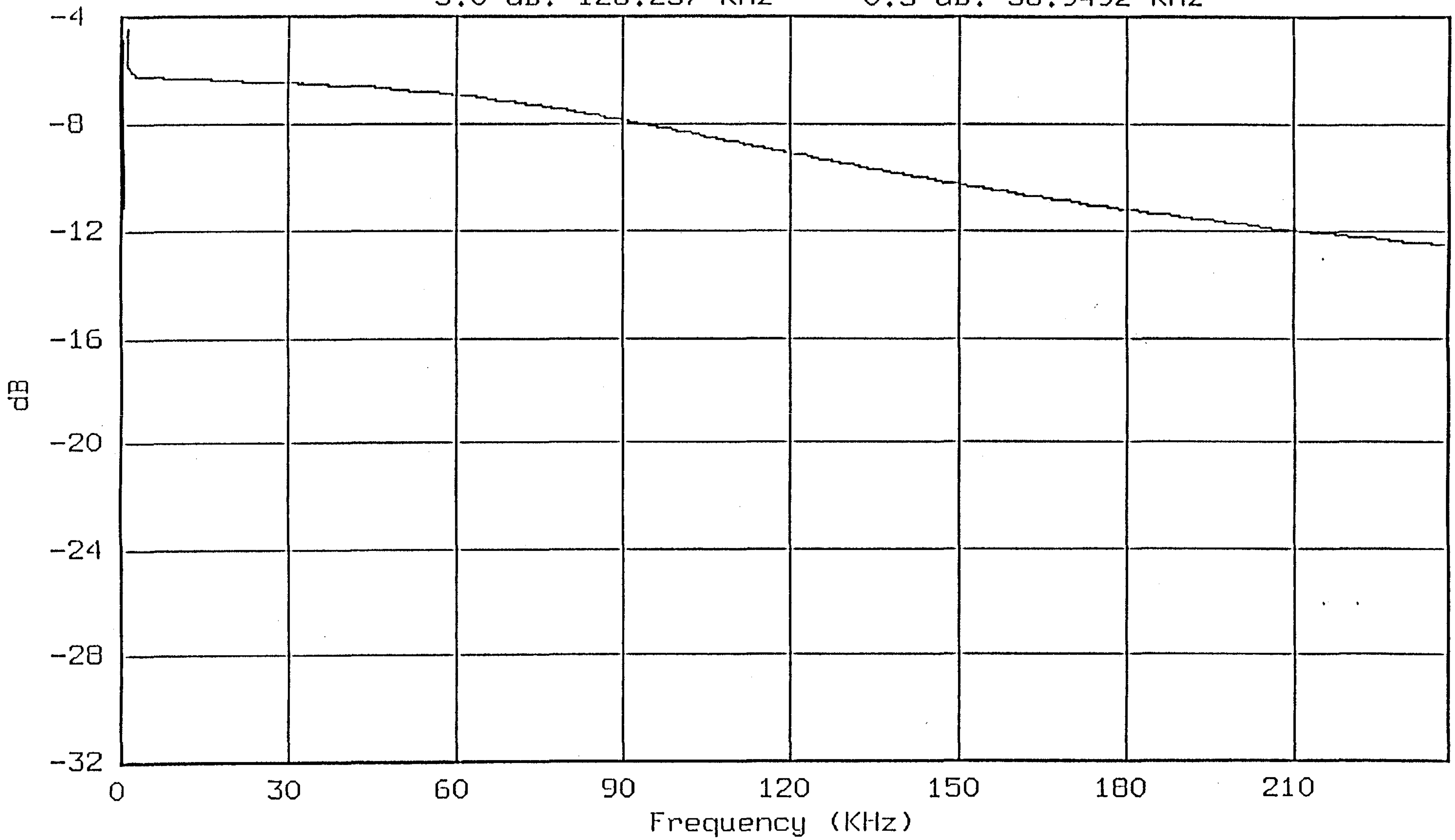
MIDAS Field Cable Response Plot 05/10/94 09:06:39 MDT

Cable Type: MW-7122 Cable Length: 750 Cable Manufacturer: MERCURY

-3.0 dB: 135.652 KHz -0.5 dB: 61.0435 KHz



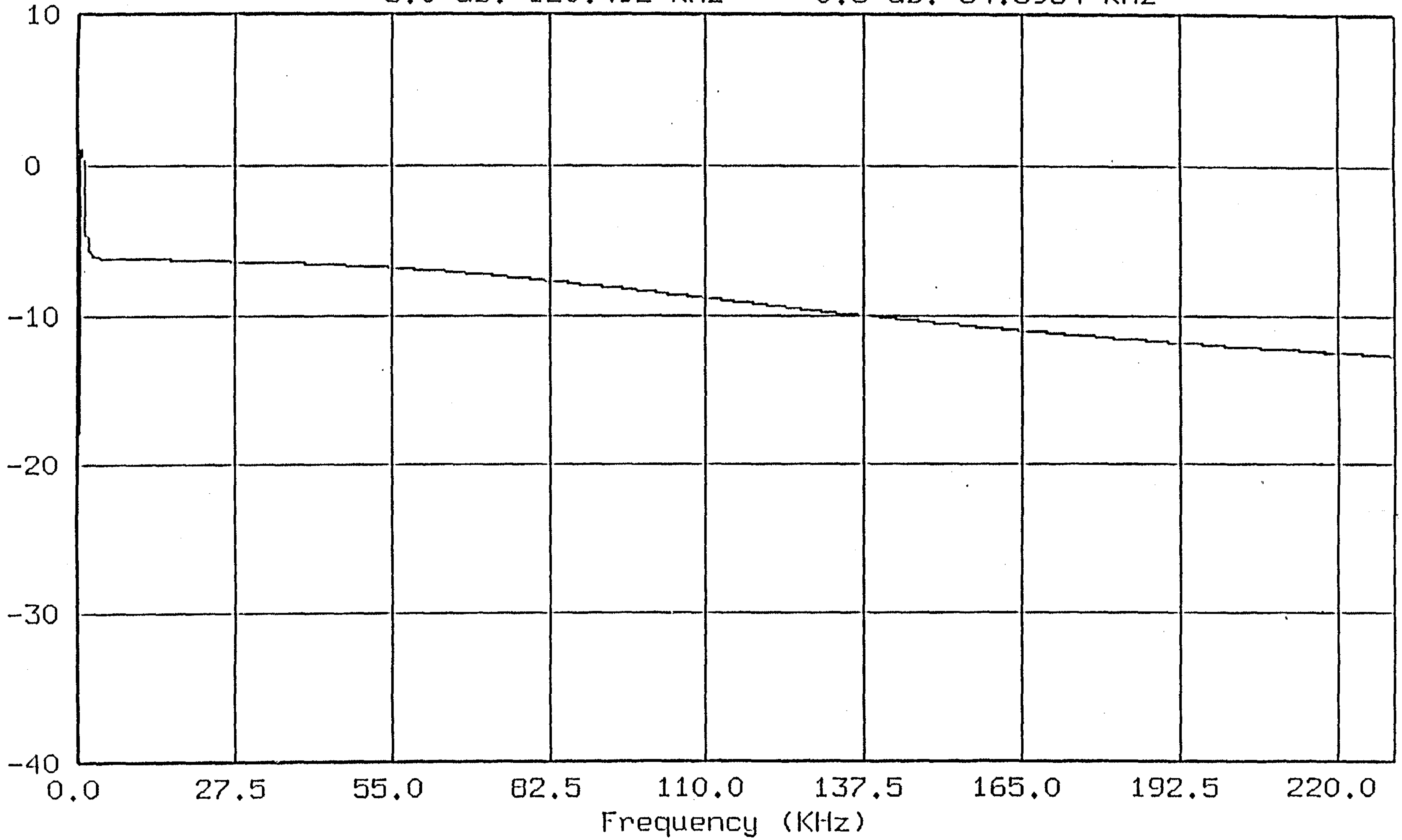
MIDAS Field Cable Response Plot 05/10/94 09:18:45 MDT
Cable Type: MW-7122 Cable Length: 800 Cable Manufacturer: MERCURY
-3.0 dB: 126.237 KHz -0.5 dB: 56.9492 KHz



MIDAS Field Cable Response Plot 05/10/94 09:22:07 MDT

Cable Type: MW-7122 · Cable Length: 850 Cable Manufacturer: MERCURY

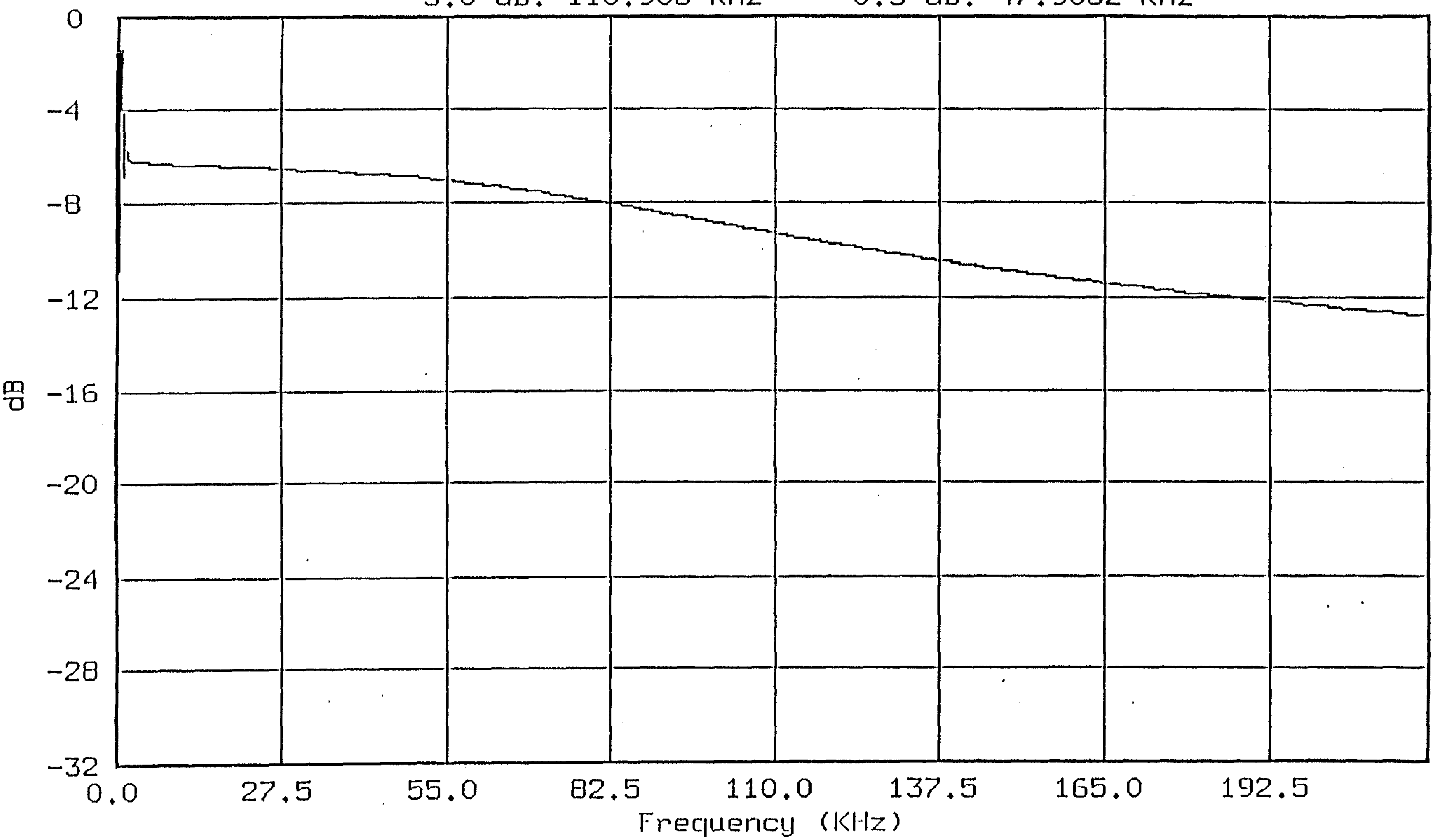
-3.0 dB: 120.492 KHz -0.5 dB: 54.3934 KHz



MIDAS Field Cable Response Plot 05/10/94 09:24:46 MDT

Cable Type: MW-7122 Cable Length: 900 Cable Manufacturer: MERCURY

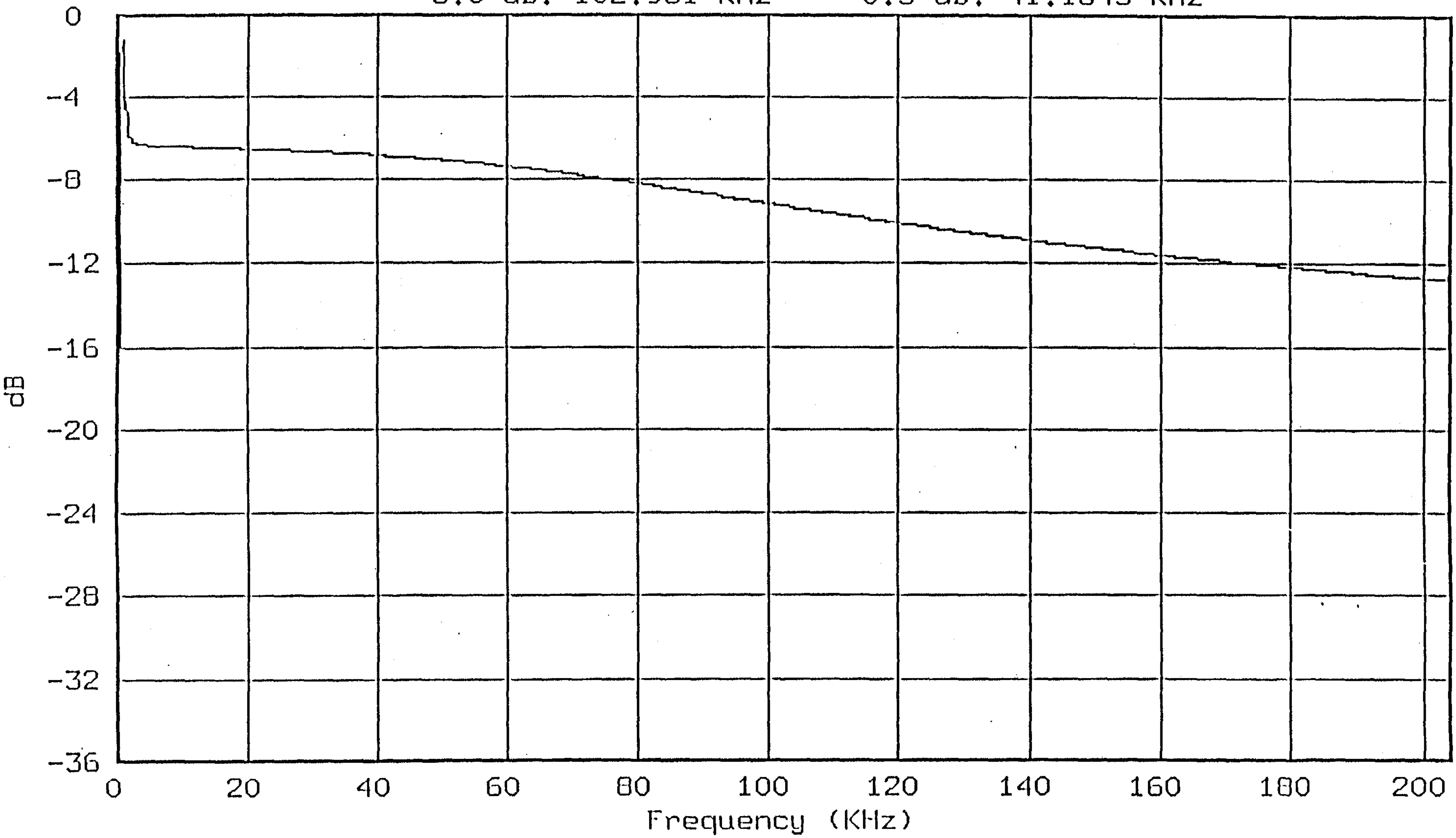
-3.0 dB: 110.906 KHz -0.5 dB: 47.9062 KHz



MIDAS Field Cable Response Plot 05/10/94 09:27:01 MDT

Cable Type: MW-7122 Cable Length: 950 Cable Manufacturer: MERCURY

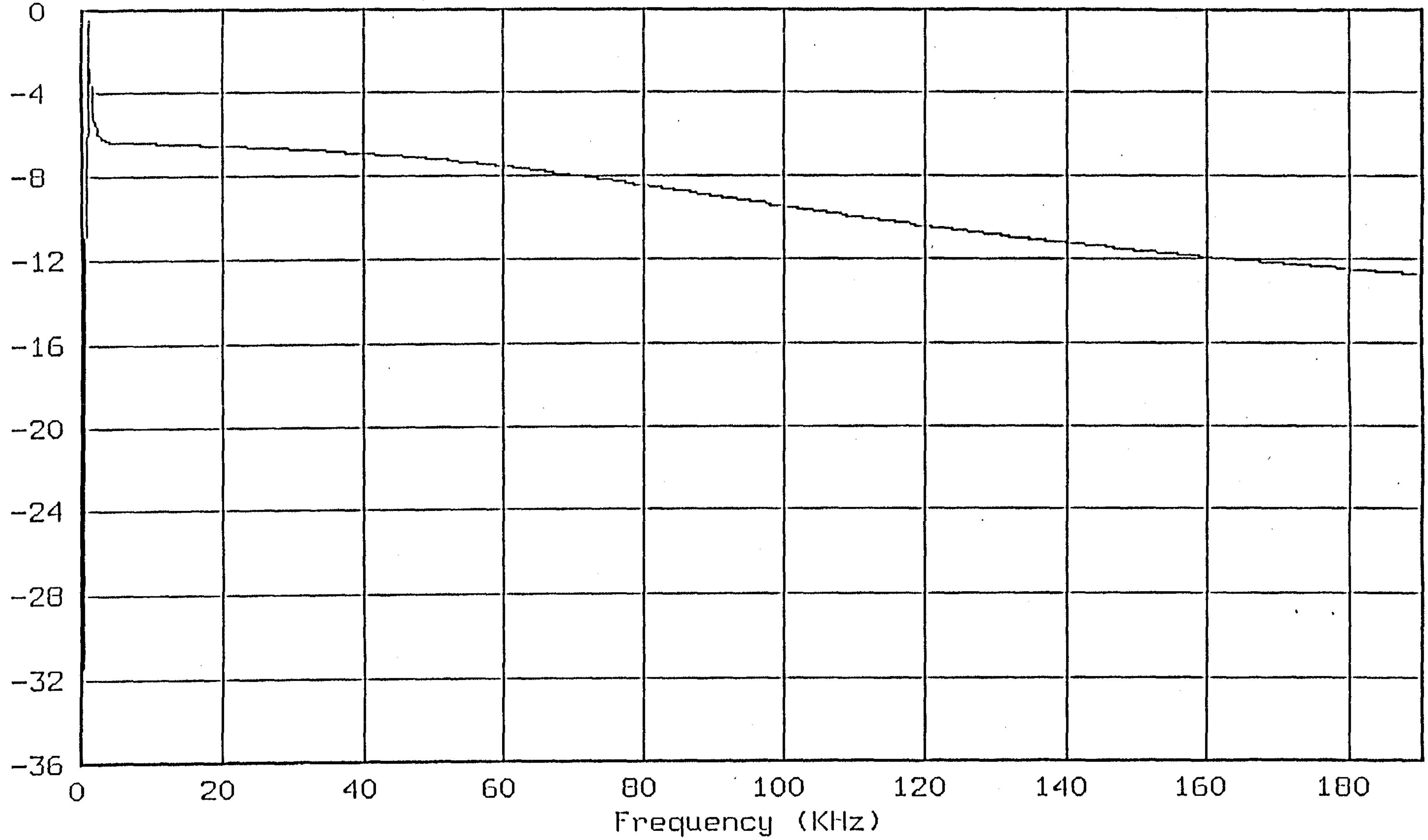
-3.0 dB: 102.961 KHz -0.5 dB: 41.1845 KHz



MIDAS Field Cable Response Plot 05/10/94 09:29:38 MDT

Cable Type: MW-7122 Cable Length: 1000 Cable Manufacturer: MERCURY

-3.0 dB: 97.1131 KHz -0.5 dB: 37.4389 KHz



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