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Propagation of Sound Through the Atmosphere: Effects of Ground Cover II

H. E. Bass and L. N. Bolen

Technical Report

1 July 1979

U. S. Army Research Office

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Physical Acoustics Research Group
The University of Mississippi
University, MS 38677

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The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Measurements of sound amplitude in the vicinity of a ground plane have been made as a function of frequency of the sound source (50 Hz - 2000 Hz), distance of propagation (5m - 300m), and surface conditions. By treating the impedance as an adjustable parameter, the surface impedance as a function of frequency was determined from the measured amplitudes using a theoretical treatment of a spherical wave in the vicinity of a locally reacting surface.

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The impedance measurements covered the frequency range 50 Hz to 1000 Hz. In this frequency range, the results for three distinctly different surfaces suggest that the impedance can be computed from the specific flow resistance and that grass has little effect on the surface impedance except for decreasing the flow resistance due to the root structure. Experimental studies of surface impedance should include measurements of soil parameters such as density, specific flow resistance, and moisture content so that comparisons can be made between the results from different laboratories and so that a data base for additional theoretical development can be extablished.

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1.0 INTRODUCTION

Propagation of sound outdoors is influenced by a variety of mechanisms which change the amplitude and phase of the wave. These include:

- Atmospheric Absorption
- Boundary Effects
- Turbulence
- Refraction.

In previous studies, atmospheric absorption was considered in terms of microscopic processes and a technique was developed which allows one to predict atmospheric absorption using simple expressions which are based on the rigorous microscopic treatment (Ref. 1-5). At low frequencies (<1 kHz), for most conditions, the presence of a boundary will effect the sound amplitude more than atmospheric absorption (Ref. 6). An earlier report (Ref. 7) considered this mechanism for frequencies between 100 Hz and 1 kHz for a field of institutional grass and a field of Sorghum Sudan grass. This report will expand the low frequency range and soil types discussed in the earlier report. Turbulence can also effect the sound field by destroying coherence and thereby reducing interference which would otherwise occur in the presence of a boundary (Ref. 8). Refraction due to a thermal or velocity gradients also influences the received sound. The measurements reported here were taken under conditions which minimized the effects of turbulence and refraction.

This study of the effect of the ground on outdoor propagation of sound through the atmosphere is the second step in a long range effort to develop procedures to reliably predict sound amplitudes a significant distance from the source and correct measured spectra to free field conditions.

This report deals primarily with experimental measurements of sound amplitude in the vicinity of a ground surface at ranges out to 300 m at frequencies between 50 Hz and 300 Hz. These measurements serve primarily to extend the data base for surface impedances. This report includes the findings in Reference 7 related to surface impedances but omits the acoustic to seismic measurements and computer programs included in that earlier report. The experimental and theoretical work on the problem of outdoor sound propagation undertaken by this laboratory is meant to complement similar efforts being made by other laboratories most notably the acoustics group at the National Research Council of Canada (Ref. 9-11), and Wyle Laboratories (Ref. 8).

The experimental techniques employed to generate the sound field and measure sound amplitude are described in Section 2. In Section 3, the experimental results are presented. Due to the large number of measurements made, the results are most often reported in terms of acoustic impedance values deduced from a model of the ground surface. Should this model, at some later date, be shown to be inadequate, the raw experimental data can be reconstructed by using the deduced impedance values to calculate the measured sound amplitude. Section 4 provides a tentative interpretation of the experimental results. Section 5 demonstrates how these results can be used in a practical application and Section 6 summarizes the results of this study.

2.0 Experimental Technique

The measurements were made by broadcasting bands of sound over prepared fields from 300 to 1000 feet in length. Microphones were placed at intervals down the range at two heights, and recordings were made of the SPL of each microphone. These recordings were then analyzed to determine the surface impedance values of the grounds. Four fields were used for these measurements.

1) Band Field and Softball Field at the University of Mississippi. The band field represented a typical institutional grass field with a hard non-porous clay soil and low moisture content (density 1300 kg/m^3 dry). This field has been undisturbed for at least 15 years. The softball field also consisted of a grass covered clay soil (density 1450 kg/m^3 dry). It, however, was prepared with dirt fill two years ago, and the grass cover is not as complete as at the band field.

2) Experimental Range at the Waterways Experiment Station in Vicksburg, Ms. This field consisted of a brown to dark brown heavy silt loam with subsoil ranging from heavy loam to silty clay loam. Measurements were made with two different moisture contents.

3) Farm near Oxford, MS. The soil and vegetation on this farm was prepared for these measurements, and soil classification was made by the USDA Sedimentation Laboratory in Oxford. The site was located in a valley bottom covered with recent alluvium deposited over Kosciusko and Tallahatta foundations The soils are palevdalts and are predominantly a silt loam with greater than 50 percent silt and 7 percent clays (1470 kg/m^3 dry). The region between 200 and 350 feet on the test range contains

more loamy sand. Measurements were made before the field was plowed, on a bare plowed field, on the field with various heights of Sorghum Sudan grass, and on a bare field after harvest. In each case measurements were made with various moisture contents.

4) Sandy Farm near England Air Force Base, Florida. This field was bare of vegetation and measurements were made with various moisture contents. The sand was uniform to a depth of six feet over the 1000 foot range.

5) Sardis Reservoir Beach. This area was bare of vegetation with six inches to a foot of loose sand overlying a clay base.

2.1 Several speaker systems were constructed for this project. An Altec 515B 15 inch diameter bass driver in a ducted port enclosure was used for the data taken at the Waterways Experiment Station. A combination of 4 of these speakers in an Electrovoice TL 606Q enclosure was used for mid-low frequency measurements (100-200 Hz). The extreme low frequency data (40-100 Hz) were taken using a EV18B speaker in a modified Electrovoice TL 505 enclosure. High frequency data (200-2000 Hz) were taken with a horn system composed of 4 University ID-60 compression drivers loaded by an inverted cone truncated with a 4 inch diameter opening.

The data analysis program assumes a spherically diverging wave front. Although a theoretical treatment for a non-spherical wave is possible, the spherical geometry eases physical interpretation of the results. The requirement for a spherical wave front dictates that the source of sound be approximated as a point source. At frequencies below 100 Hz, this represents no problem; the speakers used can be considered a source of spherical waves. Each speaker system utilized was tested to determine its directivity pattern as a function of frequency. An increased directionality at higher frequencies is characteristic of radiating circular pistons. As a result of these measurements, data above 200 Hz were not taken using the large, low frequency driver systems. The high frequency system was capable of producing a uniform distribution of sound with a deviation from sphericity of ±2dB to a frequency of 2000 Hz.

2.2 Measurements were made of the amplitude of the sound by microphones placed 1 and 2 meters above the surface of the ground at 100 foot intervals from 50 to 1000 feet from the speaker. A single stationary reference microphone was placed at ground level 50 feet from the speaker to measure any variations in sound intensity from the speaker system during the course of the experiments.

Two types of signals were broadcast over the range. Octave bands of pink noise of one minute duration were used in the original experiment at WES. Later data taken at the fields in Oxford and Florida used bands of pink noise 1/2 octave in width centered about each 1/3 octave center frequency from 40 to 2000 Hz. Data were also taken in Oxford using sweep test tones from 80-200 Hz and 180-2000 Hz. In each case the appropriate speaker system was used to assure the sphericity of the transmitted wave.

The speaker system was suspended on a large crane at WES and speaker heights varied from 1 to 10 meters above the ground. In Oxford, the speaker system was suspended from a cross member on a telephone pole placed in the field, and most of the data were taken with a speaker height of 10 feet. A portable A-frame stand was constructed for use on the band field, at Sardis Reservoir, and in Florida. This permitted speakers to be suspended at heights up to 10 feet above the ground.

The microphones used for the amplitude measurements were B&K 4125 1/2" Condenser Microphones with B&K 2632 preamplifiers and B&K 3810 power supplies. A GR 1962-9602 Electret microphone was used to monitor the speaker level. The signals from the microphones were recorded at various times on a pair of Uher 4200 2 track tape recorders, a Tandberg 4 track FM recorder, and an EMI 8 track FM recorder in special environmental packages. These data were then played back originally into a GR 1554-A 1/3 octave band analyzer for the analysis of pink noise or into a HP 3480A analyzer synchronized for use as a tracking filter for the sweep test tones. The later data were analyzed using a computer based GenRad System 1923.

The system was calibrated by recording the output from a GR 1562 sound level calibrator on each microphone-recorder channel at the beginning and end of each run. No measureable gain shift was observed during the course of any run.

2.3 Differences in air temperature with height above the earth may have a strong effect on the propagation of acoustic waves due to refractive effects. Measurements of air temperature versus height were made at each site during the course of each test period. The temperature and wind velocity was monitored using a Wallac GGA23S Thermo-Anemometer with a Ni125ANE probe. A log was kept of these variables during each testing period. Temperature gradients of less than 3°F for a 10 meter height increase were always required for data acquisition and in general the gradients were less than 2°F for 10 meters. Data was not collected when the wind speed exceeded 3m/sec.

An estimate of the effect of air turbulance on the acoustic signal was obtained by measuring the coherence length of the propagating sound waves.

Since a single source was producing the direct and reflected wave, interference effects from phase cancellation could be observed only if the waves were coherent over the path length involved. White noise and bands of pink noise were broadcast over the range. The acoustic signals received by microphones 30 meters apart were analyzed on a Honeywell SAI43A Correlation Analyzer. The coherence length measured in these experiments was greater than 30 meters for the noise. The coherence length is frequency dependent and it will be noted in the results that above 1 kHz, turbulence led to a loss of coherence at the greater propagation distances.

Moisture content of the soil can greatly affect its flow resistance and acoustic properties. The soil was sampled at the time of each measurement and the flow resistance and water content was measured and included as a parameter in each of the measurements reported. The specific flow resistance of each soil sample was measured using an instrument constructed using a design of Leonard[12]. A cylindrical sample of earth was taken from the field and the rate of air flow through the soil sample was measured as a function of differential pressure across the sample. Measurements of flow resistance were made of each soil sample using at least three differential pressures across the sample. Consistency of these results were always within 5%. However, it was found that there were inconsistencies in the measured flow resistances from multiple samples removed from the same fields. Values of flow resistance which varied by as much as a factor of 2 were observed in some fields, although measurements of the flow resistance of sand were consistent to within 10%. It was assumed that these discrepancies occured because of variations in soil structure in the 10 cm diameter plugs extracted for measurement and the effects of disturbing the soil. Root structures, fissures and inhomogenities in the loosely packed soil at the farm resulted in the largest variations. The uniform moist sand in Florida permitted more homogeneous soil samples to be tested, and resulted in the most self consistent results. The values of flow resistance reported are the average values of the samples taken at each field during the day of the acoustical measurements.

The wet and dry weight of a layer soil sample was recorded to determine moisture content. A plug of top soil of cylindrical cross section 30 cm in diameter was removed from the field, encased in a plastic bag and weighed. The soil was then dried in an air conditioned environment until weight variations ceased, and the percent moisture content of the sample was recorded.

3.0 Experimental Results

The experimental data are numbered according to the sequence in which they were collected. Table 1 gives a brief synopsis of the various data collection runs. A total of thirty sets of data were collected, each consisting of SPL measurements at four to eight microphone locations, two to six microphone heights, and typically 13 different frequencies. All data were collected at least twice for averaging. This amounts to 22,000 data points. There is no way to present all this data in a report of acceptable length. Instead only that data needed to illustrate specific points will be presented. Further, this data will be discussed in the order appropriate to a logical development of the topic, not in the order in which they were collected.

3.1 Comparison Measurements.

The ground cover most thoroughly studied in terms of a boundary to acoustic propagation is "institutional grass".[8,9] This the type cover usually encountered on college campus lawns, around government buildings, etc. Although the actual grass type varies, it is almost always well trimmed, uniform, and relatively dense. The earth under the grass has usually gone many growing seasons without tilling.

Measurements of sound amplitude over institutional grass on the University of Mississippi (UM) campus are presented in Figures 1-2. All levels are referenced to the 50 ft. position. These data (Runs 11 and 12) were collected with the speaker system 5.3 ft. from the ground plane and two microphones (one meter and two meters above the ground) which were moved between data collection locations 50 ft., 75 ft., 100 ft., 150 ft., and 200 ft. from the speaker. The source was driven

Table 1

Experimental Conditions

Run No.	Location	Type of Surface	Moisture Content	Type of Source	Date	Comments
WES I	Waterways Exp. Station	Scattered grass		Bands of noise		Ground frozen
WES II	Waterways Exp. Station	Scattered grass		Bands of noise		
2	Sorghum Sudan	Bare surface - seeds in the ground		Octave band pink noise	5-26-77	
3	Sorghum Sudan	Grass barely visible		1/2 Octave band pink noise	5-31-77	
4	Sorghum Sudan	Sparse growth		1/2 Octave band pink noise	6-8-77	
5	Sorghum Sudan	Sparse growth		1/2 Octave band pink noise	6-9-77	
6	Sorghum Sudan	10"-12" high grass			6-24-77	
7	Sorghum Sudan	22" grass	48% by weight	1/2 Octave band pink noise	7-8-77	
8	Sorghum Sudan	22" grass - bulk density of ground 1.27 x 10^3 kgm/m^3	10% by weight		7-12-77	
9	Sorghum Sudan	25" grass - grass density 8.6 mg/cm^3	8.6% by weight	1/2 Octave band pink noise and sweep tones	7-22-77	

* Run 1 aborted

10	Sorghum Sudan	1.1m grass	-	1/2 Octave band pink and sweep tones	8-2-77
11	Band field	1 1/2" Institutional Grass	-	Sweep tones 250 Hz-2KHz	8-5-77
12	Band field	1 1/2" Institutional Grass		Sweep tones 90 Hz-200 Hz	8-10-77
13	Sardis Reservoir Beach	Sand	5.6% by weight	Sweep tones	8-16-77
14	Sorghum Sudan	Field Cut	-	Sweep tones	9-5-77
15	Sorghum Sudan	Field Cut	22% by weight	Sweep tones	9-30-77
T3-T4	Softball field	1" Institutional Grass	8.33% by weight	1/2 Octave band pink noise	6-16-78
T5-T6	Softball field	1" Institutional Grass	6.25% by weight	1/2 Octave band pink noise	6-20-78
T7	Softball field	1" Institutional Grass	6.25% by weight	1/2 Octave band pink noise	6-20-78
T8	Farm	Sorgum Sudan Planted	16.5% by weight	1/2 Octave band pink noise	6-28-78
T9-T10	Farm	Sorgum Sudan 3"	5.26% by weight	1/2 Octave band pink noise	7-6-78
T11-T13	Band field	1 1/2" Institutional Grass	4.6% by weight	1/2 Octave band pink noise	7-11-78
T14-T16	Softball field	1" Institutional Grass	4.4% by weight	1/2 Octave band pink noise	7- -78
T17-T18	Softball field	1" Institutional Grass	4.4% by weight	1/2 Octave band pink noise	7-14-78

T19-T21	Farm	Sorgum Sudan 3 feet high	3.2% by weight	1/2 Octave bands of noise	7-19-78
F1-F6	Florida Sand	Freshly disked Sand	7% by weight	1/2 Octave bands of noise	7-25-78
T22-T24	Farm	Field of grass cut; matted grass on field	2.7% by weight	1/2 Octave bands of noise	8-2-78
T25-T32	Farm	Sorgum Sudan 3-4"	10.4% by weight	1/2 Octave bands of noise	8-9-78
T33-T35	Farm	Sorgum Sudan 3-4"	3.4% by weight	1/2 Octave bands of noise	8-10-78
T36-T37	Farm	Sorgum Sudan 2"; After second harvest, field dry and clear	2.1% by weight	1/2 Octave bands of noise	9-19-78

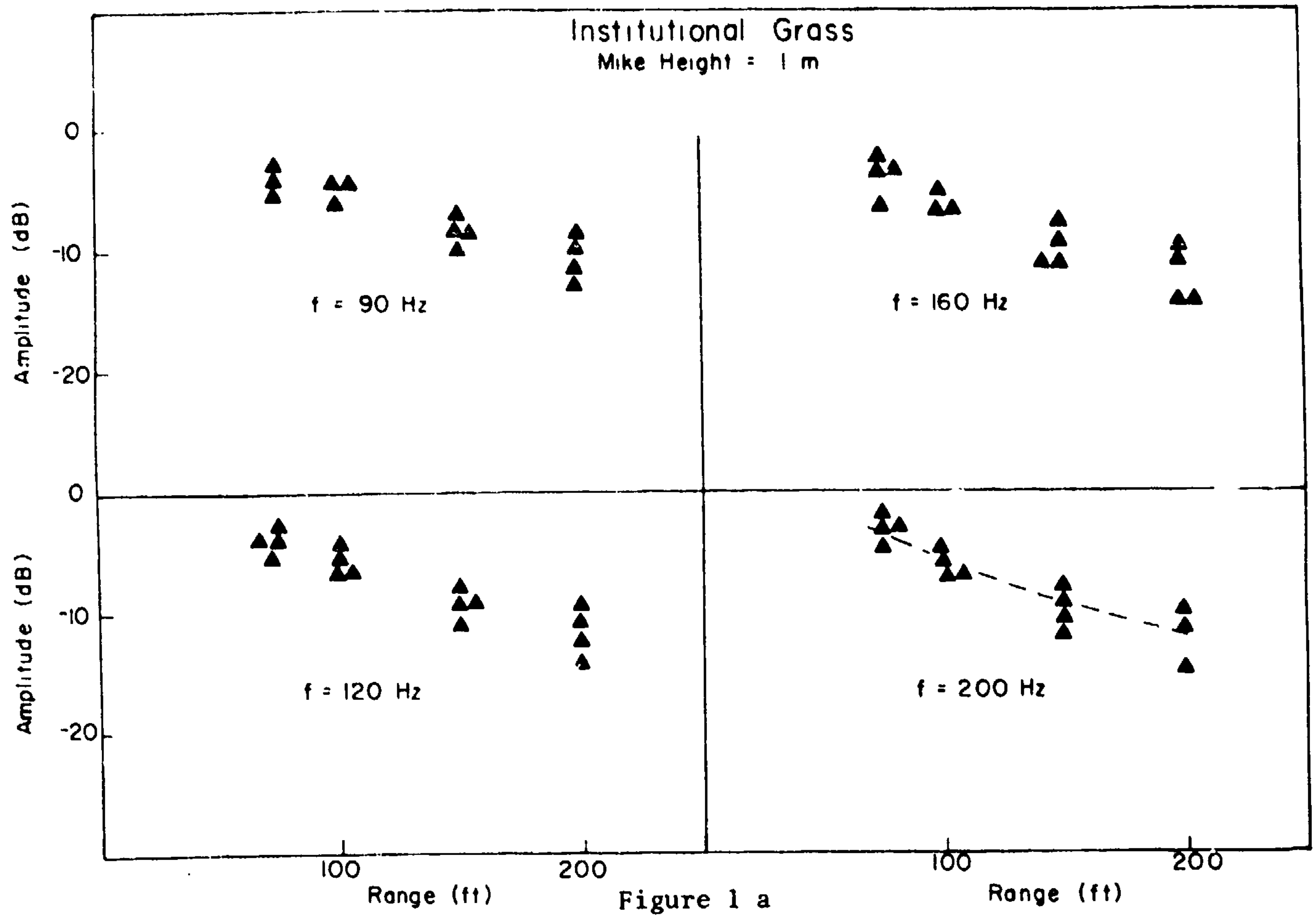

Figure 1 a

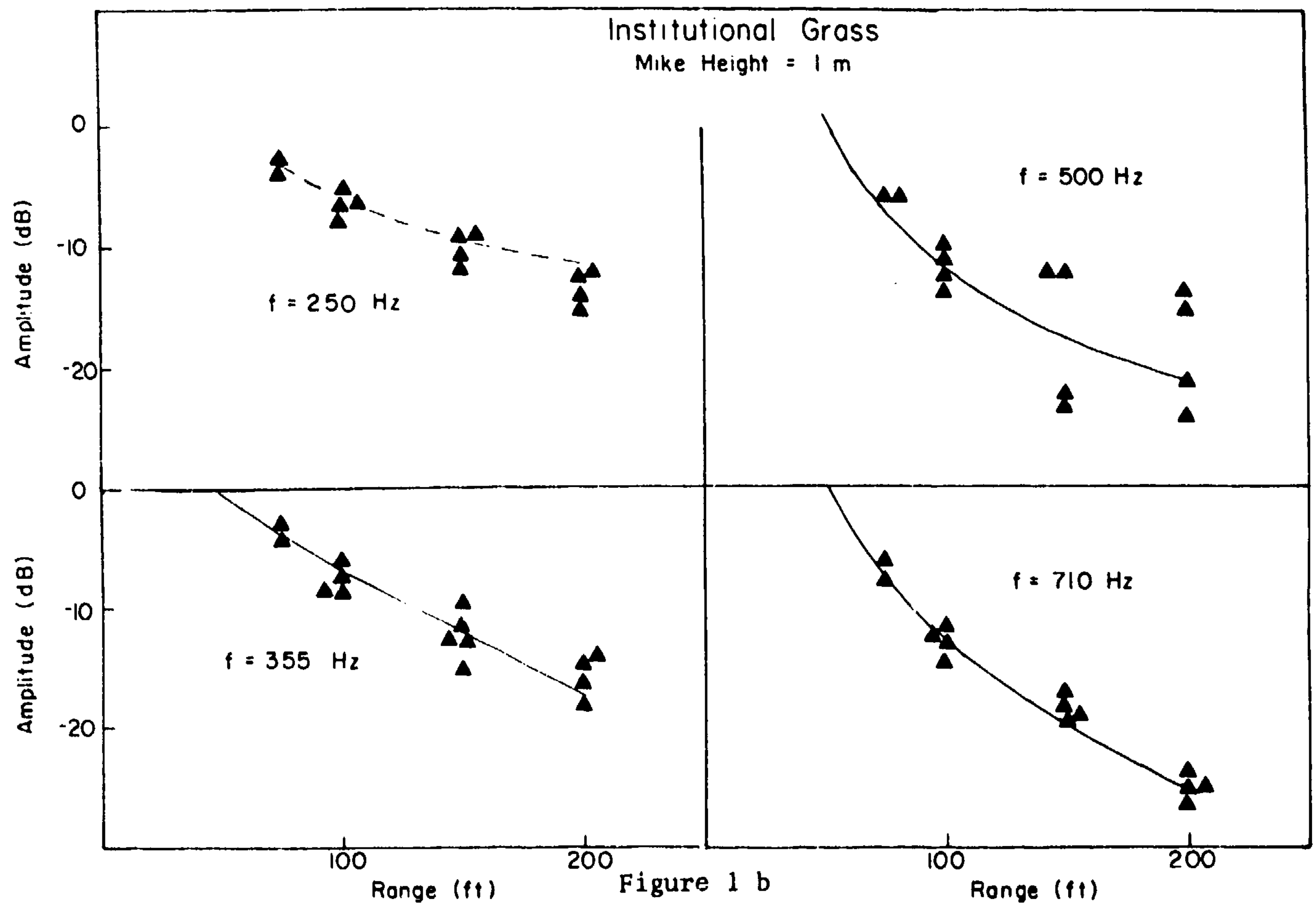

Figure 1 b

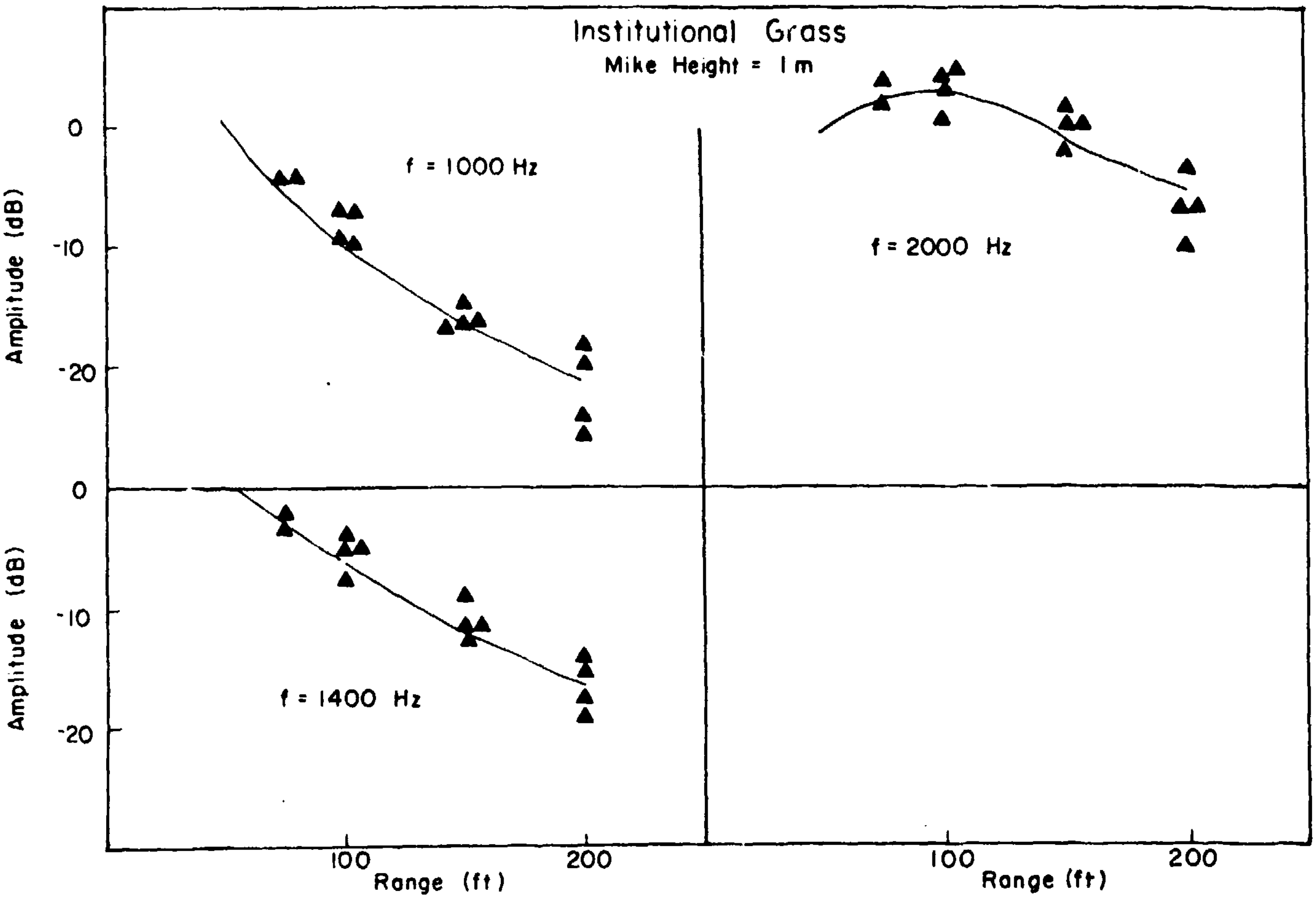
Institutional Grass
Mike Height = 1 m
f = 1000 Hz
f = 2000 Hz
f = 1400 Hz
Amplitude (dB)
Amplitude (dB)
0
-10
-20
0
-10
-20
100
200
Range (ft)
100
200
Range (ft)

Figure 1 c

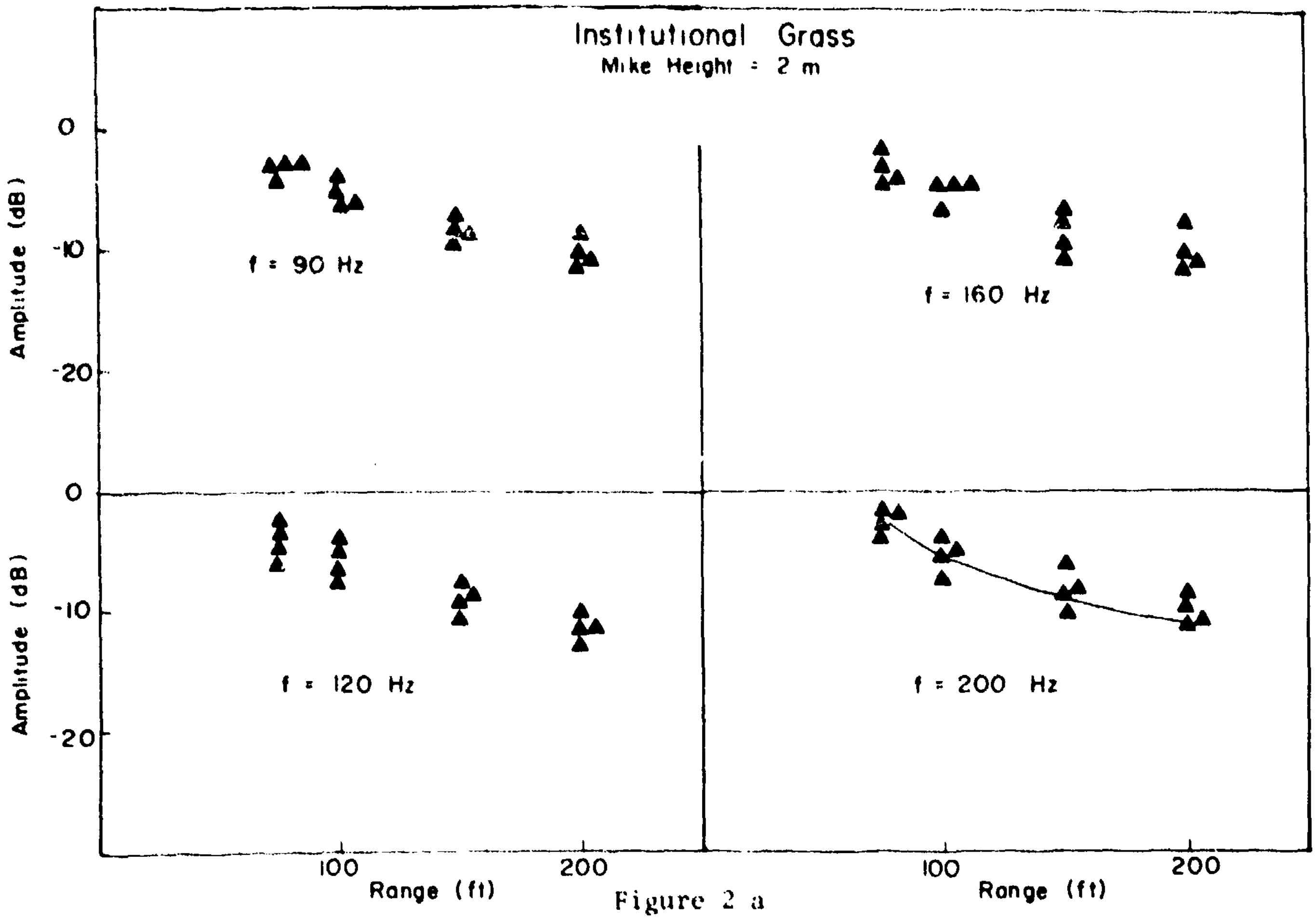

Figure 2 a

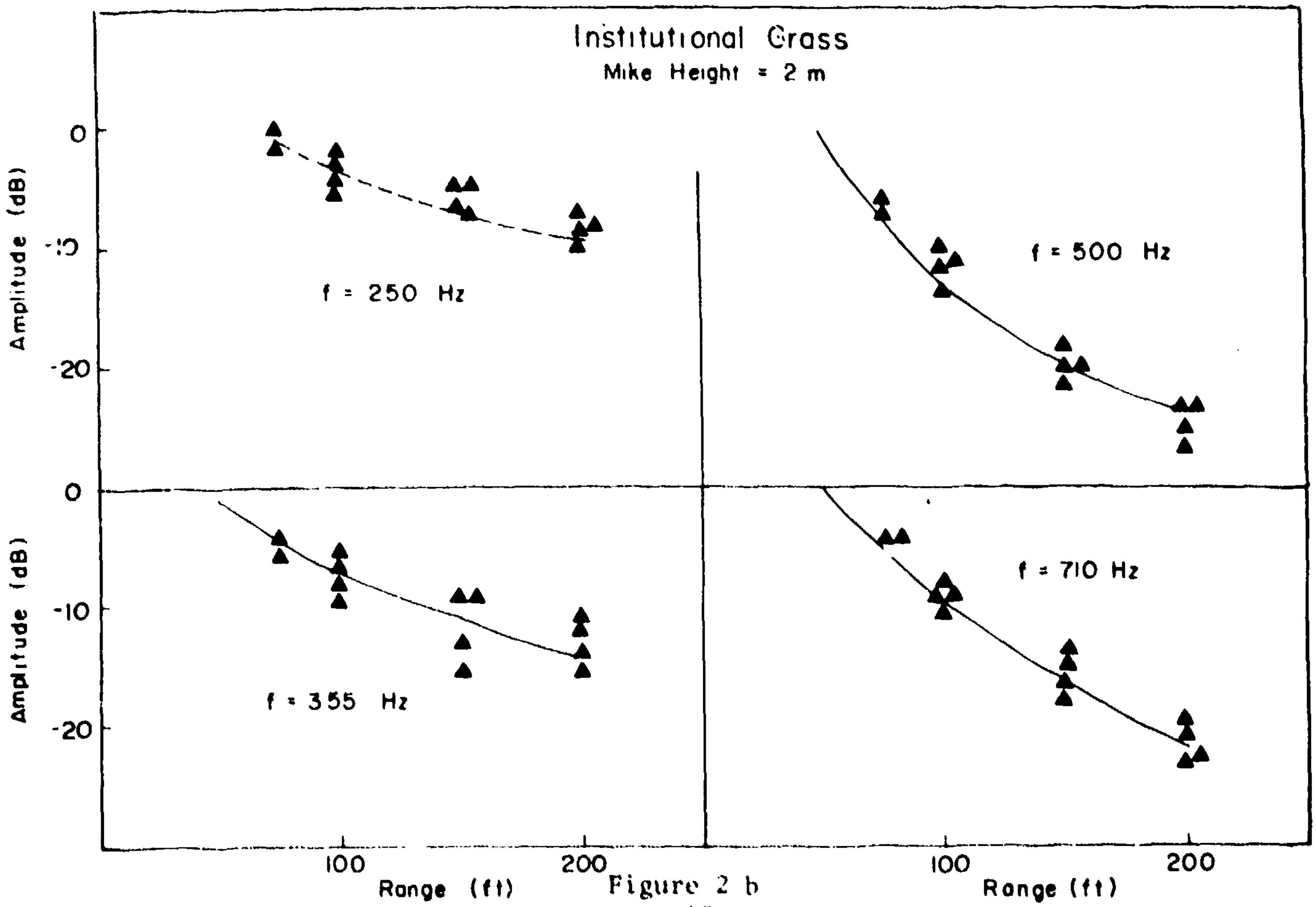

Figure 2 b

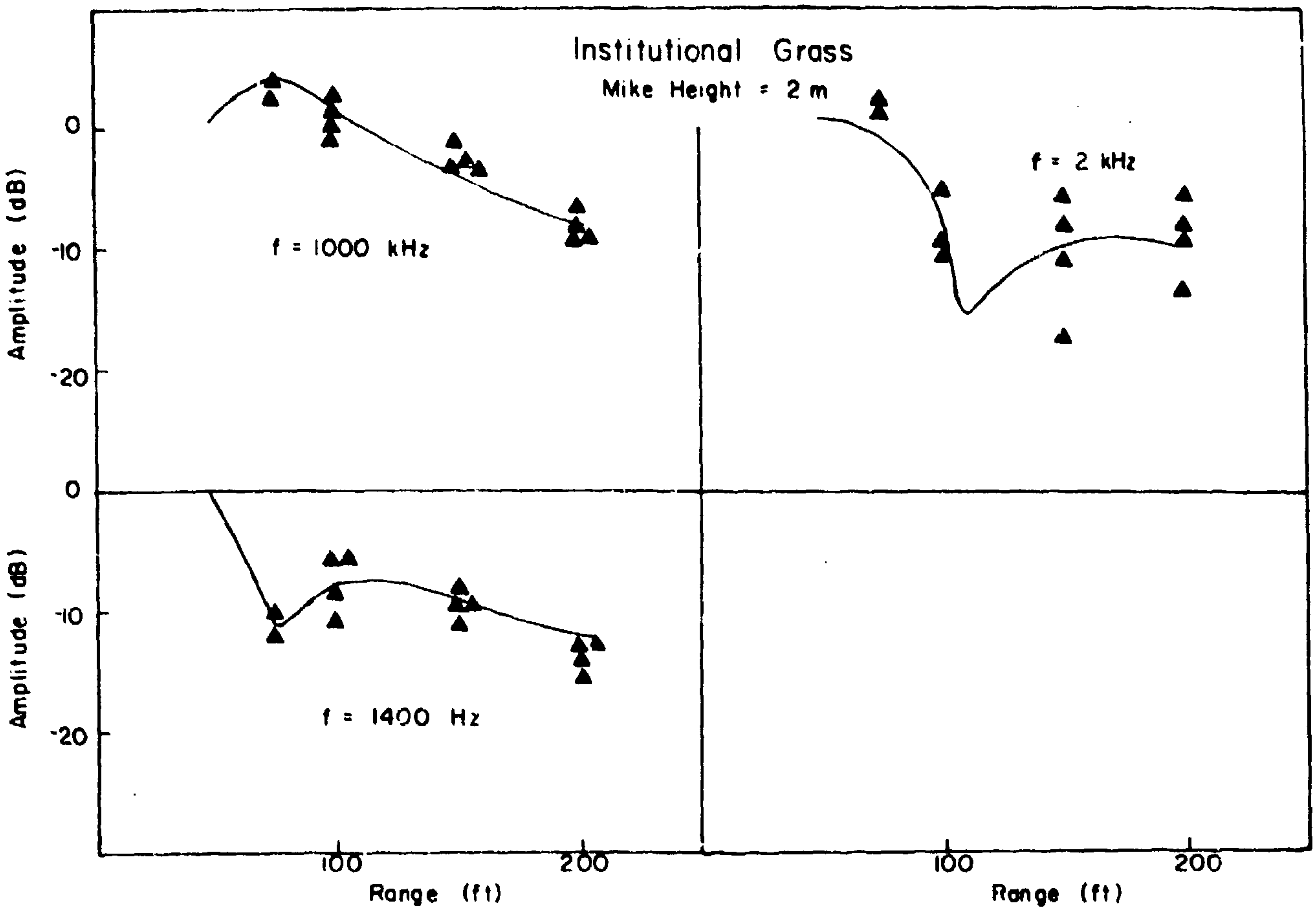
Institutional Grass
Mike Height = 2 m
f = 1000 kHz
f = 2 kHz
f = 1400 Hz
Amplitude (dB)
Amplitude (dB)
0
-10
-20
0
-10
-20
100
200
100
200
Range (ft)
Range (ft)

Figure 2 c

by a prerecorded sweep tone extending from 200 Hz to 2 kHz (Run 11) and 45 Hz to 200 Hz (Run 12).

Referring to Figures 1-2, it can be seen that the data at low frequencies are reproducible to within about 2 dB. This 2 dB variation can probably be attributed to variations in speaker output, noise, and instabilities in the recording system. A variation of ± 1 dB was anticipated and is considered acceptable. At the larger ranges, the fluctuations exceed 2 dB. This is a result of decreased signal to noise ratio but since this type of scatter should be random, by taking four points, the true SPL should be determined ± 1 dB. As the frequency increases, so does the scatter in data. At 500 Hz, this situation is worst. The first interference minimum occurs near 500 Hz. At the interference minimum, the acoustic signal decreases by as much as 30 dB thereby decreasing the S/N ratio by a like amount. Also, since interference relies on coherence between the direct and reflected waves, when the reflection coefficient is high (as it was for the field used) a small loss of coherence due to a transient turbule will greatly affect the recorded SPL. This combination of factors reaches a maximum near the first interference minimum in most all cases. Since the effect of turbulence and noise is to increase the SPL, the lowest value of SPL should be taken as the correct value unless it is much different from the general trend of the data. In practice, the lowest values were weighted by a factor of two relative to intermediate values (weighting of 1) when comparing to theoretical curves.

Referring again to Figures 1 and 2, the solid lines were computed from the theory of Donato[11] using the impedance as an adjustable parameter to achieve the best fit between theory and experiment. It can be seen that the theory is in excellent agreement with measurement. As will be discussed later, these curves are relatively independent of values chosen for the impedance at frequencies below 200 Hz. Considering the excellent agreement demonstrated here, it appears that the only quantities necessary to represent the experimental data are values of impedance. By selecting values of impedance which provide amplitude versus distance curves in good agreement with experiment, the large quantity of data can be represented by a few graphs of impedance versus frequency.

Before presenting the data in terms of impedance values, one problem should be noted. Figure 3 shows theoretical amplitude versus range curves for four frequencies with reasonable estimates of impedance (Z = Xr + iXc). Also given there are curves computed when Xr and Xc are halved. For the lower frequencies, the computed amplitude curves are very insensitive to values of Xr and Xc becoming more sensitive at higher frequency. This means that impedance values determined from amplitude versus distance curves are going to be uncertain to at least a factor of two with the uncertainty increasing at lower frequencies. At the same time, however, predicted amplitudes are less sensitive to impedance at lower frequencies hence even a very uncertain value of Z enables one to compute the amplitude accurately. Also note that at 500 Hz, a variation in Xr gives the same result as a variation in Xc. So if impedance values are to be determined by fitting the data, either Xr or Xc could be varied.

3.2 Determination of Acoustic Impedance.

In order to represent our data in terms of impedances, an iterative search procedure was used. First, reasonable guesses were made for Xr and Xc and at a particular frequency the amplitude was computed for each experimental range and microphone position. The difference between measured and computed amplitudes was computed and stored as the error. Next, Xr and Xc were each

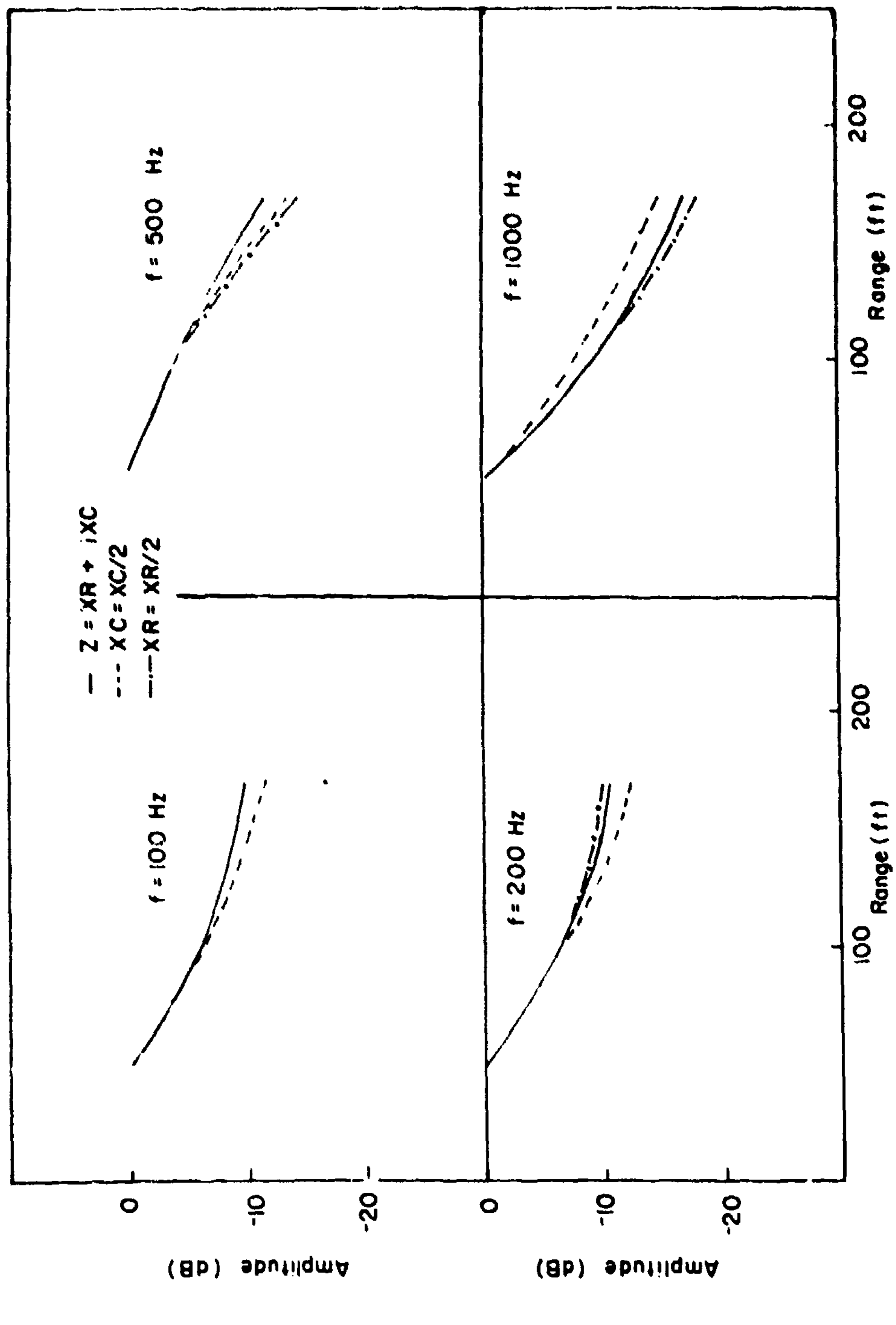
f = 100 Hz
f = 200 Hz
f = 500 Hz
f = 1000 Hz
— Z = XR + iXC
--- XC = XC/2
—·— XR = XR/2
Amplitude (dB)
0
-10
-20
100
200
Range (ft)

Figure 3

incremented a predetermined amount plus and minus creating an array of Xr's, and Xc's for which new errors were computed. The value of Xr and Xc giving the least error was used as a new starting point for the next cycle in the iterative procedure with a smaller increment. This process was continued until the best Xr and Xc were determined to within .1 ρ_o. A copy of the computer program is attached as Appendix 1 to Reference 7. Results of this iterative process are presented in Figure 4 along with curves of impedance values by Embleton, et.al.[9] The agreement between Embleton's data[9] and ours is very good considering "institutional grass" in Canada might differ from "institutional grass" in Mississippi. Impedance values were not determined below 200 Hz for this field due to the large range of Z's which would provide good agreement with measurements over the relative short range available. The solid circles were computed by simultaneously fitting data for two microphone heights. The triangles were determined by fitting data at each microphone height separately and then averaging the results. The remainder of the experimental results will be presented in the next section. Space prohibits the presentation of all data so only deduced impedance values will be discussed. It should be noted, however, that the impedance values rely on an assumed model for the surface--specifically a locally reacting porous medium. So the results are actually presented following interpretation. Raw data from which the results were determined are available from this laboratory.

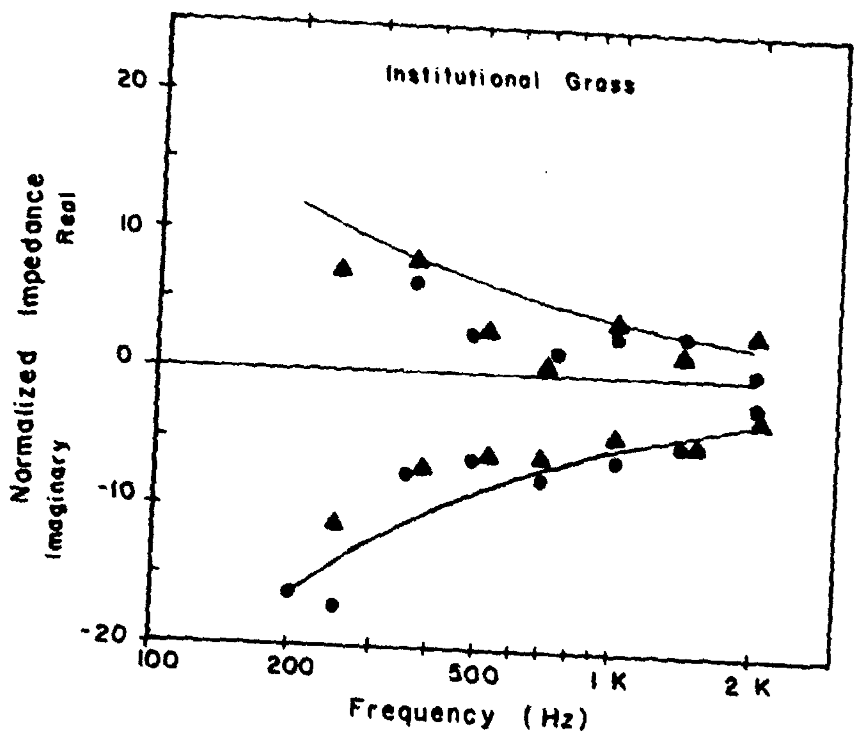
Institutional Grass
20
10
0
-10
-20
Normalized Impedance
Real
Imaginary
100
200
500
1 K
2 K
Frequency (Hz)

Figure 4

4.0 Interpretation of Results

In order to discuss the results, it is necessary to first put the outstanding problems involved in predicting the sound pressure in the vicinity of a ground plane in perspective. If the ground plane is assumed to be a locally reacting porous medium we[7] and others[8-10] have found that present theoretical treatments which assume a point sound source give reasonable agreement with experiment when the impedance is used as an adjustable parameter. The theory of Donato[11] was used to analyze the results of this work and resulted in the impedance values reported in the previous section. These values are generally consistent with impedance values reported by others when the same locally reacting model was used. The results reported here extend to a maximum range of 1000 ft. and a lower frequency limit of 40 Hz. In this range, the surface wave predicted by the theory used to analyze the data was not calculated to be a significant fraction of the measured amplitude. We can only say for sure, then, that in the frequency range studied, the locally reacting surface model as applied by Donato agrees with experiment when the impedance is treated as an adjustable parameter.

As an additional justification for at least temporarily retaining the local reaction assumption, it should be noted that no measurements on any porous acoustical materials have been made which clearly indicate the assumption is not valid. Although the analysis of most such measurements are based on the local reaction assumption, it would seem that if the assumption was not valid, there would be inconsistencies noted in at least a few of the measurements (for example a value of Z that depended non-uniformly on the frequency).

Retaining the locally reacting assumption, the basic physical mechanisms are well understood from studies of acoustic tile. One can imagine the surface as consisting of many pores held by an elastic matrix. When the acoustic wave impinges on the surface, air is forced into the pores alternately compressing the air in them. The air being forced through the pores encounters drag due to fibers in the channel and the walls of the pores so not all of the energy flows back out of the pore as the acoustic pressure oscillates. The sound velocity in the pores is slower than in free space and highly frequency dependent. The amplitude of the sound returned to the reflected wave, then, will depend on how much energy is transferred to the matrix, and the phase of the reflected wave will depend on the distance the wave travels in the pore. When all the pores are not of the same depth, reflections from different depths will add with random phases giving rise to phase cancellations.

This model is consistent with both the measured surface impedances and the seismic/acoustic ratio[7]. At high frequencies, the seismic/acoustic ratio drops dramatically suggesting that either the energy is all being reflected back into the space above the surface or the sound energy is being converted to heat by the drag at the pore walls and oscillations of fibers in the channel. The surface impedance (real part) approaches unity at high frequencies, indicating that the wave is not being reflected hence it must be absorbed. At low frequencies, the seismic/acoustic ratio increases rapidly indicating that less energy is being absorbed in the fibrous structure, i.e., the ground plane is behaving like a simple boundary. The measured surface impedance also increases at lower frequencies indicating that Z is approaching ρc of the soil (which for our cases is of the order of 10^3). If we take 200 Hz as the crossover frequency for the two types of behavior, this suggests that the pores have a depth such that near 200 Hz, the average depth is of the order of a half wavelength in the porous medium (~0.5 m assuming n = 1.5). The gross frequency dependent features of Z then, agree for a surface similar to acoustic tile.

Assuming the surface is a locally reacting porous medium, there are several approaches which can be used to characterize the surface in terms of its acoustic properties (other than impedance) which are more readily measured than impedance. The two which will be considered in detail here are those advanced by Chessell[13] (which is an extension of the earlier work of Delaney and Bazely[14]) and Donato[15] (which is an application of the general development by Morse[16]).

Chessell's approach is strictly empirical and involves only one parameter; the specific flow resistance σ (in units of gm cm^{-3} sec^{-1}). The empirical relations for the acoustic impedance are

$$Xr/\rho_o c_o = 1 + 9.08\ (f/\sigma)^{-0.75} \tag{2}$$

and

$$Xc/\rho_o c_o = -11.9\ (f/\sigma)^{-0.73}. \tag{3}$$

The expressions for the propagation coefficient $k = \alpha + i\beta$ are

$$\alpha\ /\ (\omega/c_o) = 1 + 10.8\ (f/\sigma)^{-0.70} \tag{4}$$

and

$$\beta\ /\ (\omega/c_o) = 10.3\ (f/\sigma)^{-0.59}. \tag{5}$$

In the following, the experimental results of this study will be compared to impedance values calculated using Chessell's formalism. In each case, the value of specific flow resistance (σ) in cgs Rayls is deduced from the experimental impedance values. All impedances are normalized by $\rho_0 c$ (whether specifically mentioned or not).

For reference, we will refer again to Figure 4 which gives impedance values for institutional grass. The solid curve was calculated with $\sigma = 200$. Now we will compare this result to those found for the field especially prepared for this project. At the start of the project, with the ground well tilled but no growth observable, as shown in Figure 5a, the impedance can be represented by a flow resistance of 100. This is to be expected since loose earth should be more porous than institutional grass which has been through many growing seasons without disturbance. As the grass becomes barely visible (Figure 5b) there is no noticeable change in σ. The same holds true as the grass begins to grow and reaches maturity (Figures 6a-9a). When the grass was cut, (Figure 9b) the flow resistance increased slightly (perhaps due to packing by the tractor and loose grass cuttings). After the field had sat for a month without grass and through a heavy rain, the flow resistance increased to 250 (Figure 10a). This evaluation is completely consistent with our physical model of the surface. Since the height of the grass seemed to have little effect on σ, we conclude that the primary function of the ground cover was to keep the soil loose by means of the root structure. The results of all measurements with grass cover made the first year are summarized in Figure 10b.

Results from measurements during the next growing season are presented in Figures 11-12b. As the grass was coming up, σ was determined to be 150 close to the value of 100 found the previous year. But once one crop of grass was harvested, the flow resistance increased to 200. This gradual increase in flow resistance was not expected but could be a result of differences in cultivation procedures.

So far, we have found that institutional grass has a flow resistance near 200, farmed land between 100 and 200, and a bare, recently tilled field, from 200 to 250. This clearly illustrates the importance of root structure and soil compactness. This finding was verified by measurements at the Waterways experiment station where the field has only scattered grass and the soil had been undisturbed for more than two years, σ ranges from 150 to 250.

Next we will consider a distinctively different surface, sand (Figures 14a and 14b). The Florida sand was recently tilled and quite loose giving a flow resistance near 40. These measurements are especially interesting since for a moisture content of 6.6% (as measured in Florida), Dickinson and Doak[17] found the same value. Since Dickinson and Doak used perpendicular incidence and we were near grazing incidence, this finding provides direct positive evidence in support of the locally reacting assumption. The Sardis Sand measurements were at a beach where the sand provided a thin covering for clay which was nearly saturated with water, the σ values are well within the range of those found by Dickinson and Doak for high moisture content soft sand.

The final set of measurements reported here are for the Softball Field (Figures 15a-15b). These values are near those for institutional grass but slightly greater. This is not surprising since part of the field is bare dirt. The interesting feature of the measurements is the consistency with the higher frequency measurements made over institutional grass.

Although the single parameter model appears to work well, it is not without problems. First if values of σ are computed from measurements of Xr and Xc at individual frequencies, the value of σ is invariably found to increase with

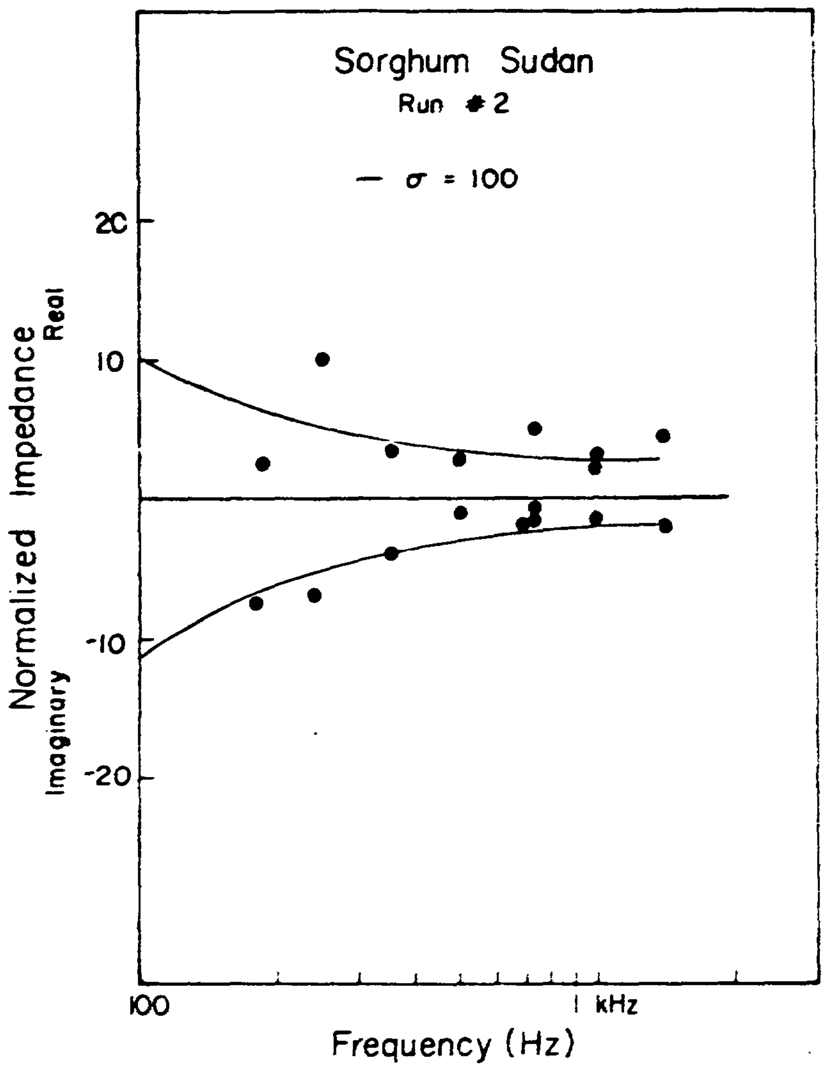

Figure 5 a

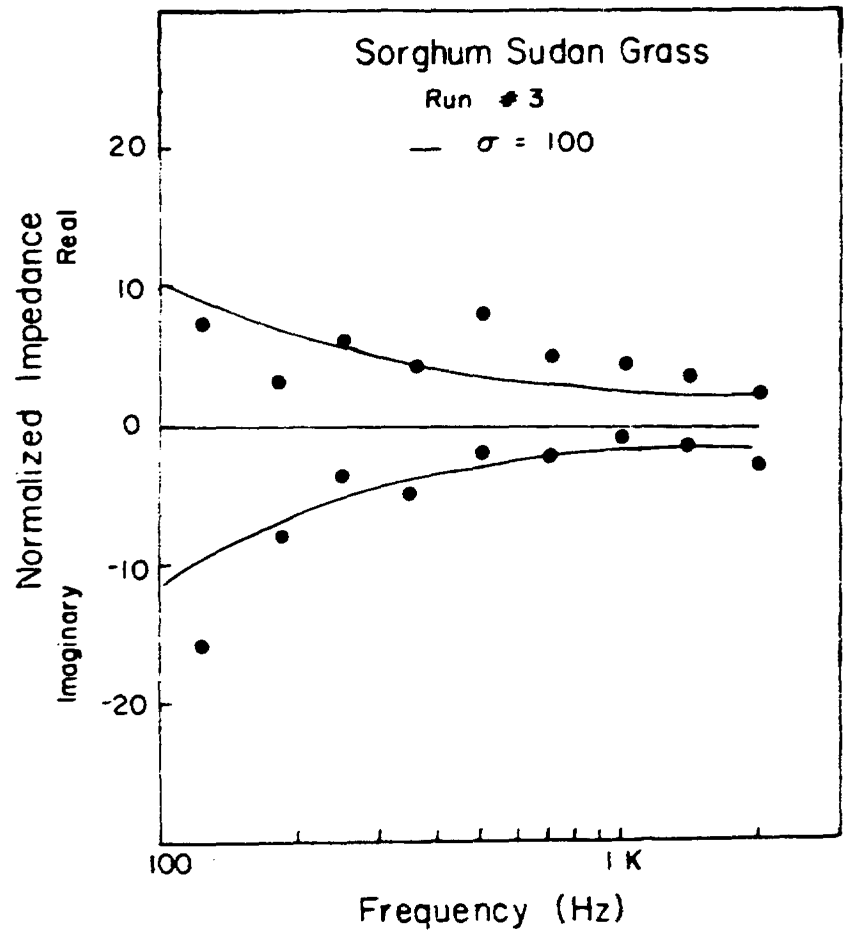

Figure 5 b

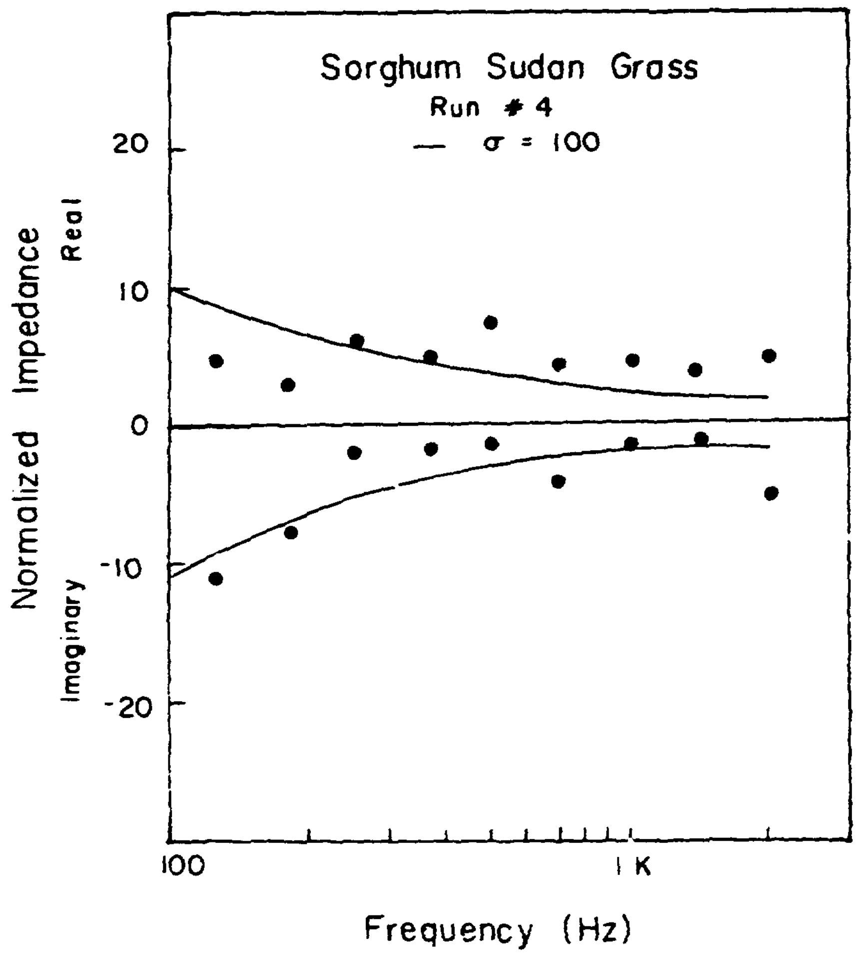

Figure 6 a

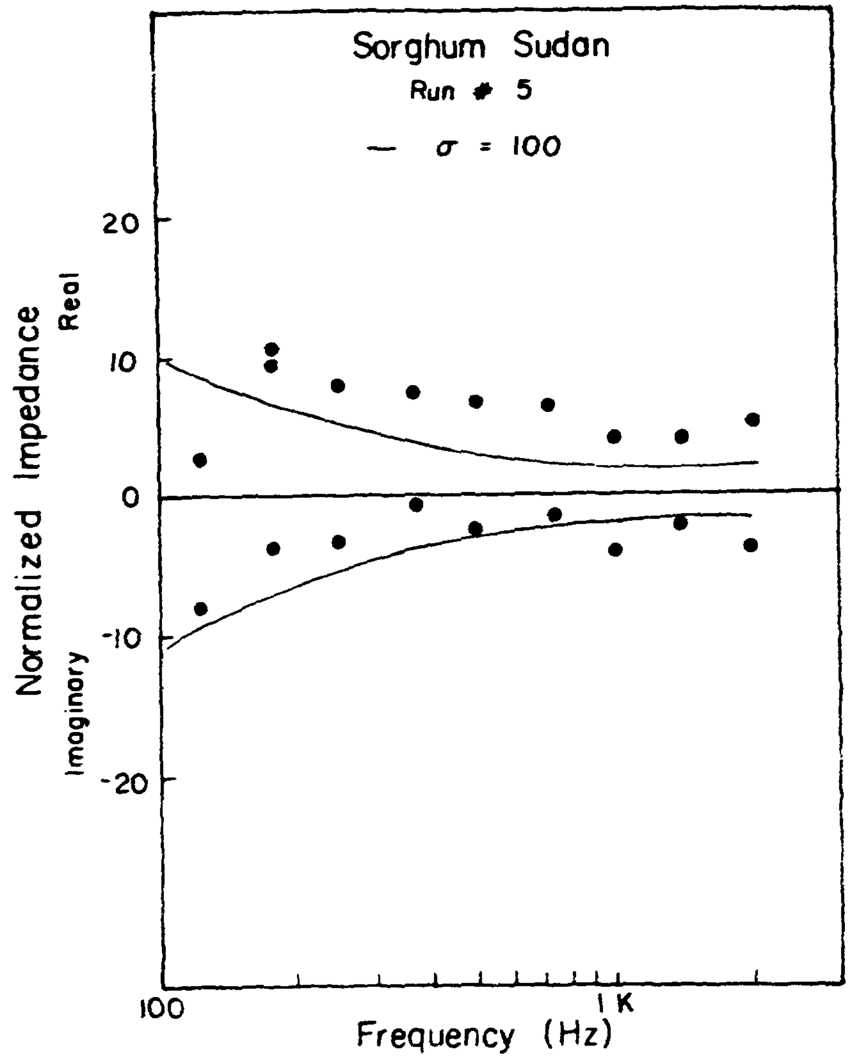

Figure 6 b

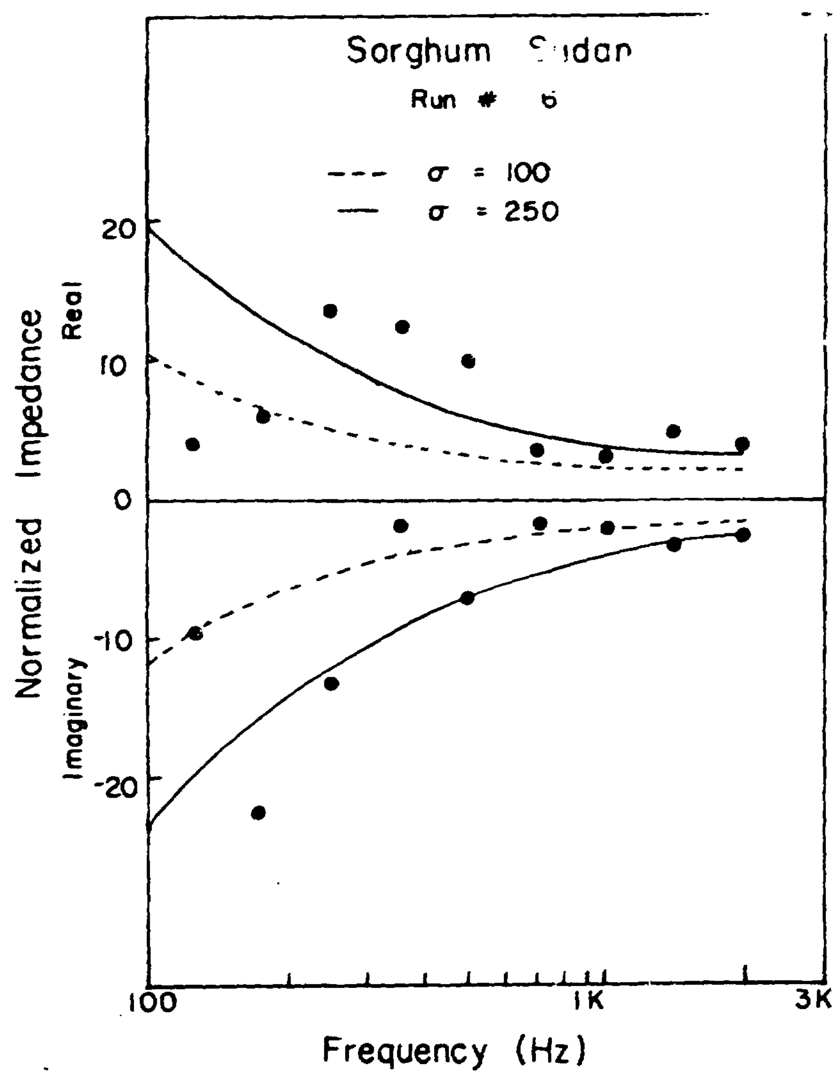

Figure 7 a

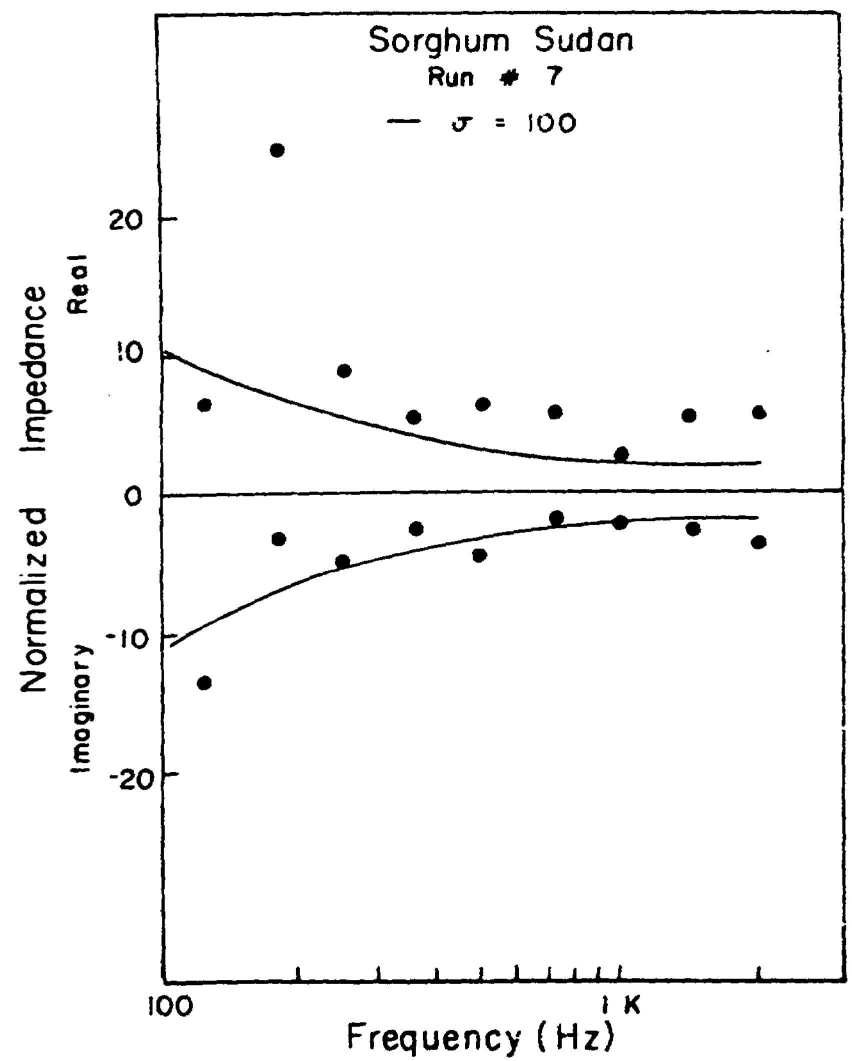

Figure 7 b

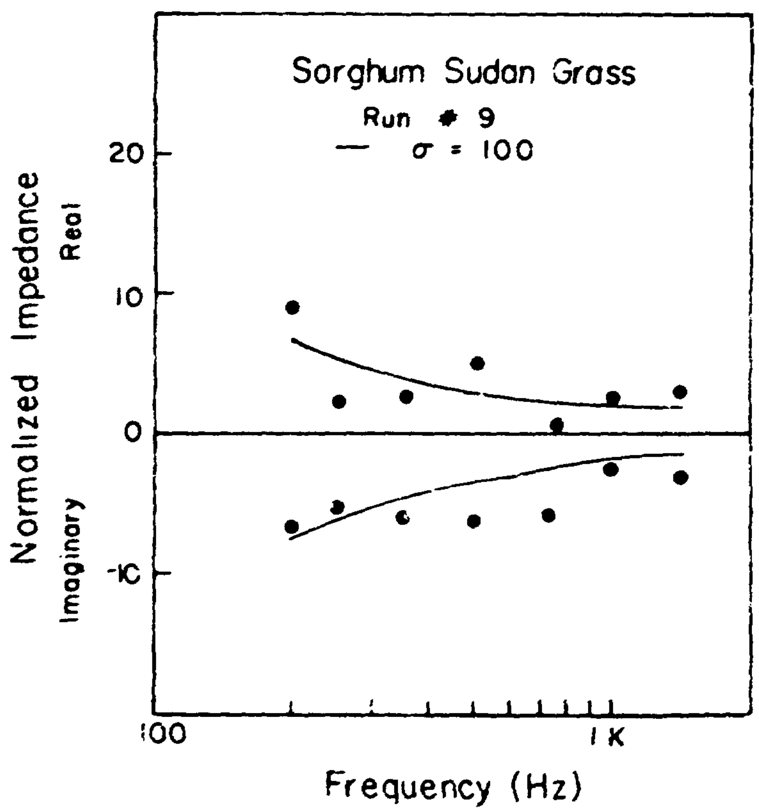

Figure 8 a

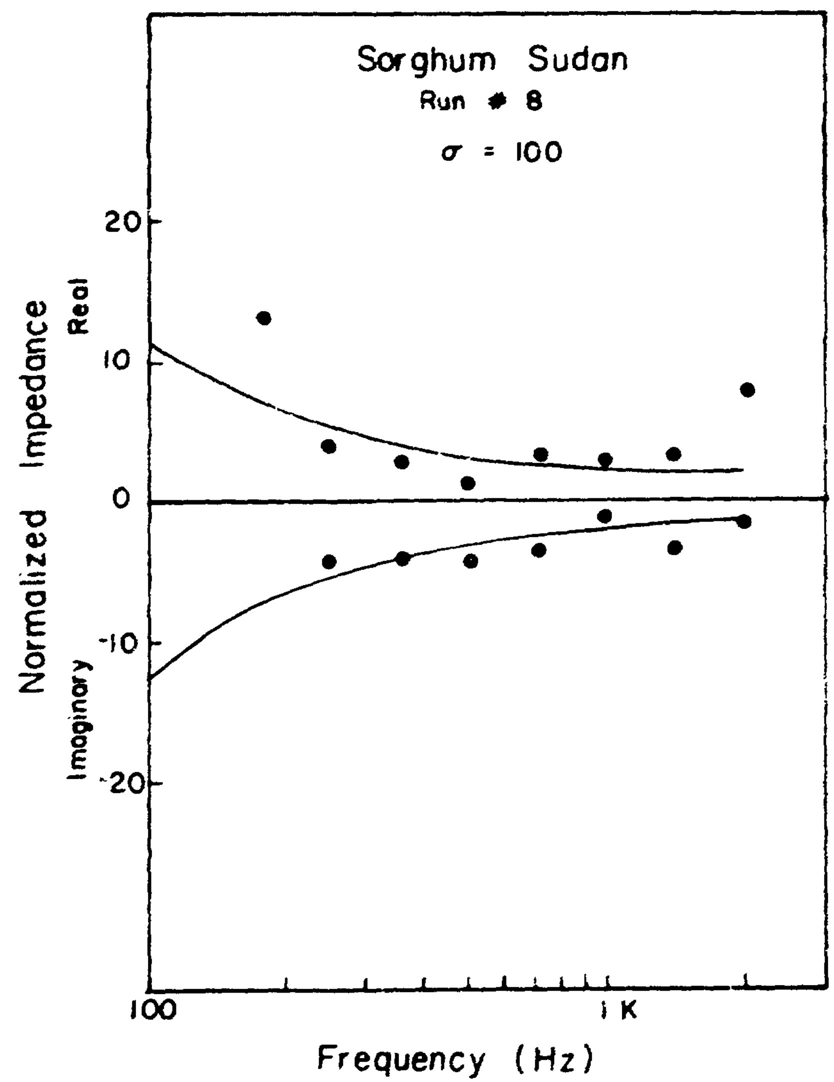

Figure 8 b

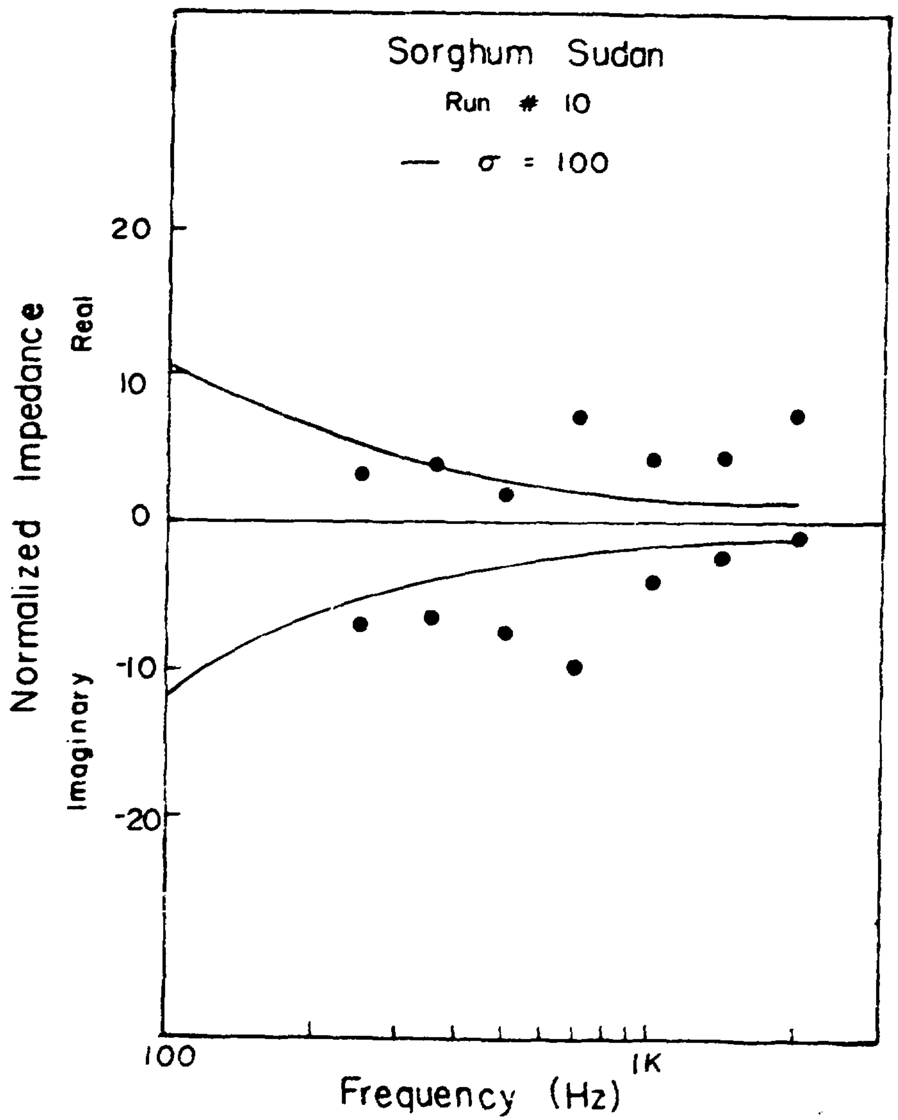

Figure 9 a

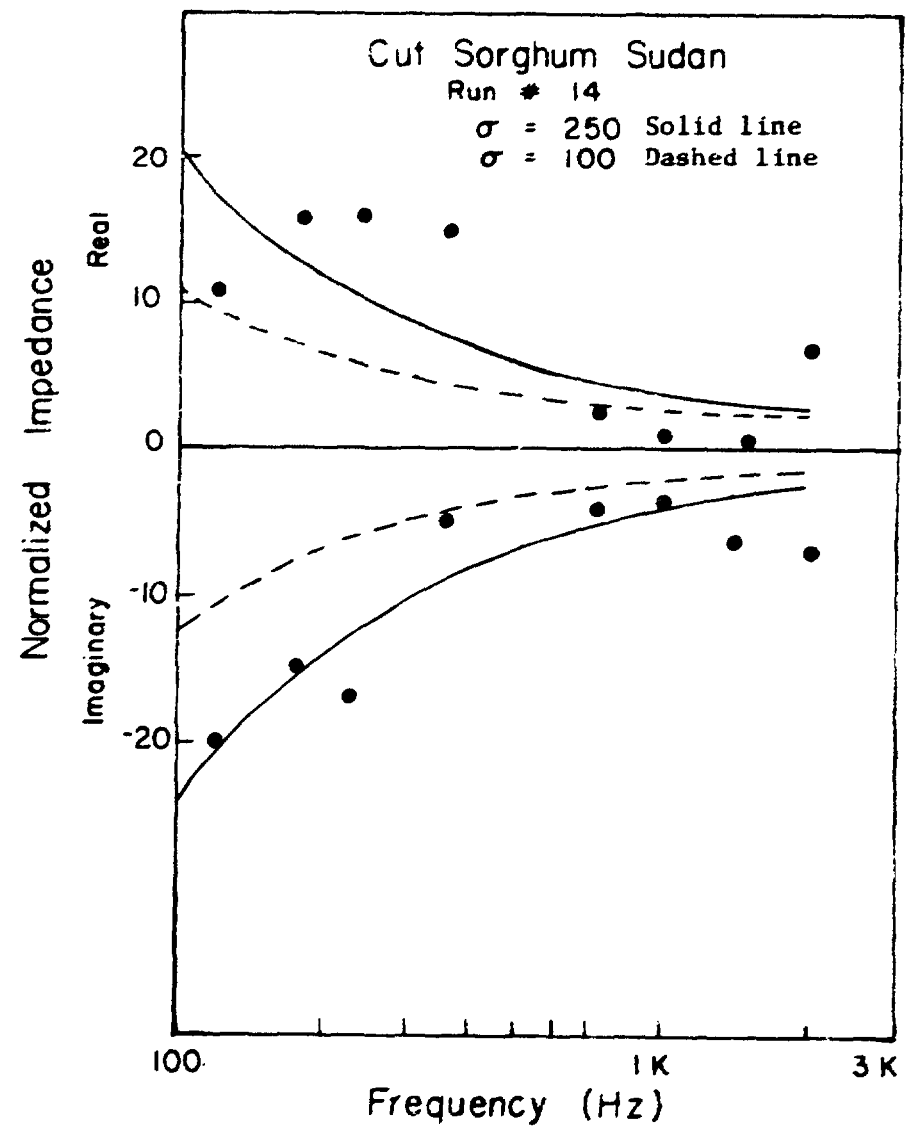

Figure 9 b

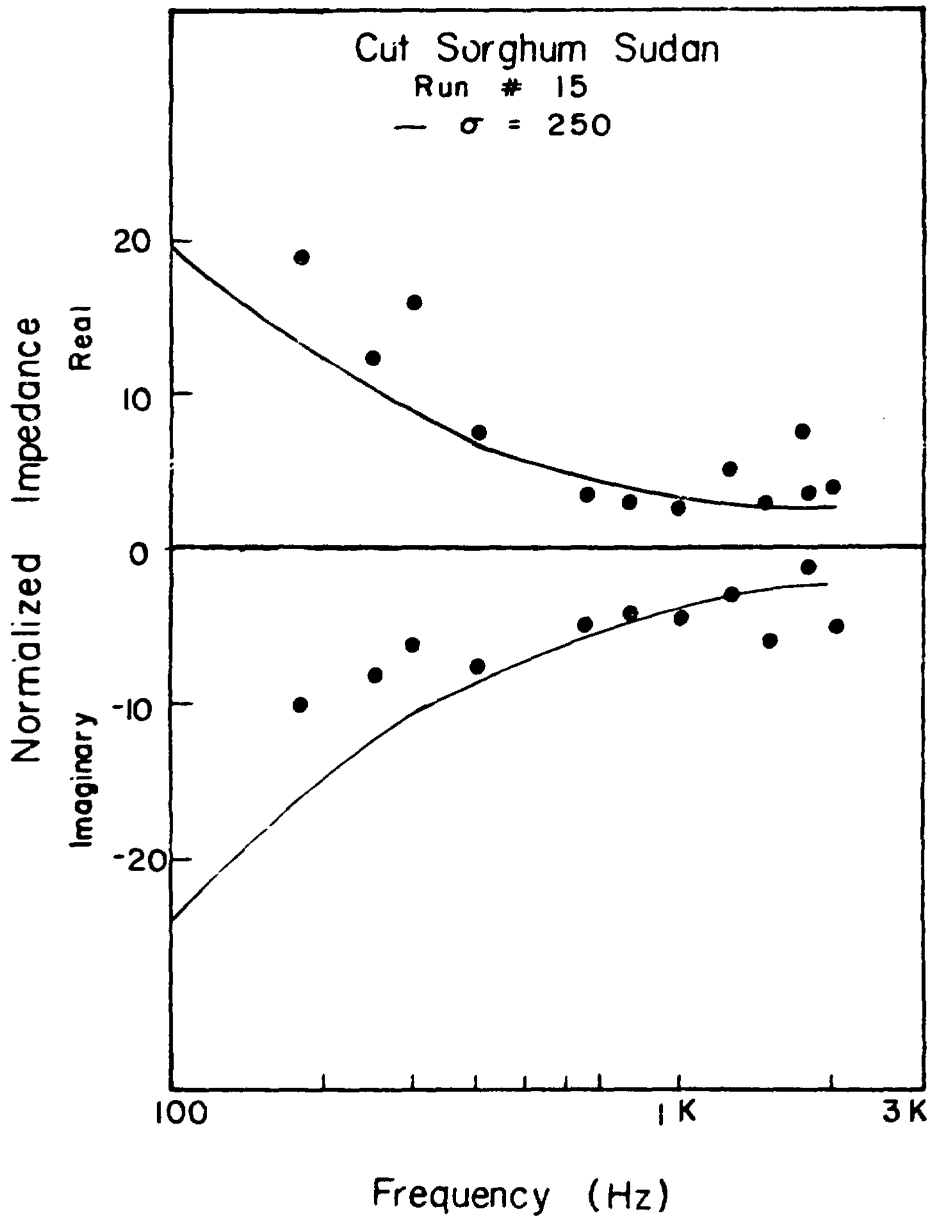

Figure 10 a

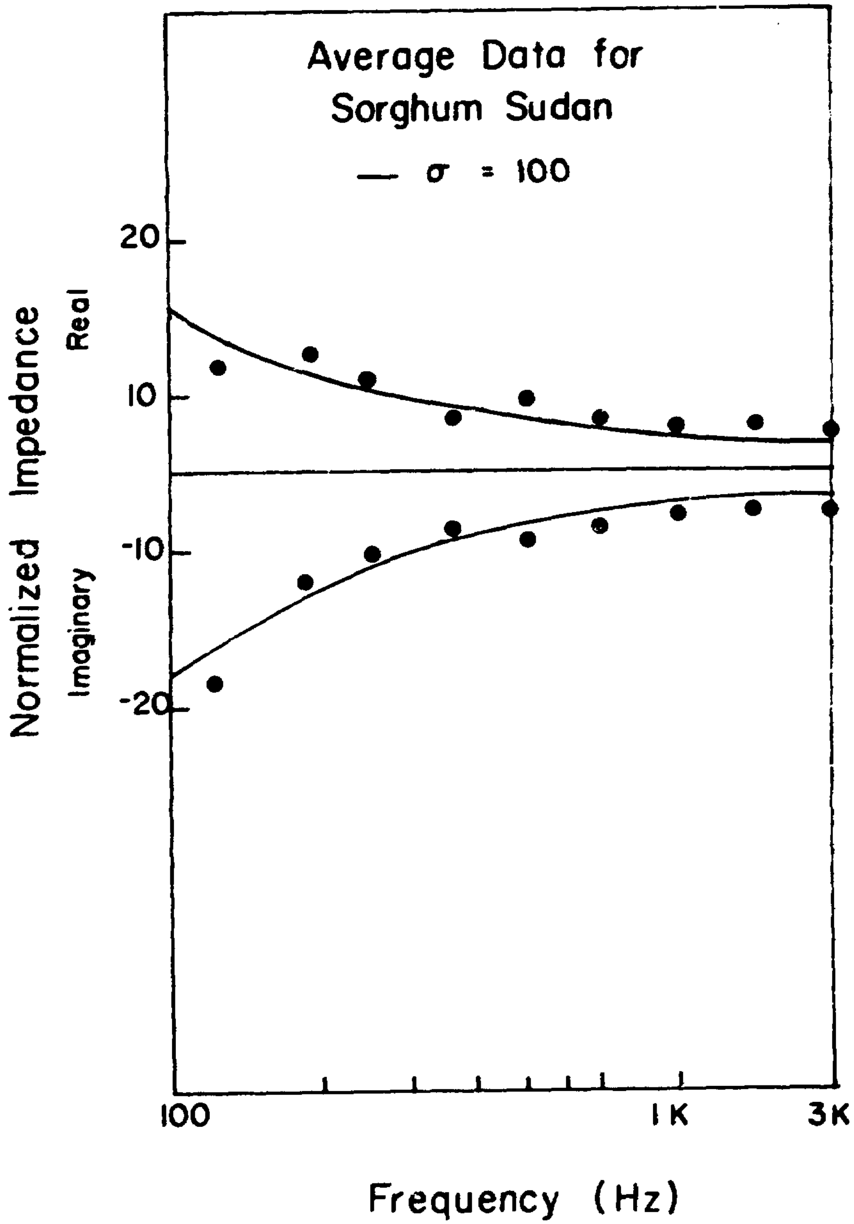

Figure 10 b

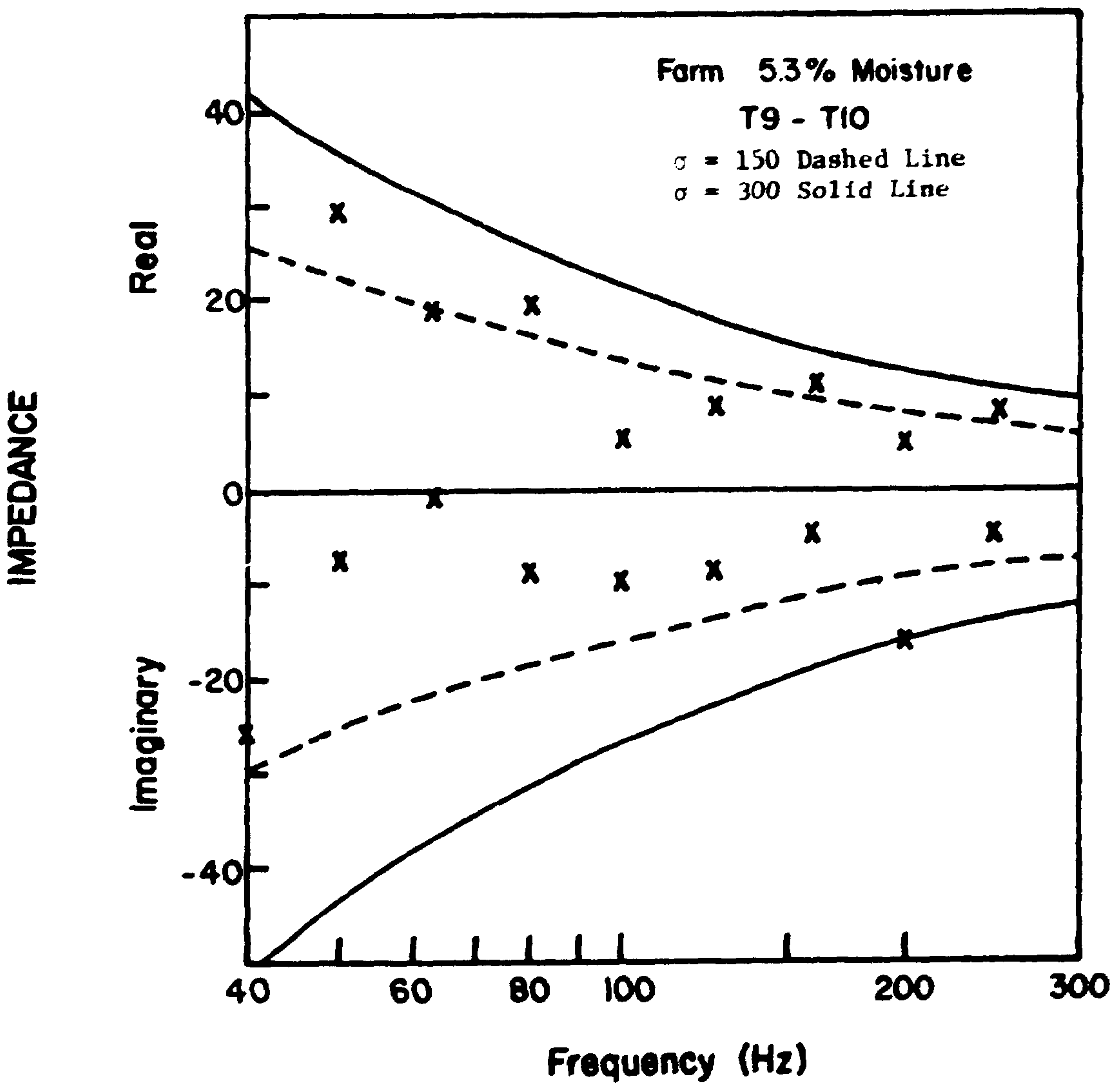
Farm 5.3% Moisture
T9 - T10
σ = 150 Dashed Line
σ = 300 Solid Line
IMPEDANCE
Real
Imaginary
40
20
0
-20
-40
40
60
80
100
200
300
Frequency (Hz)

Figure 11

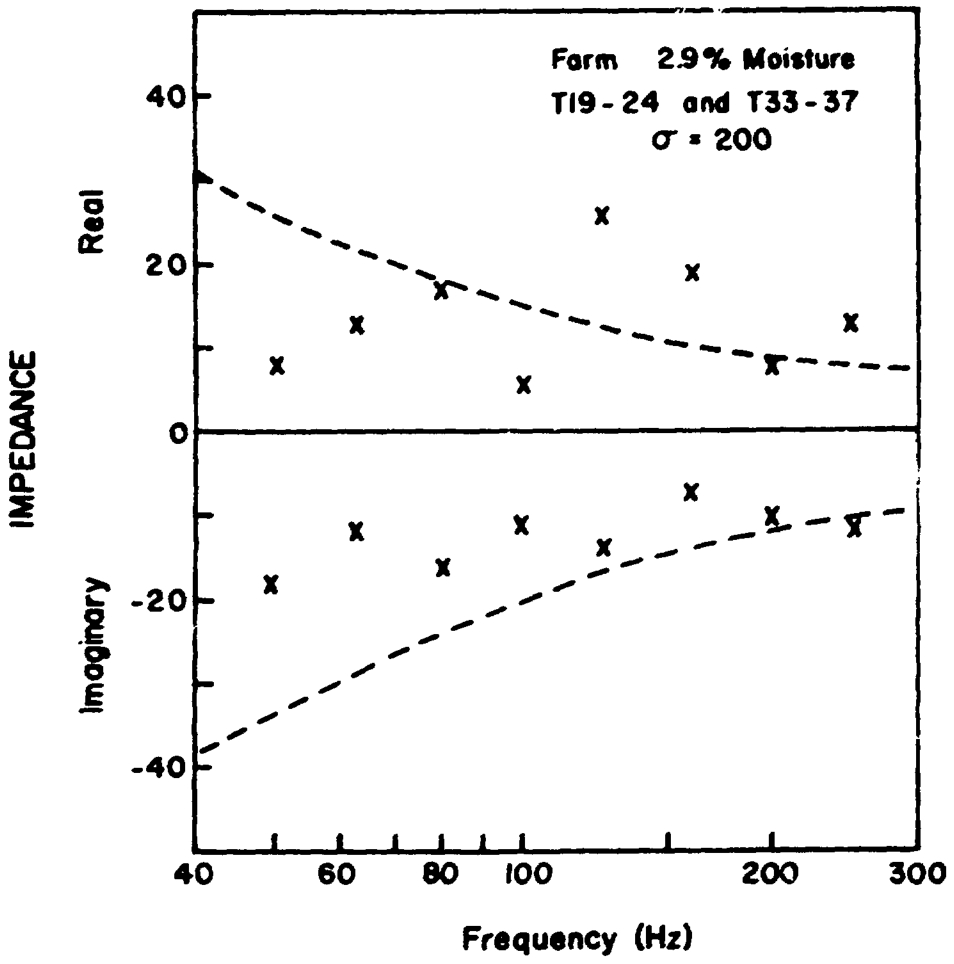

Figure 12 a

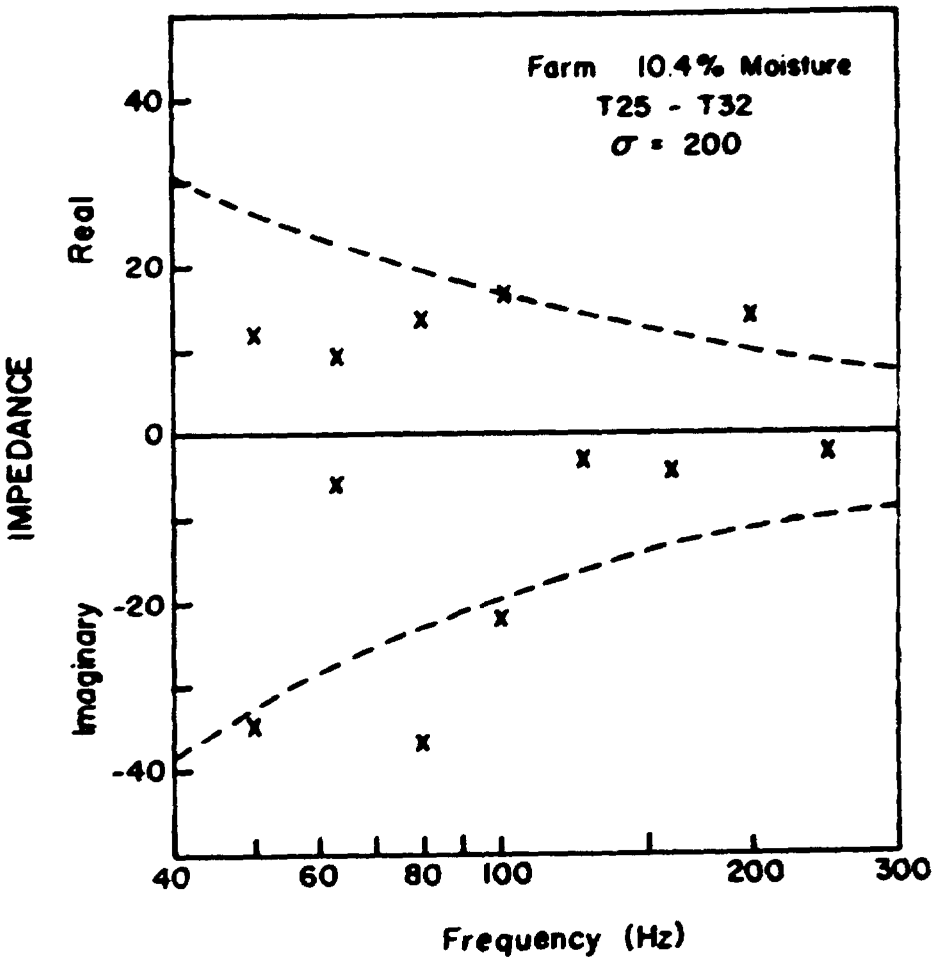

Figure 12 b

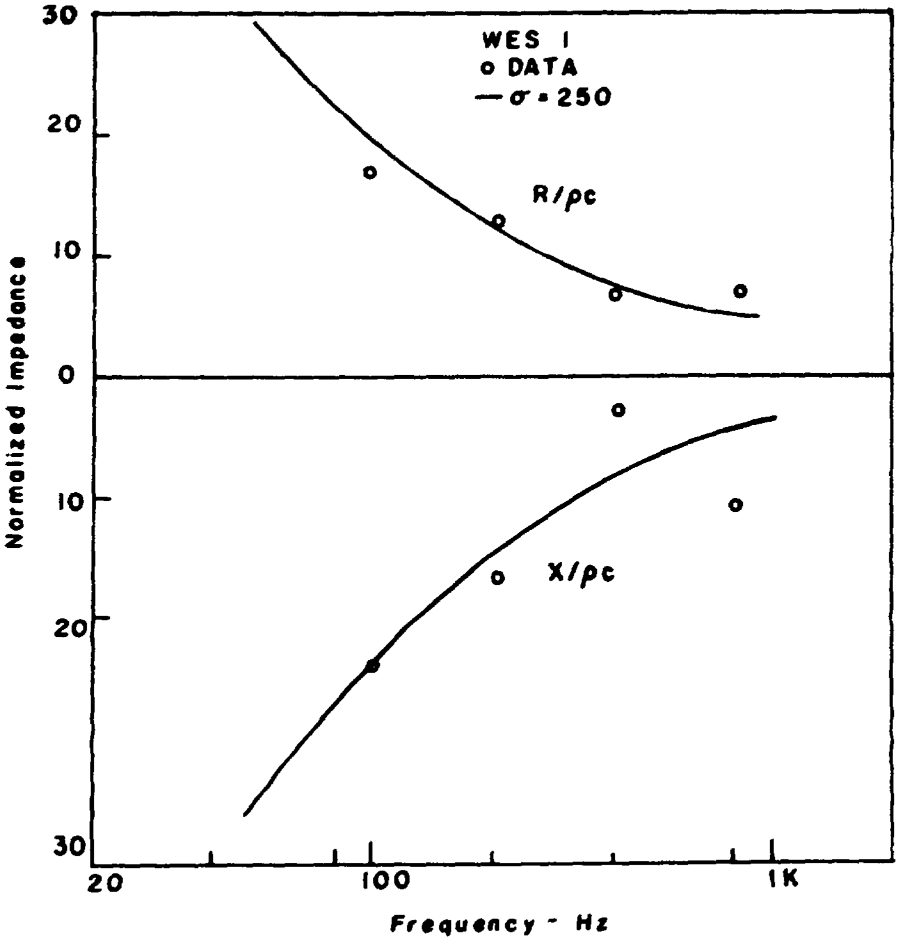

Figure 13 a

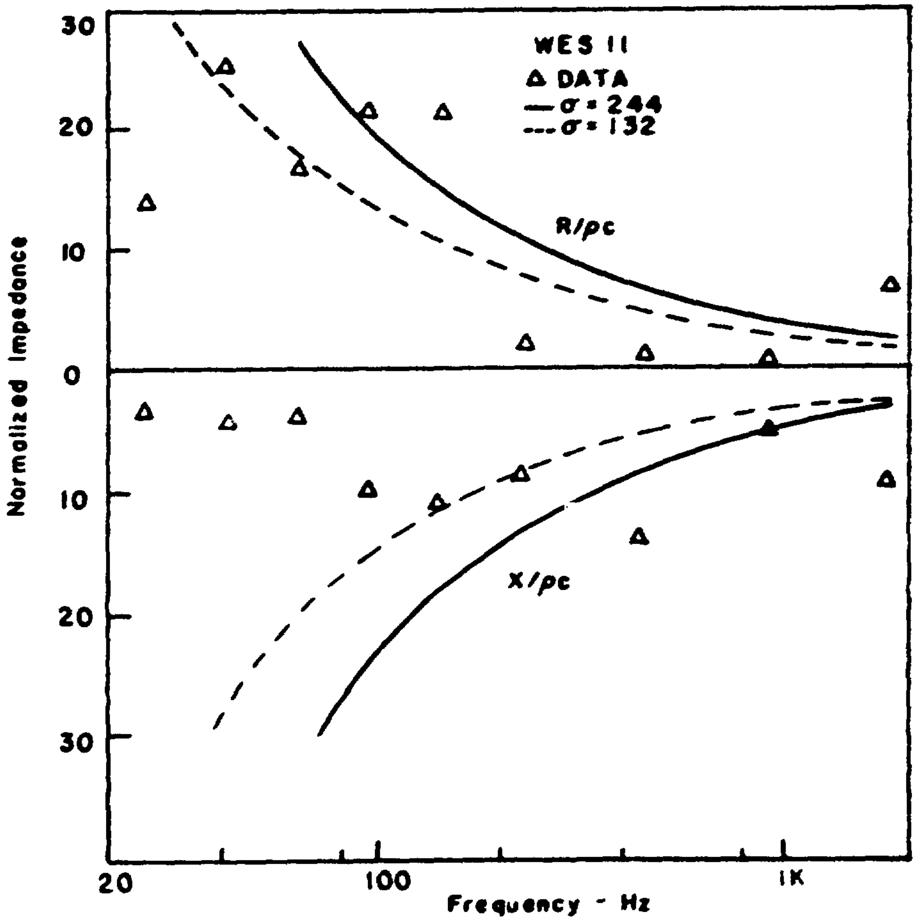

Figure 13 b

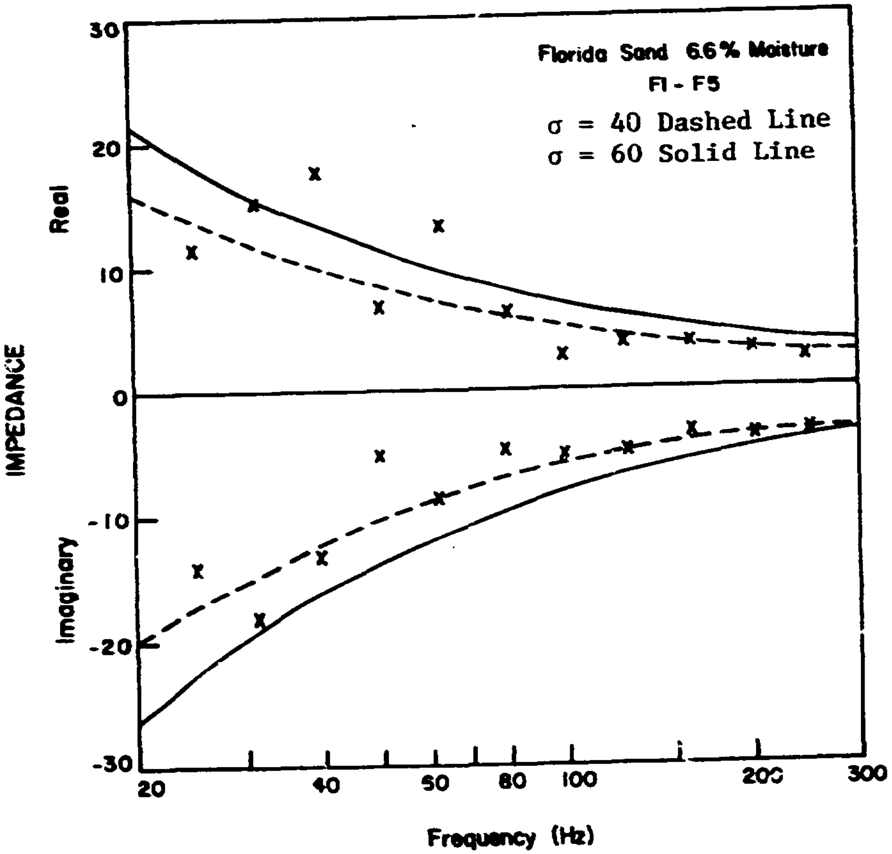

Figure 14 a

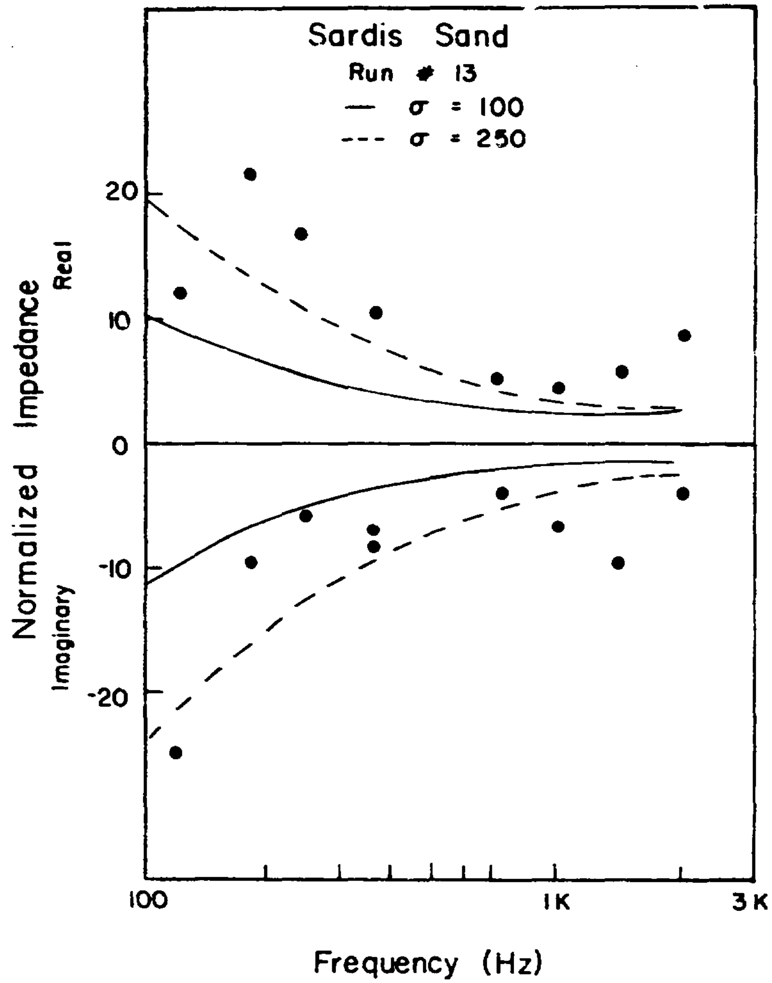

Figure 14 b

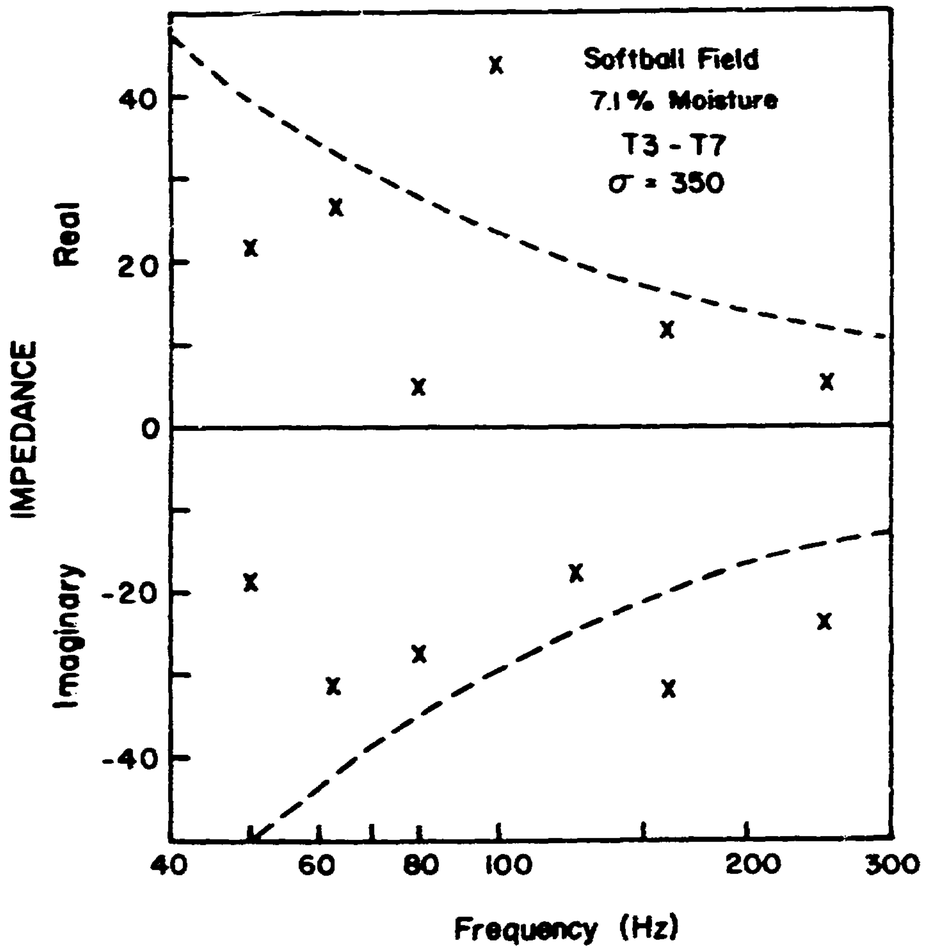

Figure 15 a

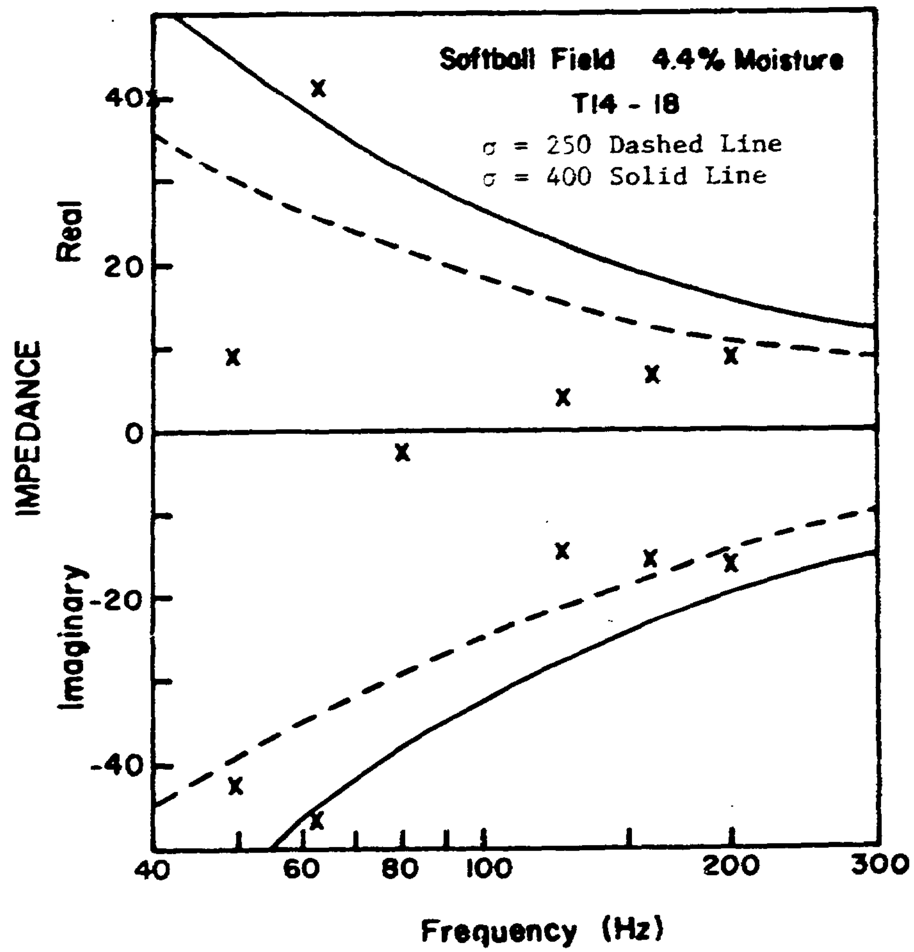

Figure 15 b

increasing frequency (See Table 11). Also, in most cases, the value of σ computed from low frequency Xr values is higher than computed from low frequency Xc values. These two observations tend to suggest that the empirical relations (Eq. (2) and (3)) do not reflect the proper frequency dependence for the results reported here and that the ratio of Xr to Xc reflected in these equations is not constant but depends on the nature of the surface. Even with these problems, however, the simplicity of this approach and the relatively good agreement with experiment makes the method worthy of consideration for field use. By measuring σ under a wide variety of conditions, tabulated values could be developed from which Z could be computed for most field conditions encountered.

Even though the empirical approach of Chessell works reasonably well for the conditions considered here, applications to other conditions would be much more reliable if the prediction procedure was based on basic physical principles. Donato[16] has made an attempt to provide such a physical approach by considering three examples; a continuous porous surface, a porous medium of fixed thickness with an infinite backing, and a porous medium with a porosity which decreases exponentially with depth. Application of these three models requires that the effective compressibility of the air in the pores, K_p, the porosity, Ω, the flow resistance of the air in the pores, Φ, and the effective density of the pore-filled air ρ_p be known. Each of these terms can, at least in principle, be computed from the physical properties of the surface or measured independently, however, the formalism for such calculations has not been developed. In addition, there is a fourth case of interest; that of a porous medium backed by a medium of finite impedance. So long as each of the quantities required to apply these

Table II

Calculated Values of Flow Resistance
for WES I Data

f	$R/\rho_0 c_0$	σ_R	$X/\rho_0 c_0$	σ_x		σ_{ave}
100	16	195	-24	261		228
200	12	258	-17	326		292
400	6	181	- 3	606		394
800	6	362	-11	718		520
					σ_{avg}	364

models must be deduced from measurements of surface impedance, this approach also becomes empirical, the only difference being that now there are more adjustable parameters available to fit the data hence, one would suppose, better agreement with theory can be achieved.

At this time, then, the single parameter empirical approach of Chessell appears to provide as good a way of representing the results as any available. Table III presents a summary of deduced flow resistances and values measured directly. Referring to Figures 11, 14a, and 15b, the solid line represents impedances computed from measured flow resistances. As can be seen, the curves calculated in this way agree, within experimental scatter, with measured impedances. This is very impressive considering:

1. The flow resistance measurements can be made in the field in a matter of minutes (provided the soil is not too hard to remove without damage).
2. The flow resistance calculation is based on a normally reacting surface model.

These two results could have a major impact on outdoor noise measurements.

Table III

Summary of Single Parameter Results
Following Chessell

Run #	σ Deduced from Z ($gm\text{-}cm^{-3}\text{-}sec^{-1}$)	σ Measured ($g\text{-}cm^{-3}\text{-}sec^{-1}$)	Grass height	% Water
WES I	300	-		
WES II	130	-		
2	100	-	none	
3	50	-	none	
4	100 50	-	0-2"	
5	50	-	0-2"	
6	150	-	10"	
7	75	-	20"	
8a-8b	80	-	22"	10.3 %
9	100	-	25"	8.6 %
10	-	-	1.1 m	11.0 %
11 and 12	200	-	.5"	-
15	350	-	0	22.0 %
T3-77	350	-	1"	7.1 %
T8	Results eratic	-	none	16.5 %
T9-T10	150	285	1"	5.3 %
T11-T13	Results eratic	-	0-2"	4.6 %
T14-T18	250	410	1"	4.4 %
T19-T29, T33-T37	200	-	2-3 feet	2.9 %
F1-F5	40	63	none	7.0 %
T25-T32	200	-	3-4"	10.4 %

5.0 Application Of Results

The results reported here can have a variety of applications. One would be the correction of measured aircraft spectra to free field conditions. This involves determining the acoustic spectrum an aircraft would have in the absence of the ground plane from measurements taken with microphones on the ground. A more interesting application is the correction of received sound for propagation effects (both air absorption and the ground plane) to identify the source (e.g. helicopter, tank, etc.) and location. Of these two applications, the first provides a more straight forward test of the prediction scheme discussed in this report.

For the purposes of this report, we were interested in considering a simple example which would provide a test of the predicted effect of the earth's surface on measured aircraft spectra. To keep matters simple, we chose to use a hovering helicopter (UH-1D) as the sound source. This enabled us to ignore Doppler effects and (to some extent) aircraft orientation. In principle these other effects can be included.

The test configuration consisted of the helicopter hovering 200 feet above a known point oriented such that the helicopter was facing down range. The microphones were spaced as described earlier but for this discussion, we are concerned only with the 200 foot and 1000 foot microphone locations. The aircraft was kept over the 0 range point by communication between the aircraft pilot and a ground based observer. The helicopter was piloted by a volunteer from our local Army ROTC unit.

The results are presented in Figures 16 and 17 . In Figure 16 the spectrum measured at 200 feet and the 1000 foot spectrum increased in amplitude by 14 dB are shown. The increase of 14 dB is that which would be expected from a spherically spreading source. At 140 Hz, the corrected 1000 foot spectrum and the measured 200 foot spectrum differ by 12.5 dB. At lower frequencies, the agreement is satisfactory. One could argue that the sound does not approximate spherical spreading at higher frequencies thus the 14 dB correction is not applicable. An examination of Figure 17 shows this not to be the case. In Figure 17 the 1000 foot spectrum is corrected by adding to each peak, the difference between the predicted propagation losses at 1000 foot and 200 foot computed for a surface with a flow resistence of 150 gm-cm^{-3}-sec^{-1}. Note that for this example, the greatest difference is 5 dB; the typical difference is 2 dB. The point with a 5 dB difference could be due to measurement error or an orientation effect (as the range increases, the part of the aircraft in direct line of sight changes). In any case, this is a significant improvement over the earlier spherical correction.

It should be noted that for this example, we did not measure impedance used in the calculation but estimated the value from the type surface (wet plowed earth). As a result, the largest errors are found near the interference minimum in the spectrum. This result suggests that with only a table of specific flow resistances, spectra corrected in the field will have deviations from true values on the order of 5 dB. The implications of this finding for target identification have not been considered, but there is little doubt in the authors' minds that a correction based on more accurate flow resistence measurements made in the field would improve agreement.

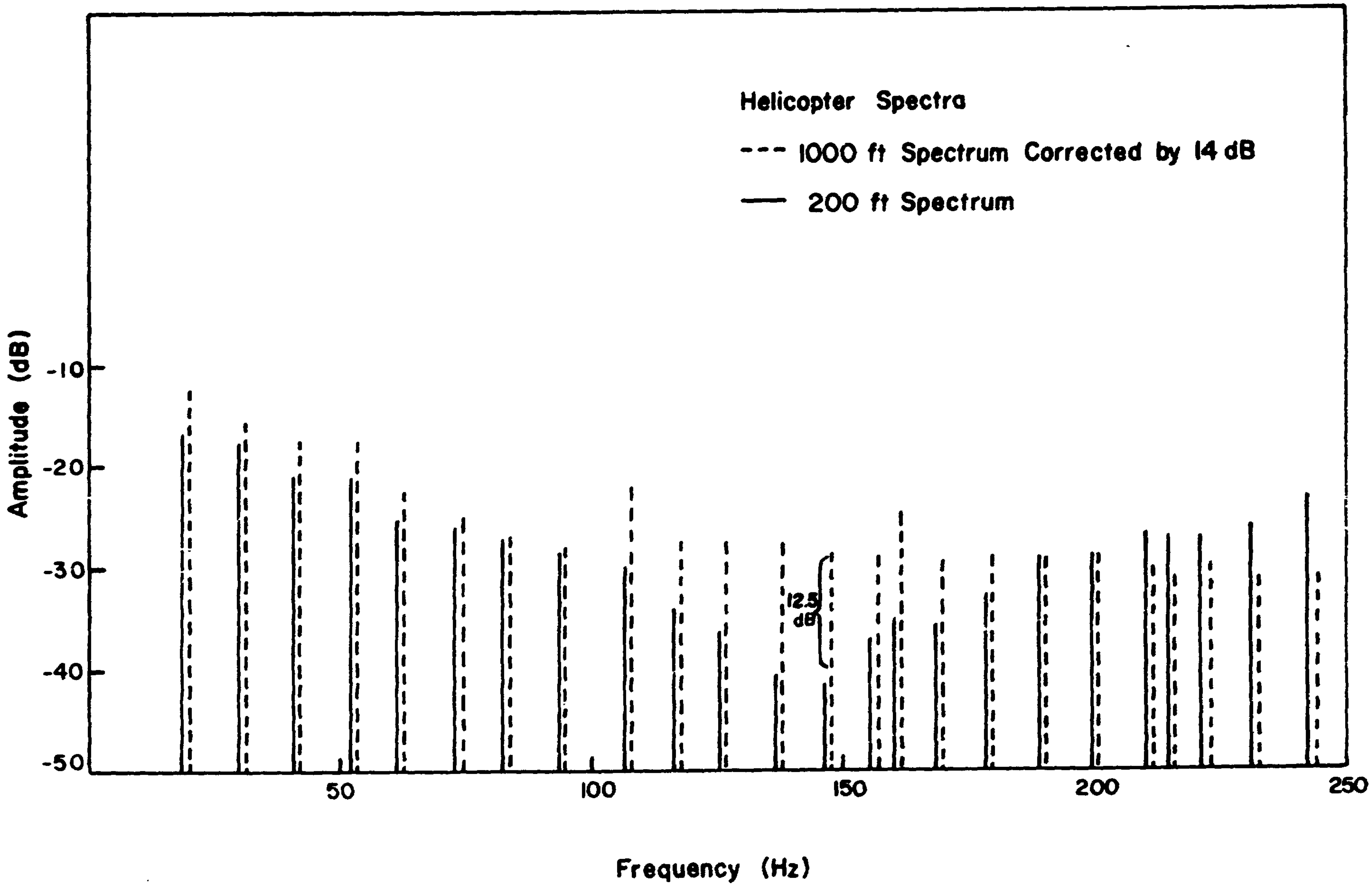
Helicopter Spectra
--- 1000 ft Spectrum Corrected by 14 dB
— 200 ft Spectrum
12.5 dB
Amplitude (dB)
-10
-20
-30
-40
-50
50
100
150
200
250
Frequency (Hz)

Figure 16

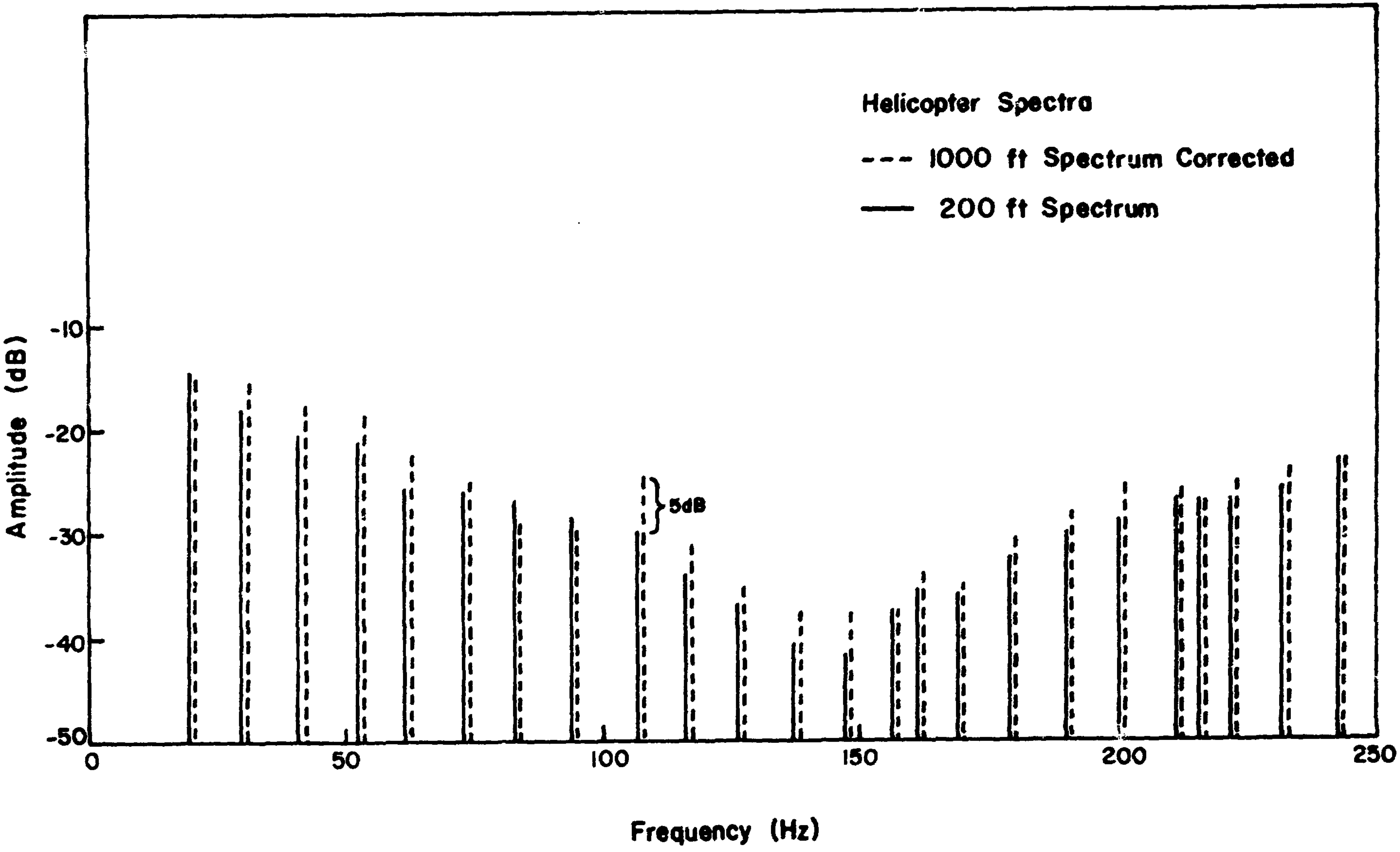
Helicopter Spectra
--- 1000 ft Spectrum Corrected
— 200 ft Spectrum
5dB
Amplitude (dB)
-10
-20
-30
-40
-50
0
50
100
150
200
250
Frequency (Hz)

Figure 17

6.0 SUMMARY AND CONCLUSIONS

Theoretical calculations of sound amplitude near a surface with a complex impedance using the formalism developed by Donato which assumes a locally reacting surface give excellent agreement with measurements provided the complex acoustic impedance is treated as an adjustable parameter at each frequency. The significant difference between this theory and plane wave reflection theory, the existence of a surface wave, was not involved in these measurements. For the measurements reported here, and earlier measurements by other investigators, the acoustic impedance as a function of frequency can be predicted within experimental uncertainty using the empirical approach of Chessell which uses specific flow resistance as the single adjustable parameter. This approach has now been tested at frequencies down to 40 Hz. Interpretation of the results in terms of the physical properties of the surface must await independent measurements of porosity, flow resistance, etc. or theoretical work which provide these quantities in terms of root structure and soil characteristics.

The specific flow resistances determined from impedance measurements to date are summarized in Table IV. The ability to measure acoustic impedance using a simple geometry as described here represents a significant improvement over previous techniques which were very time consuming. Further, since the specific flow resistance can apparently be determined by measuring impedance over a small range of frequencies, the impedance need only be measured over a range (200 Hz to 100 Hz) where measurements are simple and relatively free from problems of turbulence or the necessity of long ranges. By measuring flow resistance directly, the process of determining surface impedance can be simplified further but care must be exercised in collecting soil samples for such measurements.

The major findings of this study can be summarized as follows:

1. The formalism for determining the effects of an impedance boundary on sound propagation as advanced by Donato yields valid results down to frequencies as low as 40 Hz.
2. The local reaction assumption commonly made for porous material seems valid based on:
   a. Comparison of oblique incidence results to normal incidence results
   b. Comparison of flow resistance measured directly with those deduced from near grazing incidence sound amplitude using this assumption
3. Grass cover has little effect on the surface impedance other than to change the flow resistance due to root structure.
4. Field measurements of impedance can be vastly simplified by measuring amplitude as a function of geometry and frequency over a limited frequency range (for hard surfaces) or the flow resistance directly (for softer surfaces) and then applying the formalism of Chessell to deduce impedance as a function of frequency.
5. Experimental measurement of flow resistance using a flow resistance instrument of the Leonard design can be used with the theory of Chessell to determine the required acoustic properties of the ground surface using a simple nonacoustic mechanical technique.

Table IV

Specific Flow Resistances

Description of Surface	Flow Resistance (cgs Rayls)	Source
Dry Snow, New Fallen, 4"	10-30	Ref. 18
Sugar Snow	25-50	Ref. 18
Freshly Disced Sand	40	This work
In Forest, Pine or Hemlock	20-80	Ref. 18
Freshly Plowed Field	50-100	This work
Recently Plowed Field With Dense Stand of Grass	75-150 (moisture dependent)	This work
Bare Field (Plowed)	200-350 (moisture dependent)	This work
Institutional Grass	150-300	This Work, Ref. 18
Roadside Dirt, Ill-Defined, Small Rocks Up to 4"	300-800	Ref. 18
Sandy Silt, Hard Packed by Vehicles	800-2500	Ref. 18
"Clean" Limestone Chips, Thick Layer (1/2 to 1 inch)	1500-4000	Ref. 18
Old Dirt Roadway, Fine Stones	2000-4000	Ref. 18
Earth, Exposed and Rain-Packed	4000-8000	Ref. 18
Quarry Dirt, Fine, Very Hard Packed	5000-20,000	Ref. 18
Asphalt, Sealed by Dirt and Use	> 20,000	Ref. 18

7.0 BIBLIOGRAPHY

1. F. Douglas Shields and H. E. Bass, "Atmospheric Absorption of High Frequency Noise and Application to Fractional-Octave Bands", NASA CR-2760 (1977).

2. L. E. Evans, H. E. Bass, and L. C. Sutherland, "Atmospheric Absorption of Sound: Theoretical Predictions", J. Acoust. Soc. Am. 51, 1565-1575 (1972).

3. J. E. Piercy, "Role of the Vibrational Relaxation of Nitrogen in the Absorption of Sound in Air", J. Acoust. Soc. Am. 46, 602-604 (1969).

4. L. C. Sutherland, J. E. Piercy, H. E. Bass, and L. B. Evans, "Method for Calculating the Absorption of Sound by the Atmosphere", J. Acoust. Soc. Am. 56, S1(A) (1974).

5. "Proposed American National Standards Method for the Calculation of the Absorption of Sound by the Atmosphere", Standard S1.26/ASA 23-1978.

6. S. P. Pao and L. B. Evans, "Sound Attenuation Over Simulated Ground Cover", J. Acoust. Soc. Am. 49, 1069-1075 (1971).

7. H. E. Bass and L. N. Bolen, "Propagation of Sound Through the Atmosphere: Effects of Ground Cover", University of Mississippi Technical Report PARGUM 78-01, NTIS AD #A-058948 (1978).

8. J. E. Piercy, T. F. W. Embleton, and L. C. Sutherland, "A Review of Noise Propagation in the Atmosphere", J. Acoust. Soc. Am. 61, 1403-1418 (1977).

9. T. W. F. Embleton, J. E. Piercy, and N. Olson, "Outdoor Propagation over Ground of Finite Impedance", J. Acoust. Soc. Am. 59, 267-277 (1976).

10. J. E. Piercy and T. F. W. Embleton, "Effect of Ground on Near-Horizontal Sound Propagation", Trans. Soc. Auto Eng., Sect. I, 83, 928-932 (1974).

11. R. J. Donato, "Propagation of a Spherical Wave Near a Plane Boundary with Complex Impedance", J. Acoust. Soc. Am. 60, 34-39 (1976).

12. R. W. Leonard, "Simplified Flow Resistance Measurements", J. Acoust. Soc. Am., 17, 240-241 (1946).

13. C. I. Chessel, "Propagation of Noise Along a Finite Impedance Boundary", J. Acoust. Soc. Am. 62, 825 (1977).

14. M. E. Delaney and E. N. Bazley, "Acoustical Properties of Fibrous Absorbent Materials", Applied Acoustics 3, 105-116 (1970).

15. R. J. Donato, "Impedance Models for Grass-Covered Ground", J. Acoust. Soc. Am. 61, 1449-1452 (1977).

16. P. M. Morse and K. U. Ingard, Theoretical Acoustics (McGraw-Hill, New York, 1968), p. 252.

17. P. J. Dickinson and P. E. Doak, "Measurements of the Normal Acoustic Impedance of Ground Surfaces", J. Sound Vib. 13, 309-322 (1970).

18. J. E. Piercy and T. F. W. Embleton, "Excess Attenuation or Impedance of Common Ground Surfaces Characterized by Flow Resistance", J. Acoust. Soc. Am. 65, 563 (1979).