Atmospheric Sound Propagation Considerations for the Birdstrike Project

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Sound propagates as a longitudinal wave disturbance in compressible media such as air. If the properties of the medium vary with spatial position or if the medium itself is in motion, the sound propagation will be affected. Therefore, for the Birdstrike project it is important to understand the *potential* effects of atmospheric temperature, wind, relative humidity, and other effects that will be encountered when attempting to monitor the sound of birdcalls propagating through the air.

1 A Simple Model for Sound Propagation

There are three convenient ideal sound source models: the point, line and plane **[1, 2]**. The behavior of each model is based on the assumption that, in a homogeneous medium, sound propagation from a single point source is purely spherical. Consequently, the sound intensity in any particular direction is inversely proportional to the increasing surface area of the sphere **[1, 2]**. To a first approximation the vocalizations from a single bird can be modeled as an acoustic point source.

If we let *SWL* represent the sound pressure level measured at 1 meter from the sound source, then at a distance of r meters, the sound pressure level will be: $SPL = SWL_{point} - 10\log(4\pi r^2)\ dB$

which can be simplified as: $SPL = SWL_{point} - 20\log(r) - 11\ dB$. This is known as the standard *inverse square law* for point sources and is most often referred to as a 6dB reduction in relative intensity per doubling of distance. Note that if the ground is very hard and reflective, we can compensate for the ground reflection by replacing 11dB with 8dB because the reflective sound waves will be added to the direct ones (assuming incoherent addition). Thus, we can get: $SPL = SWL_{point} - 20\log(r) - 8\ dB$.

We know line and plane sources can be regarded as consisting of an infinite number of evenly distributed individual point sources. So, for a line source, the sound pressure level becomes: $SPL = SWL_{point} - 10\log(4\pi r)$, which results in only a 3dB reduction in relative intensity per doubling of distance. As to the plane source model, the sound pressure level can be written as: $SPL = SWL_{plane}$ **[2]**. Actually, at a very great distance or very small size, both line and plane sources will ultimately approximate an ideal point source. This is true for the case of bird sound recording.

The speed that sound propagates in air depends on the air temperature. Higher temperatures produce higher sound speed. The relationship between the temperature of air and the sound speed can be expressed as **[1, 5, 6, 7]**: $V_t = V_0\sqrt{1+\frac{t}{273}}$, where t is the Celsius temperature, V_t stands for the sound speed at temperature t, V_0 represents the sound speed at 0°C, which is 331.5 m/s. Generally speaking, for each degree Celsius increase in temperature, the speed of sound increases by 0.61 m/sec.

1.1 Effect of wind

As mentioned previously, if the air itself is moving due to wind, the sound propagating through the air will be carried in the moving air mass. We give a simple example for bird sound propagation here. We assume the temperature of the air is uniform and that there are no local variations in the sound speed except for the wind. We regard the sound source (vocalizing bird) and the dish microphone as a *point source* and *point receiver*, respectively, and assume they are in the same plane as the wind vector, e.g., in the horizontal plane. We further assume that the source (bird) and the receiver (dish) are *stationary* with respect to each other and with respect to the ground.

We describe the sound propagation vectors as follows. The speed of sound without wind for the bird vocalization is given by V_1 and its direction by θ_1, the wind speed is V_2 and its direction is θ_2, and the wind-corrected sound speed measured at the dish microphone is V and its direction is θ. Since the sound source is regarded as a stationary point source, its sound waves will emanate spherically. The spatial motion of the wave front will therefore consist of the vector sum of the spherical sound propagation vector and the wind vector. The wave front will also include sound energy reflected from the ground and from nearby obstructions, but these effects do not alter the simple propagation model.

The wind effect can be viewed as a shift in the origin of the spherical sound propagation. In other words, the wave front launched at the source is carried by the wind as it propagates toward the receiver. Thus, the dish microphone pointing direction can be optimized by aligning its primary axis with the wind-altered sound propagation vector.

1.1.1 Wind compensation example

An example of this situation is depicted in Figure 1. The semi-concentric (blue) circles indicate the wave front position with increasing time: the spherically propagating wave front is systematically shifted due to the wind so that by the time it arrives at the dish position *it appears as if it is emanating from a shifted source position*. As the receiver can only make use of the information as it receives it, the disturbance of the propagation vector can be compensated for by slightly re-pointing the dish by the angle $\Delta\theta$.

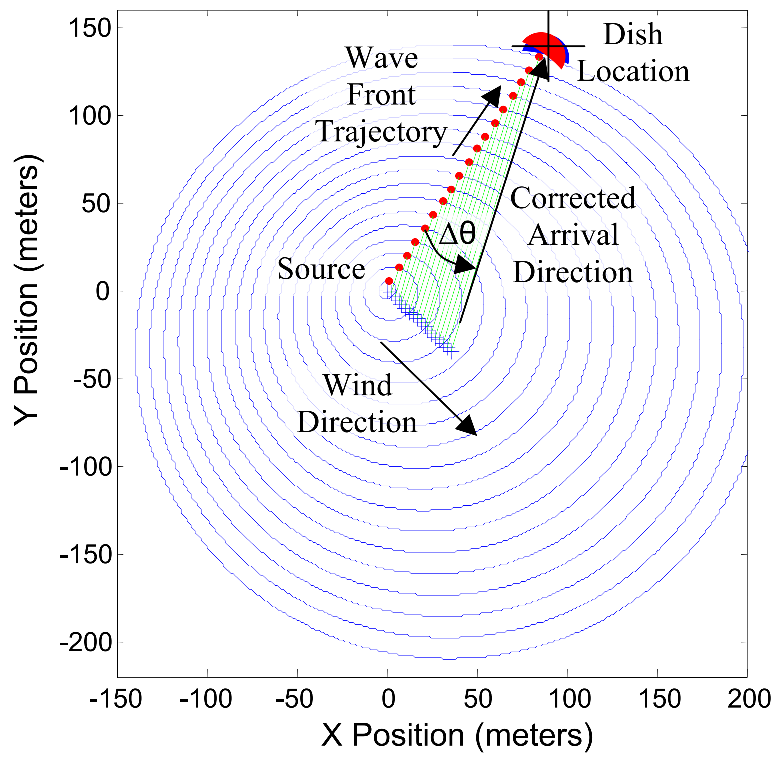


Figure 1: Effect of wind (exaggerated wind speed)

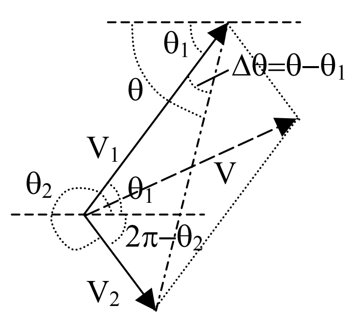


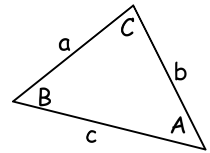
Figure 2: Geometry summary for propagation

The resultant scalar sound speed V is obtained from the magnitude of the vector sum of $\mathbf{V}_1$ and $\mathbf{V}_2$, namely

$$\begin{aligned} V^2 &= V_1^2 + V_2^2 + 2V_1V_2\cos(\theta_1 + 2\pi - \theta_2) \\ &= V_1^2 + V_2^2 + 2V_1V_2\cos(\theta_1 - \theta_2) \end{aligned},$$

The vector analysis of the angular correction can be found using the Law of Cosines:

$$c^2 = a^2 + b^2 - 2ab\cos(C) \ .$$



This yields an expression involving the angle of arrival correction Δθ:

$V_2^2 = V_1^2 + V^2 - 2V_1V\cos(\Delta\theta)$, from which Δθ can be solved.

Thus, the equations describing this behavior are as follows.

$$V_1 = V_0\sqrt{1 + \frac{t}{273}} \qquad (1)$$

$$V = \sqrt{V_1^2 + V_2^2 + 2V_1V_2\cos(\theta_1 - \theta_2)} \qquad (2)$$

$$\Delta\theta = \theta - \theta_1 = \arccos\left(\frac{V^2 + V_1^2 - V_2^2}{2VV_1}\right) * \mathrm{sgn}(\Delta\theta) \ , \qquad (3)$$

where $\mathrm{sgn}(\Delta\theta) = \begin{cases} -1 & if\ \theta_2 < \theta_1\ or\ \theta_2 > \theta_1 + 180^\circ \\ 1 & else \end{cases}$

So, if there is wind, we can steer the dish microphone by $\Delta\theta$ in order to align the primary axis of the dish with the normal to the arriving wave front (counterclockwise if positive, clockwise if negative). Note also that the slight change in sound speed corresponds to a Doppler-like frequency shift.

1.1.2 Example scenario for Panama City

Here, we take the Panama City, Florida, vicinity as an example to show how the model can be used. The average temperatures for Panama City are shown in Figure 3. **[9]**. In Table 1, we show the results of using this model for several arbitrary variables. For example, the average temperature in Panama in January is about 10°C and we assume the wind is Fresh Breeze (Table 2 shows the Beaufort Scales for wind speed **[8]**), i.e. about 10 m/s. According to Equations (1)-(3), we find that the original sound speed is 337.5 m/s. If we assume the original sound direction and wind direction are 60 and 30 degrees, respectively (these two parameters can be measured), we find that the corrected sound speed at the dish is 346.2 m/s, and the direction change is -0.8275 degree. Since the direction change is negative, we must steer the dish microphone clockwise by 0.8275 degree.

In Table 3 we show the worst-case angular correction as a function of wind speed and temperature. Here we assume the original sound speed is 312.8 m/s (for -30°C), 331.5 m/s (for 0°C), and 349.2 m/s (for 30°C). The maximum angular correction occurs for wind propagating at ±90° relative to the target-to-dish vector, and can be negative or positive. We can see that the maximum angular correction increases with the wind speed increases or the temperature decreases. Also, we can see that the increase in the maximum angular correction is approximately proportional to the increase in the wind speed or decrease in the temperature.

We know the beamwidth of the dish microphone is expressed as: $Bw = \frac{70\lambda}{D}$, where λ is the wavelength, and D is the diameter of the dish microphone. If we let D = 40cm and the frequency = 4 kHz, we find that *Bw* is 15 degrees when the temperature is 10°C. It seems that in this case we may not need to steer the dish microphone since the beamwidth of the mainlobe is much greater than the direction change. However, whether to steer the microphone or not, and how much to steer, will depend on the parameters of the dish microphone and the desired sound level.

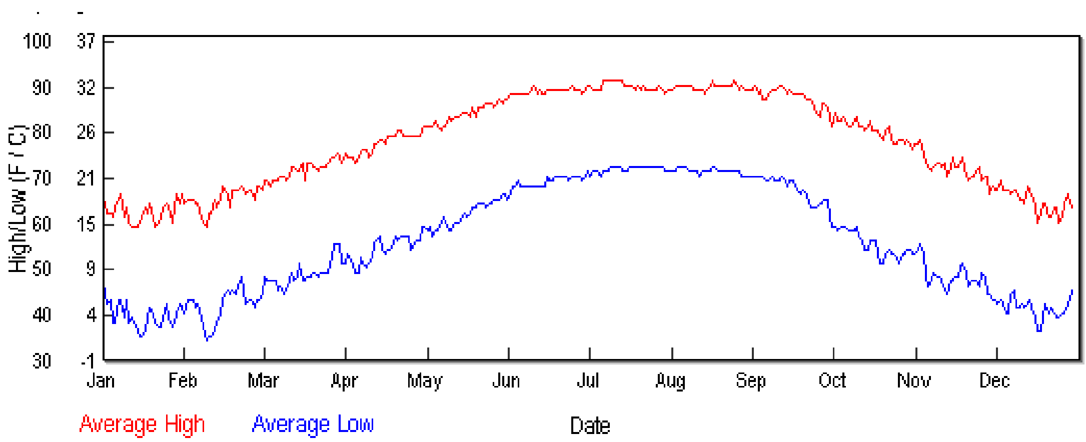


Figure 3: Average temperature information, Panama City, FL

Table 1: Example results using the simple model

Temperature (°C)	Original Sound Speed (m/s)	Original Sound Direction (°)	Wind Speed (m/s)	Wind Speed Beaufort Scales	Wind Direction (°)	Corrected Sound Speed (m/s)	Direction Change (°)
10	337.5	60	10	6	30	346.2	-0.8275
20	343.4	45	10	6	225	333.4	0
30	349.2	0	18	8	330	364.9	-1.8
-1	330.9	90	15	7	110	345.0	0.8520
35	352.1	60	25	10	30	373.9	-1.9155

Table 2: Beaufort Scale (Wind Speed)

Force	**Speed (m/s)**	**Name**	**Conditions at Sea**	**Conditions on Land**
0	< 0.45	Calm	Sea like a mirror.	Smoke rises vertically.
1	0.45 --- 1.8	Light air	Ripples only.	Smoke drifts and leaves rustle.

2	2.25--- 3.15	Light breeze	Small wavelets (0.2 m). Crests have a glassy appearance.	Wind felt on face.
3	3.6 --- 4.95	Gentle breeze	Large wavelets (0.6 m), crests begin to break.	Flags extended, leaves move.
4	5.4 --- 8.1	Moderate breeze	Small waves (1 m), some whitecaps.	Dust and small branches move.
5	8.55 --- 9.6	Fresh breeze	Moderate waves (1.8 m), many whitecaps.	Small trees begin to sway.
6	10.05 --- 13.95	Strong breeze	Large waves (3 m), probably some spray.	Large branches move, wires whistle, umbrellas are difficult to control.
7	14.4 --- 17.1	Near gale	Mounting sea (4 m) with foam blown in streaks downwind.	Whole trees in motion, inconvenience in walking.
8	17.55 --- 20.7	Gale	Moderately high waves (5.5 m), crests break into spindrift.	Difficult to walk against wind. Twigs and small branches blown off trees.
9	21.15 --- 24.3	Strong gale	High waves (7 m), dense foam, visibility affected.	Minor structural damage may occur (shingles blown off roofs).
10	24.75 --- 28.35	Storm	Very high waves (9 m), heavy sea roll, visibility impaired. Surface generally white.	Trees uprooted, structural damage likely.
11	28.8 --- 32.85	Violent storm	Exceptionally high waves (11 m), visibility poor.	Widespread damage to structures.
12	> 33.3	Hurricane	14 m waves, air filled with foam and spray, visibility bad.	Severe structural damage to buildings, wide spread devastation.

Table 3: Maximum angular correction versus wind speed and temperature

Wind Speed		*Maximum angular correction $\Delta\theta_{max}$ (°)*		
m/s	*Beaufort Scale*	*At -30°C*	*At 0°C*	*At 30°C*
0.2	0	0.0366	0.0346	0.0328
1.0	1	0.1832	0.1728	0.1641
2.0	2	0.3663	0.3457	0.3282
3.0	2	0.5495	0.5185	0.4922
4.0	3	0.7326	0.6913	0.6563
5.0	3	0.9158	0.8641	0.8203
6.0	4	1.0989	1.0369	0.9844
7.0	4	1.2820	1.2097	1.1484
8.0	4	1.4650	1.3824	1.3124
9.0	5	1.6481	1.5552	1.4764
10.0	5	1.8311	1.7279	1.6403
11.0	6	2.0140	1.9005	1.8043

12.0	6	2.1970	2.0732	1.9682
13.0	6	2.3798	2.2457	2.1320
14.0	7	2.5627	2.4183	2.2959
15.0	7	2.7455	2.5908	2.4596
16.0	7	2.9282	2.7633	2.6234
17.0	7	3.1108	2.9357	2.7871
18.0	8	3.2934	3.1080	2.9508
19.0	8	3.4760	3.2803	3.1144
20.0	8	3.6584	3.4526	3.2780

1.2 Effect of a moving source

If the vocalizing bird is moving, the simple model can be extended to include the bird's ground-relative speed (V_3) and angular trajectory (θ_3), assuming this information can be obtained from radar scan data. The propagation vector at the dish will now vary as the source moves with time, so the dish pointing vector will need to be updated while taking into account the time required for the sound to propagate from the bird to the dish. In other words, the dish should be pointed to where the bird "was" when the vocalization started, rather than where the bird "is" at that instant.

The wind effects described in the previous section will be unchanged for the moving source case, except for the propagation time correction, so the basic equations (1)-(3) require time updating to reflect the time varying geometry.

1.3 Effect of an ensemble of sources

In many cases we should expect a flock of vocalizing birds rather than a single source. The spatial distribution of the sources may be evident from the radar scans if the birds are in flight, but spatial data may be unavailable for flocks of birds on the ground or water, roosting in trees, etc. In either case the simple point-source model may be inappropriate. A strategy involving an acoustical scan (e.g., dish rotation) to determine which direction provides the greatest signal level may be productive, but that is an area for further research.

2 Other Atmospheric and Environmental Factors

In the previous section we assume that the temperature and wind is constant and we disregard other meteorological factors, so we obtain a very simple model. In the real environment conditions may be quite different. Outdoor sound propagation may vary greatly at distances of hundreds of meters from the source due to the real environment, including geometric spreading, atmospheric conditions, ground surfaces, and obstructions or reflections.

As the specific environmental conditions will vary greatly from one location to another, *it is not possible to generate comprehensive mathematical models for the general case*. Thus, the various studies and reports referenced in this section are unavoidably more anecdotal and empirical rather than fully parametric mathematical expressions.

Though the ideal point model may work in the case of bird sound recording, we can use the model designed by Bloemhof **[2, 3]** if we want a more accurate model. The atmospheric conditions also affect sound propagation. Temperature and relative humidity play an important role on sound levels, while precipitation (rain, snow, or fog) have an insignificant effect on sound levels, although these phenomena will obviously affect the humidity and may affect wind and temperature gradients, and perhaps create noise due to raindrops. It is stated in **[1]** that under normal circumstances atmospheric conditions can be neglected except where long distances or very high frequencies are involved. Since in the case of bird sound recording the distance may exceed a few hundred meters, we should take this factor into account and we may use the parameters provided in reference **[1]**.

2.1 Non-Uniform Wind and Temperature Gradients

As mentioned previously, the speed that sound propagates in air depends on the temperature of air. Higher temperatures result in a higher sound speed. In the real environment, the temperature of air is not uniform, so there will be variations in the sound speed. In the day or in summer, when the ground surface is hotter than the upper air, sound rays tend to be bent upwards slightly due to the temperature gradient. In winter or at night, when the temperature near the ground is lower than that of the upper air, sound energy tends to be bent downwards **[1, 4]**. When a wind is blowing there will always be a wind gradient, which results in sound waves propagating upwind being 'bent' upwards and those propagating downwind being 'bent' downwards. Due to the temperature and wind gradients, the sound levels measured can be very different to those predicted from geometrical spreading and atmospheric absorption considerations alone. According to **[1]**, these differences may be as great as 20 dB. These effects are particularly important in the case of bird sound recording, where sound is propagating over various surfaces including water, grass, and concrete.

2.2 Ground Surface and Obstacles

If the sound propagates over ground, there will be some attenuation because of acoustic energy losses on reflection. Smooth and hard ground will generally produce less absorption than thick grass. Higher frequencies are almost always attenuated more than lower frequencies. It is also reported that a band of trees hundreds of meters deep can achieve significant attenuation **[1, 5]**, indicating that the local vegetation and ground conditions must be considered carefully before any system deployment. Moreover, the vegetative cover will vary from season to season in deciduous zones.

There can also be significant attenuation if there is a solid obstacle which is at least high enough to obscure the 'line of sight' between the bird and the dish microphone **[6]**. We should also consider these factors because they may exist in the case of bird sound recording.

2.3 Humidity Effects

The relative humidity of the air causes frequency-dependent sound absorption due to molecular thermal relaxation. The attenuation is found to increase monotonically with increasing frequency, and is the greatest for relative humidities in the 10-30% range. The empirical data for attenuation in air at 20°C is shown in Figure 4. Below 4kHz, the worst-case humidity attenuation corresponds to 0.1dB/m.

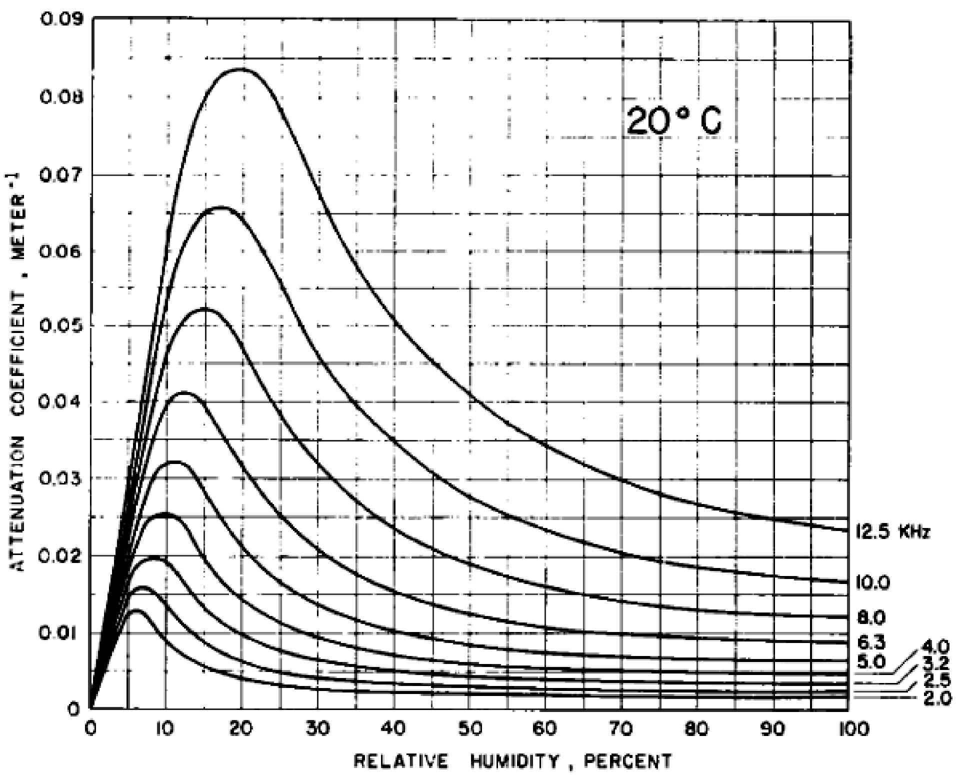


Figure 4: Attenuation coefficient versus relative humidity (%) for frequencies between 2 kHz and 12.5 kHz at 20°C (from [3], figure 5)

In summary, the importance of these atmospheric factors depends on the situation under consideration. For example, for a bird on the ground and a dish microphone very close by, say, 10 meters apart, only geometrical spreading needs to be considered. If the dish microphone is a large distance from the bird, then ground effects and atmospheric effects must also be considered. If the bird is flying overhead, then geometric spreading and atmospheric effects need to be considered **[1]**.

3 References

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