THE PREFERENTIAL DETECTION OF SOUND BY PERSONS BURIED UNDER SNOW AVALANCHE DEBRIS AS COMPARED TO PERSONS ON THE OVERLYING SURFACE

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Abstract. The preferential detection of sound by a person buried under snow can be explained by the strong attenuation of acoustic waves in snow and the relatively higher level of background acoustic noise that exists for persons above the snow surface as compared to an avalanche burial victim. This noise masks sound transmitted to persons on the snow surface causing a reduction of hearing sensitivity as compared to the burial victim. Additionally, the listening concentration of a buried individual is generally greater than for persons working on the snow surface, increasing their subjective awareness of sound.

INTRODUCTION

Persons who have been buried under deposited snow either intentionally (for example, in a snow cave) or accidentally by an avalanche are well aware of the poor sound transmission properties of snow and their effect on audibility. These effects are dramatically demonstrated in the accounts of avalanche burial survivors who could hear their rescuers talking and working above them while their shouts for help went unheard (Krasser 1967). In one case, not even four revolver shots fired by a man buried in an avalanche were heard by rescuers (Krasser 1967).

The factors that can influence audibility include impedance coupling of a sound source or receiver to snow, refraction of sound in the air above the snow surface, the mechanical interaction of sound waves with the snow, environmental noise and the physiology of the hearing process.

ACOUSTICAL PHENOMENA

Acoustic Wave Interaction with Snow

The effects of impedance, attenuation and snow cover thickness on audibility are best described by the transmission characteristics of snow which can be expressed in terms of a transmission loss TL in decibels. This transmission loss is a measure of the loss of acoustic energy for sound transmitted through the snow and is defined as

$$(1) \qquad TL = 10 \log (I_i/I_t)$$

where I_i is the incident intensity and I_t is the transmitted intensity.

Johnson (1978, 1982) used experiments and an analytical model describing the acoustical properties of snow to examine the effects of acoustic impedances and attenuation on sound transmission through snow. These results indicate that transmission losses across an air/snow interface are relatively small when compared to other material combinations and that an air pressure wave is strongly attenuated near the snow/air interface. Over 80% of the acoustic energy transmitted into a homogeneous, isotropic snow cover can be lost within 1 m of the air/snow interface. Thus, the relatively large acoustic absorption characteristics observed for snow can be attributed to pronounced attenuation in snow of acoustic waves that propagate across the air-snow interface with relatively low transmission loss.

Johnson (1978) also used the analytical model to calculate transmission losses for both stratified snow with layering similar to that found in nature and for avalanche debris, which is in general well mixed. Figure 1 shows calculated normalized transmission losses for naturally deposited snow and avalanche debris. The normalized transmission losses were obtained by

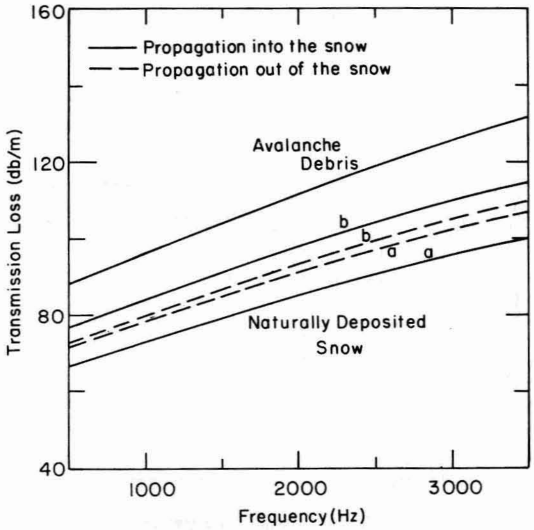

Figure 1. Calculated normalized transmission loss as a function of frequency for naturally deposited snow (curves a and b) and avalanche debris.

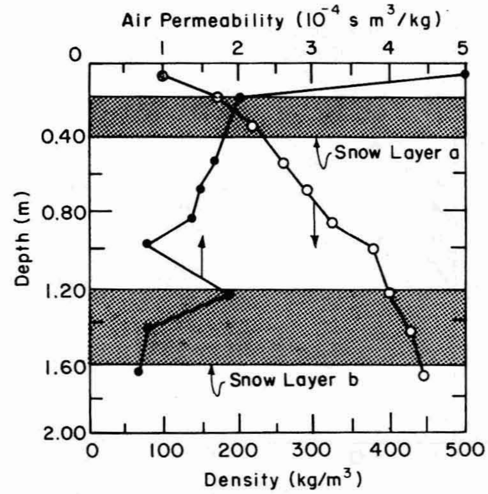

Figure 2. Measured density and air permeability profiles with depth for naturally deposited snow. Snow density and air permeability data from layers (a) and (b) were used to calculate transmission losses shown in Figure 1.

dividing the calculated transmission losses by the total thickness of the snow layer of interest. This allows a comparison of the transmission characteristics of snowpacks that have different thicknesses. Curves (a) and (b) in Figure 1 represent the transmission losses across snow layers (a) and (b) shown in Figure 2, and the avalanche debris curve is the transmission loss for the upper 0.3 m of Figure 3. Density and air permeability values given in Figures 2 and 3 show that avalanche debris is more homogeneous with depth than is naturally deposited snow. The air permeability for avalanche debris tends to be less than for comparable density natural snow as well.

Transmission losses for avalanche debris are significantly higher than for naturally deposited snow. This is due to the relatively low air permeability and homogeneous density of avalanche debris as compared to natural snow. The effect of propagation direction on transmission losses is more pronounced for natural snow than for avalanche debris (transmission losses for the avalanche debris had no apparent propagation direction dependence). Differences due to propagation direction are caused by a variation in the acoustic properties of snow as a function of depth and are relatively small when compared to the total transmission loss through the snow. For curves (a) the transmission loss for acoustic wave propagation out of the snow was calculated to be greater than for propagation into the snow. Conversely, the transmission loss for curves (b) was greater for acoustic wave propagation into the snow as compared to propagation out of the snow. This illustrates that the relative magnitudes for transmission losses cannot be reliably predicted based on propagation direction for naturally deposited snow. The transmission losses depend on the layering structure of a given snowpack, which can be very complicated. Figure 1 illustrates that transmission losses through snow are very large and that a relatively thin snow layer can greatly reduce the intensity of transmitted sound. Experimental measurements support the calculated results that indicate snow strongly reduces the intensity of sound transmitted through it. Figure 4 shows the normalized transmission losses as a function of frequency measured by Johnson (1978) for snow layer profiles (a) and (b) shown in Figure 2. The overall magnitude of the transmission losses is similar to, but more scattered than, those shown in Figure 1.

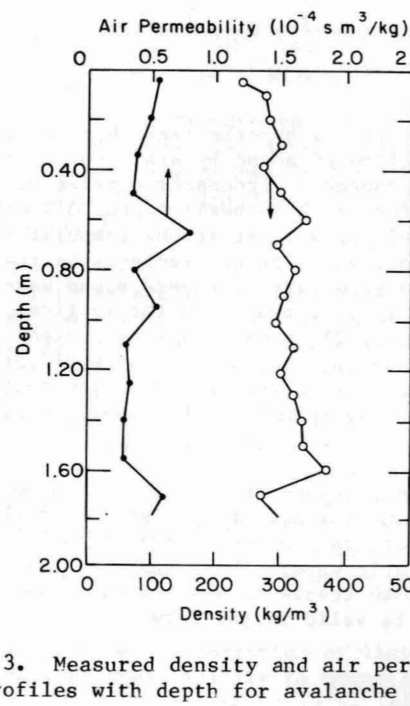

Figure 3. Measured density and air permeability profiles with depth for avalanche debris.

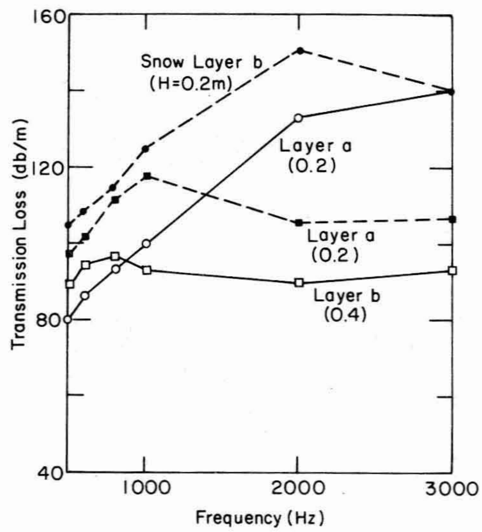

Figure 4. Experimentally determined normalized transmission loss as a function of frequency for spherical waves in naturally deposited snow. The solid curves represent acoustic wave propagation into the snow and the dashed curves represent propagation out of the snow.

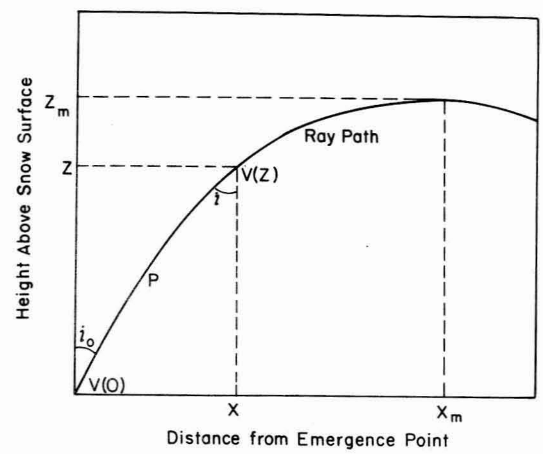

Figure 5. Ray-path in a vertically inhomogeneous medium where phase velocity is a continuous function of height.

The preceding discussion indicates that the large acoustic absorption and attenuation characteristics of snow result in little reflected acoustic energy and large transmission losses through snow. The large transmission losses for acoustic waves propagating in snow mean that even small layers of snow can greatly reduce audibility across a snow layer. Acoustic wave interaction in snow cannot, however, explain the perceived preferential detection of sound by avalanche burial victims as compared to persons above the snow.

Refraction of Acoustic Waves in Air above a Snow Surface

Krasser (1967) hypothesized that the preferential detection of sound by avalanche burial victims was caused by processes outside of a snow cover. He further hypothesized, but did not quantitatively show, that strong temperature-inversion-induced velocity gradients in the air just above a snow surface caused sound waves from the snow to refract away from the vertical, causing total reflection at a small height above the snow. Such a total reflection would prevent a person standing on a snow surface from hearing sounds emanating from beneath a snow cover.

The significance of refraction can be evaluated by estimating both the height at which total reflection occurs and the lateral travel distance of the acoustic wave. These can be determined by using ray-path theory in which Snell's law is assumed to be valid in the form

$$\text{(2)} \qquad \frac{\sin i}{V(Z)} = P$$

where i is the ray-path angle from the vertical at height Z, V(Z) is the velocity of propagation of sound in air at Z and is assumed to be a continuous function, and P is the ray parameter and is a constant for each ray-path. The geometry described by equation 2 is shown in Figure 5. The height of total reflection is Z_m and the lateral travel distance for the ray is $2X_m$. Temperature-caused propagation velocity changes can be estimated by

$$\text{(3)} \qquad V(Z) = 331.6 + 0.6\left(t_o + Z\frac{dT}{dZ}\right) = V(o) + aZ$$

where t_o is the temperature at the snow surface in degrees Celsius, V(o) is the propagation velocity of sound in air at the snow surface, a = 0.6 dT/dZ, and dT/dZ is the temperature change with height (Kinsler and Frey, 1962). The height of total reflection can be determined by setting i = 90° (that is the ray-path is horizontal) and substituting equation 3 into equation 2, giving

$$\text{(4)} \qquad Z_m = \frac{1}{a}\left(1/P - V(o)\right)$$

The horizontal travel distance associated with Z_m for a given ray-path can be determined by integrating over dx = tan i dx and is given by

$$\text{(5)} \qquad X_m = \int_o^{Z_m} \frac{V(\zeta)\, d\zeta}{\sqrt{1 - P^2\, V(\zeta)}}$$

Substitution of equation 3 into equation 5 and integrating gives

$$X_m = 1/a\sqrt{1/P^2 - V^2(o)}$$

The ray parameter is calculated from

$$P = \sin i_o/V(o)$$

where i_o is the emergence angle of the ray at Z = 0.

Figure 6 shows Z_m and X_m for emergence angles ranging from 10° to 80°, assuming that t_o = 0°C and that the temperature gradient was constant at all values of Z. The constant temperature gradient assumption produces very conservative estimates of X_m and Z_m since the temperature gradient should decrease with Z. The effect of refraction of acoustic waves on audibility can be significant only if Z_m is less than the height of a listening person and 2 X_m is less than the range of audibility without refraction. The results shown in Figure 6 indicate that Z_m is in general much greater than 2 m. Even for an extreme temperature gradient of 100°C/m, Z_m goes below 2 m only for i_o > 45°. The values for X_m are also quite large with respect to the expected range for a sound source buried in snow. These results would change very little for different values of t_o. The results shown in Figure 6 indicate that refraction of acoustic waves cannot explain the preferential detection of sound by a person buried under deposited snow.

Hearing and Noise in the Environment

The preceding discussion has shown that acoustic waves propagating through snow exhibit large transmission losses. The discussion also indicates that it is highly unlikely that the preferential detection of sound by avalanche burial victims as compared to persons on the overlying snow can be explained solely on the basis of the acoustical properties of snow. This implies that the hearing process for a person and the acoustical environment may be partially responsible for the preferential detection of sound by avalanche burial victims.

The hearing process is subjective and depends on the surrounding noise environment, the level of concentration by the listener and the auditory capabilities of the ear. The average ear responds to tones covering a frequency range of 20 to over 15,000 cycles/s and can respond to pressures as small as 10^{-5} Pa in a noise-free environment (Kinsler and Frey, 1962). The presence of noise reduces the sensitivity of the ear to other sounds and a shift in the threshold of hearing results. This phenomenon is called masking, as the noise masks any sound below a threshold intensity level. The masking effects of white noise on the threshold of hearing for a normal person are shown in Figure 7.

The results shown in Figure 7 indicate that masking noise can significantly decrease hearing sensitivity. This has an important bearing on the preferential detection of sound phenomenon in that an individual buried under deposited snow is in an anechoic noise-free environment while persons outside of the snow are in a noisy environment.

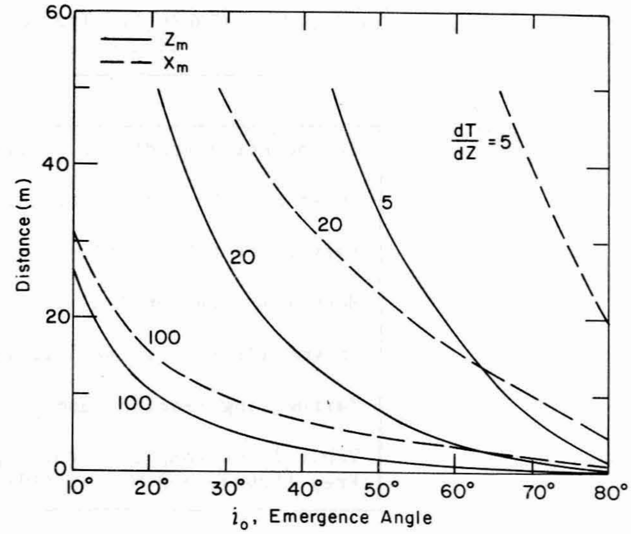

Figure 6. Height Z_m above the snow surface and lateral distance X_m at which total internal reflection occurs are plotted as a function of emergence angle from the snow surface for various atmospheric temperature gradients, dT/dZ. Refer to Figure 9 for a physical representation of Z_m and X_m.

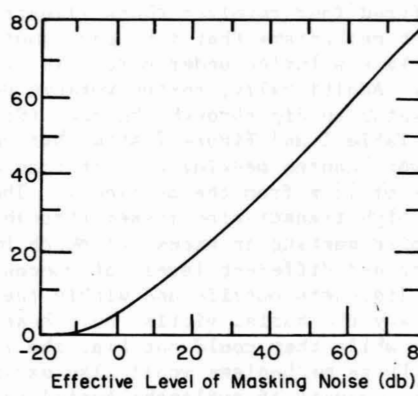

Figure 7. Relation between masking of pure tones (m) and the effective level of the masking noise. m is the change in the threshold of pure tone due to the noise (Hawkens and Stevens, 1950).

Sources of noise are wind, talking, mechanical equipment and physical activities associated with working. Table I shows typical noise levels for several different noise environments. Although noise levels above avalanche debris during a rescue have not been measured, it is reasonable to assume they would exceed those found in a broadcast studio (26 db). A 26-db noise level results in a masking of about 25-db (Fig. 7). Noise levels under snow are essentially zero, resulting in a hearing sensitivity difference between listeners on the surface and under snow of 25 db.

The relative concentration of listeners can also influence their ability to detect sound.

Table I. Typical environment noise levels.

	db
Broadcasting studio	26
Quiet suburban residential	38
Very noisy urban residential	58
Normal speech (at 1 m)	65
Snowmobile (at 6.7 m/s)	88
Earthmoving tractors and backhoes (at 15 m)	88
Table I was compiled from Bugliarello et al. (1976), Kinsler and Frey (1962), and Magrab (1975).	

This is particularly relevant to the avalanche burial victim who may be trying to detect rescue activity. Conversely, rescuers would be directing their attention to search activities and not to listening for sound coming from beneath the snow.

The incident in which an avalanche burial victim fired four revolver shots illustrates the important mechanisms that influence audibility. The victim was buried under more than six meters of snow. Additionally, rescue workers were using an excavator to dig through the snow (Fraser 1966). Table I and Figure 7 show that an excavator at work causes masking greater than 80 db at a distance of 15 m from the machinery. The combination of high transmission losses through 6 m of snow, noise masking in excess of 80 db by the excavator and different levels of concentration between listeners outside and within the snow explain why the burial victim could hear the rescuers while they could not hear the revolver shots. These mechanisms would also explain less dramatic accounts of avalanche burial survivors hearing their rescuers while going unheard.

CONCLUSIONS

Factors which can affect audibility within and outside of deposited snow include refraction of sound due to velocity gradients in the air above the snow, the interaction of sound waves with snow, environmental noise and the hearing process. Refraction effects outside of a snow cover were found to be insignificant. Interaction of sound waves with snow has the strongest influence on audibility. Impedance matching between a sound source or receiver and snow attenuation of acoustic signals in snow and snow layer thickness causes the large magnitude transmission losses observed for snow. Transmission losses for naturally deposited snow are less than for avalanche debris at the same density. This is due to lower air permeability values for avalanche debris. The transmission losses for nonplanar waves in vertically stratified snow vary slightly, depending on whether the wave is propagating in the direction of increasing or decreasing phase velocity. This is a small effect and not reliably detected by experiments. Noise in the environment and the hearing process are additional factors that affect audibility and also help to explain the preferential detection of sound by an avalanche burial victim over rescuers working on the snow surface. Environmental noise, which occurs outside of the snow and not under the snow, acts to mask sound and requires that sound intensity exceed the masking level before a listener can detect it. Additionally, the level of concentration of a listener can influence the intensity level at which a sound is detected.

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