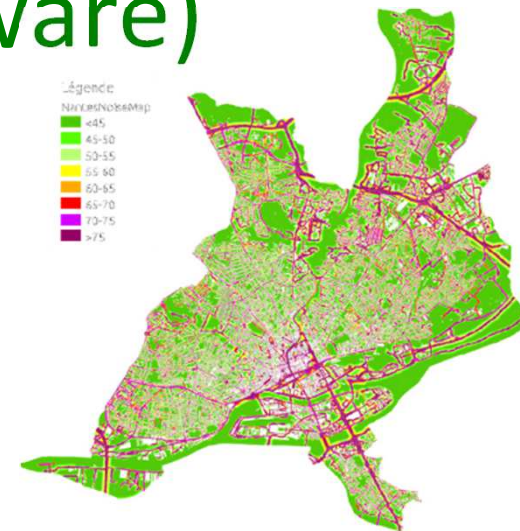
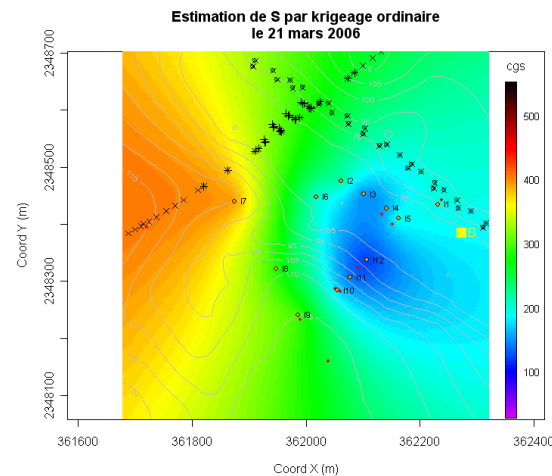




Incertitudes associées à une méthode de mesure *in situ* de l'impédance acoustique des sols (hardware + software)





Uncertainties of an *in situ* method for measuring ground acoustic impedance

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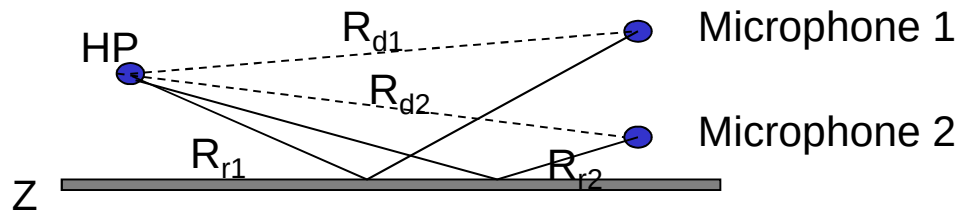
Introduction

- Ground effect on sound propagation
[Embleton, 1996] [Berengier,2003] [Attenborough, 2007]
 - Measurement of outdoor ground impedance (input parameters)
 - Need for an *in situ* method and for an automated estimation procedure
- >> Uncertainties of the procedure ?

The measurement method

2-microphones method

- Principle [Hess,1990] [Sabatier,1990] [Sabatier,1993][Guillaume,2015]



- Measurement of the spectrum transfer function between 2 points

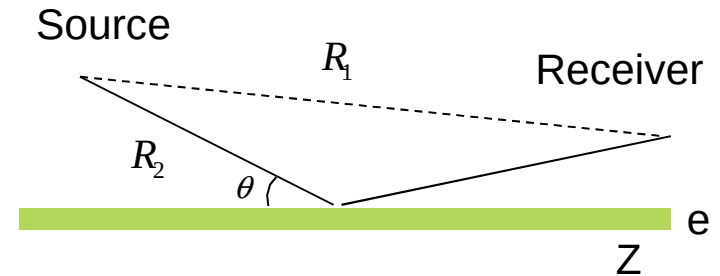
$$\Delta L = 10 \log_{10} \left| \frac{p_1}{p_2} \right|^2$$

- Estimation of the Z parameters by fitting calc/measured of ΔL

Theory

● Ground effect

- Propagation model [Rudnick, 1947]
- Spherical reflexion coefficient :
- Plane wave reflexion coefficient :
- Faadeva function :



$$p_R / S = \frac{e^{ikR_1}}{R_1} + Q \frac{e^{ikR_2}}{R_2}$$

$$Q = R_p + (1 - R_p)F(w)$$

$$R_p = \frac{Z \sin \theta - 1}{Z \sin \theta + 1}$$

$$F(w) = 1 - 2jw^{\frac{1}{2}}e^{-w} \int_{-jw}^{\infty} e^{-u^2} du$$

$$\text{with } w^2 = \frac{1}{2} jkR_{ri} \left(\sin \theta + \frac{1}{Z} \right)^2$$

Theory

- Models of acoustic impedance

- Thickness correction

$$Z_c = Z \coth(-jke)$$

- Miki model [Miki, 1990]

$$0.01 < \frac{f}{\sigma} < 1.00$$

$$\begin{cases} Z_c = Z_0 \left(1 + 5.5 \left(\frac{f}{\sigma} \right)^{-0.632} + j8.43 \left(\frac{f}{\sigma} \right)^{-0.632} \right) \\ k = k_0 \left(1 + 7.81 \left(\frac{f}{\sigma} \right)^{-0.618} + j11.41 \left(\frac{f}{\sigma} \right)^{-0.618} \right) \end{cases}$$

→ 2 unknown parameters :
 σ (air flow resistivity)
 e (thickness)

Theory

- Models of acoustic impedance

- Thickness correction

$$Z_c = Z \coth(-jke)$$

- Zwikker and Kosten model [Zwikker and Kosten, 1949]

$$Z = \sqrt{\rho K}$$

$$\rho = \frac{\alpha_\infty \rho_0}{\phi} \left[1 - \frac{2}{\lambda \sqrt{-j}} \frac{J_1(\lambda \sqrt{-j})}{J_0(\lambda \sqrt{-j})} \right]^{-1} \quad K = \frac{\rho_0}{\phi} \left[1 + \frac{2(\gamma-1)}{\sqrt{\text{Pr}} \lambda \sqrt{-j}} \frac{J_1(\sqrt{\text{Pr}} \lambda \sqrt{-j})}{J_0(\sqrt{\text{Pr}} \lambda \sqrt{-j})} \right]^{-1} \quad \lambda = \sqrt{\frac{8\omega \rho_0 \alpha_\infty}{10^3 \sigma \phi}}$$

→ 4 unknown parameters :

σ (air flow resistivity)

ϕ (open porosity)

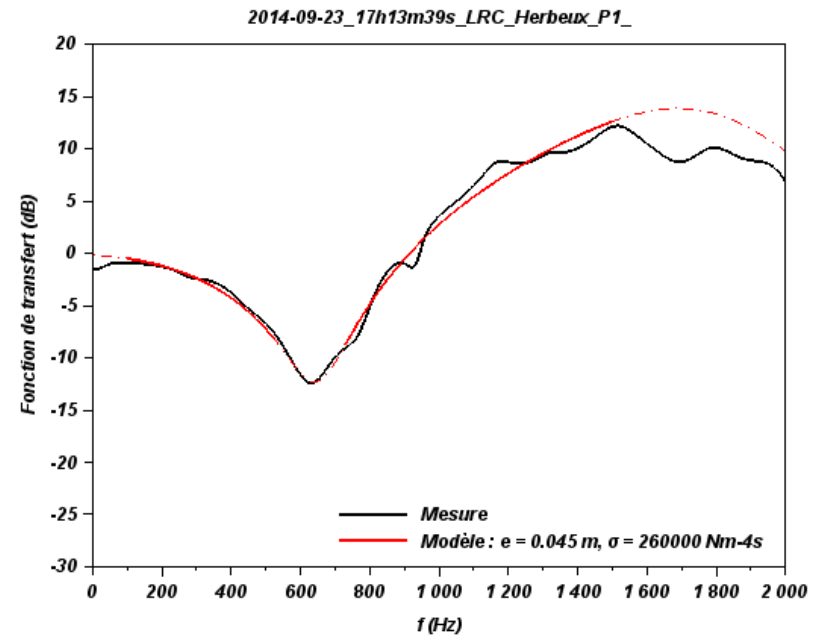
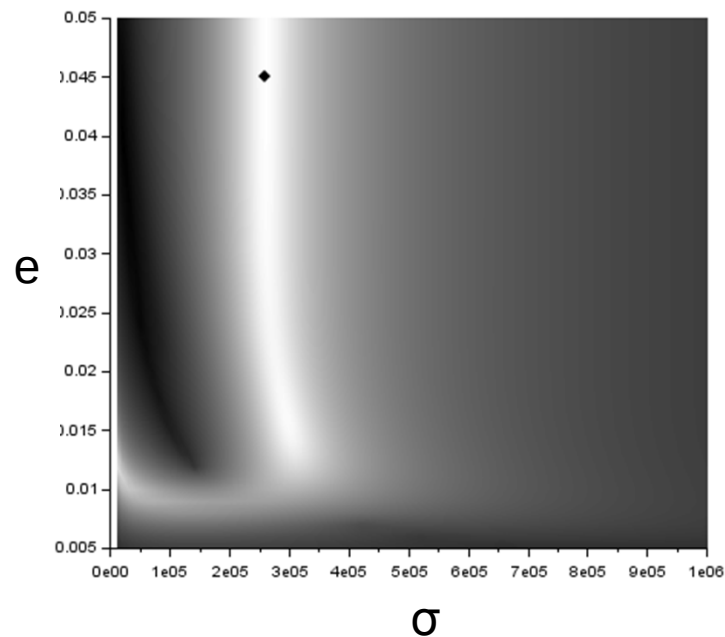
α (tortuosity)

e (thickness)

Theory

- Inverse problem : minimization of a cost function by an exhaustive search

$$F(Z) = \sum_{f \min}^{f \max} |\Delta L_{\text{calculated}}(f, Z) - \Delta L_{\text{measured}}(f, Z)|^2$$



Uncertainties estimations

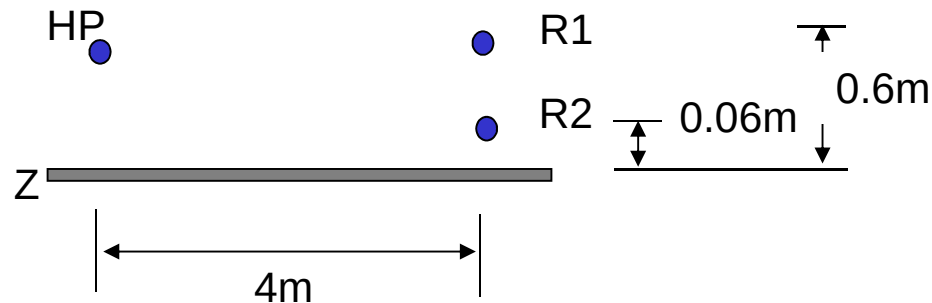
Uncertainties estimations

● Experimental apparatus

- All in one autonomous apparatus
- Scilab-based software
- In situ measurement + in situ parameters estimation



● Experimental set-up



Uncertainties estimations

- Round robin test : experimental protocol

- 5 laboratories, with the same kind of exp. device
- 3 repetitions / point
- 5 outdoor grounds
- 3 points / ground

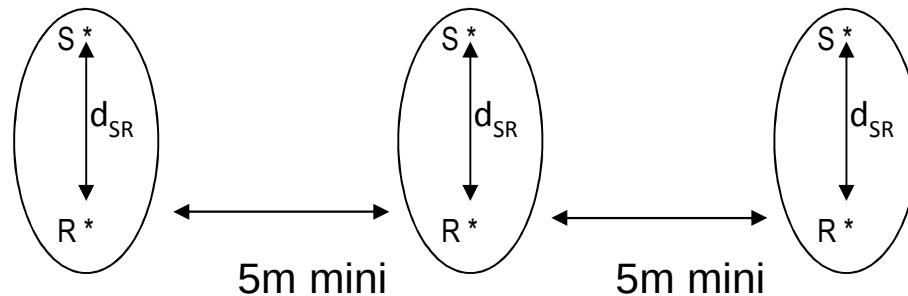
Ground i

Lab j

Point 1 x 3

Point 2 x 3

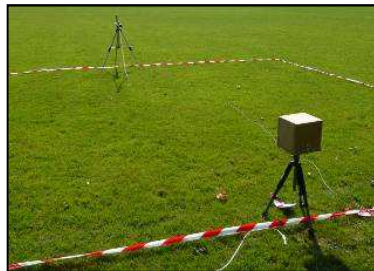
Point 3 x 3



Uncertainties estimations

- Round Robin test : experimental protocol

- 5 kinds of outdoor grounds :



Synthetic
lawn

Natural
lawn

Natural
grass

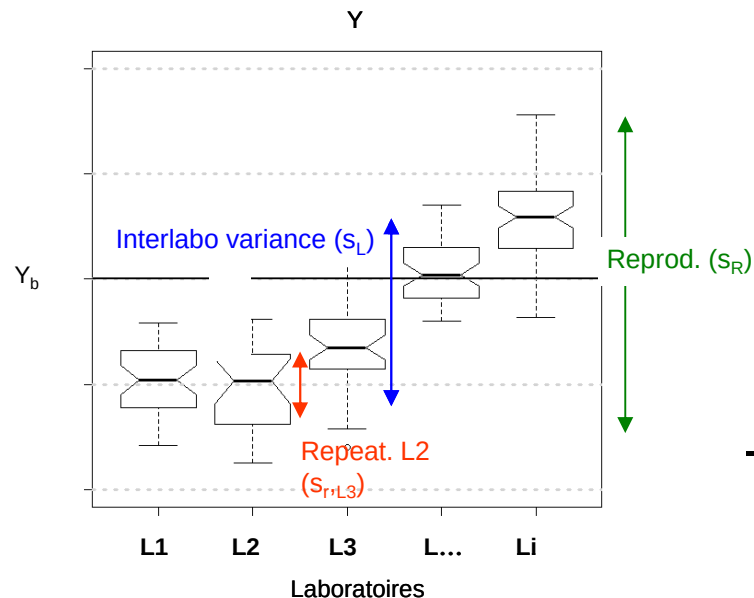
Compacted
ground

Non porous
asphalt



Uncertainties estimations

- Round Robin test : uncertainties estimations
 - ISO 5725-2 : round robin test, interlaboratory measurements
 - Uncertainties : reproducibility and repeatability

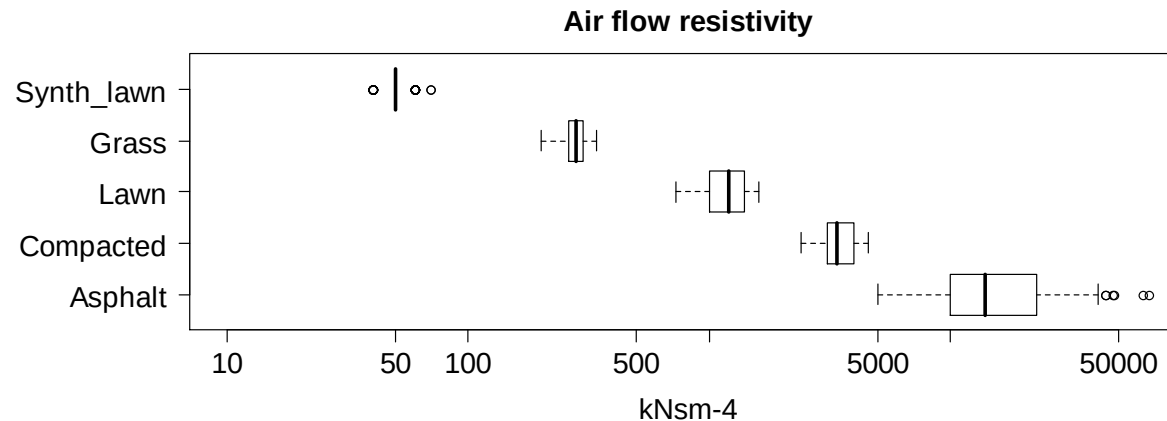


- Repeatability (s_r) : mean dispersion inside labs
- Interlabo var (s_L) : dispersion between labs
- Reproducibility : $s_R^2 = s_L^2 + s_r^2$
- Uncertainties : $Y = Y_b \pm ks_R$ ($k = 2$)

Results

Air flow resistivity uncertainties

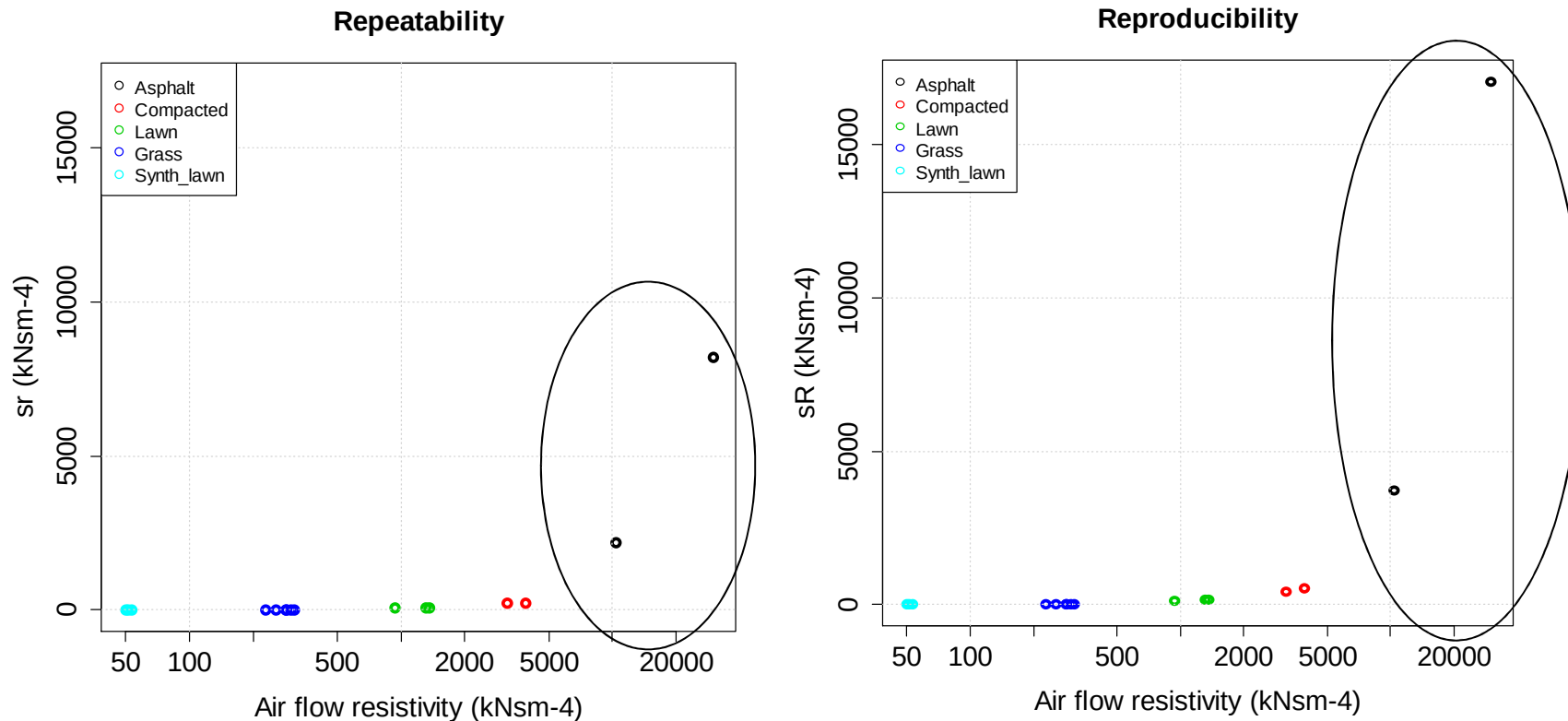
- Reprod. and repeat. vs ground type



Air flow resistivity (kNsm ⁻⁴)	Mean	s _R (reprod.)	S _r (repeat.)	s _L (interlab.)
Non porous Asphalt	19 609	15 070	13 065	7 510
Compacted ground	3 519	567	512	245
Natural lawn	1 154	248	217	119
Grass	277	34	34	6
Synthetic lawn	51	7	5	5

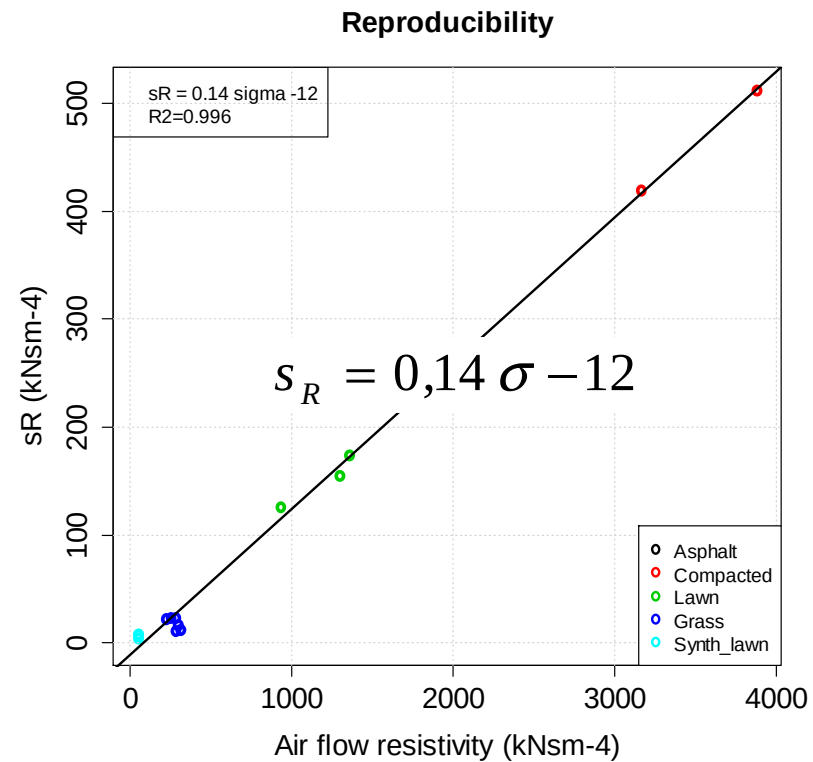
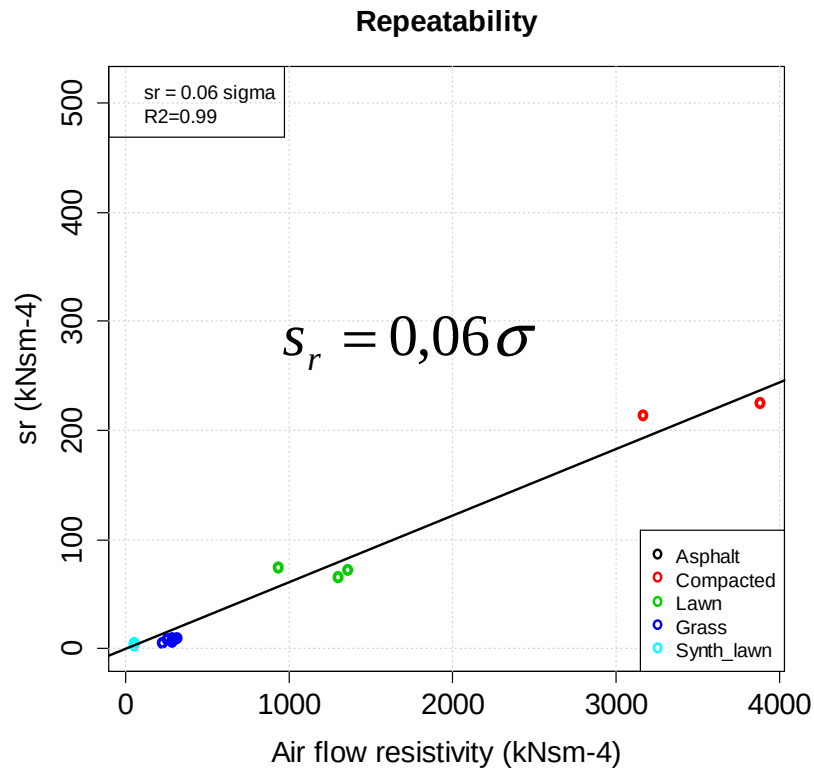
Air flow resistivity uncertainties

● Results : reprod. and repeat. vs air flow resistivity



Air flow resistivity uncertainties

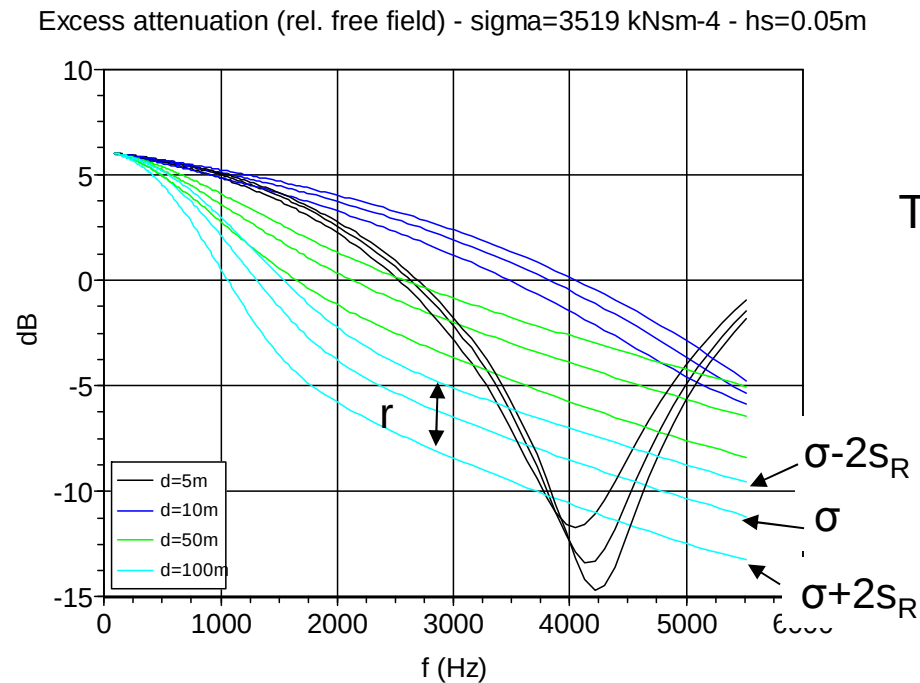
- Results : reprod. and repeat. vs air flow resistivity



$\sigma < 5\,000 \text{ kN.s.m}^{-4}$: uncertainties < 6% (resp. 14%)

Impedance induced uncertainties on SPL

- Uncertainties on sound level prediction



Type-uncertainty of sound level prediction:

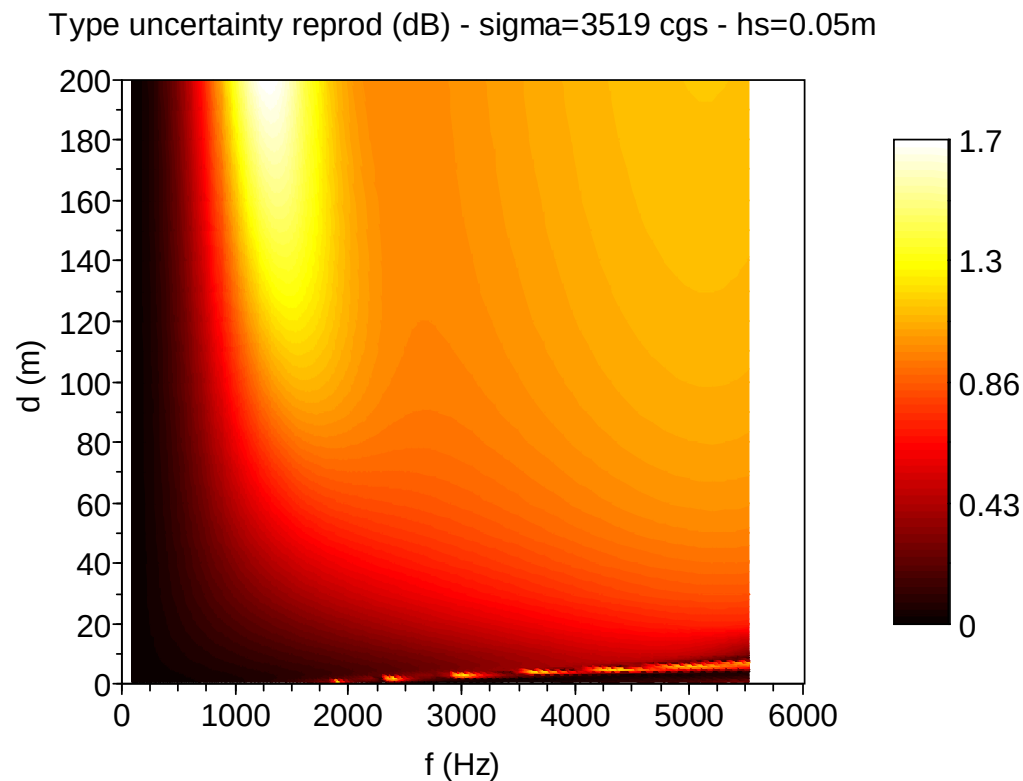
$$s = \frac{r}{2\sqrt{3}}$$

(assumption of uniform distribution)

Impedance induced uncertainties on SPL

- Uncertainties on sound level estimation

Example for $h_r=2\text{m}$, $d=1:200\text{m}$ and $f=100:5000\text{ Hz}$



Impedance induced uncertainties on SPL

- Uncertainties on sound level estimation

Maximum type-uncertainty of SPL 1/3rd octave band
(under **reproducibility** conditions)

example for $h_r=2\text{m}$, $d=1:200\text{m}$ and $f=100:5000\text{ Hz}$



	$h_s=0.05\text{ m}$	$h_s=1\text{ m}$	$h_s=3\text{ m}$	$h_s=10\text{ m}$
$\sigma = 3\ 519$	1,7 dB	2,1 dB	1,2 dB	1 dB
$\sigma = 1\ 154$	2,1 dB	2,3 dB	1,6 dB	1 dB
$\sigma = 277$	2,6 dB	2,9 dB	2,2 dB	1 dB

Type-uncertainty (1/3rd oct bands) <3 dB

Impedance induced uncertainties on SPL

- Uncertainties on sound level estimation

Maximum type-uncertainty of SPL 1/3rd octave band
(under **repeatability** conditions):

example for $h_r=2\text{m}$, $d=1:200\text{m}$ and $f=100:5000\text{ Hz}$



	$h_s=0.05\text{ m}$	$h_s=1\text{ m}$	$h_s=3\text{ m}$	$h_s=10\text{ m}$
$\sigma = 3\ 519$	0,7	1	0,6	0,6
$\sigma = 1\ 154$	1	1,2	0,8	0,6
$\sigma = 277$	1,2	1,3	1,3	0,6

Type-uncertainty (1/3rd oct bands) <1,3 dB

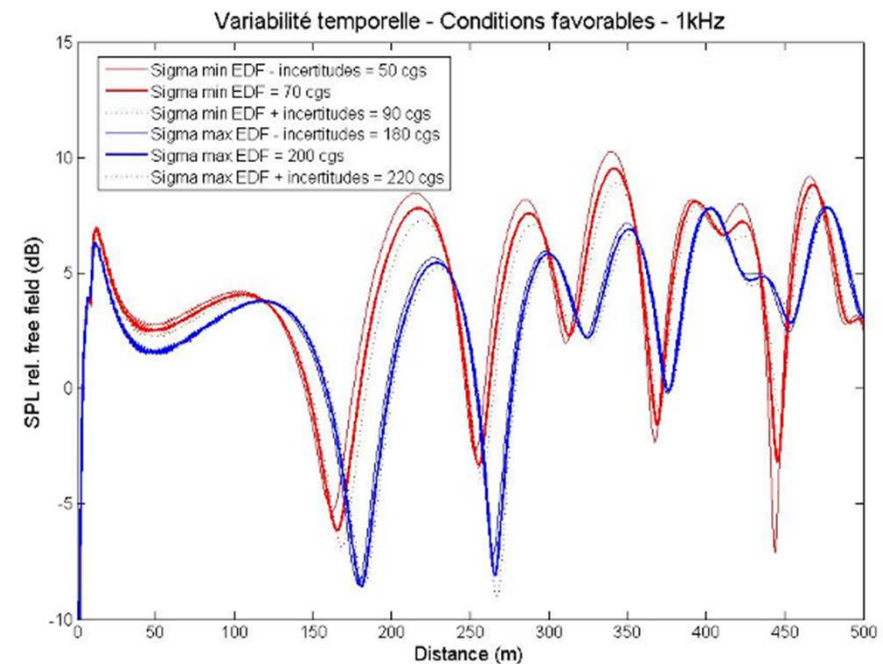
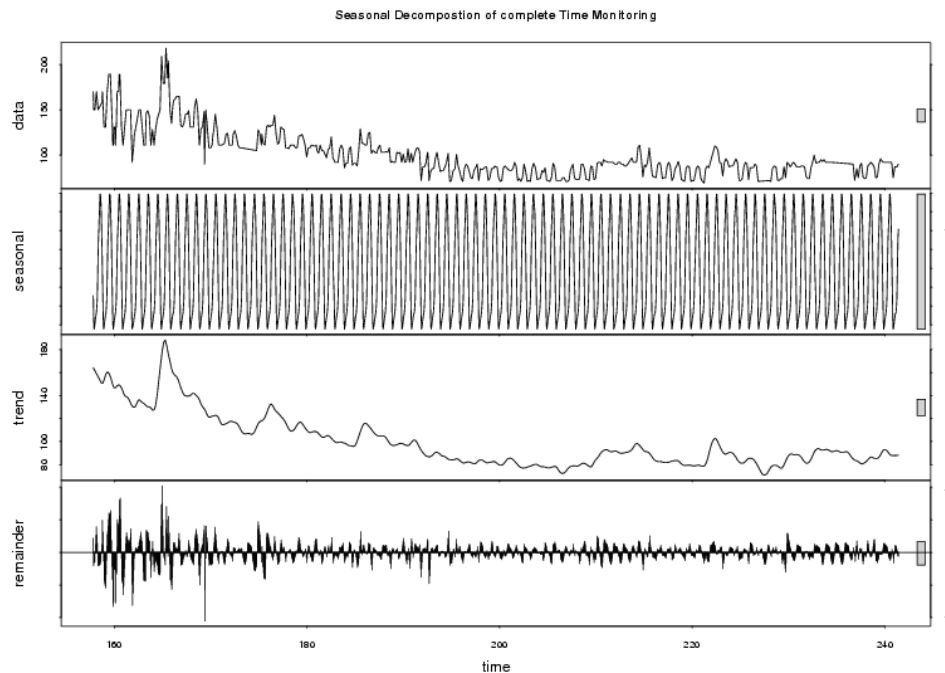
Conclusions

- Development of an autonomous in situ apparatus
- Uncertainties of the 2 microphones method for air flow resistivity
 - $\sigma > 5\,000 \text{ kN.s.m}^{-4}$: high uncertainties
 - $\sigma < 5\,000 \text{ kN.s.m}^{-4}$: $s_R < 15\%$ and $s_r < 6\%$

➔ the method is well adapted to non reflective outdoor material
- Impact on the uncertainties of sound level estimations :
 - Type-uncertainty (1/3rd oct bands) $< 3 \text{ dB}$ (reprod.) or $< 1,3 \text{ dB}$ (repeat.)
 - Note : uncertainties are probably overestimated in this study

Impedance induced uncertainties on SPL

- Variabilité temporelle de σ (3 mois)
 - Campagne expérimentale : Lannemezan_2005 (EDF R&D, Ifsttar, SNCF, ECL)
 - Traitement et analyse : thèse O. Baume (2003-2006)



Impedance induced uncertainties on SPL

● Variabilité spatio-temporelle de σ et e

- Campagnes expérimentales : Ifsttar (2013-2014)
- Traitement et analyse : thèse O. Faure (2011-2014)



(a) Synthetic lawn



(b) Grass lawn



(c) Natural ground



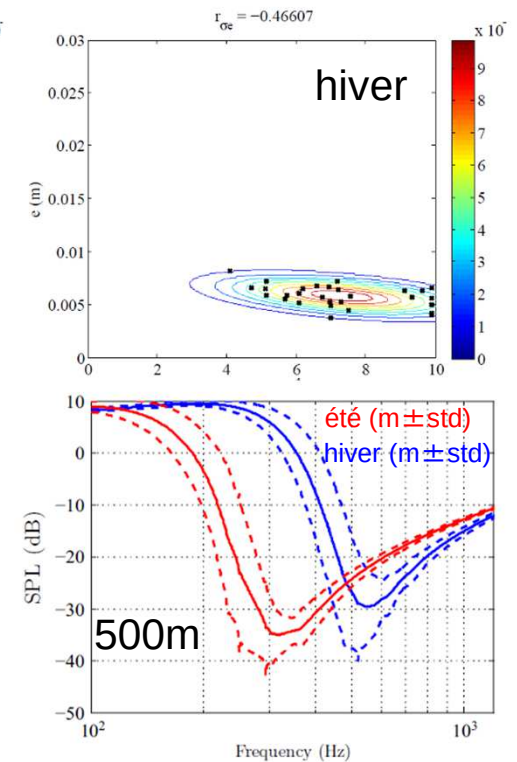
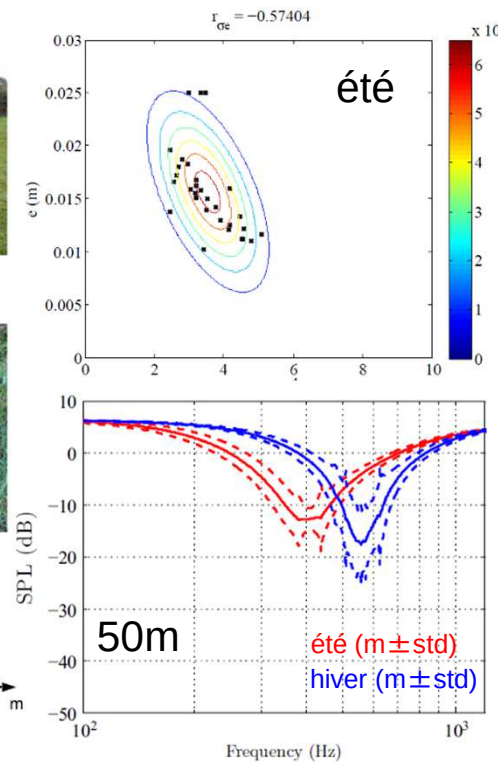
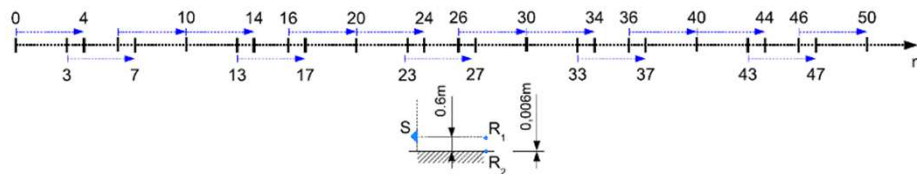
(d) Synthetic lawn



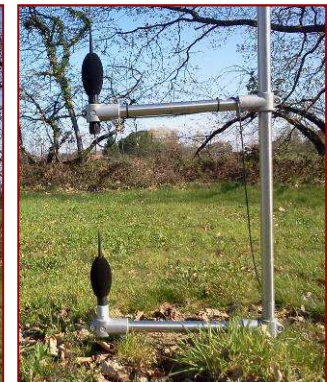
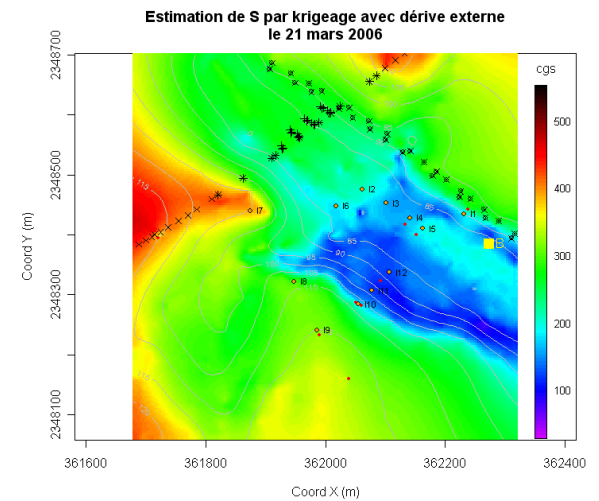
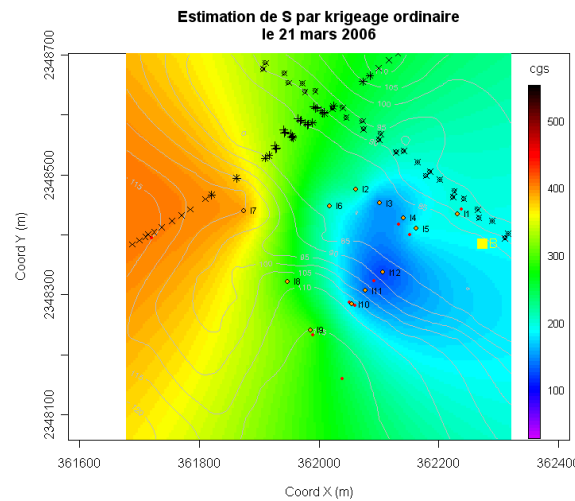
(e) Grass lawn

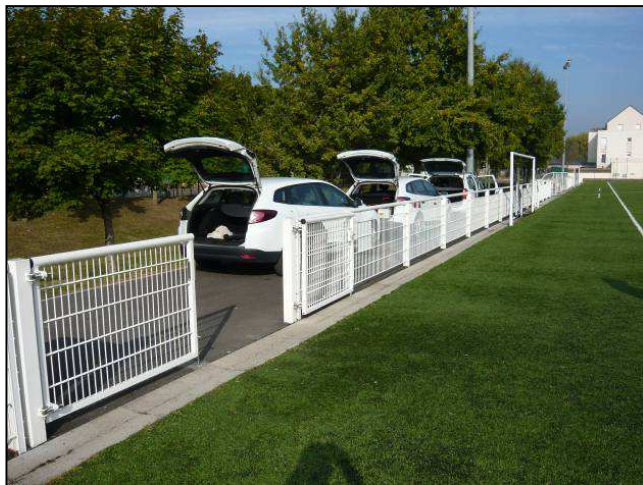


(f) Natural ground

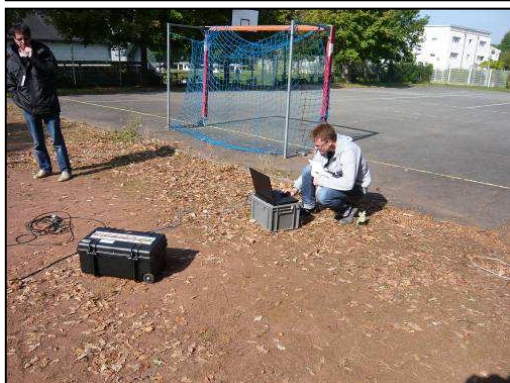


- Prototype de mesure automatique in-situ (MIAME)
- Applications diverses
 - Laboratoires intéressés : EDF R&D, ISL, RENAULT, etc.
 - Traitement et analyse : variabilité spatiale et temporelle des paramètres σ , e ... et autres ?





B. Gauvreau, D. Écotière, P. Glé, R. Boittin,
H. Lefèvre et D. Lunain tiennent à remercier...



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