ESTIMATING SURFACE FLUXES IN IRRIGATED AREAS WITH SCINTILLOMETERS

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ABSTRACT

Scintillometers directly measure area-averaged fluxes between the instrument's transmitter and receiver. In agro-hydrological applications scintillometers have several advantages over the more traditional eddy-covariance method, which are outlined in this paper. For flux estimates at field-scale only optical scintillometers can be used, which in principle give the sensible heat flux. In this paper we show that with additional measurements of net radiation and the soil heat flux, and imposing energy balance closure a good estimate of evapotranspiration is obtained.

1. INTRODUCTION

Scintillometry has proven to be a good alternative method to obtain are averaged surface fluxes over heterogeneous areas over spatial scales of up to 10 km and in non-stationary conditions in the stable surface layer (see e.g. the special issue on scintillometry in Boundary-Layer Meteorology, De Bruin, 2002). This study concerns agro-hydrological scintillometer applications of estimating surface fluxes in general and evapotranspiration (*ET*) in particular over homogeneous irrigated areas on field-scale, i.e. a scale of 50 to 500 m. Two types of scintillometers will be considered, notably the displaced beam small aperture scintillometer (DBSAS) and the large aperture scintillometer (LAS) deployed in the RAPID (Regional Advection Perturbations in an Irrigated Desert) field experiment in Idaho, USA in 1999 (De Bruin et al., 2005).

The DBSAS and the LAS are optical instruments that consist of a transmitter and receiver. The receiver records intensity fluctuations of the light beam emitted by the transmitter, which are caused by refraction of the beam upon its passage through the turbulent surface layer. These intensity fluctuations are a measure of the structure parameter of temperature, C_T^2. The DBSAS obtains also the dissipation rate of turbulent kinetic energy, ε, from the correlation between the two displaced beams. C_T^2 and ε are related to the surface fluxes of heat, *H*, and momentum, here given as the friction velocity u_*, by virtue of Monin-Obukhov similarity theory. For the LAS - that provides C_T^2 only - u_* is obtained from additional wind speed measurements and an estimate of the roughness length. *ET* can then be estimated from net radiation and soil heat flux measurements.

Note that whereas optical scintillometers are sensitive to temperature fluctuations and consequently *H*, micro-wave scintillometers are sensitive to humidity fluctuations and, in combination with a LAS, give *ET*. With a Microwave-LAS system *ET* can thus be determined directly from scintillometer turbulence measurements, without the need to include the energy balance (see e.g. Meijninger et al., 2002). However, here we are interested in estimating *ET* at field-scale and microwave scintillometers can only be operated over distances of several kilometres, so we are bound to use optical scintillometers.

The RAPID experiment concerned micrometeorological observations over extensive, well-irrigated fields covered with the fast-growing crop alfalfa surrounded by a desert. In these conditions dry, warm desert air can be advected over the cool evaporating surface by which sensible heat becomes negative and the water vapor deficit is increased, both enhancing evapotranspiration. As a result the surface layer is stably stratified and wind shear is the only turbulence generating mechanism. The DBSAS directly gives information on this process, the LAS does not. We will show that only for high wind speed conditions the heat contained in air is transported sufficiently to the surface to make *ET* exceed R_n.

We will outline the potential of scintillometers of obtaining fluxes of momentum and latent and sensible heat, and compare these with eddy covariance method based estimates for RAPID. Furthermore, scintillometers require less complex data processing and quality control procedures. Last, the transmitter and receiver of the instrument can be installed at the borders of the field by which the instrument directly measures an area averaged flux over the entire field rather then a over small, often unknown footprint and does not interfere with the farmer's activities in the field.

Note that the DBSAS also have advantages over the eddy covariance (EC) method in the often non-stationary stable surface layer, since they obtain statistically stable fluxes over very short interval times (<1 minute) as they average turbulence not only in time but also in space (Hartogensis et al., 2002).

2. SCINTILLOMETER THEORY

It is beyond the scope of this short article to give a full outline of the steps involved in getting from the raw measurements (intensity fluctuations) to fluxes. We will therefore describe some main lines only here. For more detailed information the reader is referred to the scintillometer review paper in this issue (De Bruin et al., 2006), the syllabus with selected papers by Andreas (1990), the afore mentioned Boundary-Layer Meteorology special issue (De Bruin, 2002) and the overview article by Hill (1997).

2.1 Difference between LAS and DBSAS.

A property of interest to describe the difference between the LAS and the DBSAS is the first Fresnel zone ($F = \sqrt{\lambda L}$), with λ is the wavelength, and L is the path length. The aperture diameter, D, of the DBSAS is "small" since $D < F \approx l_0$ applies. The LAS aperture is considered "large" because $l_0 < F << D$. The inner scale, l_0, marks the transition between the inertial and viscous-, energy dissipating range of eddy sizes and is of the order 0.2 cm - 2 cm near the surface. For the DBSAS F is a measure of the optically most effective eddies (~ 1 cm), which lies in the energy dissipation range of eddy scales. For the LAS D is a measure of the optically most effective eddies (~5 cm – 30 cm), which generally lies in the inertial range of eddy scales.

The description of the scintillometer principle measurement, i.e. refractive index fluctuations of the beam, involves complex wave-propagation theory and requires a theoretical form of the refractive index spectrum. It is the spectrum that contains the unknowns of the main scintillometer equation. The inertial part of the spectrum scales with C_n^2, the structure parameter of the refractive index, and follows the well-established –5/3 law. The dissipation part of the spectrum is based on a model developed by Hill (1978). His description of the dissipation spectrum is super-imposed on the inertial range formulation and exhibits a bump, the so-called Hill bump at the transition of inertial to dissipation range eddy scales, which is marked by the length scale l_0.

2.2 From raw measurements to fluxes.

The DBSAS operates two parallel beams displaced by a distance of 2.7 mm. It sees only dissipation range eddies. This means that the dissipation range spectrum containing two unknowns, C_n^2 and l_0, are needed to evaluate the raw measurements. The DBSAS method consists of solving C_n^2 and l_0 from intensity fluctuations measurements of one beam and the correlation between the two beams. C_n^2 and l_0 are directly related to C_T^2 and ε, which follow Monin-Obukhov scaling to give the sensible heat flux, H, and the momentum flux, u_*.

The LAS operates one beam. It sees primarily inertial range size eddies. This makes that the intensity fluctuations are related to C_n^2 only. To get to fluxes, one also needs a measure of the mechanically induced turbulence that contributes to the flux. For the LAS method it is customary to include wind speed measurements at a single height and an estimate of the roughness length, which, following the flux profile relationships gives u_*.

Note that for stable conditions mechanically induced turbulence is the only turbulence generating transport mechanism. The DBSAS directly contains this information through ε, whereas the LAS relies on flux profile relationships to include this transport mechanism.

We estimated ET from the scintillometer H measurements by imposing energy-balance closure, i.e.

$$ET = R_n - G - H \,, \qquad (1)$$

with R_n is net radiation and G is the soil heat flux at the surface.

3. EXPERIMENT

The RAPID experiment was carried out between 25 August and 19 September 1999 (DOY 237 – 262) in an agricultural area of 70 x 25 km in Idaho, USA. A full description of the used instrumentation can be found in De Bruin et al. (2005) and Hartogensis (2006).

In this study we will use one of the installed EC systems, mounted at 3.5 m height, consisting of a CSAT3 sonic anemometer and a KH20 hygrometer, both from Campbell Scientific Inc., Logan, USA. Raw measurements were recorded by a Campbell Scientific CR23X datalogger and stored on a laptop to be processed afterwards.

The LAS we used has a beam-aperture of 15 cm, and the incoherent light source operates at λ = 940 nm (near infrared). The instrument was built at Wageningen University, the Netherlands and was set-up over a path-length of 275 m. The height of the instrument varied along the path by ~ 0.5 m due to small-scale topographical features. Taking this into account we evaluated the effective height to be 3.15 m following Hartogensis et al. (2003). For the flux profile relations of wind-speed included in the LAS method we used wind-speed measurements taken from the sonic anemometer and a roughness length estimate of 0.03 m.

The SLS20 DBSAS we deployed uses a laser light source at $\lambda = 670$ nm (visible) which is split in two parallel beams with orthogonal polarization which are displaced from each other by a distance of 2.7 mm. It is a commercial instrument built by Scintec AG, Tübingen, Germany. We installed the DBSAS over a path length of 155 m at a height of 2.5 m.

All components that make up R_n were measured by a system consisting of a CM14 pyranometer and a CG2 pyrgeometer of Kipp and Zonen, Delft, the Netherlands. G was measured at 5 cm depth at two locations with a WS31 soil heat flux plate from TNO, Delft, the Netherlands. The heat storage above the plate was estimated using Pt100 soil thermometers built at Wageningen University, the Netherlands.

The equipment was installed between two centre-pivot irrigated alfalfa fields of approximately 1 mile by 1 mile. The experiment encompassed one full cutting cycle of alfalfa in which the crop varied between 10 cm at the start of the experiment to 35 cm at the end.

All the EC data were processed to get 30 minute averaged fluxes using the latest version of the EC-pack software package, developed by the Wageningen University (more details at www.met.wau.nl). The EC data at 3m appear not to fulfil energy balance closure, i.e. $R_n - G > ET + H$. We corrected for this effect by multiplying both the measured H and ET with a constant factor of 1.4. In this way our data artificially close the energy balance, as do we impose energy balance closure on our scintillometer ET estimate. We realize that our approach is arbitrary and that other correction procedures can be applied also. Recently, the significance of the energy balance closure problem has been recognized internationally (see e.g. the recent review paper by Culf et al., 2004).

4. RESULTS

4.1 Flux estimates from Scintillometers versus Eddy Covariance.

4.1.1 DBSAS versus Eddy Covariance.

FIGURE 1 compares the DBSAS derived turbulent fluxes against the EC derived turbulent fluxes for both stable and unstable conditions.

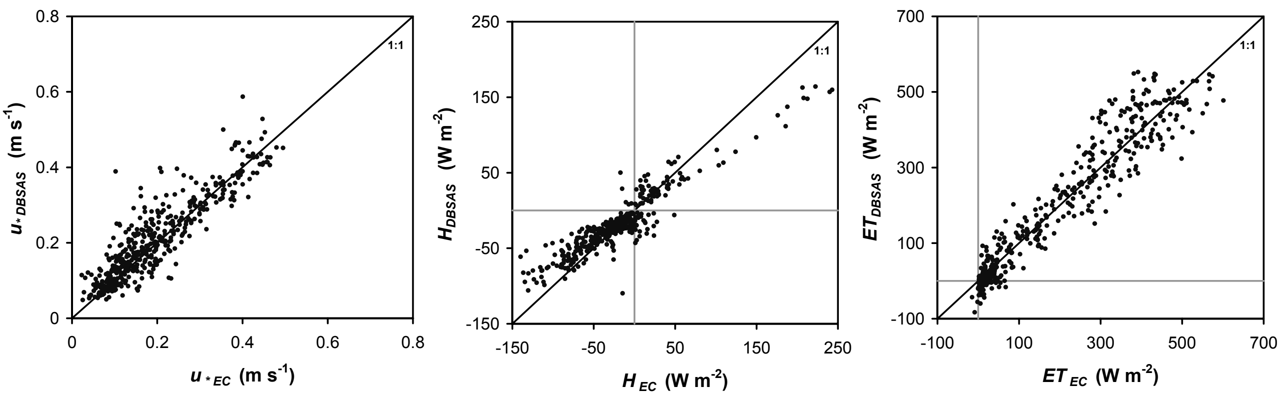

FIGURE 1. Displaced-Beam Small Aperture Scintillometer (DBSAS) fluxes versus Eddy-Covariance (EC) flux estimates during RAPID. u_* is friction velocity, H sensible heat flux and ET Evapotranspiration.

FIGURE 1 shows that a reasonable agreement is seen for the DBSAS and EC u_*, albeit with considerable scatter This is remarkable, because in several studies an overestimation of the DBSAS u_* for low values and an underestimation of the DBSAS u_* for high values have been reported with usually little scatter (e.g. De Bruin et al, 2002, Hartogensis et al, 2002 and Hartogensis, 2006). This behaviour is seen in H however. The over and underestimation of the DBSAS H for respectively low and high values of H is in part due to the energy balance closure correction we applied on the EC fluxes. The smaller scatter seen for the H comparison with respect to the u_* comparison indicates that the larger scatter seen for u_* is most likely due to errors in the EC u_* estimate, since the EC H, unlike the DBSAS estimate, is independent from u_*. The resulting ET estimates agree reasonably well considering the differences in the approaches used.

4.1.2 LAS versus Eddy Covariance.

FIGURE 2 compares the LAS derived turbulent fluxes against the EC derived turbulent fluxes for both stable and unstable conditions.

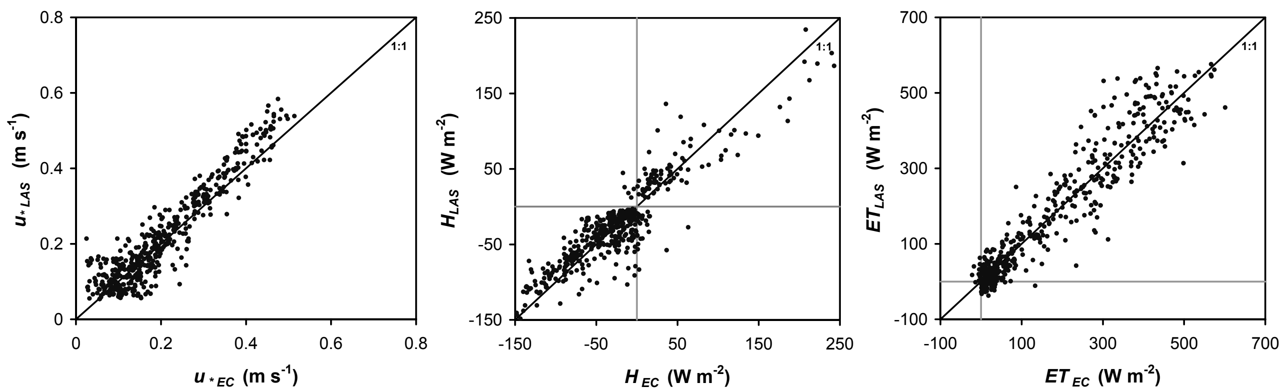

FIGURE 2. Large Aperture Scintillometer (LAS) fluxes versus Eddy-Covariance (EC) flux estimates during RAPID. u_* is friction velocity, *H* sensible heat flux and *ET* Evapotranspiration.

FIGURE 2 shows comparable results for the LAS as those depicted in FIGURE 1 for the DBSAS. For low u_* values and consequently for low values of H more scatter is seen. This is understandable because for the mechanical shear contribution to the fluxes flux profile relationships are used, which contain lower quality turbulence information than the the ε estimate used in the DBSAS method. Nevertheless, considering that the LAS is a more simple and robust instrument to operate than the DBSAS this is an encouraging result.
These findings corroborate the results of Hoedjes et al. (2002) who used a similar approach to estimate ET using a LAS over an irrigated field in North-West Mexico.

4.2 Advection versus Non-Advection conditions.

If we consider *large* horizontally homogeneous fields, as is the case for RAPID, where the atmospheric flow is in equilibrium with the underlying surface, the air temperature and humidity in the atmospheric surface layer are well adapted to the irrigated field and no longer have the properties of the dry upwind terrain. Crucial for our considerations is that a negative H implies that the atmosphere just above the surface is stably stratified and the negative buoyancy effects suppress turbulent motions. The turbulence, needed for vertical transfer of water vapour, therefore, can only be generated in a mechanical way. This means that *ET* can exceed R_n only if there is enough wind to offset the damping effects of stability. Under calm conditions it is to be expected that daily *ET* cannot exceed R_n. This common sense reasoning is supported by our measurements by EC and scintillometers in FIGURE 3.

Note that under high wind speed conditions (DOY 254), *ET* continues during night-time.

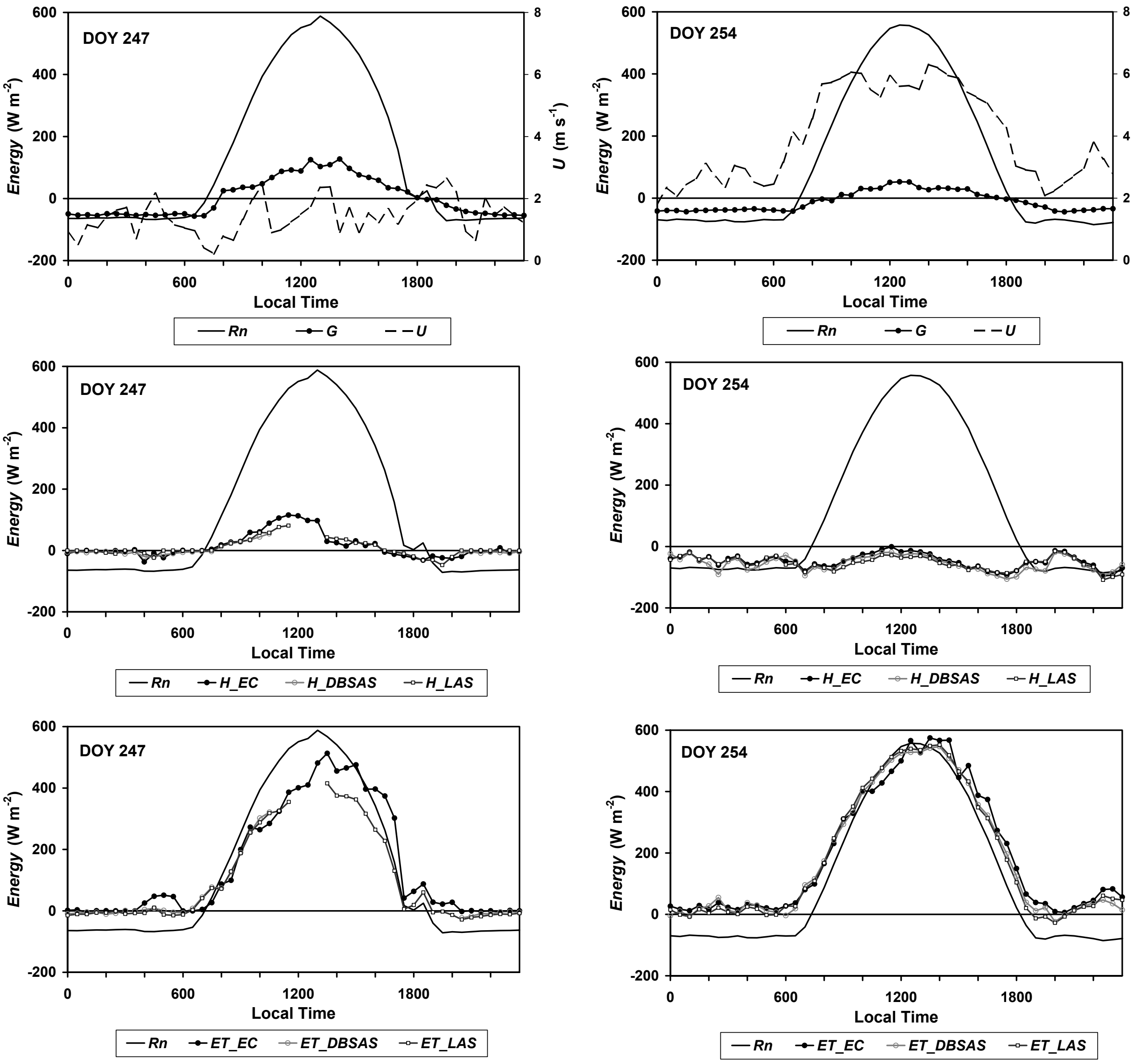

FIGURE 3. On the left (DOY 247) for a day with low wind-speed resulting in *non-advection conditions* during RAPID time series are given of (from top to bottom): net radiation (R_n), soil heat flux (*G*) and mean wind speed (*U*), the sensible heat flux (*H*) and evapotranspiration (*ET*). On the right (DOY 254) for a day with high-wind speed resulting in *advection conditions* the same parameters are depicted.

5. CONCLUSIONS

We have shown for the RAPID experiment that optical scintillometers in combination with net radiation and soil heat flux measurements form a useful system to estimate evapotranspiration in operational practice. The flux estimates obtained compare reasonably well with eddy-covariance (EC) measurements. Advantages of the scintillometer over the EC-method are

- Instruments are robust and simple to operate
- Instruments can be installed at the border a field and do not interfere with the farmer's activities in the field.
- The scintillometer footprint is better defined than the EC measurements.

The displace-beam short aperture scintillometer and the large aperture scintillometer perform comparably under the conditions encountered during the RAPID experiment.

REFERENCES

Andreas, E.L.: 1990, *Selected Papers on Turbulence in a Refractive Medium*, SPIE Milestone Series 25, SPIE – The International Society for Optical Engineering, Bellingham, 693 pp.

Culf, AD, Foken, T and Gash, JHC:2004 'The energy balance closure problem', in Kabat et al.: *Vegetation, water, humans and the climate. A new perspective on an interactive system,* Springer, Berlin, Heidelberg, 159-166.

De Bruin, H.A.R.: 2002, 'Introduction, renaissance of scintillometry', *Boundary-Layer Meteorol.* **105**, 1-4. and the papers of this special issue on scintillometry.

De Bruin, H.A.R., Meijninger, W.M.L., Smedman, A.S. and Magnusson, M.: 2002, 'Displaced-Beam Small Aperture Scintillometer test Part I: the WINTEX data set', *Boundary-Layer Meteorol.* **105**, 129-148.

De Bruin, H.A.R., Hartogensis, O.K., Allen, R.G., and Kramer, J.W.J.L., 2004: 'Regional Advection Perturbations in an Irrigated Desert (RAPID) Experiment', *Theor. Appl. Climatol.* **80**, 143-152.

De Bruin, H.A.R, W.M.L. Meijninger, W. Kohsiek, F. Beyrich, A. Moene and O.K. Hartogensis, 2006: *Turbulent surface fluxes on kilometer scale obtained with scintillometry; a review*. In: Proceedings Computational Methods in Water Resources XVI International Conference: Copenhagen, Denmark.

Hartogensis, O.K., De Bruin, H.A.R., Van De Wiel, B.J.H.: 2002, 'Displaced-Beam Small Aperture Scintillometer Test. Part II: Cases-99 Stable Boundary-Layer Experiment', *Boundary-Layer Meteorol.* **105**, 149-176.

Hartogensis, O.K., Watts, C.J., Rodriguez, J.-C., De Bruin, H.A.R.: 2003, 'Derivation of the effective height for scintillometers: La Poza experiment in Northwest Mexico', *J. Hydrometeorol.* **4**, 915-928

Hartogensis, O.K.: 2006, '*Exploring Scintillometry in the Stable Atmospheric Surface Layer*', Ph.D. thesis Wageningen University, Wageningen, Netherlands, 227p.

Hill, R.J.: 1978, 'Models of the scalar spectrum for turbulent advection. *J. Fluid Mech.* **88**, 541-562.

Hill, R.J.: 1997, 'Algorithms for obtaining atmospheric surface-layer fluxes from scintillation measurements', *J. Atmos. and Ocean Tech.* **14**, 456-467.

Hoedjes, J.C.B., Zuurbier, R.M., and Watts, C.J.: 2002, 'Large aperture scintillometer used over a homogeneous irrigated are partly affected by regional advection', *Boundary-Layer Meteorol.* **105**, 99-117.

Meijninger, W.M.L., Green, A.E., Hartogensis, O.K., Kohsiek, W., Hoedjes, J.C.B., Zuurbier, R.M., and De Bruin, H.A.R.: 2002, 'Determination of area-averaged water vapour fluxes with large aperture and radiowave scintillometers over a heterogeneous surface – flevoland field experiment', *Boundary-Layer Meteorol.* **105**, 63-83.