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The Influence of Meteorological Conditions for the Localization of an Acoustic Source by Means of a Microphone Antenna

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Summary
In this paper, we study the effect of atmospheric turbulence on sound propagation in the low atmosphere and of its influence on the localization of vehicles. In the course of experiments, the average and fluctuating meteorological magnitudes of the low atmosphere have been measured in order to have a better knowledge of the stability state, and of the rates of thermal and kinematic fluctuations of the atmosphere. The localization antenna is made up of two overlapping linear antennas, each composed of 8 microphones. The whole acoustic and meteorological data have been measured simultaneously and recorded in situ. From this information, an average value analysis has allowed us to layout the vertical speed profiles of the wind and temperature by means of the Monin-Obukhov theory of similarity. In three different cases of wave refraction, these profiles have been used for a model of propagation based on the method of rays in order to calculate the sound paths and for a calculation code of the acoustic level (PE) allowing us to know the propagation conditions of the wave between the source and the antenna. Then the localization results have been analyzed together with thermal and kinematic fluctuation results of the low atmosphere. A narrow relationship between the precision of the localization results and eigenvalues of the correlation matrix of acoustic signals has been established. The degradation of these eigenvalues is a direct consequence of the thermal and the kinematic fluctuation rates of the low atmosphere.

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1. Introduction

Sound propagation in the low atmospheric layers has been studied with experimental and numerical methods for propagation distances varying from a few hundred meters to a few kilometers [1, 2, 3, 4]. According to time-of-day, the average meteorological data will determine through the association of vertical profiles the average conditions for the propagation of sound waves. The configurations used to determine the average meteorological conditions in order to draw the temperature and wind velocity profiles are nearly the same in all experiments. The temperature sensors, the anemometers and the wind vanes are fixed on meteorological masts for low altitudes. For higher altitudes, in situ measurements are performed with captive balloons, aircraft and stratospheric balloons. From the ground, indirect measurements are possible with Doppler SODARS. The geometry of the experimental system is essentially determined by the purpose which is to be achieved (propagation of aircraft or vehicle noise) and by the profile model used to determine the variations of meteorological parameters in the low atmosphere. These variations were considered in a more or less detailed way by using different similarity theories (Monin-Obukhov [5], Obukhov-Priestley, Zilitinkevitch, Kazanski-Monin, Deardorff [6]). These various similitude theories work with different hypotheses and have different fields of application. The profiles developed by Kazanski-Monin and Deardorff are relevant in the atmospheric boundary layer. The height of this layer is about 1 km. The features and quality of the ground surface strongly influence this layer from a dynamic and thermic point of view. In this layer, we have the surface boundary layer already studied by A. S. Monin and A. M. Obukhov as well as by Priestley and Zilitinkevitch. In this surface layer, turbulence mainly depends on roughness, wind gradients and heat flow. The generated turbulence are then transported to the free atmosphere and according to the characteristics of the air mass, they can generate high gradients of temperature and hygrometry. As the French-German Research Institute of Saint-Louis (ISL) is interested in propagation of vehicle noise, this surface layer plays a very important role. The results of Monin-Obukhov were very carefully examined and we noticed that in the published research work, there was no study in which the acoustic measurements and the evaluation of average meteorological conditions and of fluctuating parameters were performed simultaneously in order to localise sound sources. On the other hand, in the framework of the trial campaigns AMI 2 organised by the RSG 11 NATO group, A. Weill and P. Naz [7] have already performed simultaneous measurements to study some aspects of the acoustic detection of aircraft. Thus, with our experiments, we tried to introduce some new elements to improve the various atmospheric and propagation models. In section 2 we describe the outdoor experimental set-up. In section 3, we present the localization results. We examine the results of the analysis of the variations of the direction and the eigenvalues for more than 24 hours. We come back to three specific points that we analyse in detail. And we show the evolution of the index of refraction according to the fluctuations of the temperature and the wind velocity.

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2. Experimental set-up

The complete experiment including the localization of acoustic sources, the measurement of average values that are characteristic of the low atmosphere and the measurement of the thermal and kinematic fluctuations took place on the ISL Proving Ground near Baldersheim (Haut-Rhin 68, France) (Figure 1).

The site is mainly located in a strongly wooded area without private housing within 10 kilometers. On the experimentation field, the ground is covered with short grass over an area of about 40,000 m^2. To the south, there is an area planted with bushes. The measuring site is oriented according to the preferential wind direction (between south and west).

For the acoustic part, we used a sound source located in the southern area. The localization measurements have been carried out with an acoustic antenna consisting of 8 B&K microphones. This antenna is oriented to the north-west, south-east and is used as geographic reference. The distance between the center of the antenna and the source is 50 m. We use the MUSIC localization code. This code was chosen because it implements the eigenvalues of the correlation matrix of the signals supplied by the microphones [8].

The meteorological mast is fitted out for the measurement of the average values of two measuring chains at respective heights of 2 m and 10 m. The measuring chain consists of sensors, transcription and acquisition units. These modules record the temperature, the wind direction and the hygrometry. The data supplied by the two measuring chains are transferred and stored on a PC via an RS232 connection. The measurement room with the systems for data control, analysis and storage is situated to the north of the antenna.

For the measurement of temperature fluctuations, one should use a thermocouple with a very low calorific capacity, a very high thermal conductance between the sensor and the measuring medium and a very low thermal conductance between the sensor and the outside environment. The dimensions of the exchange surface between the unprotected sensor and the medium should be of the order of the μm and the reference zone should have an important volume. This has a disadvantage, namely an alteration due to humidity, shocks, vibrations and a more important radiation in the reference zone. The realization of such a thermocouple requires a very efficient manufacturing process and much know-how to achieve a good reproducibility of the physical and electric characteristics as well as a good mechanical resistance. Among the different techniques used to produce thermocouples, discharging a capacity is particularly adapted for cables with small diameters; the advantage is that there is no spherical pearl at the junction point [9]. These sensors are developed and produced at the Engineering Energetic Institute in Belfort [10, 11]. The major problem is the sensitivity of this sensor type. For an S-type thermocouple, the sensitivity is about 5.9 μV/°C at about 20 °C. The digitalization of the supplied signals requires an important signal amplification, which is difficult to achieve. At present, there is no product on the market that can meet these conditions. In the framework of this study, we had to study and develop an instrumentation amplifier adaptable to the thermocouple developed at the IGE in Belfort for outside applications (Figure 2). The measuring module below can deliver an output voltage between ± 12 V for an input signal ranging from $\pm 24\,\mu$v, i.e. a temperature variation of ± 4°C.

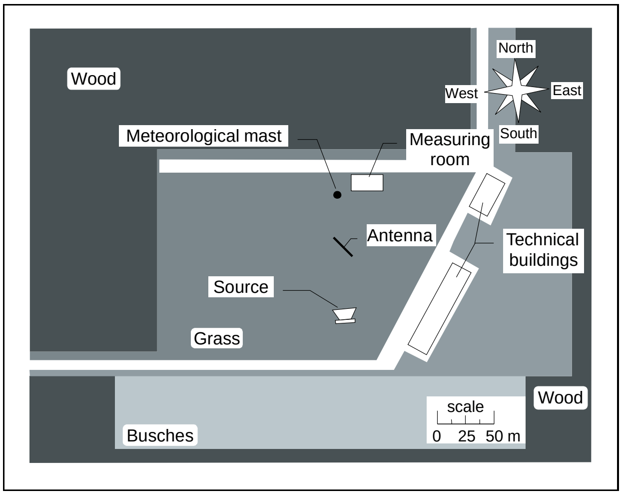

Figure 1. Device for the measurement of the average turbulent values in the low atmosphere (meteorological mast), configuration of the source, device for source localization and measuring room.

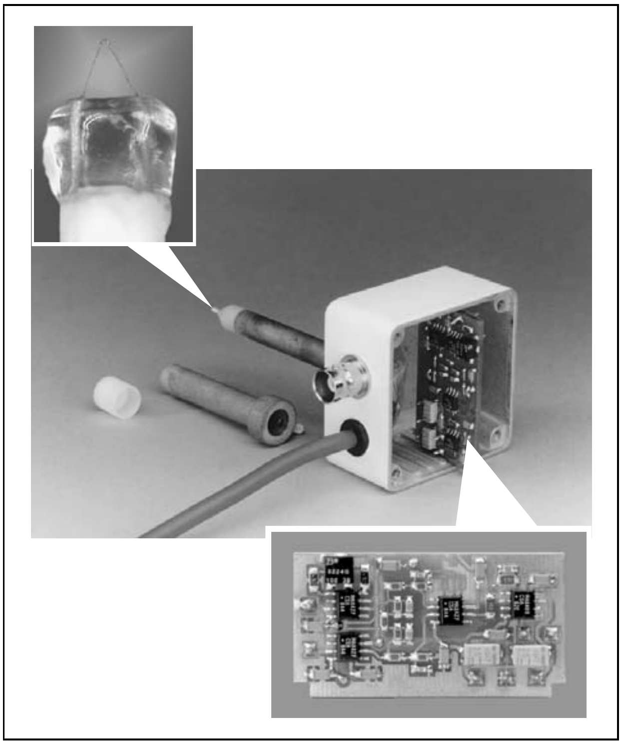

Figure 2. View of the amplification module (×500 000) and of the thermocouple of 1.27 μm.

Six anemometers at constant temperature were taken for the measurements of the velocity and the wind direction (model IFA 300 of the TSI company). The sensors used for the measurement of velocity are double sensors with 45°-crossed wires (model 1241) and simple sensors (model

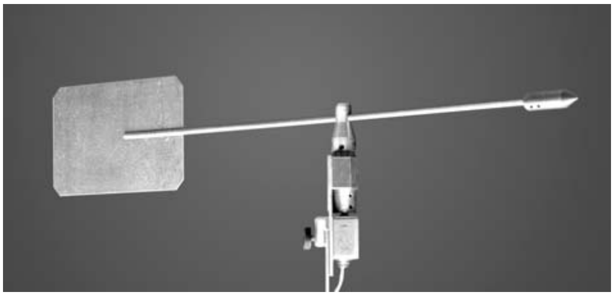

Figure 3. "Autonomous" wind vane.

1201); the double sensors only work correctly if the angle between the normal to the sensor and the flow does not exceed $\pm 30°$ [12]. In the present problem, the flow direction varies greatly. As it is not realistic to link the sensor direction to the flow direction, the measurements can only be validated if the angle of the wind direction ranges from $+30°$ to $-30°$. Therefore, an "autonomous" wind vane, which is very sensitive to the wind, has been developed [8] (Figure 3).

3. Experimental results

3.1. Localization

The errors due to acoustic level and to source geometry have been corrected so that only the atmospheric disturbances modifying the propagation path of the acoustic wave are considered by the MUSIC localization code [8]. To avoid erroneous results due to these phenomena, the results are analyzed with the 1 m antenna for a frequency of 930 Hz and an acoustic level of the source of 103 dB.

3.1.1. Variations of the direction

The deviations of the estimated angular positions for a source located to the south have been studied according to time-of-day on September 14 and 15, 1999. The results for these days are presented on the same graph to observe the evolution over more than one day; the experiments took place from 3 p.m. to 9 p.m. on September 14 and from 6 a.m. to 6 p.m. on September 15. Values close to 0 are representative of the source located to the south, whereas values close to $-45°$ indicate a source located to the south-west. This direction ($-45°$) is wrong; it is given by the localization algorithm when the microphone signal is no longer representative enough of the source.

The evolution of the angular deviations according to time-of-day for all frequencies shows two different zones where most of the results are gathered (Figure 4). The first one is included between 7 a.m. and 10 a.m. on the 15th of September: in this case, the results provided by the MUSIC algorithm are not correct. The other periods of the two days form the second period of the time. There, the localization code provides good results.

In first analysis, this can be explained by the difference between ground and air temperatures. The ground and the

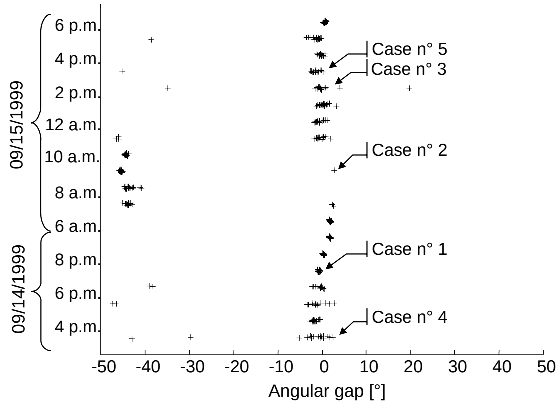

Figure 4. Angular gap on 09/14/99 and 09/15/99 according to time-of-day for acoustic supply in the south for a frequency of 930 Hz and a 103 dB-level, located with an antenna of 1 m length.

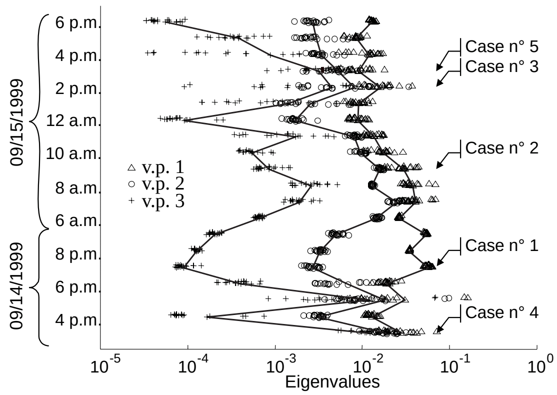

Figure 5. Three greater eigenvalues of correlation matrix on 09/14/99 and 09/15/99, according to time-of-day for an acoustic wave of 930 Hz frequency and 103 dB level, located with an antenna of 1 m length. The solid lines are the mean values of the eigenvalues.

lower atmospheric layer are colder, which leads to a gravitational kinematic turbulence. The atmosphere is in a very unstable state. To go deeper into this analysis, we first studied two detailed cases:

Case 1:
measurement begins at 07:06:52 p.m. on September 14, 1999,

Case 2:
measurement begins at 09:06:46 a.m. on September 15, 1999.

The two cases are part of different day periods and the results given by the algorithm are radically opposed as at 7 p.m., they are all exact whereas at 9 a.m. they are all erroneous, except for one.

3.1.2. Variation of the eigenvalues

The results of the analysis of the first three eigenvalues of the correlation matrix (frequency 93 Hz) according to day period on September 14 and 15, 1999 are represented on Figure 5. They show an important amplitude variation, but also a difference in value distribution according to day period: in the morning of September 15, the second and first eigenvalues are very close which is not the case at noon or at the end of the day. The amplitude variations of the first eigenvalue, which is supposed to represent the signal to localize, indicate that the attenuation of the wave through the atmosphere depends on the hour. The second and third eigenvalues also have to be weak enough compared to the first one, otherwise the first value might no longer be representative of the signal any more and then the algorithm indicates a direction of $135°$ and an angular deviation of $-45°$. The analysis of case 1 and 2 shows that the first eigenvalues are weaker in case 2 and that the results are wrong. If we consider the relation of the first two eigenvalues, which is lower than in case 2, and the third eigenvalue, which is much higher, we have an explanation of the errors of direction given by the algorithm. A detailed analysis of the values and of the relations between the eigenvalues already enables the estimation of the validity of the results given by the localization algorithm.

However, one can notice that the source coordinates are correctly indicated by the algorithm in spite of eigenvalues that seem very close in other cases:

Case 3:
measurement begins at 02:03:32 p.m. on September 15, 1999,

Case 4:
measurement begins at 03:10:33 p.m. on September 14, 1999,

Case 5:
measurement begins at 03:09:08 p.m. on September 15, 1999.

The first eigenvalues of the correlation matrix are not as high as in case 3 and in spite of this, the results are correct. Here, the amplitude is not a sufficient criterion. As for the distribution of the first eigenvalues, in case 3, they are very different according to the moment of the analysis. This explains why it seems that there is a slight difference between the eigenvalues. In fact, a point by point analysis shows a ratio of 1.5 to 7 between the first and second eigenvalues in case 3 whereas this ratio reaches a maximum of 2 in case 2. Moreover, the lowest eigenvalues in case 3 lead to a direction error (Figure 4) for the values $+20°$ and $-35°$.

3.2. Variation of the average values

A study of the eigenvalue results shows that the value and the ratio between the first and the second values vary according to day period. By considering the characteristics of the sound propagation medium as regards fluctuating parameters, average meteorological profiles and acoustic field, we can partly explain why these values are varying according to time-of-day.

The experimental set-up, the acoustic level of the source and the meteorological profiles given by the similarity theory of Monin-Obukhov provide several analysis tools:

- the paths of the acoustic rays [13] enabling the visualization of the wave paths along the propagation axis,

Table I. Average atmospheric values on 09/14/99 and 09/15/99. Case 1: 07:06 p.m., case 2: 09:06 a.m., case 3: 2:03 p.m.

Height	Time	Temp. °C	Velocity m/s	Pressure mbar	Humidity %
2 m	case 1	23.6	0.13	988.1	66
	case 2	18.2	0.14	988	99
	case 3	26.5	0.46	987.8	85
10 m	case 1	24.8	0.90	-	-
	case 2	17.2	0.40	-	-
	case 3	26.5	0.88	-	-

- the cartography of acoustic levels along the propagation axis.

For these calculations, it is necessary to know the acoustic impedance of the ground. This parameter was estimated with the "*Level Difference Method*" consisting in determining the difference of acoustic level between two microphones according to the source frequency. An iterative method is then used to determine the ground resistance σ by minimizing the distance (least squares) between the measurements and the results predicted by a propagation model. With this ground impedance and the average values of the atmosphere (Table I), we first graphed the meteorological profiles with the previously implemented calculation code, then the acoustic rays and the acoustic field in the propagation plane with the PE code [14, 15, 16] for case 1 (09/14/99 at 7 p.m.) and case 2 (09/15/99 at 9 a.m.). These methods have been programmed and introduced in the main code that performs the whole analysis. The acoustic rays are drawn using 21 rays with an angular aperture of 30° and a calculation step of 1 ms. In the PE code, the spatial resolution is 10 cm according to height and 6 cm according to propagation direction. As it is too complicated to visualize these paths, only case 1 and 2 are shown (Figure 7, Figure 9). The other paths are available under reference [8].

In case 1 (7 p.m.) (Figure 6), both profiles have a positive gradient. The ray path associated to the profiles presents some reflections on the ground. The antenna can display these reflections as potential sources if they remain consistent along the propagation path. But, they can also influence the direct wave reaching the antenna, thus making the signal temporarily inconsistent. The ray path as such does not give any quantitative information about the acoustic wave level along the propagation axis. To get more information, we graphed the levels and distribution of the acoustic field in the propagation plane calculated with the PE code. The analysis of the acoustic levels in the propagation plane (Figure 7) gives an amplitude of 62 dB at antenna level. With this high amplitude, the source level comes out better against the low frequency levels.

In case 2 (09/15/99 at 9 a.m.) (Figure 8), the scheme for the analysis is the same. The temperature and wind velocity profiles according to the altitude show a negative and positive gradient, respectively. The profile of the acoustic rays shows that the latter significantly bend upwards. This kind

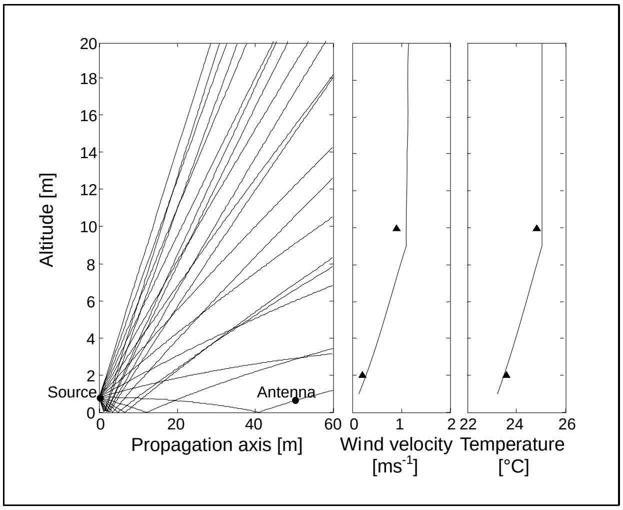

Figure 6. Development of acoustic rays, temperature profiles and wind velocity for case 1 (09/14/99 at 7 p.m.).

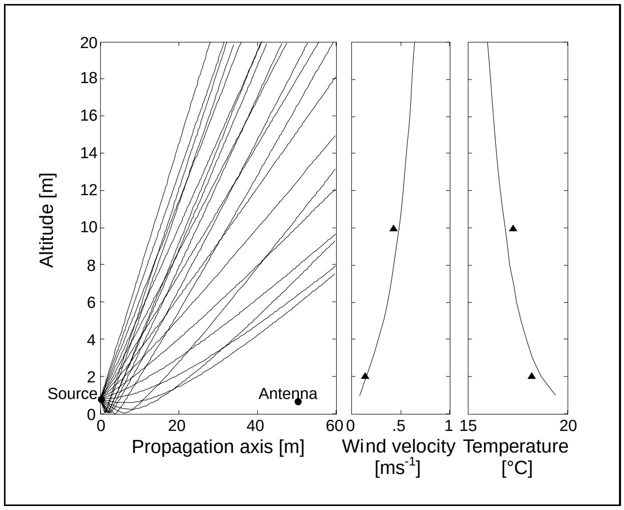

Figure 8. Development of acoustic rays, temperature profiles and wind velocity for case 2 (09/15/99 at 9 a.m.).

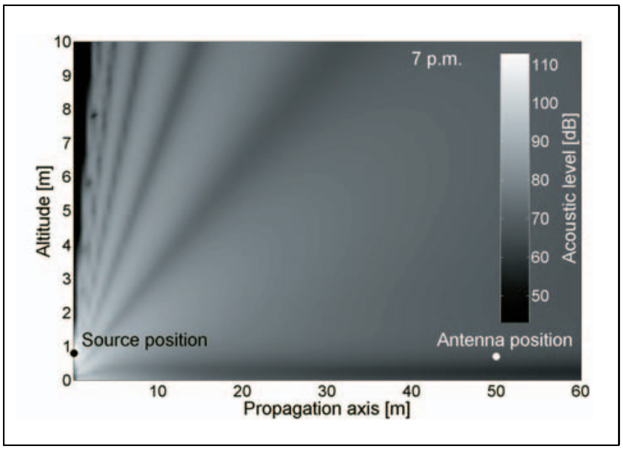

Figure 7. Acoustic levels calculated with a PE code in the propagation plane for case 1 (09/14/99 at 7 p.m.).

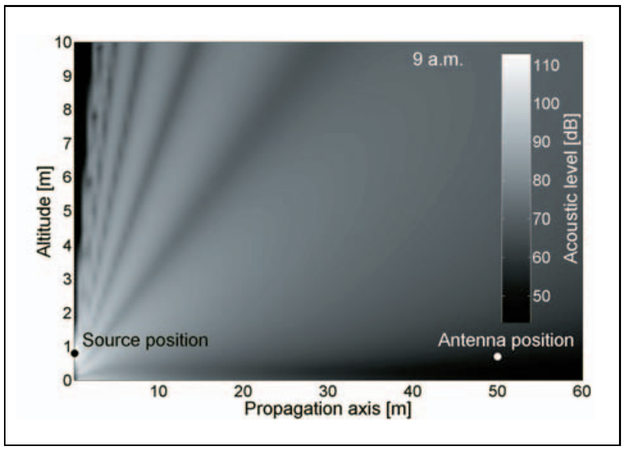

Figure 9. Acoustic levels calculated with a PE code in the propagation plane for case 2 (09/15/99 at 9 a.m.).

of profile might indicate a shadow area at antenna level. The representation of the levels in the propagation plane (Figure 9) enables us to confirm the idea of a shadow area as there is also a bending of the acoustic levels according to altitude from about 20 meters upwards.

In the early afternoon, at about 2 p.m., the atmosphere configuration has slightly changed as regards average values: wind velocity is higher and temperature is constant (Figure 10). The positive velocity gradient together with the zero temperature gradient shows an acoustic rays profile with some reflection on the ground. As in case 1, these reflections can hinder localization. The profile of the acoustic levels in the propagation plane (Figure 11) makes it possible to conclude that the antenna is located on the upper part of the shadow area. In that place the acoustic waves propagating in the atmosphere can intermittently be convected by the wind. If referring to the representations of the values and to the ratio of eigenvalues, this situation is illustrated by an important scattering of eigenvalues and a strong varying ratio between the first and the second eigenvalue. The MUSIC code gives erroneous values between $+20^\circ$ and -35° for these moments.

3.3. Evolution of the index of refraction

The former analysis of the average atmospheric values gives information on the general conditions of the wave propagation. With the measurement of the thermal and kinematic fluctuating values at the same time, the phenomena in a spectral region up to about one hundred Hertz are studied. The information transmitted in this frequency band plays an important part in extreme cases of propagation. The signals from the microphone antenna with a continuum bandwidth of 5 kHz contain information on atmospheric fluctuations. As a consequence, the localization calculation code can be influenced by these disturbances. And the rates of thermal or kinematic fluctuations are varying according to time-of-day.

The refraction index of the medium n is expressed in terms of a mean part $\langle n \rangle = c_0/c$ (c_0 is the reference sound speed

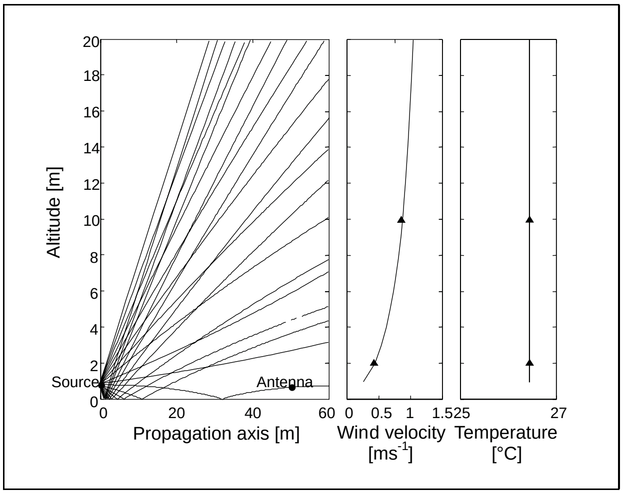

Figure 10. Development of acoustic rays, temperature profiles and wind velocity for case 3 (09/15/99 at 2 p.m.).

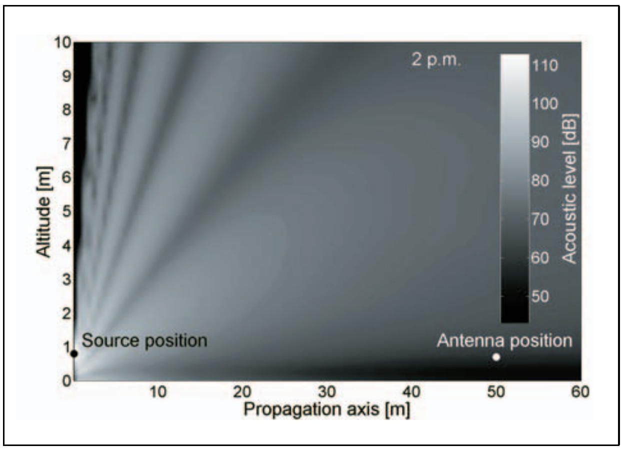

Figure 11. Acoustic levels calculated with a PE code in the propagation plane for case 3 (09/15/99 at 2 p.m.).

Table II. Rates of thermal and kinematic fluctuations of the atmosphere at three heights for case 1, 2 and 3.

Height	Time	$\mu_C \cdot 10^{-4}$	$\mu_T \cdot 10^{-4}$
2 m	case 1, 07:06 p.m. case 2, 09:06 a.m. case 3, 02:03 p.m.	0.8–0.9 1.4–1.6 2.4–2.7	2.8–3.1 5.5–6.3 8.2–10
5 m	case 1, 07:06 p.m. case 2, 09:06 a.m. case 3, 02:03 p.m.	0.9–1.2 0.5–2.0 3.2–4.4	2.9–3.1 8.5–9.5 4.2–6.6
10 m	case 1, 07:06 p.m. case 2, 09:06 a.m. case 3, 02:03 p.m.	0.1–0.2 1.3–1.5 3.5–3.9	2.2–3.1 5.0–5.7 2.2–5.0

and c is the mean local sound speed) and a random part μ related to the fluctuations of the medium. At first approximation, as the positions of the source and of the antenna are near ground, the refraction index fluctuations of the medium can be decomposed in two terms (μ_T and μ_C, respectively the thermal refraction index fluctuation and the kinematic refraction index fluctuation): $\mu = -\mu_T - \mu_C = -T_r/2T_m - u'/c_0$, where T_m is the reference temperature, T_r the fluctuation of temperature and u' the fluctuation of the wind velocity along the axis of propagation. That is why it is interesting to follow the evolution in the course of the time of the physical magnitude present in Figures 12, 13 and 14.

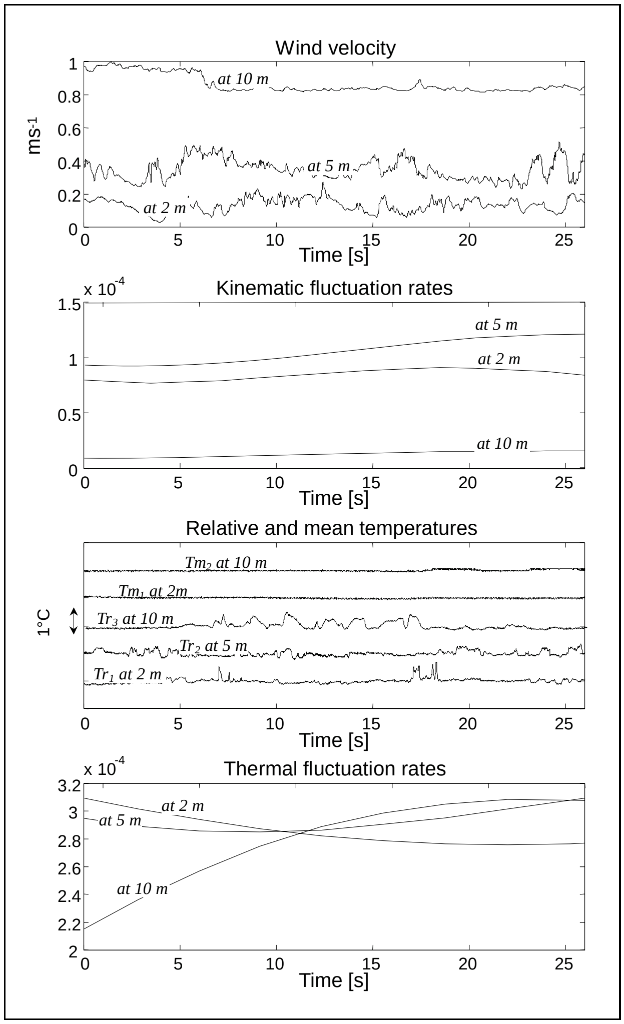

Figure 12. Wind velocity and temperature measurements as a function of time at three heights for case 1 (09/14/99 at 7 p.m.), T_m is the mean temperature and Tr_i is the relative temperature.

In Figures 12, 13 and 14, you can see the evolution during 26 s at three heights from measurements of the wind velocity and temperatures and their fluctuations rates. For the temperatures, the frequency responses of the sensor are 1 Hz for the average values and around 100 Hz for the fluctuating values. For the wind velocity, the average values are calculated over 1 s for a good homogeneity.

The evolution and the fluctuation rate on 09/14/99 at 7 p.m. (case 1, Figure 12) show that the wind is strong and fluctuates less at 10 m during the whole analysis. As for the temperature, some small structures can be noticed with a maximal amplitude of $0.5\,°$C. They last longer at 10 m but basically,

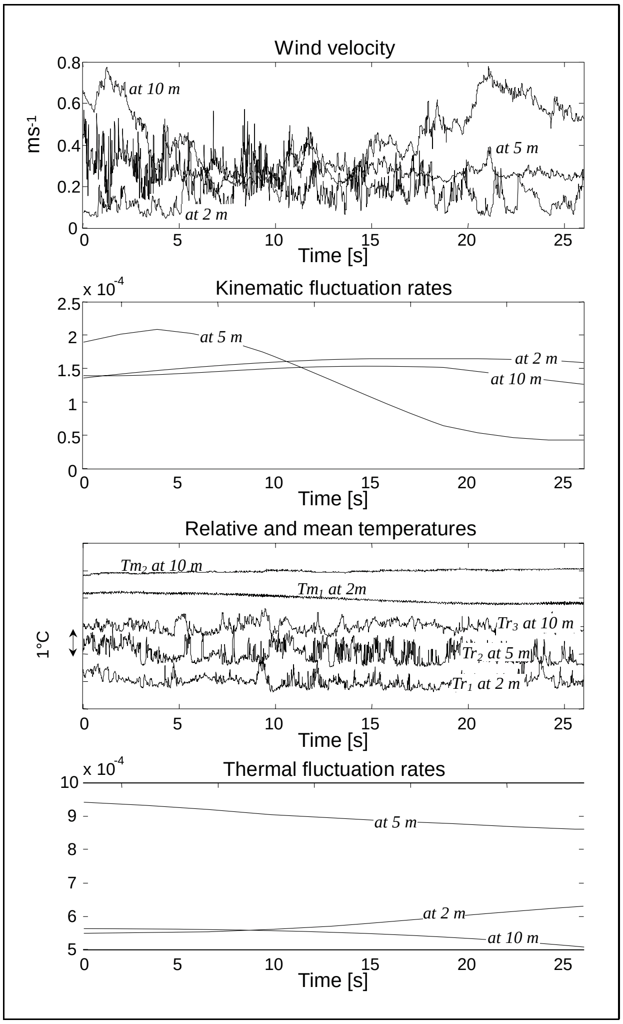

Figure 13. Wind velocity and temperature measurements as a function of time at three heights for case 2 (09/15/99 at 9 a.m.), Tm is the mean temperature and Tr_i is the relative temperature.

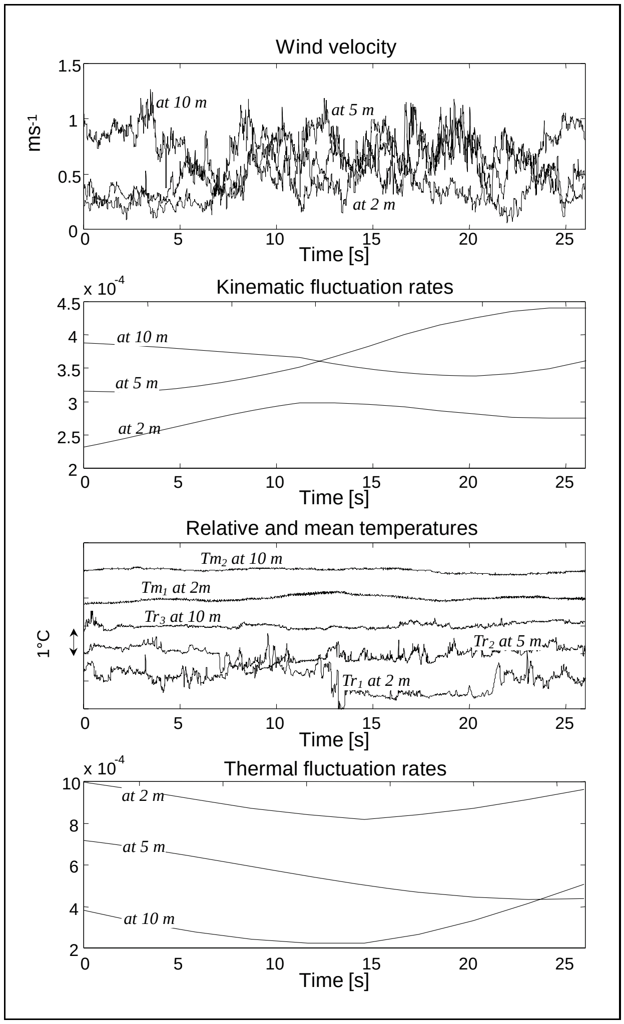

Figure 14. Wind velocity and temperature measurements as a function of time at three heights for case 3 (09/15/99 at 2 p.m.), Tm is the mean temperature and Tr_i is the relative temperature.

there are few of them. At that time, the fluctuating values of the atmosphere are very low (Table II) from a kinematic as well as from a thermal point of view.

The time records of case 1 show a much more rapid variation of wind velocity and temperature structures than in case 2 (09/15/99 at 9 a.m., Figure 13). The kinematic behaviour of the atmosphere is strongly disturbed by the atmospheric layer between 2 and 10 m. Within 26 s, the fluctuation rate increases by a factor 4. Moreover, the average rate values are higher than in case 2. The temperature amplitude varies by 1 °C and there are numerous structures. The fluctuation rates are very high at 5 m and much more important than at 2 and 10 m. At this moment, a thermal layer of the atmosphere is very turbulent.

In case 3, the wind structures are the same as in case 2 but the values are slightly higher (Figure 14). The rate of kinematic fluctuations is even higher than previously (2 to 4 times higher). There are few variations in the evolution and the values show a rate decreasing according to altitude except at recording end. For the measurement at 5 m height, despite a rather small velocity variation, the rate is higher than at 10 m. The temperature contrast is more pronounced as regards amplitudes, duration and number of structures. At 2 m, the structures show amplitude variations of $2°$ C whereas at 10 m, these variations only reach a maximum of $0.3°$C. The profiles of the temperature fluctuation rates are very high at 2 m. Thus, from a thermal and kinematic points of view, the atmosphere is very turbulent as regards fluctuating values.

4. Conclusion

In these series of measurements we characterized the average and the fluctuating meteorological parameters of the low atmosphere simultaneously with the localization of acoustic sources using an array of microphones. As all the measured data are synchronized, we are able to analyze at any given moment the state of the atmosphere close to the ground during the process of localization of the acoustic sources. The measurement of the fluctuating magnitudes was carried out with great care, in order to have a better knowledge of the stability State and of the rates of thermal and kinematic fluctuations of the atmosphere. It enables us to relate the precision of the localization results to the eigenvalues of the correlation matrix evaluated from the received acoustic signals. Three cases detailed in section 3 highlight this relation very well. This outdoor sound propagation experiment made it possible for the first time to gather information on the low atmosphere (average values as well as fluctuating ones) during the localization test of the acoustic source. In order to have a deeper understanding of the state of the low atmosphere and to confirm the localization results, we have developed and adapted sensors to obtain data concerning temperature and wind velocity fluctuation in real testing conditions. This carefully controlled study illustrates the important role played by the variability of the atmosphere in the discrimination between the eigenvalues of the correlation matrix associated with the acoustic sources and the eigenvalues associated with the noise as defined in the MUSIC method.

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