Source sensing

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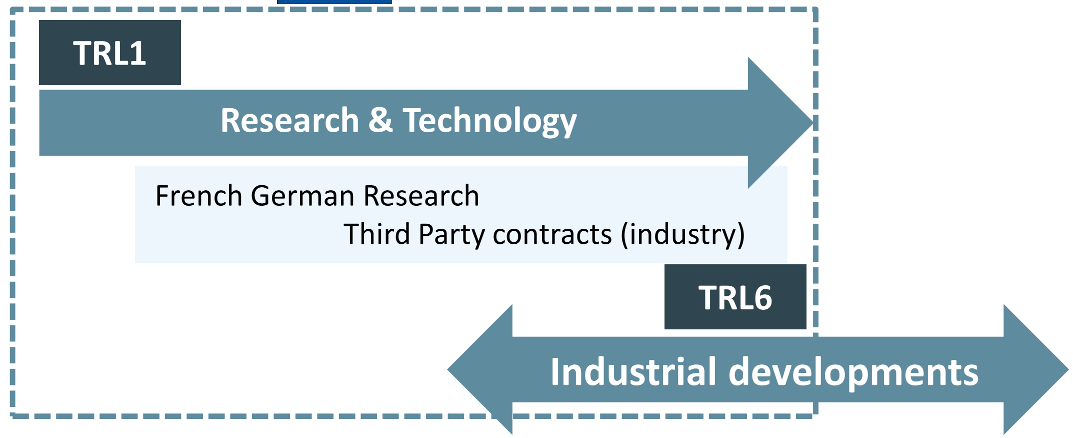
A joint initiative of:

RÉPUBLIQUE FRANÇAISE
MINISTÈRE DE LA DÉFENSE

Bundesministerium der Verteidigung

Institut Saint-Louis
Among many other topics
Acoustics for Defence & Security
- Protection
- Detection & sensing



Sylvain Cheinet

1997-2004 Lower atmosphere physics (obs, NWP)

2005 -2018 Activity « Acoustic propagation & sensing »
Outdoor acoustics: measurements, modeling,
Applications for Defence & Security

Sensing of outdoor acoustic sources

(Passive sensing)

Acoustic sensing of noise

Airport / airplane noise

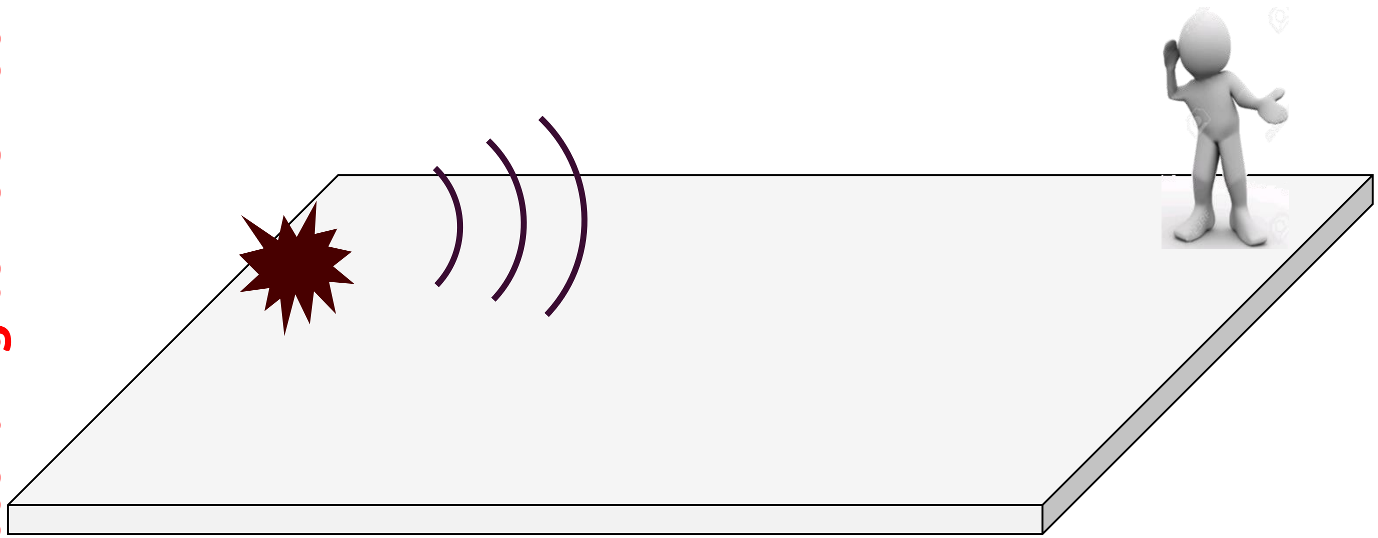
Traffic noise

Traffic noise mapping

Wind turbine noise

Monitor **noise**
e.g. neighborhood, infrastructures, transports,
(Usually) continuous sources,
Normative metrics L_{eq}

Acoustic sensing of sources



D etection
L ocalization
C lassification
I dentification
…

Monitor **sources** at the origin of sound
Metrics: sensing performance
Characterization in Pa

Acoustic sensing of sources

Noise localization
100 – 2 000 Hz

Bioacoustic monitoring
200 - 50 000 Hz

Shot monitoring
20 – 10 000 Hz

Nuclear explosion monitoring
< 10 Hz

Large diversity of applications
Many common points & challenges

Acoustic sensing systems

	Hardware	Software
Detection	Sensor selection	Denoising
Localization	Sensor spacing & positioning	Impulse / Continuous Tracking
Classification		
Identification		

Principle of beamforming with a uniform linear array

TDOA multilateration, 3 distributed sensors

Vehicle tracking with 2 bearings And a Kalman filter processing

Acoustic sensing systems

	Hardware	Software
Detection	Sensor selection	Denoising
Localization	Sensor spacing & positioning	Impulse / Continuous Tracking
Classification		Features extraction Spectral / Temporal domain, databases
Identification		… Still quite a challenge…

Cf. Bird
classification
F. Sèbe

Database & feature extraction
Tank passing-by.
Damarla, « Battlefield Acoustics », 2015

Positioning vs. other sensing technologies

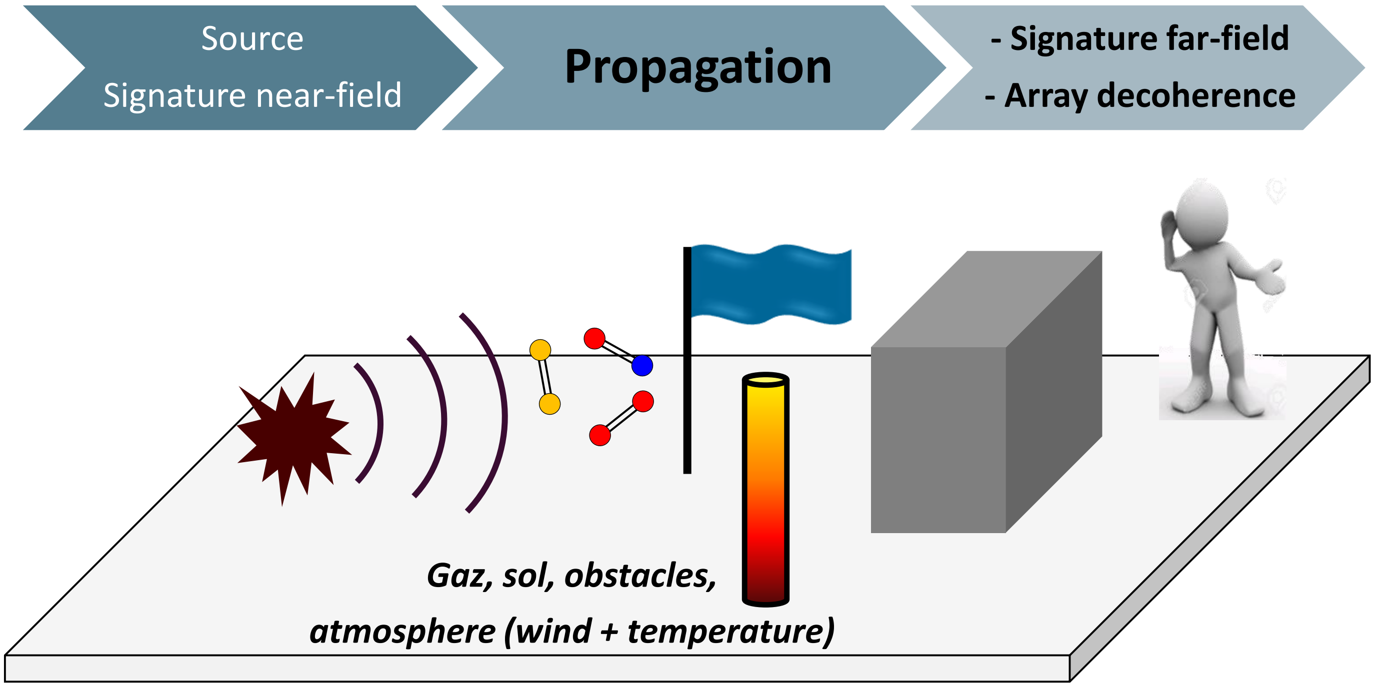
+	-
Low cost, occupation, autonomy, weight	
Robust, all-weather, day-night	
Passive, omni-directional sensing	

Positioning vs. other sensing technologies

+	-
Low cost, occupation, autonomy, weight	Not so directional, array & processing
Robust, all-weather, day-night	Sensitive to noise, denoising / filtering
Passive, omni-directional sensing	

Positioning vs. other sensing technologies

+	-
Low cost, occupation, autonomy, weight	Not so directional, array & processing
Robust, all-weather, day-night	Sensitive to noise, denoising / filtering
Passive, omni-directional sensing	**Sensitive to changing environment**



Some current trends

Fusion with other technos
e.g. DL acoustics, CI with EO/EM

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Fusion with other technos
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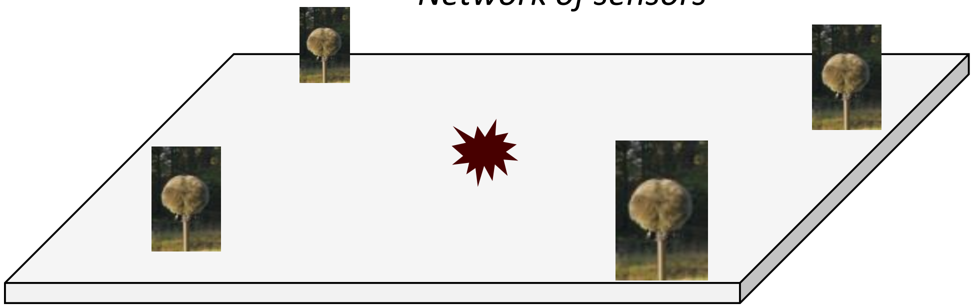
Network of sensors



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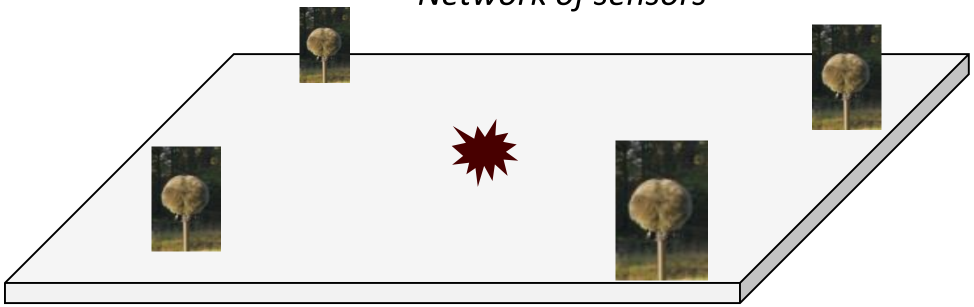

New sensors: MEMS, vector

Some current trends

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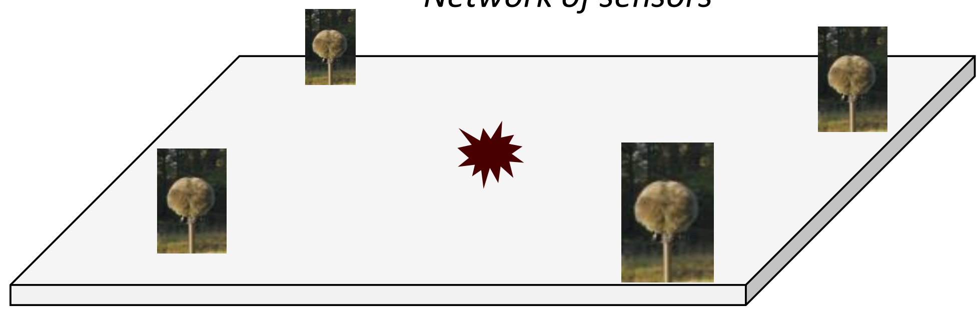


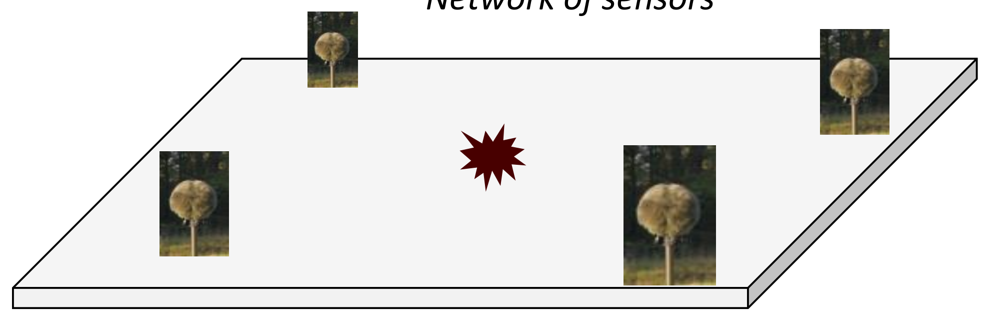
New sensors: MEMS, vector

Adapt systems to
new scenarii

Some current trends

Fusion with other technos
e.g. DL acoustics, CI with EO/EM

Network of sensors



New sensors: MEMS, vector

Adapt systems to
new scenarii

Predictions of environment & propagation

-> Prediction of system's performance

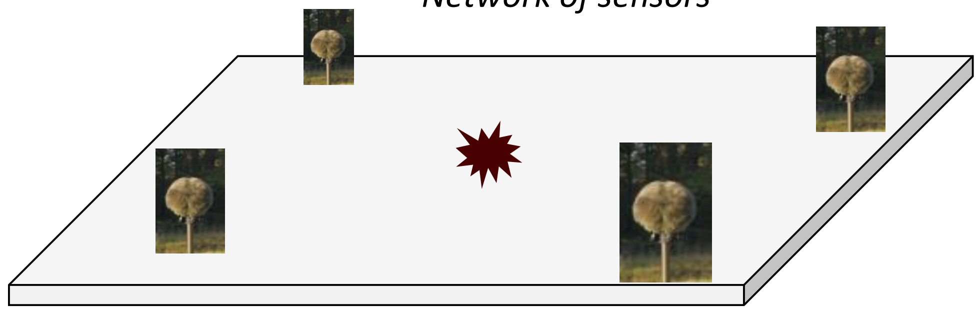
-> Support to design

-> Support to operation

Some current trends

Fusion with other technos
e.g. DL acoustics, CI with EO/EM

Network of sensors



Decoherence among sensors

New sensors: MEMS, vector

Adapt systems to new scenarii

Predictions of environment & propagation

-> Prediction of system's performance

-> Support to design

-> Support to operation

Complex env'ts (e.g. urban)

In summary,

- Acoustic sensing systems are used in various applications
    - Structural differences versus other technologies (+ / -)

- In theory, may be sensitive to outdoor environment due to propagation
    - Modulation & decoherence of signatures
    - Present trends reinforce the issue

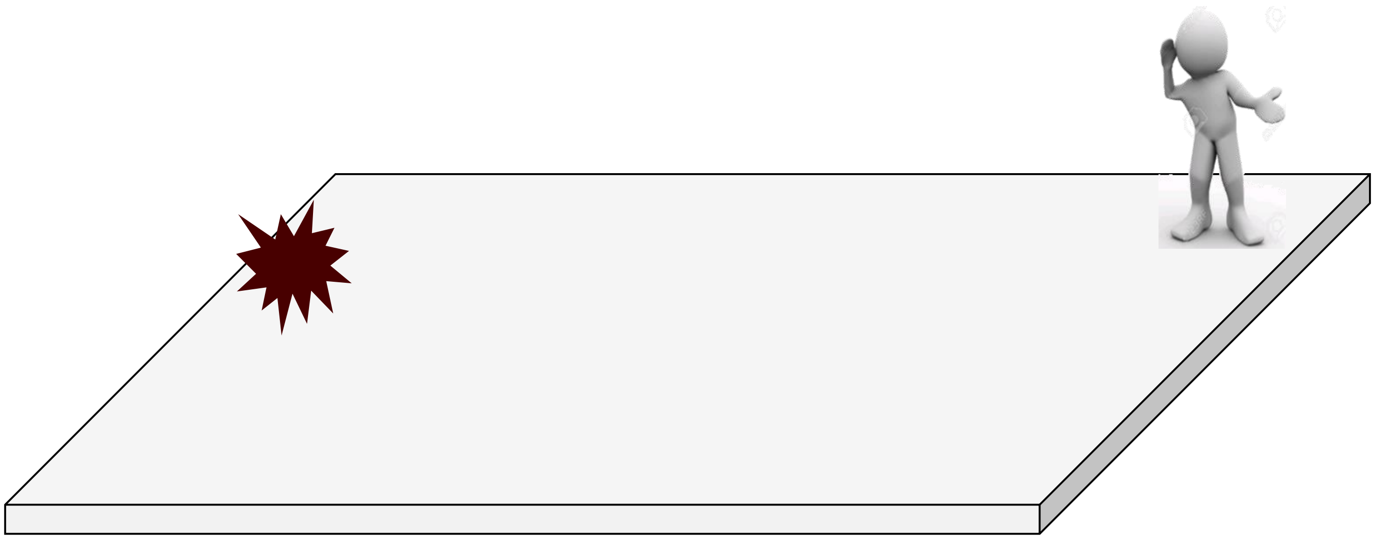
- Remainder of the presentation
    - How, really, propagation alters sensing performance
    - Monitor and improve sensing performance

Specific to each application. Here, shot sensing.

Propagation & Sensing of battlefield sounds

1. Background

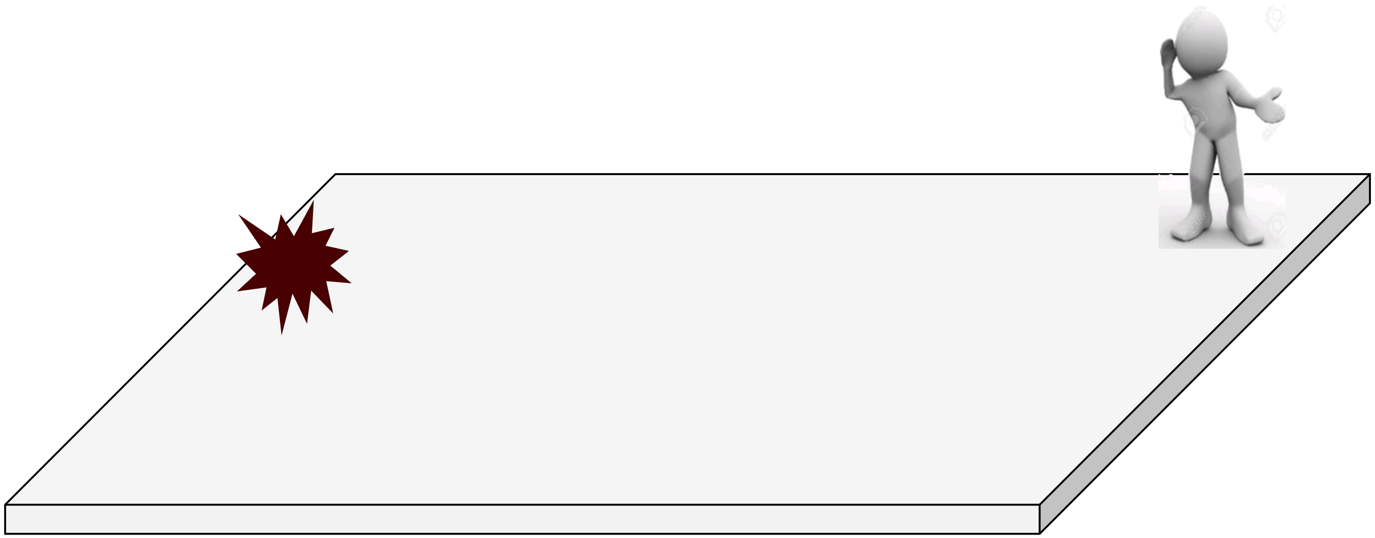
Battlefield acoustic sensing



Powerful, transient sources

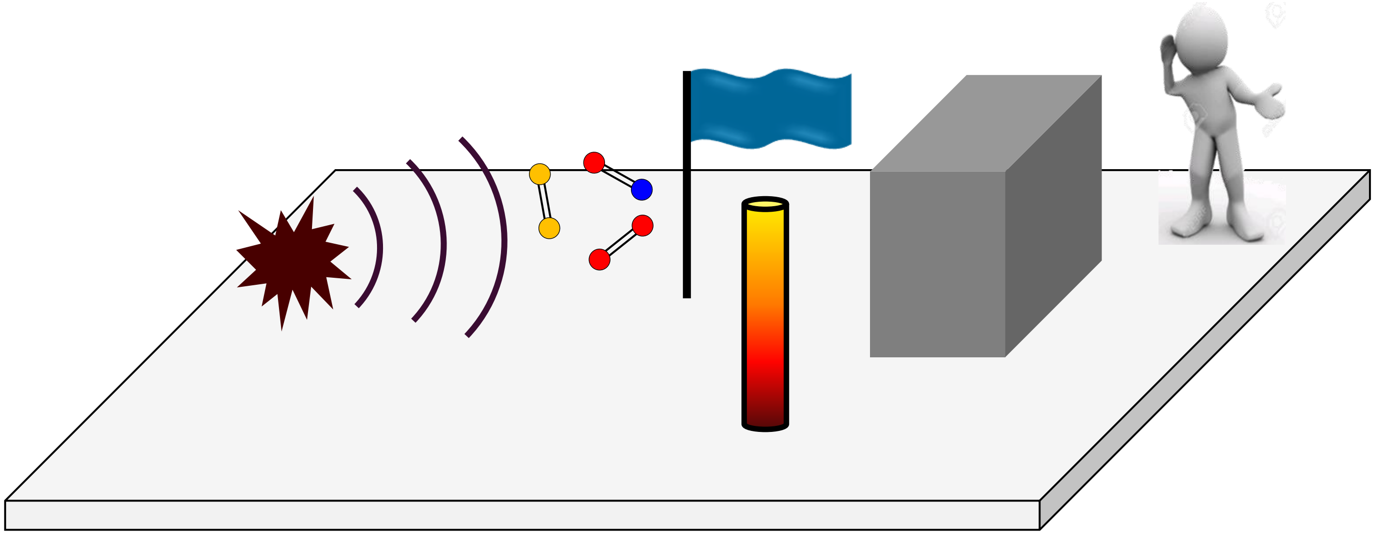
100 – 10.000 Pa, 0.5 – 50 ms

Battlefield acoustic sensing



Wide-band sensors
Antenna systems

Battlefield acoustic sensing



Ranges 100 m – 10 km

All environments

Experimental tools

Shots & field trials

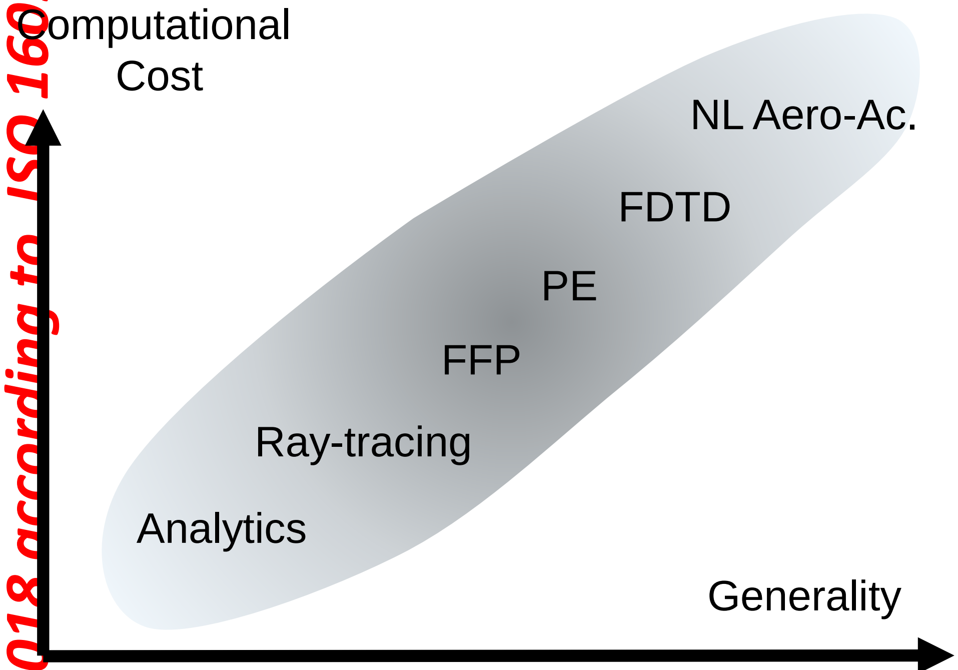
Environmental characterization

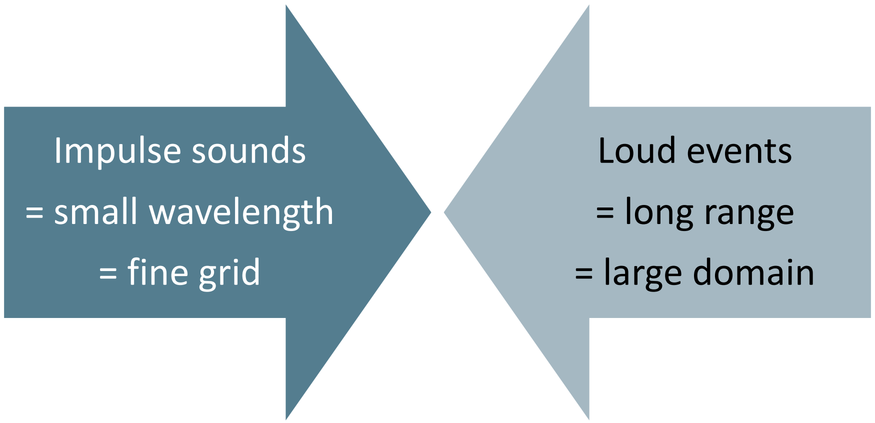
Operational systems

Acoustic sensors / array

(in-house developments)

Numerical modelling of impulse sounds





Partial relief:

Larger absorption at higher freqs

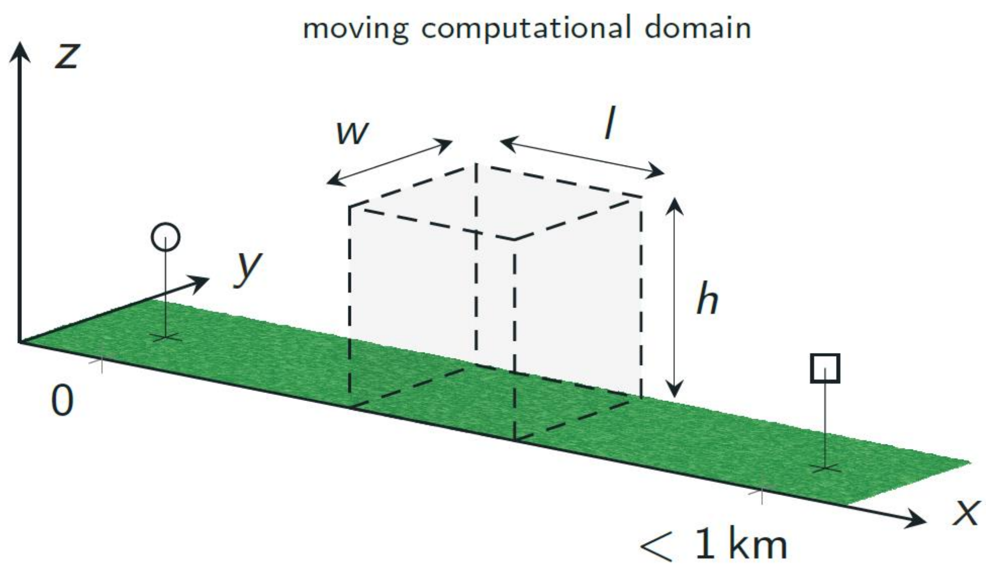
At range, low freqs are sufficient!

The ISL Time-domain Model (ITM)

$$\begin{cases} \dfrac{\partial \vec{w}_a}{\partial t} = -\left(\vec{u}.\vec{\nabla}\right)\vec{w}_a - \left(\vec{w}_a.\vec{\nabla}\right)\vec{u} - \dfrac{\vec{\nabla} p_a}{\rho} + \dfrac{\vec{F}}{\rho} \\ \dfrac{\partial p_a}{\partial t} = -\left(\vec{u}.\vec{\nabla}\right)p_a - \rho c^2 \vec{\nabla}.\vec{w}_a + \rho c^2 Q \end{cases}$$

$$(c,\rho) = \text{fonction}(P,T,q)$$

- Time domain (impulse, measurements)
- Discretization $\Delta x \propto \lambda$
- High Perf Computing
- Boundary conditions PML+ ground
- Suitable for general / complex environments



ITM
State-of-the-art
Pulses < 2000 Hz
in 3D+time at < 1 km

Propagation & Sensing of battlefield sounds

2. Propagation effects on pulses

Experiment

J. Acoust. Soc. Am., 2018

Gas cannon, 156 dB peak at 1 m

14 mics, bars of 3 mics

Environment monitoring (ground, wind)

Moderate wind (2 – 5 m/s)

Experiment

J. Acoust. Soc. Am., 2018

Gas cannon, 156 dB peak at 1 m

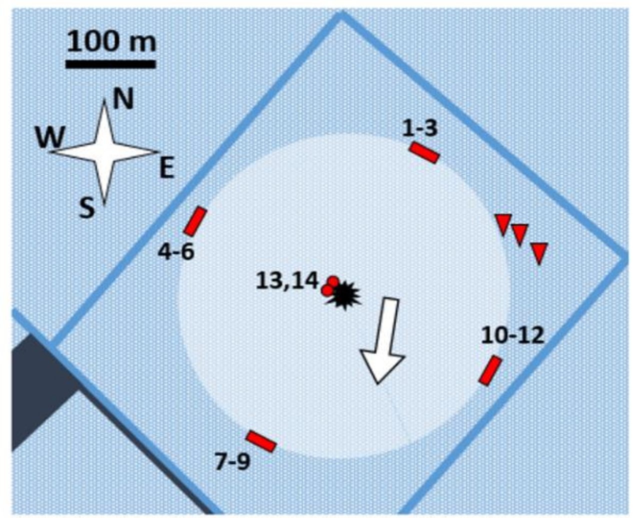
14 mics, bars of 3 mics

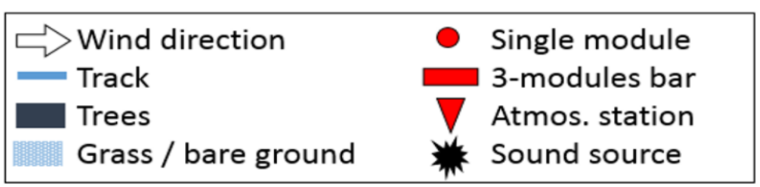
Environment monitoring (ground, wind)

Moderate wind (2 – 5 m/s)

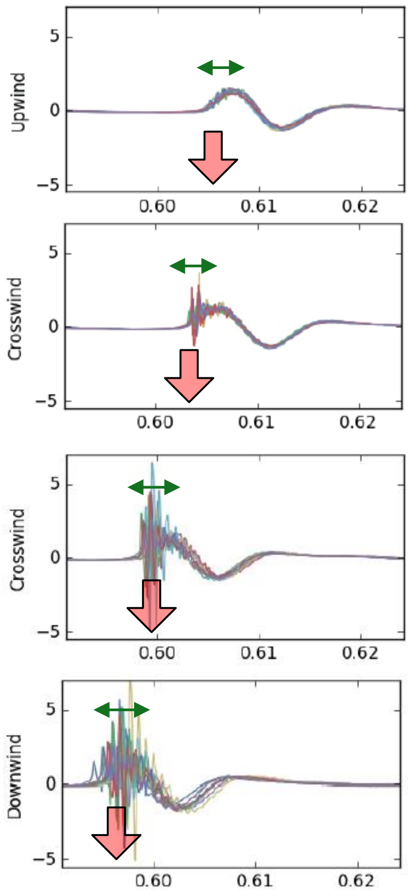
56 consecutive shots
circle configuration, 30 mn

- More experimental tests
- Literature
- Modeling (FDTD, PE, Rays)





Pulse modulations / wind convection, range



$$TOA \sim \frac{r}{(c_0 + \bar{u}\cos\theta)} + \Delta TOA + \cdots$$

Simple propagation

Wind convection

Pulse wander (turbulence)

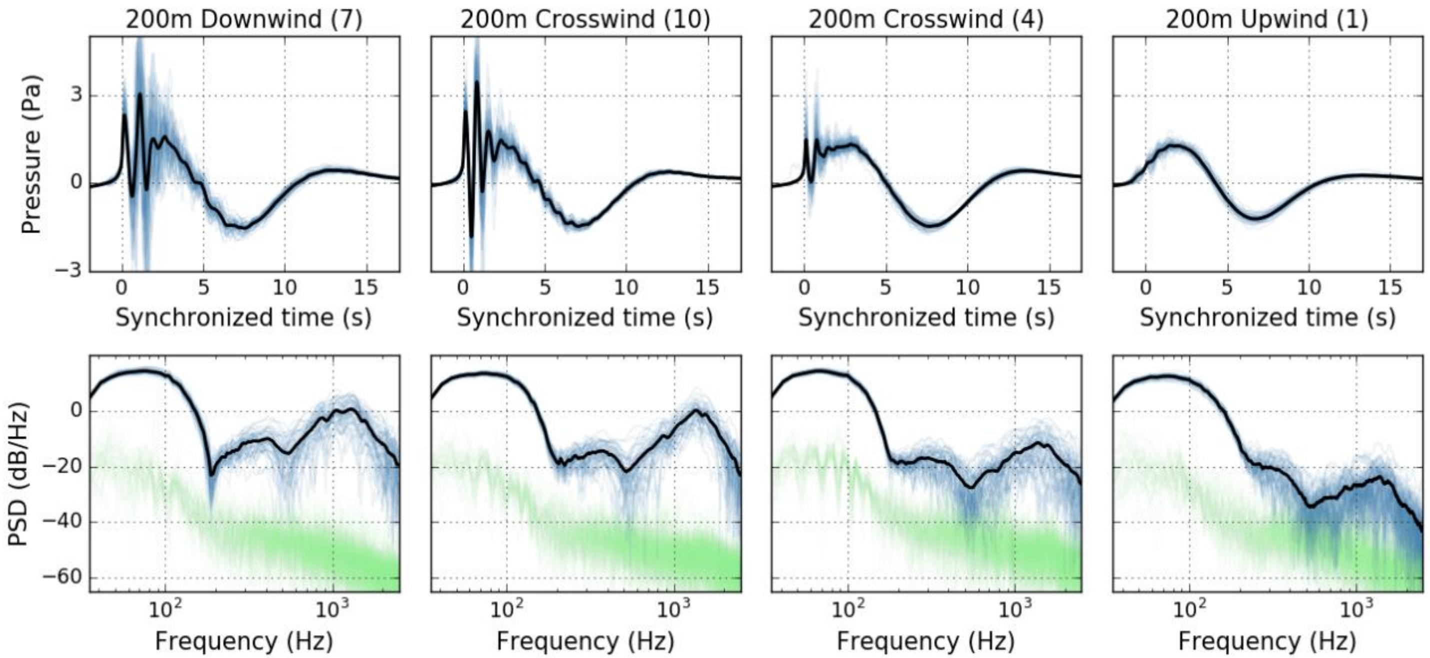
Sensor positioning uncertainty

Refraction of ray, diffraction

Hereafter, resynchronize signatures to the TOA

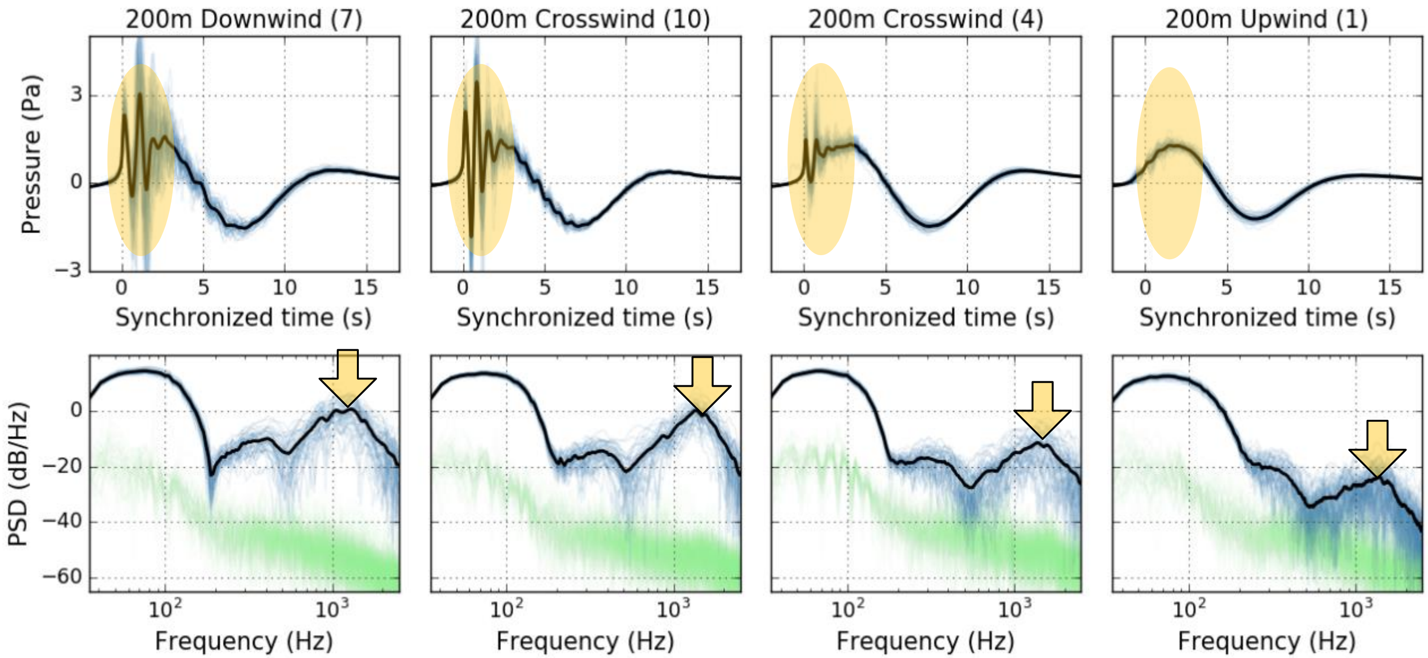
Cf. Acoustic tomography / V Ostashev

Pulse modulations / refraction

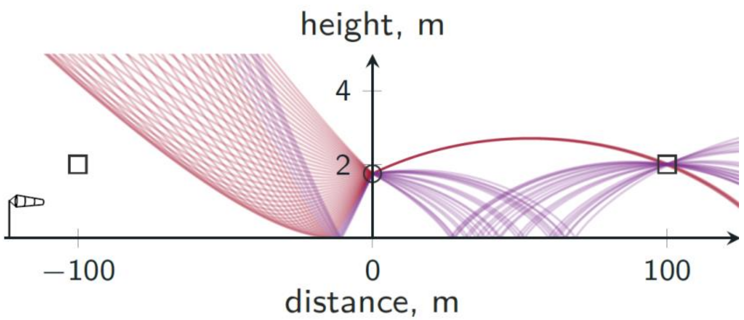


- Signal always above noise
- Strong recombinations of the signature
- Time-domain and frequency domain
- Investigate the physics of these modulations

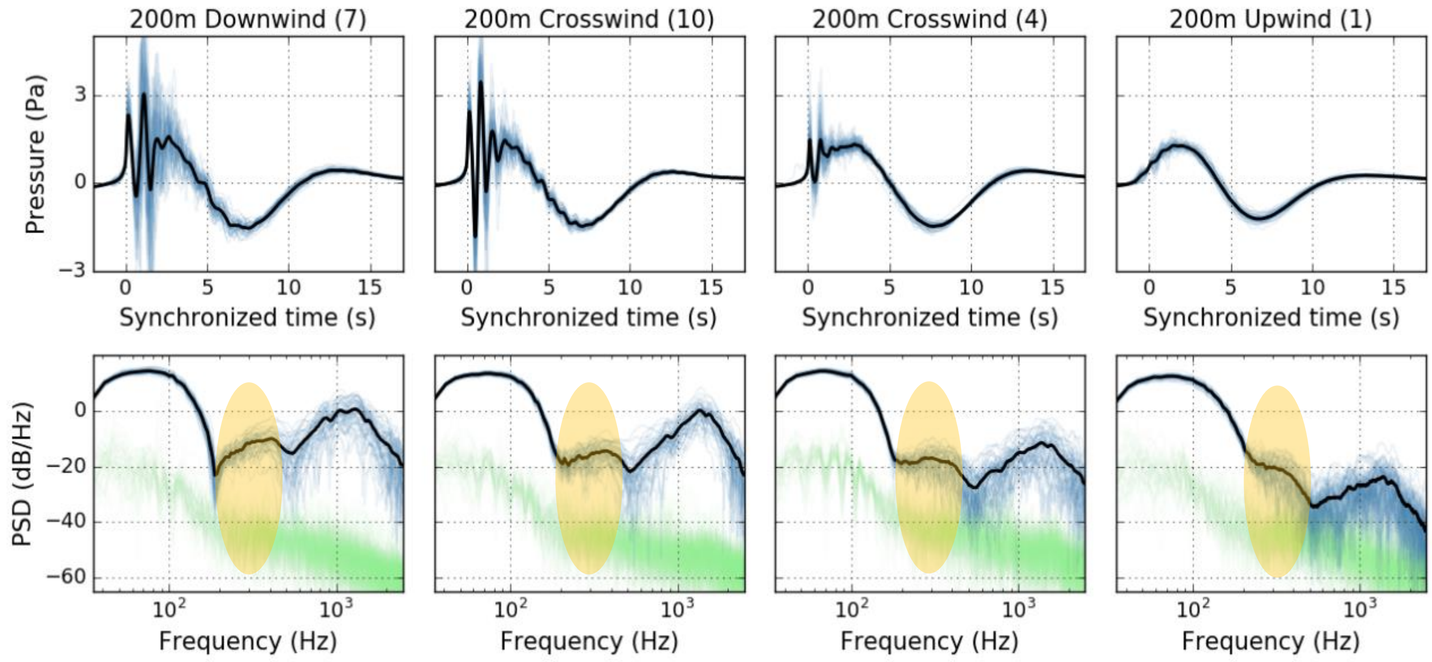
Pulse modulations / refraction



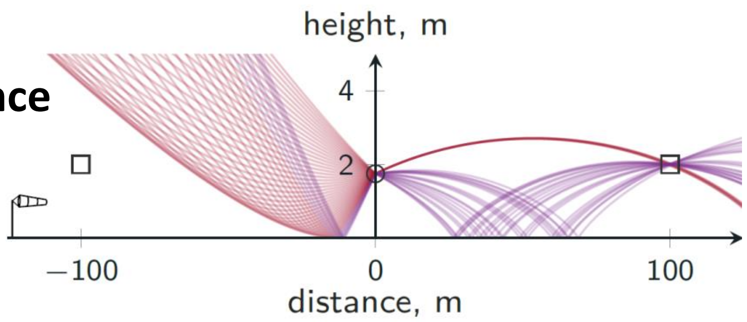
- **Refraction due to wind gradients**
- Induces duct, reflexions, shadows
- Early arrivals caused by direct rays
- Dispersive (HF)



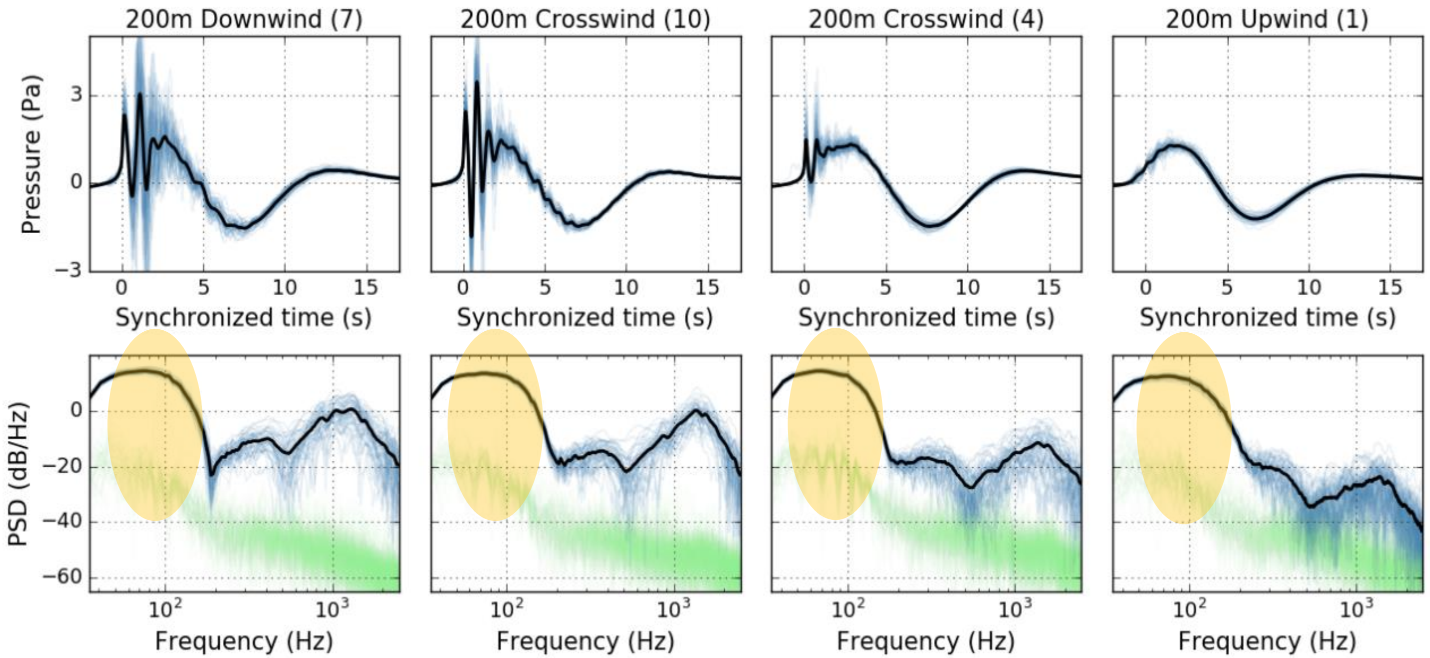
Pulse modulations / ground



- Source-caused dip at 600 Hz
- Additional dip 200 Hz due to **ground impedance**
- Enhanced downwind (more reflexions)
- The dip reinforces with range

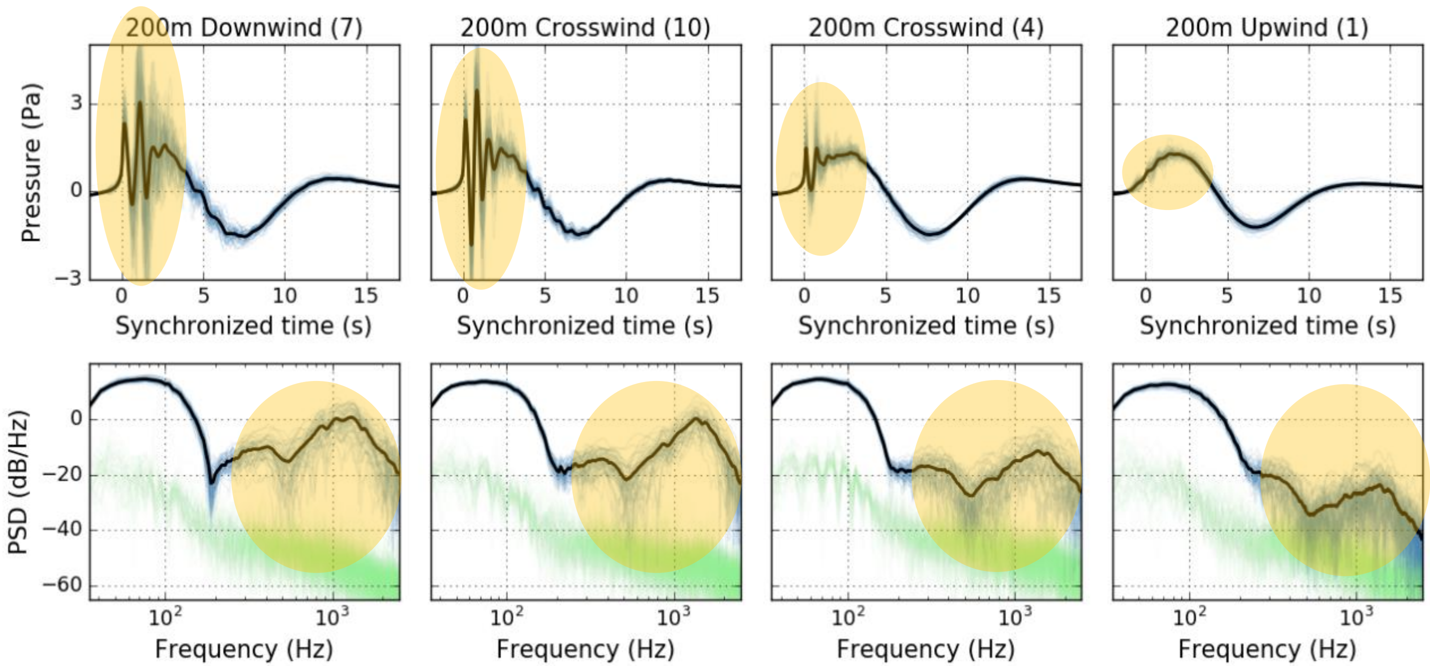


Pulse modulations / surface wave



- **Low-frequencies are unaffected** (in this experiment)
- Sensitive to ground characteristics, surface wave
- Dominates the signal upwind

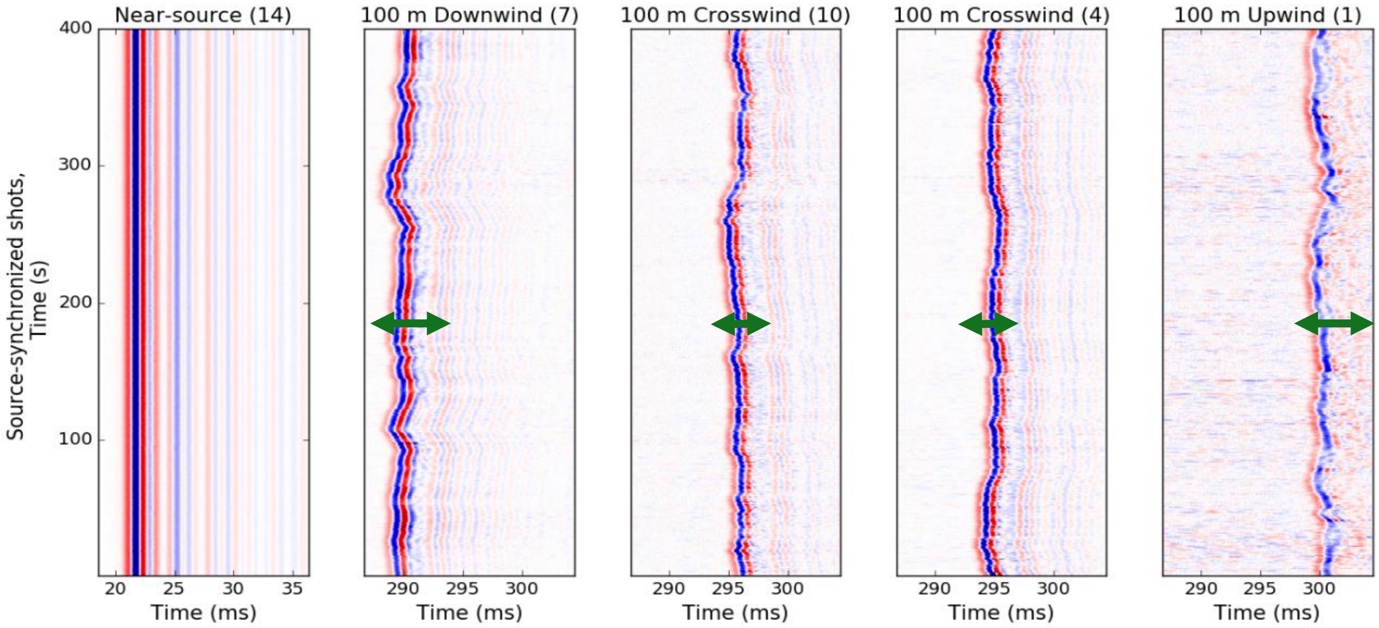
Pulse modulations / pulse spread



- All signals undergo major shot-to-shot fluctuations in shape, so-called **'spread'**
- Stronger at HF, thus more visible downwind
- Low turbulence conditions show much less of these fluctuations
- Dominantly caused by **atmospheric turbulence** (ground heterog., source)

Cf. Stochastic uncertainty,
D Ecotière

Pulse modulations / wander

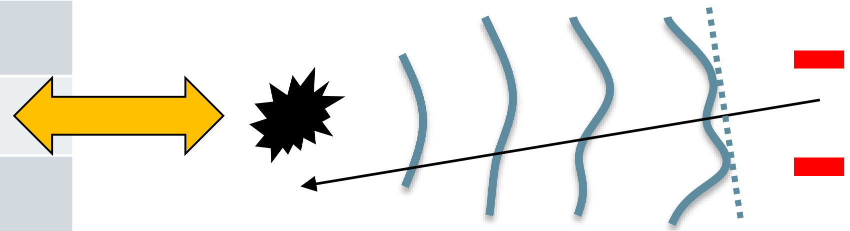


The pulse wanders (TOA randomness)
- non negligible, caused by **turbulence**

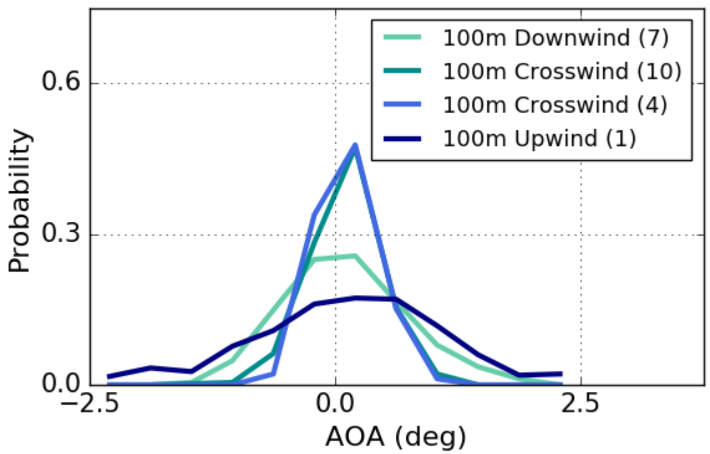
$\Delta \boldsymbol{t} = \dfrac{\boldsymbol{\sigma_u}}{\boldsymbol{c_0^2}}\sqrt{\boldsymbol{2L_uX}}$	Pulse wander scaling, classical for single freq. X (range increases) . $1/\sqrt{X}$ (path-averaging)
$\Delta t_u > \Delta t_v$	Turbulence anisotropy, $\sigma_u > \sigma_v; L_u > L_v$ Suggests larger wander streamwise

Pulse modulations / two-… coherence(s)

Coherence type	Formulation
Spatial / longitudinal	$\langle p(x,y,t)p(x+\Delta x,y,t)\rangle$
Spatial / transverse	$\langle p(x,y,t)p(x,y+\Delta y,t)\rangle$
Temporal	$\langle p(x,y,t)p(x,y,t+\Delta t)\rangle$
Frequency (FT)	$\langle p(x,y,\omega)p(x,y,\omega+\Delta\omega)\rangle$



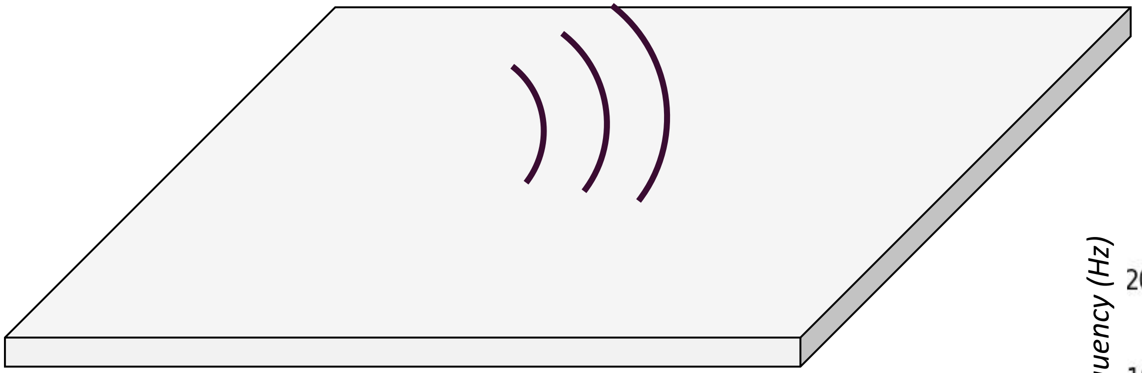
$\langle\ \ \rangle$ = average over shots
t = shot index
$\Delta. = 0$ gives normalization
$\Delta. = \infty$ gives 0

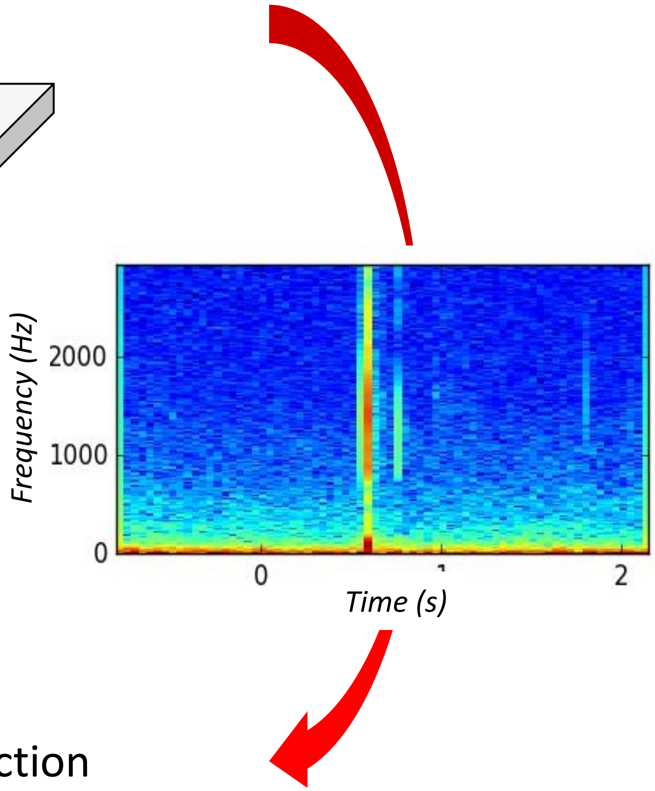


Propagation & Sensing of battlefield sounds

- 3. Impact on sensing
- Example 1: mortar shot
- Example 2: sniper shot

Example 1: mortar shot sensing





Pulse shape processing

SNR / energy	-> Detection
DTOA / beamform	-> Azimuth bearing
Spectral balance / duration	-> Classification

Example 1: expected sensitivities

<u>Detection</u>

Variations of the peak & energy (x2-3)

Expect better detection downwind

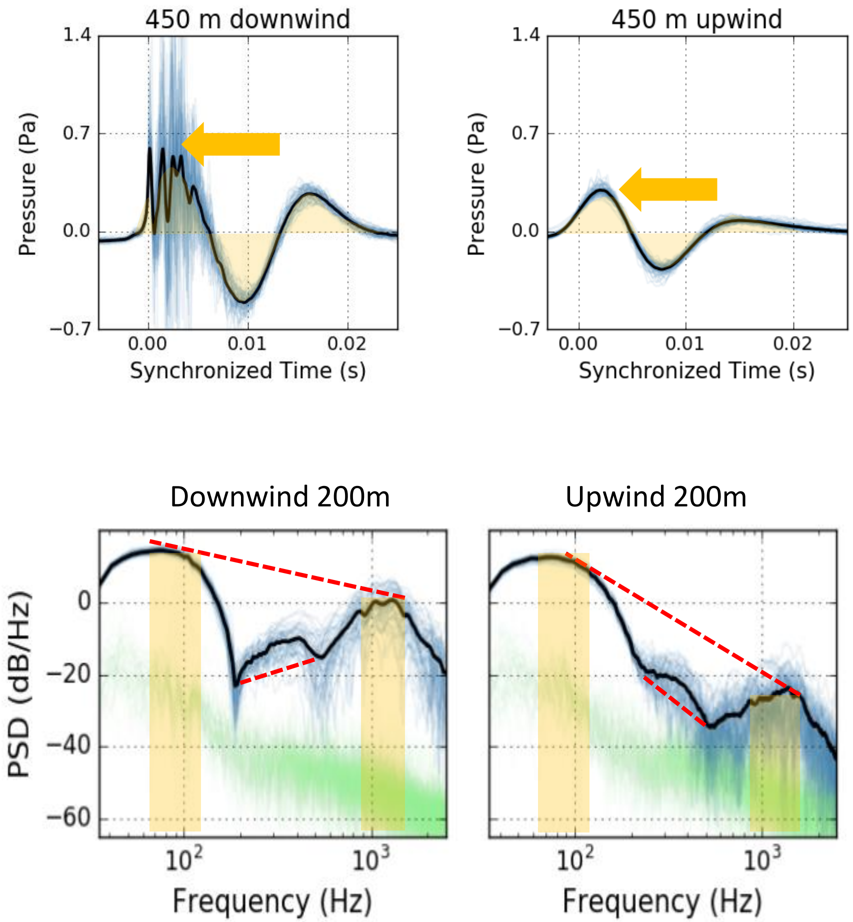
<u>Localization</u>

Expect uncertainty of some degrees

<u>Classification</u>

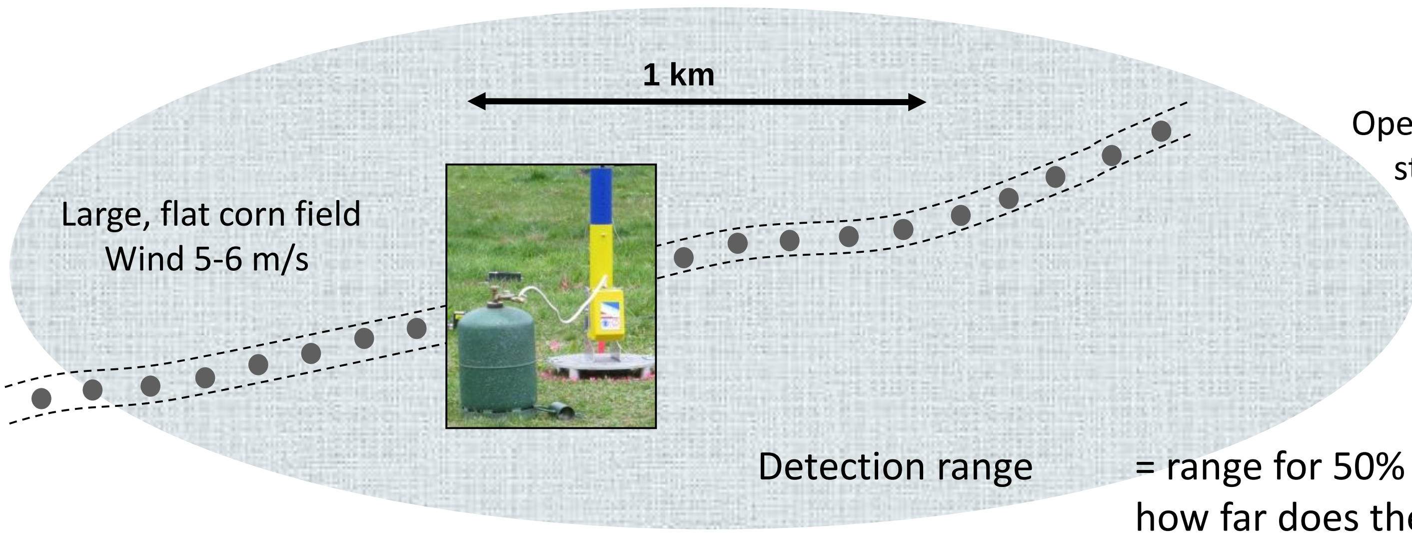
Variations of the spectral balance (25 dB)

Expect sensitivity of classification



Example 1: Sensitivity of operational system

Appl. Acoust., 2015



= range for 50% shots detected
how far does the system work?
major metric for performance

Example 1: Sensitivity of operational system

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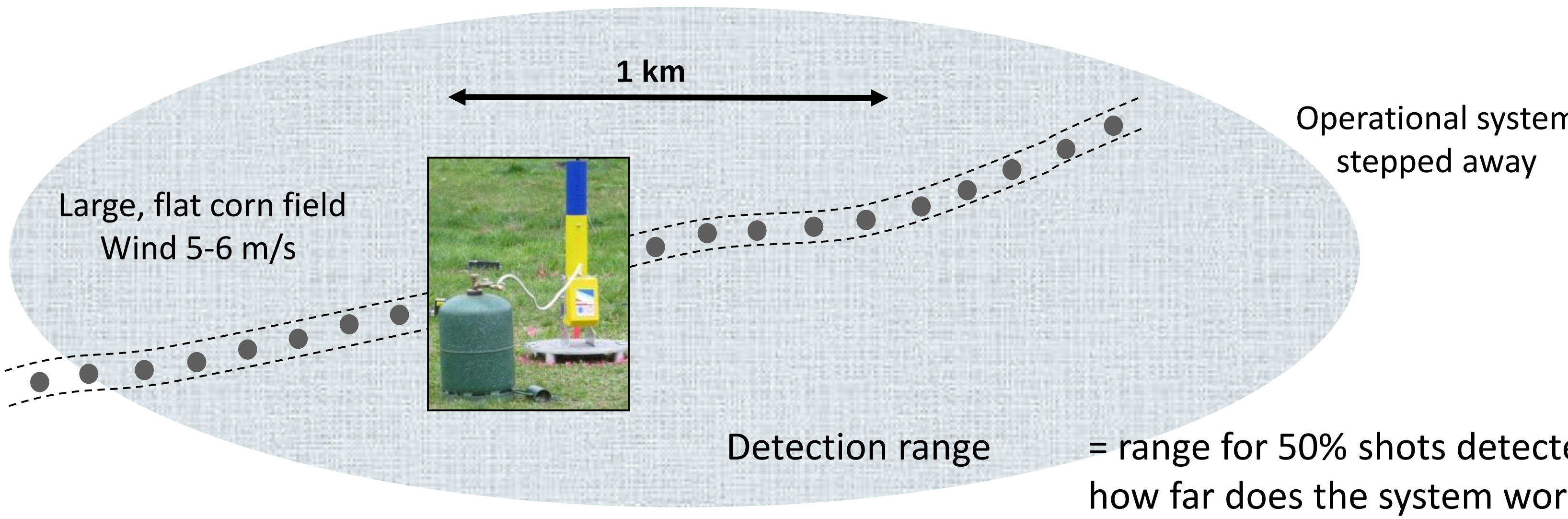


Detection range = range for 50% shots detected
how far does the system work?
major metric for performance

Position	Downwind	Upwind
Detection Range	**1150 m**	**400 m**

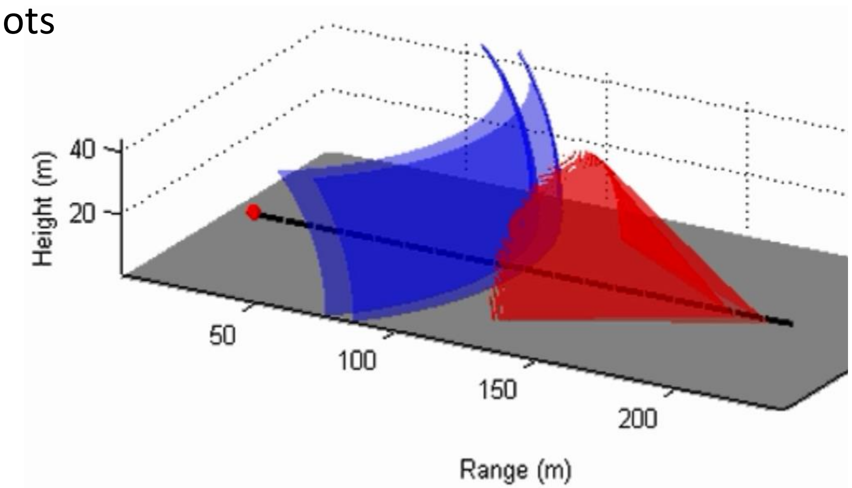
As expected,
- the detection range is much larger downwind
- localization uncertainty: 2-3°

NB: More severe weather conditions happen…

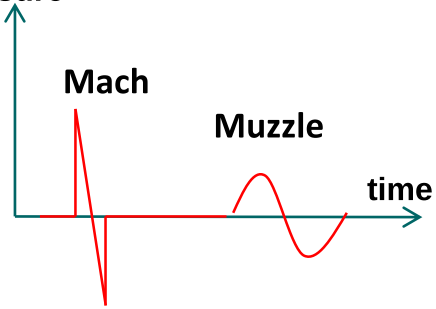
Example 2: sniper shot sensing

4 weapons,

700 **supersonic** projectile shots



4 microphones antenna



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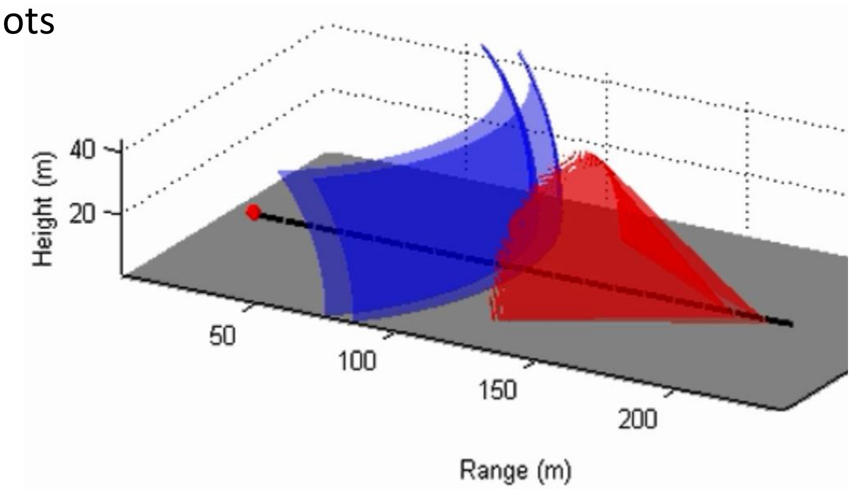

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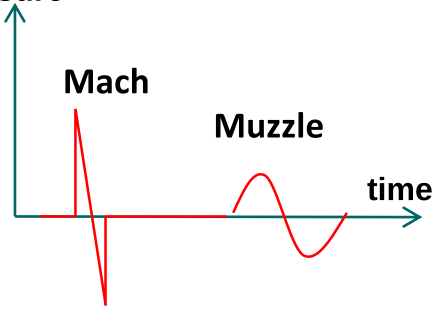


Detection	Mach+Muzzle
Loca / azimut	Muzzle
Loca / ranging	**Mach**

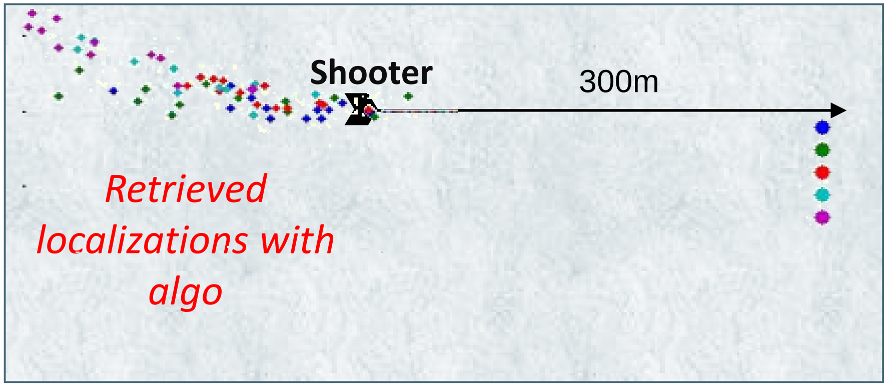
$$p_{max} = \frac{0.53 P_0 \left(M^2 - 1\right)^{1/8}}{r^{3/4}} \frac{d}{l^{1/4}}$$

$$T = \frac{1.82\ M\ r^{1/4}}{c\left(M^2 - 1\right)^{3/8}} \frac{d}{l^{1/4}}$$

Rationale:
Mach wave only depends
on propagation range

Example 2: test of standard processing algorithm

Appl. Acoust., 2015



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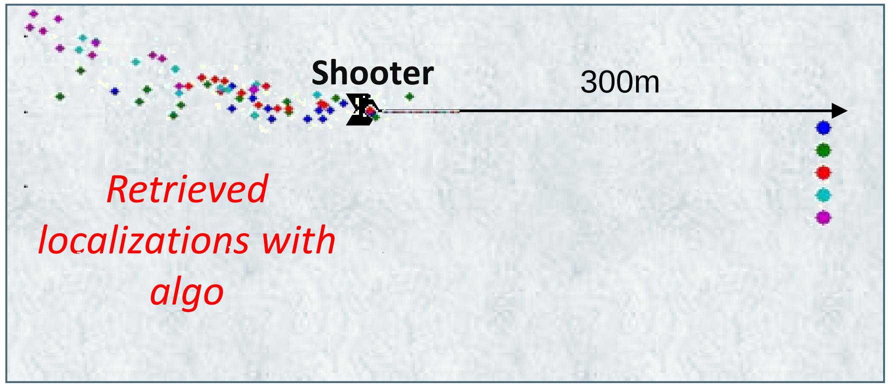
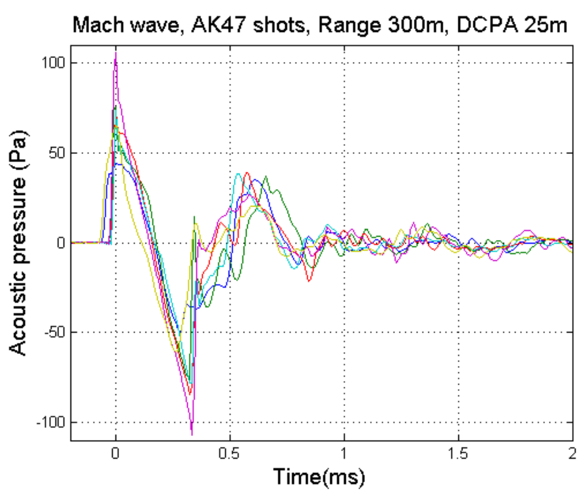




Loca / ranging	**Mach**

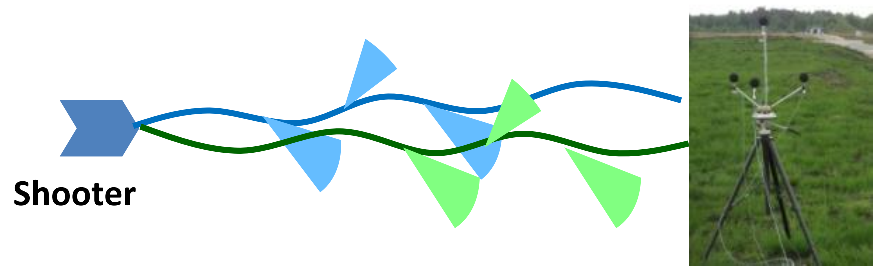
The ranging uncertainty is caused by <u>deterministic</u> processing of a <u>randomized</u> Mach wave.

Example 2: physical sensitivity

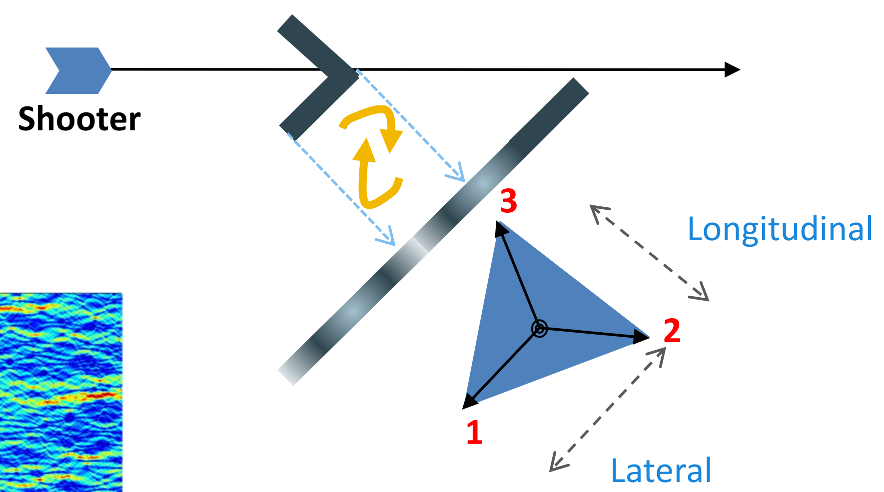
Appl. Acoust., 2015

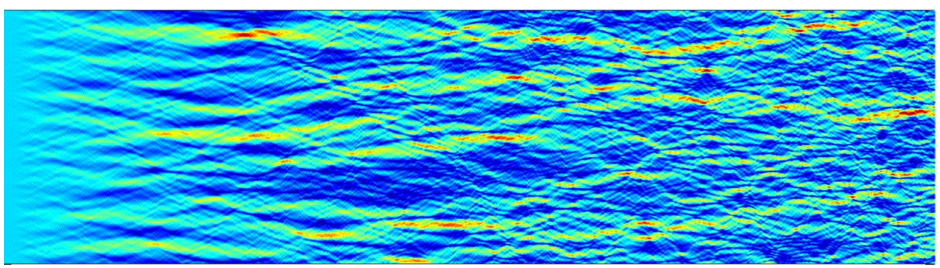
- ❑ ~~microphone reproducibility~~

- ❑ bullet oscillations
  variations on shots / noise
  Correlation among all sensors



- ❑ Mach wave « scintillates »
  Decorrelation in transverse direction





Plane wave through turbulence, ITM model, JASA, 2013

Example 2: physical sensitivity

Appl. Acoust., 2015

- ~~microphone reproducibility~~
- ~~bullet oscillations~~
  ~~variations on shots / noise~~
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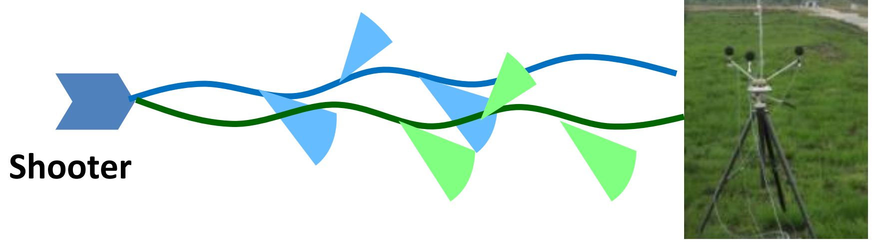
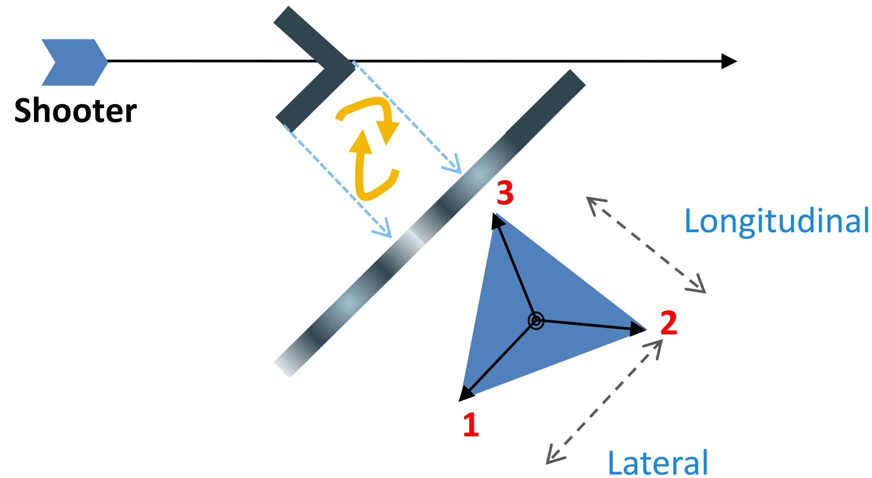
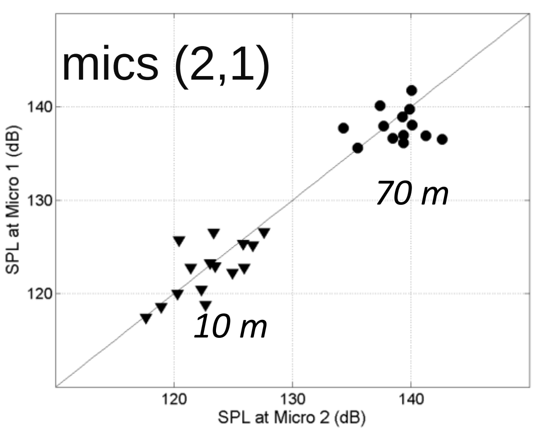






Mach wave propagation through turbulence
Explains scatter in sniper ranging

Surveillance in open environments,

A summary

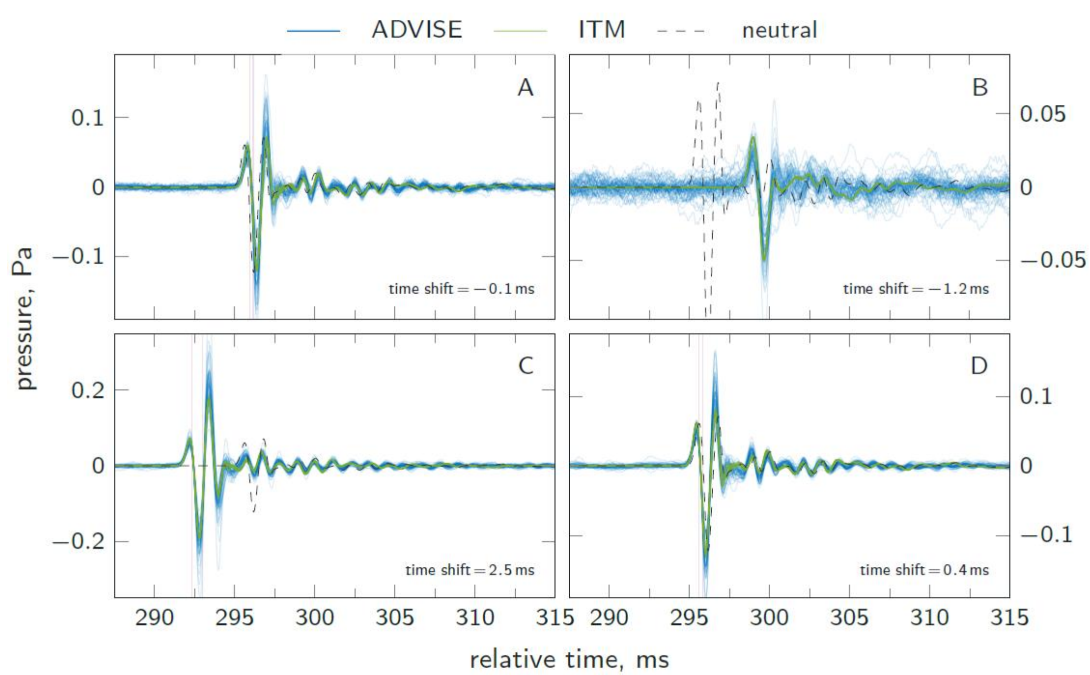
•Pulses are sensitive to the OPEN environment,

•Combined, complex parameters,

•This sensitivity affects 1st generation of sensing systems,

•Predicting these effects is still a R&D challenge

1. Predict environment
2. Predict pulse
3. … Adapt sensing



- Propagation & Sensing of battlefield sounds
    - 4. Mitigating propagation effects
    - The urban environment

Surveillance in urban / built areas

Built areas are of primary concern for surveillance

Sensing in the urban environment (1)

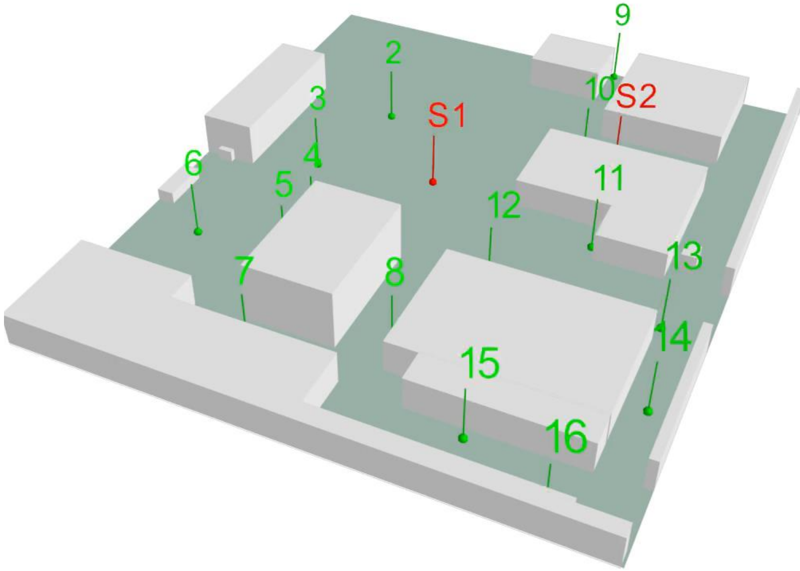
1. **Predict environment**
2. Predict pulse
3. Adapt sensing

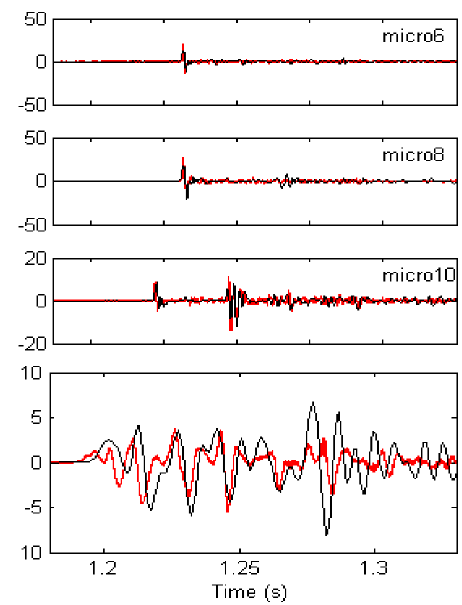
Urban maps become easily available

Sensing in the urban environment (2)

1. Predict environment
2. **Predict pulse**
3. Adapt sensing

3D+time FDTD is feasible at low wavelengths of interest

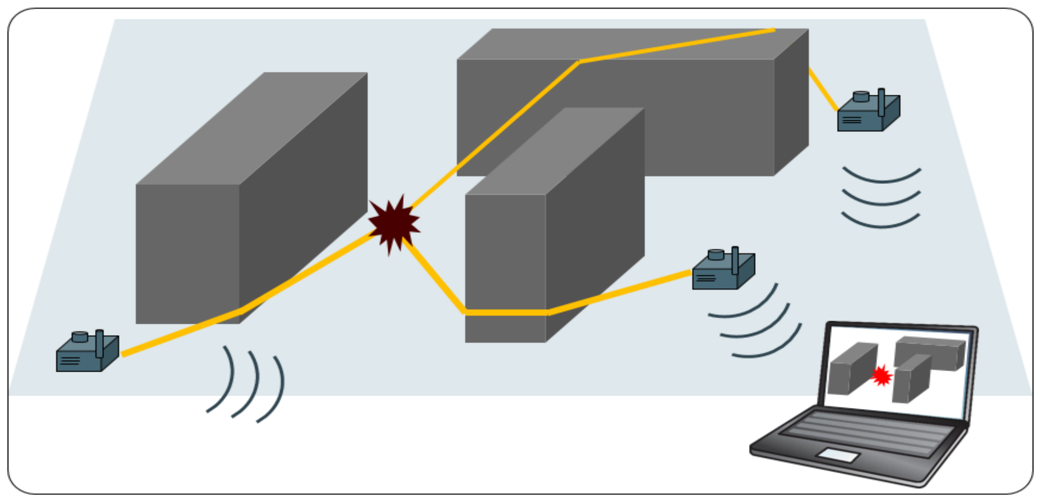




Sensing in the urban environment (3)

1. • Predict environment
2. • Predict pulse
3. • **Adapt sensing ?**

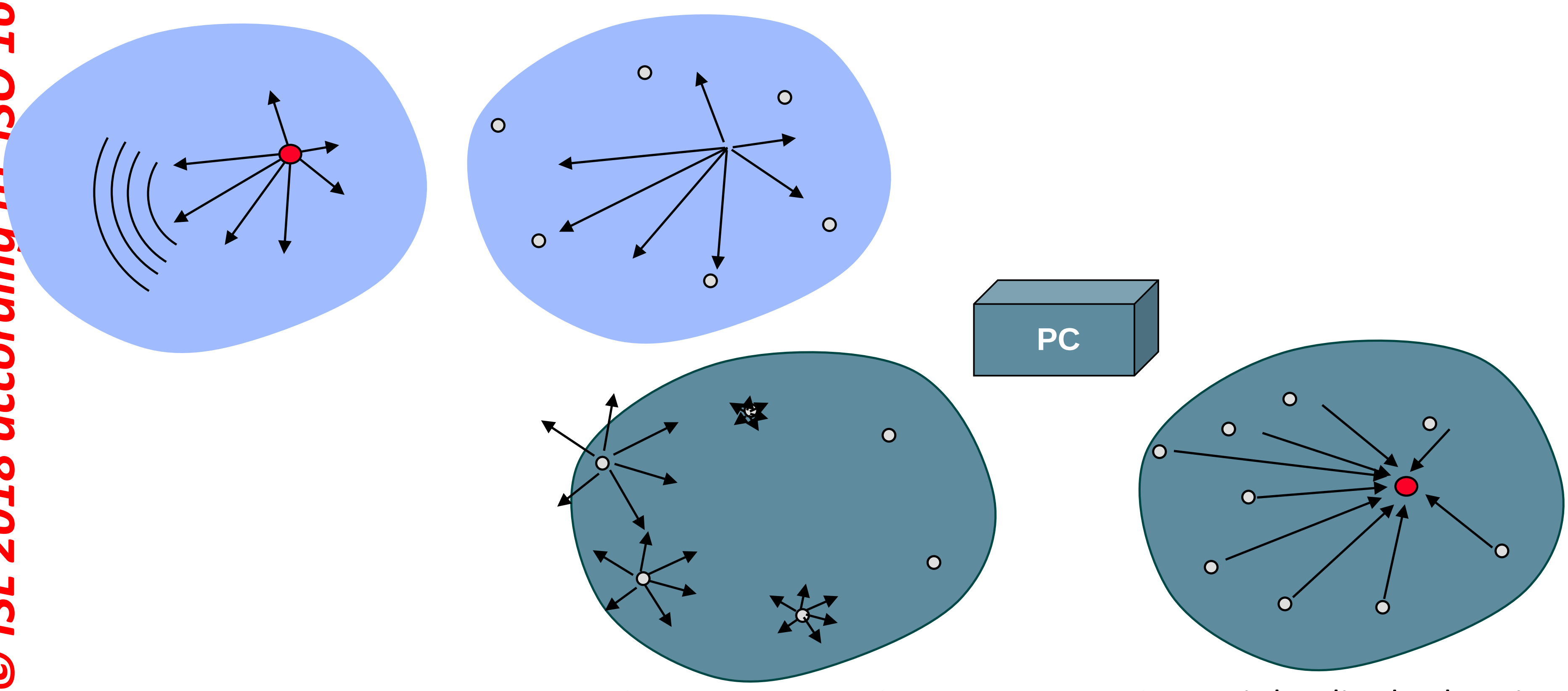
- TOA and AOA are severly affected by urban obstacles
- Multilateration (TOA), beamforming (AOA) collapse
- Functional challenge: localize explosion
10 m accuracy, block-size area, 5-10 sensors, known map



Time reversal: principle

1. Source emits throughout the environment (FORWARD)

2. Sensors record the pressure time series, the signals are collected at the PC



3. The reversed signals are synchronously propagated (BACKWARD)

4. Source is localized at location where interference is maximum

Time reversal: tests

JASA, 2016

Localization is degraded for far+NLOS microphones.

These microphones hardly contribute to the interference pattern

Damped by 3D spherical spreading + urban attenuation (forward x backward).

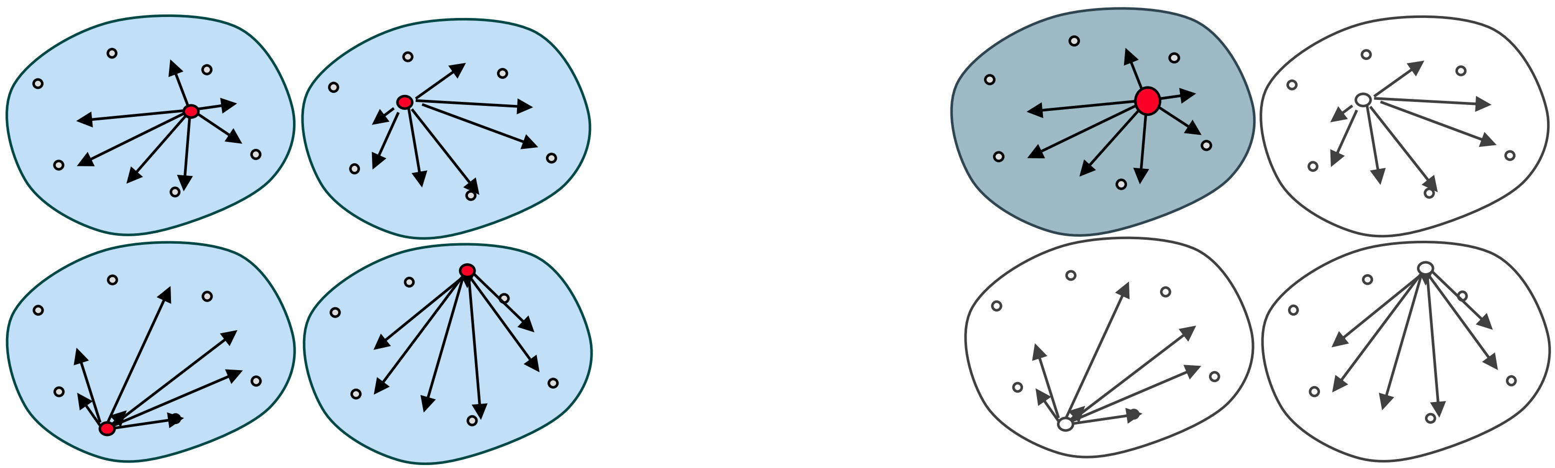
Time reversal localization suffers in outdoor environments

Signal matching

JASA, 2016

Cold phase, form a **reference database** Time-Of-First-Arrival (TOA), with simulations

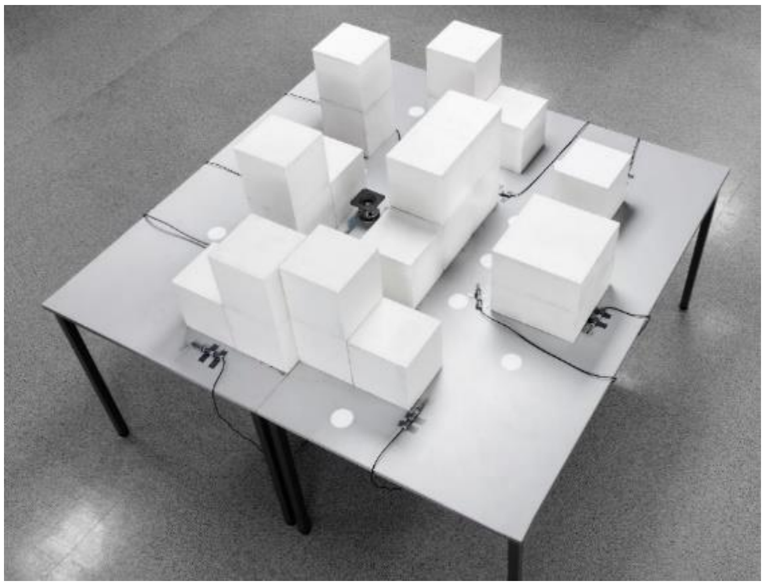
Hot phase (0.1s), TOA are measured, transmitted to PC, **best matching comparison** gives localization

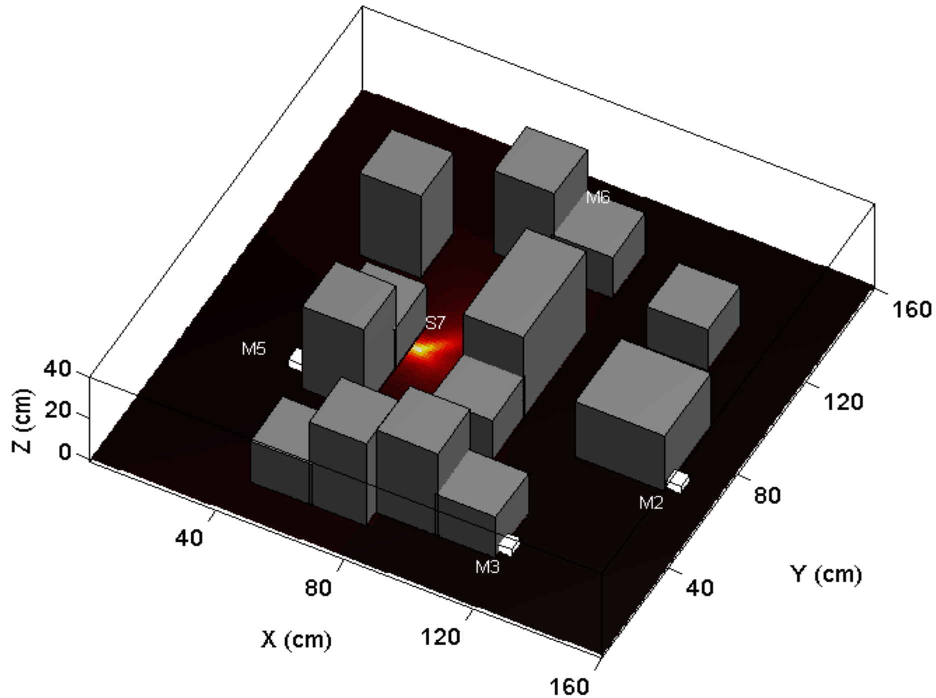


- Robust and standard, « multilateration », « time delay », *« analog prediction »*
  - **Supervised approach, 3D urban propagation model for the database**
    - Overcomes signal fading issue (no backward)

Results

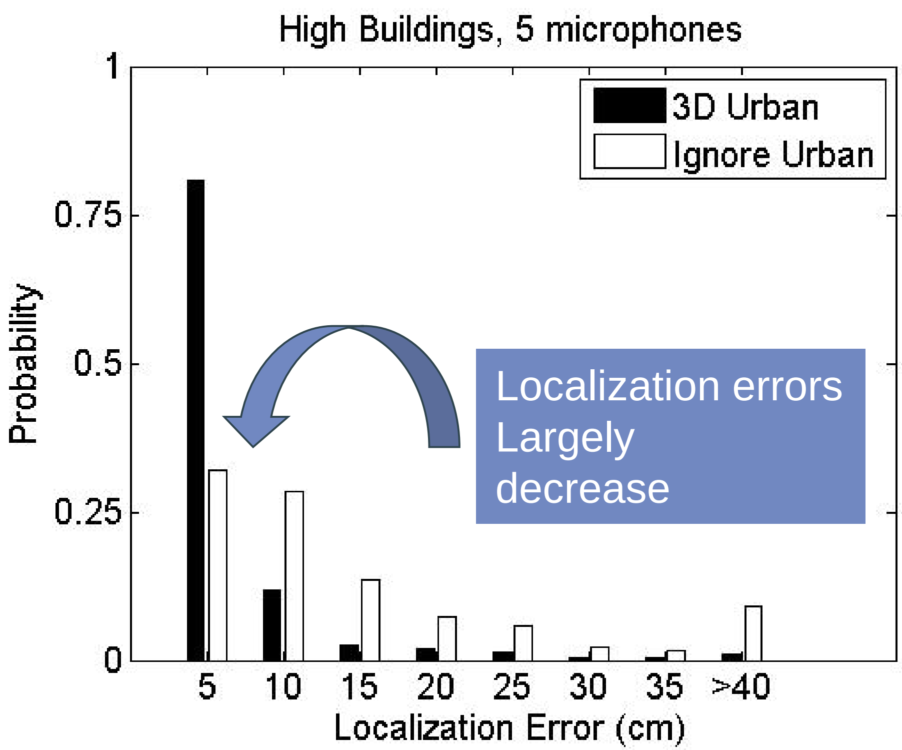
Acta Acust. Acust., 2016





Results

Acta Acust. Acust., 2016



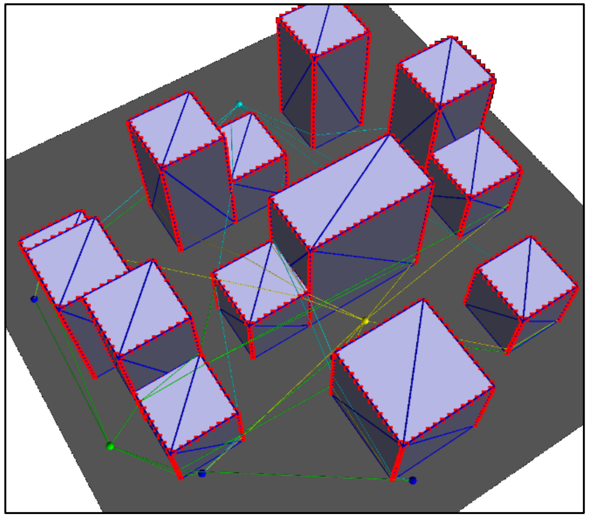
The method is efficient, including in NLOS

On-going / perspectives

Move toward application

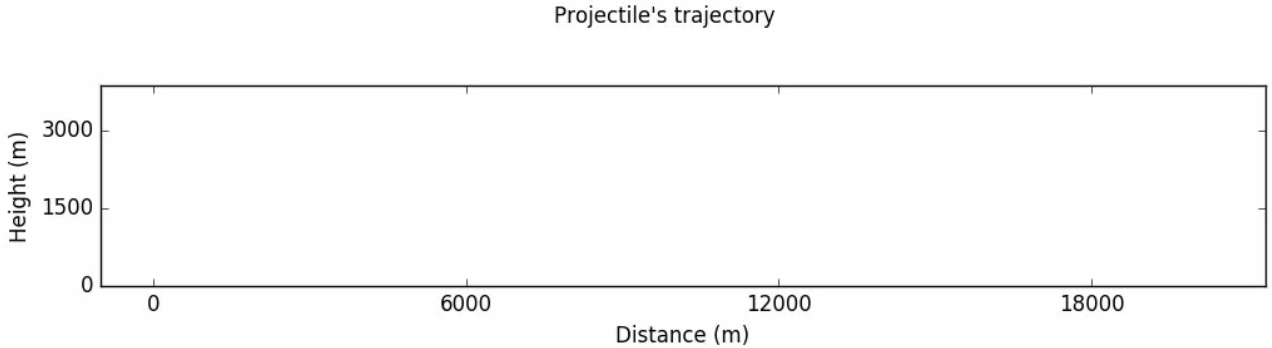
real-time calculations

demonstrator (TRL5)



Extend to other complex scenarios

artillery shot (complex)



- Propagation & Sensing of battlefield sounds

- Conclusions

Summary

Acoustic sensing systems are used in many applications

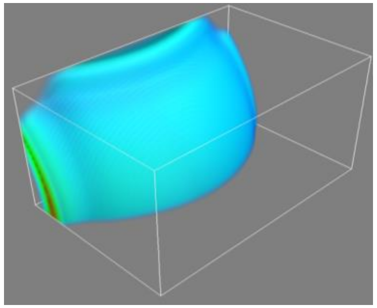
Propagation effects are a key factor to their sensing

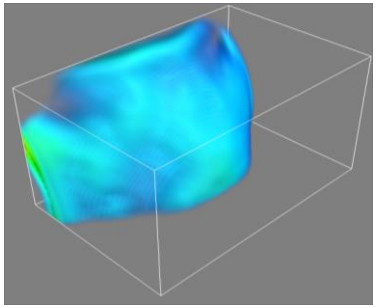
Their management is a R&D challenge: complex & promising

It requires the full panel of TRL and expertise
- experiments (real + small-scale)
- high-fidelity modeling / engineering modeling / processing
- environmental assessment

Nice opportunities of R&D

Pulse propagated in 3D after 100 m, without and with turbulence

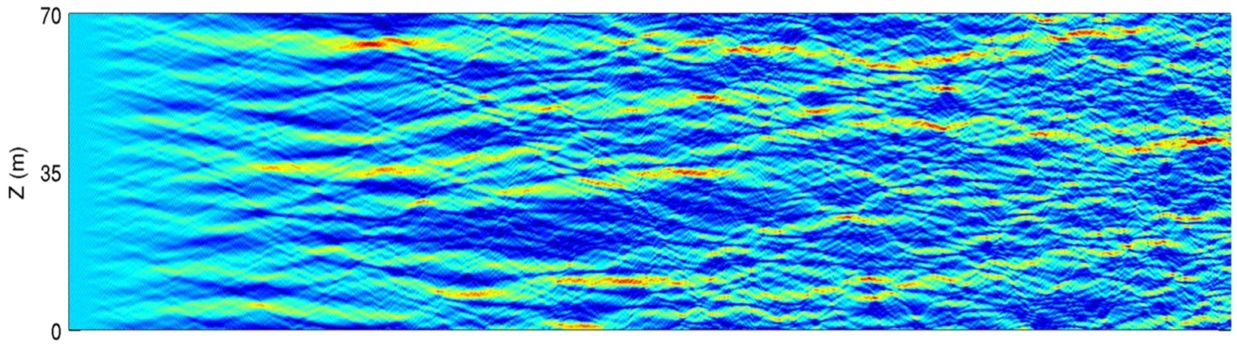




Nota Bene

Many aspects of the present « propagation & sensing » discussions are common to

- Outdoor acoustics
- Underwater acoustics (Flatté et al., 1979)
- Outdoor optics (Bound. Lay. Meteorol. 2011)
- Electro-Magnetism / Radio waves (J. Appl. Met., 2011)



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