Atmospheric absorption of sound: Further developments

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Atmospheric absorption of sound: Further developments

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This Letter is an extension of an earlier Letter by Bass *et al.*, "Atmospheric absorption of sound: Update" [J. Acoust. Soc. Am. **88**, 2019–2021 (1990)]. Errors in a formula for saturation vapor pressure are corrected, and an alternative, much simpler formula is given. The role of atmospheric pressure is emphasized by giving formulas in which the absorption, frequency, and relative humidity are all scaled with respect to atmospheric pressure. Also presented are new, more readable and useful figures showing atmospheric absorption as a function of frequency, relative humidity, and atmospheric pressure. The new figures make it possible to estimate accurately the absorption at any value of atmospheric pressure.

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Reference 1 gives improved formulas for the calculation of attenuation coefficients α due to atmospheric absorption. The purpose of this Letter is to (1) correct errors in Eq. (5) of Ref. 1, (2) call attention to an alternative equation for saturation vapor pressure, (3) provide a new form of the formulas for α and the relaxation frequencies that calls attention to the role of atmospheric pressure, and (4) present new graphs for α that are more readable and useful than the ones given in Ref. 1.

The equation for saturation vapor pressure p_{sat}, Eq. (5) in Ref. 1, should read

$$\begin{aligned}\log_{10}(p_{\text{sat}}/p_{s0}) = {} & 10.79586[1-(T_{01}/T)] \\ & -5.02808\log_{10}(T/T_{01})+1.50474 \\ & \times 10^{-4}(1-10^{-8.29692[(T/T_{01})-1]}) \\ & -4.2873\times 10^{-4} \\ & \times(1-10^{-4.76955[(T_{01}/T)-1]}) \\ & -2.2195983, \end{aligned} \tag{1}$$

where p_{s0} is the reference value of atmospheric pressure (1 atm) in the same units as p_{sat}, T is atmospheric temperature in K, T_0=293.15 K is the reference atmospheric temperature, and T_{01}=273.16 K is the triple-point isotherm temperature. While Eq. (1), as corrected here, is consistent with the existing ANSI Standard,[2] for all practical purposes the following alternative equation, which is used in a new ISO Standard,[3] provides equivalent results:

$$\log_{10}(p_{\text{sat}}/p_{s0}) = -6.8346(T_{01}/T)^{1.261}+4.6151. \tag{2}$$

If Eq. (2) is used instead of Eq. (1), values of α for frequencies from 50 to 10 000 Hz/atm and relative humidities from 10 to 90%/atm differ by less than approximately ±0.3% at −40 °C, ±0.03% at −20 °C and 0 °C, ±0.02% at 20 °C, and ±0.002% at 40 °C. Note that all the remaining expressions in Ref. 1 used to compute α are identical to those in the new ISO standard.[3]

We take occasion here to point out that Figs. 1 and 2 in Ref. 1, as well as earlier versions (see the references in Ref. 1), have more generality than is implied by the labels on the ordinates. That is, although the curves seem to be useful for only one value of atmospheric pressure p_s, namely $p_s=p_{s0}$, in fact they may be used for other values. To clarify the role of atmospheric pressure, we recast the expression for α, Eq. (1) in Ref. 1, as follows:

$$\begin{aligned}\frac{\alpha}{p_s} = \frac{F^2}{p_{s0}}\Bigg\{ & 1.84\times 10^{-11}\left(\frac{T}{T_0}\right)^{1/2} \\ & +\left(\frac{T}{T_0}\right)^{-5/2}\Bigg[0.01278\,\frac{e^{-2239.1/T}}{F_{r,\text{O}}+F^2/F_{r,\text{O}}} \\ & +0.1068\,\frac{e^{-3352/T}}{F_{r,\text{N}}+F^2/F_{r,\text{N}}}\Bigg]\Bigg\}\ \frac{\text{nepers}}{\text{m-atm}}, \end{aligned} \tag{3}$$

where $F=f/p_s$, $F_{r,\text{O}} = f_{r,\text{O}}/p_s$, and $F_{r,\text{N}} = f_{r,\text{N}}/p_s$ are frequencies scaled by atmospheric pressure, and f is frequency in Hz. Formulas for the scaled relaxation frequencies for oxygen and nitrogen are

$$F_{r,\text{O}} = \frac{1}{p_{s0}}\left(24+4.04\times 10^4 h\,\frac{0.02+h}{0.391+h}\right) \tag{4}$$

and

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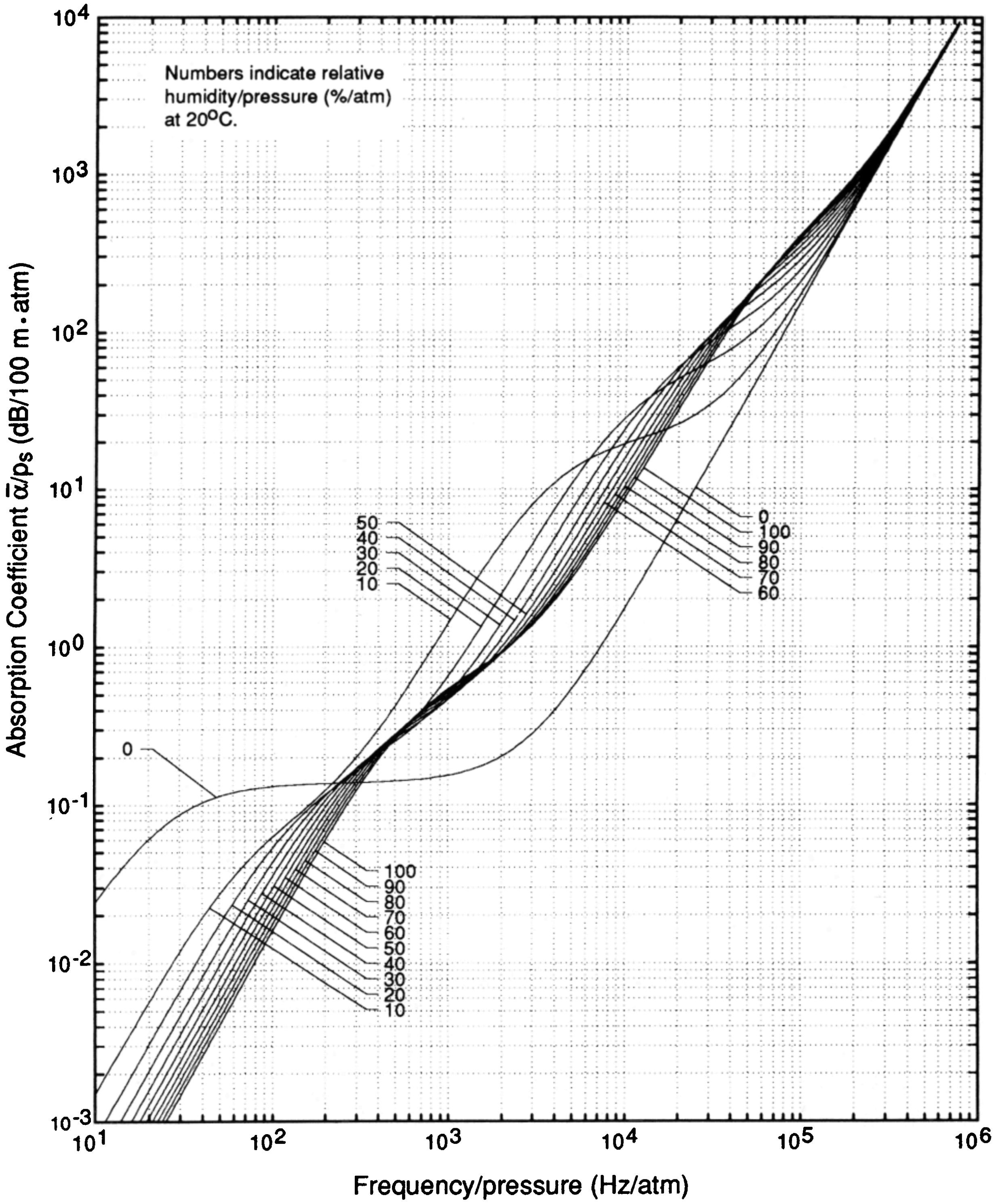

FIG. 1. Sound absorption coefficient per atmosphere, SI units, for air at 20 °C. The abscissa is frequency/pressure, and the parameter is relative humidity/pressure in the range 0 to 100%/atm.

$$F_{r,\mathrm{N}}=\frac{1}{p_{s0}}\left(\frac{T_0}{T}\right)^{1/2}\left(9+280h\right.$$
$$\left.\times\exp\left\{-4.17\left[\left(\frac{T_0}{T}\right)^{1/3}-1\right]\right\}\right),\tag{5}$$

respectively, where h is the absolute humidity (molar concentration of water vapor) in %. For completeness the relation between h and relative humidity h_r is

$$h=h_r\,\frac{p_{\mathrm{sat}}/p_{s0}}{p_s/p_{s0}}=p_{s0}\left(\frac{h_r}{p_s}\right)\left(\frac{p_{\mathrm{sat}}}{p_{s0}}\right)\%.\tag{6}$$

Although any consistent pressure units may be used, expressing the pressure in atm makes the factor p_{s0} unity, and Eqs. (3)–(5) simplify somewhat. The scaled frequency F then has units Hz/atm, the humidity parameter h_r/p_s has units %/atm, and α/p_s has units nepers/(m-atm).

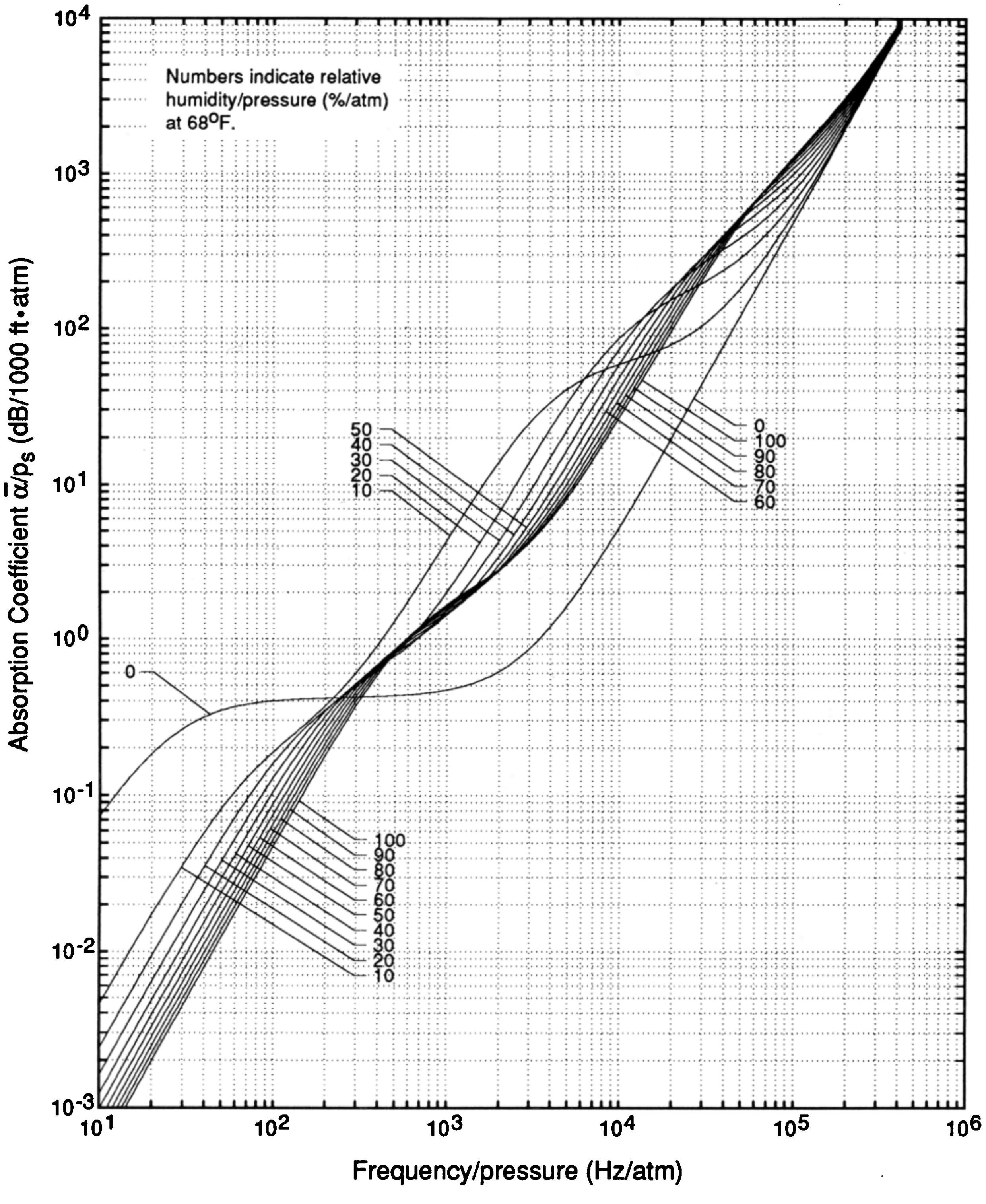

FIG. 2. Sound absorption coefficient per atmosphere, English units, for air at 68 °F. The abscissa is frequency/pressure, and the parameter is relative humidity/pressure in the range 0 to 100%/atm.

When attenuation in terms of decibels is desired, we use the symbol $\bar{\alpha}$ (dB/unit distance) to distinguish it from α (nepers/unit distance).

Figures 1 and 2 of this paper have axes labeled $\bar{\alpha}/p_s$ and f/p_s, and the relative humidity parameter is h_r/p_s. The figures are drawn to facilitate easy reading to about two significant digits. For example, find the absorption of a 1000-Hz signal at 20 °C, 10% relative humidity, and 0.5-atm atmospheric pressure. The values to use on the graph are $f/p_s=1000/0.5=2000$ Hz/atm and $h_r/p_s=10/0.5=20\%$/atm, from which we find (Fig. 1) the absorption to be $\bar{\alpha}/p_s=2.2$ dB/(100 m-atm) or $\bar{\alpha}=1.1$ dB/100 m [the more precise value, found from Eq. (3), is $\bar{\alpha}=1.078$ dB/100 m].

Note that while relative humidity h_r never exceeds 100%, the scaled quantity h_r/p_s can exceed 100%/atm at high altitude, where p_s is less than 1 atm but h_r is high.

However, the maximum value of 100%/atm for h_r/p_s that is used in Figs. 1 and 2 is sufficient to cover most conditions usually encountered below an altitude of about 3 km.

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[1]H.E. Bass, L.C. Sutherland, and A. J. Zuckerwar, "Atmospheric absorption of sound: Update," J. Acoust. Soc. Am. **88**, 2019–2021 (1990).

[2]ANSI S1.26-1978, "American National Standard Method for the Calculation of the Absorption of Sound by the Atmosphere" (American National Standards Institute, New York, 1978).

[3]ISO 9613-1:1993, "Acoustics —Attenuation of sound during propagation outdoors—Part 1: Calculation of the absorption of sound by the atmosphere" (International Organization for Standardization, Geneva, Switzerland, 1993).