



AEROSPACE RECOMMENDED PRACTICE

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Application of Pure-Tone Atmospheric Absorption Losses to One-Third Octave-Band Data

RATIONALE

Atmospheric absorption is an important component of acoustic propagation between a source and receiver. This ARP overviews an updated methodology to calculate atmospheric absorption consistent with current scientific information.

FOREWORD

The United States Department of Transportation, John A. Volpe National Transportation Systems Center (Volpe Center) Environmental Measurement and Modeling Division, in support of the Federal Aviation Administration's (FAA) Office of Environment and Energy (AEE), and working under the auspices of the Society of Automotive Engineers' (SAE) Project Working Team (PWT), has developed a method to modernize the calculation of atmospheric absorption for analysis of aircraft noise in one-third octave-bands.

The preceding standard, ARP866, was issued in August 1964 and revised as ARP866A in March 1975. Based on the theory of Kneser, the laboratory results of Harris, and field data from Rolls Royce, Boeing, and Douglas, ARP866A calculates pure-tone atmospheric absorption coefficients at either the center or lower limiting frequency of a one-third octave-band to represent attenuation over the full one-third octave-band. In contrast, this document introduces a method of calculating one-third octave-band attenuation as a function of the pure-tone attenuation at the exact mid-band frequency, over the propagation path.

Two published standards - ISO 9613-1, "Acoustics - Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere," and ANSI S1.26-1995, "Method for Calculation of the Absorption of Sound by the Atmosphere" - are referenced repeatedly throughout this document. Each presents methods for calculating atmospheric absorption in different types of analyses. The pure-tone absorption equations in the ISO and ANSI standards are functions of temperature, humidity, and atmospheric pressure, where those of ARP866A are functions only of temperature and humidity. The ISO and ANSI equations are arithmetically identical to one another and have been found to be more accurate than the corresponding equations of ARP866A. They are, therefore, adopted in this document.

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Documents

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Annex D of both the ISO and ANSI standards present a rigorous method of adapting the pure-tone algorithms for use in fractional-octave-band analysis called the Spectrum Integration or Exact Method. The Exact Method, as used in aircraft noise analysis, calculates atmospheric absorption over narrow-bands to find the cumulative attenuation across a one-third octave-band, accounting for filter effects. It, therefore, requires detailed knowledge of both the source spectrum and filter characteristics. This requirement makes its use for some applications, including aircraft noise certification, unrealistic.

Alternatively, Annex E of the ANSI standard presents an empirical method of adapting pure-tone algorithms to one-third octave-bands, known as the Approximate Method. This method avoids the need for detailed narrow-band or filter data by introducing an approximate relationship between path-length attenuation at mid-band frequencies and attenuation over full one-third octave-bands. However, its use is limited to mid-band path-length attenuations less than 50 dB.

The method described in this document (the SAE Method), retains the eased data requirements of the Approximate Method while extending its applicability to path-length attenuations greater than 50 dB. The SAE Method was designed to be consistent with Exact Method results. It is intended to replace the absorption methodologies outlined in ARP866A.

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1. SCOPE

This document presents a practical method for calculating atmospheric absorption for wide-band sounds analyzed with one-third octave-band filters, called the SAE Method. The SAE Method utilizes pure-tone attenuation algorithms originally published in ISO 9613-1 and ANSI S1.26-1995 to calculate path-length attenuation at mid-band frequencies. The equations introduced in this standard transform the pure-tone, mid-band attenuation to one-third octave-band attenuation.

The purpose of this guidance document is to extend the useful attenuation range of the Approximate Method outlined in ANSI S1.26-1995, and to replace ARP866A. Calculation of sound attenuation caused by mechanisms other than atmospheric absorption such as divergence, refraction, scattering due to turbulence, ground reflections, or non-linear propagation effects, is outside the scope of this document.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP866A Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity

2.1.2 ISO Publications

Available from International Organization for Standardization, ISO Central Secretariat, 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, Tel: +41-22-749-01-11, www.iso.org.

ISO 9613-1 Noise Acoustics - Attenuation of Sound during Propagation Outdoors - Part 1: Calculation of the Absorption of Sound by the Atmosphere, 1993

2.1.3 ANSI Publications

Available from American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

ANSI S1.26-1995 Method for Calculation of the Absorption of Sound by the Atmosphere.

2.1.4 IEC Publications

Available from International Electrotechnical Commission, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41-22-919-02-11, www.iec.ch.

IEC 61265 Electroacoustics - Instruments for Measurement of Aircraft Noise - Performance Requirements for Systems to Measure One-Third-Octave Band-Sound Pressure Levels in Noise Certification of Transport-Category Aeroplanes, 1995.

IEC 61260 Octave-Band and Fractional-Octave-Band Filters, 1995.

2.1.5 JASA Publications

Available from the Acoustical Society of America, <http://asadl.org/jasa>.

Kneser, H. O., "The interpretation of the anomalous sound-absorption in air and oxygen in terms of molecular collisions," J. Acoust. Soc. Am., Vol. 5, No. 2, pp 122-126, 1933.

Harris, C. M., "Absorption of sound in air in the audio-frequency range," J. Acoust. Soc. Am., Vol. 35, No. 1, pp 11-17, 1963.

2.1.6 INCE Publications

Available from the Institute of Noise Control Engineering, 100 E. Washington Street, Springfield, IL 62701, Tel: 217-528-9945, www.inceusa.org.

Rickley, E. J., Fleming, G. G., Roof, C. J., "Simplified procedure for computing the absorption of sound by the atmosphere," Noise Control Eng. J., Vol. 55, No. 6, pp 482-494, 2007.

Joppa, Paul D., Sutherland, Louis C., Zuckerwar, Allen J., "Representative frequency approach to the effect of bandpass filters on evaluation of sound attenuation by the atmosphere," Noise Control Eng. J., Vol. 44, No. 6, pp 261-273, 1996.

2.1.7 ICAO Publications

Available from International Civil Aviation Organization, 999 University Street, Montreal, Quebec H3C 5H7, Canada, Tel: 514-954-8219, www.icao.int.

International Civil Aviation Organization, Standards and Recommended Practices, Annex 16, "Aircraft Noise," Montreal, Quebec, Canada, January, 1972.

2.1.8 Federal Aviation Regulations

Available from the Electronic Code of Federal Regulations, <http://www.ecfr.gov>.

Code of Federal Regulations, Title 14, Part 36, Noise Standards: Aircraft Type and Worthiness Certification, Washington, D.C.: Federal Aviation Administration, Current Amendment.

2.1.9 Related Publications

Available from the U.S. Department of Commerce, Technology Administration, National Technical Information Service (NTIS), Alexandria, VA, www.ntis.gov.

Fleming, G., Roof, C., Read, D., Rapoza, A., "Evaluation of One-Third Octave-Band Filters used for Aircraft Noise Certification," Report No. DTS-74-FA753-LR5, Cambridge, MA: John A. Volpe National Transportations Systems Center, August 1997.

Rickley, E. J., Rosenbaum, J. E., Fleming, G. G., Roof, C. J., Boeker, E. R., "Development of Simplified Procedure for Computing the Absorption of Sound by the Atmosphere and Applicability to Aircraft Noise Certification: Proposed SAE Method," Report No. DOT-VNTSC-FAA-12-14, Cambridge, MA: John A. Volpe National Transportations Systems Center, November 2012.

Reherman, C. A., Roof, C. J., Fleming, G. G., "SAE ARP 866A vs. ISO 9613-1/ANSI S1.26-1995: A Sensitivity Analysis Comparing Two Procedures for Adjusting As-Measured Spectra to Reference Conditions," Cambridge, MA: John A. Volpe National Transportations Systems Center, May 2002, NTIS # PB2003-101662.

Rickley, E. J., Fleming, G. G., "Computing the Absorption of Sound by the Atmosphere and its Applicability to Aircraft Noise Certification," Cambridge, MA: John A. Volpe National Transportations Systems Center, August 1998, NTIS # PB2003-101661.

2.1.10 Other Related Publications

The following publication is provided for information purposes only and is not a required part of this SAE Aerospace Technical Report.

Coignus, Bernard, "Influence des paramètres météorologiques sur la propagation du son à travers l'atmosphère, application à la certification," Technical Report 510.0141/98, Aerospatiale, Toulouse, France, March 1998 (in French).

2.2 Definitions

2.2.1 ATMOSPHERIC ABSORPTION

The attenuation of sound caused by propagation through the atmosphere. Atmospheric absorption includes the effects of thermal losses, shear viscosity losses, and molecular relaxation losses of oxygen and nitrogen. It is a function of frequency, temperature, relative humidity and atmospheric pressure.

2.2.2 PATH-LENGTH ABSORPTION

The attenuation of sound caused by propagation through the atmosphere, over a set path-length.

2.2.3 EXACT METHOD

A spectrum integration procedure used for calculating atmospheric absorption of wideband sounds analyzed by fractional-octave-band filters. One-third octave-band filters are assumed in examples in Appendix A of this document. The Exact Method is described in detail in the ISO 9613-1 and ANSI S1.26-1995 standards.

2.2.4 APPROXIMATE METHOD

An empirical method of calculating atmospheric absorption of wideband sounds analyzed by fractional-octave-band filters. One-third octave-band filters are assumed in examples in Appendix A of this document. Band attenuation is computed as a function of path-length absorption at the mid-band frequency. The Approximate Method is described in detail in ANSI S1.26-1995 and may be substituted for the Exact Method, with errors less than $\pm 5\%$, where path-length attenuation at the exact mid-band frequency is less than 50 dB.

2.2.5 SAE METHOD

An approximate method of calculating atmospheric absorption of wideband sounds analyzed by one-third octave-band filters that does not have the 50 dB path-length attenuation limitation of the Approximate Method. The SAE Method's performance has been investigated over one-third octave-bands from 25 Hz to 20 kHz. It is described in detail herein and is consistent with the Exact Method for mid-band path-length attenuation up to 100 dB with root mean square errors less than 3%, and for mid-band attenuation up to 500 dB with root mean square errors less than 4% (Rickleby et al., 2012).

3. PROCEDURE FOR CALCULATING ATMOSPHERIC ABSORPTION

Section 3.1 outlines the procedure for calculating pure-tone (single frequency) attenuation coefficients for selected temperature, relative humidity, and atmospheric pressure values. Section 3.2 comments briefly about the Exact Method and outlines the procedure for calculating one-third octave-band attenuation using the SAE Method.

3.1 Pure-Tone Mid-band Attenuation Coefficient

The procedure for calculating single frequency atmospheric absorption effects is described in detail in the ISO 9613-1 and ANSI S1.26-1995 standards. The equations are repeated here for convenience. The pure-tone sound attenuation coefficient α , in decibels per meter, is calculated as a function of frequency, ambient atmospheric temperature, molar concentration of water vapor, and ambient atmospheric pressure as

$$\alpha(f) = 8.686 f^2 \left\{ \left[1.84 \times 10^{-11} \left(\frac{p_a}{p_r} \right)^{-1} \left(\frac{T}{T_r} \right)^{1/2} \right] + \left(\frac{T}{T_r} \right)^{-5/2} \left\{ 0.01275 \left[\exp \left(\frac{-2239.1}{T} \right) \right] \left[\frac{f_{rO}}{f_{rO}^2 + f^2} \right] + 0.1068 \left[\exp \left(\frac{-3352.0}{T} \right) \right] \left[\frac{f_{rN}}{f_{rN}^2 + f^2} \right] \right\} \right\} \quad (\text{Eq. 1})$$

where:

- f pure-tone frequency of sound in Hz
- p_a ambient atmospheric pressure in kPa
(test-day, reference-day, or representative path-length pressure, as appropriate)
- p_r reference pressure of one standard atmosphere, equal to 101.325 kPa
- T ambient atmospheric temperature in K
(test-day, reference-day, or representative path-length temperature, as appropriate)
- T_r reference ambient temperature, equal to 293.15 K

The vibrational relaxation frequencies of oxygen and nitrogen, f_{rO} and f_{rN} , respectively, in Equation 1, are calculated as

$$f_{rO} = \frac{p_a}{p_r} \left\{ 24 + \left[\frac{(4.04 \times 10^4 h)(0.02 + h)}{0.291 + h} \right] \right\} \quad (\text{Eq. 2})$$

$$f_{rN} = \frac{p_a}{p_r} \left(\frac{T}{T_r} \right)^{-1/2} \times \left(9 + 280 h \exp \left\{ -4.170 \left[\left(\frac{T}{T_r} \right)^{-1/3} - 1 \right] \right\} \right) \quad (\text{Eq. 3})$$

where h is the molar concentration of water vapor, in percent. The molar concentration of water vapor can be calculated from relative humidity, in percent, as

$$h = h_{\text{rel}} \left(\frac{p_{\text{sat}}}{p_r} \right) \left(\frac{p_a}{p_r} \right)^{-1} \quad (\text{Eq. 4})$$

Test-day, reference-day, or representative path-length relative humidity, is used as appropriate.

The saturation vapor pressure p_{sat} in Equation 4 is given by

$$p_{\text{sat}} = (p_r) 10^V \quad (\text{Eq. 5})$$

where the exponent V is

$$\begin{aligned}
 V = & 10.79586 \left[1 - \left(\frac{T_{01}}{T} \right) \right] - 5.02808 \log_{10} \left(\frac{T}{T_{01}} \right) \\
 & + 1.50474 \times 10^{-4} \{ 1 - 10^{-8.29692 [(T/T_{01}) - 1]} \} \\
 & + 0.42873 \times 10^{-3} \{ -1 + 10^{4.76955 [1 - (T_{01}/T)]} \} - 2.2195983
 \end{aligned}
 \tag{Eq. 6}$$

and T_{01} is the triple-point isotherm temperature, equal to 273.16 K.

3.2 One-Third Octave-Band Attenuation

The Exact and SAE Methods can both be used to calculate atmospheric absorption of wideband sounds analyzed by one-third octave-band filters. The ISO and ANSI standards contain descriptions of the Exact Method. The SAE Method, similar in concept to the Approximate Method contained in the ANSI standard, is introduced in this document.

The ISO and ANSI documents also outline an approach for calculating attenuation effects on propagation through a stratified atmosphere, in which attenuation is summed over discretized segments of the atmosphere. This technique is employed in the SAE Method sensitivity analysis presented in Appendix A.3.

3.2.1 Exact Method

The Exact Method is described in detail in the ISO and ANSI standards and is not repeated herein. Though it is a technically sound method for adapting pure-tone algorithms for use in fractional-octave-band analysis, the Exact Method requires detailed knowledge of one-third octave-band filter characteristics and a standardized way of obtaining narrow-band data through measurement or derivation. These requirements constitute an undue burden for some uses, including aircraft noise certification. Therefore, the Exact Method is not considered a viable option for regulatory adoption. It is used herein as a point of reference for comparison with the SAE Method.

3.2.2 SAE Method

The SAE Method was developed by Rickley et al. in 1998 based on regression analysis of data generated by the Exact Method. Its applicability extends beyond the 50 dB path-length attenuation limitation of the Approximate Method, maintaining consistency with the Exact Method out to and beyond attenuations experienced over long distance propagation, e.g., to the farthest standard tabulated propagation distance of 7620 m.

The SAE Method is an approximate method of calculating atmospheric absorption of wideband sounds analyzed by one-third octave-band filters. One-third octave-band analysis is a requirement of 14 CFR Part 36 and ICAO Annex 16, Volume I for aircraft noise certification. Once filtered, sound pressure level data include the influence of filter characteristics, the effect of which varies with the shape of the filtered spectrum. The traditional third-order Butterworth algorithms are commonly used in filter design. Therefore, a base-10 designed third-order Butterworth filter shape was assumed in the Exact Method calculations. This assumption was also made by Joppa et al. To investigate the effect of filter choice, the method was tested against an ideal filter configuration (see Rickley et al., 2012). The difference in filter choice was found to have little effect on the method's performance.

The SAE Method was developed using a set of four non-tonal source spectra with slopes of +5, 0, -2, and -5 dB per one-third octave-band, as shown in Figure 1. They were chosen to represent the span of spectral shapes found in typical aircraft data. Atmospheric absorption was calculated with the Exact Method over path-lengths out to 7620 m for these broadband sources, assuming a uniform, homogeneous atmosphere at reference pressure of 101.325 kPa. A variety of air temperature and relative humidity value pairs that substantially span the 14 CFR Part 36 allowable temperature and humidity test window were investigated. Data curves of the 25 °C and 70% temperature and relative humidity point were found to sufficiently approximate data from the other ten tested temperature and humidity pairs. They were, therefore, chosen as representative of data over the span of temperature and humidity conditions.

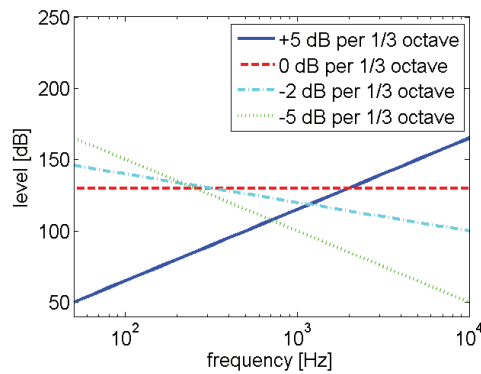


FIGURE 1 - NON-TONAL TEST SPECTRA
DATA SLOPES: -5, -2, 0, +5 dB PER 1/3 OCTAVE-BAND

A commercial statistical regression program was used on these data points to obtain an equation that approximates the one-third octave-band attenuation results calculated by the Exact Method for the four spectra, under the determined atmospheric conditions. The general form of the ANSI S1.26-1995 Approximate Method equation was used as a starting point because it was found to be in good agreement with the Exact Method for small values of absorption. The following piecewise function was determined to fit the Exact Method results. It calculates one-third octave-band attenuation $\delta_B(f_i)$ as a function of the corresponding pure-tone, path-length attenuations at the mid-band frequency $\delta_t(f_{m,i})$ as

$$\delta_B(f_i) = \begin{cases} A \times [\delta_t(f_{m,i})] \times (1 + B \times (C - D \times [\delta_t(f_{m,i})]))^E, & \delta_t(f_{m,i}) < 150 \text{ dB} \\ F + G \times [\delta_t(f_{m,i})], & \delta_t(f_{m,i}) \geq 150 \text{ dB} \end{cases} \quad (\text{Eq. 7})$$

$$F + G \times [\delta_t(f_{m,i})], \quad \delta_t(f_{m,i}) \geq 150 \text{ dB} \quad (\text{Eq. 8})$$

where:

f_i nominal mid-band frequency for one-third octave-band i

i positive integer representing band number; $i = 17$ to 40 corresponds to the standard one-third octave-band range from 50 Hz to 10 kHz; the range can be extended down to lower frequencies: $i = 14$ for the 25 Hz band, or up to higher frequencies: $i = 43$ for the 20 kHz band

Constants A through G are defined as follows:

$$A = 0.867942$$

$$B = 0.111761$$

$$C = 0.95824$$

$$D = 0.008191$$

$$E = 1.6$$

$$F = 9.2$$

$$G = 0.765$$

The mid-band path-length absorption $\delta_t(f_{m,i})$, in decibels, is calculated as

$$\delta_t(f_{m,i}) = [\alpha(f_{m,i})][s] \quad (\text{Eq. 9})$$

where $\alpha(f_{m,i})$ is the mid-band attenuation coefficient in decibels per meter (Equation 1), and s is the path-length distance in meters. The exact mid-band frequency $f_{m,i}$, in hertz, for one-third octave-band i , is calculated as

$$f_{m,i} = 10^{i/10} \quad (\text{Eq. 10})$$

NOTE: Large attenuations, such as those over 150 dB, reduce sound levels beyond the degree of practical interest. However, methods that limit their scope only to accuracy at the smaller attenuations can exhibit irregular behavior for larger attenuations. The Approximate Method, for example, follows a direct relationship between predicted band-level attenuation and pure-tone mid-band attenuation only up to mid-band attenuations of approximately 300 dB. After this point, the relationship is inverted, as shown in Figure 2. This breakdown of the model can introduce errors where mid-band attenuation is large. Therefore, the goal in extending the valid attenuation range is to ensure the correct trend of attenuation is maintained and anomalies are avoided.

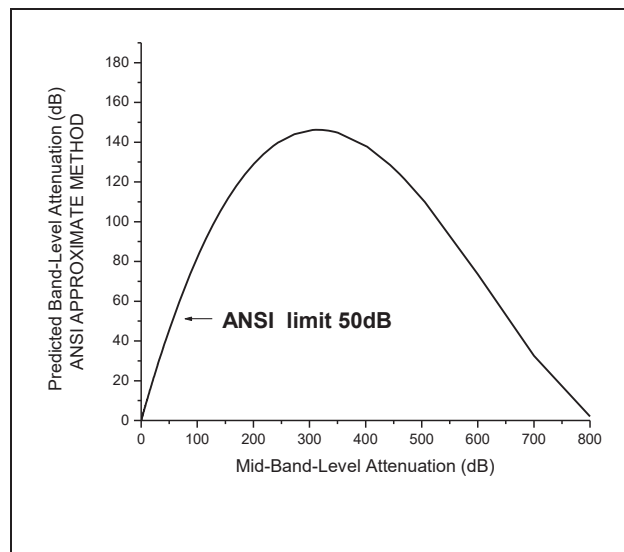


FIGURE 2 - APPROXIMATE METHOD
ANSI FUNCTION - APPROXIMATE METHOD
PREDICTED VERSUS MID-BAND-LEVEL ATTENUATION

The SAE Method is a reciprocal process and can be used for both source-to-receiver and receiver-to-source distances.

4. LIMITATIONS

The calculation procedures described herein should be used with caution in estimating sound propagation losses. When long propagation distances are involved, there may be large discrepancies between observed and estimated sound pressure levels unless careful consideration is given to the actual spectrum shape of the noise source, the true propagation path-length, the actual condition of the atmosphere between the source and receiver, and the level of background noise present. In the high-frequency bands in particular, atmospheric absorption can cause sound from the noise source to fall below the level of background noise. Additional losses can be caused by effects of the ground surface. These losses can be substantial and are outside the scope of this document.