

Scintillometer Intercomparison Study—Continued

J. Kleissl · C. J. Watts · J. C. Rodriguez · S. Naif ·
E. R. Vivoni

Received: 2 September 2008 / Accepted: 12 January 2009 / Published online: 6 February 2009
© The Author(s) 2009. This article is published with open access at Springerlink.com

Abstract An earlier study by one of the authors reported significant differences of up to 21% in linear regression slopes between six Kipp & Zonen large-aperture scintillometers. In this note, the consistency of this increasingly popular instrument for measuring sensible heat fluxes at the km scale was quantified by comparing measurements from four Scintec boundary-layer scintillometers and one large-aperture scintillometer over nearly identical transects. The Kipp & Zonen instrument's sensible heat fluxes were more than 20% larger than those from the Scintec instruments, while the difference in regression slopes amongst the Scintec instruments was 3% or less.

Keywords Instrument intercomparison · Large-aperture scintillometer · Sensible heat flux

1 Introduction

Partitioning the available thermal energy at the ground surface into latent $L_v E$ (L_v is the latent heat of vaporisation, and E is evaporation) and sensible H heat fluxes is a major challenge for remote sensing algorithms and numerical hydrometeorological models. While the scale of the footprint of point measurements of H typically is considerably smaller than a satellite pixel or numerical model grid cell, scintillometers offer the unique possibility of measuring H averaged over the km scale (e.g. McAnaney et al. 1995; de Bruin et al. 1995; Meijninger et al. 2002; Schüttemeyer 2005; Kleissl et al. 2009).

J. Kleissl (✉) · S. Naif
Department of Mechanical and Aerospace Engineering, University of California, San Diego, USA
e-mail: jkleissl@ucsd.edu

C. J. Watts · J. C. Rodriguez
Departamento de Fisica, Universidad de Sonora, Sonora, Mexico

E. R. Vivoni
Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology,
Socorro, NM, USA

Eddy-covariance systems (e.g. Lee et al. 2004) measure H directly from covariances in the vertical velocity w and air temperature T . Loescher et al. (2005) found differences in H among eight sensors ranged from -1 to $+8\%$ when averaged over all measurements and corrected for mean temperature offsets. Linear regressions of seven instruments versus the eighth instrument in neutral to unstable stability conditions showed insignificant offsets, slope differences ranging from 19 – 31% , coefficients of variation typically greater than 90 – 98% , and standard deviations of the slopes of 7 – 11% . Using six large-aperture scintillometers (LAS) manufactured by Kipp & Zonen (K&Z), The Netherlands, Kleissl et al. (2008) found differences in the regression slopes for H of up to 21% , with typical differences of 5 – 6% . We extend and improve upon this study by (i) using short horizontal paths over homogeneous terrain, and (ii) intercomparing scintillometers from different manufacturers, in particular three boundary-layer scintillometers (BLS) from Scintec, Germany, and one K&Z LAS.

2 Field Experiments and Data Processing

All measurements were taken over a flood-irrigated (i.e. close to flat) peanut field (20% ground cover) of $630\text{ m} \times 225\text{ m}$ near Rayon, Sonora, Mexico (29.722581° N , $110.591534^\circ\text{ W}$, 570 m above mean sea level, WGS84) during the summer season characterized by the North American monsoon. The height of the furrows and plants were 0.05 and 0.15 m , respectively. As sketched in Fig. 1, we deployed two new single-beam Scintec BLS450 (s/n $^{00}78$, $^{00}79$), one 2006 double-beam Scintec BLS900 (s/n $^{00}59$), and one 2005 K&Z LAS (s/n 050026; this LAS was not used in the intercomparison study by Kleissl et al. (2008)). The LAS calibration was checked according to the manufacturer's instructions and was found to be within specifications (mean deviation of 10 mV or 1.1%). Also before the experiment, the BLS900's signal processing unit's hardware and software were updated.

The K&Z LAS and the Scintec BLS450 and BLS900 are commercial off-the-shelf systems that are designed for applications with path lengths from 500 m to 5000 m using apertures of 0.152 m (LAS) and 0.145 m (BLS). While the LAS uses a Fresnel lens to focus the received radiation onto the photo diode, the BLSs collimate the beam(s) by a plane convex lens onto one (BLS450) or two (BLS900) Si photodiodes. Absorption fluctuations may be falsely interpreted as scintillations, hence artificially increasing the derived sensible heat flux. Using the "two-in-one" configuration of the BLS900, the structure parameter of the refractive index, C_n^2 , could be corrected for absorption fluctuations due to dust or humidity. To standardize the intercomparison, the two beams in the BLS900 are treated as two separate transects and the absorption correction is not applied; absorption corrections cannot be applied to the LAS and BLS450. For the same reason the saturation correction and inner and outer scale corrections as suggested by the Scintec processing software are not applied. The BLS output was recorded and stored internally as 1-min averages using a 5 Hz transmitter setting. The LAS also computed C_n^2 internally and output analog voltages for C_n^2 and signal strength that were sampled by a CR10X datalogger at 1 Hz , and stored as 1-min averages. All C_n^2 output was reprocessed with the correct transect geometry to obtain the sensible heat flux, H .

On July 8, 1800 MST a meteorological station was located near the transect centre that included measurements of net radiation (K&Z NR-Lite, $z = 1.55\text{ m}$), wind speed U (RM Young 05103, $z = 2.7\text{ m}$), air temperature T and relative humidity (Vaisala HMP45C, $z = 1.55\text{ m}$), and two soil heat-flux plates at the top and bottom of the furrows (Hukseflux, $z = -0.01\text{ m}$). Data for July 7 1800 to July 8 1800 MST were obtained from an eddy-covariance tower 2 km north-west of the field site. Air pressure p was interpolated horizontally

and extrapolated vertically from the Eta Data Assimilation System (EDAS) weather model archive at 3-h and 80-km resolution.

Since correlation coefficients between scintillometer measurements are very large (Kleissl et al. 2008) short experiments suffice to obtain statistically convergent results. Thus each of our experiments was set-up for about one day. Due to the wide beam of the BLS, any two parallel BLS transects with the transmitter pointing in the same direction would have to be spaced laterally by at least $\approx 0.14L$, L being the transect length. Consequently, to avoid cross-contamination of two separate transmitter signals at one receiver, experiment 1 was designed with three BLS receivers feeding off of one BLS900 transmitter (Fig. 1). The LAS transect was parallel, but pointed in the opposite direction, thus avoiding the $0.14L$ spacing requirement. For experiment 2, the BLS receivers '78 and '79 were exchanged, while transects BLS'59 and LAS were left unchanged. Having different instruments over identical transect geometries allowed us to control the effects of slightly different footprint and transect geometry (especially beam height). For experiment 3, the BLS'78 and LAS were dismantled

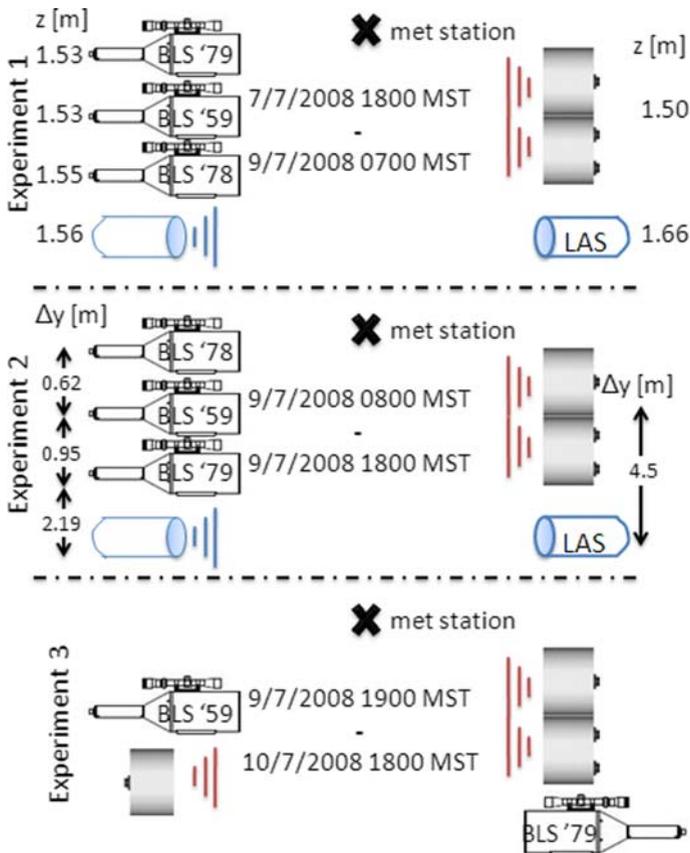


Fig. 1 Set-up of three scintillometer intercomparison experiments. The sketch of experiment 1 shows the heights of the centre of the receivers and transmitters, while experiment 2 shows the lateral distance between the instruments. These numbers, as well as the BLS900 double-beam transect’s location, were identical for all three experiments. Between experiments 1 and 2 the BLS receivers '78 and '79 were exchanged. In experiment 3, BLS450 '79 was set-up as a separate transect with receiver and transmitter

and two separate and opposite BLS transects were set-up to investigate the effect of BLS transmitter differences (Fig. 1). Height measurements gave accuracies of ≈ 0.03 m or 2% in relative height of the beams, while the transect lengths were $L = 635 \pm 0.3$ m. The height accuracy produces about 1% uncertainty in the results for H , while the length accuracy of 0.05% or better does not affect the results significantly (Hartogensis et al. 2003).

A LAS receiver measures intensity fluctuations in the radiation emitted by the transmitter to derive the structure parameter of the refractive index, C_n^2 . H can be calculated iteratively using Monin-Obukhov similarity theory, viz

$$\left(\frac{-0.78 \times 10^{-6} p}{T^2}\right)^{-2} C_n^2 \left(1 + \frac{0.03}{BR}\right)^{-2} z_{\text{eff}}^{2/3} = T_*^2 f_T(z_{\text{eff}}/L_{\text{MO}}), \tag{1}$$

$$L_{\text{MO}} = \frac{u_*^2 T}{g \kappa T_*}, \tag{2}$$

$$H = -\rho_{\text{air}} c_p u_* T_*, \tag{3}$$

where BR is the Bowen Ratio (we assume $BR = 1$), g is the gravitational acceleration, $\kappa = 0.4$ is the von Karman constant, z_{eff} is the effective beam height, and $f_T(\zeta) = c_1(1 - c_2\zeta)^{-2/3}$ is the universal stability functions for unstable conditions with $c_1 = 4.9$, $c_2 = 6.1$, (Wyngaard et al. 1971; Andreas 1989; de Bruin et al. 1993). The friction velocity u_* is derived from estimates of the roughness length $z_o = 0.01$ m, the integrated flux-profile relationships (Panofsky and Dutton 1984), and measurements of U . In this short note we refer to Kleissl et al. (2008); Hill et al. (1992), and de Bruin (2002) for a detailed discussion of scintillometer theory and data processing.

3 Results and Discussion

Intense nocturnal monsoon rainfall had occurred in the region during the week before the study, resulting in high soil moisture. July 8 was mostly cloudy with maximum net radiation of 450 W m^{-2} and a brief cloudy period related to thunderstorms in the early afternoon. July 9 and 10 were overcast in the morning, but mostly sunny in the afternoon with maximum net radiation of 600 W m^{-2} . Daytime and nighttime soil heat fluxes were 10–20% and 100% of the net radiation, respectively; H was about 15% of net radiation in the daytime. Figure 2 shows the time series of C_n^2 for the duration of the experiment and for the different scintillometers; while C_n^2 is positive definite, it is proportional to the magnitude of H (Eqs. 1–3). A thunderstorm rain event occurred on July 10 at 0400 MST resulting in the loss of the scintillometer signal for one hour. C_n^2 follows the trends of net radiation described earlier.

Since C_n^2 depends on height (Eq. 1) while H does not, we present comparisons of H , where z_{eff} differs for each transect, but all other parameters in Eqs. 1–3 are identical. Consequently our results are insensitive to the choice of BR and meteorological parameters, as errors in these variables affect all scintillometer measurements equally. The BLS900 '59 was chosen as the reference measurement since it was the only instrument that was not moved during the field campaign. Only unstable daytime measurements are analyzed.

Figure 3 shows scatter plots of H . For experiment 1, all BLS scintillometers show near perfect agreement, with regression slope differences of 1% or better. At a regression slope of 1%, neither H from two beams of the double beam BLS900 nor H from the three different receivers are significantly different. However, H from the LAS is more than 20% larger than

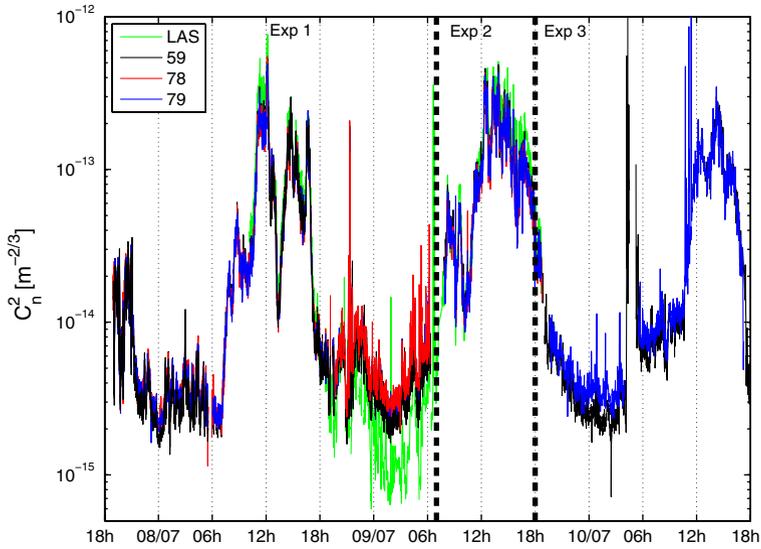


Fig. 2 Semi-logarithmic plot of the structure parameter of the refractive index (C_n^2) for the duration of the field experiment. Only the last two digits of the serial number are shown in the axis labels. For the BLS900 '59 only the result for beam 1 is shown

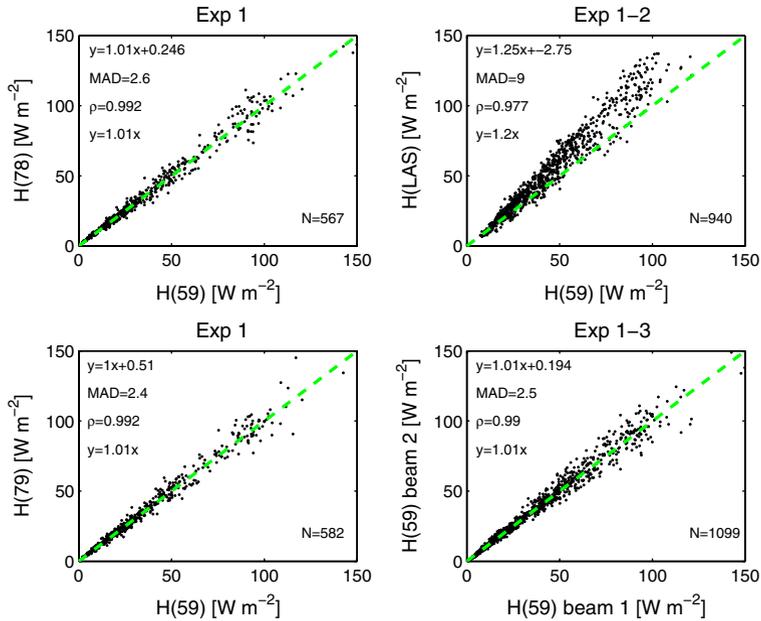


Fig. 3 Scatter plots of H from beam 1 of BLS900⁰⁰59 (x -axis) versus the other scintillometers. The experiment is listed in the title of each subplot. The text indicates the regression equations $H = aH_{BLS,59}$ and $H = aH_{BLS,59} + b$, the mean absolute deviation $\text{mean}|H_{BLS,59} - H|$, the correlation coefficient $\rho(H_{BLS,59}, H)$, and number of 1-min samples N . The green dashed line is the 1:1 line

Table 1 Linear regression slopes of sensible heat fluxes between different scintillometers in unstable conditions

	BLS900 '59 beam 2	BLS450 '78	BLS450 '79	K&Z LAS
BLS900 '59 beam 1—Exp 1	$1.01x + 0.19$	$1.01x + 0.25$	$1.00x + 0.51$	$1.25x - 2.75$
BLS900 '59 beam 1—Exp 2	same	$0.99x + 0.73$	$0.99x + 0.8$	same
BLS900 '59 beam 1—Exp 3	same	—	$0.97x + 1.54$	—

The width of the 95% confidence intervals for the regression slopes and intercepts are 0.017 and 0.894 W m^{-2} , respectively, or less

H from the BLSs. The scatter in the results increases for larger heat fluxes since these data points were taken in unsteady conditions with broken clouds on July 9, 2008 1200–1500 MST (Fig. 2).

Correlation coefficients were about 0.99 for the BLSs. The LAS-BLS intercomparison shows a smaller correlation (0.98) and larger mean absolute deviation. Despite the short averaging time of 1 min the correlation coefficients are larger than those from intercomparisons of eddy-covariance measurements (average $R^2 = 0.94$, Loescher et al. (2005)) and only slightly smaller than the 10-min averaged correlation coefficients of Kleissl et al. (2008). This indicates the fundamental robustness of scintillometry due to path averaging and accuracy of the photodiode.

Linear regression equations for the other experiments are shown in Table 1. Since the regression slopes between scintillometers BLS '78 and BLS '79 for experiments 1 and 2 were not significantly different, any slight differences in transect paths or errors in measurements of transect height (Fig. 1) did not affect our results. When two separate BLS transects were deployed in experiment 3, the regression slopes were statistically significantly different, but on the same order as uncertainties in the measurement of transect height and still better than other surface-flux measurement techniques (Hartogensis et al. 2003; Loescher et al. 2005). All linear regression intercepts were small (less than 3 W m^{-2}) and most were not significantly different from zero.

In summary, linear regression of H showed significant differences between instruments from different manufacturers of the same magnitude (20%) as differences between K&Z LASs (Kleissl et al. 2008). Since Hartogensis et al. (2008) found instrument errors in the K&Z LAS, our new findings suggest that the differences observed by Kleissl et al. (2008) and the larger H for the LAS in our study are due to electronic or optical problems in the K&Z LAS. However, fundamentally the scintillation technique is very robust and consistent as demonstrated by the Scintec sensors, which showed differences of 3% or better and that were mostly not statistically significant. The Scintec BLS scintillometer consistency appears to be better than any other instrument for continuous environmental heat-flux measurements.

Acknowledgements This study was sponsored by UC-MEXUS grant CN-08-223 and NSF IRES program (OISE 0553852). The K&Z LAS and the two Scintec BLS450 were provided by the Mexican National Water Commission through their regional office in Hermosillo, Sonora.

Open Access This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

References

Andreas E (1989) Two-wavelength method of measuring path averaged turbulent surface heat fluxes. *J Atmos Ocean Technol* 6:280–292

- de Bruin H (2002) Introduction: renaissance of scintillometry. *Boundary-Layer Meteorol* 105(1):1–4
- de Bruin H, Kohsiek W, van den Hurk B (1993) A verification of some methods to determine the fluxes of momentum, sensible heat, and water vapor using standard deviation and structure parameter of scalar meteorological quantities. *Boundary-Layer Meteorol* 63:231–257
- de Bruin H, van den Hurk B, Kohsiek W (1995) The scintillation method tested over a dry vineyard area. *Boundary-Layer Meteorol* 76:25–40
- Hartogensis O, Watts C, Rodriguez J-C, de Bruin H (2003) Derivation of an effective height for scintillometers: La Poza experiment in northwest Mexico. *J Hydrometeorol* 4:915–928
- Hartogensis O, Kesteren BV, Evans J, Bradford J, Moene A, Holtslag A (2008) Sensible and latent heat fluxes with an optical and millimeter wave scintillometer system at the chilbolton test range. In: Proceedings 8th annual meeting of the European Meteorological Society (EMS), Amsterdam, The Netherlands
- Hill R, Ochs G, Wilson J (1992) Measuring surface-layer fluxes of heat and momentum using optical scintillation. *Boundary-Layer Meteorol* 58:391–408
- Kleissl J, Gomez J, Hong S-H, Hendrickx J, Rahn T, Defoor W (2008) Large aperture scintillometer inter-comparison study. *Boundary-Layer Meteorol* 128:133–150
- Kleissl J, Hong S-H, Hendrickx J (2009) New mexico scintillometer network in support of remote sensing, and hydrologic and meteorological models. *Bull Amer Meteorol Soc* 90(2)
- Lee X, Massman W, Law B (2004) *Handbook of micrometeorology: a guide for surface flux measurement and analysis*. Springer, Berlin, 250 pp
- Loescher H, Ocheltree T, Tanner B, Swiatek E, Dano B, Wong J, Zimmerman G, Campbell J, Stock C, Jacobsen L, Shiga Y, Kollas J, Liburdy J, Law B (2005) Comparison of temperature and wind statistics in contrasting environments among different sonic anemometer-thermometers. *Agric Forest Meteorol* 133:119–139
- McAnaney K, Green A, Astill M (1995) Large-aperture scintillometry: the homogeneous case. *Agric Forest Meteorol* 76:149–162
- Meijninger W, Hartogensis O, Kohsiek W, Hoedjes J, Zuurbier R, de Bruin H (2002) Determination of area averaged sensible heat fluxes with a large aperture scintillometer over a heterogeneous surface—flevoland field experiment. *Boundary-Layer Meteorol* 105:63–83
- Panofsky H, Dutton J (1984) *Atmospheric turbulence*. Wiley, New York, 397 pp
- Schüttemeyer D (2005) *The surface energy balance over drying semi-arid terrain in West Africa*. Ph.D. thesis, Wageningen University, Wageningen, The Netherlands
- Wyngaard J, Izumi Y, Collings SA Jr (1971) Behavior of the refractive-index-structure parameter near the ground. *J Opt Soc Amer* 61:1646–1650