9.2 SCINTILLOMETER FLUXES OF SENSIBLE AND LATENT HEAT OVER A HETEROGENEOUS AREA – A CONTRIBUTION TO LITFASS-2003

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1. INTRODUCTION

Surface fluxes of sensible heat (*H*) and evaporation (L_vE) are important in many atmospheric processes and can be measured with reasonable accuracy over homogeneous areas. However, surface fluxes that are representative for large natural landscapes (comparable to the grid box size of numerical models or satellite remote sensing pixels) are more difficult to determine because at these scales the earth's surface is always heterogeneous.

The scintillation technique is one of the few techniques that can provide fluxes at scales of several kilometers (10km). For example the combination of a large aperture optical scintillometer (LAS) and a microwave scintillometer (MWS), also known as the two-wavelength method (Andreas, 1989), can provide the fluxes of both *H* and L_vE at kilometer scales.

So far there have been only a few experiments with (optical) scintillometers operated over heterogeneous terrain (see e.g. Beyrich *et al*., 2002; Meijninger *et al*., 2002a) and only one experiment that systematically investigated the two-wavelength method using mircowave scintillometers (Meijninger et al., 2002b).

In this study we will present the results of scintillometer measurements carried out during the LITFASS-2003 experiment (Lindenberg, Germany) using three large aperture scintillometers (LAS) and one microwave scintillometer (MWS). The main goal of this study is to investigate the performance of the scintillometers in providing area-representative fluxes over a complex heterogeneous area. For that we will compare the scintillometer results against aggregated eddy-correlation (EC) measurements using a footprint model (following Meijninger *et al*., 2002a,b). In addition we will also discuss briefly some aspects that require further attention, such as uncertainty in the stability functions, outer scale effects, saturation and the correlation between temperature and humidity (R_{Tq}) that plays an important role in the two-wavelength method.

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2. EXPERIMENTAL SETUP

The orography of the Lindenberg area (20×20km^2) has been formed by inland glaciers during the last ice age and is characterized by slight, irregular undulations and a number of small lakes. The land use consists of 43% forest, 45% farmland, 7% open water and 5% villages, making it an ideal complex area for testing the scintillation technique.

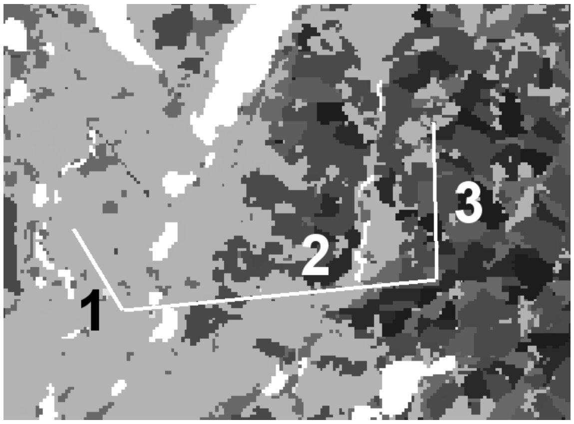

Figure 1: The Lindenberg area and the 3 scintillometers paths (1: Forest-LAS, 2: XLAS, 3: LAS-MWS). The white areas are open water, dark areas farmland and light gray areas forest.

One LAS together with the MWS were installed over a path of 4.7km (effective height 43.6m). The source area of these scintillometers consists roughly of 10% forest and 90% farmland. A second LAS was installed over a homogenous forest (path length 3km, effective height 46.8m). Finally, an extra large aperture scintillometer (XLAS) was set-up over a path length of 10.8km (effective height 69.7m). The source area of the XLAS consists roughly of 70% forests and 30% farmland. The scintillometer paths are shown in Figure 1.

3. THEORY

3.1 *The Scintillation Method*

The LAS and XLAS scintillometers operate at a near-visible wavelength (λ = 930 nm), making them most sensitive to turbulent temperature fluctuations. The microwave scintillometer operates at a wavelength of 3.2 mm (94 GHz). At this wavelength also turbulent water vapor fluctuations are important. By applying the Monin-Obukhov Similarity Theory (MOST) the fluxes of sensible heat (*H*) can be derived from the LAS and XLAS measurements and from the LAS-MWS combination (two-wavelength method) also the latent heat flux (L_vE). In the MOST procedure we used local wind speed data to determine the friction velocity and net radiation plus soil heat flux data for the moisture correction (LAS and XLAS only). For the two-wavelength method we used in-situ R_{Tq} data from an EC system (at same height as LAS-MWS).

There are a number of expressions for the stability function that is required in the MOST procedure (Andreas, 1988; De Bruin *et al.*, 1995). For example in the free convective limit the function proposed by De Bruin gives a 16% higher flux than using the function proposed by Andreas. In this study we have taken the average of both expressions to derive the average fluxes of sensible heat and latent heat plus their uncertainty (see error bars in figures in section 4). Furthermore we included uncertainties of all required input parameters and data in the error bars.

3.2 *Footprint Analysis*

In order to validate the fluxes of sensible heat and latent heat of the scintillometers that are installed over mixed areas (i.e., the LAS-MWS combination and the XLAS) against the in-situ EC measurements we used an analytical footprint model. Considering the atmospheric conditions (wind direction and atmospheric stability) we determined the source area of the scintillometers (see Meijninger *et al.*, 2002a,b). Finally, by combining the source area with the spatial weighting function of the scintillometer and the land use map (Figure 1) we have determined the relative contribution of each surface type, namely forest, open water and farmland (as a function of wind direction and stability).

4. RESULTS

4.1 *Forest LAS*

In Figure 2 the sensible heat fluxes of the LAS are plotted against the EC measured fluxes. In the figure all data of the experiment are shown for both daytime and nighttime periods. As mentioned before, the error bars show the uncertainty of the LAS fluxes, which is mostly related to the consensus in the stability functions and uncertainty in the used zero-displacement height. The figure shows that the LAS gives slightly higher values than the EC method.

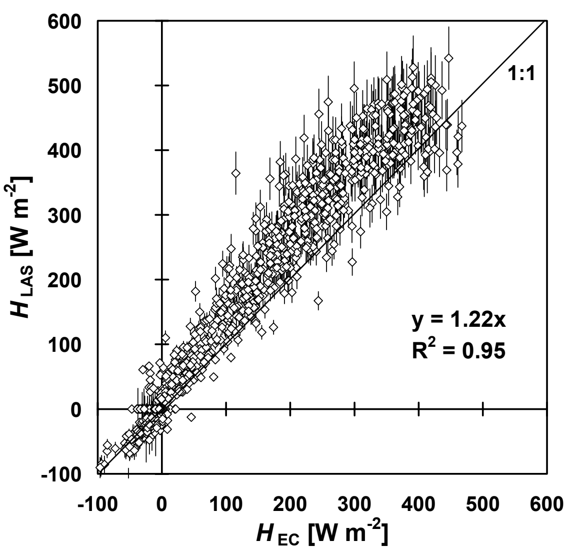

Figure 2: Sensible heat flux of the Forest-LAS (plus tolerances) plotted against the EC measured fluxes of sensible heat (Day number 139-168).

In Figure 3 the results of one of the Golden days (Day number 153) are shown. Again it can be seen that the LAS gives slightly higher fluxes than the EC system. Interesting to see is that both Figures show that also during night-time (stable) periods the LAS performs very well.

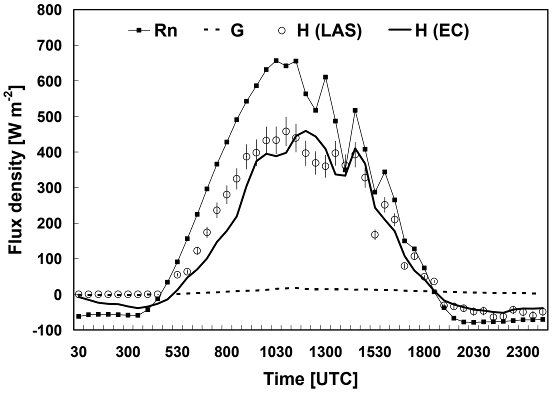

Figure 3: Diurnal cycle of the sensible heat flux measured by the LAS and EC system plotted against time together with the net radiation (R_n) and soil heat flux (G_s) (Golden day number 153).

4.2 *LAS-MWS*

Unfortunately the MWS of the LAS-MWS system broke down during the experiment. Therefore we can present only the first 10 days. In Figure 4 the sensible heat flux results of the LAS-MWS system (unstable conditions only) are plotted against the area-averaged fluxes of the estimated source area. The latter results are derived from the in-situ EC measurements using a footprint model.

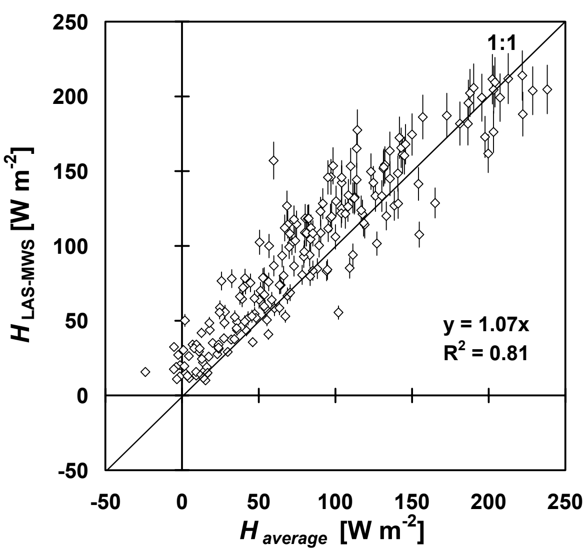

Figure 4: Sensible heat flux (plus tolerance) of the LAS-RWS combination plotted against the area-averaged flux of sensible heat (Day number 139-149, unstable periods only).

It can be seen that the both results agree very well. In Figure 5 the latent heat fluxes are compared. This Figure shows that the LAS-MWS system gives higher fluxes than the aggregated EC measurements. It must be noted that most EC systems show a gap in the energy balance closure while the LAS-MWS system does not (see Figure 6). Since the MWS is most sensitive to eddies in the order of the first Freznel zone ($F = \sqrt{\lambda L} \approx 4\text{m}$) it is also possible that the MWS is more sensitive to outer scale effects (that might be related to surface heterogeneities) than the LAS ($F = \sqrt{\lambda L} \approx 0.06\text{m}$). The influence of absorption at 94 GHz is very small and therefore not considered here (A. Lüdi, *pers. communication*)

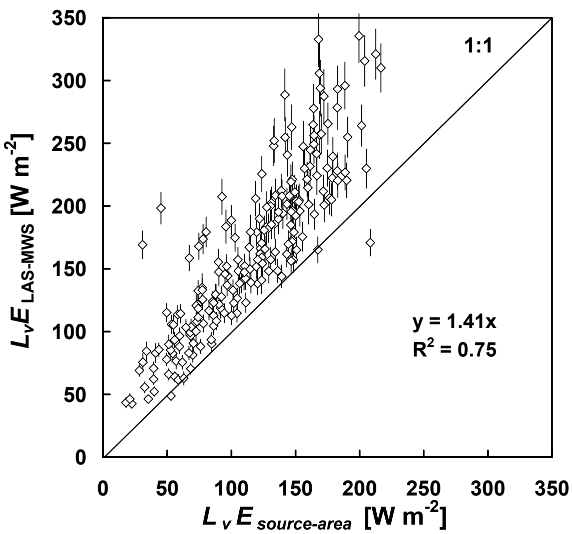

Figure 5: Latent heat flux of the LAS-MWS combination (plus tolerances) plotted against the area-averaged flux of latent heat (Day number 139-149, unstable periods only).

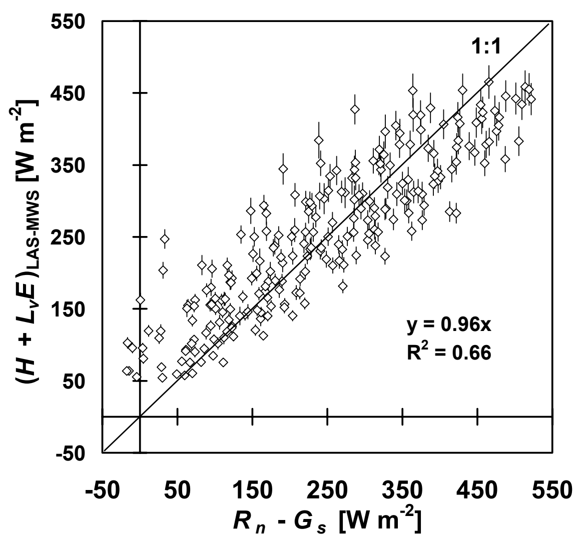

Figure 6: Energy balance closure of the LAS-MWS system compared to the available energy (R_n– G_s).

4.3 *XLAS*

In Figure 7 the XLAS fluxes are compared with the aggregated EC measurements. It can be seen that the XLAS fluxes systematically underestimate the EC fluxes. This phenomenon is known as saturation of the XLAS signal. Here it is a combined result of the long path length of the XLAS and the high sensible heat flux of the forest (up to 600 W.m^{-2}).

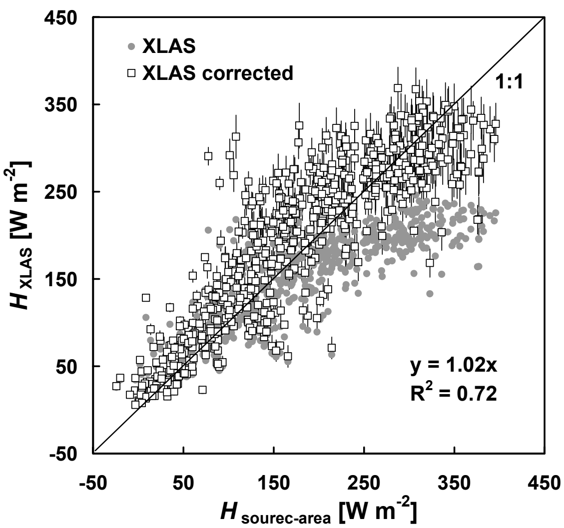

Figure 7: Non-corrected and corrected sensible heat flux of the XLAS (plus tolerances) plotted against the area-averaged flux of sensible heat (Day number 139-168).

As long as the saturation stays small (i.e. no super saturation occurs) it is possible to correct for the saturation effect. Here we used the correction of Kohsiek *et al*. (2002), which is based on the saturation criterion of Frehlich and Ochs (1990):

$$H_{XLAS\_corr} = (1 + 0.002 H_{XLAS}) H_{XLAS} \qquad (1)$$

In Figure 7 the corrected XLAS fluxes are shown. It can be seen that the corrected fluxes agree much better with the averaged EC fluxes. Unfortunately, there is still no consensus about the saturation point, and the following correction (Kohsiek *et al*., 2002). For example, according to the saturation criterion of Frehlich and Ochs the LAS of the LAS-MWS system and the Forest-LAS should also experience saturation. However, the results don't show this (Figure 2 and 4), indicating that the criterion of Frehlich and Ochs might be too strict

5. CONCLUSIONS & FUTURE PLANS

The results demonstrate that the scintillometers give fluxes of sensible and latent heat that are comparable to the aggregated EC fluxes and that the scintillation method can be applied over heterogeneous areas (see also Beyrich *et al*., 2004, see **9.1**). Aspects that we will focus on are the impact of R_{Tq} on the LAS-MWS system (using the LES results of Uhlenbrock *et al.,* 2004, see **9.3**), saturation of the optical scintillometers, the influence of outer scale effects on the MWS, and the application of scintillometers during night-time (stable) periods.

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