ACOUSTIC TRAVEL TIME TOMOGRAPHY TO DETECT NEAR-SURFACE AREA COVERING WIND AND TEMPERATURE DATA

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ABSTRACT

Meteorological numerical models predict data in an area averaged or volume-averaged grid structure. In contrary to such predictions most of the near-surface meteorological observations are point measurements. Comparisons are only indirectly possible if the point measurements are extrapolated to an area or volume.

One possible way out is provided by acoustic travel time tomography.

Sound speed depends on air temperature, humidity and wind velocity. Observations of acoustic travel times between a transmitter and a receiver include information on these meteorological parameters. Several sound transmitter and receiver, set up in pairs, provide line-integrated information for variably directions covering a natural terrain.

These line-integrated travel times are the starting point for a tomographic inversion algorithm.

The algorithm produces wind and temperature fields variable from time to time and from place to place in a grid structure, which could be compared with the numerically calculated data of, e.g., highly resolved Large-Eddy Simulation models.

The here documented tomographic experiment covers two types of earth surfaces (grass and bare soil) to get information on the non-homogeneous heating of a real landscape.

1. INTRODUCTION

Tomography, for the purpose in this study, is a technique for measuring, analysing and imaging, which generates a cross-section of the investigated medium using the medium’s response to the probing energy of an external source. Starting at an energy source the energy waves propagate through the medium and therefore contain information on the state of the probing object. Hence a spatially representation of properties in the medium follows. The main advantages of tomographic methods over conventional point measurements are a nearly synoptical overview of the quantity being researched and the remote sensing capacity, i.e. tomographic measuring does not influence the medium under investigation. When compared to others, these methods also permit the monitoring of regions that are difficult to observe directly. The comparatively higher amount of information (number of acoustic sources × number of receivers) and its effect as a spatial filter for sub-grid-scale of turbulence elements are additional advantages of tomography (WILSON and THOMSON, 1994, Munk et al., 1995).

If air is treated as an ideal gas under adiabatic conditions, the Laplace equation for the speed of sound can be applied:

$$c_L = \sqrt{\gamma R\, T_{av}} \qquad (1)$$

where c_L is the Laplace speed of sound, γ is the specific heat ratio of dry air, R is the specific gas constant of dry air and T_{av} is the acoustic virtual temperature. The temperature derived from the speed of sound in air is similar to the virtual temperature (defined as the temperature at which dry air has the same density as moist air under the same pressure) including the different specific heats of water and dry air:

$$T_{av} \cong T(1+0.513q) \qquad (2)$$

where q is the specific humidity. In addition to the spatial and temporal changes i.e. in air temperature, the influence from the wind field also affects the sound velocity. This influence leads in the two-dimensional case to the (horizontally) effective speed of sound:

$$\vec{c}_{eff}\left(T_{av},\vec{v}_{hor}\right) = c_L\left(T_{av}\left(t,x,y\right)\right)\cdot\vec{n} + \vec{v}_{hor}\left(t,x,y\right) \qquad (3)$$

where $\vec{n}$ is the unit vector normal to the wave-front and $\vec{v}_{hor}$ is the horizontal wind vector.

As a result the observed speed of sound can be described as depending on air temperature, air humidity and the wind vector as well. The aim of the acoustic travel time tomography is to recalculate the time dependent development of the horizontal field of wind velocity $\vec{v}(t,x,y)$ as well as the air temperature field $T(t,x,y)$ neglecting the effect of horizontal variability of air moisture.

The experimental application of a tomographic horizontally-sliced scheme to the atmospheric surface layer has been verified by SPIESBERGER and FRISTRUP (1990), who describe a method for passive locating the calls of animals, and also by WILSON and THOMSON (1994), who concentrate on the characteristics of the atmosphere. What these studies have in common is that, depending on the inverse technique used (stochastic inverse), only relative deviations from a (known) mean value can be derived. In contrast to these studies, ARNOLD et al. (1999), RAABE et al. (2001) and ZIEMANN et al. (1999a, b) have demonstrated the applicability of acoustic travel-time tomography to detect absolute values of meteorological quantities (temperature and wind vector) with out additional information apart from air humidity. The combination of measurements and reconstruction technique is used e.g. to observe the divergence in the air temperature and wind field in comparison to energy budget observations (RAABE et. al., 2002).

2. MEASUREMENTS

Within the framework of the VERTIKO network project (German Funding – AFO2000) the field experiments STINHO (**ST**ructure of the turbulent transfer above **INHO**mogeneous surfaces) are carried out.

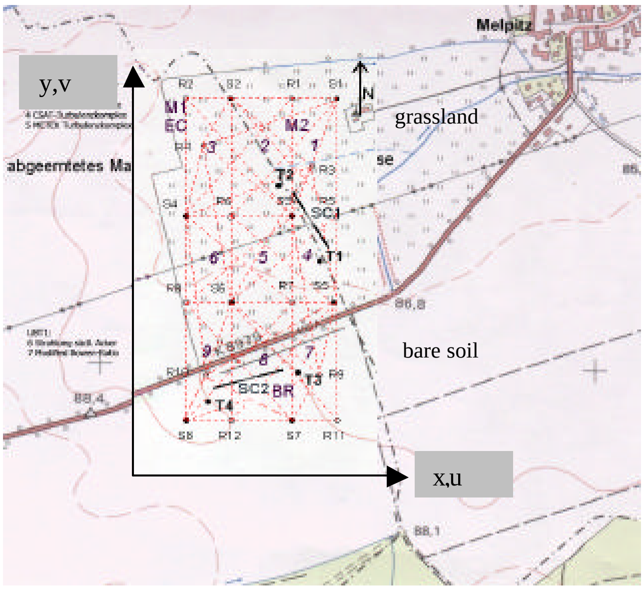
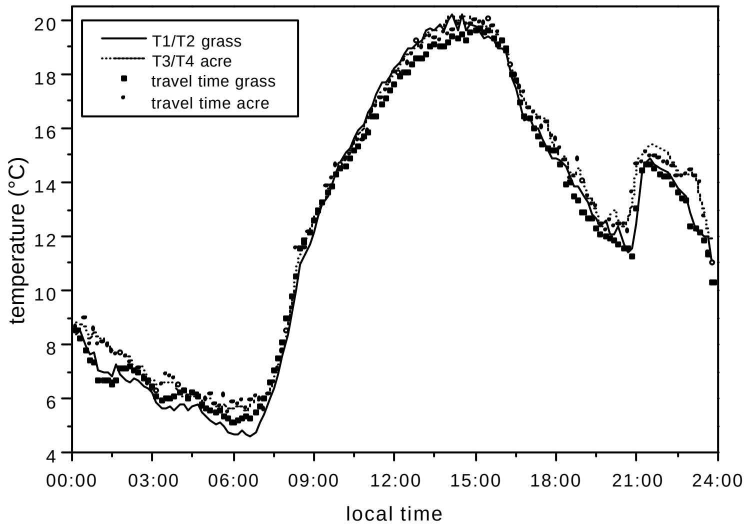


Fig. 1:Layout of the area under investigation (300 x 700 m^2) at the research station Melpitz. The northern part was grassland and southerly of the road was bare soil (acre). The dotted lines represent the acoustic rays between source and receiver of the tomographic array and the numbers (1…9) are the wind cells.
R1… R12: acoustic receiver
S1 … S8: acoustic sources
T1 … T4: air temperatur sensor
M1, M2: 12m profile mast
SC1, SC2: scintillometer
EC: eddy correlation
BR: bowen-ratio

The first experiment STINHO-1 was conducted at the research station of the Institute for Tropospheric Research (IfT) in Melpitz (45 km north east from Leipzig) in autumn 2001. The investigation area with an extension of 300 m x 700 m was arranged over a region with different surface properties: one part was grassland and the other was a recently tilled acre (Fig. 1). Thus due to the different vegetation and surface properties and depending on the radiation conditions, horizontal gradients in the meteorological fields were expected.

For the acoustic tomography twelve sound sources and eight receivers were positioned at the borders or inside the array. The positions of the transmitters and receivers were set in such a way that the covering of the investigation area with sound paths is optimal. Due to the appropriated configuration of the transmitter and receiver and the extension of the array we get 4 X 8 grid cells for the air temperature and 9 cells for the wind speed (Fig. 1 and Fig. 4).
The wind speed was analysed by use of the reciprocal sound propagation inside the nine cells. Fig. 2 shows the comparison between conventional wind speed and air temperature observations.



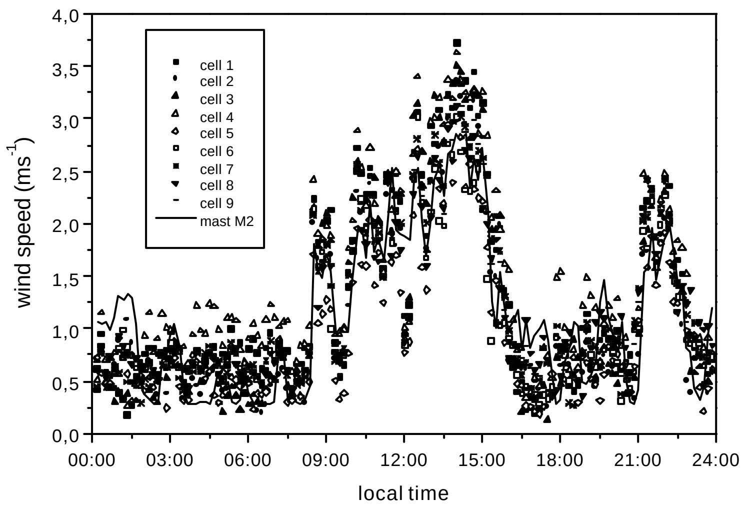


Fig. 2 : Experiment STINHO-1: Comparison of air temperature and wind measurements 06.10.2001. Diurnal course of the
- air temperature registered by acoustic tomography (travel time) and humitter (T1…T4) above variable land use types (grass and acre)
- wind speed inside the nine wind cells and at the profile mast M2

On the analysed day only low wind speeds were observed and the differences inside the array are quite small (about 0.5 to 1.0 ms^{-1}). A high analogy between the travel time determinations and the wind speed measurements at a meteorological mast at position M2 (Fig. 2) can be seen. The comparison of the air temperature measurements at point T1 to T4 with the observations by the acoustic tomography show only slight deviations from time to time.
The detection of the wind vector for 9 grid cells makes it possible to calculate the divergence of the horizontal wind field. To characterise the single wind components the index is identical to the number of the cells of the wind grid (s. Fig. 1):

$$\mathrm{Div}\left(\vec{\mathbf{v}}_{\mathrm{Hor}}\right) = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = \frac{u_4 - u_6}{\Delta x} + \frac{v_2 - v_8}{\Delta y} \qquad (4)$$

and $\Delta x = 100\,\mathrm{m}, \quad \Delta y = 200\,\mathrm{m}$ are used. Evidently there is observed an anti-parallel course of the diurnal variability of the turbulent heat fluxes and of the divergence of the horizontal wind field (Fig. 3). The divergence of the horizontal wind field must be balanced by a transport in the vertical direction which means a vertical wind component w. This wind component can be calculated using the equation of continuity:

$$w = -\int \mathrm{Div}\left(\vec{\mathbf{v}}_{\mathrm{Hor}}\right) dz\ . \qquad (5)$$

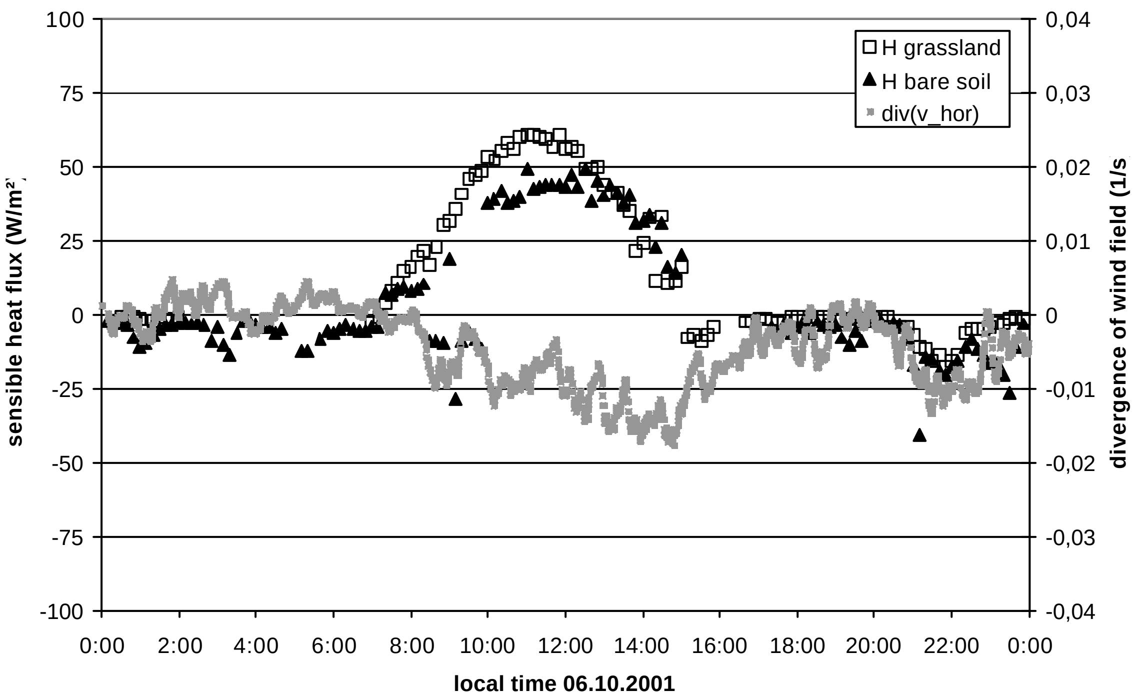


Fig. 3: Diurnal course of the vertical sensible heat fluxes measured with the scintillometer SC1 over grassland and SC2 over bare soil (for positions see Fig. 1) in comparison to the tomographically observed divergence in the horizontal wind field.

Obviously the sensitivity of the acoustic travel time measurements are good enough to show the connections between vertical transport of heat at one side and the horizontal divergence in the velocity field at the other side. The turbulent fluxes of sensible heat are recorded using scintillometer technique (see Thiermann and Grassl, 1992). These fluxes are line-averaged quantities representing a line of a lentgh of 150m (s. Fig. 1).

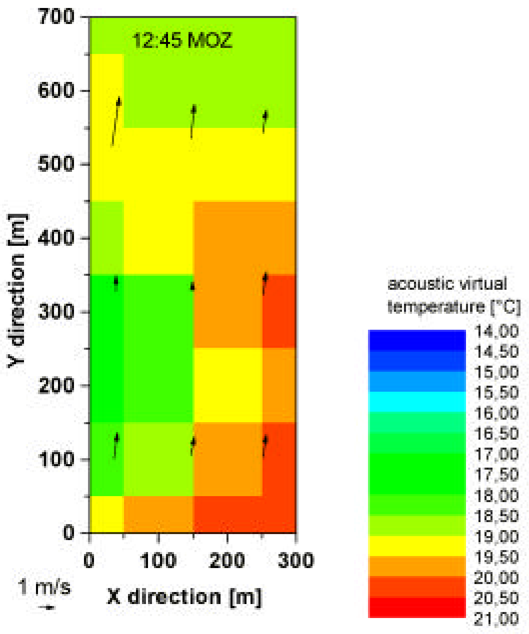


Fig. 4: Tomogram of the acoustic virtual temperature (32 cells) and wind speed (arrows in 9 cells) on the 6 October 2001 at 12:45 MOZ (local time).

The tomographic system, based on acoustic travel time measurements followed by an tomographic reconstruction algorithm (SIRT, see ZIEMANN 2000) produces in the currently realised form every minute one so called air temperature and wind speed tomogramm (s. Fig. 4) showing the horizontal variability of air temperature and wind speed within the area under investigation. These data sets are the starting point for further investigation. Analyses have shown (ARNOLD, 2000) that within the margins of error of 0.3 10^{-3}s for the travel time measurements, and over distances of more than 150 m between transmitter and receiver, an accuracy in air temperature reading of ± 0.5 K and of ± 0.5 ms^{-1} for the wind speed can be realised.

4. OUTLOOK

The acoustic travel-time tomography makes it possible to derive variation in spatially-averaged air temperature and wind data.

The results derived from observations provide information on the horizontal homogeneity of the measuring field with respect to the air temperature over time periods of several hours or even longer. For general results, the degree of non-homogeneity of a measuring field should be analysed tomographically, however, under differing meteorological (e.g., atmospheric stratification) and environmental (e.g., type of vegetation) conditions. It can be seen, that the tomographic system is able to record horizontal divergences in velocity field.

The sensitivity of the tomographic measurements are sufficient to compare the measurements with an numerical highly resolved model of atmospheric motion, e.g. a Large-Eddy Simulation Model (Weinbrecht, Raasch, 2001).

Prospective developments are possible in the field of the experimental arrangement. A major effort will be put into upgrading the existing version to a three-dimensional monitoring system. This could be achieved either by installing microphones at different heights above the ground (mounted on telescope mast) or by including a SODAR algorithm which utilises the backscatter from the atmospheric turbulence (ARNOLD et al., 2001).

Acknowledgements

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