The Effect of Environment on Sound Propagation

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Not Refereed

The second in a series of articles taken from a paper entitled "Factors Affecting Outdoor Sound Propagation", submitted in part fulfillment of a course at Massey University, 2006

Refraction

Refraction of sound is the bending of sound waves caused by propagation through continually varying media or medium conditions[54].

Kircher found that sound tended to be higher with northerly or easterly winds than when the wind was southerly or westerly, a conclusion with which *Derham* agreed.

Experimental observations of the effect of wind were carried out by *Delaroche*[55] but, although most of his data appear valid, certain aspects (namely his conclusion that cross-wind propagation is even more effective than down-wind propagation) defy explanation.

Humboldt[56], whilst exploring in Spanish America, made systematic observations of the propagation of noise produced by the Orinoco Falls, concluding that propagation was less favourable by day than by night due to inhomogeneities caused by the unequal heating of the different ground surface under the action of the sun's rays.

Refraction due to wind shear and its effect on the propagation of sound was first explained by *Stokes*[57] who correctly described the formation of a sound shadow upwind of a source.

Note that in this case sound transmission is non-reciprocal i.e. when a wind gradient is present, the path taken by the sound in going from source to receiver is not same as that taken by sound travelling in the reverse direction, and the attenuation of sound between two given points but in opposite directions can be very different.

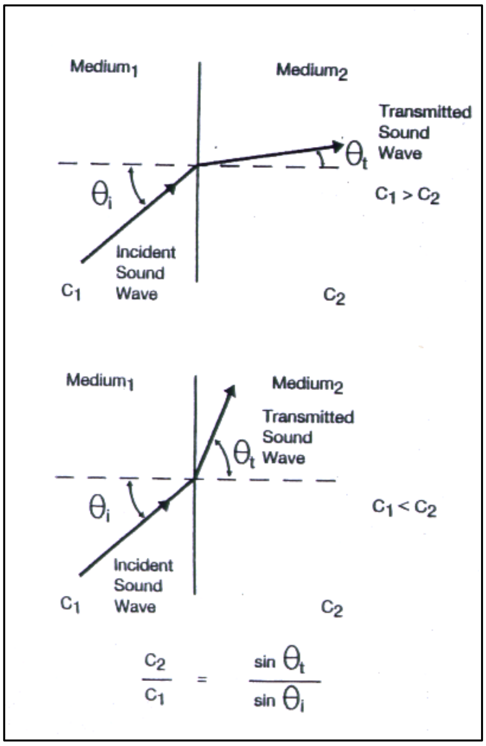

Figure 1. Concept of Snells Law when the speed of sound in medium and incident medium being $c_1 > c_2$ and $c_2 < c_1$ respectively[61].

Reynolds[58], who had independently discovered wind refraction effects published by *Stokes*, showed that refraction due to temperature gradient would also occur and that under lapse conditions typically prevailing during the day could produce sound shadowing.

Acoustic refraction due to change in sound velocity obeys laws very similar to those accounting for the optical refraction first discovered by *Snell* about the year 1621 but first published by *Descartes*[59].

Wiener and Keast[60] carried out an extensive field study of near-ground sound propagation which included sound shadowing but to date their data on shadow zone attenuation does not seem to have been compared with theoretical predication so the validity of the theory is not fully established. In practice it is found that **sound shadows typically lead to excess attenuations of around 20 to 30dB** and that such shadows can begin to show themselves within 50m of a ground level source.

Sound Refraction appears to be one of the areas of sound propagation which may be in need of further attention, for refraction can constitute a major attenuation process under practical conditions of noise propagation.

As discussed, refraction of sound is scientifically described as the bending of sound waves caused by propagation through continually varying media or medium conditions. In physics, acoustical refraction my be described by ***Snell's Law*** as follows:

$c_2/c_1 = \sin \theta_t / \sin \theta_i$

where;

c_2 = speed of sound in medium (such as air)

c_1 = speed of sound in the incident medium

θ_t = is the angle of transmission

θ_i = is the angle of incidence.

Snells law dictates that sound will change direction when traveling into a medium that conducts sound at a different speed. This can occur

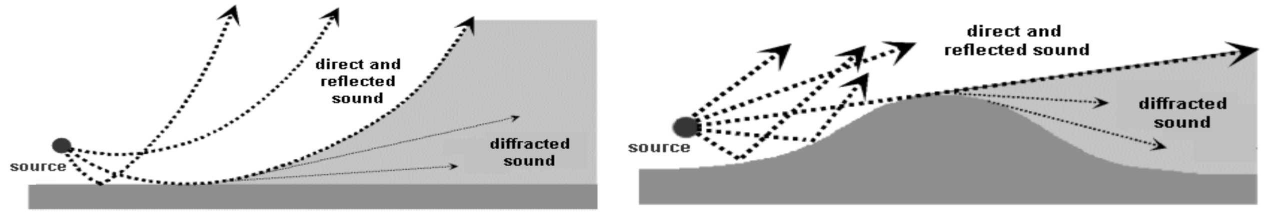

Figure 2: (Left): Diffraction into an acoustical shadow in the condition of upward refraction. (Right): Diffraction into an acoustical shadow behind a hill[63].

when a sound wave travels into a different medium or when a sound wave travels into a different condition in the same medium. Sound speed and direction change accordingly, as illustrated in **Figure 1.**

Sound waves would propagate rectilinearly only if the speed of sound is constant in space and there is no wind. Since the sound speed depends on temperature which in particular varies with height, the sound speed is almost never constant in space.

Moreover, the air is often moved by the wind that also carries the sound waves with different speeds. The additional speed of the sound due to wind also depends on height as the wind velocity increases with increasing distance above ground.

In a medium with varying speed of sound, the wave no longer propagates rectilinearly. They are much more refracted, i.e. they propagate along curved lines. This also happens to sound waves in the atmosphere.

Refraction is often visualised by sound rays that describe the direction of wave propagation like light rays.

Refraction of sound rays occurs if the sound velocity and/or wind speed changes along the ray path, i.e. there are gradients of wind and temperature. The refraction influences the sound level.

The angle of sound incidence at the ground changes, which results in varying ground attenuation. In downwind conditions and/or temperature inversion, the sound rays are bent downwards, and in upwind conditions and/or lapse, they are bent upwards. Upwind conditions and/or lapse create areas, known as sound shadow zones, where no direct sound ray can reach.

The refractive effects of temperature gradients and wind component gradients in the direction of propagation are additive. As the refractive conditions change, the path lengths of the various waves intersecting at the receiver change.

Thus, depending on the phase relationships between these waves, some frequencies will be amplified and others subdued.

Inside acoustical shadows, the noise is strongly damped and the noise level is substantially lower than it would be at the same range without upward refraction (up to approximately 20dB).

On the contrary, downward refraction (temperature inversion or downwind propagation) causes multiple reflections at the ground and is known as a condition that is favourable to sound propagation over long distances (but not when the ground is acoustically hard).

Diffraction of Sound Waves

Diffraction is the phenomenon of sound waves apparently bending around or over barriers and walls. This occurs when the wavelength of the incident sound on the barrier is comparable to or larger than the height and width dimensions of the barrier[62].

The diffraction of sound waves is an important mechanism that sheds acoustical energy into *acoustical shadows,* i.e. into areas that are prevented from direct incidence of sound by an obstacle.

As a result of diffraction it is therefore possible, for example, to hear the noise of a road even in the "backyard" of a building. A physical explanation of diffraction is ***Van Huygen's Principle*** of elementary waves.

Diffraction also happens at convexly curved terrain surfaces, e.g. at the edges of slopes and hills. Diffraction is further responsible for the incidence of sound energy into acoustical shadows that were formed by upward refraction by sound waves. Therefore it is not completely quiet in shadow zones.

Reflection of Sound Waves

Reflection of sound occurs when sound waves "bounce off" a surface at the same angle, with respect to a line perpendicular to the surface, at which the sound was incident on the surface (i.e. the angle of incidence = angle of reflection, similar to when light encounters a mirror). Figure 3 illustrates the concept of reflection (for a smooth flat surface).

Sound waves that hit the surface of an obstacle (ground, building, noise barrier etc.) are reflected with some of the sound energy being absorbed. It is a general rule that the incidence angle and the reflection angle are equal.

Sound waves that directly reach a receiver (direct sound ray) could superimpose onto the waves that were reflected (reflected sound ray). In the case of a coherent source of sound of a given frequency (wave length) and dependent on the respective travel distance, the sound at a receiver position is either amplified (*constructive interference*) or reduced (*destructive interference*).

Scattering of Sound Waves

Scattering of sound occurs when sound waves are propagating through the atmosphere and meet a region of inhomogeneity (a local variation in sound speed or air density) and some of their energy is re-directed into many other directions.

In environmental noise situations, scattering is caused by air turbulence, rough surfaces, and obstacles such as trees. The scattering of sound by rain, snow or fog at ordinary frequencies can occur but is generally insignificant[65].

Above rough ground surfaces the atmosphere is mostly turbulent, i.e. fluctuating eddies in the wind field lead to random perturbations of air pressure and density.

If the size of the eddies is in the order of the wave length of the sound wave, a part of the sound energy is scattered and deviated from its original direction of propagation.

Scattering of sound waves is also caused by obstacles in the air, for example twigs and leaves of trees and bushes.

Scattering and diffraction may be responsible for the penetration of sound energy into acoustical shadow zones behind larger obstacles (buildings, hills) or in the situation of upward refraction.

Turbulence

Turbulence can be composed of vertical movements, up and down, which may exist in the atmosphere at that particular level. One cause could be obstructions on the Earth's surface which surprisingly can have an effect in disturbing the air flow up to some 500 metres.

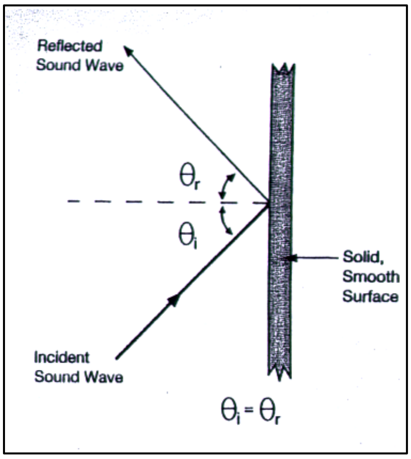

Figure 3: The concept of reflecting sound waves (smooth, flat surface)[64].

Consider how an obstruction in the bed of a stream or river can cause ripples or even 'rapids' at the surface of the water.

Again, such a situation can occur in the higher levels due to atmospheric variations.

This turbulence can result in parcels of air of differing temperatures and humidity mixing and causing condensation[66].

Turbulence in the atmosphere will cause sound fluctuations, the amplitude of which generally increases with frequency and with increasing distance[67].

Ingard reported gustiness causing an excess attenuation of 4 to 6 dB/100m but this was an average value, and the sound level at the receiver could go up by 20dB and possibly more.

Ingard also calculated that for most of the time over distances of approx 2km the attenuation due to irregularities in the wind structure such as gustiness seemed to have a major effect of the magnitude of excess attenuation through air.

Beranek[68] noted that some experiments have found reductions of 10 to 20 dBA over 1.5 to 2.5km due to turbulent mixing in air during windy conditions.

Wind

Wind is the movement of air. Warm air rises, so air that is warmed by the sun rises up into the Earth's atmosphere. Cold air particles rush in to fill the gap left by the rising warm air and that movement of air causes wind.

When the warm air particles cool they drop down, get warmed again and rise again. The faster that air is warmed and rises the faster the winds that are created.

Isobars can tell an instant story as they have a similar relationship to terrain contours on a map. Contours when seen close together indicate steep rising terrain over a short distance. Isobars when closer together on a chart depict a sharp change in pressure over a short distance.

Air pressure is simply the weight of all the air vertically above a place. At mean sea level the air pressure is approx 1000 hectoPascals (hPa) while at altitudes of 10,000m (or around the height of Mount Everest) the air pressure is nearer 300 hPa.

Whenever there is a difference in air pressure between two places on the Earths surface, the wind will try to even things up by blowing from high pressure to low.

The bigger the difference in pressure between the two areas, the stronger the wind will blow. Air has the properties of a fluid and naturally demands equilibrium, the urge from high pressure areas to low pressure areas is known as the ***pressure gradient force***.

The concept of the wind moving from high to low is however not that straightforward. The Earths spin affects winds, currents and anything else which is free to move over the surface.

In the case of wind the air tries to flow straight from the high pressure area to low at the equator. At the same time the earth is spinning so the path is actually a sweeping curve.

Because the Earth is spinning, the winds are pushed off course to the right of their expected path in the northern hemisphere and to the left in the southern hemisphere.

Winds in the northern hemisphere circulate anticlockwise around the areas of low pressure and clockwise in the southern hemisphere. This is known as the ***Coriolis Effect*** (a force which deflects the air mass).

The same thing happens in smaller scale highs and lows. Instead of blowing straight out from a high, the winds spiral outwards; clockwise in the northern hemisphere and anticlockwise in the southern hemisphere.

All ***local wind systems*** are created by adjacent areas being unevenly heated by the sun. During the day as the hill, terrain or mountain slopes absorb sunshine, the air directly in contact with them starts to rise as it becomes warmer, and therefore less dense and lighter than the valley air. Cooler air from the valley below rushes in to replace it, creating a breeze blowing up the slope.

At night the situation is reversed, with no sun to warm the air cooling mountain slope, the increasing dense heavier air “slides” down into the valley producing a breeze in the opposite direction.

Solar heating affects land and bodies

of water differently. Air over land warms and cools faster than over the sea. These temperature contrasts generate offshore breezes and onshore sea breezes.

Coastal regions of oceans or large lakes have their own local wind systems.

When moving air encounters mountains or other such barriers, it can do only one of two things. First it can flow around them and through the gaps between them. When funneled into a deep narrow valley, airflow will speed up and cause the wind to blow from a particular direction.

However in most cases the wind does not simply move around a barrier but goes up and over it. Conditions may then be right for what is known as the ***Foehn Effect***. Although its impact will depend upon local weather conditions and whether the topography involves gentle slopes, steep hillside or mountains, these variable phenomena are often responsible for small-scale weather patterns known as ***microclimates***.

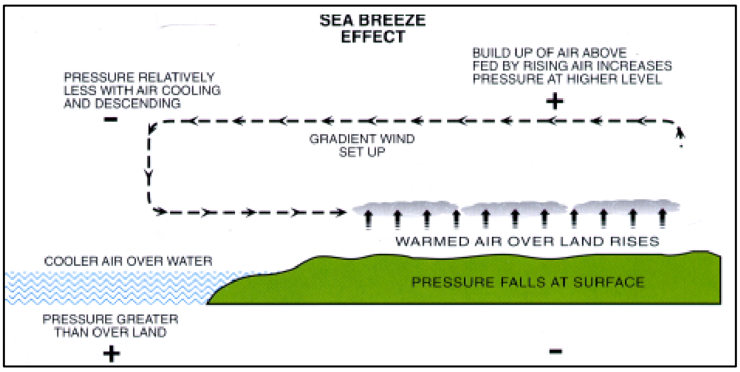

Figure 4: Concept of Sea Breeze Effect[71]**.**

Due to the properties of convection, the air over land is usually warmer than air over the sea. When those air particles above the land are warmed enough to rise into the atmosphere the cold air from over the sea comes rushing in to fill the gap.

That is why we often get cold winds from the sea. Land areas warm up much more quickly than the sea; thus the air in contact with the warm ground for a few kilometres inland from the coast can become less dense and relatively lighter then the air over the water.

Being lighter, the air over the land rises and a slight decrease in pressure takes place at the surface. However, the rising air meeting the air above forms a higher pressure layer aloft and this sets up a gradient where the flow of air moves out towards the sea.

At the same time the cooler, denser air over the sea flows in to fill the lower pressure area at the surface. This is known as ***Sea Breeze Effect*** (as illustrated in **Figure 4**) and it will invariably override the prevailing wind at the time in the lower levels – given that the latter is not too strong.

Conversely, when the sun goes down the land radiates its warmth into the atmosphere far quicker then the sea, so causing a reverse effect.

Katabatic Winds

When the sun goes down, the air on top of the mountain, being at a greater height, is cooler than the air at the bottom.

Thus, on becoming denser and heavier, it flows down the mountain side into the valley; this flow is known as a ***katabatic wind***.

Anabatic Winds

In the morning, when the sun rises, the valley will warm more quickly than the mountain top. This warmer air, being less dense, will begin to rise up the slopes; this air flow is known as an ***anabatic wind***.

Figure 5 illustrates a schematic of the Katabatic and Anabatic winds.

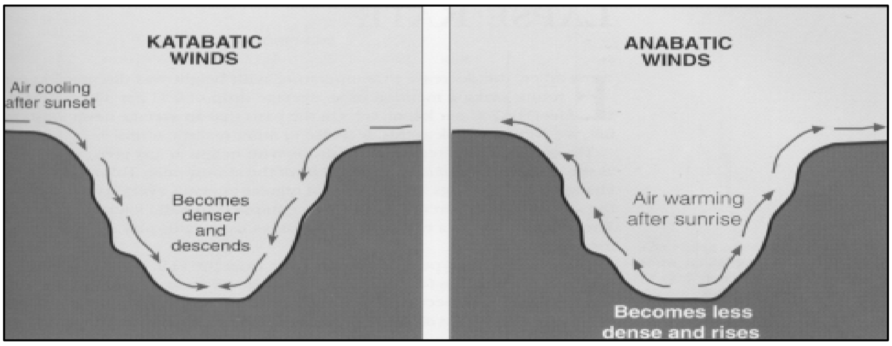

Figure 5: Schematic of the Katabatic and Anabatic winds[72].

Within dense vegetation such as a forest, air movements are reduced where complete calm exists at ground level.

This calm is an outstanding feature because it influences both temperature and humidity and hence the way outdoors sound propagates.

Figure 6 illustrates the distribution of velocities with height as affected by the canopy of a forest for wind velocities. Note the decrease in velocity near the ground.

Turbulence can be caused by gusting of or obstructions to the wind flow. This introduces fluctuations of noise levels.

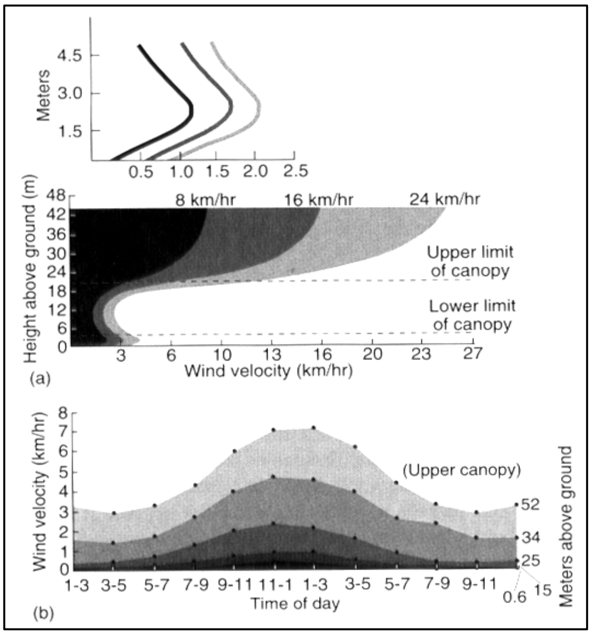

Figure 6: (a) Distribution of wind velocities with height as affect by the canopy of a forest for wind velocity 43m above the ground. (b) Average wind velocity during a June day inside a forest[73].

The sound is scattered in the turbulent region and results in either an increase or a decrease in the levels received at a given position.

Vegetation also deflects wind flow up and over its top. If the vegetation is narrow such as windbreak or hedge the microclimate on the leeward side may be affected.

The deflected wind creates eddies immediately behind the vegetation, in which wind speed is low. Beyond is an area of turbulence in which the climate tends to be drier and cooler than normally exists.

The same principles apply for a barrier such as an acoustic barrier. **Figure 7a** illustrates the effect of a hedge or windbreak (barrier).

Figure 7b illustrates the effect of wind induced turbulence on sound propagation over a solid purpose built noise barrier.

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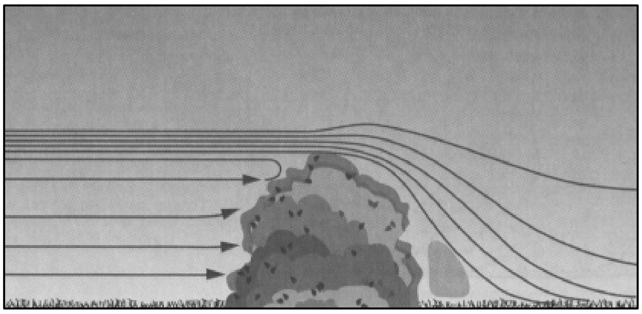

Figure 7A: The effect of a windbreak on wind flow. Note the area of relative calm close to the barrier and the degree of turbulence some distance beyond[74].

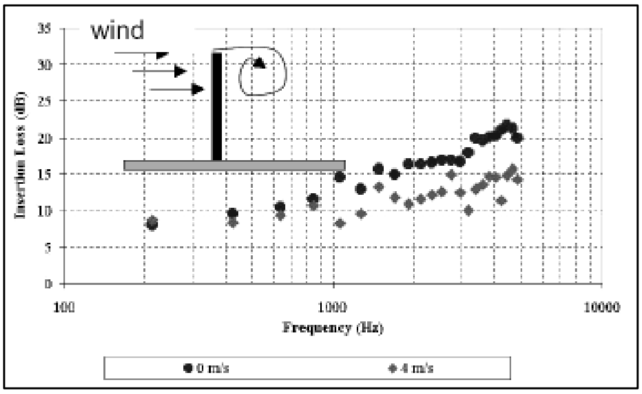

Figure 7B: Effects of wind induced turbulence on sound propagation over a solid noise screen[75].

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