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V. E. Ostashev, G. H. Goedecke.

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New Mexico State University
1620 Standley Drive
Academic Res. Bldg A, Rm 100
Las Cruces, NM 88003 -

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Report Title

Acoustic Tomography of the Atmosphere

ABSTRACT

In this project, theoretical foundations for construction and operation of the state-of-the-art array for acoustic tomography of the atmosphere were developed. (The array was built at the Boulder Atmospheric Observatory under the ARO sponsorship, project DAAD19-03-1-0341.) First, the travel times of sound propagation between different pairs of sources and receivers of the array were expressed in terms of the temperature and wind velocity fields within the tomographic volume. Then, a solution of the inverse problem - the reconstruction of the temperature and velocity fields from the measured travel times – was studied in detail. A new inverse algorithm for solution of the inverse problem in acoustic tomography of the atmosphere, time-dependent stochastic inversion (TDSI), was developed. Numerical simulations of acoustic tomography of the atmosphere showed that TDSI gives much better reconstruction of temperature and velocity fields than other inverse algorithms known in the literature. Then, TDSI was used in 2D outdoor and indoor tomography experiments carried out by scientists from the University of Leipzig, Germany. As a result, the temperature and velocity fields within tomographic areas were reconstructed and monitored in time. The developed TDSI algorithm will be used in operation of the state-of-the-art array for acoustic tomography of the atmosphere.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

[1] S. N. Vecherin, V. E. Ostashev, G. H. Goedecke, D. K. Wilson, and A. G. Voronovich, "Time-dependent stochastic inversion in acoustic travel-time tomography of the atmosphere," J. Acoust. Soc. Am. 119, No 5, 2579-2588 (2006).
[2] G. H. Goedecke, D. K. Wilson, and V. E. Ostashev, "Quasi-wavelet models of turbulent temperature fluctuations," Boundary-Layer Meteorology 120, 1-23 (2006).

Number of Papers published in peer-reviewed journals: 2.00

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Number of Papers published in non peer-reviewed journals: 0.00

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Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

[3] V. E. Ostashev, S. N. Vecherin, D. K. Wilson, and S. L. Collier, "Correlation functions of temperature and velocity fluctuations in a turbulent atmosphere," J. Acoust. Soc. Am. 119, No 5, Pt. 2, 3264 (2006).
[4] V. E. Ostashev, S. N. Vecherin, D. K. Wilson, A. Ziemann, M. Barth, and K. Arnold, "Acoustic travel-time tomography of temperature and wind velocity fields in the atmosphere," J. Acoust. Soc. Am. 120, No 5, Pt. 2, 3336 (2006).
[5] S. N. Vecherin, V. E. Ostashev, D. K. Wilson, A. Ziemann, M. Barth, and K. Arnold, "Reconstruction of turbulent fields in acoustic tomography experiments," Proc. 12th Intern. Symp. on Long Range Sound Propagation, New Orleans, 364-384 (2006).
[6] G. H. Goedecke, V. E. Ostashev, and D. K. Wilson, "Quasi-wavelet models of turbulent temperature and shear-driven velocity fluctuations," Proc. 11th Intern. Symp. on Long Range Sound Propagation, Fairlee, VT, June 1-3, 225-239 (2004).
[7] S. N. Vecherin, V. E. Ostashev, D. K. Wilson, A. G. Voronovich, G. H. Goedecke, S. L. Collier, J. M. Noble, and D. Ligon, "Forward and inverse problems of acoustic tomography of the atmosphere," Proc. 11th Intern. Symp. on Long Range Sound Propagation, Fairlee, VT, June 1-3, 293-312 (2004).
[8] S. L. Collier, D. A. Ligon, J. M. Noble, E. Patton, P. Sullivan, and V. E. Ostashev, "Acoustic tomographic array simulation," Proc. 11th Intern. Symp. on Long Range Sound Propagation, Fairlee, VT, June 1-3, 274-292 (2004).
[9] V. E. Ostashev, S. N. Vecherin, G. H. Goedecke, D. K. Wilson, A. G. Voronovich, and E. G. Patton, "Numerical simulation of acoustic tomography of the atmosphere," J. Acoust. Soc. Am. 117, No 4, Pt. 2, 2532 (2005).
[10] D. K. Wilson, V. E. Ostashev, S. N. Vecherin, A. G. Voronovich, S. L. Collier, and J. M. Noble, "Assessment of acoustic travel-time tomography of the atmospheric surface layer," Proceedings of AMS Symposium on Boundary Layers and Turbulence, Portland, ME (2004).

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(d) Manuscripts

[11] S. N. Vecherin, V. E. Ostashev, A. Ziemann, D. K. Wilson, K. Arnold, and M. Barth, "Tomographic reconstruction of atmospheric turbulence with the use of time-dependent stochastic inversion," J. Acoust. Soc. Am. (submitted, 2006).

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Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Sergey Vecherin	0.50
FTE Equivalent:	**0.50**
Total Number:	**1**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Vladimir Ostashev	0.35	No
George Goedecke	0.04	No
FTE Equivalent:	**0.39**	
Total Number:	**2**	

Names of Under Graduate students supported

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Total Number:	

Student Metrics

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The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME	
S. N. Vecherin	
Total Number:	1

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Final Progress Report

1. Statement of the problem studied

Knowledge about temperature T and wind velocity fields $\mathbf{v}$ in the atmospheric boundary layer is important in several fields: development of 3D models of temperature and velocity fluctuations, experimental verification of Large Eddy Simulation (LES) and Direct Numerical Simulation, visualization of different dynamic processes in the atmosphere, studies of the effects of atmospheric turbulence on acoustic and electromagnetic wave propagation, etc. Currently, the temperature and/or velocity fields at the height of several meters above the ground are measured by two techniques: in situ measurements and by using volume-imaging lidars. These fields can also be measured by using acoustic tomography of the atmosphere which can have certain advantages in comparison with both techniques. Currently there is only one 2D array for acoustic tomography of the atmosphere, operated by the Institute for Meteorology, the University of Leipzig, Germany.

This project has been devoted to theoretical studies of acoustic tomography of the atmosphere and was closely related to the ARO Project DAAD19-03-1-0341 and the DURIP project DAAD19-02-1-0123. Towards accomplishment of the latter two projects, the 3D state-of-the-art array for acoustic tomography of the atmosphere has been build at the Boulder Atmospheric Observatory (BAO) near Boulder, CO. The array has three source and five receiver towers located on the perimeter of a square with the side length of 80 m (see Fig. 1). Sources and receivers (microphones) are located on the towers at three different levels ranging from 10 to 30 feet. One of the source towers is shown in Fig. 2. The array will be used to measure the travel times t_i of sound propagation between different pairs of sources and receives, where the index i indicates the i-th sound propagation path.

The main goals of the current theoretical project were to provide theoretical foundations for construction and operation of the state-of-the-art array for acoustic tomography of the atmosphere. In particular, accurate and robust algorithms for solution of the inverse problem in acoustic tomography of the atmosphere - reconstruction of the temperature T and wind velocity $\mathbf{v}$ fields within the tomographic volume given the measured travel times t_i and positions of sources and receivers - had to be developed. Furthermore, an optimal layout of the array had to be suggested.

2. Summary of the most important results

Towards accomplishment of this project, solution of the forward problem in acoustic tomography of the atmosphere was developed: The travel times t_i of sound propagation between different pairs of sources and receivers shown in Fig. 1 were expressed in terms of temperature T and velocity $\mathbf{v}$ fields within the tomographic volume. Then, known approaches for solution of the inverse problem were considered. It was shown that none of these known approaches gives satisfactory reconstruction of temperature and velocity fields in acoustic tomography of the atmosphere. The reason for this is that acoustic tomography of the atmosphere is a highly underdetermined inverse problem: The values of T and $\mathbf{v}$ fields need to be reconstructed at a large number of spatial points given only a limited number of sources and receivers (i.e. the travel times t_i).

To overcome this problem, a new algorithm for reconstruction of T and $\mathbf{v}$ fields in acoustic tomography of the atmosphere, a time-dependent stochastic inversion (TDSI), was developed. The main idea of the TDSI is to increase the number of data (the travel times t_i) without increasing the number of sources and receivers. This is achieved by repeated measurements of t_i (say, every 10 s) and then reconstruction of T and $\mathbf{v}$ fields using several sets of the travel times t_i. Numerical simulations of acoustic tomography of the atmosphere showed that the TDSI gives a better reconstruction of T and $\mathbf{v}$ fields than the inverse algorithms known in the literature: the classical cell approach, Monte-Carlo approach, basis function approach, and stochastic inversion. The TDSI was applied to the recon-

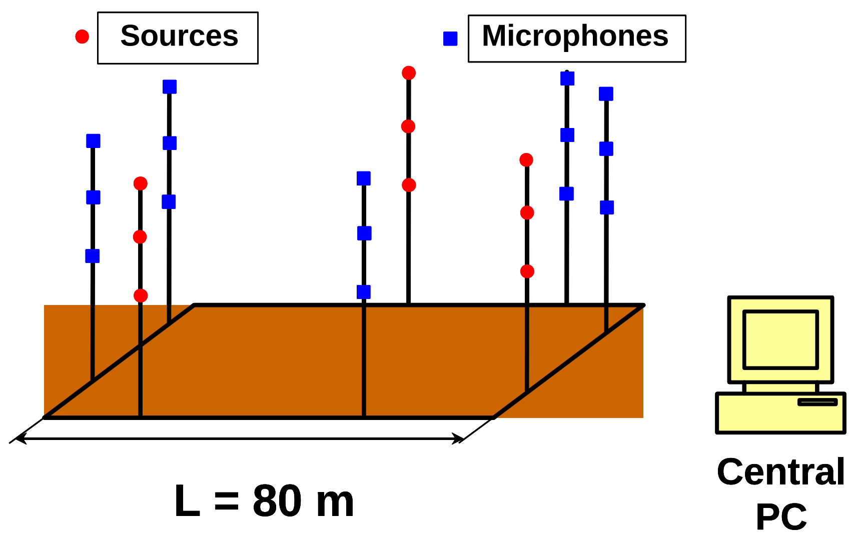

Figure 1: A scheme of the 3D array for acoustic tomography fo the atmosphere.

Figure 2: A source tower of the acoustic tomography array.

struction of temperature and velocity fields in outdoor and indoor acoustic tomography experiments carried out by scientists from the University of Leipzig.

Furthermore, we did numerical simulation of the state-of-the-art array for acoustic tomography of the atmosphere. This allowed us to obtain an optimal layout of the array shown in Fig. 1. Finally, note that solutions of the forward and inverse problems in acoustic tomography of the atmosphere were obtained for both 2D and 3D geometries.

Specific tasks of the project and their accomplishment are as follows:

Task 1. Forward problem in acoustic tomography.
The forward problem in acoustic tomography of the atmosphere was solved. The travel times t_i of sound propagation between different pairs of sources and receivers were expressed in terms of the temperature T and wind velocity $\mathbf{v}$ fields within the tomographic volume. Then, the temperature and wind velocity fields were expressed as the following sums: $T = \overline{T} + \tilde{T}$ and $\mathbf{v} = \overline{\mathbf{v}} + \tilde{\mathbf{v}}$. Here, $\overline{T}$ and $\overline{\mathbf{v}}$ are the mean values of the temperature and wind velocity, and $\tilde{T}$ and $\tilde{\mathbf{v}}$ are their fluctuating parts. It was shown that the forward problem can be linearized with respect to the fluctuations in temperature and wind velocity.

A numerical code for calculating the travel times t_i, given the temperature T and velocity $\mathbf{v}$ fields, was developed. In this code, the temperature and velocity fields within a tomographic volume or area were modeled using quasi-wavelets or LES. The code was later used in numerical simulations of acoustic tomography of the atmosphere.

Task 2. Reconstruction of the mean fields within tomographic volume.
In solution of the inverse problem of acoustic tomography of the atmosphere, it is worthwhile to separate the reconstruction of the mean values of temperature and velocity, $\overline{T}$ and $\overline{\mathbf{v}}$, from the reconstruction of their fluctuating parts, $\tilde{T}$ and $\tilde{\mathbf{v}}$. The reconstruction of $\overline{T}$ and $\overline{\mathbf{v}}$ was done by the following approach. First, $\tilde{T}$ and $\tilde{\mathbf{v}}$ were set to zero in the forward problem. Then assuming that the travel times t_i are known, the resulting equations were solved for $\overline{T}$ and $\overline{\mathbf{v}}$ using the least square solution. Numerical simulations of this approach showed a good reconstruction of the mean temperature and velocity fields for both 2D and 3D tomography arrays.

As an example of such numerical simulations, consider a 2D array for acoustic tomography of the atmosphere shown in Fig. 3. (Note that the array consists of sources and receivers located at the upper level of the 3D array shown in Fig. 1.) The figure also shows the x-component of the wind velocity, v_x which was obtained using a snapshot of LES. The mean value of v_x shown in Fig. 3 is 3.09 m/s. Using solution of the forward problem, the travel times t_i of sound propagation between sources and receivers in Fig. 3 were calculated. Then, the mean value of $\overline{v}_x$ was obtained using solution of the inverse problem described above. The reconstructed value of $\overline{v}_x$ was 3.11 /ms, i.e., it was very close to the actual value of $\overline{v}_x$. The LES and reconstructed values of $\overline{v}_x$ are given in Table 1. The Table also shows the LES and reconstructed values of the y-component of the mean wind velocity, $\overline{v}_y$ and the mean temperature $\overline{T}$ obtained for the same LES snapshot. Table 1 clearly shows that the LES and reconstructed values of the mean temperature and wind velocity fields are very close. The described approach for reconstruction of the mean fields works well even for relatively large errors in measurements of t_i.

Mean fields	$\overline{v}_x$ (m/s)	$\overline{v}_y$ (m/s)	$\overline{T}$ (K)
LES	3.09	1.73	301.73
Reconstructed	3.11	1.85	301.85

Table 1. LES and reconstructed values of the mean temperature and wind velocity.

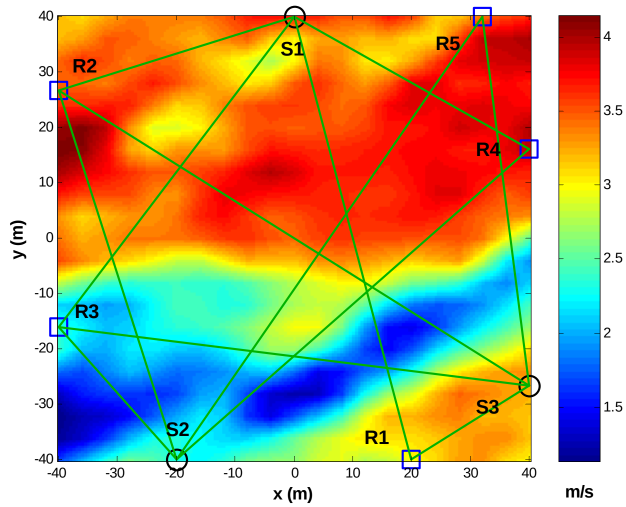

Figure 3: A scheme of 2D array for acoustic tomography. S1- S3 are sources, R1-R5 are receivers. Solid lines correspond to sound propagation paths. Colors indicate the value of the x-component of the velocity field, v_x.

Task 3. Inverses algorithms for reconstruction of fluctuations.

After Task 2 was accomplished, the reconstruction of temperature and wind velocity fields was reduced to the reconstruction of their fluctuating parts, $\tilde{T}$ and $\tilde{\mathbf{v}}$. To do the latter reconstruction, we tried to use several inverse algorithms known in the literature: the classical cell approach, Monte-Carlo approach, basis function approach, and stochastic approach. In the classical cell approach, the tomographic area was divided into cells where the values of $\tilde{T}$ and $\tilde{\mathbf{v}}$ were assumed constant. Then, the singular value decomposition approach was used to solve the inverse problem. The results obtained showed that the $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields can be reconstructed with a good accuracy if the inverse problem is overdetermined and are reconstructed with large errors if the inverse problem is underdetermined. For the 2D array shown in Fig. 3, the inverse problem is overdetermined if the tomographic area is split into 4 large cells with the size 40×40 m^2 and is underdetermined if the tomographic area is split into 9 cells with the size 26.7×26.7 m^2. Such large tomographic cells do not allow reconstruction of the $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields with any details. Thus, the classical cell approach is not appropriate for solution of the inverse problem in acoustic tomography of the atmosphere. Similarly, it was shown that the inverse Monte-Carlo approach is not adequate for this problem.

In the basis function approach, the $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields are modeled as sums of given functions (e.g. cosine and sine functions) with coefficients to be determined. The inverse problem is to find these unknown coefficients. It was shown that, in acoustic tomography of the atmosphere, the basis function approach combined with the hypothesis of frozen turbulence can give much better reconstruction of the $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields than the cell and Monte-Carlo approaches do. However in the basis function approach, the reconstruction of the $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields is very sensitive to the errors in measurements of the travel times t_i. Therefore, it was worthwhile to consider a stochastic inversion , which is less sensitive to these errors.

Task 4. Stochastic inversion.

In stochastic inversion, the $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields are assumed to be random functions with given spatial correlation functions of temperature and wind velocity fluctuations, $B_T(\mathbf{R})$ and $B_{ij}(\mathbf{R})$. Here $\mathbf{R} = (x, y, z)$ are spatial coordinates and $i, j = 1, 2, 3$. Then, the $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields are reconstructed using these correlation functions and the values of t_i.

In 2D numerical simulations of acoustic tomography of the atmosphere, different forms of B_T and B_{ij} were used to reconstruct the $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields: the exponential, Gaussian, von Kármán, and a new correlation function having dependence on the distance R between two points of observation given by $\exp\left(-R^{2/3}/L_0^{2/3}\right)$. Here, L_0 is the outer length-scale of turbulence. The numerical simulations showed that the reconstructed $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields are very similar for these correlation functions if their parameters are chosen properly. Therefore, B_T and B_{ij} were chosen as Gaussian correlation functions. This allowed to do some calculations needed in the stochastic inversion analytically.

The $\tilde{v}_x$ field reconstructed with the use of the stochastic inversion is shown in Fig. 4(b). Figure 4(a) shows the original $\tilde{v}_x$ field obtained from the same LES snapshot shown in Fig. 3. The locations of sources and receivers were also the same as in Fig. 3. Comparing the LES and reconstructed $\tilde{v}_x$ fields, one can see that the main contours of velocity fluctuations are reproduced correctly. However, small features of velocity fluctuations were not reconstructed. The mean squared error of reconstruction of the $\tilde{v}_x$ field, normalized to the variance of this field, was 0.37. Reconstruction of the $\tilde{T}$ and $\tilde{v}_y$ fields showed similar results.

To improve the reconstruction of the $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields, one could increase the number of sources and receivers in a tomography array. However, additional sensors increase the cost of the array. Furthermore, the large number of sensors can significantly distort the T and $\mathbf{v}$ fields within a tomographic volume (area). Therefore, we developed a new approach, the TDSI, which allows to significantly improve the reconstruction of $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields without increasing the number of sources and receivers.

Task 5. Time-dependent stochastic inversion (TDSI)

The main idea of the TDSI is to assume that the $\tilde{T}(\mathbf{R}, t)$ and $\mathbf{v}(\tilde{\mathbf{R}}, t)$ fields are random functions in both space and time with known spatial-temporal correlation functions $B_T(\mathbf{r}, t)$ and $B_{ij}(\mathbf{r}, t)$, where t is time. To take the full advantage of the TDSI, the travel times t_i need to be measured repeatedly at the time moments $t = \tau_1$, $t = \tau_2$, ... $t = \tau_N$, where N the number of travel time measurements. Then, the fields $T(\mathbf{r}, t)$ and $\mathbf{v}(\mathbf{r}, t)$ are reconstructed given N sets of t_i and assuming that the spatial-temporal correlation functions $B_T(\mathbf{r}, t)$ and $B_{ij}(\mathbf{r}, t)$ are known. To obtain these functions, a theory of locally frozen turbulence was developed. This theory generalizes the widely used hypothesis of (perfectly) frozen turbulence to the case when turbulence is advected with the wind which velocity can change in space and time. Using the developed theory of locally frozen turbulence, the spatial-temporal correlation functions $B_T(\mathbf{R}, t)$ and $B_{ij}(\mathbf{R}, t)$ were expressed in terms of the spatial correlation functions $B_T(\mathbf{R})$ and $B_{ij}(\mathbf{R})$. The concrete forms of the spatial-temporal correlation functions were obtained assuming that $B_T(\mathbf{r})$ and $B_{ij}(\mathbf{r})$ are given by Gaussian correlation functions.

The developed TDSI was used in 2D and 3D numerical simulations of acoustic tomography of the atmosphere. The effects of the errors in measurements of t_i on the reconstruction of the $\tilde{T}$ and $\tilde{\mathbf{v}}$ fields were studied.

Figure 4(c) shows the $\tilde{v}_x$ field reconstructed with the use of the TDSI in a 2D numerical simulation. In this reconstruction, it was assumed that the travel times t_i were measured 7 times when the LES field (shown in Fig. 3) was moving through the tomographic area. Comparison between Figs. 4(a)-(c) reveals that the TDSI allows us to significantly improve the reconstruction of the $\tilde{v}_x$ field. Now not only the contours of this field but also its small details can be seen in Fig. 4(c). The normalized mean squared error in this reconstruction is 0.22, which is about half as much as that in Fig. 4(b). Similar results were obtained in the reconstruction of $\tilde{T}$ and $\tilde{v}_y$ fields.

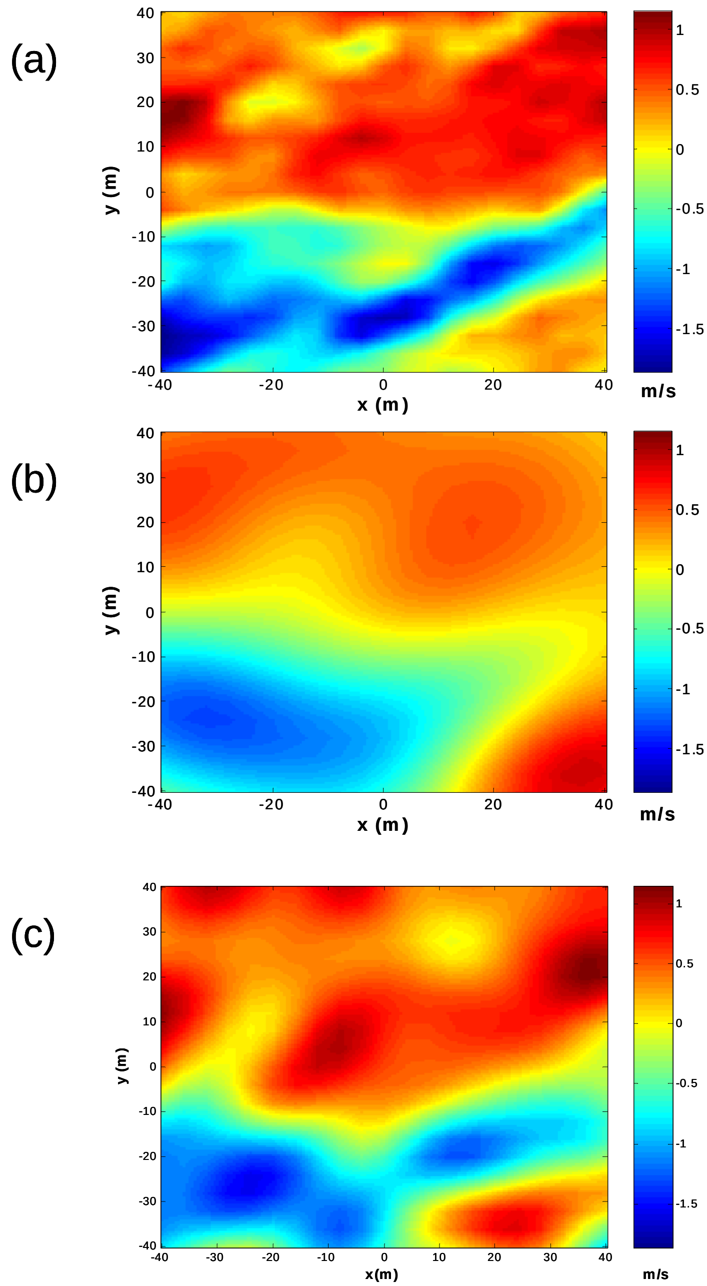

Figure 4: The velocity field $\tilde{v}_x$. (a) LES. (b) Reconstruction of the $\tilde{v}_x$ field using stochastic inversion. (c) Reconstruction of the $\tilde{v}_x$ field using TDSI.

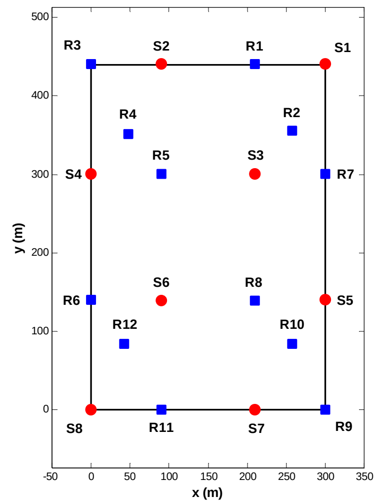

Figure 5: A scheme of outdoor tomography array. S1-S8 are sources, R1-R12 are receivers.

Task 6. Reconstruction of temperature and wind velocity fields in outdoor tomography experiment.
The developed TDSI was applied to the reconstruction of the temperature and wind velocity fields in outdoor acoustic tomography experiment STINHO carried out by scientists from the University of Leipzig in summer of 2002 near the Meteorological Observatory of the German Weather Service Lindenberg. STINHO was an extensive meteorological experiment to study the effects of heterogeneous surfaces on the turbulent heat exchange and horizontal turbulent fluxes over heterogeneous surface. Numerous meteorological equipment including an acoustic tomography array was used to measure parameters of the atmospheric boundary layer. The scheme of the array is shown in Fig. 5. In the figure, red circles and blue squares indicate sound sources and receivers (microphones), respectively. The tomography array consisted of 8 sources and 12 receivers which were positioned within a horizontally located rectangle with sides 300 and 440 m. The sources and receivers were placed at the height of about 2 m above the ground which consisted of grassland and a small field of bare soil.

German scientists provided us with the travel times t_i measured every minute from midnight till 5 p.m. on July 6, 2005 and locations of sources and receivers. Figure 6 shows the mean values of temperature and two components of wind velocity within the tomographic area reconstructed with the use of the approach developed in Task 2. The reconstruction corresponds to 11:45 a.m. - 12:15 p.m. The vertical bars indicate the estimated errors of the reconstruction. After the mean fields were estimated, the TDSI was employed to reconstruct the fluctuations in temperature and wind velocity. The reconstructed fluctuations were added to the mean fields. The resulting total temperature T and wind velocity fields $\mathbf{v}$ are plotted in Fig. 7. (The reconstruction corresponds to 12:00 p.m.) In the first of these figures, arrows indicate the direction of wind velocity. Several “warm” and “cold” temperature eddies, and “fast” and “slow” velocity eddies are seen in Fig. 7. Note that the expected errors in the reconstruction of temperature and wind velocity fields were 0.24 °C and 0.2 m/s, respectively. Therefore, the temperature and wind velocity eddies shown in Fig. 7, were reconstructed reliably. Also note that, at two spatial points inside the tomographic area, the reconstructed values of T agree with those measured in situ.

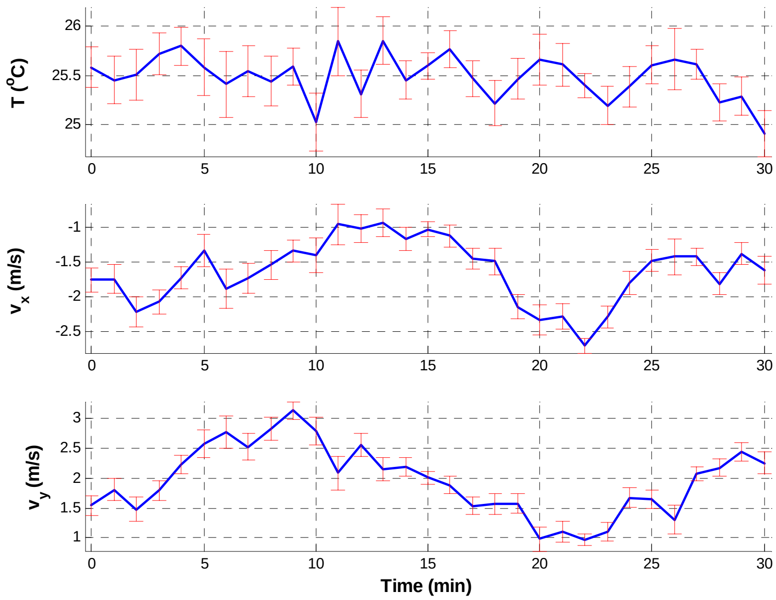

Figure 6: Mean values of temperature and two components of wind velocity reconstructed in outdoor tomography experiment.

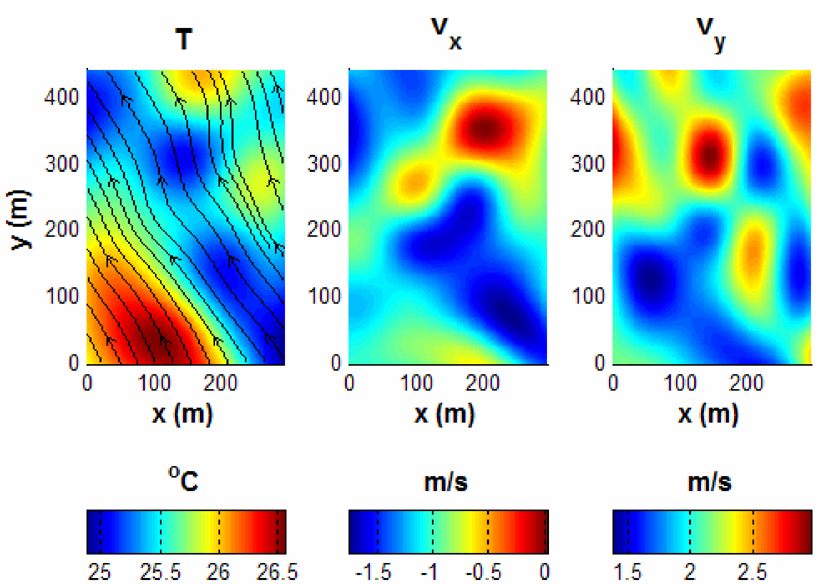

Figure 7: Temperature and two components of wind velocity reconstructed with the use of TDSI in outdoor tomography experiment.

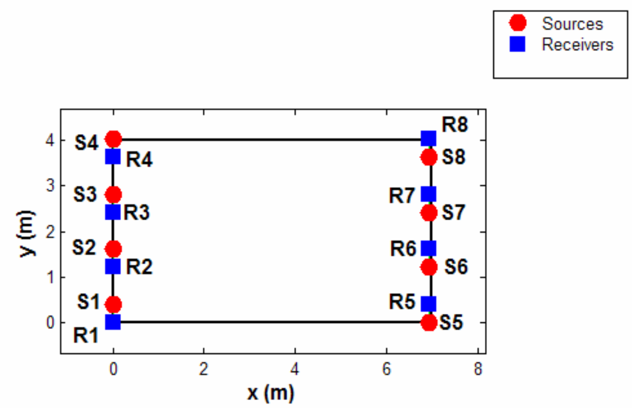

Figure 8: A scheme of indoor tomography array. S1-S8 are sources, R1-R8 are receivers.

The TDSI allowed us also to monitor the evolution of the reconstructed temperature T and wind velocity $\mathbf{v}$ fields in time. The corresponding movies of T and $\mathbf{v}$ fields were obtained.

Task 7. Reconstruction of temperature and velocity fields in indoor tomography experiment.

The scientists from the University of Leipzig also provided us with the travel times t_i and locations of sources and receivers for an acoustic tomography experiment carried out in a large tank. The tank had horizontally located heating and cooling plates between which convection and turbulence could develop. The small-scale acoustic tomography array with the size 4×7 m^2 was located in a vertical plane between these plates. The scheme of the array is shown in Fig. 8. The array consisted of eight sources and eight microphones. The travel times of sound propagation between sources and receivers were measured every 20 s between 8 a.m. and 5 p.m. during January 17 through 19, 2005.

Figure 9 shows the temperature T and velocity $\mathbf{v}$ fields reconstructed with the use of the TDSI at 2:00 p.m. on January 18, 2005. In this figure, arrows indicate the direction of velocity. It follows from Fig. 9(a) that the temperature varies between 40 and 42.6 °C. The estimated error of reconstruction is 0.07 °C. Figure 9(b) shows the reconstructed velocity field. The value of medium velocity is small (less than 0.65 m/s) as one would expect for convection. The estimated error of reconstruction of the velocity field is 0.05 m/s.

Task 8. Optimal layout of the acoustic tomography array.

An approach was developed for finding an optimal location of source and receiver towers in the state-of-the-art array for acoustic tomography of the atmosphere at the BAO, Boulder, CO. The main idea of this approach is to find such location of sources and receivers which results in a maximum value of the inverse condition number of the inversion matrix. This approach and the inverse algorithms considered in Tasks 3-5 were used to find an optimal location of three source and five receiver towers. The resulting optimal geometry of the array is shown in Fig. 1. The array was build using this geometry.

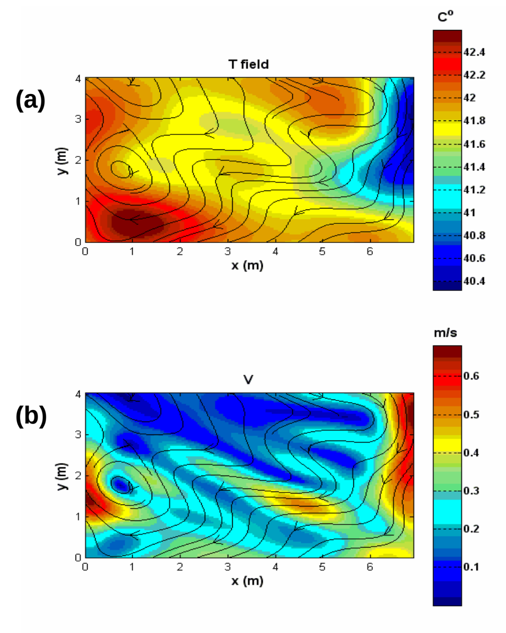

Figure 9: Temperature and magnitude of velocity fields reconstructed with the use of TDSI in indoor tomography experiment.

3. List of all publications supported under this grant:

3.1. Papers published in peer-reviewed journals

[1] S. N. Vecherin, V. E. Ostashev, G. H. Goedecke, D. K. Wilson, and A. G. Voronovich, "Time-dependent stochastic inversion in acoustic travel-time tomography of the atmosphere," J. Acoust. Soc. Am. **119,** No 5, 2579-2588 (2006).

[2] G. H. Goedecke, D. K. Wilson, and V. E. Ostashev, "Quasi-wavelet models of turbulent temperature fluctuations," Boundary-Layer Meteorology **120**, 1-23 (2006).

3.2. Papers published in conference proceedings

[3] V. E. Ostashev, S. N. Vecherin, D. K. Wilson, and S. L. Collier, "Correlation functions of temperature and velocity fluctuations in a turbulent atmosphere," J. Acoust. Soc. Am. **119**, No 5, Pt. 2, 3264 (2006).

[4] V. E. Ostashev, S. N. Vecherin, D. K. Wilson, A. Ziemann, M. Barth, and K. Arnold, "Acoustic travel-time tomography of temperature and wind velocity fields in the atmosphere," J. Acoust. Soc. Am. **120**, No 5, Pt. 2, 3336 (2006).

[5] S. N. Vecherin, V. E. Ostashev, D. K. Wilson, A. Ziemann, M. Barth, and K. Arnold, "Reconstruction of turbulent fields in acoustic tomography experiments," Proc. 12th Intern. Symp. on Long Range Sound Propagation, New Orleans, 364-384 (2006).

[6] G. H. Goedecke, V. E. Ostashev, and D. K. Wilson, "Quasi-wavelet models of turbulent temperature and shear-driven velocity fluctuations," Proc. 11th Intern. Symp. on Long Range Sound Propagation, Fairlee, VT, June 1-3, 225-239 (2004).

[7] S. N. Vecherin, V. E. Ostashev, D. K. Wilson, A. G. Voronovich, G. H. Goedecke, S. L. Collier, J. M. Noble, and D. Ligon, "Forward and inverse problems of acoustic tomography of the atmosphere,"

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[8] S. L. Collier, D. A. Ligon, J. M. Noble, E. Patton, P. Sullivan, and V. E. Ostashev, "Acoustic tomographic array simulation," Proc. 11th Intern. Symp. on Long Range Sound Propagation, Fairlee, VT, June 1-3, 274-292 (2004).
[9] V. E. Ostashev, S. N. Vecherin, G. H. Goedecke, D. K. Wilson, A. G. Voronovich, and E. G. Patton, "Numerical simulation of acoustic tomography of the atmosphere," J. Acoust. Soc. Am. **117**, No 4, Pt. 2, 2532 (2005).
[10] D. K. Wilson, V. E. Ostashev, S. N. Vecherin, A. G. Voronovich, S. L. Collier, and J. M. Noble, "Assessment of acoustic travel-time tomography of the atmospheric surface layer," Proceedings of AMS Symposium on Boundary Layers and Turbulence, Portland, ME (2004).

3.3. Manuscripts submitted, but not published

[11] S. N. Vecherin, V. E. Ostashev, A. Ziemann, D. K. Wilson, K. Arnold, and M. Barth, "Tomographic reconstruction of atmospheric turbulence with the use of time-dependent stochastic inversion," J. Acoust. Soc. Am. (submitted, 2006).

3.4. Manuscripts in preparation

[12] S. N. Vecherin, V. E. Ostashev, and D. K. Wilson, "Numerical simulation of 3D acoustic tomography of the atmosphere," J. Acous. Soc. Am. (to be submitted)

3.5. Ph.D. Dissertations

[13] S. N. Vecherin, "Acoustic travel-time tomography of the atmosphere", Ph.D. Dissertation, New Mexico State University (April, 2007).

4. **List of all participating scientific personnel**

Dr. V.E. Ostashev.
Dr. G.H. Goedecke.
Ph. D. student, S. N. Vecherin. Ph.D. defended on April 5, 2007.

5. **Report of inventions**

None.