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AMERICAN NATIONAL STANDARD

**Method for Determining the Acoustic Impedance of
Ground Surfaces**

Secretariat:

Acoustical Society of America

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American National Standards Institute, Inc.

Abstract

This Standard describes procedures for obtaining the real and imaginary parts of normalized acoustic impedance ratio of ground surfaces from *in-situ* measurements of the sound pressure levels at two vertically separated microphones using specified geometries and the averaged values of the difference between the simultaneous instantaneous sound-pressure signals at the two microphones. It extends and revises the template method given in the 1999 edition to enable the user to obtain values of the normalized specific acoustic impedance ratio of the ground entirely from measurements and independently of any model for the acoustic impedance of the ground surface except as a check on the validity of the resulting values.

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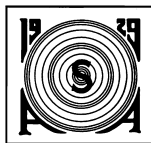
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Foreword

[This Foreword is for information only and is not a part of the American National Standard ANSI/ASA S1.18-2010 American National Standard Method for Determining the Acoustic Impedance of Ground Surfaces.]

This Standard comprises a part of a group of definitions, standards, and specifications for use in acoustics. It was developed and approved by Accredited Standards Committee S1, Acoustics, under its approved operating procedures. Those procedures have been accredited by the American National Standards Institute (ANSI). The Scope of Accredited Standards Committee S1 is as follows:

Standards, specifications, methods of measurement and test, and terminology in the field of physical acoustics, including architectural acoustics, electroacoustics, sonics and ultrasonics, and underwater sound, but excluding those aspects which pertain to biological safety, tolerances, and comfort.

This Standard is a revision of ANSI S1.18-1999, which has been technically revised. The template method is augmented by a procedure to utilize measurements of the magnitude and relative phase of the averaged ratio of the difference between instantaneous sound-pressure signals at two specific locations relative to the location of a sound source and thereby deduce the real and imaginary parts of the complex normalized specific acoustic impedance ratio.

This Standard is not comparable to any existing ISO Standard.

This Standard includes 5 Annexes, all of which are informative and are not considered part of this Standard.

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Introduction

Experimental techniques to measure impedance include the use of an impedance tube, techniques that measure the sound pressure levels above a surface, and direct measurements of sound pressure and volume velocity.

This Standard does not consider the direct measurement of sound pressure and volume velocity.

The impedance tube is in common use to measure the acoustic impedance of porous materials. It has the advantage of a straightforward theoretical framework that allows direct determination of both the real and imaginary parts of the impedance. However, its application in the field to obtain ground impedance suffers from two major disadvantages. First, it requires an accurate measurement of the distance from the first interference minimum to an ill-defined test surface, and, secondly, it is invasive. This Standard does not recommend the use of an impedance tube for the measurement of the acoustic impedance of a ground surface.

Techniques that use measurements of sound pressure levels above a surface include several variations based on the type of excitation, angle of incidence, number of microphones, and fitting methods. All enjoy the advantage that the measurement is performed on the ground in its natural condition. However, because of the spherical wavefront, the theoretical framework is mathematically intricate. Annexes C and D detail the expressions and special functions used in the calculations in Clause 4.

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American National Standard

Method for Determining the Acoustic Impedance of Ground Surfaces

1 Scope

Outdoor sound close to the ground is influenced by the acoustical properties of the ground. This Standard describes recommended procedures to characterize, and the instruments to measure quantities that may be used to deduce, the acoustical properties of ground surfaces. Although this Standard is intended primarily for outdoor measurements, indoor measurement of undisturbed portions of a ground surface, such as sod, is within its scope also.

The Standard yields the real and imaginary parts of the normalized specific acoustic impedance ratio of ground surfaces in the frequency range between 250 and 4000 Hz for outdoor sound propagation predictions. The Standard uses measurements of the interference between direct and ground-reflected sound to deduce both normalized specific acoustic impedance ratio and impedance model parameters. The impedance-ratio model parameters of effective flow resistivity and a porosity factor, determined from best fits to the templates of calculated level differences, may be used to estimate the normalized specific acoustic impedance ratio at frequencies outside the specified range.

The basic purpose of this Standard is to establish uniform procedures for obtaining the real and imaginary parts of the normalized specific acoustic impedance ratio of ground surfaces outdoors.

The method is applicable to all nominally flat, commonly occurring surfaces including grassland or snow-covered ground.

The method is not applicable to rough grounds where the variation in height is greater than half of the shortest wavelength of interest. For the specified upper frequency of 4 kHz this limits the variation in height to about 5 cm. See also Clause 4.4.

2 Normative references

The following referenced documents are indispensable for the application of this Standard. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ANSI S1.1, American National Standard Acoustical Terminology

ANSI/ASA S1.11, American National Standard Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters

ANSI S1.40, American National Standard Specifications and Verification Procedures for Sound Calibrators

IEC 61672-1, Electroacoustics — Sound level meters — Part 1: Specifications

3 Terms and definitions

For the purposes of this Standard, the terms and definitions given in ANSI S1.1 and the following apply:

3.1

specific acoustic impedance, Z_s

at a point in a sound field, quotient of sound pressure by particle velocity

NOTE 1 Unit, pascal per (meter per second) [Pa/(m/s)].

NOTE 2 The real part of the specific acoustic impedance is specific acoustic resistance; the imaginary part is specific acoustic reactance.

3.2

specific acoustic admittance, β

reciprocal of the specific acoustic impedance

NOTE 1 Unit, (meter per second) per pascal [(m/s)/Pa].

NOTE 2 The real part of specific acoustic admittance is specific acoustic conductance; the imaginary part is specific acoustic susceptance.

3.3

normalized specific acoustic impedance ratio

ratio of specific acoustic impedance of a ground surface to the characteristic impedance of air at specified atmospheric conditions

3.4

complex sound pressure ratio

ratio of magnitudes and relative phase of the pressures measured by two spatially separated microphones subjected to sound emitted by the same point source

NOTE This definition is specific to this Standard and is not within the scope of ANSI S1.1-1999 (R 2004).

4 Measurement method

4.1 Recommended geometries

The measurement of level difference spectra shall be conducted using **both of** the following two geometries (see Figure 1):

Geometry A

Source height (h_s) = 0.325 m

Upper microphone height (h_t) = 0.46 m

Lower microphone height (h_b) = 0.23 m

Horizontal separation (d) = 1.75 m

Geometry B

Source height (h_s) = 0.20 m

Upper microphone height (h_t) = 0.20 m

Lower microphone height (h_b) = 0.05 m

Horizontal separation (d) = 1.0 m

Note that these geometries will not yield satisfactory results if the ground impedance is high. But, in this case, accurate values for ground impedance should not be necessary and it is recommended that Steps 2 to 4 be omitted from the procedure detailed in 4.5.1.

Geometry A covers the broadest range of frequencies. Geometry B emphasizes ground effect at frequencies above 1000 Hz and may be better suited for hard grounds.

As long as the horizontal separation of the source and the receiver is not greater than 3.0 m or not less than 1.0 m and the angles of incidence are broadly the same as those for geometries A and B, the user has discretion in the choice of the geometry. However, it is essential that the source and receiver positions be measured as accurately as possible (i.e., to within ± 0.01 m), and the test report shall include information on the geometry used for measurements. If Figures 3a through 4d are used, then the geometry must correspond to those specified above to within ± 0.01 m.

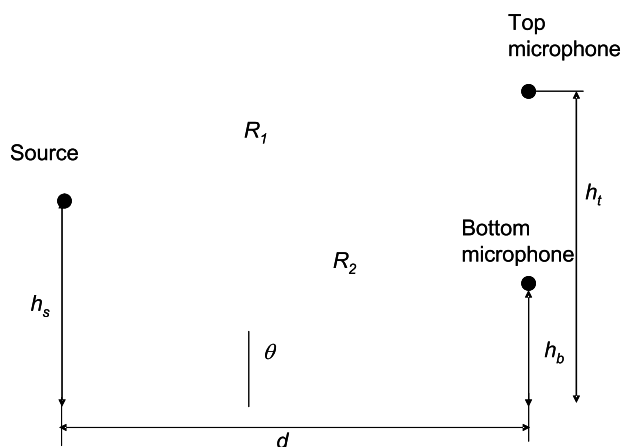


Figure 1 – Geometrical definitions: h_s = source height, h_t = top microphone height, h_b = bottom microphone height, d = source/receiver horizontal separation

4.2 Time convention

A harmonic time dependence of $e^{-i\omega t}$ is assumed throughout this Standard. However, certain spectrum analyzers assume an alternative harmonic time convention of $e^{+i\omega t}$. The user shall ascertain the time dependence used by the analysis equipment. If the alternative dependence is used, the complex sound pressure ratio, $T(f)$, as measured and recorded by such equipment, shall be converted to its conjugate before carrying out the procedure set out in this clause.

4.3 Measurement procedure

The test signal shall have frequency content between 250 Hz and 4 kHz. Signals may be continuous broad band, continuous discrete tones, stepped tones, tone bursts or impulses.

The minimum recommended frequency resolution is a 1/3 octave band such as might be achieved by use of sound level meters with a band-pass filter.

The use of a spectrum analyzer should lead to a higher frequency resolution (see 5.4).

The sound source shall generate a sound pressure level that is at least 10 dB higher than the ambient sound pressure level in each 1/3 octave band in the frequency range of interest from 250 Hz to 4 kHz. The sound source shall have a smooth free-field frequency response with no significant maxima or minima over the principal frequency range of interest.

It is to be expected that the acoustic impedance of the ground surface will vary with location. Consequently, a sufficient number of measurements shall be taken to establish the variability with position. The source and the receiver shall be translated or rotated, or by both techniques, moved to an adjacent piece of nominally identical ground. A minimum of four independent measurements shall be made for every geometry and location.

The total signal complex sound pressure ratio, $T(f)$ [see Equation (C.1) in Annex C], is obtained by the same procedure for each test location and each geometry.

Ideally, microphones should be selected that have nominally identical pressure sensitivity, nominally identical frequency response, and nominally identical phase response. These characteristics will require extensive calibrations. Despite calibration of the microphones, there will be some relative phase response. It is essential to take account of this for the complex sound pressure ratio method (see 4.5.1, Step 2) by averaging the complex pressure ratios obtained before and after reversing the positions of the upper and lower microphones. This procedure is advisable also when the template method (see 4.5.1, Step 1) only is used.

4.4 Ground and environmental conditions

No acoustical data shall be measured when the average wind velocity exceeds 5 m/s when measured at a height of 2.0 m above the ground. A wind speed of 5 m/s or less is desirable for level difference measurements using two microphones simultaneously. Although use of a single microphone for successive measurements at the two positions is not recommended, it might give reasonable results by the template method (see 4.5.1, Step 1) as long as a more restrictive wind speed limit of 2.5 m/s is observed.

No measurement shall be made during any form of precipitation.

The ground shall be in the condition desired for the measurements. It can be dry, wet, snow covered, frozen, or in any other condition provided that there is an accurate description of it in the test report. If the ground of interest is frequently wet and ground impedance values are needed for this common condition, soil moisture content shall be determined from a moisture-sealed soil sample taken in a representative ground location immediately after the ground impedance measurements. The moisture content may be determined by measuring the percent change in weight of the soil sample, relative to the dry weight, before and after drying it completely in a suitable drying oven. This moisture content shall be included in the test report.

A ground profile that is convex or concave over the test site is not covered by this Standard. Over the distance d (see Figure 1), the test site shall be flat within ± 0.05 m and there should not be any reflecting objects within ten times the separation distance between source and receiver.

Rough ground surfaces with a variation in height of less than 0.05 m may be treated as flat ground for the purpose of this Standard. In the case of sloping ground, the source and microphone heights shall be measured perpendicular to the surface.

NOTE 1 For the purposes of this Standard, reference meteorological conditions are:

Static air pressure	101.325 kPa
Air temperature	288.15 K (15 °C)
Relative humidity	50 %

For these values $\rho_0 c_0 = 416.45 \text{ Pa/(m/s)}$.

The uncertainty in the specific acoustic (characteristic) impedance, ρc of air introduced by differences between the conditions prevailing at the time of measurement and the reference meteorological conditions is not important in comparison to the other uncertainties in determining the normalized specific ground impedance ratio.

NOTE 2 The specific acoustic (characteristic) impedance, ρc of air for any normal range of temperatures, T in Kelvin and Relative Humidity, RH, in %, and at a sea level atmospheric pressure of 1.01325 kPa, can be defined, to an accuracy of better than $\pm 0.2\%$, by: $\rho c = 428.0 / [(T/273.15)^{1/2} (1 + 1.95 \times 10^{-5} \times \text{RH}(\%))]$ Pa/(m/s).

4.5 Determination of the normalized specific acoustic impedance ratio

4.5.1 Steps for obtaining real and imaginary parts of normalized specific acoustic impedance ratio

The real and imaginary parts of the normalized specific acoustic impedance ratio ($Z_s / \rho_0 c_0$) of the ground, henceforth abbreviated to normalized surface impedance, shall be obtained by best fit between measured and calculated level differences using the following four steps:

Step 1 - Template method

The magnitude of the measured level difference spectrum, $LD(f)$ [see Equation (C.3)], shall be compared with that predicted using either (or both) of the two models specified in 4.5.2 and 4.5.3. This Standard provides a set of predicted level difference magnitudes and tables for each of the recommended geometries and for each normalized surface impedance model for use as templates to yield best-fit values of model parameters. Equations (C.1) through (C.9) in Annex C enable the user to calculate level difference spectra for other normalized surface impedance models.

The measured level difference spectrum shall be the average of those measured before and after switching the microphone locations. The difference given by Equation (8) between the measured and calculated $LD(f)$, based on the templates (Figures 3 through 5) or use of Tables 1 through 6 in Clause 9, shall be determined and the parameters for which this difference is minimum shall be found using the procedure set out in 4.6. The impedance spectrum corresponding to the best-fit parameters shall be determined using the appropriate formulae in 4.5.2 and 4.5.3.

Step 2 - Complex sound pressure ratio method

The measured complex sound pressure ratio, $T(f)$ [Equation (C.1)], shall be the arithmetic average of the magnitudes (in dB) and the phases of averaged complex pressure ratios obtained before and after reversing the microphone positions.

The real and imaginary parts of the surface impedance shall be determined at each measured frequency that give the minimum difference between measured and computed complex sound pressure ratio for each of the geometries A and B. An efficient procedure for finding best-fit values is given in Clause 4.7. The procedure shall be repeated for each measurement.

Step 3 - Smoothing (optional)

If a narrow-band spectrum is recorded, the resulting complex normalized surface impedance from Step 2 may be smoothed by a 5-point moving average method. If one-third octaves are used, the resulting impedance spectrum might be sufficiently smooth.

Step 4 - Comparisons

The real and imaginary parts of the normalized surface impedance deduced from each of the geometries shall be plotted on the same axes and validated by comparison with the model-predicted impedance spectrum resulting from Step 1.

4.5.2 One-parameter model

According to this model, and assuming a harmonic time dependence of $e^{-i\omega t}$, the real and imaginary parts of the normalized specific acoustic impedance ratio are respectively given by:

$$\text{Re}(Z_s / \rho_0 c_0) = 1 + 9.08 (1000 f / \sigma_{\text{eff}})^{0.75} \quad (1)$$

$$\text{Im}(Z_s / \rho_0 c_0) = 11.9 (1000 f / \sigma_{\text{eff}})^{0.73} \quad (2)$$

where f is the frequency and σ_{eff} (in kPa s/m^2) is a parameter representing an effective flow resistivity of the ground. Naturally occurring ground surfaces may be expected to have effective flow resistivities in the range 10000 to $30 \times 10^3 \text{ kPa s/m}^2$. Typical effective flow resistivity values inferred from measured data are tabulated in Annex B for a variety of different ground types.

Templates 1A and 1B show level difference curves calculated for geometries A and B using this one-parameter model with the specified values of effective flow resistivity. The level differences calculated at each one-third octave band center frequency between 250 and 4000 Hz for the specified values of effective flow resistivity are tabulated in the corresponding tables for geometries A and B, respectively. The real and imaginary parts of the normalized acoustic surface impedance ratio are calculated from Equations (1) and (2), respectively, for the value of σ_{eff} that yields the best fit to the measured data.

4.5.3 Two-parameter model

This model is appropriate where ground properties vary with depth. The real and imaginary parts of the normalized specific acoustic impedance ratio are respectively given by:

$$\operatorname{Re}(Z_s / \rho_0 c_0) = \frac{1}{\sqrt{\pi \gamma \rho_0}} \sqrt{\frac{\sigma_e}{f}} \quad (3)$$

$$\operatorname{Im}(Z_s / \rho_0 c_0) = \frac{1}{\sqrt{\pi \gamma \rho_0}} \sqrt{\frac{\sigma_e}{f}} + \frac{c_0 \alpha_e}{4 \pi f} \quad (4)$$

where γ is the ratio of specific heats in air and σ_e (in kPa s/m²) is a parameter representing an effective flow resistivity of the ground (**note that σ_e , while also an effective flow resistivity, is not the same as σ_{eff} , in the one-parameter model**). The additional parameter, α_e (/m), represents an effective rate of change of porosity with depth. Naturally occurring ground surfaces may be expected to have effective flow resistivities, σ_e , in the range 5000 to 30×10^3 kPa s/m². The lower end of this range would be typical of thick, newly fallen snow. The upper end would correspond to compacted fine grain soil. In terms of the two-parameter model the parameter α_e may be expected to vary between 3 and 250 m⁻¹. Typical parameter values inferred from measured data are tabulated in Annex B for a variety of different ground types.

Templates 2A and 2B show level difference curves calculated for geometries A and B using this two-parameter model with specified values of the parameter pair σ_e and α_e , respectively. The level differences calculated at each one-third octave band center frequency between 250 and 4000 Hz using the specified values of the parameter pair are tabulated in the corresponding tables for geometries A and B. The real and imaginary parts of the normalized acoustic surface impedance ratio shall be calculated from Equations (3) and (4), respectively, for the value of the parameter pair σ_e and α_e that yields the best fit to the measured data.

4.5.4 User-defined model

It may not be possible to obtain a good fit between measured and calculated level differences for some grounds when using the templates provided with this Standard. In such cases, either results obtained using the impedance fitting approach (Step 2 of the procedure) may be usable, or the ground type falls outside the scope of the Standard. If the user wishes to calculate custom templates from any impedance model appropriate for naturally occurring grounds information about the required calculations is given in Annexes C and D.

4.6 Procedure to determine best fit in Step 1

For each measurement and each frequency (or frequency band) record the complex sound pressure ratio, T , between the top and bottom microphone.

For each frequency, f , calculate the level difference averaged over n measurements using:

$$LD_{av}(f) = 10 \lg \left(\frac{1}{n} \sum_{j=1}^n |T_j(f)| \right) \quad (5)$$

When the range of values of magnitude of T at each frequency is not greater than 5 dB, a simple arithmetic mean of the level differences may be used for LD_{av} . For such cases:

$$LD_{av}(f) = \frac{1}{n} \sum_{j=1}^n LD_j(f) \quad (6)$$

where LD_j are the individual (measured) level difference measurements at a given frequency.

Then calculate the standard deviation, $\phi(f)$, in decibels, at each frequency using:

$$\phi(f) = \left[\frac{1}{n-1} \sum_{j=1}^n (LD_j(f) - LD_{av}(f))^2 \right]^{1/2} \quad (7)$$

The set of calculated level differences $LD_c(f)$ that produce the best fit to the measured values are those that minimize the value of E given by Equation (8):

$$E = \sum_f \left(\frac{LD_c(f) - LD_{av}(f)}{\phi(f)} \right)^2 \quad (8)$$

where $\sum_f$ indicates a sum over all frequencies. The number of times Equation (8) needs to be calculated can be reduced by first plotting the measured level differences on the corresponding templates and visually eliminating the curves that *obviously* do not correspond to a good fit.

The formulae needed to calculate LD_c are given in Annex C. In the case of the one-parameter model, the normalized specific acoustic impedance ratio of the ground shall be calculated from Equations (1) and (2) using the value of σ_{eff} that minimizes Equation (8). In the case of the two-parameter model, the normalized specific acoustic impedance ratio shall be calculated from Equations (3) and (4) using the parameter pair σ_e and α_e that minimizes Equation (8). Example measurements made above four ground surfaces are reported in Annex A.

4.7 Minimization procedure for Step 2

Although the eventual output of this Standard is the normalized specific acoustic impedance ratio of a ground surface, the quantity deduced in the calculations for Step 2 is the inverse of this *viz.* the normalized specific acoustic admittance. The normalized specific acoustic admittance of the ground surface shall be obtained by an iterative method (the Newton-Raphson method is used in the accompanying software, see Annex E) involving the measured and calculated complex sound pressure ratios between two microphones. The process shall be repeated for each measurement. It is recommended that the complex sound pressure ratios determined from repeated measurements for a given geometry be averaged and that obviously incorrect ones be discarded before the normalized specific acoustic impedance ratio is calculated.

Start at the lowest frequency with an admittance value (x_0) of $0.0 + i0.0$ corresponding to perfectly reflecting ground. The complex admittance of the ground surface under investigation is the value giving the best fit between measured complex sound pressure ratio, T_m , and the computed value, T .

In the Newton-Raphson method, a 'better' approximation, say x_{n+1} , to specific admittance can be obtained from: