Experimental and numerical simulation of sound propagation in the atmosphere: effects of turbulence and non linearities

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17th CEAS-ASC and 3rd X-Noise EV Workshop, Sevilla, 24-25 September 2013

Outline

- Introduction and motivations
- Design of model experiments
- Numerical simulations via Monte-Carlo techniques
- Taking into account mean vertical gradients
- Effects of non linearity and application to sonic boom propagation
- Conclusions and on-going work
- List of references

Long Range Sound Propagation in the atmosphere

Propagation of acoustic waves in the atmosphere is affected by numerous (often combined) effects: mean temperature gradients, wind velocity, ground and topography and random temperature and velocity fluctuations ("turbulence").

Need to study separately each effect in well controlled conditions: Development of dedicated laboratory scale experiments, supplemented by numerical simulations.

Complete similarity? No, but similar effects can be obtained in small scale facilities by using very high frequency waves (ultrasound) and adjusting the strength of the random perturbations.

Influence of turbulence on sound propagation

Schematically we can consider 2 situations:

- Localized effects (such as propagation through a shear layer in wind tunnel experiments); the effect is essentially a scattering of the wave outside the initial direction of propagation, and it is usually treated through the Born (single scattering) approximation or the Rytov approximation (small perturbations).

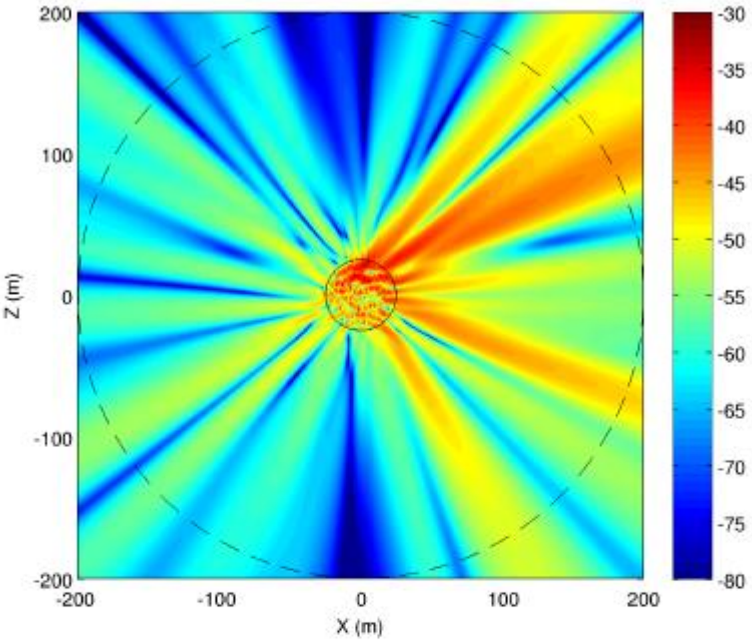
- Propagation through an extended region of turbulence (large distance compared to characteristic turbulent length scales): multiple scattering, wave front distortion, loss of coherence, strong intensity fluctuations.

Illustrations of

- Scattering of a plane wave by a blob of turbulence (f=50Hz, outer scale of temperature fluctuations l=2.5m, rms value of temperature fluctuations 1K); *only the scattered part of the field is displayed.*

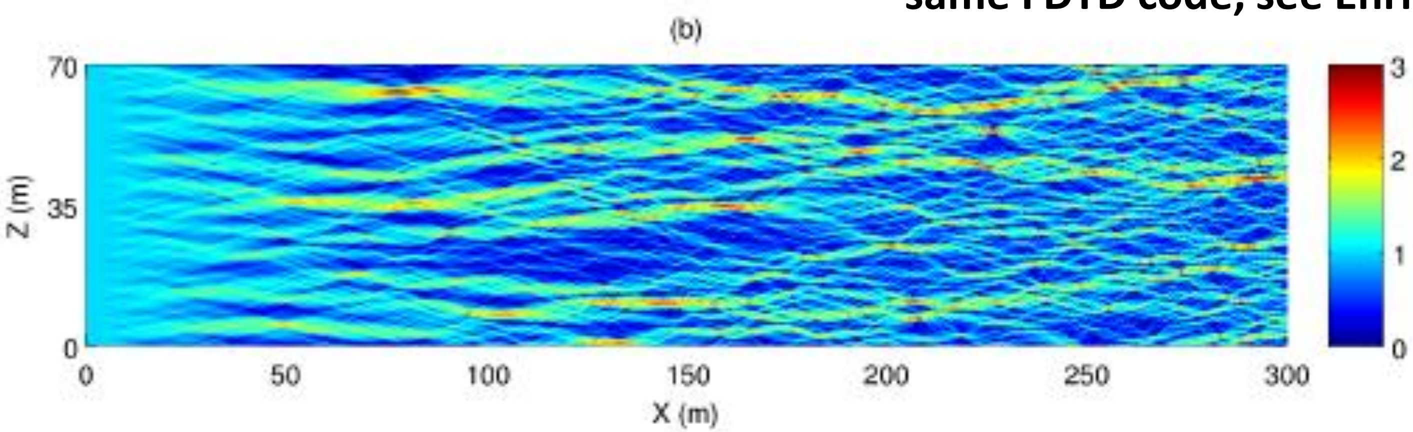
- Wavefront distortion by an extended turbulent medium and associated pressure amplitude fluctuations (f=300Hz, l=5m, rms value of wind fluctuations 4m/s)

Numerical simulations in the time domain (FDTD), see details in
Cheinet, Ehrhardt, Juvé & Blanc-Benon, 2012, JASA 132 (4)
Ehrhardt, Cheinet, Juvé & Blanc-Benon, 2013, JASA 133 (4)



Scattering of a plane wave by random temperature fluctuations, computed by a FDTD code, see Cheinet & al., 2012.

Pressure fluctuations induced by random velocity perturbations, and computed by the same FDTD code, see Ehrhardt & al., 2013.



Influence of turbulence (cont'd)

What is the role of turbulent fluctuations?

-Temperature fluctuations will randomly change the local speed of sound

-Velocity fluctuations will randomly convect the wave at a different speed *(very simplified story! For details, see Ostashev, Juvé & Blanc-Benon, Acta Acustica 83, 1997)*

The important parameters are the rms value of the fluctuations in the "index of refraction", μ.

$$\frac{T'}{2T_0} \text{ and } \frac{u_1'}{c_0}$$

Note that it is the velocity component in the direction of propagation which is important (so this effect is not isotropic)

and the transverse coherence length of these fluctuations.
One can make an optical analogy considering randomly distributed lenses focusing and defocusing sound waves.

Influence of turbulence (cont'd)

For line of sight propagation, the description of the fluctuations is usually based on the successive statistical moments of the pressure fluctuations:

$$p_{ac}(x,t) = p\exp(i\omega t);\ p = \langle p \rangle + p';$$

$\langle p \rangle$ is the coherent field (it corresponds to the level at the emission frequency); p' is the incoherent field (associated to spectral broadening).

Turbulence will induce the decrease of the coherent field, the de-correlation of pressure fluctuations, intensity fluctuations characterized by complicated pdfs, …

Theoretical approach and numerical simulations

The classical theory of propagation through turbulence dates back to Tatarski (1971); it relies on a paraxial or parabolic approximation (small angle approximation) of the Helmholtz equation and a sort of Markov approximation to obtain closed form equations for the first two statistical moments (coherent wave, mean SPL and transverse correlation).

Extensions have been made (in particular by Ostashev) to take into account the presence of a reflecting surface or a mean sound speed gradient.

One has often to rely on numerical simulations of (approximate) equations for the moments or on Monte-Carlo approaches where the propagation through individual realizations of the turbulent field is considered and statistical averaging is done a posteriori.

Main consequences of turbulence

When there is no mean gradient and for homogeneous turbulence in free field, the 2 main effects are :

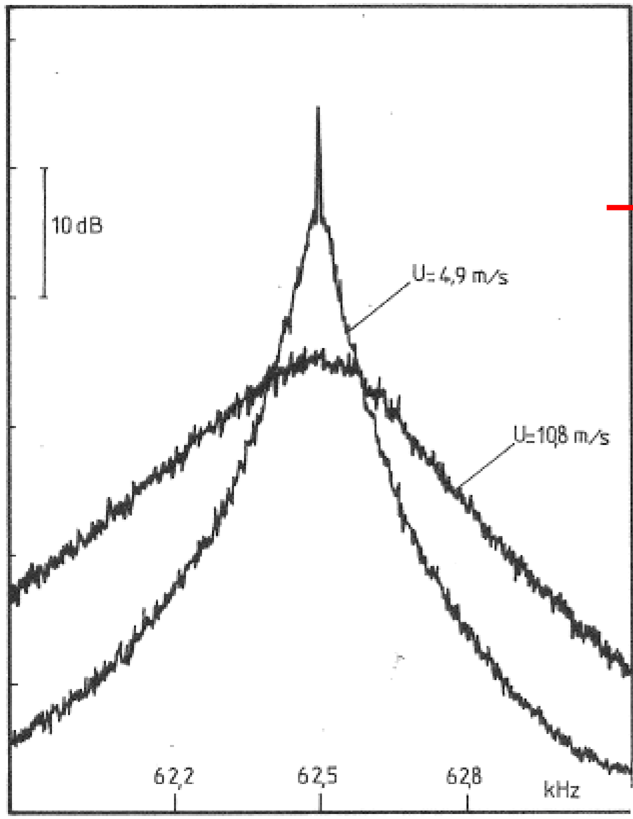
-The attenuation of the coherent wave (spectral broadening; spatial de-correlation implying limitation of the resolving power of source localization methods)

-The increase of fluctuations in the acoustic level, characterized by the scintillation index

$$\sigma_I^2 = \frac{\langle p^4 \rangle - \langle p^2 \rangle^2}{\langle p^2 \rangle^2}$$

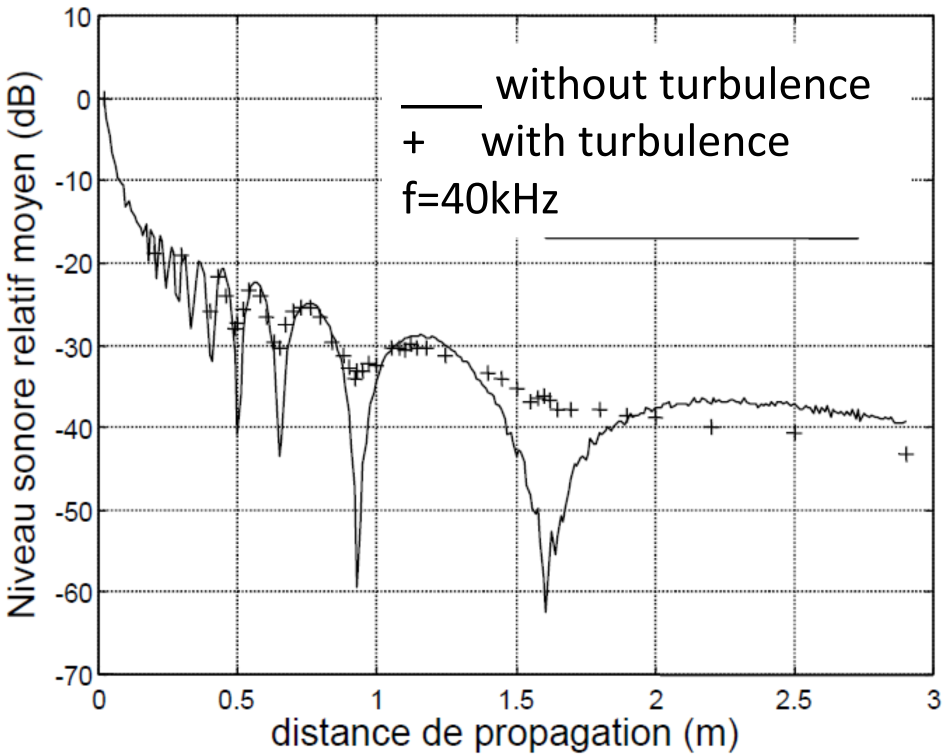
In the presence of a (partially) reflecting ground the interference pattern will be "blurred", the level in the destructive interference fringes being increased by scattering from the regions of constructive interferences.

Experimental illustration (lab)



Spectral broadening of an initially pure tone due to propagation in a turbulent plane jet

Modification of the interference pattern due to coherence loss between the direct and the reflected paths.



Design of lab experiments

The most influent parameters are:

Wave frequency f, distance of propagation L, intensity of turbulent fluctuations μ and integral length scale of these fluctuations l.

Complete similarity with atmospheric propagation is not possible but similar effects can be reproduced; the attenuation of the coherent part of the wave is a good indicator; it is controlled by

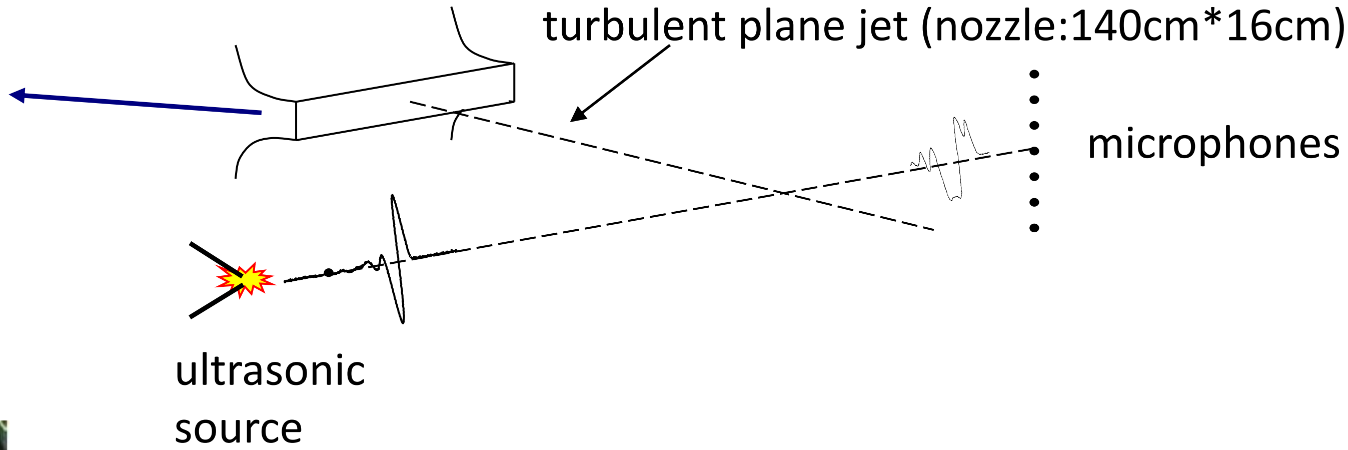
$$\alpha = \mu^2 f^2 lL; \mu = T'/2T_0 \text{ or } u'/c_0$$

	T'	l	L	f
atmosphere	1°	10m	1 km	1kHz
lab	5°	0.1m	5m	?

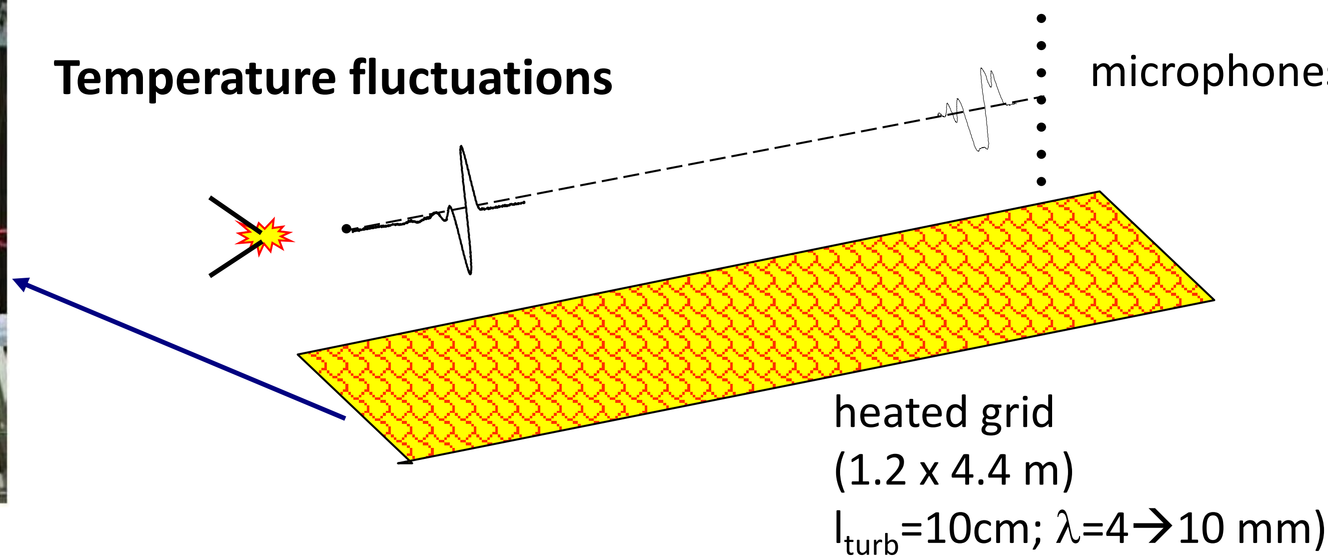
$$\alpha_{atm} \sim 3.10^4 \sim \alpha_{lab} \text{ with } f = 30kHz$$

Laboratory scale experiments:
Propagation through turbulence at ECLyon

Velocity fluctuations



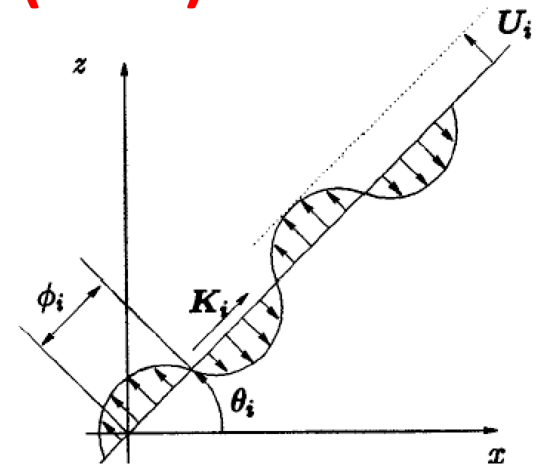
Temperature fluctuations



Modeling of random fluctuations: Random Fourier Modes (RFM)*

$$\vec{v}(\vec{x}) = \sum_{i=1}^{N} \vec{U}(\vec{K}^i)\cos(\vec{K}^i \cdot \vec{x} + \phi^i)$$

$N = 100$

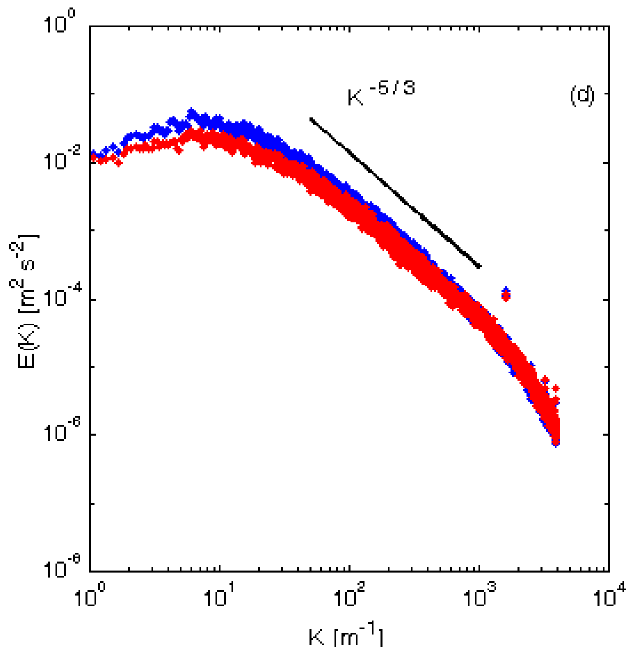


- **Wave-vector direction and phase ϕ of the modes are uniformly distributed over [0, π] to ensure isotropy and statistical homogeneity**

- **Amplitudes of modes are fixed according to a given form of the energy spectrum.**

The modified von Karman spectrum is a good approximation of experiments

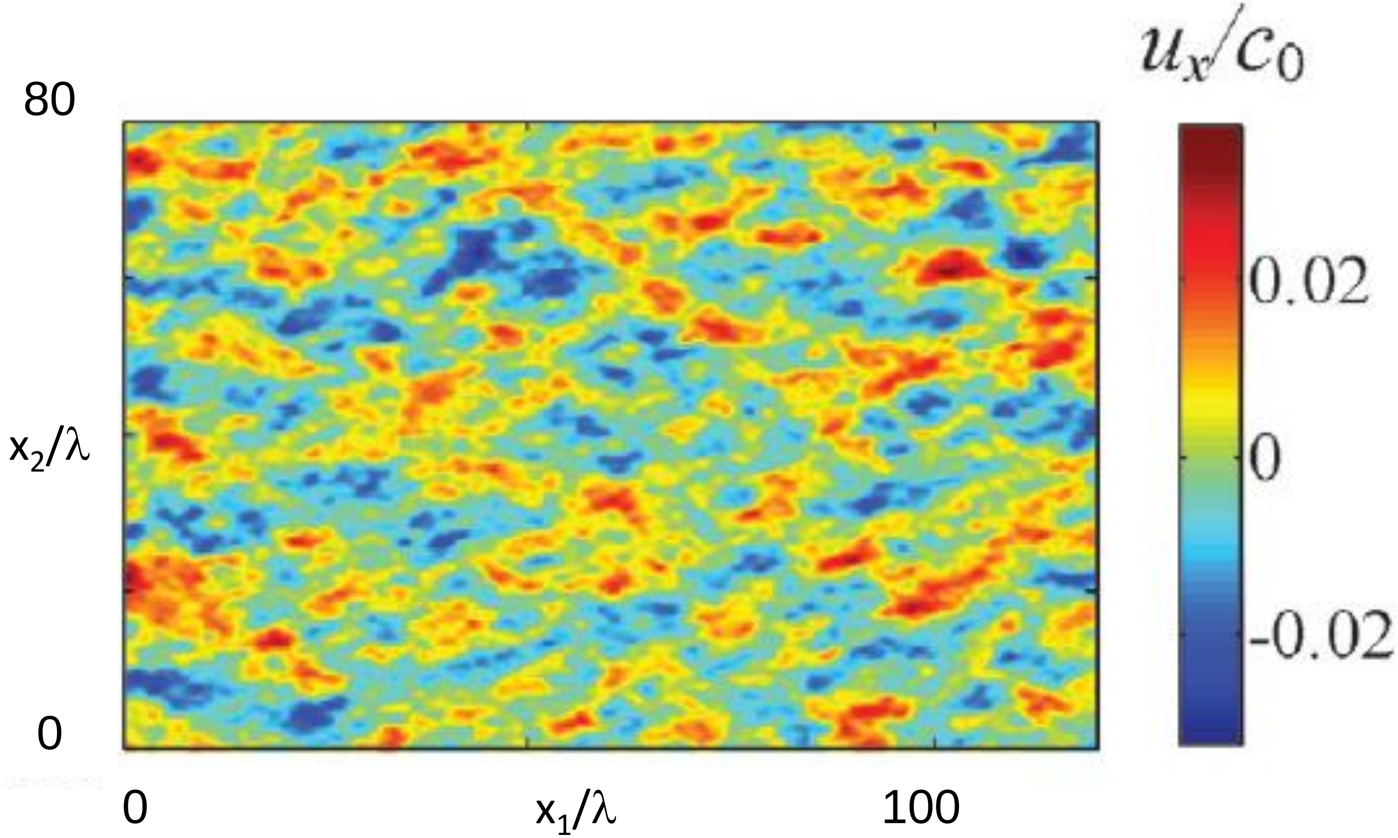
$$E = \frac{8v^2}{9}\frac{K^3}{L_0^{2/3}(K^2 + L_0^{-2})^{14/6}}\exp(-\left(\frac{Kl_0}{2}\right)^2)$$



** Other techniques can be used, RFG (Frehlich), spatial filtering of random fields …*

K

Typical realization of the random velocity field (Mach number of longitudinal fluctuations)



Acoustic waves are propagated using a **wide angle parabolic equation** code in the frequency domain, or (more recently) with LEEs in the time domain.

Taking into account refraction by mean gradients in laboratory experiments

One of the main effect of turbulence is to increase the sound level when deterministic shadow zones exist.

This is the case when there is a decrease of temperature with height (usual situation) or when considering upwind propagation. In these situations the acoustic rays are bent upward and a deep shadow zone is formed at some distance from the source:

There exists a limiting ray separating the insonified region and the shadow zone where no ray can penetrate and where the sound level is due only to diffraction in the deterministic case (no turbulence).

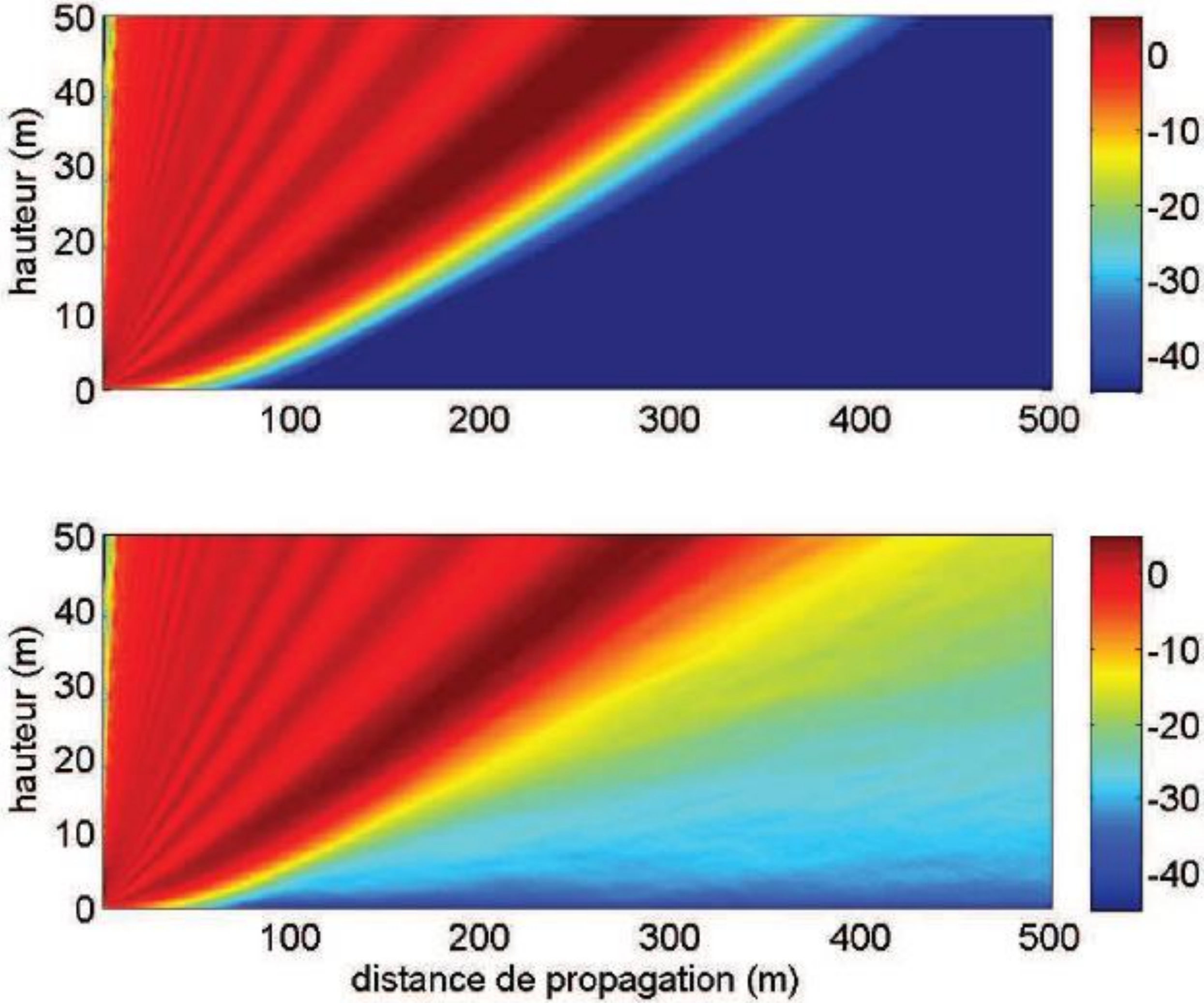
With turbulence, and except at very low frequency, the pressure level is fixed by wave scattering.

Numerical simulation of sound propagation in an upward refracting atmosphere

(f=800Hz, Wide Angle Parabolic Equation)

Without turbulence

With turbulence

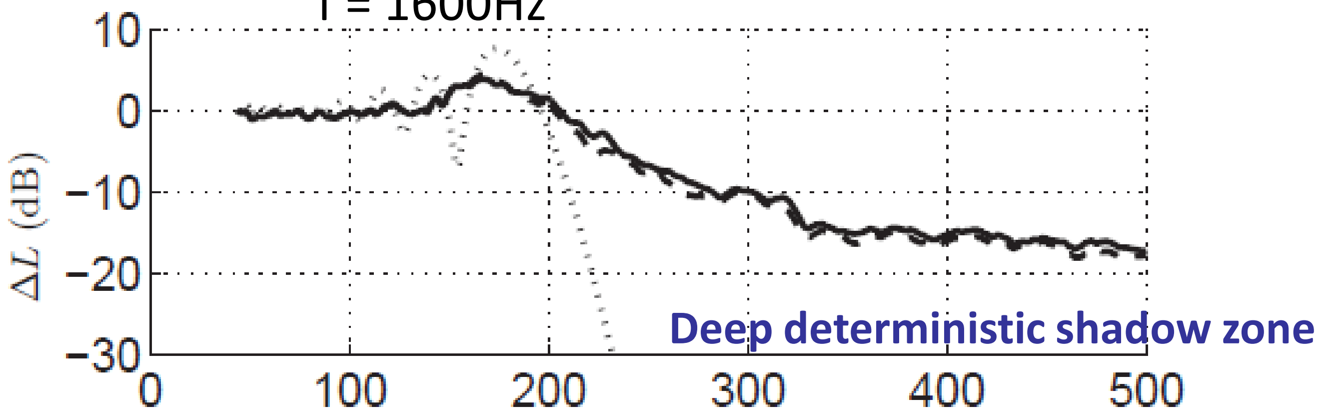


Level relative to free field (dB)

..... without turbulence

____ with turbulence

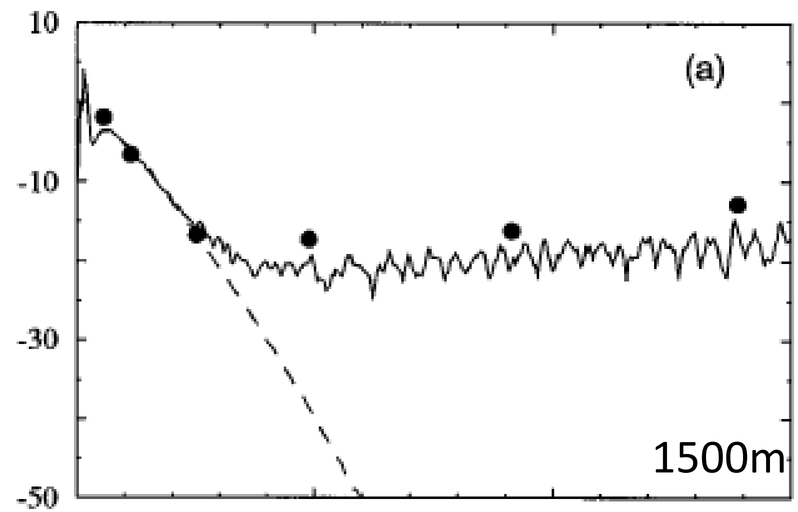
f = 1600Hz



Propagation distance (m)

The level (relative to free field) in the shadow zone is nearly constant**; this was known for a long time by experimentalists (Wiener & Keast).**

This level is due to scattering of the sound field from the illuminated region into the shadow zone**.**



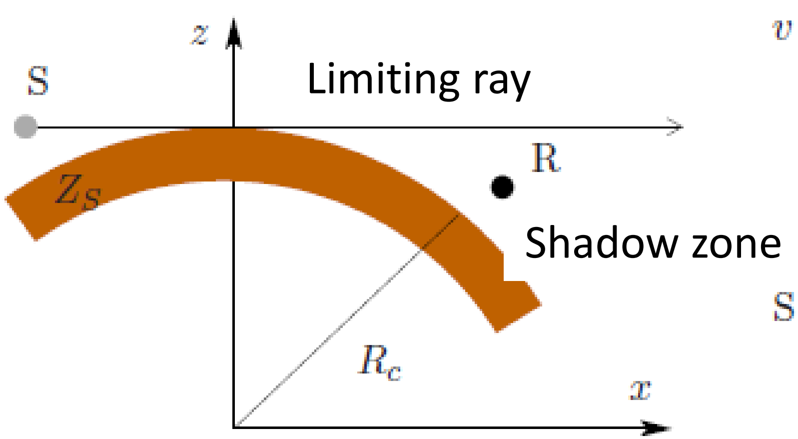
Comparison between experimental data and numerical simulations; f=424Hz, weak refractive conditions

Chevret et al., JASA, 1996

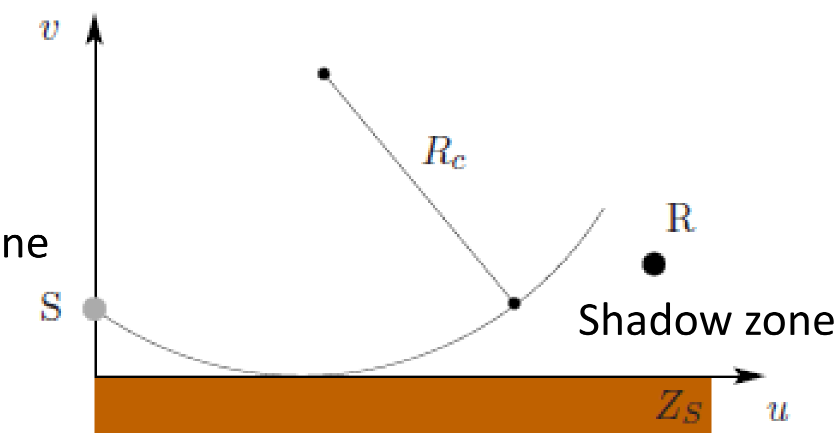
Taking into account refraction by mean gradients in laboratory experiments

The idea is to use the "flattening earth" technique. It can be shown that these 2 situations are equivalent (for certain types of vertical gradients)

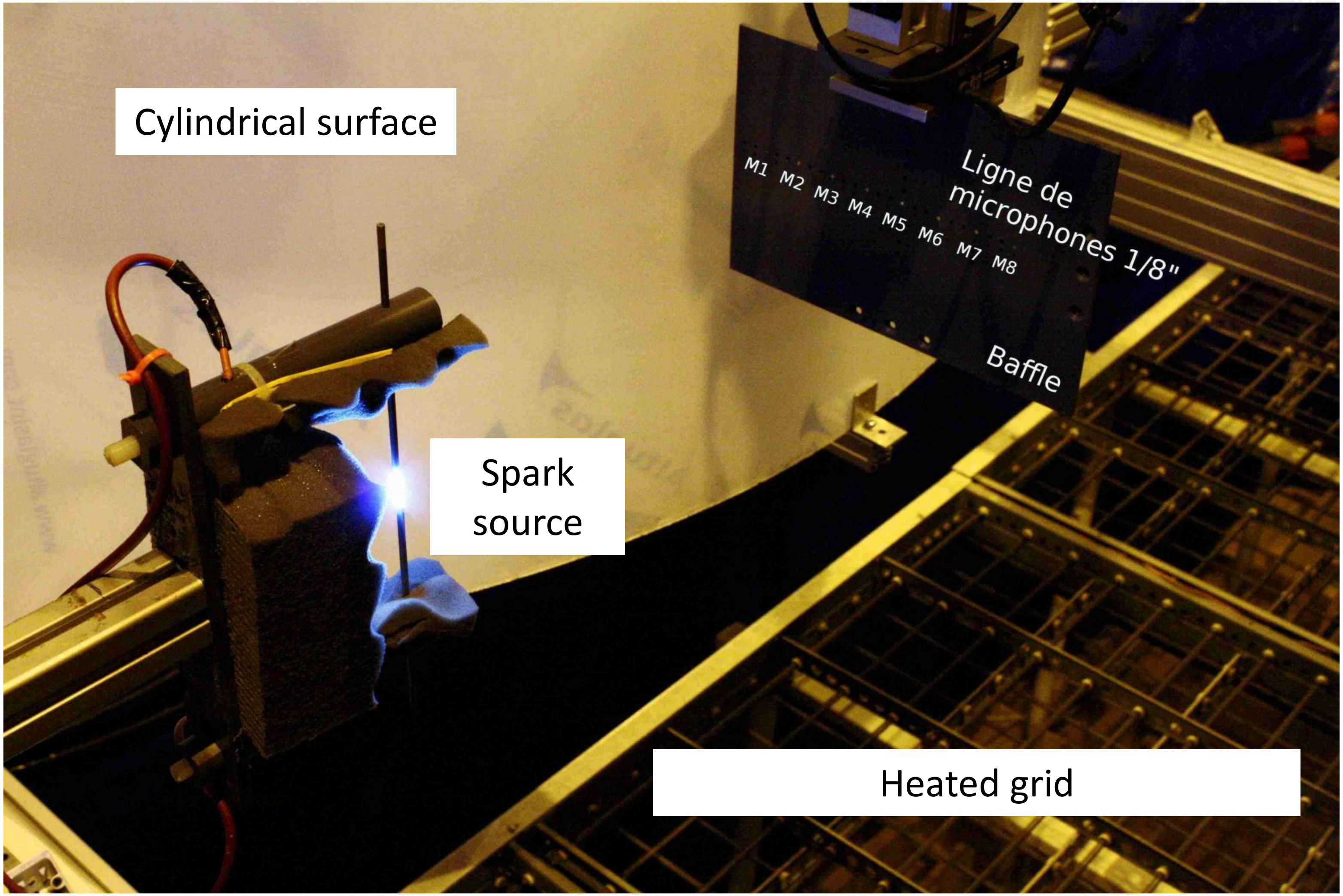
Propagation in an homogeneous medium above a cylindrical surface



Propagation above a flat surface with negative sound speed gradient



Experimental set-up in ECL anechoïc chamber



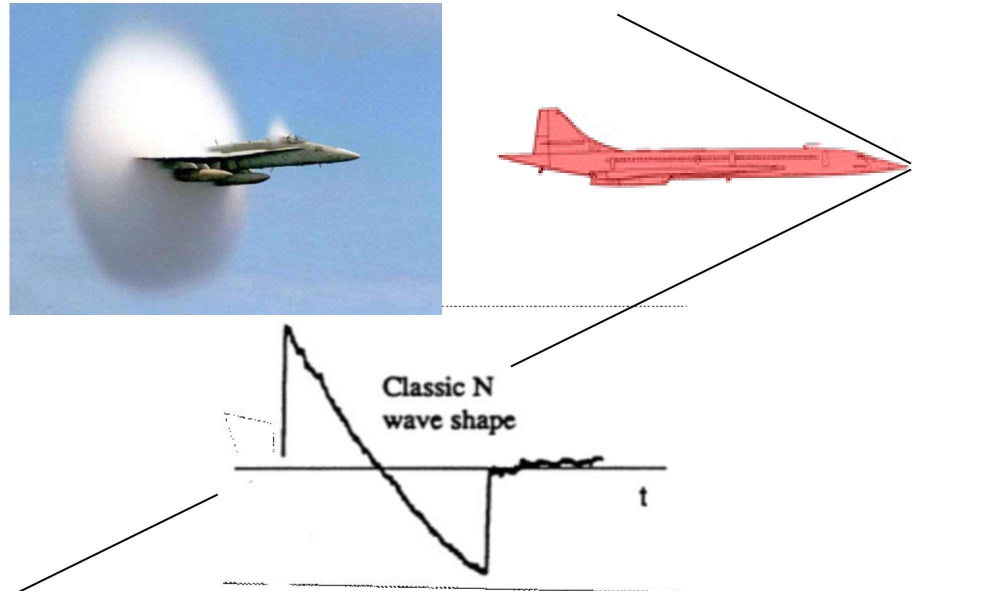
Influence of atmospheric turbulence on primary sonic boom

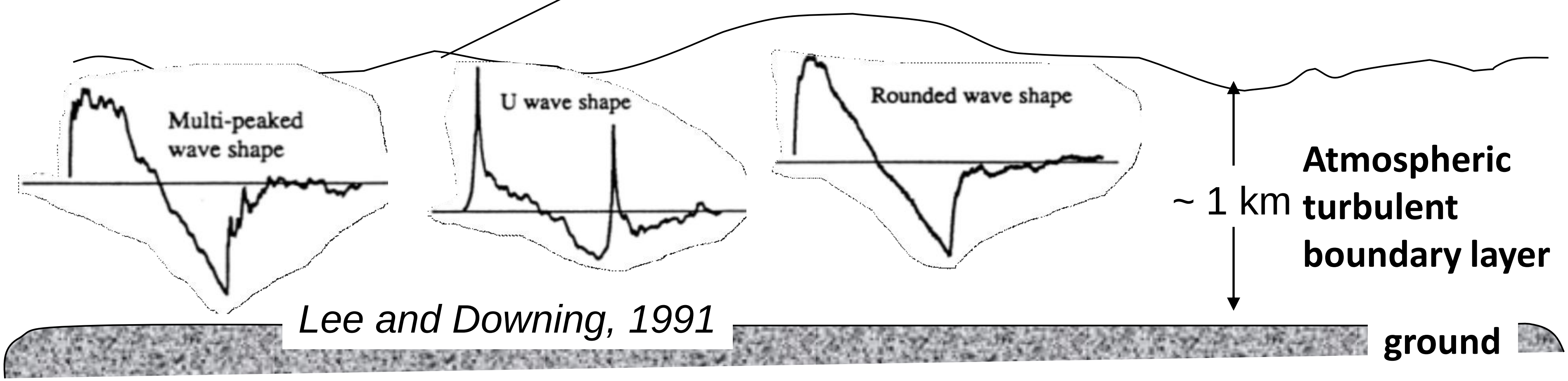
Turbulence

- temperature perturbations
- velocity perturbations

Random scattering & focusing

Distortion of waveforms





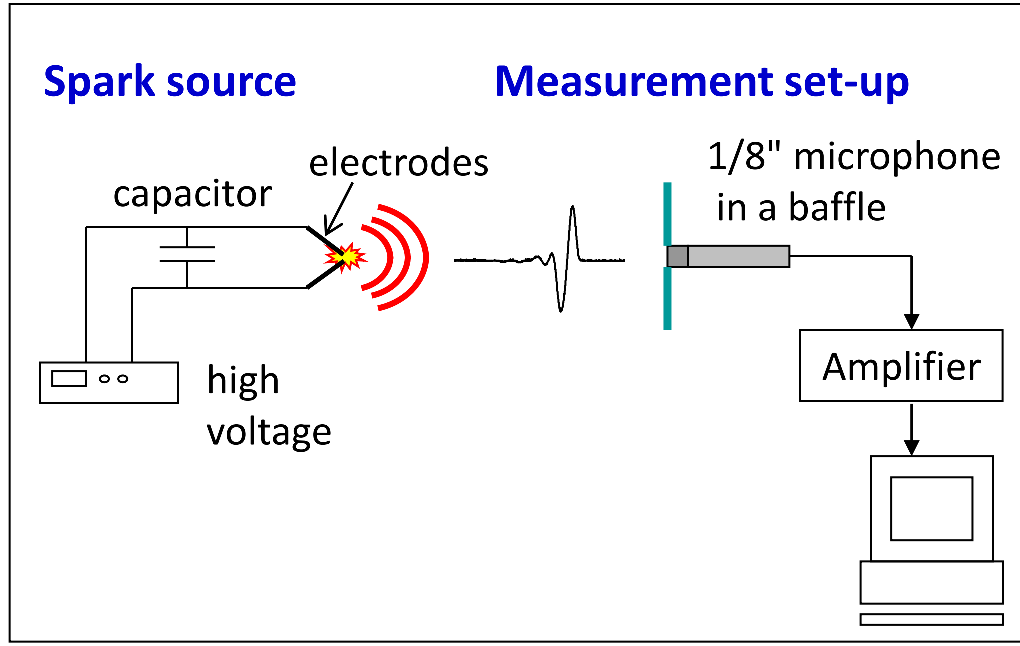
Atmospheric propagation versus model experiments

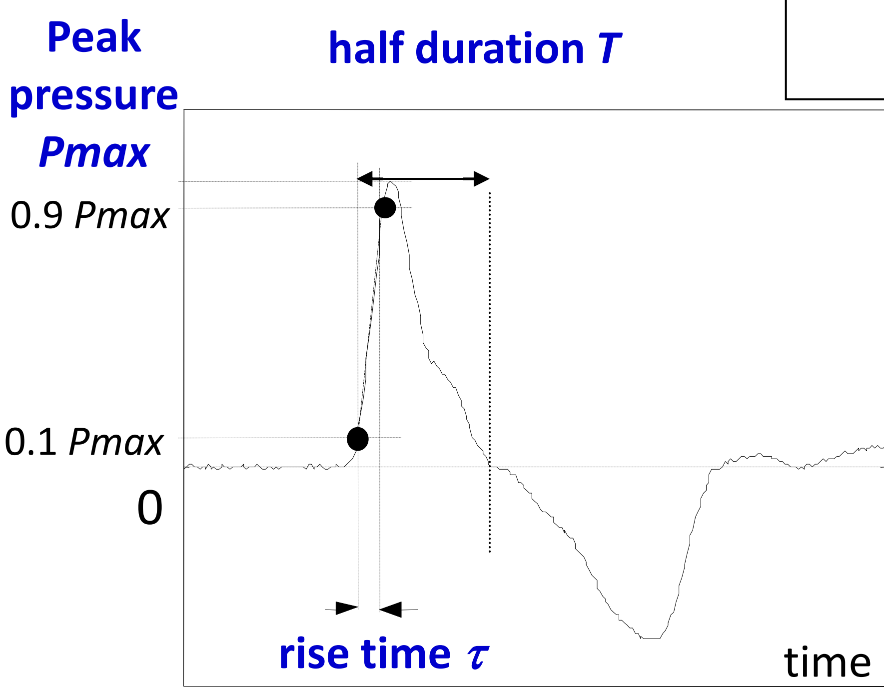
	sonic boom	model experiment
Maximum peak pressure	10-600 Pa	10-600 Pa
Rise time	0.5-10 ms	2-10 μs
Duration	80-300 ms	25-45 μs
Turbulence outer scale	100-200 m	10 cm
Propagation distance through turbulence	few km	0.5 to 4.5 m

Approximately 1/1000 scale model. Again, complete similarity is not possible, due to the interplay of various physical mechanisms: non linear effects, thermo-viscous dissipation, focusing effect of turbulence ...

The idea is to choose experimental conditions in the Lab to reproduce the main effects observed in the field (i.e. the various forms of the pressure signature); this can be achieved by changing the propagation distance and/or the intensity of turbulent fluctuations.

Acoustic N-waves are generated by an electric spark source





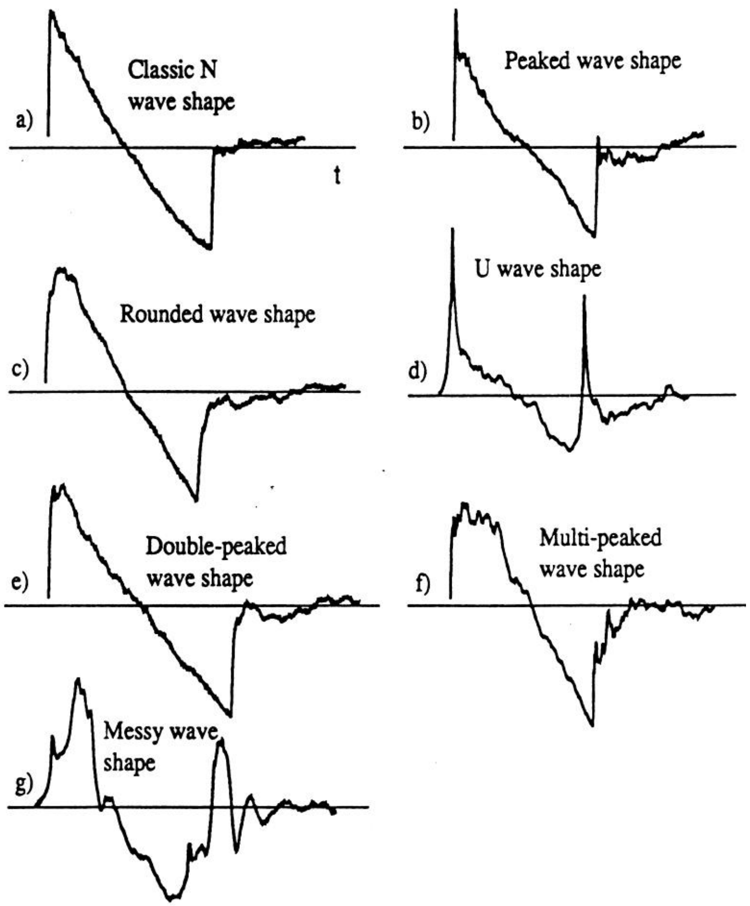
Pulse length, $\lambda=2c_0T$ (typically 1cm)

N-wave parameters
at 1.1 m from the source

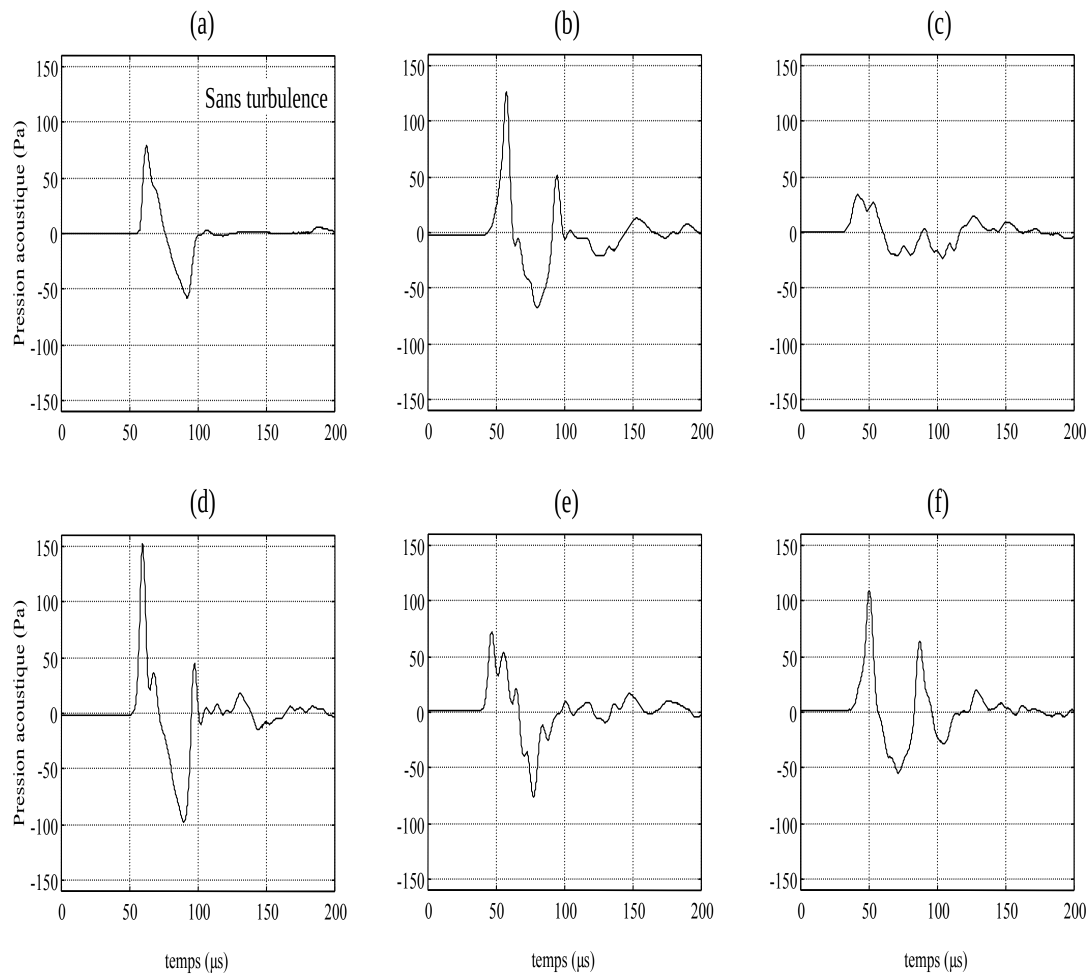
- ***Pmax*** = 120 Pa
- τ **=** 2.8 µs
- ***T*** = 14 µs

Sonic boom / model experiment waveforms

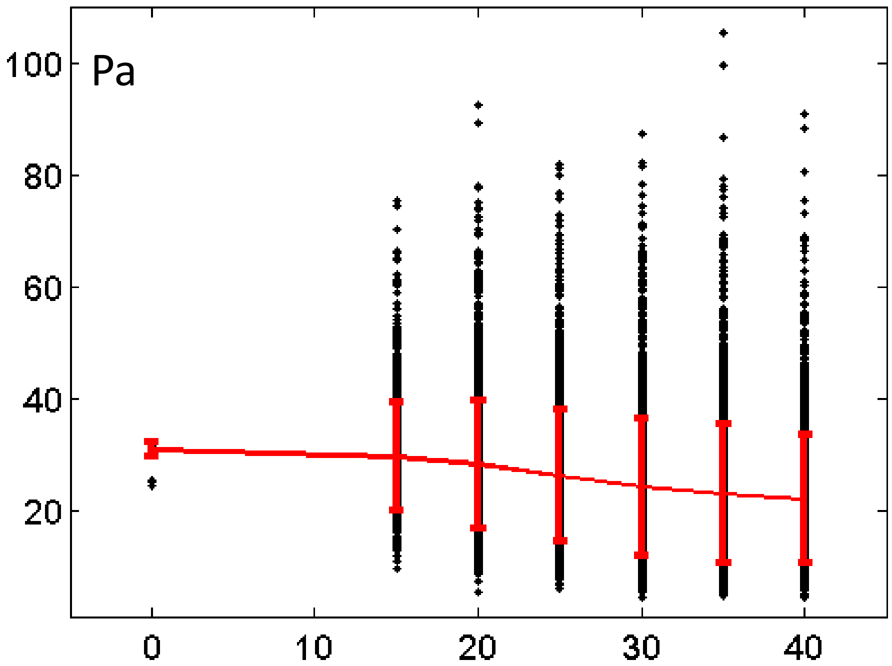
Sonic booms
(Lee and Downing, 1991)

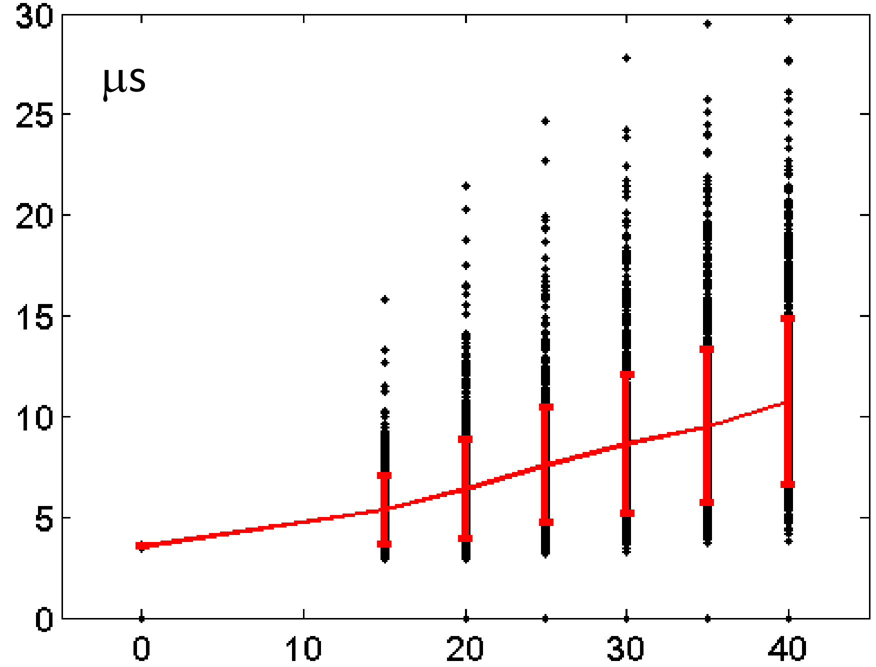


Model experiment :
Propagation through a turbulent jet



Influence of turbulent velocity fluctuations on maximum pressure and rise time (no mean gradient)

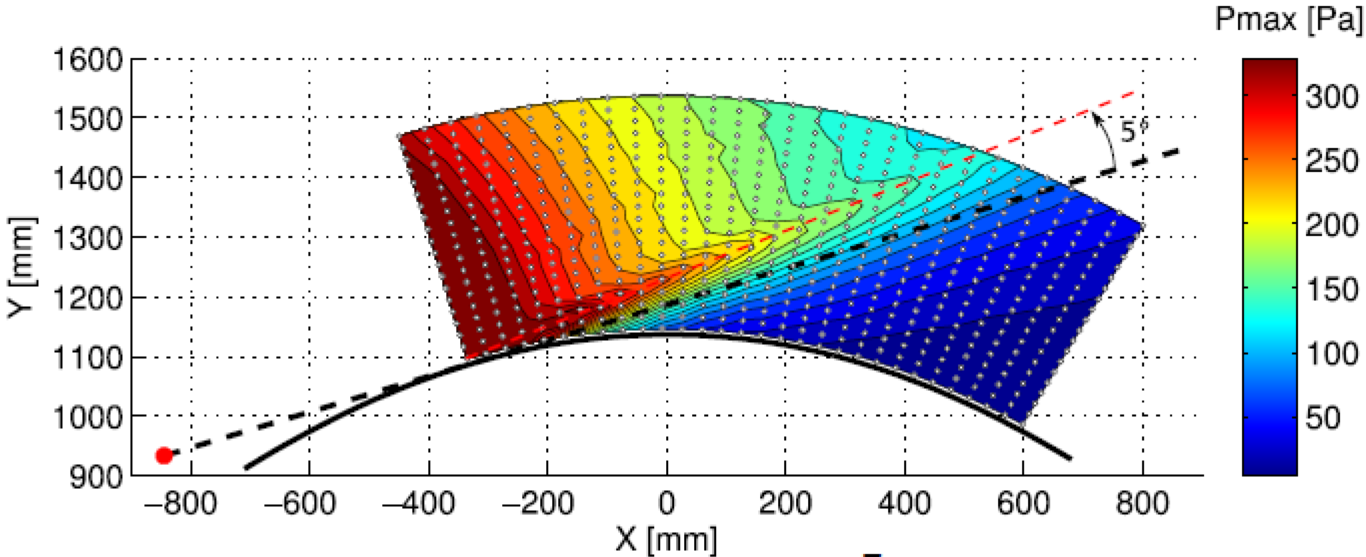


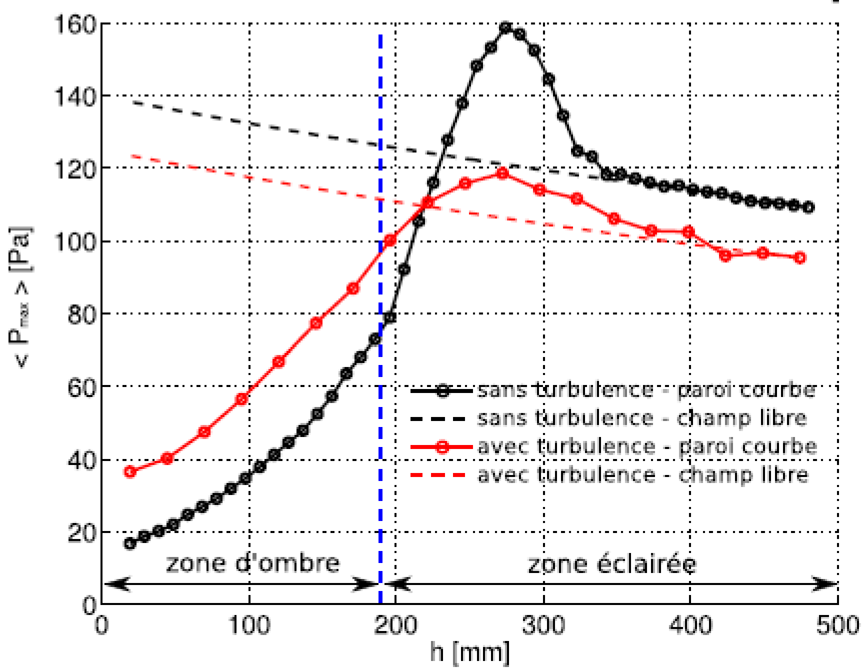


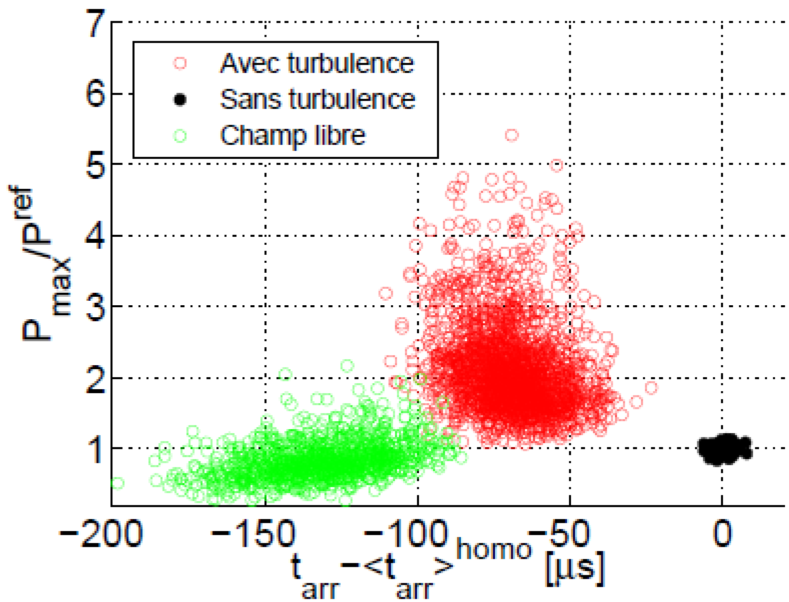
Jet mean velocity (m/s)

On average, peak level reduced and rise time increased: good news; BUT events with very high peak level (up to 4 times the value observed without turbulence) and short rise time are observed: bad news!

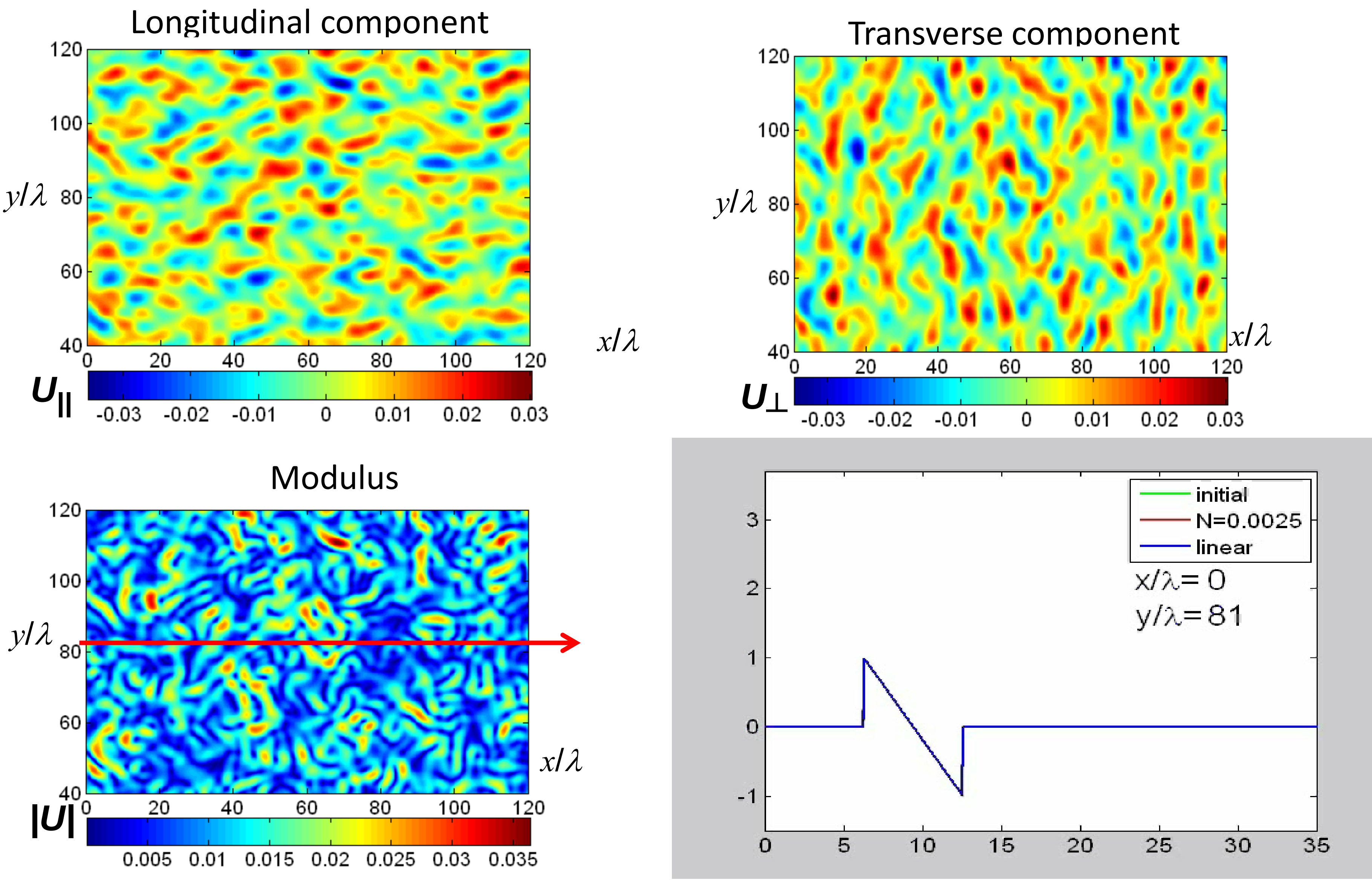
Influence of a simulated mean sound speed gradient







Numerical simulation of N-wave propagation through a turbulent velocity field (KZK equation)



Conclusions and on-going work

The main effects of atmospheric turbulence on sound propagation can be reproduced at laboratory scale, even if complete similarity is not possible.

These effects have been studied both for linear propagation and for non linear propagation to simulate sonic-boom characteristics.

The main advantage of lab experiments is the possibility of isolating the role of various parameters: temperature or velocity fluctuations (each playing a different role), effect of ground and mean vertical sound speed gradient. And thus sets of statistically well converged data can be generated to benchmark theoretical models and numerical simulations.

On-going work

On the experimental side the main focus is on pushing the measurements toward very high frequencies (up to 500kHz) to obtain better estimates of the rise time of N-waves for example; this includes the development of optical techniques (interferometry) or of MEMS microphones.

On the numerical side several routes are studied in different research groups, but the central theme is time-domain simulations and use of the high fidelity techniques developed in computational aeroacoustics. As an example of on-going work at ECL, the full compressible Navier-Stokes equations (in 2D at the moment) are solved to simulate propagation of infrasonic waves (0.1→1Hz) in the atmosphere over several hundred of kilometers, in the context of the Comprehensive Nuclear Test Ban Treaty Organization .

Another key issue will be the coupling of these propagation codes with meteorological data taken from high resolution codes.

List of references
(most of them can be downloaded from *http://acoustique.ec-lyon.fr)*

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Non-linear propagation

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