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Final Progress Report

Array for acoustic tomography of the atmosphere at the Boulder Atmospheric Observatory

PI: Dr. Alfred J. Bedard, Co-PI: Dr. Vladimir E. Ostashev

1 Background

Acoustic tomography of the atmospheric surface layer (ASL) enables remote sensing and monitoring of the temperature and wind velocity fields. It is based on the measurements of the travel times of sound propagation between acoustic sources (usually, speakers) and microphones, which constitute the tomography array (Fig. 1). The temperature and wind velocity fields inside the tomographic region are reconstructed using inverse algorithms. Acoustic tomography is the only remote sensing technique for simultaneous measurements of the temperature and wind velocity fields with subsequent reconstruction of the heat and momentum fluxes. None of the existing meteorological instrumentation enables such remote sensing. The accuracy of tomographic reconstruction of temperature and velocity can be as good as 0.1 K and 0.1 m/s, respectively, the temporal resolution can be 0.1 s, and the spatial resolution can be 1 m x 1 m. These resolutions might be increased further by development of the inverse algorithms and more accurate measurements of the travel times.

Using several grants from the U.S. Army Research Office, we developed and extended theoretical foundations of acoustic tomography of the atmosphere, such as development of new inverse algorithms and performing numerical simulations of tomography arrays. Furthermore, an array for acoustic tomography of the ASL was built in 2008 at the Boulder Atmospheric Observatory (BAO). The BAO tomography array consisted of eight towers located along the perimeter of a square with the side length 80 m x 80 m (Fig. 1). Speakers and microphones were installed on the towers at the height of 8 m. A tower in the middle of the array carried a sonic anemometer and temperature probe.

Figure 2 depicts one of the towers of the BAO tomography array. A speaker and a microphone are installed at 8 m above the ground. Instrumentation box carries a microphone preamplifier and power outlet. A building behind the tower is the BAO Visitor Center (VC), where the acoustic tomography operation center was located. Cables in underground conduits connected instrumentation on this tower and other towers with the acoustic tomography operation center.

Figure 3 shows the acoustic tomography operation center. The central command and data

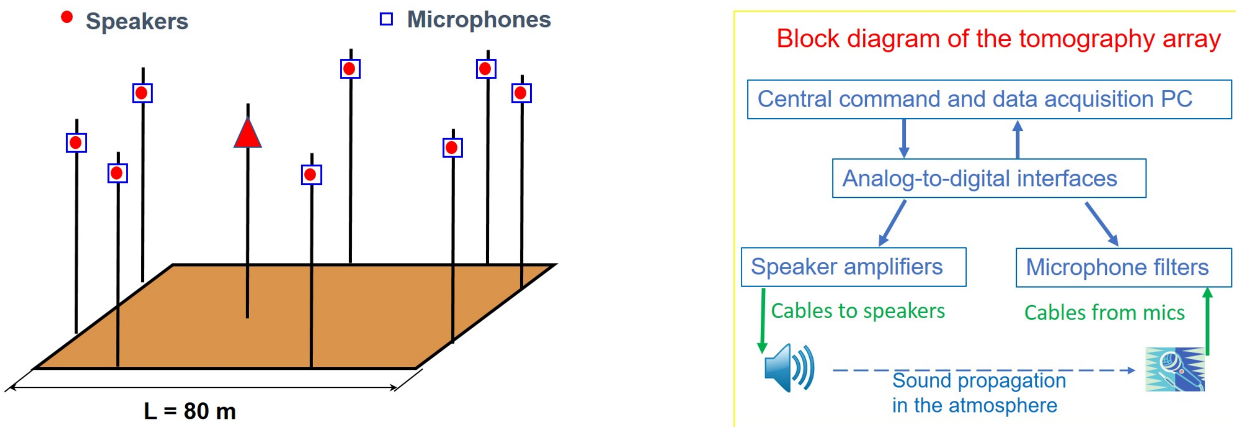

Figure 1: Schematics of the BAO acoustic tomography array. Shown are eight towers located along the perimeter of a square with the side length 80 m. Each tower carries a speaker and microphone installed 8 m above the ground. A tower in the middle of the array carries a sonic anemometer and temperature probe. (Right) Block diagram of the tomography array.

acquisition computer is on the desk. The rack on the left carries AD interfaces, microphone filters, and speaker amplifiers. Software was developed to run acoustic tomography experiments from the central PC and to store all data on the PC. Acoustic signals were transmitted every 0.5 s. Microphones recorded transmitted signals. Wind velocity and temperature were simultaneously recorded. These data were used to determine the travel times of sound propagation between the speakers and microphones, from the which the temperature and wind velocity fields inside the tomographic region were reconstructed. Figure 4 depicts an example of the tomographic reconstruction. The BAO tomography array was the only facility for acoustic tomography in the U.S.

Since 2005, the results obtained in our studies of acoustic tomography of the atmosphere have been summarized in 7 peer-reviewed papers [1-7], 16 papers and abstracts in proceedings of conferences [8-23], and a Ph.D. dissertation [24]. An overview of the current status of acoustic tomography of the ASL is presented in Sec. 3.7 of a recently published book [25].

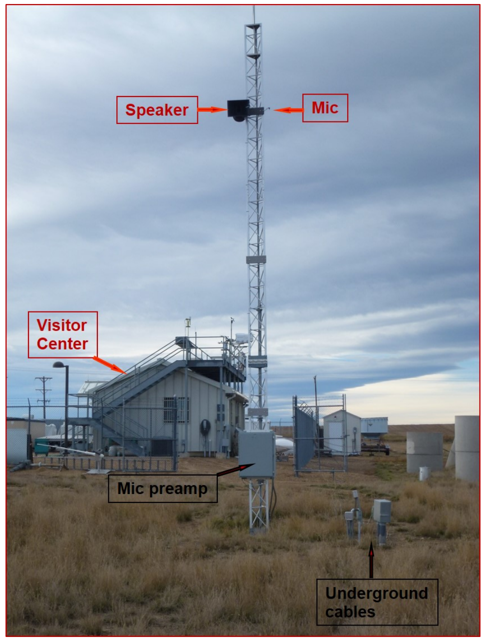

Figure 2: One of the towers of the BAO acoustic tomography array. A building behind the tower is the BAO Visitor Center, where the acoustic tomography operation center was located.

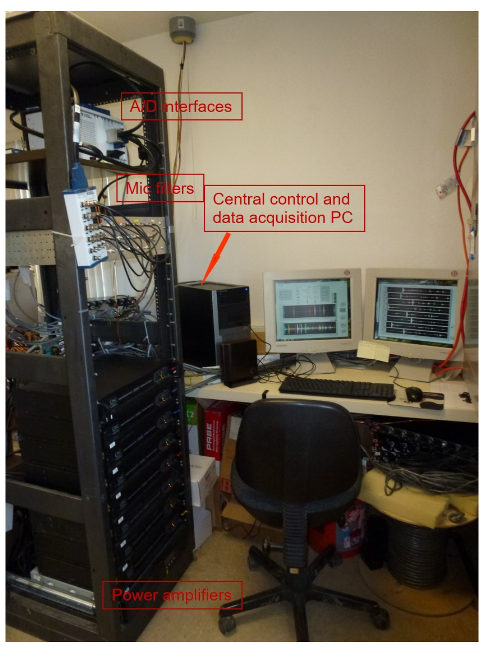

Figure 3: Acoustic tomography operation center inside the BAO Visitor Center.

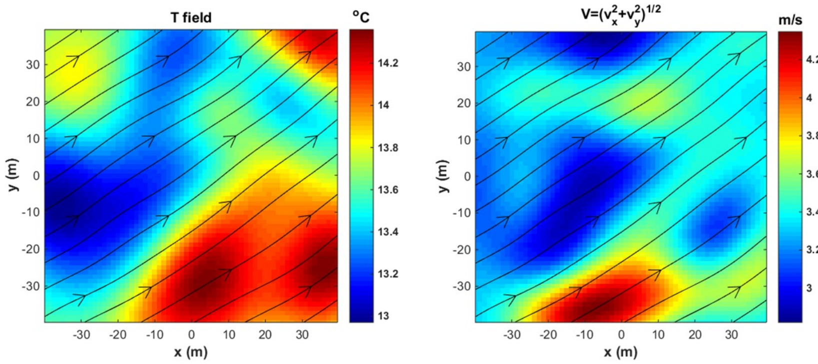

Figure 4: (Left) temperature and (right) wind speed obtained with the BAO acoustic tomography array on 9 November, 2014. Arrows indicate the direction of the wind velocity. The expected errors in tomographic reconstructions are 0.1 K and 0.1 m/s.

2 Project Scope

The goals of this DURIP grant were to acquire instrumentation for the BAO acoustic tomography array and upgrade capabilities of the array. Unfortunately, after several decades of operation, the BAO was suddenly decommissioned in 2016. We had no forewarning of the de-commissioning of the BAO.

Therefore, we had to change the initial goals of the project. The new goals of the projects became as follows:

(i) Dismantle the BAO acoustic tomography array and store all its components.

(ii) Find a new site for the acoustic tomography array.

(iii) Relocate all equipment of the acoustic tomography array to a new site.

(iv) Rebuild the acoustic tomography array at a new site.

3 Work completed

3.1 Dismantling the BAO acoustic tomography array

Dismantling the BAO acoustic tomography array and storing its components was a time consuming work:
(i) Many cables connecting different components of the array were disconnected.
(ii) Speakers, microphones, instrumentation boxes, a sonic anemometer, and a temperature probe were taken off from the towers.
(iii) 10 towers of the tomography array (9 shown in Fig. 1 and a spare tower) were taken off from their concrete foundations.
(iv) One cubic yard concrete foundations for the towers were dug out from the ground and recycled.
(v) The dismantled acoustic tomography array consisted of about 100 pieces such as towers, speakers, speaker amplifiers, and boxes with smaller equipment. All these components of the array were safely stored.

DURIP funds had not been utilized to dismantle the BAO acoustic tomography array and store its components. We used internal funds and labor for this purpose.

3.2 Finding a new site for the acoustic tomography array

Finding a new site for the acoustic tomography array, which would be similar to the BAO, was very challenging. This new site had to have several important characteristics such as:
(i) A site should belong to a government laboratory or university department.
(ii) The host of a site should be interested in rebuilding the acoustic tomography array.
(iii) A site should have an infrastructure to support the acoustic tomography array and a flat terrain.

Initially, we identified two Boulder Colorado sites. One was south of Boulder at the Marshall Field Site operated by the National Center for Atmospheric Research (NCAR). The other was north of Boulder at the Table Mountain operated by the the National Institute for Standards and Technology (NIST), Department of Commerce. The terrain was ideal at both of these locations. Both sites have long (over 50 years), stable histories of scientific use. However, despite of extensive negotiations and sites' explorations, we were unable to reach agreements with the corresponding agencies for rebuilding the acoustic tomography array at these sites.

Then, we found an organization, the National Renewable Energy Laboratory (NREL/DOE), located near Boulder, CO, which was interested in rebuilding the tomography array on its experimental site, the National Wind Turbine Center (NWTC). The NWTC has a long term interest in acoustic tomography of the wind turbine wakes. This is a very large and well maintained experimental site with many highly qualified engineers and technicians.

After extensive negations between the University of Colorado at Boulder and NREL, a Purchase Order for rebuilding the acoustic tomography array at the NWTC was finalized.

DURIP funds had not been utilized to find a new site for the acoustic tomography array. We used our own time for this purpose.

3.3 Relocating the acoustic tomography equipment to the NWTC

All acoustic tomography equipment (about 100 pieces) was relocated to the NWTC. Some instrumentation such speaker amplifiers, PC, AD interfaces, and microphone filters were stored in a climate control environment.

A flatbed truck was rented to relocate 10 towers (each 30 feet long) of the tomography array. Forklifts were used to download and upload the towers from the truck.

DURIP funds had not been used to relocate the components of the tomography array to the NWTC. We used internal funds and labor for this purpose.

3.4 Rebuilding the acoustic tomography array at the NWTC

Rebuilding of the acoustic tomography array at the NWTC has began successfully.

A Co-PI, Dr. Vladimir Ostashev, had to have extensive training and orientation to get

Figure 5: Portable base of a tower of the NWTC acoustic tomography array.

access to the NWTC. The environmental and safety regulations had to be complied with before the rebuilding of the acoustic tomography array at the NWTC began.

A site for the towers of the tomography array was carefully chosen. It was decided that the NWTC acoustic tomography array will have the same layout as the BAO tomography array (Fig. 1), except that a sonic anemometer and temperature probe will be located on one of the towers along the perimeter of the array rather than on a tower in the middle of the array.

It was also decided to anchor the towers to portable bases (Fig. 5) rather than to massive concrete blocks in the ground as was the case for the BAO tomography array. In addition to reducing costs, this new design makes the tomography array relocatable, which is advantages for two purposes. First, the tomographic reconstruction of the temperature and wind velocity fields is very sensitive to the towers' location and can be improved by small adjustment of their coordinates. Second, the NWTC acoustic tomography if desired, can be relocated to another site for a new experimental campaign. To be able to use portable bases, extensive studies have been done to ensure stability of the towers during high wind events.

Figure 6: Eight towers of the NWTC acoustic tomography array and a modular building, where the acoustic tomography operation center is located.

Then, eight towers of the NWTC acoustic tomography array were erected and anchored to portable bases, see Fig. 6. An accurate surveying was utilized to ensure that the coordinates of these towers are the same as those of the BAO tomography array (Fig. 1).

The acoustic tomography operation has been assembled inside a small modular building, which is seen in Fig. 6. This building has a climate control and is also used to store spare components of the NWTC tomography array. Figure 7 is a picture of the acoustic tomography operation center located inside this modular building. A central command and data acquisition PC is under the desk. The rack carries AD interfaces, speaker amplifiers, and other equipment.

Figure 7: Acoustic tomography operation center of the NWTC acoustic tomography array in a climate control modular building.

4 Expenditures

(i) QSC PLX3602 dual channel speaker amplifier. Quantity 2. Total price $2,118.00.

(ii) Purchase Order to NWTC/NREL to rebuild the acoustic tomography array, $59,973.

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