P2.3

A NOVEL METHOD FOR THE STUDY OF NEAR-SURFACE TURBULENCE USING 3-D HOT-FILM ANEMOMETRY: OTIHS

Gregory S. Poulos, Steve Semmer, John Militzer and Gordon Maclean

NCAR, Earth Observing Laboratory, Boulder, Colorado, USA

1. INTRODUCTION

Hot-film and hot-wire constant temperature anemometry techniques have been used for the study of the smallest scales of turbulence and dissipation rate of turbulent kinetic energy, ε, in the near-surface atmosphere for approximately a century (e.g. King 1914, Jorgensen 1971, Larsen and Busch 1974, Perry 1982, Bruun 1995). These generally delicate devices are subject to a number of sensitivities that make them less amenable to routine outdoor use and to the difficult translation of a laboratory calibration to the field, including calibration drift (Slager 2001, van Dijk and Nieuwstadt 2004a, b). In addition, hot-film anemometers are subject to a limited range of valid attack angles compared with sonic anemometers (see Figure 1). Under field observation conditions where wind direction is seldom uniform for extended periods it is therefore frequently difficult to gather a statistically significant data set using such systems (Hogstrom et al. 1980).

At NCAR's Earth Observing Laboratory we have created a system that seeks to provide this capability while removing some of these limitations – the Outdoor Three-dimensional, *In-situ* calibrated Hot-film anemometry System (OTIHS). The OTIHS, 1) allows for *in-situ* calibration by embedding the three-dimensional hot-film anemometers within Campbell CSAT3 sonic anemometers, 2) ensures that observations are within the acceptable attack angles of the 3-d hot-film system using a software-driven motor system for the automated re-orientation of the system into the mean wind, and 3) utilizes relatively robust, commercially available three-dimensional hot-film sensors.

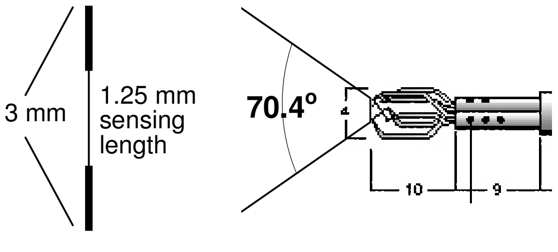

Figure 1. Left: An exaggerated schematic of a single fiber film and its sensing length. Right: A schematic of the three-dimensional hot-film constant temperature anemometer used in OTIHS. Dimensions are in mm and a depiction of its 70.4° acceptance cone for turbulence measurements is shown.

2. BACKGROUND

Recent research studies that have included the utilization of constant temperature anemometers within the near-field of sonic anemometers are;

1) Skelly et al. (2002) who used laboratory calibration and a fixed orientation with a three-dimensional hot-film anemometer to evaluate, with noted uncertainty, the effect of path-length averaging on the accuracy of flux estimates in the statically stable boundary layer;

2) Slager (2001) and Slager et al. (2004) who used a single, fixed, hot-wire anemometer and sonic anemometer for *in-situ* calibration and an evaluation of the accuracy of estimates of ε, noting the attenuation of sonic anemometer signals at πD where D is sonic pathlength of O[10] cm.;

3) Hogstrom and Smedman (2004) who utilized a three-dimensional hot-film anemometer swiveled into the wind via wind vane and laboratory calibration to study the accuracy of sonic anemometers.

Until OTIHS, no system had attempted to combine the favorable attributes of all of these systems.

Also, van Dijk and Nieuwstadt (2004a, b) have clearly shown that a look-up table method of calibration of three-dimensional wire/film sensors is the only means by which probes can be calibrated such that the measurements provide the turbulent flow field with 10% accuracy. Skelly et al. 2002 have shown that sonic anemometers may be incapable of capturing the fluxes in statically stable conditions based on data analyzed from CASES-99 (Poulos et al. 2002). The reason for this is that under statically stable weak wind conditions (low Reynolds number, $Re = UL/\eta$, where U is a representative velocity, L is a relevant length scale and $\eta = 1.5 \times 10^{-5}\ m^2\ s^{-1}$), the turbulent production scale for spectral energy density of the velocity components becomes much closer to the pathlength of the sonic anemometer. In order to study the turbulent transport of quantities in the stably stratified boundary layer, it is therefore necessary to measure those higher wavenumbers of the inertial subrange that are not accessible by sonic anemometry.

This, in turn, requires measuring turbulent fluctuations to the Taylor microscale,λ, where,

$$\lambda = L\,Re^{-1/2}.$$

λ is of O[10] mm for most atmospheric flows, including the statically stable boundary layer. Physically, the Taylor microscale represents the highest wavenumber that can be considered a part of inertial subrange for a given turbulent flow and therefore contribute to their covariances.

For example, when the winds are weak and the Richardson number achieves large values or the Monin-Obhukov length, L, becomes small and positive, then the turbulence becomes weak, smaller scale and quasi-two-dimensional (e.g. 'pancake eddies'). More importantly, significant portions of the turbulent flux may become immeasurable by current sonic anemometers. Thus, a satisfying understanding of these fluxes and balances could be hampered by the exclusive use of sonic anemometry for these purposes. With regards to practical application, fundamental assumptions underlying surface layer theory and therefore numerical parameterizations based upon surface layer theory also breakdown in stable conditions (Poulos et al. 2003). As a result, under these conditions, numerical weather prediction, large-eddy simulation, global climate simulation and worst-case air pollution and toxic substance calculations are subject to great uncertainty and possible miscalculation.

As a critical component of the turbulent kinetic energy budget and for a variety of other atmospheric research applications, it is desirable to estimate ε with considerable fidelity under the full range of atmospheric stability (Tatarkskii 2005). In order to achieve sufficient robustness for outdoor field work, hot-film systems were chosen, and therefore direct measurement of dissipation is not generally possible. However, a number of robust dissipation estimate options are available for a system able to measure λ. The required sampling frequency to resolve λ in very stably-stratified conditions is ~500 Hz and in extreme cases may be ~1000 Hz. To be conservative, we have chosen to operate each OTIHS at 2000Hz with the low-pass anti-aliasing filter at 1000Hz. Thus, the time and space scales for which OTIHS is configured will allow robust ε estimates.

3. SYSTEM COMPONENTS

Three OTIHSs were built, each comprised of the following components,

a) a Campbell CSAT3 thermosonic anemometer,
b) a Dantec three-dimensional fiber-film probe and probe support,
c) a Dantec MiniCTA,
d) a custom fabricated motor-drive system, and,
e) various cabling and associated hardware to connect to the data acquisition system.

The 3-d hot-film anemometer selected for use in OTIHS is made by Dantec Dynamics, Inc, Model number 55R91 and is shown schematically in Figure 1. The bridge circuitry, and analogue output was provided by the Dantec Miniature CTA (model number 54T30) which operates in the range of 0 to 5 V. It is possible to use a voltage offset between -0.9 and -2.2 V and apply 2-5x gain, although none were used in the initial application. To this was attached a 16-bit analogue to digital converter and data acquisition system. This system is capable of resolving voltage fluctuations of 0.15 mV, which corresponds to a sensitivity of ~1 mm s^{-1} in velocity (the sensitivity is dependent on cooling velocity). Wind tunnel tests indicated that the use of offset and gain would allow for up to a 4x improvement in voltage resolution. The data acquisition system was configured to accept 9 channels of 2000 Hz input from three hot-film sensors, the 60 Hz input from three Campbell CSAT3 sonic anemometers and various motor driver inputs.

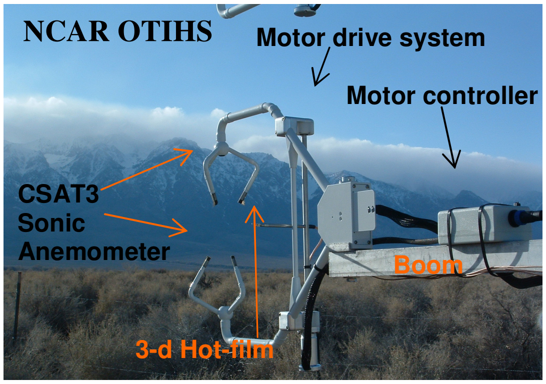

Figure 2. A picture of one OTIHS in the field during the Terrain-induced Rotors Experiment (held in the Owens Valley near Independence, California) during March 2006. Note the motor drive system attached to the right side of the sonic anemometer looking toward the mountains.

Each of three orthogonal thin-films span 3 mm across the prong ends and have a sensing length of 1.25 mm (Figure 1), such that the three-dimensional wind vector can be measured down to scales of approximately 5 mm. The tri-axial configuration of this probe limits the range of undistorted approach angles for the incipient flow to plus or minus 35.2^{o} (or an ‘acceptance cone’ of 70.4^{o}).

The thin-film fiber substrate is composed of quartz with D = 70 microns. The film of nickel is cathode sputtered onto the substrate to a thickness of 0.1 micron. An additional protective coating of quartz is sputtered onto the nickel film of 0.5 microns in thickness. The theoretical frequency limit for these films is 90 kHz, although for atmospheric applications the scales relevant to the sensing length of this instrument make the utilization of this capability unnecessary.

The custom motor drive system was fabricated at NCAR's Design and Fabrication Facility (see Figure 3) with the goal of minimized flow distortion. Since the CSAT3 provides the data for the *in-situ* calibration of the hot-film anemometer, a critical design factor was to minimize interference with the sonic anemometer measurement. Since the probe support (horizontal yellow cylinder in Figure 3) is 6 mm in diameter and is oriented horizontally, we conservatively treated it as a vertical cylinder and ensured that the hot-film probe was more than 20 radii from the centroid of the sonic claws. The probe support was then modified to the appropriate length.

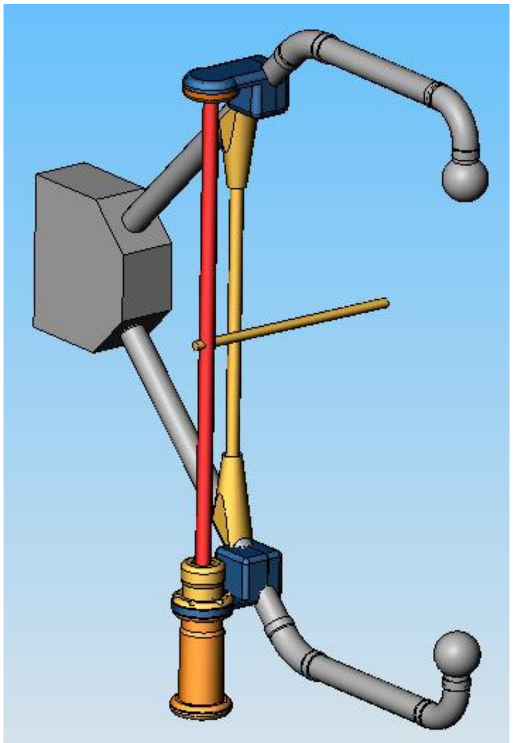

Figure 3. A schematic drawing of the motor drive system with the hot-film probe support pointed at 90° from the zero position (sonic claws and hot-film anemometer not pictured). Courtesy Jack Fox, NCAR EOL.

The motor drive system components were fabricated such that they could attach to the rear of the 45° CSAT3 arms but far enough forward to allow maximum range of motion for the hot-film. The full rotational range in this configuration is 235°. The zero position of the motor system was set to be parallel to the sonic anemometer arms, and thus the system has 95° of clockwise range and 140° counterclockwise range from zero. The system is built such that it can be mounted upside-down on the opposite side of the sonic anemometer to allow for alternative preferred wind directions (as dictated by the relevant wind rose for a given application). Each system component was built with rounded edges and to the minimum form factor.

The vertical post (red cylinder in Figure 3) of the motor drive system was attached to a software driven, optically-triggered 1700:1 torque-multiplied motor and seated to a matching guide for stability. In this post was drilled a horizontally-oriented guide hole for the hot-film probe support.

The probe support orientation is controlled by software contained within the motor controller box (see Figure 2) that sends positioning signals to the motor every 30 s or another user-specified interval. Those signals are generated from an averaging process on the data acquisition system that reports mean wind direction from the sonic anemometer to the motor control software.

Given the symmetric 35.2° acceptance angle for the hot-film probe, the probe is only repositioned if the mean wind direction has changed by over a fixed user-specified angle. The value for this fixed angle is typically set to 15-20° such that the hot-film anemometer is moved as infrequently as possible while conservatively assuring that the approach angle of the incident flow does not exceed the acceptance cone. In practice, 20 Hz wind direction data from the sonic anemometer is consulted to ensure the acceptance limits have not been exceeded.

4. IN-SITU CALIBRATION

The *in-situ* calibration method for this system is not yet complete but is analogous to those of Slager (2001) and van Dijk and Nieuwstadt (2004a, b). These methods are being developed based on first-use data from the Terrain-induced Rotors Experiment which was held in the Owens Valley of eastern California March-April 2006.

5. CONCLUSIONS

In this study we have described the newly developed NCAR Outdoor Three-dimensional *In-situ* calibrated Hot-film anemometry System (OTIHS). OTIHS has been designed to enable well-calibrated, research-grade field measurements of the smallest scales of the atmospheric inertial subrange to the Taylor microscale, λ. *In-situ* calibration methods are being tested based on first measurements taken at the Terrain-induced Rotors Experiment in the Owens Valley of eastern California.

Acknowledgements: *We gratefully acknowledge the advice of Arjan van Dijk, Tom Horst and Steve Oncley in the development of OTIHS. We further acknowledge the guidance and skill provided by Jack Fox and the Design and Fabrication Services group at NCAR. The National Center for Atmospheric Research is funded by the National Science Foundation.*

6. References

Bruun, H., 1995: Hot-wire anemometry. Oxford University Press, New York.

Hogstrom, U., L. Enger and E. Knudsen, 1980: A complete system for probing the detailed structure of atmospheric boundary layer flow. Report No. 60, Meteorologiska Institutioinen, Uppsala University, 41 pp.

Hogstrom, U. and A-S. Smedman, 2004: Accuracy of sonic anemometers: Laminar wind-tunnel calibrations caompared t atmospheri in situ calibrations against a reference instrument. *Bound.-Layer Meteor.*, **111**, 33-54.

Jorgensen, F. 1971: Directional sensitivity of wire and fibre-film probes. DISA Information, No. 11, 31-37.

King, L. 1914: On the convection of heat from small cylinders in a stream of fluid: determinatio of the convective constants of small platinum wires with applications to hot-wire anemometry. *Phil. Trans. R. Soc. London*, **A 214**, 373-432.

Larsen, S. E. and N. E. Busch, 1974: Hot wire measurements in the atmosphere. Disa Information, No. 16, 15-34.

Perry, A. E., 1982: Hot-wire anemometry. Oxford University Press, New York. pp. 184.

Poulos, G. S. and S. P. Burns, 2003: An evaluation of bulk Ri-based surface layer flux formulae for stable and very stable conditions with intermittent turbulence. *J. Atmos. Sci.,* **60***,* 2523-2537. (*William Blumen Memorial and CASES-99 Special Issue*).

Poulos, G. S., Blumen, W., and 11 co-authors, 2002: CASES-99: A comprehensive investigation of the stable nocturnal boundary layer. *Bull. Amer. Meteor. Soc.*, **83**, 555-581.

Skelly, B. T. D. R. Miller and T. H. Meyer 2002: Triple hot-film anemometer performance in CASES-99 and a comparison with sonic anemometer measurements. *Bound.-Layer Meteor.*, **105**, 275-304.

Slager, J. P., 2001: Measuring the viscous dissipation of turbulent kinetic energy with a hotwire and a sonic anemometer. Graduate Thesis, Utrecht University, Netherlands, Institute for Marine and Atmospheric Research, Report V 01-10.

Slager, J., P. G. Duynkerke and A. van Dijk, 2004: Measuring the viscous dissipation of turbulent kinetic energy with a hotwire and a sonic anemometer. XXth Conference on Boundary Layers and Turbulence…

Tatarskii, V. I., 2005: Use of the 4/5 Kolmogorov equation for describing some characteristics of fully developed turbulence. *Phys. Fluids*, **17**, 1-12.

van Dijk, A. and F. T. M. Nieuwstadt, 2004a: The calibration of (multi)hot-wire probes. 1. Temperature calibration. *Exp. Fluids*, **36**, 540-549.

van Dijk, A. and F. T. M. Nieuwstadt, 2004b: The calibration of (multi)hot-wire probes. 2. Velocity calibration. *Exp. Fluids*, **36**, 550-564.