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# An Acoustic Ground Impedance Measurement

by John Williams

ARL-TN-221 July 2004

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# An Acoustic Ground Impedance Measurement

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***Survivability/Lethality Analysis Directorate***

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**14. ABSTRACT**
A measurement of the acoustic ground impedance was made on soil composed of sand and clay covered by splotchy amounts of long grass. A sound pressure-volume velocity device was used to make the measurement. The real part of the ground impedance ranged from 46,662 Pa.s/m$^3$ at 20Hz to 3,076 Pa.s/m$^3$ at 260Hz. The magnitude of the imaginary part of the ground impedance ranged from 66,974 Pa.s/m$^3$ at 20Hz to 4,005 Pa.s/m$^3$ at 260Hz. These data are available to any interested researcher in the field of sound propagation.

**15. SUBJECT TERMS**
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# 1. Introduction

Sound propagating outdoors is attenuated by three factors: 1) geometrical spreading, 2) atmospheric absorption, and 3) excess attenuation. (*1*) One aspect of excess attenuation is complex ground impedance. This technical note presents the results of one measurement of acoustic ground impedance (AGI) conducted by the Survivability/Lethality Analysis Directorate of the U.S. Army Research Laboratory.

# 2. Instrumentation

The measurement was done using the patented AGI meter developed by the National Aeronautics and Space Administration (NASA) in the early 1980s. (*2*) This device uses the direct sound pressure-volume velocity method for frequencies between 20 and 260 Hz. Its basic design consists of a Helmholtz resonator and a cam-driven piston to create the volume velocity. The ground or surface whose impedance is to be measured serves as one wall of the Helmholtz chamber.

Figure 1 is a picture of the bottom half of the chamber imbedded in the ground.

Figure 2 shows the entire chamber on the ground. On the left side of the chamber in figure 2, one can see the preamplifier of a Bruel & Kjaer (B&K) type 4145 microphone, which is inserted into an opening in the chamber until it is flush with the wall. The microphone measures the sound pressure level in the chamber and was calibrated with a B&K type 4228 piston phone. A quarter-inch airhose connects to the top of the chamber, as seen in figure 2.

Furthermore, the AGI meter is controlled by a control unit, as shown in figure 3.

In this study, two outputs were recorded from the control box: 1) the microphone output, which measures the sound pressure in the chamber, and 2) the phase angle between the volume velocity and sound pressure. These data were recorded on a TEAC RD-145T digital audio tape recorder for later analysis.

Figure 1. The bottom half of AGI chamber imbedded in the ground.

Figure 2. The entire AGI chamber on the ground.

Figure 3. The AGI chamber with control box.

## 3. Data and Analysis

This measurement was done on 15 September 2003 at Eglin Air Force Base, FL. The exact location was within 10 m of the following geographical coordinates, given in the World Geodetic Survey 1984 datum:

- longitude $86^{o}17'45.8180''$ W
- latitude $30^{o}38'22.5689''$ N

This location was 66 m above mean sea level. The following meteorological conditions existed at the time of the measurement:

- Air temperature = 29 $^{o}$C
- Soil temperature = 26 $^{o}$C
- Dew point = 17 $^{o}$C
- Relative humidity = 47 percent
- Barometric pressure = 1019 mbar

The ground cover consisted of splotchy long grass and weeds. The soil was mostly dry sand and clay. Figures 1-3 feature close-ups of the ground. Figure 4 shows a wider field view of the area.

Figure 4. A wide field view of the area where the ground impedance was measured.

The AGI meter was run at frequencies from 20 to 260 Hz, in 20-Hz increments. As mentioned in section 2, the two signals from the AGI control box were recorded digitally at a sample rate of 48,000 Hz for about 30 s at each frequency. These digital signals were later copied directly onto the hard drive of a desktop computer, where they were analyzed using The Math Works, Inc., Matrix Laboratory (MATLAB) software.

Figure 5 shows an example of the raw digitized signals. The time axis is expressed in seconds so that one can easily calculate that this is the 100-Hz signal. The top signal, with the large direct current bias, is the volume velocity. The bottom signal is the sound pressure level inside the chamber. The sound pressure signal is very nearly a sine wave, but the volume velocity signal is more interesting. Figure 6 shows a detail of the volume velocity signal.

In figure 6, the mean value of the volume velocity signal has been subtracted out. The signal is flatter on the tops and bottoms, and has many small impulse-type signals in it. Figure 7 shows an even more detailed view of these aspects.

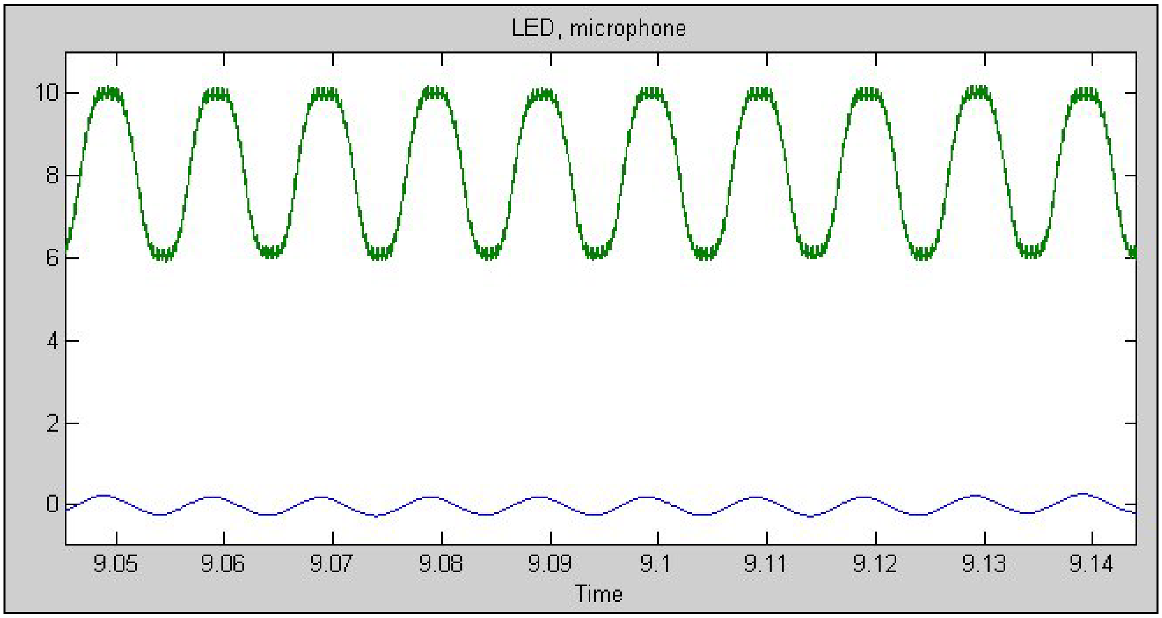


Figure 5. Raw digitized AGI meter signals.

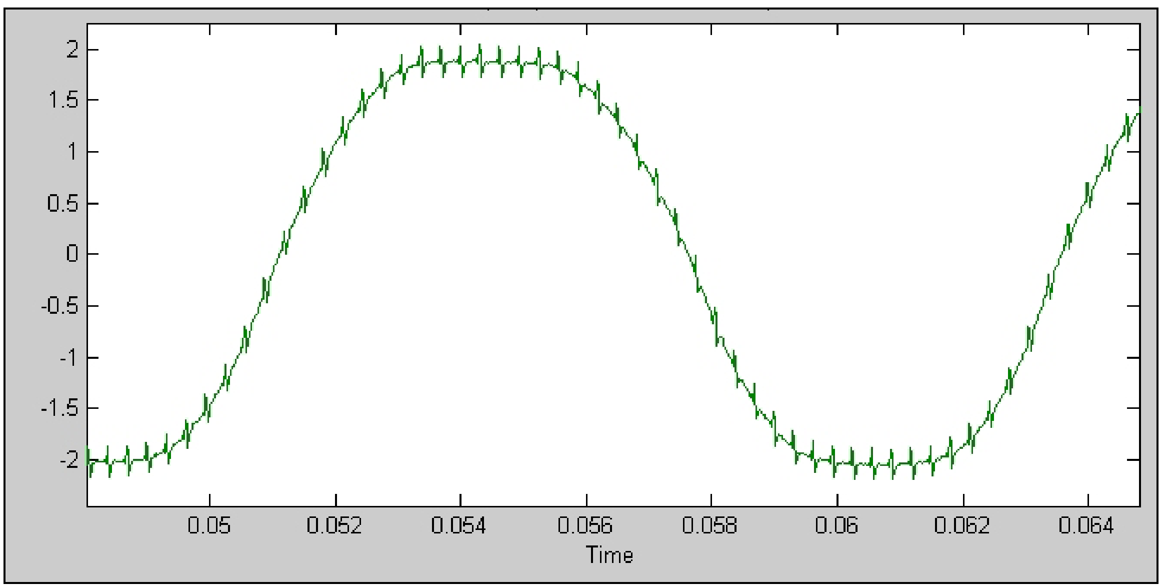


Figure 6. Detail of the volume velocity signal with mean extracted.

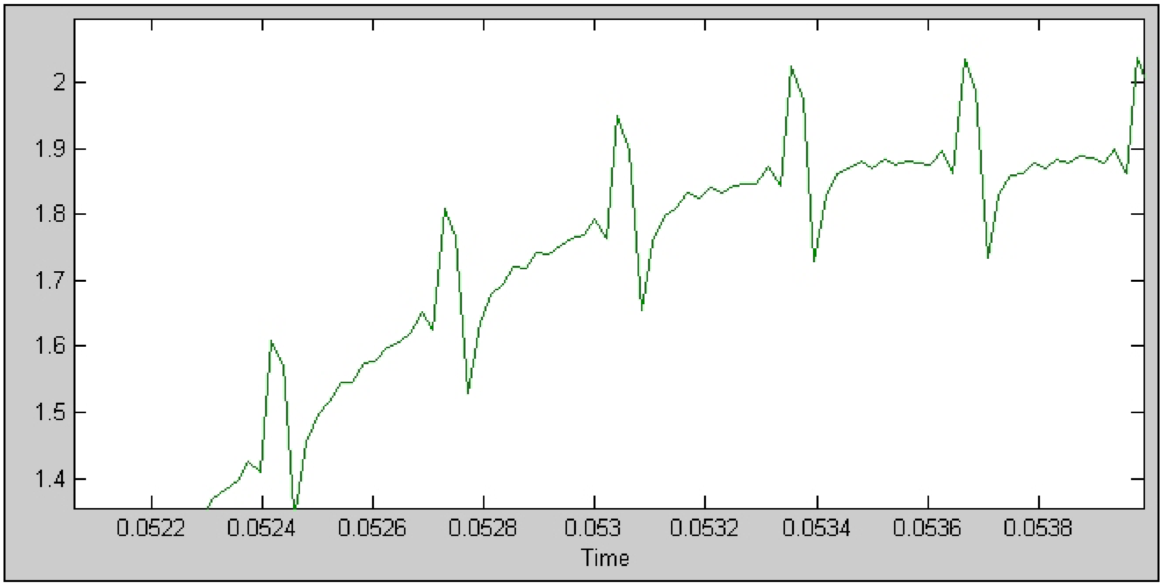


Figure 7. Extreme detail view of the volume velocity signal.

The analysis was done following the NASA Acoustic Ground Impedance Meter Operating Instructions (*3*). The equations and constants used were as follows:

$$R = \frac{G}{G^2 + B^2} = \text{real part of ground impedance (Pa.s/m}^3\text{)}$$

$$X = \frac{-B}{G^2 + B^2} = \text{imaginary part of ground impedance (Pa.s/m}^3\text{)}$$

$$G = h\{\sin(\theta_2 - \theta_1)/(KV_1)\} = \text{real part of surface admittance}$$

$$B = h\{ [\cos(\theta_2 - \theta_1)/(KV_2)] - [1/(KV_1)] \} = \text{imaginary part of surface admittance}$$

$$h = \frac{2\pi f.A_N.S_0}{1 - [ f/f_A]^2}$$

$V_1$, $\theta_1$ = voltage and phase of volume velocity

$V_2$, $\theta_2$ = voltage and phase of sound pressure

$K$ = calibration factor (V/Pa)—about 21.6 Pa/V (*2*)

$A_N$ = area of the measurement chamber (.000285 $m^2$)

$S_0$ = root mean square (rms) piston stroke (0.0007184 m)

$f_A$ = piston resonant frequency (700Hz)

$f$ = frequency

The rms voltages of all signals were calculated in MATLAB after importing the digitized signals. The calibration factor, *K*, was found to be 21.82 Pa/V, which was very close to the *K* given in the NASA Acoustic Ground Impedance Meter Operating Instructions (*3*). The phase difference between the two signals was calculated using a specially written MATLAB script that extracted the mean, normalized the signals, and then shifted one signal, sample by sample, with respect to the other until the sum of the squares of the differences was found to be a minimum. The amount of shift is proportional to the phase difference. Although more elegant methods for finding phase difference are available, this brute-force method was quite effective for this small-scale analysis and took only a few seconds at each frequency. Figure 8 expresses the phase difference graphically.

In figure 8, the time difference between the signals seems to be about 0.001625 s. For this 80-Hz signal, the phase difference would be $2\pi(0.001625 \text{ s})(80 \text{ Hz}) = 0.8168$ radians or $46.8^o$. In fact, the MATLAB script calculated it to be $45.6^o$.

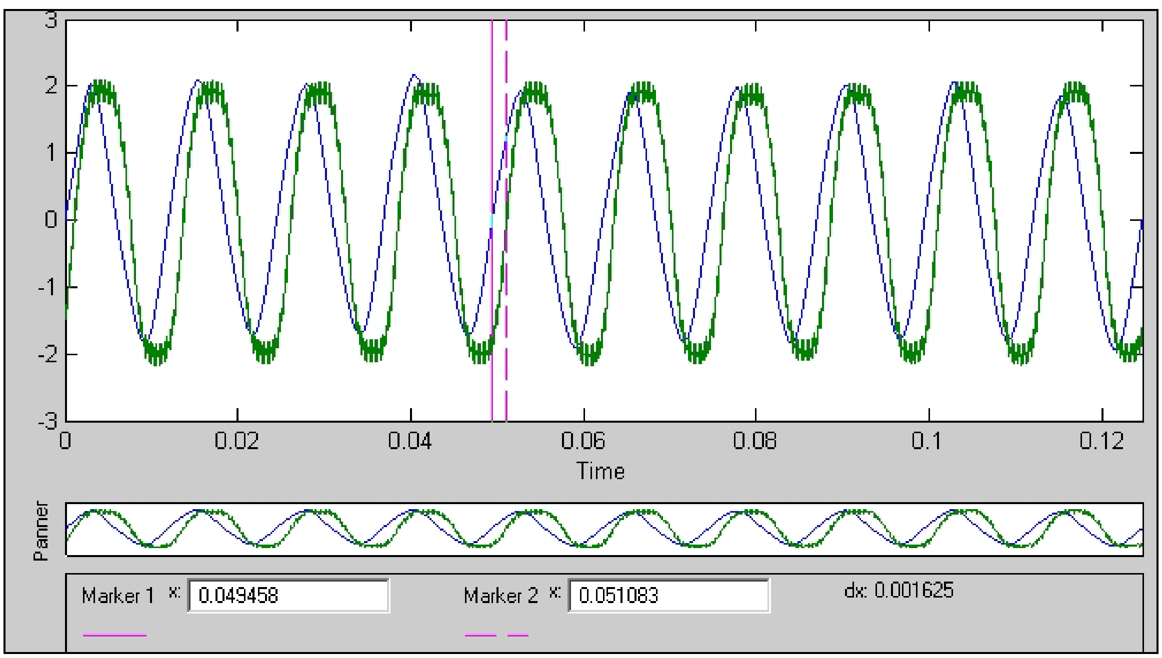


Figure 8. The phase difference between the two signals.

Table 1 gives all measured and calculated values at each frequency. Figure 9 plots the phase difference as a function of frequency and figure 10 plots the values of *R* and *X* as functions of frequency.

Figure 10 and table 1 show that some *R* values are negative, which would seem to be physically unrealizable. This anomaly happens whenever the phase difference is negative, as shown in figure 9.

Note that the NASA Acoustic Ground Impedance Meter Operating Instructions (*3*) assume that complex impedance is written as Z = R + jX; however, the designer of the AGI meter has informed the author that ground impedance is traditionally expressed as Z = R – jX. Thus, when expressing the values for *X* as detailed in this technical note traditionally, one should apply a negative sign to those values.

Figures 11 and 12 plot the magnitude and phase of *Z* with respect to frequency.

Table 1. Measured and calculated values at each frequency.

| **Freq (Hz)** | **Phase Diff (deg)** | **h** | **V1** | **V2** | **G** | **B** | **R** | **X** | **‖Z‖** | **Angle (Z) [deg]** |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 | 132.40 | 2.57499E-05 | 0.12443 | 1.40096 | 7.00331E-06 | -1.00517E-05 | 46662.85 | 66974.22 | 81627.01 | 55.13 |
| 40 | 100.10 | 5.16264E-05 | 0.11486 | 1.48584 | 2.02788E-05 | -2.08772E-05 | 23939.41 | 24645.88 | 34358.62 | 45.83 |
| 60 | 71.55 | 7.77580E-05 | 0.13203 | 1.51388 | 2.56023E-05 | -2.62446E-05 | 19045.66 | 19523.49 | 27274.60 | 45.71 |
| 80 | 45.60 | 1.04278E-04 | 0.13433 | 1.50455 | 2.54175E-05 | -3.33530E-05 | 14454.34 | 18967.02 | 23846.93 | 52.69 |
| 100 | 10.50 | 1.31325E-04 | 0.15559 | 1.51388 | 7.04910E-06 | -3.47725E-05 | 5599.80 | 27623.20 | 28185.08 | 78.54 |
| 120 | -39.10 | 1.59047E-04 | 0.19207 | 1.50455 | -2.39333E-05 | -3.41891E-05 | -13741.37 | 19629.79 | 23961.51 | 124.99 |
| 140 | -94.80 | 1.87606E-04 | 0.16246 | 1.47962 | -5.27359E-05 | -5.34077E-05 | -9361.19 | 9480.45 | 13323.32 | 134.64 |
| 160 | -129.60 | 2.17178E-04 | 0.11687 | 1.51388 | -6.56161E-05 | -8.93496E-05 | -5339.50 | 7270.80 | 9020.80 | 126.29 |
| 180 | -150.80 | 2.47955E-04 | 0.10562 | 1.52636 | -5.24862E-05 | -1.14083E-04 | -3328.28 | 7234.30 | 7963.20 | 114.71 |
| 200 | -169.50 | 2.80159E-04 | 0.11219 | 1.48740 | -2.08554E-05 | -1.22930E-04 | -1341.48 | 7907.15 | 8020.14 | 99.63 |
| 220 | 156.60 | 3.14037E-04 | 0.15497 | 1.49521 | 3.68823E-05 | -1.01701E-04 | 3151.40 | 8689.84 | 9243.63 | 70.07 |
| 240 | 90.90 | 3.49875E-04 | 0.16005 | 1.46406 | 1.00168E-04 | -1.00353E-04 | 4982.42 | 4991.60 | 7052.70 | 45.05 |
| 260 | 46.80 | 3.88004E-04 | 0.10748 | 1.44847 | 1.20598E-04 | -1.57034E-04 | 3076.21 | 4005.60 | 5050.53 | 52.48 |

NOTES: Freq = frequency
Phase Diff = Phase Difference

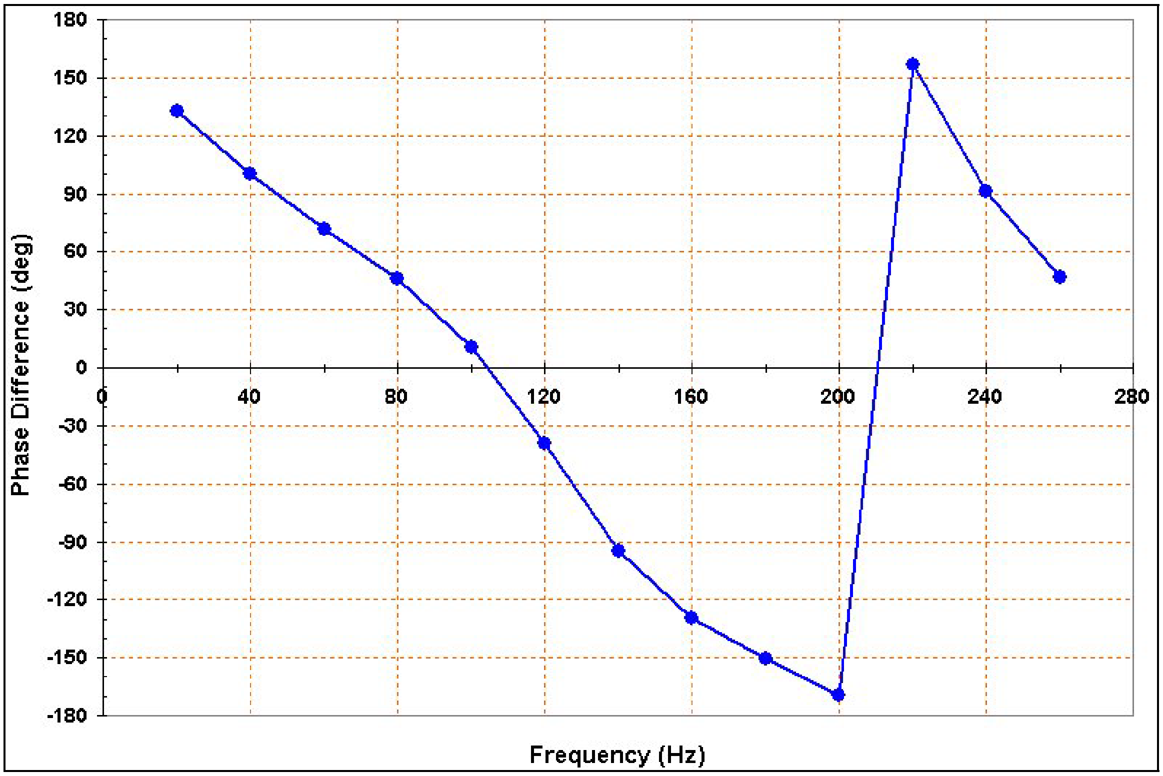


Figure 9. The phase difference as a function of frequency.

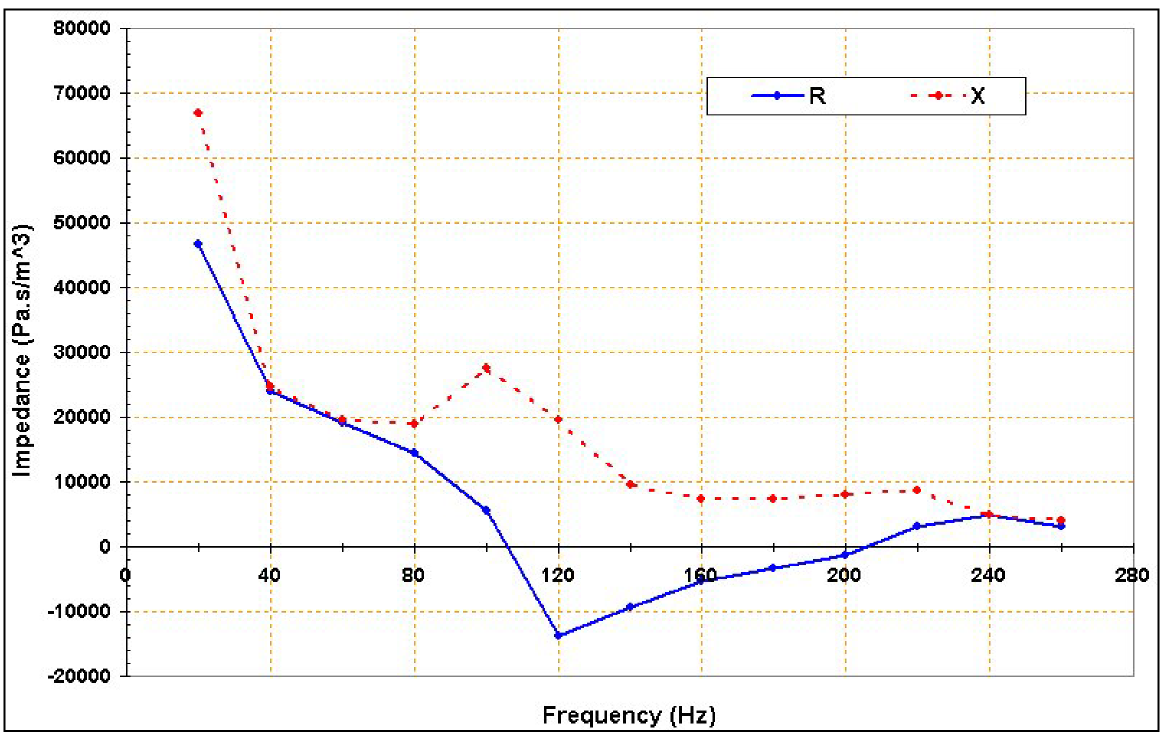


Figure 10. The real and imaginary parts of the ground impedance versus frequency.

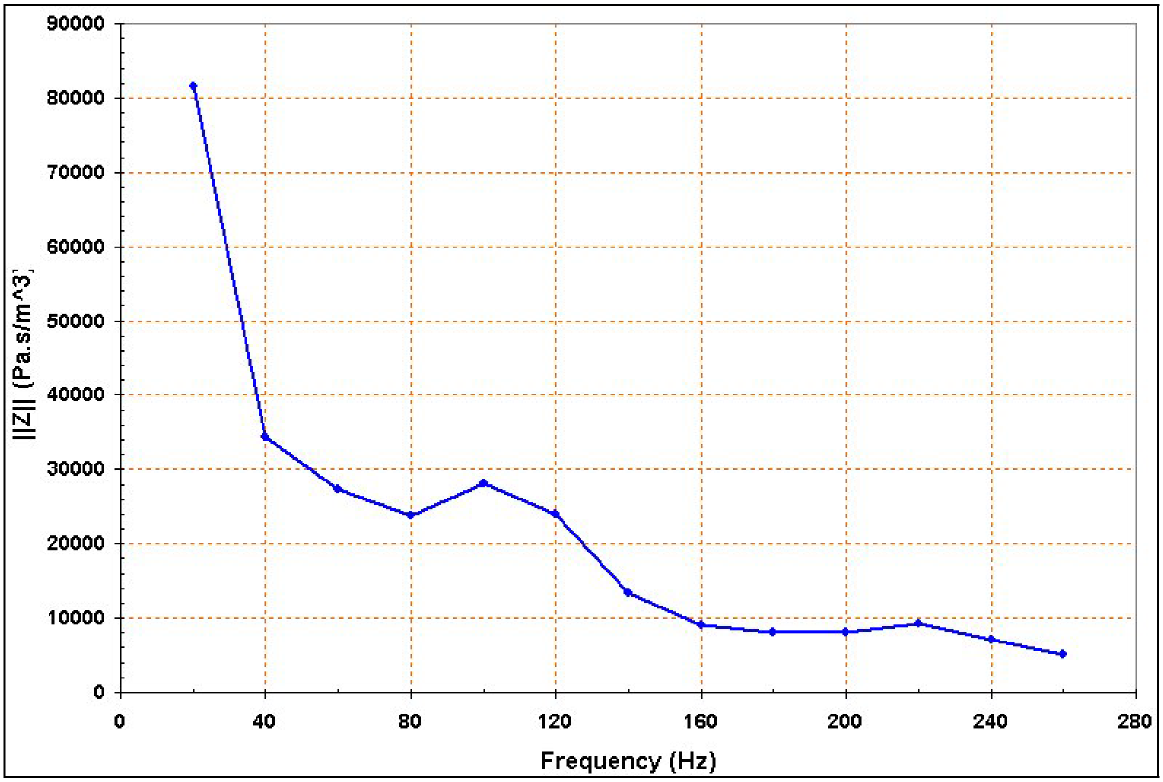


Figure 11. The magnitude of ground impedance versus frequency.

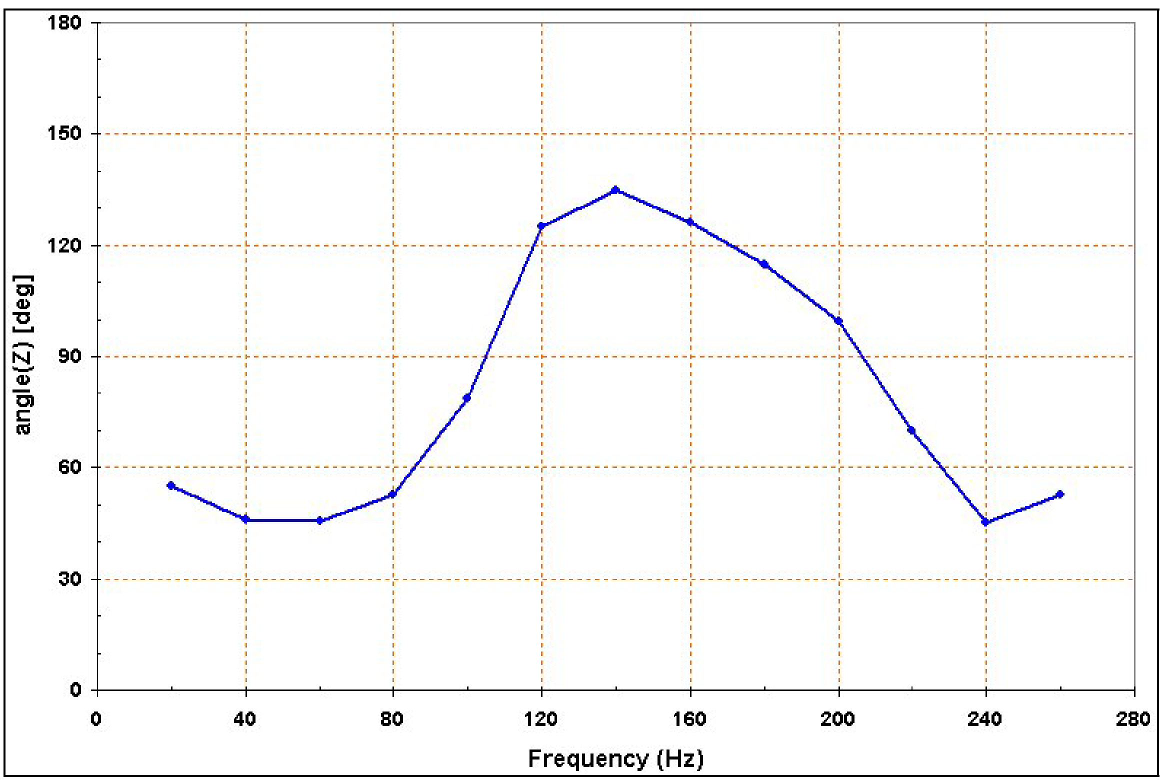


Figure 12. The phase of complex ground impedance versus frequency.

# 4. Conclusions

Measurements of AGI versus frequency are given in this technical note. These measurements were done at one location on one day using the sound pressure-volume velocity method. The raw data and intermediate processed results are available to any interested reader and can be received by contacting the following:

Director
U.S. Army Research Laboratory
Survivability/Lethality Analysis Directorate
Building 1624
White Sands Missile Range, NM 88002-5513
USA

## 5. References


1. Sutherland, L. C.; Daigle, G. A. Atmospheric Sound Propagation. In *Encyclopedia of Acoustics*, Vol. 1; Crocker, M. J., Editor-in-Chief; John Wiley & Sons, Inc.: New York, NY, 1997; pp 341–365.

2. Zuckerwar, A.J. *Acoustic Ground Impedance Meter. J. Acoust. Soc. Am.* **1983,** *73* (6), 2180–2186

3. Zuckerwar, A.J. National Aeronautics and Space Administration. *NASA Acoustic Ground Impedance Meter Operating Instructions*. Email. February 27, 2002.

## Acronyms

| | |
|---|---|
| AGI | acoustic ground impedance |
| B&K | Bruel & Kjaer |
| C | Celsius |
| Hz | hertz |
| m | meter |
| MATLAB | Matrix Laboratory |
| mbar | millibar |
| NASA | National Aeronautics and Space Administration |
| rms | root mean square |
| s | second |

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