4aPA4. Propagation of N-waves in a turbulent and refracting atmosphere with
ground effects (laboratory-scale experiment)
Sébastien Ollivier*, Edouard Salze and Philippe Blanc-Benon

*Corresponding author's address: LMFA UMR CNRS 5509, University of Lyon, Ecole Centrale de Lyon, Ecully, 69134, -, France, sebastien.ollivier@univ-lyon1.fr

Sound propagation in a refracting atmosphere leads to the formation of a geometrical shadow zone close to the ground, and of an illuminated zone above a limiting ray. Without turbulence, acoustic waves can be diffracted into the shadow zone close to the ground. When propagating through a turbulent atmosphere, it is known that waves can be distorted, scattered or focused. In order to investigate how turbulence modifies the pressure field into the shadow zone, a well controlled laboratory-scale experiment has been performed. An electrical spark source is used to generate short duration (20 μs) and high pressure (1500 Pa) N-waves. A convex surface models the effect of an upward refracting atmosphere, and a heating grid generates thermal turbulence. To compute statistics of wave parameters variation, seven 1/8 inch microphones have been used to record 2000 waves at each position after propagation through the turbulent field. Wave parameters (peak pressure, rise time) obtained with turbulence are compared to data obtained without turbulence. Results show that turbulence scatters sound into the shadow zone, which increases significantly the noise level.

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INTRODUCTION

In the atmosphere, negative sound-speed gradients refract upward acoustical rays, leading to the formation of an acoustical shadow zone above the ground. However, as illustrated in figure 1, in a turbulent and refracting atmosphere acoustic energy can be transmitted into the shadow zone either by atmospheric turbulence, that randomly deviates propagation paths and scatters acoustic waves, or by the diffraction by the ground. Concerning aircraft noise, the consequence of the scattering of energy into the shadow zone is the widening of the primary carpet predicted from geometrical acoustics approximation. The study of the influence of turbulence and ground on the propagation into a shadow zone is therefore of major interest to estimate annoyance due to aircraft noise. The interest for the study of the propagation of high amplitude $N$-waves in a turbulent and refracting atmosphere concerns mainly sonic boom, but general results also apply to any wideband noise source. Some authors performed outdoors measurements in order to study the propagation of sound into a shadow zone in real atmospheric conditions \[1, 2\], but the difficulty to control separately the refraction due to temperature or wind gradients, and atmospheric turbulence limits the analysis. In order to control separately the effects of ground reflections, refraction and atmospheric turbulence, downscaled experiments can be performed in laboratory. A major advantage of laboratory experiments is that the acoustic source and the propagation medium can be well controlled, and a large number of waves randomly distorted by turbulence can be recorded. With this approach, using turbulent jets and spark sound sources, the propagation of $N$-waves through kinematic turbulence has been studied by Lipkens and later by Averianov \[7, 8\].

To study sound propagation into a shadow zone (without turbulence), laboratory-scale experiments have been performed using a temperature gradient \[3\], or an inhomogeneous mixing of CO$_2$ and air \[4\]. However, it is difficult to control a sound-speed gradient using these methods, therefore an alternative approach is to study how sound propagates in a geometrical shadow zone created by a curved boundary (without temperature or density gradient), as illustrated in figure 2. Linear and non-linear sound propagation into a shadow zone have been studied by several authors \[2, 5, 6\]. Laboratory scale experiments with turbulence above a curved rigid boundary have already been performed by the present authors in linear propagation regime \[9\], and also in nonlinear propagation regime \[10\]. However, some open questions remained after this last study, mainly because of some limitations of the experimental setup. Taking advantage of extensive characterizations of pressure $N$-waves generated by a spark source\[13\] and of a much better knowledge of microphones response, a new experiment has been designed to study nonlinear propagation of $N$ waves through a turbulent atmosphere above a curved boundary that create a geometrical shadow zone similarly to the effect of a soundspeed gradient. In this communication, some results of this experiment will be discussed, and the two mechanisms responsible for sound propagation into the shadow zone are highlighted: diffraction by the ground, and turbulence scattering (figure 1).

![Figure 1: Schematic of sound propagation in a turbulent and refracting atmosphere over a flat surface](image)

DESCRIPTION OF THE EXPERIMENT

An electrical spark source is used to generate short duration and high pressure $N$-waves. The source is made of two tungsten electrodes separated by a gap of 20 mm and connected to a 20 kV electrical supply. The voltage between the electrodes is increased, and when the voltage is enough high, a short duration spark is generated. Due to the sudden local heating when the spark is generated, a pressure pulse is emitted.
**FIGURE 2:** Formation of a shadow zone above a convex boundary.

**FIGURE 3:** Waveform recorded at 30 cm from the spark source (black line) and corresponding ideal N-wave (red lines). Definition of the positive peak pressure $P_{\text{max}}$, half-duration $T$ and rise time $\tau$. 
Since the pressure level is very high (tens of kPa) the propagation is nonlinear, and the waveform evolves towards an $N$-wave a few centimeters away from the source. Acoustic waves are measured using 1/8 inch Brüel & Kjær microphones (type 4138) which are flush-mounted in a baffle in order to postpone diffraction effects. The microphone signal is amplified using a Brüel & Kjær Nexus amplifier, whose frequency response has been extended (-3dB cut-off at 200 kHz). The amplifier output voltage is digitized at a sampling frequency of 10 MHz. The microphone baffle is mounted on a turntable and both the position and the angle of the baffle are remote-controlled. The microphone directivity in the high frequency range has a great influence on the measured waveforms [11], thus the baffle is oriented perpendicularly to the ray path (normal incidence). The characteristics of the emitted wave have been studied in details previously by the present authors using both microphones and optical methods [12, 13, 14]. As illustrated in figure 3, the parameters of the wave discussed hereafter are: the positive peak pressure of the wave $P_{\text{max}}$; the "half duration" $T$, defined as the time interval between the middle of the front shock and the first zero-crossing of the waveform; and the rise time $\tau$ of the front shock. The rise time is defined here as the time interval during which the pressure rises from 10% to 90% of the positive peak pressure $P_{\text{max}}$. Typical values at 30 cm from the source are $P_{\text{max}} = 700$ Pa, $T = 22$ $\mu$s and $\tau = 0.4$ $\mu$s [13]. In figure 3, the measured waveform (black line) is plotted together with the corresponding theoretical symmetric $N$-wave (red line). The generated pressure wave is not exactly symmetric, and additional differences are mainly caused by the filtering of the microphone: the limited frequency response of the microphone causes an overestimation of the rise time, and oscillations at the resonant frequency of the microphone appear on the measured waveform [11, 12, 13, 15].

Thermal turbulence is generated by a 4.4m x 1m heating grid of electrical resistors, with a square mesh of 9 cm. Temperature fluctuations have been measured 1.6 meter above the grid and analyzed. The mean temperature is 35°C, and the root-mean square fluctuations is of the order of 5°C, leading to about 0.8% fluctuations of the refraction index. The turbulence outer scale is of the order of 20 cm, and the spectrum of temperature fluctuations fits with an excellent agreement a modified von Kármán theoretical spectrum.

To create an acoustical shadow zone, the sound source is placed close to a smooth and rigid convex cylindrical surface with a radius of one meter. The positions of the microphone, the source and the surface is shown in figure 4. Without turbulence, 60 waveforms are recorded at each position, and between 500 and 2000 with turbulence. In next section, results measured in the illuminated zone (position A), in the shadow zone (positions B and C), and along the height $h$ (blue line in figure 4) are discussed.

**RESULTS**

**Waveforms and spectra without turbulence**

Without turbulence, waveforms measured in the illuminated zone (position A) and in the acoustical shadow zone (position B) are plotted in figure 5.a. The origin of the time axis is set to $t_0$ for each waveform, $t_0$ being the zero-crossing of the waveform. The wave measured at the position A in the illuminated zone is...
the summation of the direct wave and the reflected wave, which leads to a wider positive half-duration $T$ ($\sim 30 \mu s$). The peak pressure $P_{\text{max}}$ is about 100 Pa, the rise time $\tau$ is the shortest rise time that can be measured by the microphone ($\sim 3 \mu s$). The spectrum plotted in figure 5.b is limited in the high frequency range by the microphone bandwidth. The wave measured at the position B in the shadow zone is much lower ($P_{\text{max}} = 25$ Pa), the waveform is more rounded, there no more shocks, and the resonance of the microphone (around 140 kHz) is not excited. The spectrum plotted with a red line in figure 5.b confirms that only low frequencies are transmitted into the shadow zone.

**Peak pressure $P_{\text{max}}$ as a function of height $h$, with and without turbulence**

The waveforms have been measured for variable height $h$ (see figure 4). The average of the positive peak pressure values $\langle P_{\text{max}} \rangle$ is plotted in figure 6 as a function of $h$, without turbulence (black lines) and with turbulence (red lines). The height corresponding to the positions A and B are also indicated. If $h > 340$ mm, the measured pressure level corresponds to the one that has been measured in free field during a previous experiment, in both homogeneous and turbulent cases [16]. In the range 210(mm) $< h < 340$(mm), the direct and the reflected waves interfere, resulting in the increase of the peak pressure level. Then, if $h < 210$ mm, the microphone is in the shadow zone, and the pressure level decreases with $h$. Comparing the average peak pressure value with and without turbulence, it appears that turbulence has opposite influence in the illuminated and in the shadow zones. First, in the illuminated zone, turbulence decreases the average peak pressure as it has been reported previously in free field experiments [7, 8, 16]. In the shadow zone, the opposite effect is found: the average peak pressure $\langle P_{\text{max}} \rangle$ is about 20 Pa higher with turbulence. Further analysis leads to the conclusion that this amplification is due to the scattering of sound by inhomogeneities from the illuminated zone to the shadow zone.

**Analysis of the 2000 recorded waveforms at point C with turbulence**

Figure 7 is a scatter plot obtained from 2000 waveforms measured at point C in the shadow zone (see figure 4). For each waveform, the amplification factor of the peak pressure $P_{\text{max}} / \langle P_{\text{max}}^{\text{homo}} \rangle$ is plotted as a function of the relative arrival time of the wave $t_{\text{arr}} - \langle t_{\text{arr}}^{\text{homo}} \rangle$ for each waveform. $\langle P_{\text{max}}^{\text{homo}} \rangle$ is the average positive peak pressure, measured without turbulence at the same position, and $\langle t_{\text{arr}}^{\text{homo}} \rangle$ is the average arrival time of the waves, without turbulence at the same position. The arrival times are shorter with turbulence because the mean temperature is higher when the grid of resistors is heated, resulting in the increase of the mean sound-speed. With turbulence the sound level is amplified: the average value of the amplification factor
**FIGURE 6:** Average positive peak pressure $\langle P_{\text{max}} \rangle$ as a function of $h$. Black solid line: without turbulence, with the curved boundary. Black dashed line: without turbulence, free field (same source-position distance). Red solid line: with turbulence, with the curved boundary. Red dashed line: with turbulence, free field (same source-position distance). The blue vertical dash line indicates the geometrical limit between the illuminated and the shadow zones.

**FIGURE 7:** Scatter plot of $P_{\text{max}}$ amplification factor $P_{\text{max}}/\langle P_{\text{homo}} \rangle$ as a function of relative arrival time $t_{\text{arr}} - \langle t_{\text{arr}}^{\text{homo}} \rangle$, for every 2000 waveforms measured in point C with turbulence (red circles) in the shadow zone. $\langle P_{\text{homo}} \rangle$ is the mean positive peak pressure without turbulence, and $\langle t_{\text{arr}}^{\text{homo}} \rangle$ is the mean arrival time of the waves without turbulence, at the same position.
\( P_{\text{max}} / P_{\text{homo max}} \) is 2.06, the standard deviation is 0.59. In average, the effect of thermal turbulence is therefore to double the mean pressure level at the position C in the shadow zone. The statistical analysis shows that only 5 over 2000 waves are attenuated, contrary to free field measurements where both amplification and attenuation of the pressure level occur randomly [16, 20]. The maximum value of the amplification factor \( P_{\text{max}} / P_{\text{homo max}} \) is 7.06, and the minimum value is 0.85. The corresponding waveform with a pressure level amplified by 7.06 is presented in figure 8 together with the reference waveform measured without turbulence at the same position. The shape of the amplified waveform is very close to a so-called U-wave, resulting from the focusing the of the initial N-wave [17, 18, 19]. The wave has clearly more energy in the high frequency range with turbulence. Further analysis of data from simultaneous measurement by seven microphones permits to conclude that the main mechanism responsible for the increase of the peak pressure into the shadow zone is the scattering of sound from the illuminated zone to the shadow zone rather than the focusing of waves diffracted by the surface.

**CONCLUSION**

A laboratory-scale experiment has been designed to study the non-linear propagation of N-waves in a turbulent and refracting atmosphere. The experiment gives the opportunity to control separately the effects of nonlinear propagation, propagation through turbulence, and the effect of a sound-speed gradient near the ground. Thermal turbulence is found to decrease the pressure level in the illuminated region, as is the case in free-field. In the shadow zone, thermal turbulence is found to increase the pressure level by 2 in average. The pressure level can be up to 7 times higher with turbulence. A practical consequence of these results is that atmospheric turbulence has to be considered when estimating the level of airplane noise into an acoustical shadow zone.

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**REFERENCES**


