P2.11 DISPLACED-BEAM SMALL APERTURE SCINTILLOMETER TEST: CASES-99 STABLE BOUNDARY LAYER EXPERIMENT

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1. INTRODUCTION

We test a Displaced-Beam Small Aperture (laser) Scintillometer (DBSAS) under stable nighttime conditions. With this instrument the inner length scale of turbulence, l_0 and the structure parameter of the refraction index, C_n^2 can be determined over a path-length of up to 250 m. From these parameters fluxes of sensible heat and momentum can be derived applying Monin-Obukhov similarity theory (MOST). The DBSAS derived fluxes are therefore not only averaged in time but in space as well, which allows a shorter flux-averaging time. Furthermore, averaging out of eddies over the measurement volume - as is the case with a sonic anemometer - does not play a role, which allows low observation heights. Both aspects are a major advantage in turbulence measurements in the stable boundary layer (SBL), which is often very shallow and non-stationary in nature.

A drawback of the DBSAS method is that it relies on a prescribed form of the refractive index spectrum in the dissipation range for which still no universal expression has been established. This issue will be discussed in section 2. In addition the superiority of the DBSAS over the eddy-covariance method to obtain statically stable fluxes over short averaging times will be illustrated. Last, a comparison will be presented between eddy covariance and DBSAS derived fluxes as well as the turbulence variables, C_n^2 and ε, the dissipation rate of turbulent kinetic energy (TKE), which follows directly from l_0.

2. THEORY

A scintillometer consists of a transmitter and a receiver. The receiver measures the intensity fluctuations in the radiation emitted by the transmitter caused by refractive scattering of turbulent eddies in the scintillometer path. In this investigation we use the SLS20 DBSAS manufactured by Scintec AG (Thiermann, 1992). With this instrument a light beam of one source is split into two parallel, displaced beams with orthogonal polarizations. By determining both the variances of the logarithm of the amplitude of the two beams, B_1 and B_2 and the covariance of the logarithm of the amplitude fluctuations between the two beams, B_{12}, one can solve l_0 and C_n^2. The Scintec SLS20 uses a low power class 3a type laser at a wavelength, λ of 670 nm, a beam displacement distance, d of 2.7 mm and a detector diameter, D of 2.5 mm.

At optical wavelengths the contribution of temperature fluctuations dominates the scintillometer signal, i.e. the structure parameter of temperature C_T^2 can be deduced from the C_n^2 measurement. ε can be deduced from l_0 and the definition of the Kolmogorov scale,

$$\eta = l_0\left(\frac{3\beta}{\mathrm{Pr}}\right)^{-\frac{3}{4}} = \left(\frac{\nu^3}{\varepsilon}\right)^{\frac{1}{4}}, \qquad (1)$$

where β is the Obukhov-Corrsin constant (=3.47), Pr the Prandtl number (=0.72) and ν is the kinematic viscosity. C_T^2 and ε follow MOST to give fluxes of heat and momentum.

The procedure we followed to calculate 10 minute averaged ε and C_T^2 from 6 s measurements of B_{12} and B_1 is after Frehlich (1992). This accounts for the lognormal distribution of l_0, C_n^2 and ε, as well as the effect of intermittency on β.

In deriving l_0 and C_n^2 from the B_1 and B_{12} measurements, one integrates over the full spectrum of the refractive index, $\phi_n = 0.033\, C_n^2\, k^{-11/3} f_A$. The first part of ϕ_n describes the inertial range of the spectrum and f_A describes the decay of the refractive index fluctuations in the dissipation range and equals unity in the inertial range. The form of the inertial range of the spectrum is well known. For f_A Hill and Clifford (1978) developed a physical model, which they fitted to the limited data set of Champagne et al. (1977).

Based on Eq. (1) of Hill and Lataitis (1989) we derive the spectral weighting functions $W_{12}(k)$ and $W_1(k)$ which show how the Hill-spectrum, f_A is weighted in determining B_{12} and B_1:

$$W_{12}(k) = 4\pi^2 K^2\, 0.033\, C_n^2 \int_0^L k^{-\frac{8}{3}} J_0(kd) \sin^2\left[\frac{k^2 x(L-x)}{2KL}\right] \times \left[\frac{4J_1^2(kDx/2L)}{(kDx/2L)^2}\right] dx \qquad (2)$$

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where x is the co-ordinate along path length L, $K = 2\pi/\lambda$ is the optical wave-number, k the turbulent spatial wave-number, and J_0 and J_1 are Bessel functions of the first kind. $W_1(k)$ follows directly from Eq. (1) for d = 0. Convolution of $W_{12}(k)$ and $W_1(k)$ with f_A yields B_{12} and B_1 respectively.

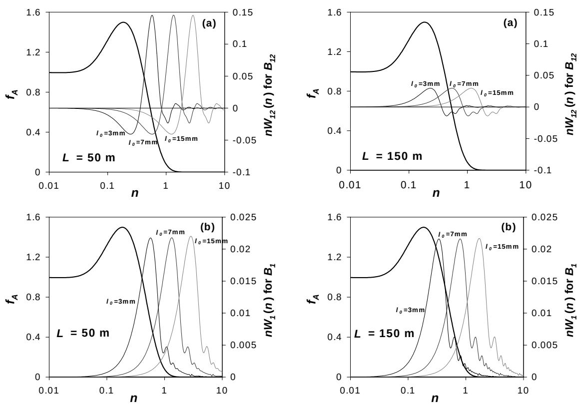

Figure 1: Hill spectrum, f_A plus its weighting functions W_{12} and W_1 in determining B_{12} (Fig. 1a) and B_1 (Fig. 1b) for 3 values of the inner scale, l_0 and 2 different path lengths, L.

Fig. 1 shows the weighting functions $W_{12}(n)$ and $W_1(n)$ ($n = k\eta$) together with Hill's formulation of f_A for a number of path lengths and inner scale lengths. The instrument constants are those of the Scintec SLS20 DBSAS. All $W(n)$ are scaled such that $\int W(n)dn = 1$ to make it possible to compare $W(n)$ for different l_0 and L. In addition, $nW(n)$ is plotted rather then $W(n)$ to ensure that the area under any portion of this semi-log plot is proportional to the total weight.

First, Fig. 1 shows that for small l_0 $W_{12}(n)$ and $W_1(n)$ comprise the entire f_A spectrum with most weight on the continuous fall-off part of f_A where all models agree. For large l_0 however, most weighting is where f_A is already 0 and only a small part of the spectrum at high wave-numbers contributes to B_{12} and B_1.

Second, Fig. 1a shows that for different L, $W_{12}(n)$ is almost stationary, but exhibits large changes in the amplitude. For L = 50 m $W_{12}(n)$ has a large negative peak where f_A is non zero, which is in fact so large that the convolution between $W_{12}(n)$ and f_A, i.e. B_{12} gives a negative number. The large amplitudes in $W_{12}(n)$ for short path lengths will make the determination of B_{12} more sensitive to the actual form of f_A.

Third, Fig. 1b shows that for different L, $W_1(n)$ has constant amplitude, but shifts to lower wave-numbers for larger L. This means that for large l_0 and short path lengths the total f_A, which is contributes to B_{12} and B_1 is limited even more.

It can be concluded from Fig. 1 that for large l_0, especially for short path lengths the theoretical basis for this type of DBSAS derived l_0 is quite slim since only a very small part of f_A is weighted, therefore heavily depending on its exact form, as well as that of the weighting function.

C_T^2 and ε are also determined from eddy covariance data for comparison. C_T^2 is a scaling parameter of the temperature spectrum in the inertial range and is defined as:

$$C_T^2 = \frac{D_T}{r^{2/3}} = \frac{\overline{\left[T(x) - T(x+r)\right]^2}}{r^{2/3}} \tag{3}$$

, where D_T denotes the structure function, $T(x)$ denotes the temperature at position x and $T(x+r)$ denotes the temperature at position separated from x by a distance r. Using Taylor's frozen turbulence approximation C_T^2 can be calculated from an eddy-covariance time series. We estimated C_T^2 for $r \approx 1$ m.

ε is determined from the inertial range spectrum of the TKE. Considering only the longitudinal wind component S_u, the spectral energy density is described by

$$S_u(\kappa) = \alpha\, \varepsilon^{2/3} k^{-5/3} \tag{4}$$

, where α is the Kolmogorov constant (= 0.55) and k is the spatial wave-number. Hartogensis et al. (2002) describe the procedures we follow here to estimate C_T^2 and ε from eddy covariance data in more detail

3. RESULTS

3.1 Experiment

The Scintec SLS20 scintillometer described here was operated during the CASES-99 stable boundary layer experiment that took place during October 1999 at a grassland site near the town of Leon (50km east of Wichita), Kansas, USA. Poulos et al. (2002) give a comprehensive description of CASES-99. The scintillometer was installed over a path-length of 112m at a height of 2.45 m. The eddy-covariance system - set-up at a height of 2.65 m and operated at 20Hz - consisted of a CSAT3 sonic anemometer and a KH20 Krypton hygrometer, both from Campbell Scientific Inc., Logan, USA.

3.2 Space And Time Averaging By Scintillometers

Fig. 2 shows the 6 s averaged sensible heat flux, H of the DBSAS for the night of 4 to 5 October. Based on these very short period DBSAS fluxes, the non-stationary turbulent structures can clearly be distinguished with very little scatter.

Fig. 3 shows the DBSAS and eddy covariance H for different flux averaging periods. Conversely to Fig. 2, Fig 3 is characterized by continuous turbulence. Both the DBSAS and eddy covariance fluxes jitter up and down in part due to turbulent structures in the signals and in part due to noise because of incomplete flux statistics, indicating that the averaging time is still too short. We argue that if the statistical error in H estimated by the standard deviation, σ_H of the eddy covariance and DBSAS flux is the same for a certain averaging-interval they contain the same turbulent information. Equally, if σ_H of one instrument remains the same for two consecutive averaging intervals, at the shorter of the two a stable, noise-free flux was already attained.

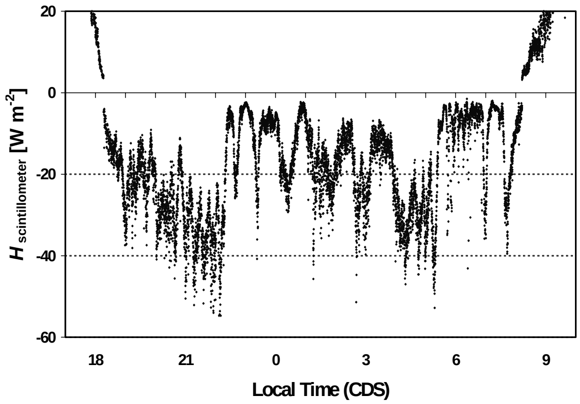

Figure 2: 6 s averaged DBSAS sensible heat flux, H for non-stationary turbulence night of 4 to 5 October of CASES-99.

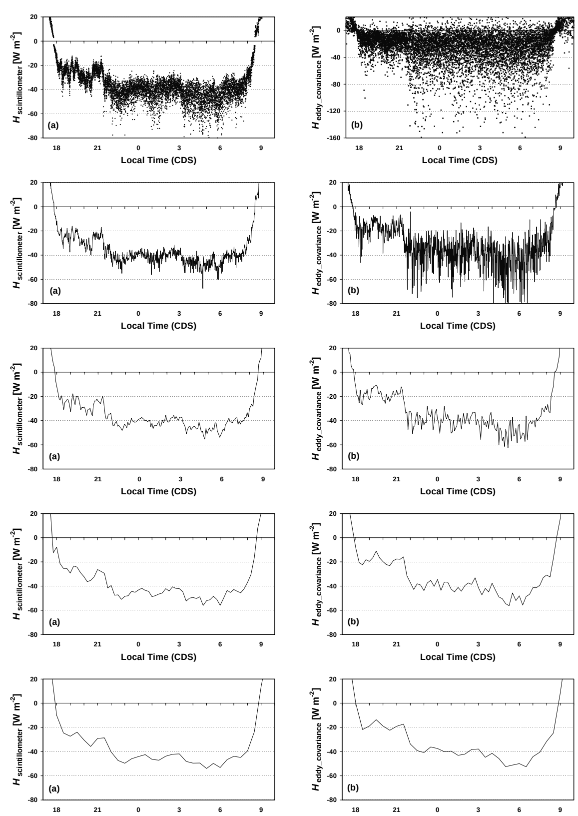

Figure 3: Sensible heat flux, H for the night of 24 to 25 October during CASES-99 of the DBSAS (a) and eddy covariance system (b) using averaging periods of 6 seconds, 1 minute, 5 minutes, 15 minutes and 30 minutes.

Fig. 4 depicts σ_H for the eddy covariance method and the DBSAS for the continuous turbulent period between 22:30 and 5:00 of Fig. 3. It quantifies the superiority of the DBSAS statistical error.

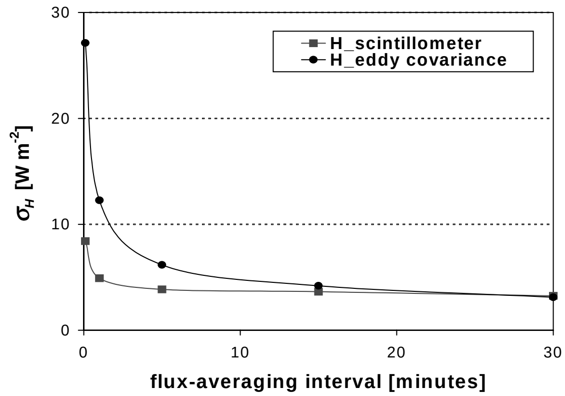

Figure 4: Standard deviation of the sensible heat flux, (σ_H) for the DBSAS and eddy covariance system between 22:30 of 24 October and 5:00 of 25 October during CASES-99 as a function of flux-averaging time.

3.3 DBSAS Compared With Eddy Covariance Data

De Bruin et al. (2002) and Hartogensis et al. (2002) found that the DBSAS l_0 measurements seem to be biased for, yet, unknown reasons. This results in an overestimation of the friction velocity u_* for small u_* values (large l_0) and an underestimation in u_* for large u_* values (small l_0).

De Bruin et al. (2002) attributed these effects to the influence of white noise and inactive turbulence on the DBSAS signal for which they proposed empirical correction functions.

In this study we try to attribute these systematic errors to instrument variables only. It was found that the u_* underestimation for high u_* disappears by lowering the beam displacement, d by a margin within the accuracy with which the DBSAS manufacturer specifies d (d = 2.6 instead of 2.7 mm). For small u_* only a small part of the Hill-spectrum is weighted at high wave numbers. This indicates that the theoretical basis for the DBSAS for small u_* is limited. In Hartogensis et al. (2002) these issues are discussed in greater detail.

In Figs. 5 shows the comparison between DBSAS and eddy-covariance derived ε, C_T^2. This illustrates the performance of the DBSAS independent of MOST. Fig.6 shows a comparison of the flux-variables u_*, θ_* and H.

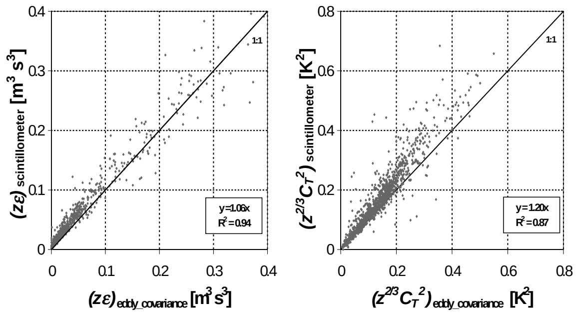

Figure 5: Comparison of 10 minute averaged TKE dissipation rate, ε (Fig. 5a) and structure parameter of temperature, C_T^2 (Fig. 5b) determined from DBSAS and eddy covariance data.

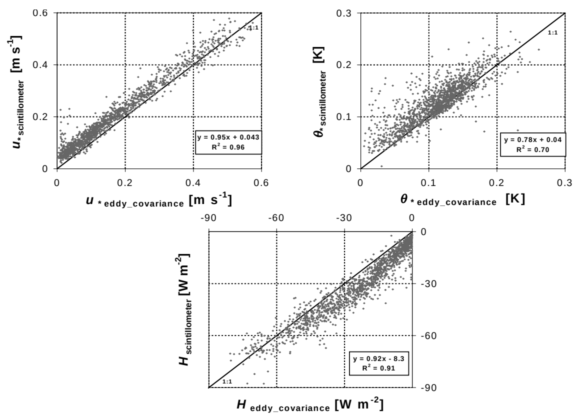

Figure 6: Comparison between the 10 minute averaged DBSAS and eddy covariance derived friction velocity, u_*, temperature scale, θ_* and sensible heat flux, H

4. CONCLUSIONS

The DBSAS is a powerful research instrument in determining the dissipation rate of TKE, ε, the structure parameter of temperature, C_T^2 and the heat and momentum flux; especially in the often non-stationary and shallow SBL where fluxes need to be determined over short averaging periods and close to the surface.

By adapting the working hypothesis of an adjusted displacement distance between the two DBSAS beams, the reported underestimation in u_* for large u_* values (small l_0) disappears. For small u_* (large l_0) the accuracy of the estimated u_* becomes more and more limited. This is illustrated by the fact that only a very small part of the refractive index spectrum in the dissipation range, f_A is weighted in determining l_0, making the method very sensitive to the exact form of f_A. The application of f_A in stable conditions has never been thoroughly examined. We feel that more work has to be done on this issue, i.e. investigation of f_A for a variety of stratification classes.

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