High resolution in situ profiling of temperature, wind speed and turbulence with the 2009 CIRES turbulence sensor: new designs, performances, and applications

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ABSTRACT

Development of high-rate turbulence sensors for high resolution measurements of the atmospheric boundary layer began in 1998 to augment the Cooperative Institute for Research in Environmental Sciences (CIRES) tethered lifting system (TLS). Cold-wire and hot-wire sensors measure with high accuracy and resolution the streamwise temperature and wind speed fluctuations. The temperature structure constant C_T^2 and energy dissipations rate ε are estimated with spectral processing and small-scale turbulence scaling laws. In addition, other important turbulence parameters such as the Reynolds number, Buoyancy Reynolds number, turbulent Froude number, gradient Richardson number, Ozmidov scale, and temperature inner scale are determined. The TLS is ideally suited for accurate measurements of the local gradients since the sensors slowly ascend through the atmosphere which eliminates the constant bias from estimates of gradients.

Over the past decade, major engineering efforts have improved the turbulence sensor package with the development of new circuit designs of higher bandwidth, lower instrumental noise, and better calibration signals. In March 2009, data was collected at the Boulder Atmospheric Observatory (BAO) with the latest prototype instrument to investigate the turbulence structure of the nocturnal boundary layer and residual layer. The first results of the analysis of this data will be presented with a focus on investigating recent theories for stably stratified turbulence and the implications for future measurement systems, especially the very challenging low turbulence conditions. In addition, an overview of the new TLS equipment to be acquired in 2009 will be presented and new measurement configurations will be discussed.

THE TETHERED LIFTING SYSTEM (TLS)

The TLS combines high-rate (1kHz), low-noise, turbulence sensors that measure temperature, windspeed, small-scale turbulence statistics (C_T^2 and ε), as well as other standard meteorological quantities (pressure, wind direction, humidity,…), with newly acquired state-of-the art winches designed to meet the performance requirements for field operations (portability, autonomous operation) and precise profiling (steady and precise ascent-descent rates, from a fraction of a m/s up to ~3 m/s).

The lifting platform is either a 25' or a 30' long aerodynamic blimp (7'-8' diameter) with a maximum lifting payload of up to 16 lbs and 25 lbs respectively. The system is either operated in profiling mode or can be parked at altitudes of interests up to 3 km above ground.

Figure 1. left panel, shows the turbulence payload suspended from the 21' blimp before launch. The turbulence payload (Figure 1 right panel) is attached to a custom harness that permits the payload to align itself with the wind and maintain its vertical orientation.

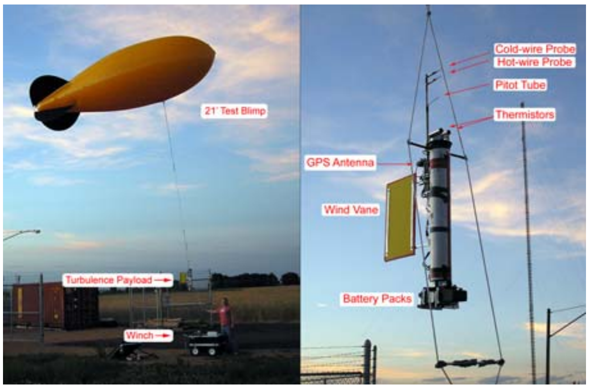

Figure 1. The TLS (left) and turbulence payload (right).

Three newly designed winches permit the simultaneous operation of multiple TLS's for better spatial coverage as well as improved profiling capabilities. Additionally, multiple turbulence sensors can be flown on each tether to increase the range of research applications the TLS can offer such as the structure of waves and their effects on turbulence in stable conditions.

THE TLS MEASUREMENTS

The flagship component of the TLS is its turbulence payload which has been continuously improved over the past 10 years to meet the challenging performance requirements of small-scale turbulence measurements in stable low-turbulence conditions.

High resolution temperature measurements are made with a fast-response fine-wire (5 micron) probe and custom low noise cold wire electronic boards. The cold wire data are logged at a 1 kHz sampling rate and are calibrated with respect to a small bead thermistor sensor which was calibrated in a controlled temperature bath at the National Center for Atmospheric Research (NCAR) instrument facility.

The absolute accuracy of the temperature measurements is determined by the absolute accuracy of the thermistor calibration and by the accuracy of the calibration algorithm. The spectral calibration produces a slope accuracy better than 0.3% (Figure 2) and the absolute nighttime accuracy is better than 0.1C.

© Proceedings of the 8th International Symposium on Tropospheric Profiling, ISBN 978-90-6960-233-2
Delft, The Netherlands, October 2009. Editors, A. Apituley, H.W.J. Russchenberg, W.A.A. Monna

Velocity measurements are made with the same fast-response fine wire probes used for temperature, and with low-noise, low power hot wire circuit boards.

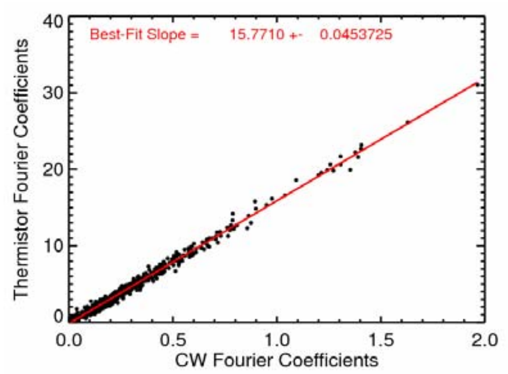

Figure 2. Spectral calibration of the coldwire temperature sensor against the thermistor data.

Hotwire velocity is calibrated with a pitot tube that was calibrated at the NCAR wind tunnel. The velocity is calibrated to an absolute accuracy better than 0.03 m/s, and a slope accuracy better than 0.1% (Figure 3).

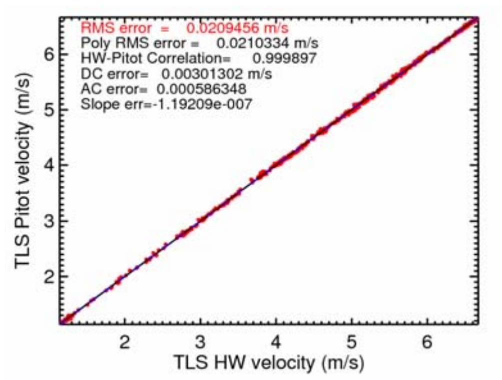

Figure 3. Hotwire velocity sensor calibration with respect to the pitot tube data.

Small-scale turbulence statistics are computed by fitting theoretical curves to the temperature and velocity spectra assuming the small-scale turbulence is locally homogeneous and isotropic and assuming Taylor's frozen flow hypothesis is valid, which is well satisfied for short time intervals [1]. For stably stratified turbulent layers, the assumption of isotropy is valid for a buoyancy Reynolds number larger than 100.

The energy dissipation rate ε is computed from fitting the velocity spectra to a model which assumes a Gaussian cut-off function for the high–wavenumber region of the three dimensional spectrum and accounts for the -5/3 power law of turbulence in the inertial range, as well as the rollover at the Kolmogorov microscale [1]. An example of such a fit is shown in Figure 4 for 100 seconds of data collected at constant altitude in the residual layer above the nocturnal boundary layer.

The temperature structure constant C_T^2 is also computed by fitting the temperature spectrum to a model which also consists of the characteristic -5/3 power law of turbulence in the inertial range and the Hill bump at the inner scale [1].

For both temperature and velocity spectra, the accuracy of the estimates depends on the number of spectral coefficients used for the fit. Benefitting for the high bandwidth of the instruments (1 kHz) and low noise properties of the electronics, 1-second estimates can be achieved with an accuracy better than 15%.

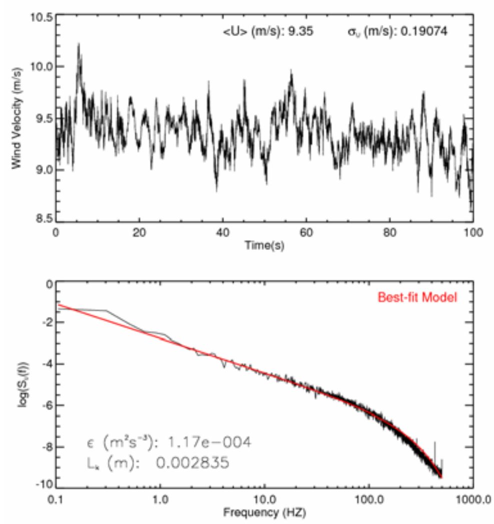

Figure 4. Example of typical high rate data (in this case Hotwire) and spectrum fitted to theoretical model.

Figure 5 shows an example of typical TLS profiles of wind speed and energy dissipation rate. The energy dissipation rate was calculated using 2-seconds long spectra while the velocity profile is from 1 second averages of the raw 1 kHz data.

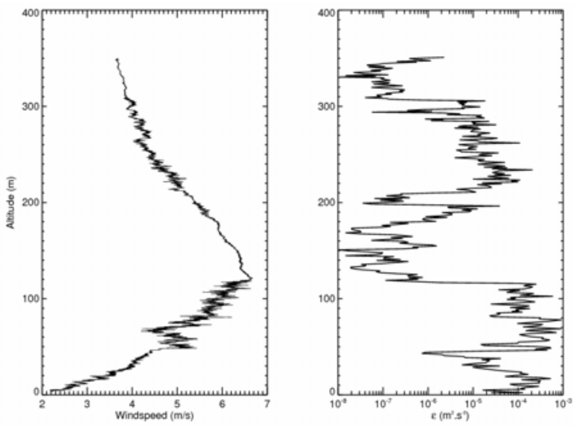

Figure 5. Typical high resolution TLS profiles (Left: Hotwire velocity; Right: energy dissipation rate)

This plot shows how well the TLS high resolution data capture and resolve the rapid changes in turbulence intensity that occur over fractions of meters. Similar observations of sharp interfaces and small scale structures that would typically be missed by instruments with larger spatial averaging, coarser vertical resolutions, or less sensitivity, have been presented in[2], [3] and [4].

RESEARCH APPLICATIONS

High quality profiles of mean and turbulent statistics are logistically difficult using instrumented towers or instrumented aircrafts.

The high-resolution velocity, temperature, and turbulence data provide unique measurements of the turbulent structure of stable regions offering unique research opportunities in various areas.

The recent addition of three new winches and the current development of five additional turbulence payloads will permit new measurement geometries and field operations.

The following is a short list of some of the research applications for the TLS.

3.1 Transition region characterization

Figure 6 shows uncalibrated data recently acquired in July 15, 2009 during an evening transition while testing the performances of the latest prototype payload. The TLS took about 10 minutes to reach the top before coming back down. The changes of the atmosphere's structure experienced during these 10-20 minutes are dramatic and more focused measurements will be collected at the boulder atmospheric observatory (BAO) throughout the year to better characterize these structural changes. Multiple packages and multiple TLS's are required to better capture the atmospheric dynamics and rapid changes that occur over such short period of times.

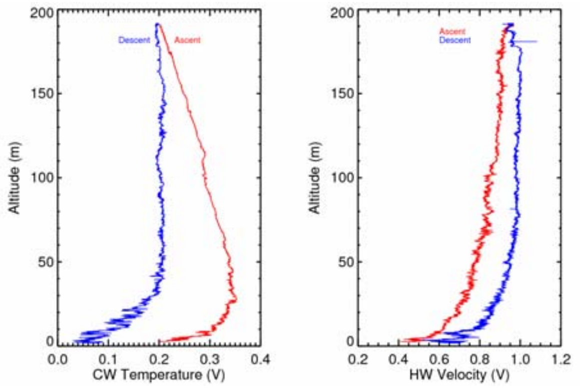

Figure 6. Profiles of temperature (left) and windspeed (right) during the evening transition.

3.2 Verification of stably stratified turbulence theory

Turbulent scaling laws for stably stratified flows are difficult to verify because high spatial resolution measurements are required to sample the important scales of turbulence from the Kolmogorov scale to the energy input scales.

Additionally, many important turbulent scaling laws and model parameterization require accurate estimates of the vertical gradients and the small-scale turbulence statistics. The TLS data is ideally suited for providing these high resolution measurements and accurate gradients for verification of steady-state turbulence theories.

Additionally, thanks to recent progresses in Direct Numerical Simulation (DNS) of stably stratified regimes, DNS calculations are now getting closer to matching the parameter space of the TLS data, especially in low turbulence regions where the turbulent Reynolds number is small.

3.3 Turbulence intermittency

Reference [5] studied the effect of ducted gravity waves on turbulence intermittency and proposed a mechanism for predicting events of enhanced turbulence. The newly acquired winches and turbulence payloads are critical for a complete evaluation of these wave generated turbulence mechanisms [5].

3.4 Remote sensors verification data

The high resolution turbulence measurements are also essential for the verification and understanding of new remote sensing techniques for measurements of turbulence profiles such as the scanning Doppler lidar. The TLS can be used as truth for turbulence profiles (Figure 7) and the use of multiple winches will permit a better spatial sampling of the lidar measurement domain.

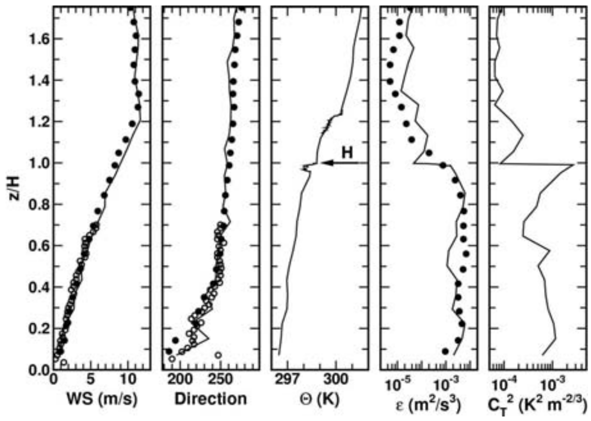

Figure 7. Comparison of Lidar (black dots) and TLS (solid line) data averaged to 5 m vertical resolution.

3.5 Vertical gradients averaging domain

Another important problem is the determination of the correct averaging domain for estimates of the gradient Richardson number (Ri), especially for the stable boundary layer and the residual layer. Reference [6] used the high resolution TLS data to study the effect of vertical averaging scales on the gradient Richardson number. Accurate error analysis of these estimates of Ri require the small scale turbulence statistics over the space-time volume of the measurements. This requires multiple sensor packages on spaced TLS platforms.

3.6 Boundary layer structure and dynamics

Data acquired with a previous version of the turbulence payload during the month of December 2008, revealed the presence of layers of unprecedented low turbulence intensity. Figure 8 shows a time series and corresponding spectra for two subsections of the hot-wire velocity data from a 0-250m ascent and consecutive descent. The turbulence intensity in the quiet regions is surprisingly low and will be further investigated in the coming winter months. Such extreme low turbulence layers do however require sensor improvements.

3.7 Instrument improvements needs

Although Figure 8 shows some occasional interference in the data, these data were collected with a previous version of the turbulence payload of lesser quality. Improvements have since been made in the isolation of the ground lines and connectors that have fixed these problems.

Figure 8 and 9 however show that in very low turbulence conditions, interferences contaminate the spectra at the higher frequencies. For 1-second spectra estimates, less of the -5/3 power law of the inertial range can be fitted because of the proximity of the noise floor, thus reducing the accuracy of the estimates.

In figure 8 the low turbulence spectrum (red) reveals a major interference at ~20 Hz that we believe to be due to vibration of the wind vane. The latest prototype sensor was improved to isolate the probes from such sources of mechanical noise. However no verification data are yet available because of the absence of such low turbulence regions from the data collected in the following spring and summer of 2009.

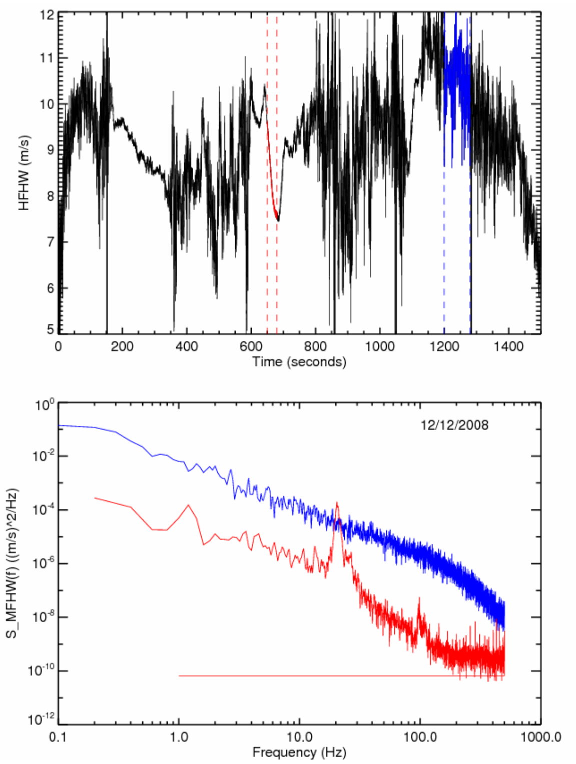

Figure 8. High resolution Hotwire velocity time series (top) and spectral densities for a very quiet (red) and a more turbulent (blue) layers.

Further instrument development efforts will emphasize pushing down the noise floor by using more sensitive probes and improving the data logger's bit -resolution (currently a 16 bit digitizer) and improving the overall noise performances of the electronics.

ACKNOWLEGMENTS

The authors would like to specially thank Dr. Walter Bach from the Army Research Office (ARO) for his support and key role in the development and improvements of the TLS technology.

Dr. Steve Nelson from the National Science Foundation (NSF) for funding our research.

Dr. Dan Wolfe (NOAA), site manager of the Boulder Atmospheric Observatory (BAO), for giving us access to the facility and permitting measurements in the shadow of their 300 m tall instrumented tower.

Steve Semmer (NCAR) for extensive help with the calibration of our instruments in the wind tunnel and temperature controlled bath.

Dr. Ben Balsley, and Dr. Florence Bocquet for helping with field measurements and research discussions.

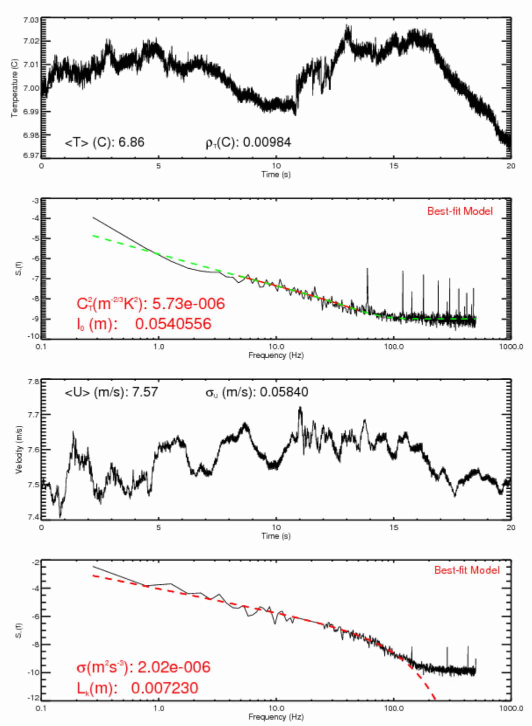

Figure 9. Temperature and velocity time series and spectra for low turbulence.

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