A PRELIMINARY ANALYSIS OF MEASUREMENTS FROM A NEAR-FIELD POLLUTANTS DISPERSION CAMPAIGN IN A STRATIFIED SURFACE LAYER

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Abstract: In order to study pollutants dispersion in a stably stratified surface layer at small scales, a pollutants dispersion field experiment program is being conducted on the site "SIRTA" in the southern suburb of Paris. The objective of the campaign is to measure at high resolution both wind turbulence and concentration of a tracer gas in a stable surface layer and in near-field. Relationships are expected between concentration fluctuations and passage of turbulent structure. In a preliminary campaign held during the winter of 2012 with continuous gas releases, we have 12 ultrasonic anemometers measuring wind velocity and temperature at 10Hz, and 6 photo-ionisation detectors measuring gas concentration at 50Hz. Turbulence is verified to be anisotropic by calculating variances, integral length scales and power spectra for the three velocity components. A -1 power law subrange has been found in velocity power spectra in a lower frequency region next to the inertial subrange. Also, we have deduced eddy advection velocity from spatial velocity cross-correlation and found it greater than mean wind speed measured directly by sensors. Concentration measurements are corrected by using a baseline method. Significant relationships between concentration and turbulence measurements at high frequency are still under further study.

Key words: *Atmospheric dispersion, stable atmosphere, sonic anemometer, turbulence, coherent structure***.**

INTRODUCTION

Pollutants dispersion in a stable atmospheric boundary layer and in complex environment is still a phenomenon that is relatively poorly described by modelling and difficult to reproduce in a wind tunnel. Nevertheless, this topic is of major interest in the field of air pollution from human activities such as industrial risks and road transportation. An experimental program consisting in measuring pollutants dispersion in a stratified surface layer and in near-field (less than 200m) is carried out on the site SIRTA (Site Instrumental de Recherche par Télédétection Atmosphérique), on the campus of the Ecole Polytechnique, about 20km south of Paris. The aim of the program is to characterize the fine structure of turbulence and associated dispersion through high temporal and spatial resolution measurements. These measurements are performed through an extensive network of ultrasonic anemometers measuring wind turbulence and through photo-ionization detectors measuring concentration of a tracer gas. A preliminary campaign was held during the winter of 2012. This paper first introduces background elements of this SIRTA experimental program. Then, it presents several methods and results in data processing and analysis from a study of some preliminary tracer tests.

SIRTA EXPERIMENTAL PROGRAM

Before the start of the SIRTA campaign, a bibliographical study was made on previous campaigns conducted by other research groups in the world, including several campaigns organized by the Met Office in United-Kingdom (Mylne, K.R. and P.J. Mason, 1991; Mylne K.R., 1992; Mylne K.R. *et al.*, 1996), the urban dispersion experiment MUST (Mock Urban Setting Test) and the CASES-99 Field Experiment both held in the US. Taking into account the literature review, we have defined the objectives: document simultaneously, in high temporal and spatial resolution and in near field, wind fluctuations and concentration fluctuations of a tracer gas. Concentration fluctuations should be related to the passage of turbulent structure. Thus, the characteristics are defined as follows:

- 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 simultaneously turbulence and concentration of tracer gas.

Figure 1 shows the whole measurement area in SIRTA field. Our campaign is carried out in Zone 1 which is bounded in the north by a wooded area and in the south by a road. We choose the site for the campaign because we can benefit from existing infrastructure and instruments operating in routine mode on this site (Haeffelin M. et al., 2005). Also, there were already some interesting experiments carried out on this site which can inspire us in data analysis (Fesquet C., 2008) and in modeling (Zaïdi H. et al., 2012). Several specific meteorological conditions are required to perform the tracer experiment. After a climatic study based on site data between April 2007 and September 2009, we choose criteria as follows: As the measurement zone is oriented along the east-west axis, wind direction must be such that plume is transported from the dissemination point to the instrumented area, being as close as possible to 90° (easterly wind); Wind velocity must be 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.

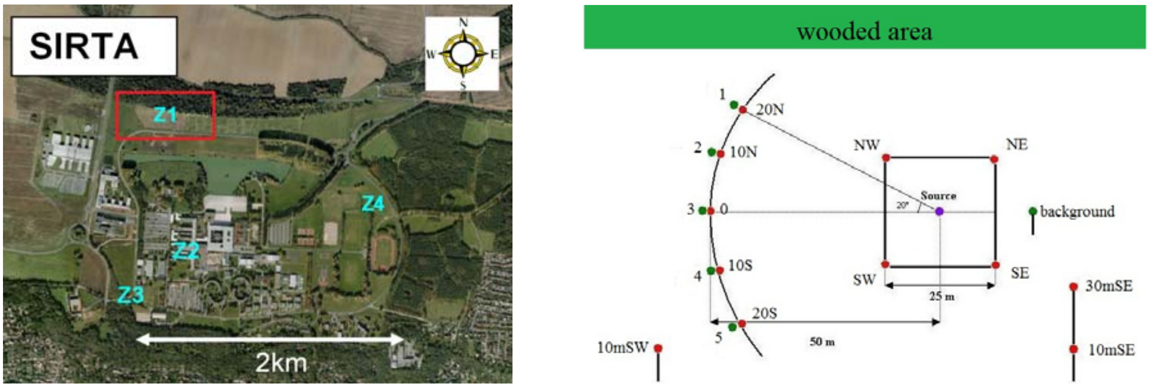

Figure 1. Whole measurement area in the SIRTA field (left) and sensors position for the preliminary campaign in Zone 1 (right): 1 source (violet dot), 12 ultrasonic anemometers (red dots), and 6 PIDs (green dots).

Concerning the experimental devices, dynamic measurements are mainly provided by ultrasonic anemometers, measuring three components of wind speed and air temperature at 10Hz. Propylene is chosen as the tracer gas because of its low toxicity, low boiling point, low cost and low ionization potential. Photo-ionisation detector (PID) is chosen to measure the gas concentration at 50Hz, because of its good sensitivity to propylene.

Figure 1 (right) shows position of sensors. Red dots represent ultrasonic anemometers. There are four of them placed respectively at four corners of a square of side 25m centered on the release point. They are named according to their positions: NE (northeast), NW (northwest), SE (southeast) and SO (southwest). We denote them as "sonic square" in the following. There are five anemometers arranged in a circle arc with radius 50m, centered on the source. They are named according to the angle with respect to the East-West axis as 20N, 10N, 0, 10S and 20S. We denote them as "sonic arc at 50m" in the following. All the nine anemometers are at height of 3m. In addition, there is another ultrasonic anemometer at the top of a 10m mast in the southwest of the field which is called "10mSW". Similarly, for the other two ultrasonic anemometers at heights of 10m and 30m on a 30m mast in the southeast of the field, they are called "10mSE" and "30mSE". Green dots represent the PIDs. There are five of them in the same position as the five ultrasonic anemometers at "sonic arc at 50m". They are numbered from north to south by 1, 2, 3, 4 and 5. Another PID is positioned upstream of the source to measure background concentration and it is called “background”.

A preliminary campaign was held from January to March 2012, during which several tracer tests were carried out with continuous release. We select an Intensive Observation Period (IOP) on 21st March for data processing and analysis. This IOP, lasting about one and half hour (from 20:41 to 22:12) with a continuous gas release for about an hour, has the best data quality at this time. However, the mass flow controller failed to control the gas flux properly, which limits analysis for concentration measurements.

SONIC DATA PROCESSING AND ANALYSIS

Raw data obtained from ultrasonic anemometers are three wind speed components (u, v, w) in meteorological reference and temperature T all at 10Hz. Applied data processing and analysis results are presented as follows.

Statistics

Turbulent variables such as turbulent kinetic energy TKE, friction velocity u_*, vertical heat flux Q_0 and Monin-Obukhov length L_{MO}, are reported in table 1, in which a and b are streamwise and crosswind components of the velocity, and dd is the horizontal wind direction. They have been calculated over a sub-period of about 30min in the IOP (from 20:58 to 21:31) during which meteorological conditions are almost stationary. Note that all the processing and analysis for sonic data in the next parts are based on the data of this sub-period.

The nine anemometers generally agreed well with each other. The three variances show that the flow measured is strongly anisotropic. The positive values of L_{MO} indicate that the measurement period is clearly a stable stratification situation. However, the mean wind velocity measured by anemometers on the south is always greater than that measured on the north, and the wind direction has a singular value given by anemometer 20N. These are probably due to the northern wood which slows down wind velocity and reorients wind direction. Also, anemometer SE gives higher values of σ_w^2, u_* and L_{MO}, which can be explained by the presence of a close upstream shelter. Same calculations are made for anemometers 10mSW, 10mSE and 30mSE. Vertical temperature profile for a stable stratification condition is verified. We find L_{MO} ~ 50m and 120m at heights of 10m and 30m, which implies that the surface layer is closer to neutral stratification with increasing altitude.

Table 1. Statistical values of nine anemometers calculated from the 30min sub-period data of the IOP on 21st March 2012.

	NE	NW	SE	SW	20N	10N	0	10S	20S
dd_{moy} (°)	82.9	83.1	81.9	83.5	90.4	84.4	85.5	82.0	85.6
a_{moy} (ms^{-1})	1.50	1.58	1.93	2.16	1.50	1.77	1.99	2.12	2.09
σ_a^2 (m^2s^{-2})	0.27	0.29	0.33	0.33	0.28	0.29	0.24	0.28	0.33
σ_b^2 (m^2s^{-2})	0.18	0.21	0.23	0.25	0.23	0.22	0.22	0.25	0.24
σ_w^2 (m^2s^{-2})	0.07	0.07	0.11	0.09	0.07	0.08	0.08	0.08	0.09
TKE(m^2s^{-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
L_{aa} (m)	13.46	12.79	15.08	18.59	14.10	17.35	15.55	13.78	18.84
L_{bb} (m)	5.39	6.32	5.22	7.99	6.60	7.61	7.38	7.63	6.49
L_{ww} (m)	1.65	1.90	2.71	2.59	2.10	1.95	2.39	1.91	1.88

Integral length scale

Next, we deduct integral length scales L from velocity autocorrelation with $L = a_{moy} T_e$, where T_e is an integral time scale obtained with approximation that T_e equals to the time lag where the autocorrelation coefficient goes below e^{-1} for the first time. Integral length scales of three wind velocity components have different order of magnitude (see table 1) which shows again that turbulence near the ground is strongly anisotropic in stable conditions. They have also greater values with increasing altitude. For example, we have L_{ww} ~ 2m, 5m and 6m at heights of 3m, 10m and 30m respectively.

Velocity cross-correlation

The spatial cross correlation of velocity is a useful tool for examining the validity of Taylor's hypothesis and for determining the eddy advection velocity (Powell D.C. and C.E. Elderkin, 1974).

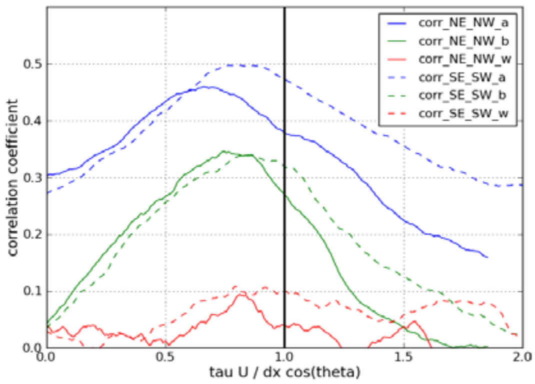

Figure 2. Spatial cross-correlation of anemometers couples (NE, NW) and (SE, SW) as a function of normalised time lag.

Table 2. Comparison between mean wind speed and eddy advection speed deducted from spatial cross-correlation.

	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

Figure 2 plots the cross-correlation coefficients of anemometers couples (NE, NW) and (SE, SW) as a function of normalised time lag $\tau U/dxcos\theta$, where U is the average mean wind speed of two correlated anemometers, dx is the distance between them, and θ is the deviation of the mean wind direction from a direction parallel to their separation (Horst T.W. *et al.* 2004). The cross-correlation peak reaches up to 0.5 for streamwise component, whereas vertical components are poorly correlated. Theoretically, the cross-correlation peak should occur at $\tau U/dxcos\theta$=1. However, they are all on the left of the vertical line at $\tau U/dxcos\theta$=1. Defining the eddy advection velocity as $U_{adv}=dxcos\theta/\tau_{max}$, where τ_{max} is the time lag at the maximum correlation, the curves in figure 2 imply that U_{adv} is higher than the mean wind speed U measured directly by the anemometer at the same level. Table 2 compares the mean wind speed and eddy advection speed deducted from spatial cross-correlation, and a ratio of the eddy advection velocity to the mean wind speed is estimated as $r=U_{adv}/U$. We notice that U_{adv} is about 20% to 50% greater than U. Similar results were found in HATS field program (Horst T.W. *et al.* 2004). Explanation can be that there is a strong vertical velocity gradient in the surface layer near the ground, and eddy advection is probably affected by the flow at higher level where velocity is larger than that at height of 3m. Moreover, it is possible that Taylor's hypothesis is not well respected during the experiment which means that eddies evolve faster than they travel the distance between two correlated anemometers. The velocity cross-correlation at higher level for anemometers (10mSE, 10mSW) is very noisy, probably due to the large distance (about 120m) between them.

Power spectra

Power spectrum is another way to study turbulence structure. In a first step, we compared the *TKE* power spectra with Kolmogorov's theory which implies the existence of an inertial subrange in the spectra. However, instead of following the -5/3 power law, it has a slope between -1 and -5/3. According to Carlotti P. and P. Drobinski (2004) and Drobinski P. *et al.* (2004), very close to the ground, there is a layer dominated both by shear and blocking by the ground. In this layer, eddies coming from upper layers are stretched along the wind direction, thus losing their isotropy, and a k_1^{-1} subrange is observed in velocity spectra for horizontal components of the velocity. Figure 3 shows the three velocity components power spectra at heights of 3m, 10m and 30m. Since the spectra showed are the average spectra of anemometers at the same level, spectra at 30m and 10m are much more fluctuating than those at 3m because of fewer sensors at these levels. Nevertheless, we can still observe that there is a frequency lag in spectrum form between vertical velocity and horizontal ones, which is a typical characteristic for stable stratification, and that the vertical velocity spectrum is increasingly close to the others with increasing height, which means a less anisotropic turbulence at higher levels. Moreover, k_1^{-1} subrange can be found in every spectrum (slope 0 in figure 3), which is consistent with the above mentioned papers. However, this spectral subrange is observed even on the vertical component, which was not the case in Drobinski P. et al. (2004) for near-neutral situations.

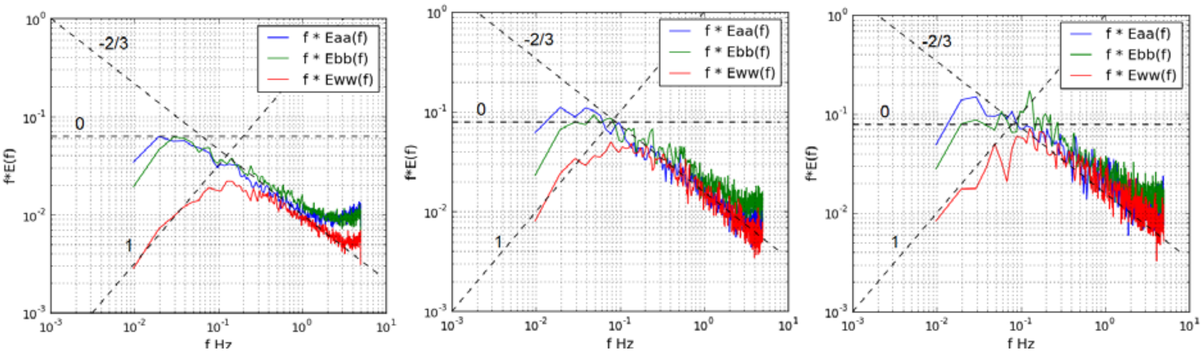

Figure 3. Velocity components power spectra *f E(f)* at heights of 3m (left), 10m (middle) and 30m (right), calculated by the mean of the anemometers at the same level.

CONCENTRATION DATA PROCESSING AND ANALYSIS

Raw data obtained from PIDs is gas concentration in ppm (parts-per-million, 10^{-6}) at 50 Hz. As the mass flow controller failed to control gas flux during the first experiment performed in 2012, we cannot derive quantitative analysis from its concentration data. However, after some modifications in the gas pipe, a new IOP has been carried out recently on 18th February 2013 which lasts for 83 min (from 16:21 to 17:45) with a gas release of one hour and a better function of the mass flow controller. So we present here concentration data of this new IOP.

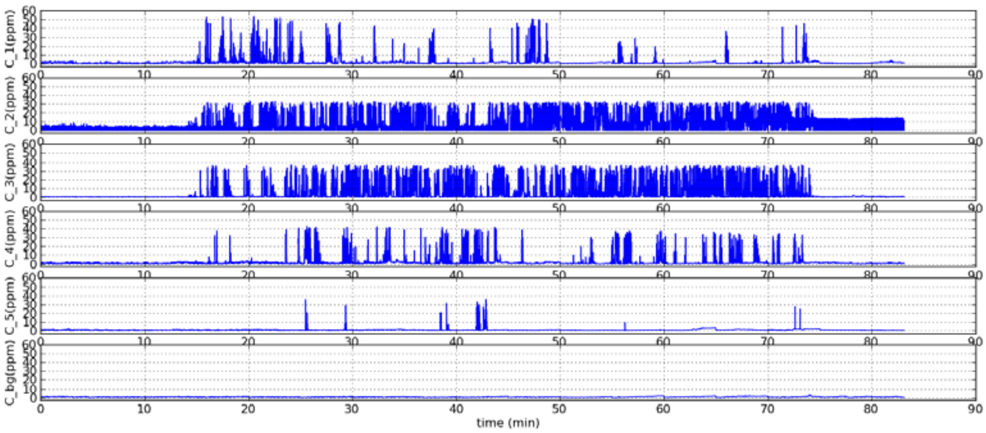

Figure 4. Concentration data after value correction for the IOP on 18th February 2013 for PIDs (from top to bottom) 1, 2, 3, 4, 5 and background.

We eliminate negative values as invalid data by linear interpolation of its neighbours that have non-negative values. Next, inspired by Mylne K.R. (1992), we apply a similar baseline method to remove sensor drift and background concentration from each PID measurements. Our baseline is deducted from the average of the 200 smallest values every 5min. Then we obtain the concentration data ready for statistical analysis plotted in figure 4. We observe that PIDs 2 and 3 detected most of the concentration peaks, which is consistent with the wind direction during the IOP which is slightly North-East. We draw also concentration histograms for the release period (not shown), and we obtain log-normal distributions for all the PIDs' data except that the PID background's histogram is narrower and closer to a Gaussian distribution.

CONCLUSION AND PERSPECTIVE

In this paper we have briefly presented data processing and analysis for a preliminary turbulence and tracer experiment at SIRTA site in stable conditions. From turbulence data, we verified first meteorological criteria demanded for the tracer test such as wind direction and velocity, vertical temperature profile and stable stratification condition. Then, we characterized the turbulence in the surface layer near the ground by calculating variances, integral length scales and spectra for the three velocity components, showing the strong anisotropy of these properties. From spatial velocity cross-correlation, we have deduced that the eddy advection velocity is greater than the mean wind velocity measured directly by anemometers at the same level. What's more, we found a k_1^{-1} subrange in spectra of the three velocity components which shows the existence of an eddy surface layer very close to the ground. The concentration data obtained during the first periods of observations are difficult to analyse due to some problem with the mass flow controller. However, recent measurements performed after modifications of the gas pipe showed that it was possible to better control the mass flow and thus to obtain larger and more consistent values for the concentrations 50m downwind from the source.

More data processing and analysis are expected. We will try to find reason for $U_{adv} > U$ using coherent spectra. We are going to apply wavelet analysis methods to explore coherent structures in the turbulence. From velocity power spectra, we intend to identify the frequency limit between k_1^{-1} subrange and inertial subrange, and deduce the energy dissipation rate. For concentration data, we are still looking for other methods which can use the background concentration measurements in data correction. Also, we are thinking to filter out the noise and to study its power spectra as what we do for turbulence data. Another part in our data analysis will be to find relationships between turbulence and concentration fluctuations. Several more new PIDs and ultrasonic anemometers will allow to extend the instrumental set-up both horizontally and vertically. Finally this data set will allow detailed comparisons in different configurations with numerical simulations which will be carried out with the open source CFD code Code_Saturne developed at CEREA, with different turbulence modeling levels and with Eulerian and Lagrangian dispersion.

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