TURBULENT SURFACE FLUXES ON KILOMETRE SCALE OBTAINED WITH SCINTILLOMETRY; A REVIEW

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ABSTRACT

A brief review is presented of the work we carried out in the last years on long-path scintillometer systems to measure fluxes of sensible and latent heat on kilometre scales. Results are presented of various field experiments, e.g. Flevoland (The Netherlands), LITFASS-98 (Germany), EVA_GRIPS (Germany) and GLOWA-Volta (Ghana).

1. INTRODUCTION

Field studies carried over different landscape types have revealed that the scintillation method provides reliable fluxes of sensible heat (*H*) and latent heat (L_vE) (where L_v is latent heat of vaporization) on kilometre scale. Meijninger et al. (2002a) presented a systematic study on the question whether a Large Aperture Scintillometer (LAS) can be used over heterogeneous flat agricultural terrain in the Flevopolder (The Netherlands). In the same study we tested the LAS in combination with a radio wave scintillometer (27 GHz) (see Meijninger et al., 2002b). Beyrich et al. (2002) carried out a long-term test of the LAS in Lindenberg (Germany) in the context of the LITFASS-98 project over partly forested and undulating agricultural terrain. Kohsiek et al. (2002) presented a long-term test of an extra Large Aperture Scintillometer (XLAS) for a normal year at Cabauw (The Netherlands) over polder landscape. Recently, Kohsiek et al. (2006) analysed XLAS data gathered at Cabauw during a dry year and in Lindenberg (Germany). The latter experiment (LITFASS-2003) was in the framework of the EVA_GRIPS project (see Beyrich et al., 2006) in which several scintillometers were used: one LAS was set-up over a forest and a combined LAS-millimetre wave scintillometer (94 GHz) installed over the same path as used by Beyrich et al. (2002). Schüttemeyer (2005) tested the LAS at three locations in Ghana.

The objective of this paper is to present a brief review of the scintillation method and some results of several long-path scintillometer studies. Our work can be regarded as a renaissance of research done earlier in the 1970’s to 1990’s (see DeBruin, 2002).

2. THEORETICAL BACKGROUND

A scintillometer consists of a transmitter containing a source producing a beam (with diameter D) of electro-magnetic radiation (with wavelength λ) parallel to the surface, and a receiver installed at a distance L (i.e. the path length). Atmospheric turbulence causes the scintillation effect, by which the measured signal at the receiver fluctuates. The variance of the natural logarithm of the received intensity (I) is the main parameter measured by the scintillometer. The LAS and XLAS, which are designed and built by the Meteorology and Air Quality Group (Moene, 2005), are governed by the following equation

$$C_n^2 = 4.48\sigma_\chi^2 D^{\frac{7}{3}} L^{-3}, \tag{1}$$

where σ_χ^2 is the variance of the natural logarithm of amplitude (χ) fluctuations ($\sigma_{\ln I}^2 = 4\sigma_\chi^2$).

For the radio wave (RWS at 27 GHz) and millimetre wave scintillometers (MWS at 94 GHz) the relation between σ_χ^2 and C_n^2 is given by

$$C_n^2 = 8.06\sigma_\chi{}^2 k^{\frac{-7}{6}} L^{\frac{-11}{6}}, \tag{2}$$

with optical wave number $k = \dfrac{2\pi}{\lambda}$.

The structure parameter of the refractive index of air C_n^2 is given by

$$C_n^2(\lambda) = \frac{A_T^2(\lambda)}{\overline{T}^2} C_T^2 + \frac{2A_T(\lambda)A_Q(\lambda)}{\overline{T}\overline{Q}} C_{TQ} + \frac{A_Q^2(\lambda)}{\overline{Q}^2} C_Q^2, \tag{3}$$

in which T is the absolute temperature, Q the absolute humidity [kg m^{-3}], C_T^2 and C_Q^2 structure parameters for T and Q, respectively and C_{TQ} the structure parameter between T and Q. A_T and A_Q are wavelength dependent constants. It can be shown that

$$C_{TQ} = r_{TQ}\sqrt{C_T^2 C_Q^2}, \tag{4}$$

in which r_{TQ} is the correlation coefficient between T and Q in the inertial sub-range. For more details see Meijninger et al. (2002b; 2006).

For the near-infrared wavelength at which the LAS and XLAS operate, the first term in the r.h.s. of equation 3 dominates, i.e. the water vapour effects are relatively small (Moene, 2003). At radio and millimetre wavelengths the last two terms of equation 3 become important. In short, a LAS and XLAS yield C_T^2 corrected for water vapour effects and a radio or millimetre wave scintillometer yields C_Q^2, using an estimate for r_{TQ}. The latter can be obtained in different ways (see Lüdi et al, 2006; Meijninger et al., 2006).

Next step is to apply Monin Obukhov Similarity Theory (MOST) to derive the fluxes of sensible heat flux H and evaporation E from C_T^2 and C_Q^2. For unstable conditions these read

$$\frac{C_T^2 (z-d)^{\frac{2}{3}}}{T_*^2} = \frac{C_Q^2 (z-d)^{\frac{2}{3}}}{Q_*^2} = c_1 \left(1 - c_2 \frac{z-d}{L_{Ob}}\right)^{-\frac{2}{3}}, \tag{5}$$

in which d is the zero-plane displacement, c_1 and c_2 are empirical constants, $L_{Ob} = \frac{u_*^2 T}{g k_v T_*}$ the Obukhov length with the temperature scale $T_* = \frac{-H}{\rho c_p u_*}$ (ρ is the density of air and c_p is the specific heat of air at constant pressure), the humidity scale $Q_* = \frac{-E}{u_*}$ and the friction velocity u_*. For the LAS the 'standard' MOST relation between u_* and wind speed (u) and a given roughness length (z_{0m}) are needed also.

To avoid saturation, the scintillometers have to be installed relatively high above the surface (see Kohsiek et al., 2006). This has the advantage that during daytime the free convection (H_{fc} and $L_v E_{fc}$) limit of equation 5 yields good approximations for H and $L_v E$,

$$H_{fc} \approx (z-d) \left(\frac{g}{T}\right)^{\frac{1}{2}} \left(C_T^2\right)^{\frac{3}{4}}, \tag{6}$$

$$L_v E_{fc} \approx (z-d) \left(\frac{g}{T}\right)^{\frac{1}{2}} \left(C_T^2\right)^{\frac{1}{4}} \left(C_Q^2\right)^{\frac{1}{2}}. \tag{7}$$

3. RESULTS

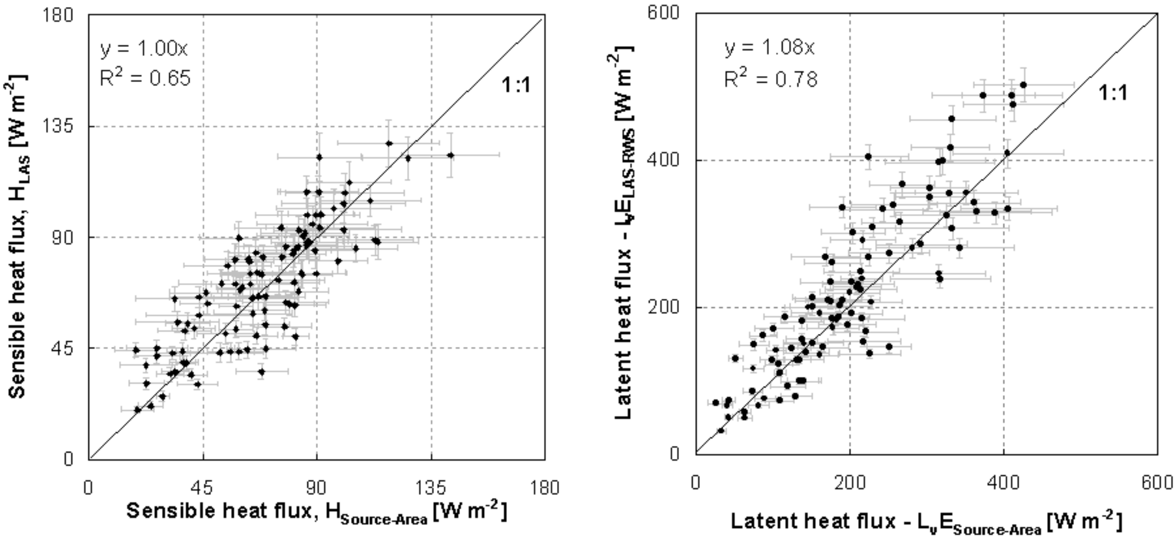

FIGURE 1. Comparison between fluxes (30-minute mean values) measured with the LAS and (footprint weighed) EC observations. Left panel: *H* obtained with the LAS. Right panel: $L_v E$ obtained with combined LAS-Radio wave scintillometer (reproduced from Meijninger et al., 2002a,b).

In FIGURE 1 the scintillometer results are shown of the Flevoland field experiment. The surface beneath the 2.2 km long path of the LAS consists of rectangular fields covered with wheat, potatoes, sugar beat or onions. Above these crops eddy-covariance (EC) stations were installed as well as radiation sensors and soil heat flux plates. In the left panel the sensible heat flux derived from the LAS measurements are compared with area-averaged EC observations. Detailed information of the EC measurements is given in Meijninger et al. (2002a;b). In the right panel the latent heat flux results (measured with the combined LAS-radio wave scintillometer system) are compared. The required correlation coefficient between temperature and humidity (r_{TQ}) in the so-called two-wavelength method are taken from one of the EC stations. The errors bars depicted in both figures represent the uncertainty of the fluxes.

Beyrich et al. (2002) discusses the results of a long-term test of the LAS at Lindenberg (Germany) over a path length of 4.7 km (which is operational since April 1998). This LITFASS study region is a 20×20 km^2 area around the Meteorological Observatory Lindenberg (MOL) of German Weather Service (DWD). The LITFASS area corresponds to the model domain of a non-hydrostatic micro-scale model with a grid size of 100 m (the LITFASS Local Model – LLM) the development of which is part of the LITFASS project. The central part of the area represents just one grid cell (14×14 km^2) of the 'Deutschland-Modell', the operational high-resolution NWP model of DWD until the end of 1999.

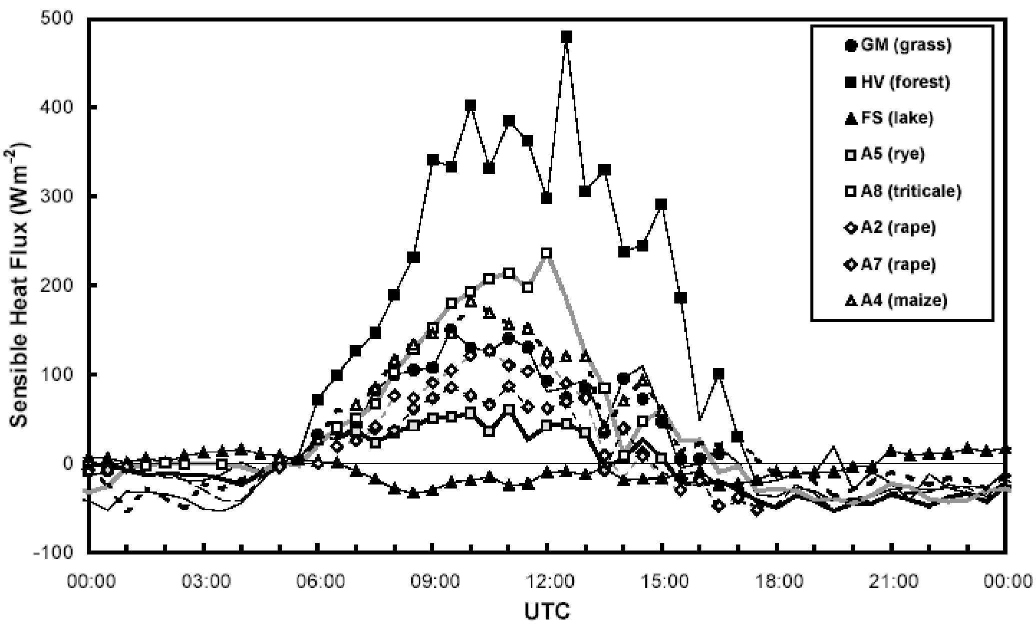

FIGURE 2. Diurnal cycle of the sensible heat flux (measured with EC-stations) over different surfaces for 25 May 2003 (reproduced from Beyrich et al., 2006).

The orography has been formed by the inland glaciers during the last ice age, and is characterized by slight, irregular undulations of the terrain and by the existence of a number of small and medium-sized lakes. The land use in the LITFASS area is dominated by forest (42%) and agricultural farmland (41%); other relevant surface types are lakes (7%), meadows (5%) and villages (4%). The forest is mainly situated in the western part of the area while agriculture is dominant in the eastern part. This mixture of surface types is rather typical for the whole region and even for larger parts of northern Central Europe south of the Baltic Sea. To illustrate the heterogeneity of the LITFASS landscape in FIGURE 2 the diurnal variation of the sensible heat flux is depicted for 25 May. The 'skills' of the LAS instruments are depicted in FIGURE 3 together with the composite EC fluxes. It can be seen that the scintillometers perform well. In FIGURE 4 the results for the latent heat flux are shown obtained from the LAS-millimetre wave scintillometer system (using measured r_{TQ}) over the same mixed farmland. The LAS-MWS values are about 25% higher than the EC observations. However, the latter suffers from the energy-balance 'non-closure' problems (approximately 30%).

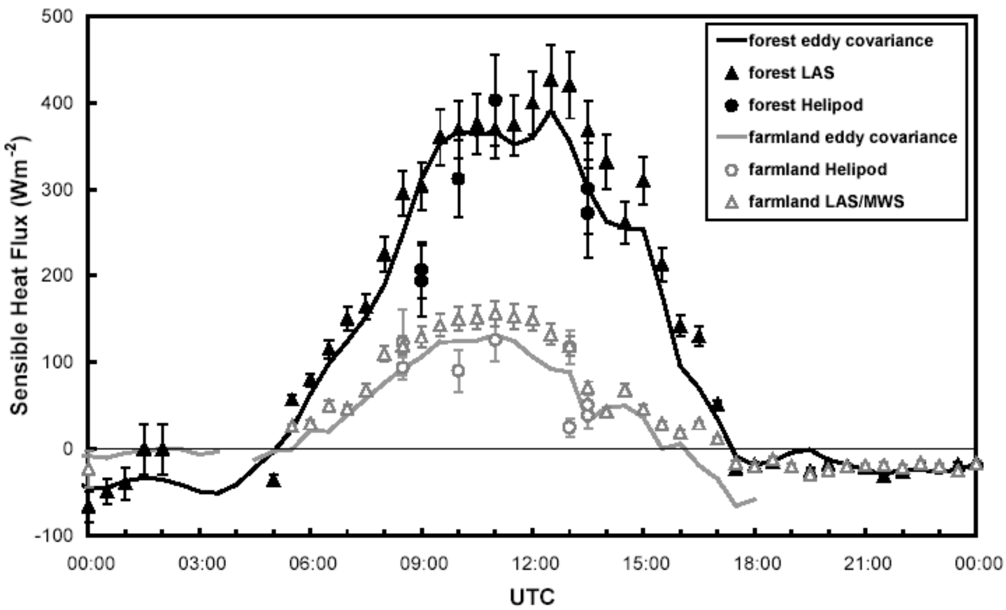

FIGURE 3. Diurnal cycle of the sensible heat fluxes over farmland and forest. Comparison of the composites from the EC observations with the line-averaged fluxes derived from the LAS and Helipod measurements on 25 May 2003 (reproduced from Beyrich et al., 2006).

Schüttemeyer et al. (2006) examined the applicability of a system consisting of a LAS, radiometers and soil heat flux plates to measure the seasonal cycle of the components of the surface energy balance in the Volta basin in West Africa (see FIGURE 5). This climate is characterized by a strong north-south gradient of mean annual rainfall and the occurrence of pronounced dry and wet seasons within one annual cycle, causing a strong seasonal variation in the natural vegetation cover. For comparison EC observations of the fluxes of momentum, sensible and latent heat were performed as well (FIGURE 6). Measurements of a full seasonal cycle in 2002/2003 are gathered (including the rapid wet-to-dry transition after the wet season) at three locations in Ghana (see FIGURE 5): one in the humid tropical southern region, one in the north close to the Sahel and one in between.

This study was part of the GLOWA-Volta Project, which has the goal of creating a scientifically sound decision-support system (DSS) for the assessment, development and sustainable use of water resources by means of an integrated model (Schüttemeyer et al., 2006). The applicability of the LAS under harsh environmental conditions in a tropical country such as Ghana was clearly demonstrated in this study.

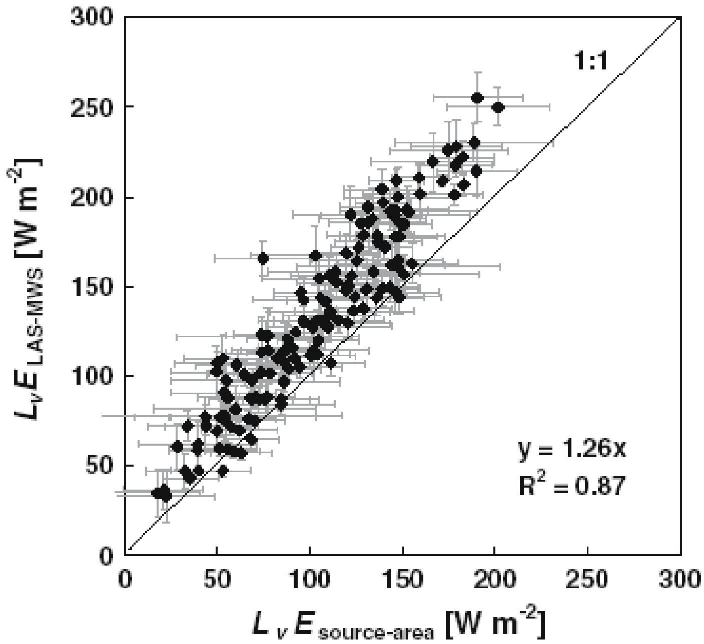

FIGURE 4. Scatter plot of the latent heat fluxes of the LAS-MWS versus the aggregated EC fluxes (reproduced from Meijninger et al., 2006).

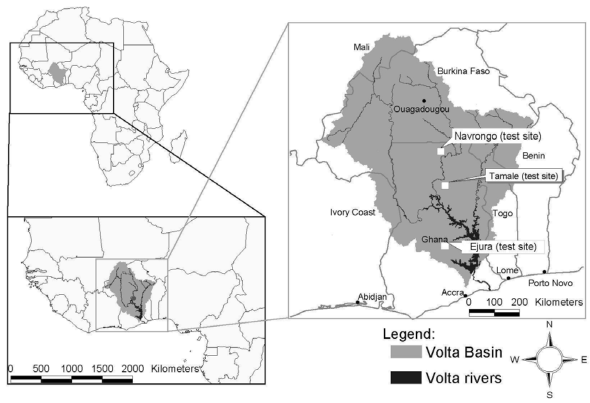

FIGURE 5. Locations of the 3 LAS instruments in the GLOWA-Volta project in Ghana (reproduced from Schüttemeyer et al., 2006).

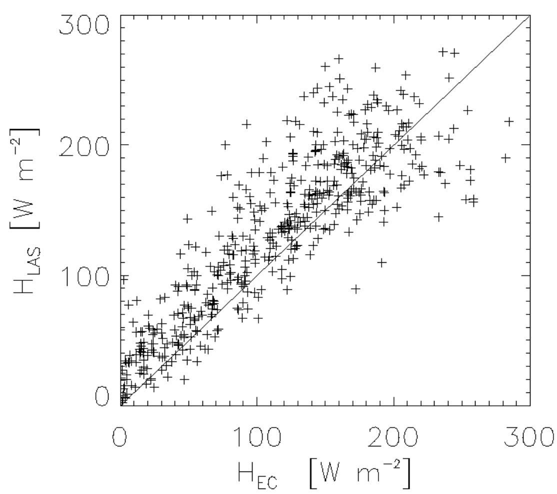

FIGURE 6. Comparison between LAS and a single-point EC station at Tamale (Ghana) (reproduced from Schüttemeyer et al., 2006).

4. DISCUSSION AND CONCLUDING REMARKS

The scintillation method has been tested in other experiments, which are not shown in section 3. Some more examples are studies of a XLAS over paths of 10 km (Kohsiek et al., 2002; 2006) and LAS experiments in Greece (DeBruin et al., 1996), Turkey (Meijninger and DeBruin, 2000). In general, it can be concluded that the scintillation method performs well at scales of several kilometres over (moderately) heterogeneous terrain. In several projects scintillometers are used in combination with remote-sensing techniques (see e.g. Gieske and Meijninger, 2005; Hemakumara et al., 2002; Jia et al., 2003; see also www.met.wau.nl).

Long-range scintillometer measurements (>2 km) with the LAS and XLAS require tall towers or hills for the installation. In some cases this means that the instrument is measuring over slanted paths (Hartogensis et al., 2005).

In case the scintillometer is installed too close to the surface or when the surface conditions become (very) dry, saturation may occur. Recently, this saturation phenomenon has been studied by Kohsiek et al. (2006) using XLAS data. They also demonstrate that the LAS and XLAS can be corrected for this saturation effect.

Our research on the combined LAS-radio/millimetre wave scintillometer system revealed that in particularly the R/MWS is sensitive to mast vibrations (Meijninger et al., 2006). A minor disadvantage of this two-wavelength method is the requirement of *in-situ* r_{TQ} data (see Meijninger et al., 2002b; 2006). Recently, Lüdi et al. (2006) showed that r_{TQ} can be derived from the LAS-MWS measurements directly (so-called bi-chromatic correlation). More research is required to make this method operational. So far, a LAS-R/MWS system has not been tested under semi-arid conditions. Note that the Centre for Ecology and Hydrology (CEH), Wallingford (UK) now uses a LAS-MWS system for measuring evaporation in catchments (R. Harding, personal communication).

5. LITERATURE

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