6.8 ACOUSTIC TOMOGRAPHIC MEASUREMENTS IN THE ATMOSPHERIC SURFACE LAYER

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1. Introduction

Numerical simulations represent a solution of the hydrodynamic equations over a discrete grid structure. In comparison with such numerical data, horizontally integrated measurements are able to provide data sets in a consistent structure. Acoustic travel time tomography is a technique, which can be used to observe area-averaged air temperature and wind fields in their horizontal and temporal variability. This technique uses the dependence of sound speed on temperature and wind velocity to derive the distribution of these quantities within the measuring area. Such observations can be used to decide whether the point measurements produce data which are representative for the complete experimental area, and thus for the simulations. Furthermore, the acoustic travel time data can be rearranged in a structure, which is comparable with the numerical grid structure of numerical models.

2. Acoustic Tomography

The acoustic tomographic system consists of several sound transmitters and receivers, which are distributed within a landscape. The receivers and transmitters were arranged in such a way that the covering of the area under investigation with sound paths is optimal (as homogenous as possible) and to avoid an overlapping of the recorded different sound-source signals at any one receiver. From the recorded travel times along each path the speed of sound is estimated under the precondition of known sound path lengths (Raabe et al., 2002; Arnold et al., 2004).

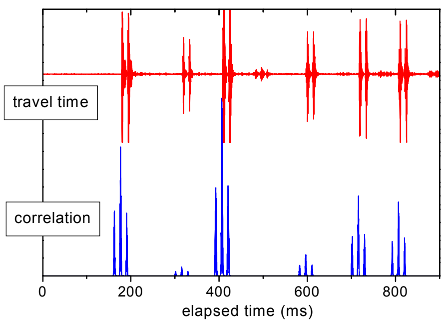

Figure 1: Example of the received signal (here: six sound sources) at one microphone and the calculated cross-correlation function. The location of the maximum of the correlation peak indicates the travel time for the corresponding source-receiver combination.

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All sources simultaneously transmit a signal (e.g. sine double burst with frequency of 1000 Hz). The travel time of each signal is estimated from the recorded data by cross correlation between the received and the transmitted signal. Each peak of the cross-correlation is associated with a specific ray path. The time delay corresponds to the travel time of the transmitted signal (see fig. 1).

To recalculate the searched meteorological parameter from the sound speed some approximations and requirements are necessary. In the following, some of these are presented.

3. Sound speed in humid and moving air

The acoustic measurements produce a set of acoustic travel time data of the sound signals along different sound paths. The lengths of the sound paths are exactly determined during the set-up of the array, therefore the sound speed for each sound path can be calculated. In the (theoretical) case of non-moving air the speed of sound is given by the Laplace approximation:

$$c_L = \sqrt{\gamma_L R_L T} \qquad (1)$$

where c_L is the speed of sound, γ_L is the specific heat ratio, R_L is the gas constant for humid air and T is the temperature. However, we have to consider that the specific heat ratio depends on the temperature, air composition and humidity.

$$\gamma_L(T) = \frac{c_{pa}(T) + m c_{pw}(T)}{c_{va}(T) + m c_{vw}(T)} \qquad (2)$$

where c_p and c_v are the specific heats at constant pressure and volume, respectively, and m is the mixing ratio (a: dry air, w: water vapour). Because dry air is a mixture of different gases, the specific heat at constant pressure has to be considered for each (i) gas component according to its molar contribution:

$$c_{pa}(T) = \sum_i \frac{c_{pai}(T)\Psi_i M_i}{\overline{M}} \qquad (3)$$

where M is the molar mass contribution and Ψ is the mole fraction.

The temperature dependence of the specific heat at constant pressure can be estimated by use of quantum physics or empirical approximations.

Here the theoretical and experimental thermodynamic data of Baehr et al. (1968) were used, because this data include also the range below 300 K. The temperature dependence of the specific heat was calculated using a polynomial regression of the tabulated data.

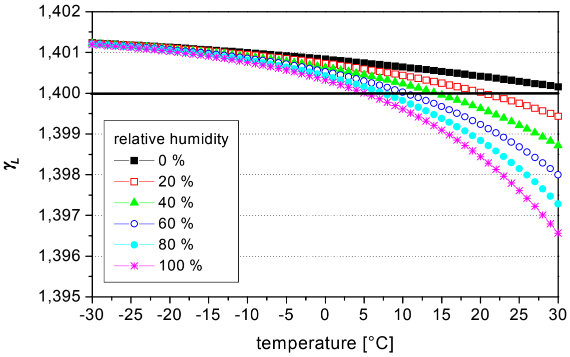

Figure 2. Variation of the specific heat ratio of humid air with temperature at various relative humidities.

Figure 2 illustrates that for typical ambient conditions the value for γ_L of 1.4 is adequate, however at higher temperatures and air humidities an explicit calculation is necessary. The deviation to the standard value of 1.4 cause a change of the sound speed in the range of 0.1 ms^{-1} at -10°C and 0.3 ms^{-1} at +30°C (at 80% relative humidity).

Under conditions of sound propagation through a moving air volume, the effective sound speed has to be considered, which is a superposition of the Laplace sound speed field and the wind field.

$$\vec{c}(T,\vec{v}) = c_L(T(t,x,y,z))\vec{n} + \vec{v}(t,x,y,z) \tag{4}$$

$\vec{n}$ is the unit vector in the direction of the sound wave.

To separate the different influences on the sound speed several methods are applicable: Here the iterative solution, the reciprocal, and bidirectional sound propagation are introduced.

The iterative algorithm for the separation of the temperature and the wind field is based on the variation of one of this parameters (Arnold et al., 2001). At the first step the wind speed and direction or the temperature are changed until the mean value deviation of the Laplace sound speed reaches a minimum:

$$\frac{1}{n}\sum\left|c_L - \bar{c}_L\right| \rightarrow min \tag{5}$$

The selection of the parameters for the iteration cycle depends on the actual meteorological conditions as well as on the features of the measuring site. As a result, one parameter for each sound path can be estimated separately (e.g., temperature) and the other parameter for the different parts or the entire array (e.g., wind vector).

It is also possible to use the reciprocal sound propagation between two transducers. This pair of transducers act concurrently as transmitters and receivers. If the times of flight in each direction, τ_{up} and τ_{down}, are measured, the wind component u along the line of transducers is given by

$$u = \frac{D}{2}\left(\frac{1}{\tau_{\mathrm{up}}} - \frac{1}{\tau_{\mathrm{down}}}\right) \tag{6}$$

where D is the distance between the transducers. The Laplace sound speed c_L is determined independently if the reciprocal times of flight are added.

$$c_L = \frac{D}{2}\left(\frac{1}{\tau_{\mathrm{up}}} + \frac{1}{\tau_{\mathrm{down}}}\right) \tag{7}$$

To enlarge the investigated area and to increase the spatial information content the bidirectional sound propagation can be used. Thereto the transducers are arranged with a spatial offset up to several hundred meters. This spatial extension of the sources and receivers presuppose an almost homogeneous wind field inside the bidirectional cells, which is not given in the real atmosphere at any times.

Both methods were applied during the introduced field experiment and the advantages and disadvantages were checked.

4. Experimental realisations

A micro-meteorological field experiment within the scope of the STINHO-project (STructure of turbulent transport under INHOmogeneous conditions) was performed at the boundary layer research field of the Meteorological Observatory Lindenberg (DWD, German Meteorological Service) in the summer of 2002 to investigate the interaction of an inhomogeneously heated surface with the turbulent atmosphere. During this experiment, several configurations of the acoustic tomographic system were tested and the results were compared with conventional meteorological measurements.

4.1 Setup with reciprocal sound propagation

Above homogeneous grassland eight sound transducers were arranged within an array of 250 m × 300 m (see figure 3).

This configuration enabled the possibility of reciprocal sound propagation between all transducers and therefore the possibility to separate the temperature and wind influence on the effective sound speed for each of the 28 propagation paths.

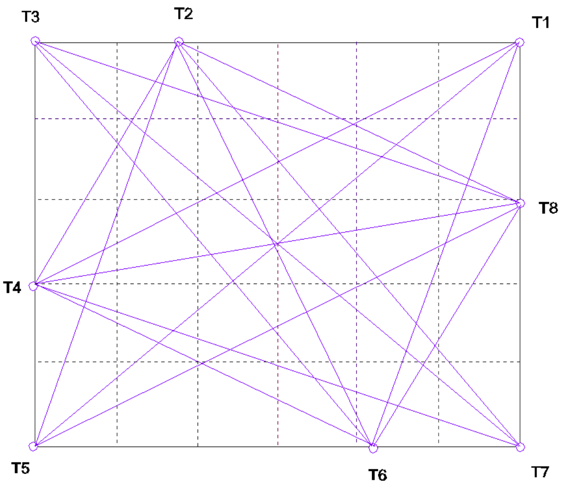

Figure 3. Layout of the tomographic array (extension: 250 m × 300 m) with eight combined speakers and microphones (transducer T1 … T8; see Fig. 4). The solid lines represent the direct sound paths and the dotted grid a cell dimension of 50 m × 50 m for the tomographic reconstruction of the temperature distribution.

As well, the arrangement can be used for the iterative separation of the temperature and wind influence on the 56 direct paths (one direction) between the sound sources and receivers.

Figure 4. Example of combined sound source and receiver at a tripod. The measuring microphone (with a windscreen) is mounted at a tube above the twin speakers (pressure chambers).

In figure 5 the daily course of the acoustically determined horizontal wind speed values (iterative and reciprocal decomposition) is compared with the standard sensors at the profile mast. As a result, a measurement at one point is confronted with two acoustically determined area-averaged wind speed values.

The iterative solution provides one representative value of the wind speed for the whole array, which consists of 56 single information, whereas the reciprocal sound propagation provides the wind components along each of the 28 source-receiver-paths. However, to calculate the amount of the wind speed an average over the 12 orthogonal connections at the border (T3-T2; T3-T2,…) was used. The 16 inclined wind components were not considered for the calculation of the amount, because their effect on the horizontal wind speed is difficult to define.

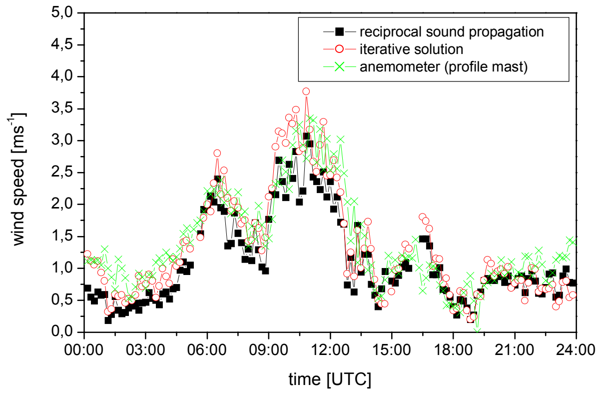

Figure 5. Daily course of the amount of the horizontal wind speed on June the 17th, 2002 (10-min mean), measured with the three methods: reciprocal sound propagation, iterative solution, and profile mast (anemometer).

Figure 5 demonstrates that on this day under low wind conditions only small deviations between both acoustical analysing methods and the anemometer wind speed measurements were observed. The iterative solution provides mostly higher values of the wind speed than the reciprocal method. Because the iterative solution includes the entire array and uses significantly more information this value is particularly suitable for a representative spatially averaged value.

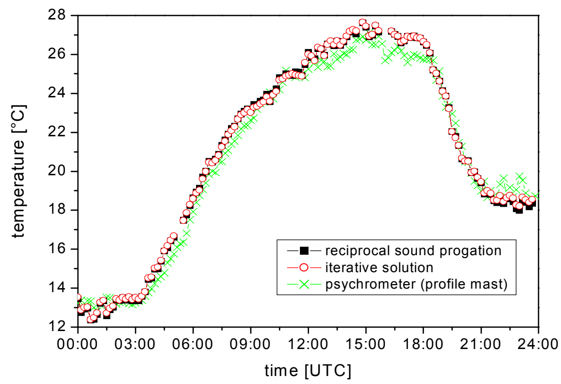

Figure 6. Daily course of the air temperature (at 2 m above ground) on June the 17th, 2002 (10-min mean), estimated with: reciprocal sound propagation, iterative solution, and profile mast (psychrometer).

The different methods for the separation of the wind and temperature influence on the sound speed have only a small effect on the recalculated air temperature (fig. 6). Differences are only visible between the acoustic values and the conventional sensors, which can be traced back to the inhomogeneous temperature field and the influence of the sensor characteristic.

4.2 Setup with bidirectional sound propagation

To demonstrate the method of bidirectional sound propagation a configuration with eight sound sources and twelve receivers is introduced.

For the bidirectional sound propagation the sources and receivers were arranged perpendicular, and with a spatial offset. Using several transducers, an array of several composite rectangles can be constructed (see fig. 7).

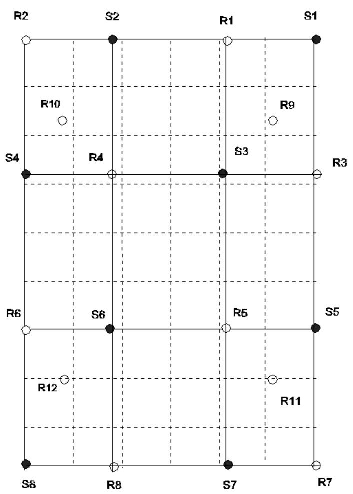

Figure 7. Layout of the tomographic array (300 m × 440 m) with eight speakers (S1…S8) and twelve receivers (R1…R12). The solid lines represent the wind cells and the dotted grids mark a distance of 50 m.

This arrangement allows to divide the area into nine grid cells for the calculation of the wind field, and into 35 grid cells for the air temperature. Two examples of horizontal temperature and wind speed slices are given in figure 8. At this morning, a homogeneous temperature distribution with slight winds from easterly directions was observed.

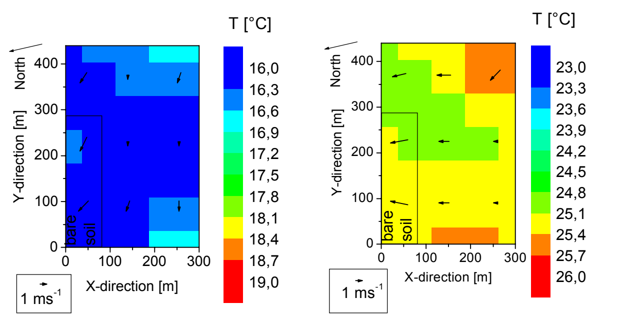

Figure 8. Horizontal slices through the acoustically-determined (10-min-averaged) air temperature and wind field (arrows) at a height of 2 m above the ground on July 06th, 2002 at 05:30 UTC (left) and at 10:50 UTC (right).

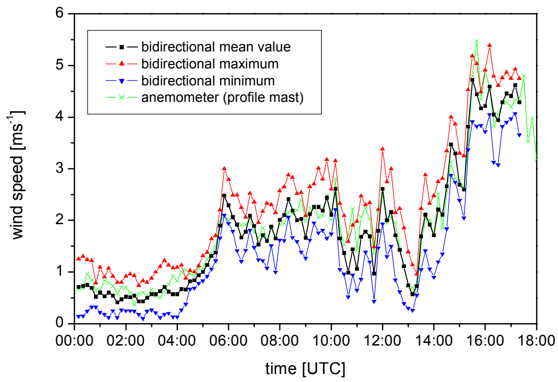

Figure 9. Comparison of the horizontal amount of the wind speed on July the 6th, 2002 (10-min mean) between the bidirectional sound propagation (maximum and minimum values inside nine cells) with the profile mast.

Using the bidirectional sound propagation for this configuration the wind components are available for nine cells with an extension of 100 m to 200 m. Figure 9 demonstrates that even for this rather small array (300 m × 440 m) clear differences of the horizontal wind speed are observed. However, the averaged values of the nine cells agrees with the anemometer at the profile mast very well.

5. Discussion

This investigation pointed out that the value from the kinetic gas theory for the specific heat ratio (1.4) is only valid for a small temperature range. Especially for low or rather high temperatures, the dependence of the specific heat on the temperature has to be considered to correctly estimate temperature data, outgoing from sound speed values.

Several methods for the separation of the different influences on the sound speed (temperature, wind) were introduced and compared with data obtained from a measuring campaign which has been introduced as well. The iterative solution supposes a homogeneous wind field and provides, depending on the number of sound paths, a spatially resolved temperature information. If the reciprocal sound propagation is used, the number of sound paths is cut in half, however, the wind component along each propagation path is quantifiable. As a result, the iterative solution is especially suited to estimate area-averaged values, whereas the reciprocal method guarantees a clear separation of the influence of the wind and temperature effect on the effective sound speed.

To find an optimisation between the spatial resolution and a clear separation the bidirectional sound propagation, with spatially shifted transducers, was introduced.

Acknowledgements

Our special thanks go to Dr. F. Beyrich (DWD) for the data provision and the assistance during the Lindenberg field experiment. We would like to thank F. Weiße and M. Engelhorn for their support in the development and manufacturing of the acoustic measuring system.

The STINHO project was performed as a part of the VERTICO (VERTIcal transports of energy and trace gases at anchor stations under COmplex natural conditions) network which has been funded by the German Federal Ministry of Education and Research (BmBF) in the framework of the AFO-2000 research programme (grant No. 07ATF37).

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