# A Preliminary Analysis of Measurements from a Near-Field Pollutants Dispersion Campaign in a Stratified Surface Layer

Xiao Wei, Eric Dupont, Bertrand Carissimo, Eric Gilbert and Luc Musson-Genon

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# Introduction

- **Pollutants dispersion in a stable atmospheric boundary layer and in complex environment still relatively poorly described by modeling**
- **Stable condition difficult to reproduce in a wind tunnel**
- **Major interest in the field of air pollution from human activities (industrial risks, road transportation, etc.)**

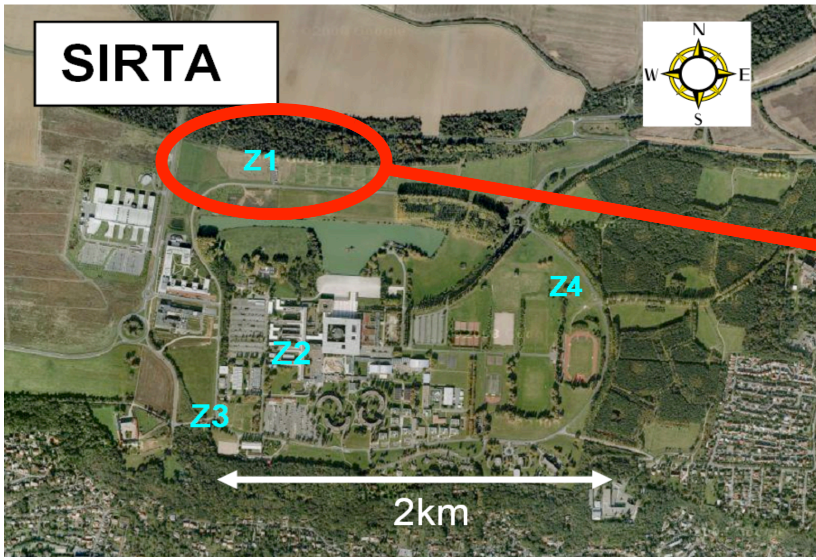
- **Experimental program on the site SIRTA (Site Instrumental de Recherche par Télédétection Atmosphérique) measuring structure of turbulence and associated pollutants dispersion through high temporal and spatial resolution measurements in a stratified surface layer and in near-field**

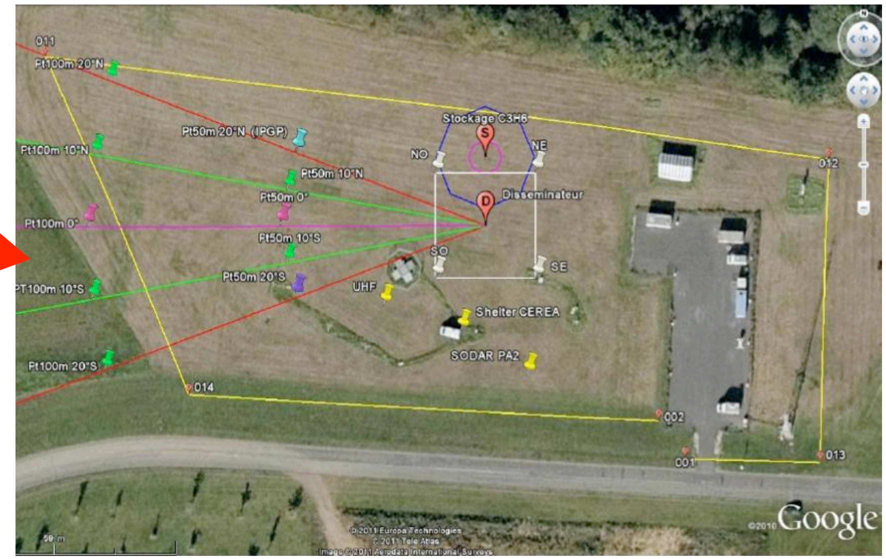
# Contents

# SIRTA experimental program: objectives and characteristics

- **Objectives:**
  - Document in high temporal and spatial resolution and in near field, wind fluctuations and concentration fluctuations of a tracer gas
  - Relationships expected between concentration fluctuations and passage of turbulent structure
- **Characteristics:**
  - Experiment in near field (50 to 200 m)
  - Focus on stable thermal stratification, but may include some neutral stratification or slightly convective situations
  - High frequency measurements (about 10Hz) to cover the entire frequency spectrum of fluctuations
  - Large number of sensors measuring turbulence and concentration of tracer gas

# SIRTA experimental program: field and meteorological conditions




- **Meteorological conditions :**
  - Wind direction between 75° and 105°, being as close as possible to 90° (easterly wind)
  - Wind velocity between about 1 and 5 $ms^{-1}$ (at the release height i.e. 3 m) in order to stay in unfavorable dispersion conditions
  - Temperature difference *T(30m) - T(10m)* must be positive, assuring to be in stable stratification.

# SIRTA experimental program: devices

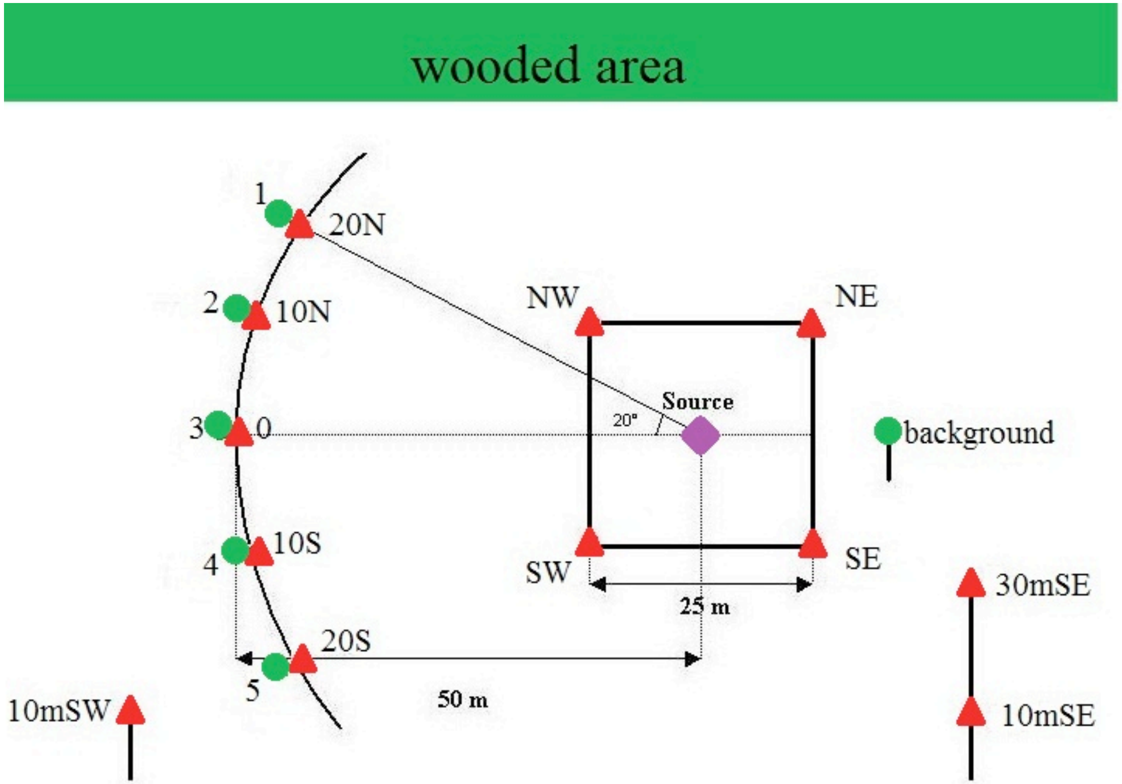
Tracer gas


Ultrasonic anemometers (front) and PID (behind)

Ultrasonic anemometers

- **Tracer gas: propylene**
  - Low toxicity
  - Low boiling point
  - Low cost
  - Low ionization potential
- **Ultrasonic anemometer:**
  - Measuring at 10 Hz
  - Three components of wind speed and air temperature
- **Photo ionization detector (PID):**
  - Measuring at 50Hz
  - Gas concentration
  - Sensible to propylene and to other volatile organic compounds (VOCs)

# SIRTA experimental program: sensors position




- **Source (at 3m height)**
- **Ultrasonic anemometers:**
  - "Sonic square" (at 3m height) : NW, NE, SW, SE
  - "sonic arc at 50m" (at 3m height) : 20N, 10N, 0, 10S, 20S
  - Two masts: 10mSW, 10mSE and 30mSE
- **PIDs :**
  - From north to south: PID 1, 2, 3, 4, 5 (at 3m height)
  - PID background (at 3m height)

# Sonic data processing and analysis: statistics

- **Preliminary campaign was held from January to March 2012**
- **Intensive Observation Period (IOP) on 21st March 2012: lasting about 1h30 (from 20:41 to 22:12) with a continuous gas release for about an hour**

- ***(u, v, w)* in meteorological reference and *(a,b,w)* in rotated frame**
- ***dd* as mean wind direction**
- **Selection of a 30min sub-period ( from 20:58 to 21:30) with stationary meteorological conditions**

| | NE | NW | SE | SW | 20N | 10N | 0 | 10S | 20S |
|---|---|---|---|---|---|---|---|---|---|
| $dd_{mean}$ (°) | 82.9 | 83.1 | 81.9 | 83.5 | 90.4 | 84.4 | 85.5 | 82.0 | 85.6 |
| $a_{mean}$ (ms$^{-1}$) | 1.50 | 1.58 | 1.93 | 2.16 | 1.50 | 1.77 | 1.99 | 2.12 | 2.09 |
| $\sigma_a^2$ (m$^2$s$^{-2}$) | 0.27 | 0.29 | 0.33 | 0.33 | 0.28 | 0.29 | 0.24 | 0.28 | 0.33 |
| $\sigma_b^2$ (m$^2$s$^{-2}$) | 0.18 | 0.21 | 0.23 | 0.25 | 0.23 | 0.22 | 0.22 | 0.25 | 0.24 |
| $\sigma_w^2$ (m$^2$s$^{-2}$) | 0.07 | 0.07 | 0.11 | 0.09 | 0.07 | 0.08 | 0.08 | 0.08 | 0.09 |
| $TKE$(m$^2$s$^{-2}$) | 0.26 | 0.28 | 0.33 | 0.34 | 0.29 | 0.29 | 0.27 | 0.31 | 0.33 |
| $u_*$ (ms$^{-1}$) | 0.18 | 0.19 | 0.25 | 0.22 | 0.19 | 0.19 | 0.18 | 0.20 | 0.21 |
| $Q_0$ $(Kms^{-1})$ | -0.04 | -0.03 | -0.04 | -0.04 | -0.03 | -0.05 | -0.04 | -0.04 | -0.04 |
| $L_{MO}$ (m) | 11 | 14 | 27 | 17 | 14 | 11 | 11 | 14 | 19 |

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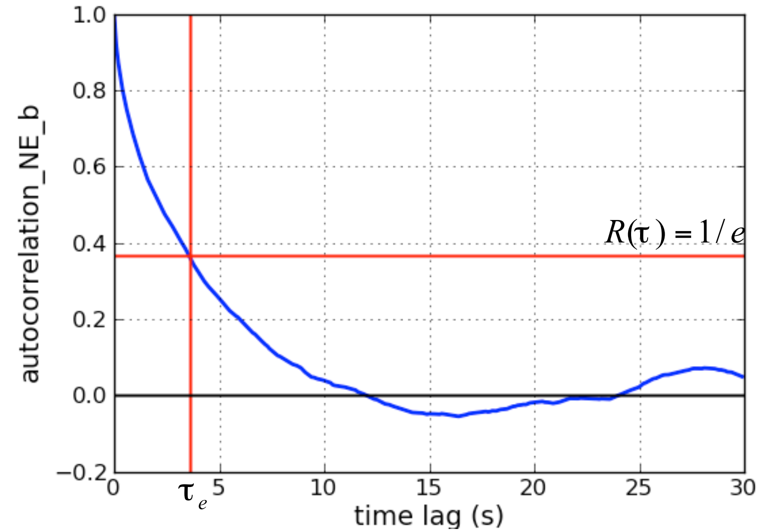
# Sonic data processing and analysis: integral length scale

- **Integral length scale : characteristic of the largest scales in a turbulent flow**

$$L = a_{moy} T_e$$

- **Integral time scale approximation**

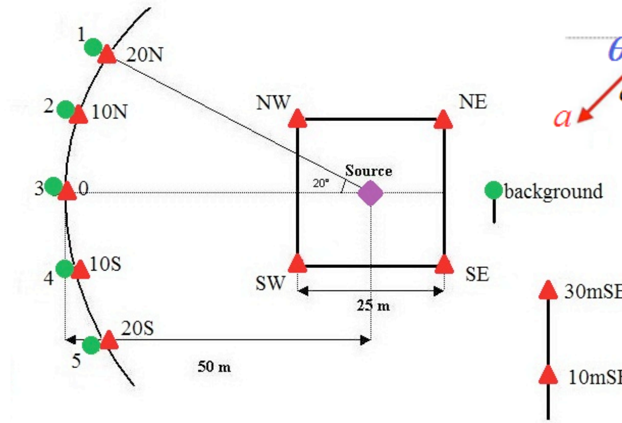
$$T_i = \int_0^{\infty} R(\tau)\,d\tau \qquad T_e = \int_0^{\tau_e} R(\tau)\,d\tau \approx \tau_e$$

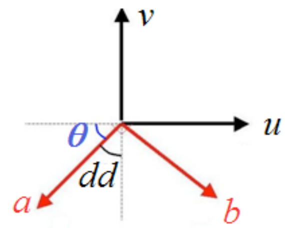


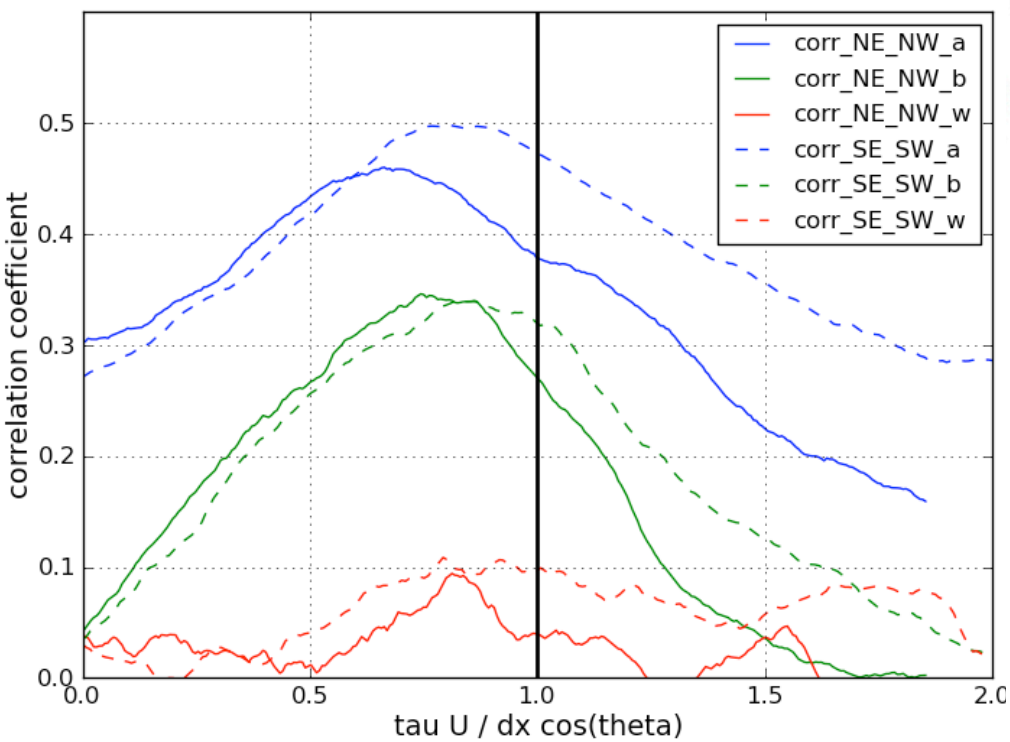

| | NE | NW | SE | SW | 20N | 10N | 0 | 10S | 20S | 10m SW | 10m SE | 30m SE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $L_{aa}$ (m) | 13.46 | 12.79 | 15.08 | 18.59 | 14.10 | 17.35 | 15.55 | 13.78 | 18.84 | 15.37 | 28.58 | 31.98 |
| $L_{bb}$ (m) | 5.39 | 6.32 | 5.22 | 7.99 | 6.60 | 7.61 | 7.38 | 7.63 | 6.49 | 7.98 | 9.99 | 10.33 |
| $L_{ww}$ (m) | 1.65 | 1.90 | 2.71 | 2.59 | 2.10 | 1.95 | 2.39 | 1.91 | 1.88 | 4.43 | 5.51 | 5.90 |

- **Quantified anisotropy of turbulence near ground in stable conditions**
- ***L* increasing with altitude**

# Sonic data processing and analysis: velocity cross-correlation




Spatial cross-correlation of anemometers (NE,NW) and (SE,SW) as a function of a normalized time lag

- **Normalized time lag :**

$$\tau_{norm} = \frac{\tau}{t_{th}} \quad \text{with} \quad t_{th} = \frac{dx_{eff}}{U} = \frac{dx\cos(\theta)}{U}$$

- **Cross-correlation peak reaching up to 0.5 for streamwise component**

- **Peaks on the left of the vertical line at $\tau U/dx\cos\theta=1$**

# Sonic data processing and analysis: velocity cross-correlation

- **Eddy advection velocity:**

$$U_{adv} = dx_{eff} / \tau_{max}$$

- **Ratio of the eddy advection velocity to the mean wind speed**

$$r = U_{adv} / U$$

| | $U$ (ms$^{-1}$) | $U_{adv\,a}$ (ms$^{-1}$) | $U_{adv\,b}$ (ms$^{-1}$) | $U_{adv\,w}$ (ms$^{-1}$) | $r_a$ | $r_b$ | $r_w$ |
|---|---|---|---|---|---|---|---|
| (NE, NW) | 1.54 | 2.31 | 2.06 | 1.89 | 1.50 | 1.34 | 1.23 |
| (SE, SW) | 2.05 | 2.53 | 2.48 | 2.58 | 1.23 | 1.19 | 1.26 |

- **Discussion:**
  - $U_{adv}$ 20% to 50% greater than $U$
  - Similar results found in HATS field program (Horst T.W. *et al.* 2004)
  - Strong vertical velocity gradient in the surface layer near the ground and eddy advection affected by the flow at higher level
  - Taylor's hypothesis not well respected during the experiment

T.W. Horst, J. Klessl, and D.H. Lenshow. HATS : Field Observations to Obtain Spatially Filtered Turbulence Fields from Crosswind Arrays of Sonic Anemometers in the Atmospheric Surface Layer. Journal of the Atmospheric Sciences, 61, 2003.

# Sonic data processing and analysis: power spectra

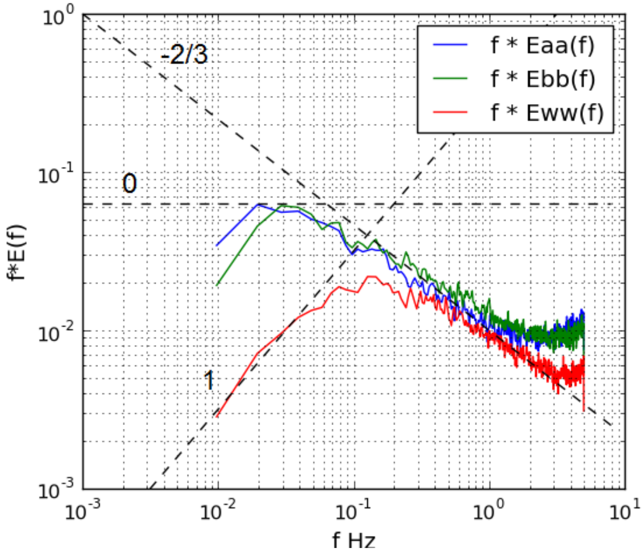
- **TKE power spectra**
  - Comparison with Kolmogorov's theory
  - Existence of an inertial subrange
  - Slope between -1 and -5/3
- **Eddy surface layer very close to ground (Drobinski *et al.* 2004) :**
  - Eddies coming from upper layers stretched along wind direction and lose their isotropy
  - Three regions found in velocity spectra (in near-neutral stratification)

$$\begin{cases} E_{ii}(k) \propto k^{-5/3} & \text{for} \quad k \geq k_u \\ E_{ii}(k) \propto k^{-1} & \text{for} \quad k_u \geq k \geq k_l \\ E_{ii}(k) \propto k^{0} & \text{for} \quad k_l \geq k \end{cases} \qquad i = (a, b)$$

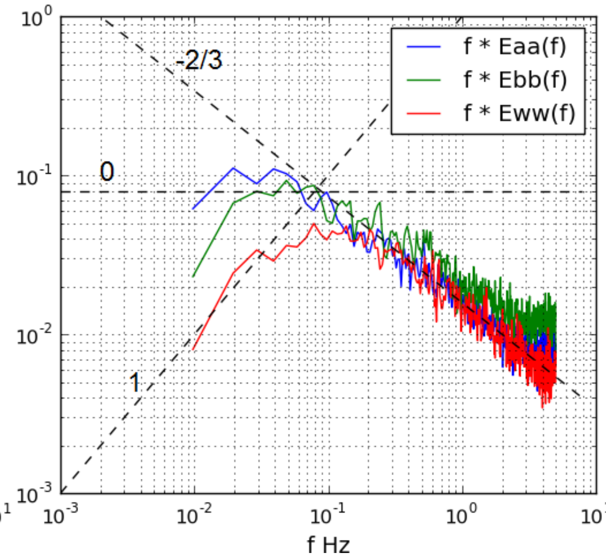
$$\begin{cases} E_{ww}(k) \propto k^{-5/3} & \text{for} \quad k \geq k_u \\ E_{ww}(k) \propto k^{0} & \text{for} \quad k_l \geq k \end{cases}$$

Drobinski, P., P. Carlotti, R.K. Newsom, R.M. Banta, R.C. Foster, J. Redelsperger, 2004: The Structure of the Near-Neutral Atmospheric Surface Layer. *J. Atmos. Sci.*, **61**, 699–714.

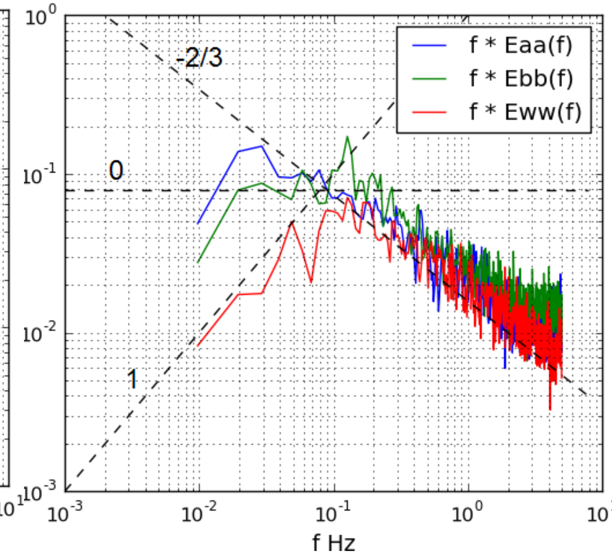
# Sonic data processing and analysis: power spectra




3m




10m



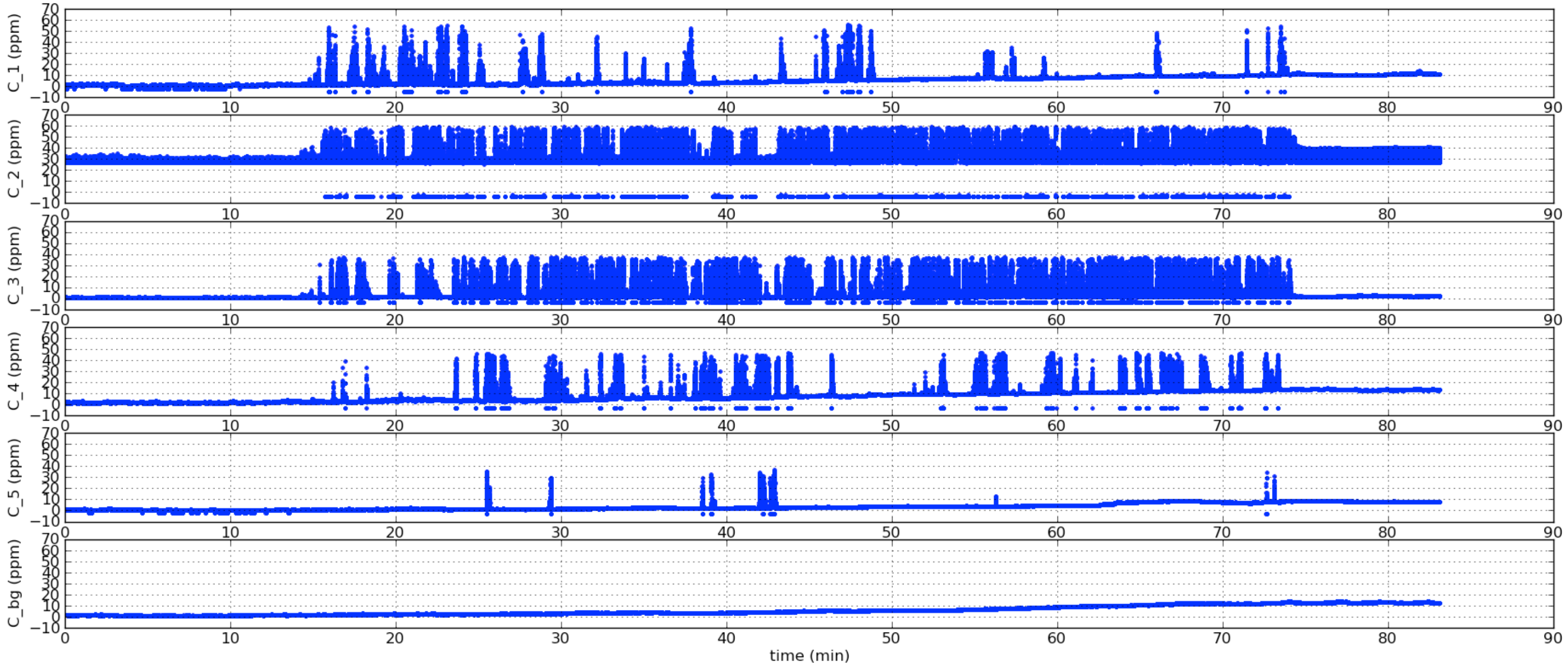

30m

- **Discussion:**
  - Average spectra of anemometers at the same level
  - Different spectrum form between vertical and horizontal velocity components
  - Vertical velocity spectrum increasingly closed to the others with increasing heights
    → less anisotropic turbulence at higher level
  - Some evidence of $k^{-1}$ subrange found in spectra (slope 0 in figures)

# Concentration data processing and analysis: value correction

- **Problem with the mass flow controller → better concentration data quality for the new IOP on 18th Feb. 2013: lasting for 83min (from 16:21 to 17:45) with a continuous gas release of an hour**

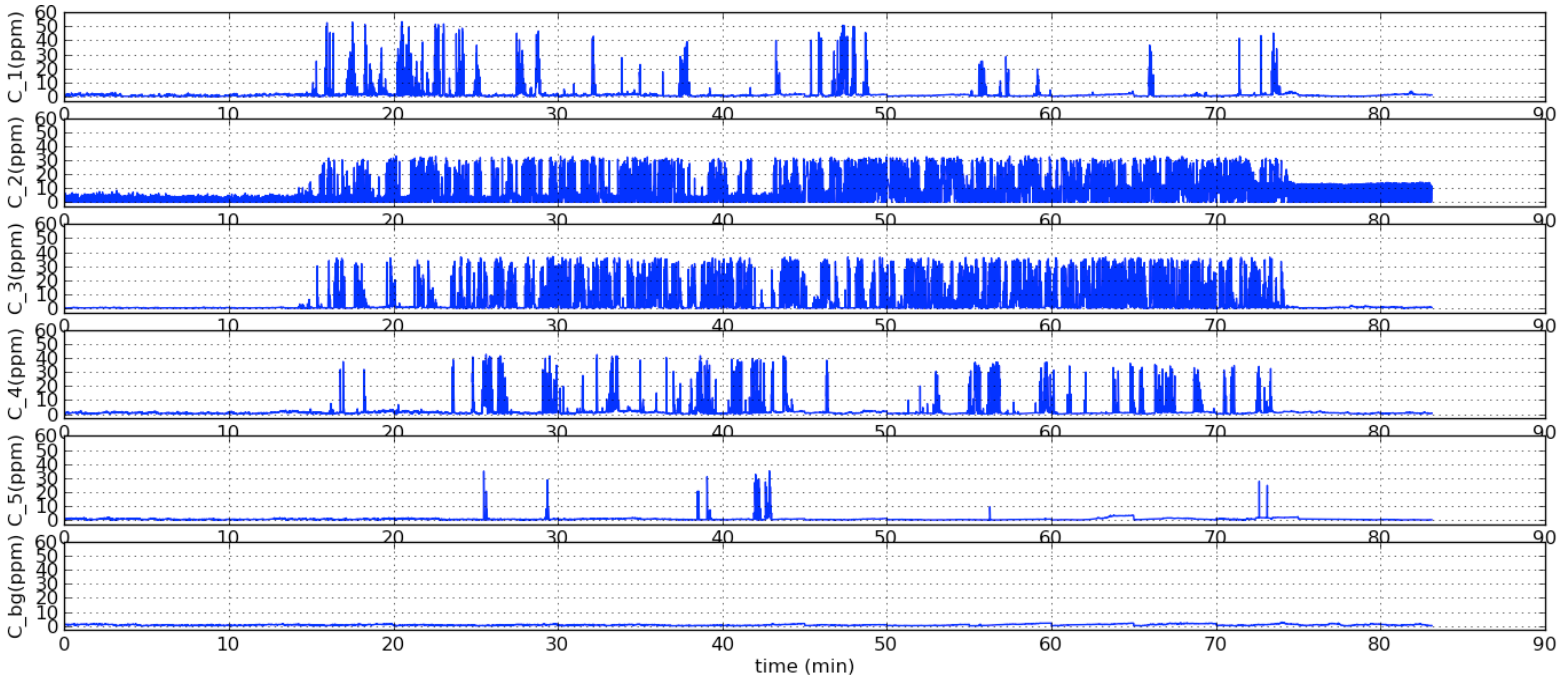
- **Raw data: gas concentration in ppm at 50 Hz**
  - Negative values (calibration interval problem)
  - Sensor drift and non zero off-set
  - Background concentration




Concentration raw data for the IOP on 18th February 2013 for PIDs (from top to bottom) 1, 2, 3, 4, 5 and background.

# Concentration data processing and analysis: value correction

- **Negative values elimination: linear interpolation of its non-negative neighbors**
- **Baseline method to remove sensors drift and background concentration: average of the 200 smallest values every 5min**




Concentration data after value correction for the IOP on 18th February 2013 for PIDs (from top to bottom) 1, 2, 3, 4, 5 and background.

# Conclusion and perspective

- **Sonic data processing and analysis:**
  - Characterization of the turbulence by integral length scale showing strong anisotropy: $L_{aa} > L_{bb} >> L_{ww}$
  - Spatial velocity cross-correlation: $U_{adv} > U$
  - Velocity spectra : evidence of -1 power law at intermediate frequency subrange
- **Concentration data processing and analysis:**
  - Value correction using a baseline method
- **Perspective:**
  - More data processing and analysis for new IOPs:
    - Sonic data: coherent spectra, wavelet analysis, dissipation rate, etc.
    - Concentration data: data correction by background measurements, power spectra, etc.
  - Relationships between turbulence and concentration fluctuations
  - Additional ultrasonic anemometers and PIDs allowing to extend the instrumental set-up
  - Numerical simulations with the open source CFD code Code_Saturne developed at CEREA using different turbulence models ($k$-ε, $R_{ij}$-ε and LES)

# THANK YOU FOR YOUR ATTENTION

**Email : xiao.wei@edf.fr**