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Blending History with Physics: Acoustic Refraction

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R
efraction is a traditional and
important concept in introduct
ory physics courses. The basic ideas
are often demonstrated through anal
gy and with ripple tanks, with sub
sequent discussion usually focusing
on optical refraction. Mirages,
prisms, lenses, fiber optics, and rain
bows all serve to illustrate the phe
nomenon.

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 interdis
ciplinary possibilities. The propaga
tion of sound outdoors has a signifi
cant 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. 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 atten
uation of the sound ($A_T$) is a com
bination of three factors: geometric
spreading of the wave $A_S$, atmospher
ic absorption $A_A$, and extra attenua
tion $A_E$, 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 turbu
lence). The effects can be described
by

$$A_T = A_S + A_A + A_E$$ (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 refract
ed downward by this wind shear.
Thus, sounds tend to be heard more
clearly at greater distances downwind
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:

\[ c \ (\text{m/s}) = 331.36 + 0.6067T \]  

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

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

\[ R = c_0/G \]  

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 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**