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Blending History with Physics: Acoustic Refraction

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Refraction is a traditional and important concept in introductory physics courses. The basic ideas are often demonstrated through analogy and with ripple tanks, with subsequent discussion usually focusing on optical refraction. Mirages, prisms, lenses, fiber optics, and rainbows all serve to illustrate the phenomenon.

Acoustic refraction is usually

ignored or given brief mention in introductory texts. I would like here to point out that the study of bending sound waves is not only an excellent ancillary to the normal optical approach, but also is rich in interdisciplinary possibilities. The propagation of sound outdoors has a significant historical context, especially in warfare. My own research has been directed towards the effects of sound

on command decisions in the U.S. Civil War, but the phenomenon has been noted for several centuries.

Outdoor Sound Propagation

Outdoor sound propagation has been studied extensively and there are several excellent review articles describing the phenomenon.¹ What follows is a brief summary of the main points.

There are two primary reasons why a person close to an outdoor sound source will not hear sound from the source. First, matter between the source and potential receiver can interact with the sound wave in several ways. The total attenuation of the sound (A_T) is a combination of three factors: geometric spreading of the wave A_S , atmospheric absorption A_A , and extra attenuation A_E , which groups together all other effects (for example: ground reflections, nonhomogeneity in the atmosphere, diffraction and reflection due to barriers, and scattering and diffraction due to atmospheric turbulence). The effects can be described by

$$A_T = A_S + A_A + A_E \quad (1)$$

The second reason for inaudibility outdoors, and the focus of this note, is that the sound wave may be refracted due to wind or temperature effects. Normally, wind velocity increases with altitude (since frictional effects are less with greater altitude) and sound waves are refracted upward. Sound waves traveling in the same direction as the wind will be refracted downward by this wind shear. Thus, sounds tend to be heard more clearly at greater distances downwind

Fig. 1. Effects of wind shear on sound waves.

Fig. 2. Long-range audibility and acoustic shadows resulting from acoustic refraction followed by ground reflections. Top of figure is a profile of sounds emanating from a source in a temperature inversion; bottom part of figure is an overhead view of the same situation.

from the sound source than upwind. This effect is shown in Fig. 1.

The lower atmosphere normally exhibits a decreasing temperature profile with increasing altitude, and sound waves refract upward (in much the same way that light waves refract upward in the traditional mirage example). The speed of sound in dry air may be found from the following equation:

$$c \text{ (m/s)} = 331.36 + 0.6067 T \quad (2)$$

where c is the speed of sound and T is temperature in degrees centigrade.

A vertical temperature gradient of 10°C/km has the same refractive effect as a vertical wind shear of 6 m/s per km .² For the idealized case of a constant sound-speed gradient, sound waves will refract in a circular arc with radius R given by:

$$R = c_0/G \quad (3)$$

where c_0 is the sound speed at the source and G is the sound speed gradient.

When the sound speed gradient, G , changes sign at a substantial height (due to wind-induced downward refraction or from a temperature inversion, with higher temperatures aloft), sound waves can be refracted back down to the ground. This scenario can cause the sound to be audible at some distance from the source, while observers closer to the source hear nothing. The latter folks are said to be in an acoustic shadow zone. If there is adequate ground reflection, the effect can repeat itself, causing a "bulls-eye" pattern of rings of audibility and inaudibility around the source (see Fig. 2). This effect can cause audibility of sounds of battle at unusually long distances: at times, the battle of Gettysburg was inaudible ten miles away, while it was heard clearly at times in Pittsburgh, 160 miles (250 km) to the west.

An Example from the Civil War

Because of the nature of commu-

nications and military strategy in the 1860s, if a military commander inadvertently placed himself in an acoustic shadow it often had disastrous consequences. Space does not permit an extensive description of the effects of unusual acoustics in the U.S. Civil War; the interested reader is encouraged to read previous articles by the author (reprints available).^{3,4} Here is a brief account of one of the various instances from that war.

At Iuka, Mississippi, on Sept. 20, 1862, Major General Ulysses S. Grant formulated a plan typical of the day, with sounds of battle acting as a trigger for troop movements. His plan, if successful, would have brought about the defeat of one of the primary Confederate armies (under Sterling Price). Grant's plan called for forces under Brigadier General William Rosecrans to come upon Iuka (where Price's men were based) from the south. The remainder of Grant's men, under Major General Edward Ord, were to wait four miles north of Iuka until the sounds of engagement between Rosecrans's forces and those of Price were heard.

Late in the afternoon, Ord and Grant saw smoke rising from Iuka but heard nothing and assumed that Price was burning supplies to prevent their capture. Rosecrans and Price had actually been engaged for over two hours, but by the time couriers notified Grant it was too late: Price had slipped out between the two Union armies and avoided the intended pincer movement.

The culprit in this case was a strong wind blowing from north to south that had placed Grant and Ord in an acoustic shadow as sounds of battle were refracted upward over their heads.

Comment

My students seem to find such real-life cases of the effects of refraction to be interesting and I encourage others to try this interdisciplinary angle on an old topic. There are many such cases from the Civil War, and

those interested in exploring the topic more deeply will find a variety of examples from both earlier and later periods (especially from World War I).

References

1. For example, see L. C. Sutherland and G. A. Daigle, in *Handbook of Acoustics* edited by M. J. Crocker (Wiley, New York, 1998), Chap. 28.
2. R. G. Fleagle and J. A. Businger, *An Introduction to Atmospheric Physics* (Academic Press, New York, 1963), p. 306.
3. Charles Ross, "Shh! Battle in progress," *Civil War Times Illus.* **35**, 56-62 (1996).
4. Charles Ross, "Outdoor sound propagation in the US Civil War," *Applied Acoust.* **59**, 137-147 (2000).