Passive acoustic measurements of wind velocity and sound speed in air

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Abstract: Random acoustic fields generated by uncorrelated sources in moving media contain information about the propagation environment, including sound speed and flow velocity. This information can be recovered by noise interferometry. Here interferometric techniques are applied to road traffic noise. Acoustic travel times and their nonreciprocity are retrieved from two-point cross-correlation functions of noise. The feasibility of passive acoustic measurements of wind velocity using diffuse noise is experimentally demonstrated for the first time. The accuracy of the interferometric measurements of sound speed and wind velocity is confirmed by comparison with *in situ* measurements of wind, air temperature, and humidity.

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1. Introduction

Acoustic noise is often diffuse in the sense that it is generated by spatially distributed uncorrelated sources rather than a few dominant compact sources. Two-point correlations of a diffuse noise field in a fluid flow can be used to retrieve information about the fluid and the flow. Bass *et al.*[1] demonstrated that wind velocity can be measured by cross-correlating turbulent pressure pulsations advected by wind past a three-microphone array. Having established a connection between the dynamics of microbarom observations by multiple infrasound arrays with a major sudden stratospheric warming event, Evers and Siegmund[2] proposed using variations of the back azimuths and intensity of microbaroms recorded on the ground to monitor the wind and temperature structure of the stratosphere. Haney[3] found that the positions of maxima of microbarom cross-correlations at Fourpeaked Volcano in Alaska are consistent with independent temperature measurements and concluded that infrasound noise correlations can be used as an acoustic thermometer. Godin[4–6] showed theoretically that for various types of noise sources, a two-point cross-correlation function of diffuse noise in generic inhomogeneous moving media approximates the sum of Green's functions describing sound propagation in opposite directions between the two points. Thus measurement of the cross-correlation function should allow one to quantify the flow-induced acoustic nonreciprocity and determine the travel times of waves propagating in opposite directions that are normally obtained in reciprocal transmissions experiments[7] employing acoustic transceivers. Similar conclusions were drawn by Wapenaar,[8] although the actual derivation in Ref. 8 applies only to the case of uniform flow. In a numerical study, Fricke *et al.*[9] showed that

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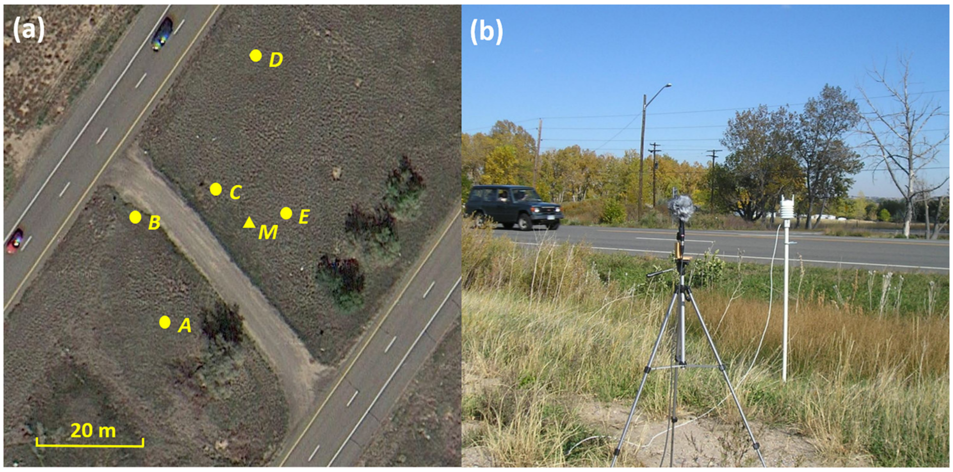

Fig. 1. (Color online) Setup of field experiments. (a) Layout of experiments 4 and 5 on November 6, 2012. Letters *A–E* indicate positions of microphones; *M* indicates the position of a weather station. (b) A microphone with wind screen mounted on a tripod (in the foreground) and a weather station near a road.

travel times of stratospherically refracted infrasound can be passively measured by cross-correlation of microbaroms; the travel times subsequently can be used to estimate temperature and wind profiles.

This paper reports the first experimental proof of the concept that velocity of fluid flow can be measured by interferometry of acoustic noise. We employ road traffic noise, which is ubiquitous in populated areas, as a means of atmospheric sounding and present the results of retrieval of wind velocity and sound speed in air from noise cross-correlations.

2. Experiments

Road traffic provides a persistent, distributed source of audible noise with the time-averaged strength of the noise source varying gradually along the road away from traffic lights. With its sources located in the vicinity of a narrow strip on the ground, the noise field is by no means isotropic or equipartitioned but is nevertheless suitable[4,6] for application of noise interferometry. Passive characterization of flow-induced acoustic nonreciprocity and measurements of flow velocity require that noise propagates in opposite directions through an array of receivers,[4,6] making areas between busy roads a preferred location for a microphone array [Fig. 1(a)].

The instrumentation employed in our experiments consisted of omnidirectional measurement microphones MiniSPL manufactured by NTI AG, a WXT520 weather station manufactured by Vaisala Inc., and a battery-powered computer, which recorded acoustic signals and meteorological data. The number of microphones used was either four or five, depending upon the particular experiment. Five short-term experiments

Table 1. Field experiments.

	Date	Duration (min)	Temperature (°C)	Humidity (%)	Wind (m/s)	Number of microphones
1	Nov. 1, 2010	100	16	29	2.4	4
2	Dec. 3, 2010	40	17	18	6.5	4
3	Apr. 12, 2011	60	15	21	2.0	4
4	Nov. 6, 2012	60	16	34	1.8	5
5	Nov. 6, 2012	90	16	34	1.8	5

were conducted in the vicinity of Boulder, Colorado, during a 2-yr period. Details of the experiments and relevant environment conditions are summarized in Table 1.

Figure 1(a) illustrates the locations of five microphones *A*–*E* and the weather station *M* during a typical experiment. Figure 1(b) shows a tripod-mounted microphone with a wind screen as well as the weather station. The distance between microphones varied from 15 to 50 m. Microphone signals were digitized with a sampling frequency of 20 kHz after analog filtering with the pass band from 40 Hz to 6 kHz. The analog filtering suppresses strong signal fluctuations due to low-frequency turbulent pressure pulsations and prevents aliasing during signal digitizing. The distances between microphones were measured with a laser range meter with an accuracy of a few millimeters. The weather station provided wind vector measurements every 3 s, and temperature, pressure, and humidity measurements every 60 s.

3. Results

Digitized time series of pressure recorded by the microphones were used to calculate the two-point cross-correlation function of noise for each microphone pair. $N \geq 2$ microphones give $N(N-1)/2$ distinct correlation functions. A high-pass digital filter with a cut-off frequency of 120 Hz was applied to the signals before cross-correlation estimation. Figure 2 shows typical cross-correlations between the pressure fluctuations that were recorded by various microphones during experiment 4, the layout of which is shown in Fig. 1. The top line corresponds to the correlation between microphones *D* and *E*, and the bottom line corresponds to the microphones *A* and *B*. Microphone pairs are indicated by two-letter codes to the right of the plots. The correlation functions shown in Fig. 2 were obtained by averaging the noise records over a period of approximately 20 min. The magnitude of the correlations is not utilized in this study, and the correlation functions are shown in relative units.

One can clearly see in Fig. 2 that the correlation functions exhibit strong and nearly symmetric maxima. The maxima occur close to time delays $t = \pm L/c$, where c is the sound speed and L is the distance between the microphones and correspond to sound propagation between the microphones. (We did not observe any maxima attributable to

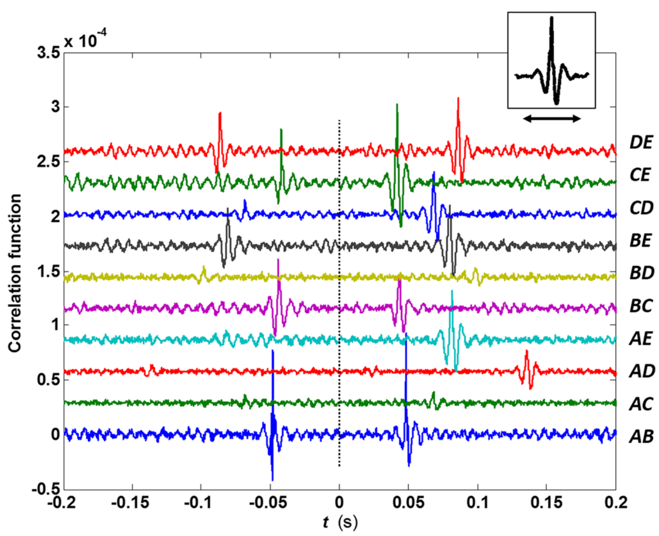

Fig. 2. (Color online) An example of noise cross-correlation functions measured for different microphone pairs. The cross-correlations are shown as functions of the time delay t and were obtained in experiment 4. Microphone pairs are identified by letters to the right of the plots with positions of the microphones *A*–*E* shown in Fig. 1(a). The cross-correlation functions are arbitrary normalized and shifted along the y axis for clarity. The inset shows the reference (averaged) cross-correlation function used to retrieve the acoustic travel times by the "correlation of correlations" method.

advection of turbulent pressure fluctuations[1] at the wind velocity.) Some of the maxima are much weaker than others. It is explained primarily by the different orientation of the microphone pairs; if the sound source along the line connecting two microphones is weak, the resulting maximum of the cross-correlation function will be weak.[4,6] Generally, the strongest correlations are observed in the directions close to the normal to the roads, and the weakest correlations occur in directions almost parallel to the roads.

The cross-correlation function of diffuse noise recorded at points A and B is theoretically predicted to have pronounced peaks and troughs at positive time delays t close to travel times of various deterministic arrivals propagating from A to B and at negative time delays close to the travel times from B to A.[4–6,8] For direct ray arrivals, the signature of the deterministic arrival, i.e., the shape of the peaks and troughs, does not depend on the distance between A and B or the direction of propagation as long as sound absorption is negligible.[4,6] The signature is controlled by the power spectrum and geometry of the distributed noise source. These properties suggest the following method of passive measurements of deterministic travel times, which will be referred to as "correlation of correlations." First, a reference cross-correlation function is calculated by stacking all measured cross-correlation functions with positive time delays and time-reversed cross-correlation functions with negative time delays. Then deterministic travel time at positive time delays for any pair of receivers is determined as the position of the maximum of the cross-correlation between the measured and reference cross-correlation functions. Deterministic travel time at negative time delays is determined in the same manner except for using the time-reversed reference cross-correlation function. This method is superficially similar to the "correlation of the coda of the correlation" technique of Stehly *et al.*[10] but relies on ballistic waves and main peaks of the noise cross-correlation function rather than scattered waves and tails of the cross-correlation function.

Direct ray paths connecting microphones are nearly horizontal for our experimental conditions. Acoustic travel times along such paths can be calculated in the effective sound-speed approximation with an accuracy to terms of the second order in the ratio $V/c \sim 10^{-2}$ of the wind and sound speeds.[11] In this approximation, a moving fluid with flow velocity $\mathbf{V}$ and sound speed c is replaced with a motionless fluid with the effective sound speed $c_{eff} = c + V_t$, where V_t is the projection of $\mathbf{V}$ on the horizontal line from the source to the receiver.[11] In a layered medium, where c and $\mathbf{V}$ are functions of height z, rays connecting points at the same height generally have some curvature. To leading order,[12] the actual ray travel time T is smaller than the travel time along the horizontal line by $\delta T = \left(dc_{eff}/dz\right)^2 T^3/24$. At $O(1)$ m elevations, the wind-speed gradient greatly exceeds the sound-speed gradient, and $dc_{eff}/dz \approx dV_t/dz$. The derivative dV_t/dz is readily estimated for the logarithmic wind profile, and the curvature correction to the travel time proves to be of the order $V^2/c^2 \sim 10^{-4}$. Neglecting terms of this order, the acoustic travel time $T = L/(c + V_t)$, where L is the horizontal separation between the source and receiver. Then the sound speed and the projection of V_{AB} of the wind velocity on the direction from a microphone A to a microphone B can be calculated as $c = \left(T_{AB}^{-1} + T_{BA}^{-1}\right)L/2$, $V_{AB} = \left(T_{AB}^{-1} - T_{BA}^{-1}\right)L/2$, where T_{AB} and T_{BA} are acoustic travel times from A to B and from B to A, respectively. Obviously, $V_{AB} = 0$ when the travel times are reciprocal ($T_{AB} = T_{BA}$). With the noise interferometry approach, the deterministic travel times T_{AB} and T_{BA} are retrieved from the cross-correlation of noise recorded at points A and B. To measure horizontal wind vector $\mathbf{V}$, it suffices to determine projections V_{AB} for any two non-parallel directions.

The "correlation of correlations" method of retrieving deterministic travel times and their inversion for sound speed and wind velocity have been verified by numerical simulations in the geometry of field experiment 4 [Fig. 1(a)]. The simulations assumed a homogeneous, uniformly moving atmosphere above a rigid ground, which allowed us to use the exact, analytic Green's functions[13] when modeling noise fields due to uncorrelated point sources distributed along the roads.

Passive measurements of acoustic nonreciprocity require rather accurate retrieval of deterministic travel times from noise cross-correlations. To do this, we first calculated the reference cross-correlation function by measuring a correlation function averaged over the total duration of the experiment and all the microphone pairs. For experiment 4, the result is illustrated in the inset at the top of Fig. 2. Then individual correlation functions, which were found with data averaging over a relatively short period of time (10 min for experiments 1–3 and 6 min for experiments 4 and 5) were correlated with the reference cross-correlation function using variable time shifts in a search for the correlation maximum. The "correlation of correlations" technique allowed us to locate the maxima quite accurately even for a signal-to-noise ratio much lower than those shown in Fig. 2, which resulted in a reduction of the necessary data accumulation time and in more rapid measurements of the wind velocity.

The passive travel-time measurements give an overdetermined set of linear algebraic equations for the sound speed and two horizontal components of the wind velocity. These equations were solved using the least squares approach. Figure 3(a) presents the results of the sound-speed measurements using noise interferometry as well as the sound-speed values calculated[14] from the air temperature and humidity measured by the weather station. The traditional, *in situ* measurements serve as the ground truth for evaluating interferometric results. Five data points in Fig. 3(a) correspond to the five experiments listed in Table 1. Vertical error bars show estimates of the measurement errors by the passive acoustic method. Horizontal error bars characterize the uncertainty in the ground truth and were calculated as the standard deviation of the sound speed resulting from the variations during the experiment of the measured air temperature and humidity. Within the experimental errors, the results of the passive acoustic measurements always coincide with the ground truth.

Figures 3(b) and 3(c) summarize the results of our wind velocity measurements. Each symbol represents simultaneous measurements of either a south-north or east-west component of the wind velocity by two methods: path-averaged measurements using noise interferometry and point measurements, which serve as a proxy for the ground truth. It was found that the wind velocity changes much faster than the sound speed, and therefore the averaging times used in Figs. 3(b) and 3(c) are smaller than in Fig. 3(a). Each symbol in Figs. 3(b) and 3(c) is obtained using 10 min averaging for experiments 1–3 and 6 min averaging for experiments 4 and 5. The vertical axis shows the wind velocity projection V_n retrieved from acoustic noise interferometry, and the horizontal axis shows the corresponding wind vector projection V_l measured directly by the weather station. In general, we see quite good agreement between the

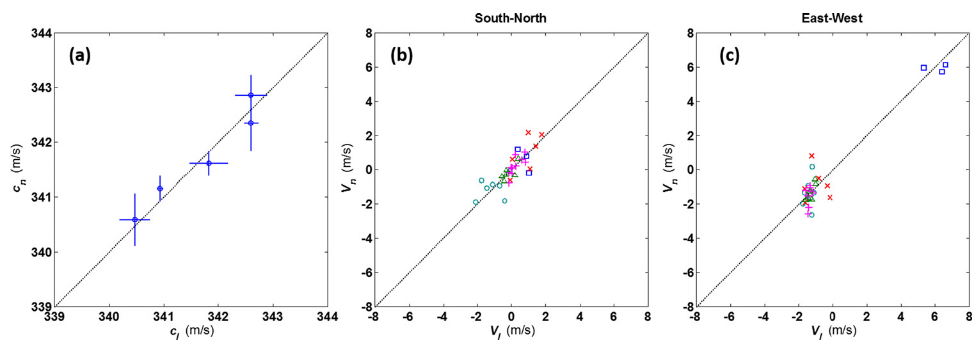

Fig. 3. (Color online) Comparison of results of passive acoustic and traditional, *in situ* measurements of atmospheric parameters. (a) Sound speed retrieved from passive travel time measurements, c_n, and from temperature and humidity measured by the weather station, c_l. Five data points correspond to five distinct experiments. Estimates of the accuracy of the passive and *in situ* measurements are shown by vertical and horizontal error bars, respectively. (b) South-north component of the wind velocity retrieved from nonreciprocity of acoustic travel times, V_n, and measured by the weather station, V_l. Every symbol shows the wind velocity component measured by the two methods. Circles, squares, crosses, triangles, and pluses correspond to experiments 1–5, respectively. Each symbol is obtained during 10 min averaging for experiments 1–3 and 6 min averaging for experiments 4 and 5. (c) Same as (b) but for the east-west component of the wind velocity. The accuracy of wind velocity measurements is discussed in the text.

passive acoustic and the traditional measurements. Slightly smaller scattering of the data obtained during experiments 4 and 5 can be attributed to improvements in the data acquisition hardware implemented after experiment 3.

Experimental errors in the passive measurements of the wind velocity and uncertainty in the ground truth were evaluated in the same way as for the sound speed. [Error bars are not shown in Figs. 3(b) and 3(c) to avoid clutter.] The standard deviation of wind velocity components measured by the weather station varied between 0.8 and 1.7 m/s depending on the average wind speed. Estimates of errors in the interferometric retrieval of the sound speed and wind velocity were based on estimates of the accuracy of the correlation function maximum position, i.e., on estimates of the accuracy of passive measurements of the acoustic travel time. This accuracy was estimated from the width of the correlation function maximum. After the maximum position was determined by the "correlation of correlations" method, the width of the maximum was measured at half of its height level, and that width was used to estimate the errors in the maximum location and, consequently, errors in the wind and sound-speed retrievals. Random errors were decreased by a factor equal to the square root of the number of microphone pairs involved in the calculation of the wind velocity vector. We found the error of wind projection retrieval to be within 0.6–1.3 m/s for each data point in Figs. 3(b) and 3(c). These errors are comparable to the standard deviation of the wind velocity components measured by the weather station. Most of the passive and traditional measurements agree much better than our conservative accuracy estimates suggest, see Figs. 3(b) and 3(c).

4. Conclusion

We have demonstrated experimentally the feasibility of accurate measurements of air temperature and wind velocity using ambient acoustic noise as a probing signal. Theoretical predictions[4–6,8] have been confirmed that flow-induced acoustic nonreciprocity can be quantified by measurements of cross-correlations of diffuse noise and subsequently used to retrieve the flow velocity. The experimental results suggest the feasibility of a low-cost, passive acoustic system for tomography of the atmospheric boundary layer. On a larger scale, interferometry of infrasonic noise can provide wind velocity and temperature measurements in the sparsely sampled upper atmosphere. Passive measurements of nonreciprocity may also prove useful in acoustic oceanography[15] to measure ocean currents and in seismology. If the nonreciprocity of core phases[16] of seismic waves were measured with noise interferometry, it could provide unprecedented insights into the rotation of the Earth's core.

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