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14. ABSTRACT
The main objective of the project was to study the intermittent atmospheric surface layer on the basis of observations collected with one or two
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Report Title

Measurement Science of the Intermittent Atmospheric Boundary Layer

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The main objective of the project was to study the intermittent atmospheric surface layer on the basis of observations collected with one or two
optical telescopes observing an array of test lights and up to twelve sonics placed along a horizontal propagation path of length ca. 200 m. During the reporting period, experimental data collected in June 2010 were analyzed, and a more sophisticated experiment was conducted in June 2011. The analysis of the 2010 data set confirmed that the optical retrievals of (1) temporal fluctuations of path-averaged, vertical temperature gradient fluctuations, (2) path averages of the transverse wind velocity, and (3) path averages of the temperature structure parameter agreed well with the sonic measurements down to time scales of 1 minute or even less.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

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

Received	Paper
2011/08/31 1' 4	Ganesh K. Subramanian, Andreas Muschinski. First Observations of Microbaroms with Single Absolute Barometers, Journal of Atmospheric and Oceanic Technology, (07 2011): 933. doi: 10.1175/2011JTECHA1526.1

TOTAL: 1

Number of Papers published in peer-reviewed journals:

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

Received	Paper
2010/10/06 2' 1	Mario Behn, Vincent Hohreiter, Andreas Muschinski. A scalable datalogging system with serial interfaces and integrated GPS time stamping, Journal of Atmospheric and Oceanic Technology, (01 2008): . doi:

TOTAL: 1

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Muschinski, A., K. Hu, L. M. Root, S. Tichkule, and S. N. Wijesundara, 2010: Angle-of-arrival fluctuations of light propagating through the intermittent nocturnal surface layer. Oral presentation at AGU Fall Meeting 2010 (13-17 Dec. 2010, San Francisco, CA).

Tichkule, S., K. Hu, L. M. Root, S. N. Wijesundara, and A. Muschinski, 2011: On the retrieval of beam transverse wind velocity using angles of arrival from spatially separated light sources. Oral presentation at the USNC-URSI National Radio Science Meeting (5-8 Jan. 2011, Boulder, CO).

Hu, K., L. M. Root, S. Tichkule, S. N. Wijesundara, and A. Muschinski, 2011: Optical and sonic observations of fluctuations of the vertical temperature gradient in the intermittent nocturnal atmospheric surface layer. Oral presentation at the USNC-URSI National Radio Science Meeting (5-8 Jan. 2011, Boulder, CO).

Muschinski, A., and S. J. Frasier, 2011: Vertical fluxes of local clear-air radar and sodar reflectivity in the convective boundary layer. Oral presentation at the USNC-URSI National Radio Science Meeting (5-8 Jan. 2011, Boulder, CO).

Muschinski, A., 2011: Vertical fluxes of local structure parameters in the convective boundary layer. Invited presentation at the international workshop "Models versus physical laws/first principles, or why models work" (2-4 Feb. 2011, Vienna, Austria).

Muschinski, A., 2011: Doppler velocities resulting from clear-air reflectivity fluxes. Seminar presentation (8 Mar. 2011, EECE Dept. and NOAA/CU CET, University of Colorado at Boulder, Boulder, CO).

Muschinski, A., 2011: Optical and ultrasonic observations of the nocturnal atmospheric surface layer. Seminar presentation (10 Mar. 2011, NCAR/MMM, Boulder, CO).

Number of Presentations: 7.00

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

Received Paper

TOTAL:

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

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

Received Paper

TOTAL:

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

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Shiril Tichkule	0.50	
Kekai Hu	0.50	
FTE Equivalent:	**1.00**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Andreas Muschinski	0.20	No
FTE Equivalent:	**0.20**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Shanka Wijesundara	0.50	
FTE Equivalent:	**0.50**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	1.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	1.00
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:......	1.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	1.00
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
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	1.00

Names of Personnel receiving masters degrees

NAME

Shiril Tichkule

Total Number: 1

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment.

Technology Transfer

Scientific Progress and Accomplishments

1 Introduction

During the reporting period (September 1, 2010 through January 31, 2012), we reviewed, refined and generalized the theoretical foundations to analyze and interpret the optical and in-situ data that we had collected during a field experiment conducted in June 2010 at the Boulder Atmospheric Observatory (BAO) site near Erie, CO. The optically retrieved time series of (1) temporal fluctuations of the path-averaged, vertical temperature gradient, of (2) the path-averaged, beam-transverse horizontal velocity component, and of (3) the path-averaged temperature structure parameter turned out to agree very well with in-situ reference measurements. Preliminary results have been presented at various conference presentations and seminars, and a masters thesis (Tichkule, 2011) has been prepared on the basis of this dataset. Various manuscripts are being prepared for submission to scientific journals.

In May/June 2011, a more sophisticated experiment, involving four sonic towers along a 150 m long propagation path was conducted, again at the BAO site.

The data-acquisition system and the spectral analysis routines that we have developed over the years (supported in part through the current grant and the previous ARO grant) formed the basis of a pioneering study on ocean-generated infrasound observed at a location 100 miles inland (Subramanian, 2009; Subramanian and Muschinski, 2011). That study is only tangentially related to the current research project and is not described here in any further detail.

In Section 2, we summarize the general theoretical approach to interpret the various statistics computed from the time series of the centroid coordinates of the four test lights simultaneously observed with one or two telescopes. (So far, we have used only a single telescope.) In Section 3, we present and discuss two measurement examples: First, time series of optically retrieved path averages of the temperature structure parameter; second, time series of optically retrieved path averages of the beam-transverse horizontal velocities. Both time series are compared with the respective observables extracted from in-situ measurements collected with sonics.

Work on this project stopped in August 2012 when the P.I. (Andreas Muschinski) left the University of Massachusetts and joined the Boulder office of NorthWest Research Associates (NWRA). M.S. graduate Shiril Tichkule followed the P.I. to Boulder and joined the Ph.D. program of the University of Colorado's Dept. of Electrical, Computer and Energy Engineering in September 2011. The project was re-awarded to the P.I. through his new employer, NWRA, on March 1, 2012.

2 Theory

Within the framework of weak-scattering theory (Rytov approximation, Born approximation, or geometrical-optics approximation), the aperture-averaged AOA fluctuation can be written as a volume integral over a component of the refractive-index gradient fluctuation. That is, the vertical AOA fluctuation α_{ij} can be written as

$$\alpha_{ij} = \iiint g_{ij}(\mathbf{r}) \frac{\partial n(\mathbf{r})}{\partial z} d^3 r, \tag{1}$$

and the horizontal AOA fluctuation can be written as

$$\beta_{ij} = \iiint g_{ij}(\mathbf{r}) \frac{\partial n(\mathbf{r})}{\partial y} d^3 r, \tag{2}$$

where the indices i and j denote the source and the receiver, respectively, such that the spatial weighting function, or sampling function, $g_{ij}(\mathbf{r})$ is an instrument function that depends on the absolute and relative locations of the source and the receiver and in general depends also on other characteristics such as the diameter and shape of the source and the diameter and and shape of the receiving aperture.[1] Here,

$$\mathbf{r} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}, \tag{3}$$

where the x-axis points from the source to the receiver, the z-axis points up, and the y-axis points to the left (seen from the source), such that the coordinate system is right-handed.

Therefore, the covariance of, say, the horizontal AOA fluctuation observed with the source i and the receiver j and the mth local time derivative of the horizontal AOA fluctuation observed with the source k and the receiver l is given by

$$\left\langle \beta_{ij} \frac{\partial^m}{\partial t^m} \beta_{kl} \right\rangle = \iiint \iiint g_{ij}(\mathbf{r}') g_{kl}(\mathbf{r}'') \left\langle \frac{\partial n(\mathbf{r}')}{\partial y'} \frac{\partial^m}{\partial t^m} \frac{\partial n(\mathbf{r}'')}{\partial y''} \right\rangle d^3 r' d^3 r'' \tag{4}$$

or, in a more compact notation,

$$\left\langle \beta_{ij} \frac{\partial^m}{\partial t^m} \beta_{kl} \right\rangle = \iiint \iiint G_{ijkl}(\mathbf{r}', \mathbf{r}'') R_{yy}^{(m)}(\mathbf{r}', \mathbf{r}'') d^3 r' d^3 r'', \tag{5}$$

where

$$G_{ijkl}(\mathbf{r}', \mathbf{r}'') = g_{ij}(\mathbf{r}') g_{kl}(\mathbf{r}'') \tag{6}$$

is the product of the two instrument functions characterizing the source-receiver combination i, j and the source-receiver combination k, l, respectively, and

$$R_{yy}^{(m)}(\mathbf{r}', \mathbf{r}'') = \left\langle \frac{\partial n(\mathbf{r}')}{\partial y'} \frac{\partial^m}{\partial t^m} \frac{\partial n(\mathbf{r}'')}{\partial y''} \right\rangle \tag{7}$$

is the two-point cross-covariance function of the y-component of the gradient of the refractive-index fluctuation at the location $\mathbf{r}'$ and the y-component of the mth time derivative of the y-component of the gradient of the refractive-index fluctuation at the location $\mathbf{r}''$.

Two-point cross-covariance functions very similar[2] to $R_{yy}^{(m)}(\mathbf{r}', \mathbf{r}'')$, $R_{zz}^{(m)}(\mathbf{r}', \mathbf{r}'')$, $R_{yz}^{(m)}(\mathbf{r}', \mathbf{r}'')$, and $R_{zy}^{(m)}(\mathbf{r}', \mathbf{r}'')$ were introduced, evaluated and discussed by Muschinski (2004) and Muschinski et al. (2005) in the context of a generalized measurement theory of clear-air Doppler radar windprofilers.

[1] One of our working assumptions has been that we can idealize the receiving aperture as a circular, uniformly filled aperture, and the source aperture as a point aperture. Of course, these assumptions simplify the theory considerably.

[2] Muschinski (2004) and Muschinski et al. (2005) considered two-point cross-covariance functions of refractive-index fluctuations and time derivatives of refractive-index fluctuations, two-point cross-covariance functions of *spatial derivatives* of refractive-index fluctuations and time derivatives of *spatial derivatives* of refractive-index fluctuations.

We have set up our experiments such that the spacing between the sources are small compared to the propagation path length L. Then, using the Markov approximation along the propagation paths and assuming that the turbulence transverse to the propagation direction is locally homogeneous and isotropic within the propagation channel, the six-dimensional integral in (4) and (5) can be reduced to a one-dimensional integral along the propagation direction:

$$\left\langle \beta_{ij} \frac{\partial^m}{\partial t^m} \beta_{kl} \right\rangle = \int_0^L P_{ijkl}(x) M_{yy}^{(m)}(x) dx. \tag{8}$$

Here, $P_{ijkl}(x)$ is a path-weighting function and $M_{yy}^{(m)}(x)$ is a "meteorological function", and both functions can be derived from $G_{ijkl}(\mathbf{r}', \mathbf{r}'')$ and $R_{yy}^{(m)}(\mathbf{r}', \mathbf{r}'')$.

In the simplest case, we have $m = 0$, and because in the inertial subrange $M_{yy}^{(0)}(x)$ scales with $\widetilde{C_n^2}(x)$, the horizontal-AOA covariance tensor can be written as a path integral of $\widetilde{C_n^2}(x)$:

$$\langle \beta_{ik} \beta_{jl} \rangle = \int_0^L P_{ijkl}(x) \gamma \widetilde{C_n^2}(x) dx, \tag{9}$$

where γ is a constant coefficient that can be theoretically determined.[3]

Once $P_{ijkl}(x)$ and γ have been derived from $G_{ijkl}(\mathbf{r}', \mathbf{r}'')$ and $R_{yy}^{(0)}(\mathbf{r}', \mathbf{r}'')$, the relationship (9) can be used to retrieve $\widetilde{C_n^2}$ along the propagation path from measurements of the covariance tensor $\langle \beta_{ik} \beta_{jl} \rangle$. How well-posed this inversion problem is will depend primarily on the choice of the relative locations of the sources and receivers. If one assumes that $\widetilde{C_n^2} = C_n^2$ is constant in the range of x values at which $P_{ijkl}(x)$ has significant weight, one obtains

$$\langle \beta_{ik} \beta_{jl} \rangle = A_{ijkl} C_n^2, \tag{10}$$

where

$$A_{ijkl} = \int_0^L \gamma P_{ijkl}(x) dx. \tag{11}$$

Obviously, this result can be used for an initial and simple check, based on the measured covariance tensor $\langle \beta_{ik} \beta_{jl} \rangle$, whether $\widetilde{C_n^2}$ is approximately homogeneous along the propagation path.

The cases $m = 1$ and $m = 2$ will be examined along the lines presented in Muschinski (2004) and Muschinski et al. (2005). We expect that $M_{yy}^{(1)}(x)$ can be expressed in terms of $\widetilde{C_n^2}(x)$ and the lateral wind velocity $v_y(x)$, and that $M_{yy}^{(2)}(x)$ depends also on the *variance* of the lateral wind velocity. Correspondingly, we expect $M_{yz}^{(2)}(x)$ to carry information about the covariance of the lateral and vertical wind velocity fluctuations, that is, about the vertical flux of lateral momentum.

The analysis of the path-weighting functions $P_{ijkl}(x)$ and the "meteorological functions" $M_{yy}^{(m)}(x)$, $M_{yz}^{(m)}(x)$, $M_{zy}^{(m)}(x)$ and $M_{zz}^{(m)}(x)$ is to a large extent "virgin territory", and a significant part of the theoretical work will be devoted to this analysis as well as to the question of how stable the solutions of the various inversion problems are.

[3] Here we assume that the diameter of the telescope is small compared to the outer scale of turbulence and large compared to the inner scale, which is not necessarily the case in the nocturnal ASL.

3 Observations

Since 2005, we have conducted a series of focused field experiments involving a large-aperture telescope equipped with a CCD camera and up to twelve sonics mounted on up to four portable towers along the propagation path (Behn, 2006; Cheon et al., 2007; Cheon, 2008; Behn et al., 2008; Whiteman et al., 2008; Tichkule, 2011), and up to three ultrasensitive quartz-crystal barometers in order to observe the mean pressure and pressure fluctuations associated with gravity waves and infrasound (Subramanian, 2009; Subramanian and Muschinski, 2011).

In the following two subsections, we present measurement examples in order to demonstrate that temperature structure parameters and lateral wind velocities can be effectively retrieved from optical AOA statistics estimated from test-light image centroids. We will show that the optically retrieved quantities (based on the geometrical-optics approximation) compare well with independent in-situ observations even if the data are processed in a relatively simple manner. These measurement examples are applications only of simple cases (single telescope, m=0, m=1) of the general measurement theory described in Section 2.

We collected the data presented in the following in a field experiment conducted during the night of 15/16 June, 2010 at the BAO site. The experimental setup was practically identical with the one described by Cheon et al. (2007), except that LEDs were now used instead of krypton flashlight bulbs, and twelve sonics (instead of a single sonics) were mounted on two 20-ft towers along the propagation path.

The propagation path was horizontal, at 1.7 m AGL, and 182 m long, with the telescope at one end and the test-light array at the other end. A CCD camera captured telescope images of four LED test lights (vertical spacing 7.5 cm, horizontal spacing 10 cm) at a rate of 30 frames per second. From each image, vertical and horizontal centroid coordinates were estimated for each of the four test lights, such that each image provided four vertical ($\alpha_1, ..., \alpha_4$) and four horizontal ($\beta_1, ..., \beta_4$) angles-of-arrival (AOAs).

Six sonics were mounted on a 20-ft tower located 47 m away from the telescope and 2 m away from the propagation path. The two lowest sonics—the only ones that are used for the measurement examples presented here—were at 1.45 m and 2.13 m AGL. The sampling frequency of the sonic data (temperature and the three wind-velocity components) was 32 Hz.

3.1 First measurement example: Temperature structure parameter

Figure 1 shows two time series of the temperature structure parameter, C_T^2, one of which was estimated from sonic data (black dots) and the other one from horizontal-AOA variances (red dots). Each data point is a 30-s estimate.

The optically retrieved C_T^2 values were obtained by means of

$$C_T^2 = \frac{\overline{\left(\beta_1 - \overline{\beta_1}\right)^2} D^{1/3}}{\gamma_s b L}, \tag{12}$$

where the overbar stands for averaging over 30 s, D = 35 cm is the aperture diameter, γ_s = $(3/8) \times 2.383 = 1.064$ is the coefficient for spherical waves in the geometrical-optics limit (Cheon and Muschinski, 2007, eq. 37 on p. 420), L = 182 m was the propagation path length, and $b = (ap/T^2)^2$

is the constant of proportionality that relates the temperature structure parameter to the refractive-index structure parameter, where $a = 7.9 \times 10^{-7}$K/Pa for red light, $p = 839$ hPa was the surface air pressure, and $T = 288$ K was the air temperature.

The sonic-retrieved C_T^2 values were obtained by means of

$$C_T^2 = \left(\frac{ap}{T^2}\right)^2 \frac{\overline{\left(\Delta T_{12} - \overline{\Delta T_{12}}\right)^2}}{\Delta z_{12}^{2/3}}, \tag{13}$$

where $\Delta T_{12} = T(z_2) - T(z_1)$ and $\Delta z_{12} = z_2 - z_1$ and where $z_1 = 1.45$ m AGL and $z_2 = 2.13$ m AGL were the heights of the lowest two sonics. (The height of the propagation path was 1.7 m AGL.)

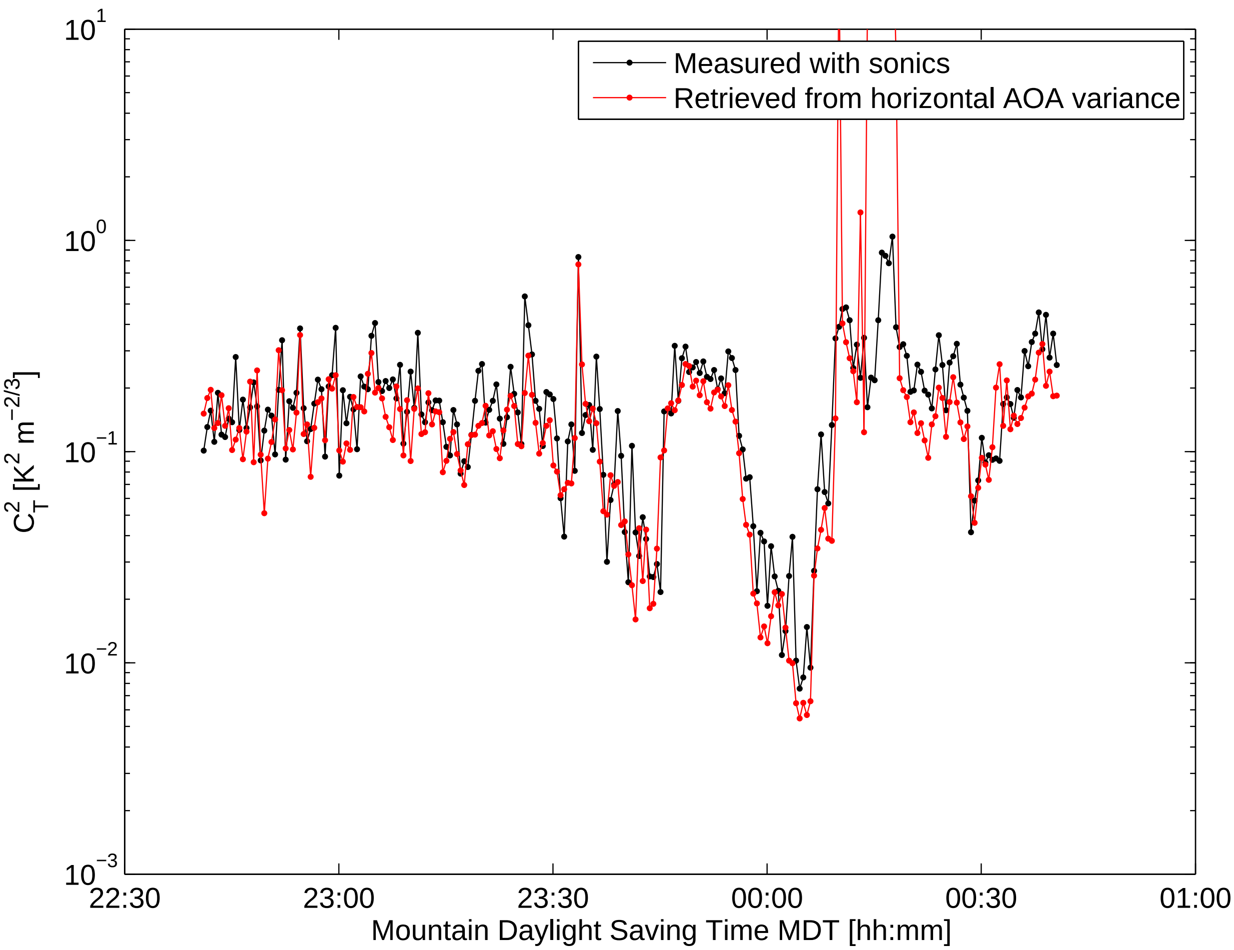

Figure 1: *Time series of the temperature structure parameter, C_T^2, 1.7 m AGL, measured with a pair of vertically spaced sonics (black) and retrieved from horizontal AOA fluctuations of a single testlight observed with a CCD camera mounted on a telescope at a distance of 182 m.*

Figure 1 shows that the two C_T^2 estimates track each other nicely down to time scales of 30 s, even though the optically retrieved C_T^2 values are path averages while the sonic-measured C_T^2 values are essentially point measurements. The sonic-measured values are systematically larger than the optical C_T^2 retrievals, by 20 or 30%. This bias may be caused by various mechanisms, including

(1) anisotropy of the turbulent temperature field in the nocturnal ASL at the sonic separation length scale $z_{12} = 68$ cm, (2) the fact that close to the ground C_T^2 decreases strongly with increasing height, and (3) possible systematic inhomogeneities of C_T^2 along the propagation path due to possible roughness inhomogeneities.

3.2 Second measurement example: Horizontal wind velocity

Figure 2 shows time series of beam-transverse, horizontal wind velocities observed with a sonic anemometer (black dots) and retrieved from the delays of horizontal-AOA fluctuations from a pair of horizontally spaced test lights (LEDs) observed with the same telescope (blue dots). The horizontal spacing was 10 cm.

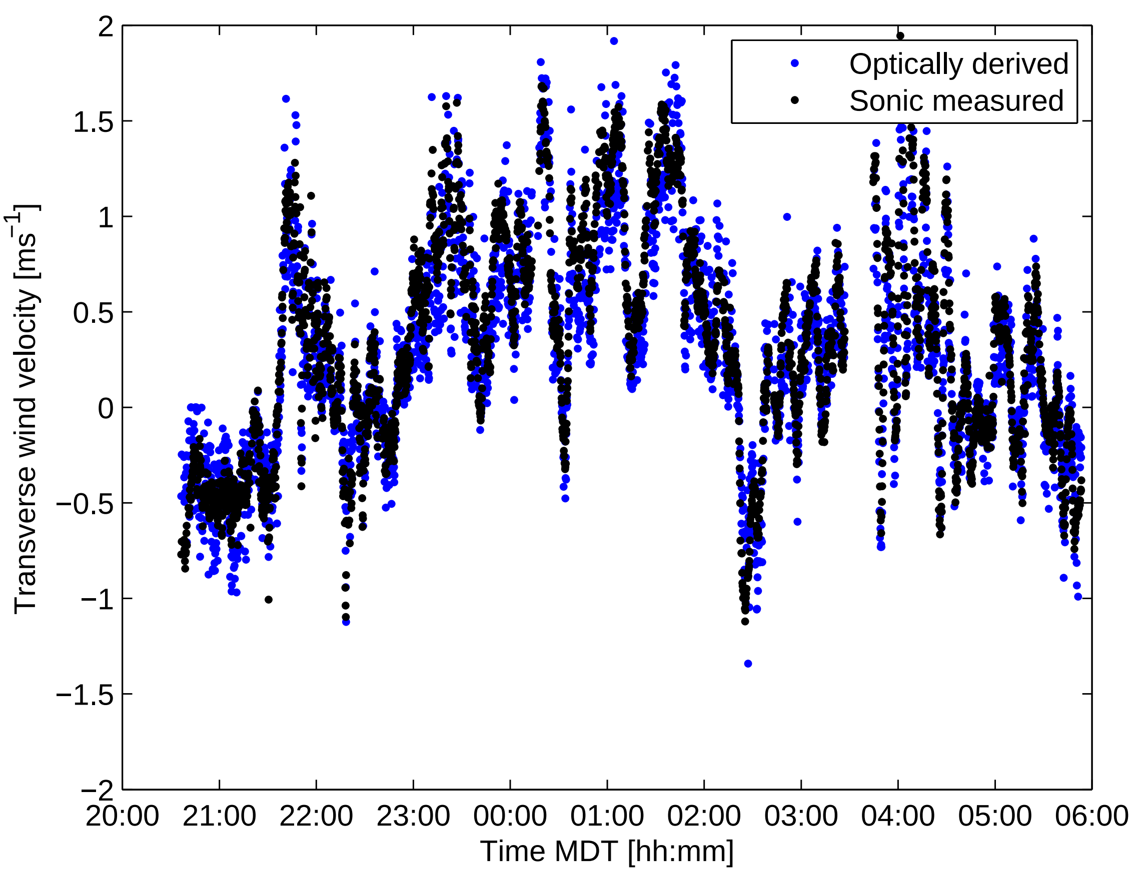

Figure 2: *Time series of path-transverse, horizontal wind velocities observed with an ultrasonic anemometer (black dots) and retrieved from optical AOA fluctuations by means of the slope-at-zero-lag method. Each data point represents a 10-s average.*

The transverse wind velocities, v_t, were retrieved by means of the "slope-at-zero-lag" method. Details of the data processing can be found in Shiril Tichkule's MS thesis (Tichkule, 2011).

Each data point represents an average over 10 s. The two time series track each other well but not perfectly, which is not surprising because the optical data represent (weighted) quasi-instantaneous path averages of the transverse wind velocity, while the sonic data are quasi-instantaneous point measurements. The r.m.s. difference between the two time series is about 20 $\mathrm{cm\,s^{-1}}$, which is probably the result of spatial variability in the horizontal wind field at length scales between a few tens of meters and the path length. However, there appears to be no significant bias between the optically retrieved and the sonic-measured velocities. 2-h averages of the differences between sonic-measured and optically retrieved wind velocities obtained in this experiment do not exceed 3 $\mathrm{cm\,s^{-1}}$.

4 Summary of the most important results

We demonstrated that the optical angle-of-arrival fluctuations observed with a large-aperture telescope equipped with a moderately fast CCD camera can be used to retrieve, with high sensitivity and accuracy, path averages of

- the vertical temperature gradient (not discussed in this report)
- the transverse wind velocity
- the temperature structure parameter

along a horizontal propagation path (200 m path length, 1.7 m above ground level) in the atmospheric surface layer.

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