Validation of Acoustic Travel Time Tomography in comparison with conventional in situ measurements

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Introduction

The method of acoustic travel-time-tomography (A-TOM) is characterised by the use of an acoustic signal from an external source (transmitter), which is detected via a receiver. By inverting several single measurements, one can obtain information about the spatial distribution of the parameter which influence the travel time. Their quality is defined by uncertainties during the determination of input parameters (travel-time, distance) as well as by the attainable resolution. In contrast to the wind-velocity ascertained by acoustic travel-time-tomography, the acoustically determined air temperatures differ systematically from conventional in-situ measurements (e.g. Ultra Sonic Anemometer, Pt100- probes). These differences are particularly noteworthy during short-wave radiation and higher wind speeds. Basic causes are systematic differences during the calculation of meteorological data using the travel time of sound and/or the insufficiency of conventional in-situ measurements. The aim is to investigate the reasons of these differences in the air temperature by means of a systematically field experiment.

Acoustic Travel Time Tomography

The acoustic travel-time-tomography uses the dependence of the sound speed on the meteorological conditions [1]. At known distance between transmitter and receiver the sound speed can be calculated by measuring the travel-time of an acoustic signal. Since this time is principally determined by air-temperature and wind-field, both measures can be derived from sound speed. The coupled influence of the temperature and wind field can be separated by use of an experimental setup with reciprocal measuring paths [2]. The Laplace equation of sound speed in air and the used method to compare the temperature measurements are:

$$c_L = \sqrt{\gamma_a(T)\, R_a\, T_{av}} \tag{1}$$

$$T_{av} = T\left(1 + 0.513q\right) \tag{2}$$

where c_L represents the Laplace's sound speed. $\gamma_a(T)=c_p/c_v$ stands for the specific heat ratio (c_p and c_v are the specific heats at constant pressure and constant volume) in which c_p depends on temperature. R_a stands for the special gas constant for dry air, T_{av} is the acoustic virtual temperature; T is the air temperature und q the specific humidity of air. However the temperature dependence of $c_p(T)$ was normally ignored because it was widely accepted that the influence on the speed of sound is relatively insignificant. This simplification leads at a certain temperature range to significant deviations in the calculated speed of sound [3].

Field Experiment

During a four-week period of comparative measurements at an area of 140 x 160 m^2 the following aspects were explored: First the impact of different wind-directions and wind-velocities on the measured travel-times and the resulting air temperature. Second the influence of meteorological conditions on the observed temperatures between the measuring systems, particularly during strong short-wave radiation. It was also attempted to solve the question whether the use of virtual acoustic sources in the determination of travel-times is possible.

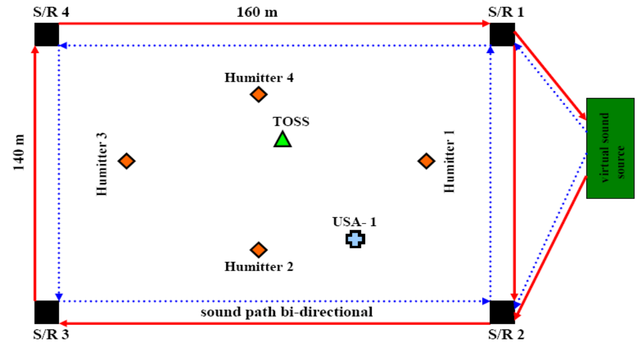

Figure 1: Principle layout of the field experiment. The figure shows the position of the different sensors, the position of the virtual sound source as well as the bi-directional sound paths.

The following equipment was used in the field experiment: the ground-based remote sensing method of acoustic travel-time-tomography consisting of 4 transmitters (eight speakers) and 4 receivers; an ultra sonic anemometer (USA-1) by Metek; 4 sensors for temperature and humidity (Humitter 50 U/Y) by Vaisala as well as an automatic climate station (TOSS).

Operating Mode

The acoustic measuring system is a self-made apparatus developed at the LIM [2]. It was designed for the stand-alone use in open field independent on the power supply system. The system consists of a flexible number of transmitters (speakers) and receivers (microphones). A lap-top is the central control module, which executes the data-recording and the management of the complete system. All devices are connected via a loop wiring system and can thus be programmed and configured by the central control module. Frequency-synthesizers produce the signals (figure 2.). Here the emitted signal was a double peak with a frequency of 1000 Hz. The data-transfer is realised via a loop wiring system, which also transmits all measured parameter from the control module to the frequency-synthesizer and the transmitters. The receivers send the collected data back to the central control module, which will then be processed and saved.

Compression-speakers from the Doppler-SODAR-apparatus DS 100 operate as transmitters.

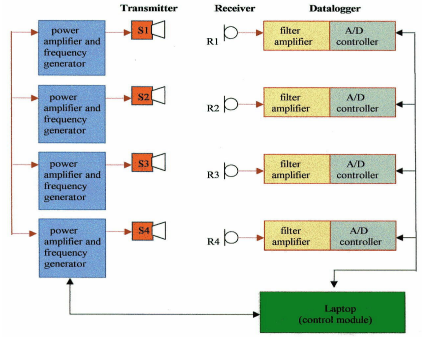

Figure 2: Block diagram of the measuring system; operating mode.

The receivers are 1 inch condenser-microphones (model MK/MV). One can choose between two operating modes – manual and automatic measuring sequence. Via frequency-synthesizers the signal is transmitted to the speakers and then reflected. The received signal was amplified and after that filtered by a bandpass. The complete measured signals were transmitted via the data-line and finally saved at the central control module. The allocation of the signals of each sound source is realised via the different travel-times of the acoustic signals, which requires high accuracy in the determination of the positions of transmitters and receivers [3].

Results

The following introduces a few results from the field experiment. The figures 3 and 4 represent that the use of virtual acoustic sources is possible. The virtual acoustic source was a shed closed to the measuring field. The reflected signal can be identified by the travel-times.

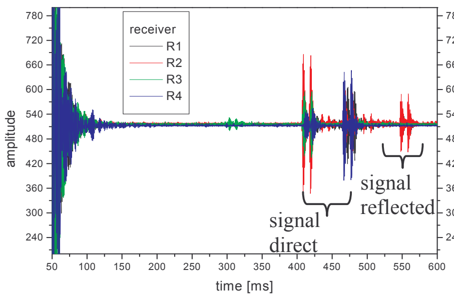

Figure 3: Sample of all received signals as a result of the experimental setup. The signal is a double peak with a duration of 4 milliseconds per peak.

The first double peaks between 400 ms and 425 ms (milliseconds) are corresponds to the sound path of 140 m. At the point of approximately 455 ms the signals are corresponds to the sound path of 160 m. The figure 4 shows the comparison of different temperature measures as well as the temperature calculated by the reflected signal. Obvious is the data leakage of the reflected signal (circle symbol) from 15:00 to 18:00 p.m. The overestimation of the automatic climate station TOSS amounts up to 2.5 K. From this follows that the TOSS station expects to get an error of radiation. This error can be expressed by the relative bias of the specific humidity (equation 2; fig. 5).

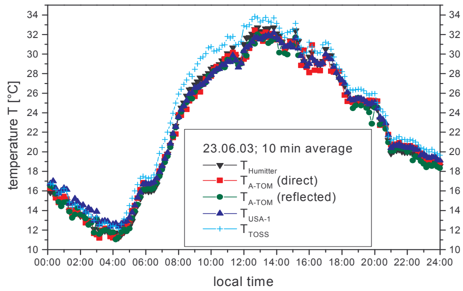

Figure 4: Diurnal course of air temperature measured with the different methods: A-TOM, USA-1, Humitter, TOSS.

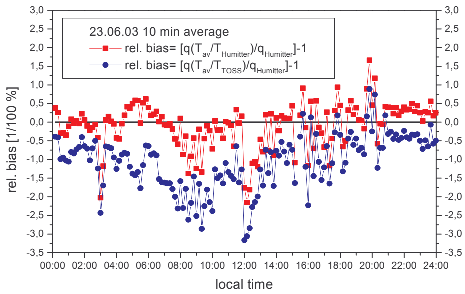

Figure 5: Relative bias of the humitter (red curve) and TOSS measures (blue curve) calculated from the specific humidity (eq. 2).

In figure 5 the negative values of specific humidity are positive radiation error (during day time) and positive values are negative radiation error (during night time). No error of radiation shows the black curve. At the influence of radiation the TOSS has the maximum deviation (approx. 325%).

Summary

The values of sound velocities can be converted into spatial averages of temperature and wind speeds. The values of temperature have an accuracy of 0.3 K. Thus the acoustic measuring system is comparable to standard sensors. The standard sensors are influenced by radiation especially the automatic climate station TOSS. The experiment has shown that the use of virtual acoustic sources is possible.

References

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