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Thin laser beam wandering and intensity fluctuations method for evapotranspiration measurement

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ABSTRACT

We compare in this study two simple optical setups to measure the atmospheric turbulence characterized by the refractive index structure parameter C_n^2. The corresponding heat flux values sensed by the laser beam propagation are calculated leading to the plant evapotranspiration. The results are discussed and compared to measurements obtained with a well-known and calibrated eddy-covariant instrument. A fine analysis gives a good insight of the accuracy of the optical devices proposed here to measure the crop evapotranspiration. Additional evapotranspiration values calculated with meteorological sensor data and the use of different models are also compared in parallel.

1. Introduction

Climate change and water demand are increasing over the past years. Water resource management is becoming essential for agriculture. One of the long term solutions lies in understanding how one can improve the efficiency with which water is used to reduce wastage. As water use for agriculture is subject to increasing scrutiny from policy makers and environmentalists, the result is that agriculture is under growing pressure to demonstrate that water is being used efficiently. Numerous methods are available to provide informations on crop water use (or evapotranspiration, ET), crop irrigation requirements, and efficiency with which crops area produced, or water use efficiency. Of these, field level methods (e.g. lysimeters, Eddy covariance, Bowen Ratio, surface renewal, scintillometry, soil water balance) used to estimate (or measure) evapotranspiration (ET) from surfaces have been evaluated extensively in the past.

Thus, crop evapotranspiration knowledge is a precious asset for the evaluation of water losses and for precision irrigation. Several ways to remotely obtain a value of evapotranspiration exist, but only one *takes into account the* strength of the small fluctuations in the index of refraction due to temperatures fluctuations through the measurement of the refractive index structure of air C_n^2 via an optical metrology with scintillometric measurements of a laser beam.

A scintillometer is an instrument that consists of a transmitter and a receiver. The receiver measures intensity fluctuations in the radiation emitted by the transmitter caused by refractive scattering of turbulent eddies in the scintillometer path. Scintillometers exist since the 1970's [1], and mostly use large aperture devices [2] to measure the refractive index structure parameter C_n^2 with the variance of intensity fluctuation measurements. Other techniques used to obtain C_n^2 consist in the acquisition of the angle of arrival (AoA) or the beam wandering. When laser light travels through the atmosphere, phase and amplitude fluctuations due to optical turbulence are experienced. The mean square of AoA fluctuations or position fluctuations is related to the phase structure function (wavefront) of the laser beam perturbed by the turbid medium. A newly different method to sense the atmospheric turbulence measures intensity fluctuations after propagation in a turbulent medium patterned on a holographic plate [3].

However if the scintillometer method is well known, the beam wandering method is less used and the holographic method has never been used in surface heat measurements. Generally, when the measurement of C_n^2 is made over a path in a range (>50 m, intensity fluctuations is used only. Beam wandering measurements with a collimated laser beam leading to values of C_n^2 have

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been made in laboratory experiments at small scales and in real conditions over longer distances, but never to indirectly measure the surface heat flux to our knowledge.

We propose in this study a scintillometer based on a thin collimated laser beam in the aim to measure values of C_n^2 over a crop field. We show that this scintillometer has several advantages and drawbacks. The obtained values of refractive index structure parameter can then be used to compute the sensible flux and the latent heat flux over the laser beam path when they are coupled to other meteorological data.

We measure in our experiment C_n^2 values using both the intensity fluctuations and the wandering fluctuations of the beam over a long beam propagation path with the developed device. The results obtained with the two methods are compared to data obtained with a micrometeorological method and a 3D sonic anemometer. In this work we give in a first part a general formulation of the different methods used to measure C_n^2 and we review the different works based on the beam wandering fluctuations to measure C_n^2. In a second part we explain the measurement of the surface heat flow (H) and the evapotranspiration (λE). The third part describes the experimental setup used for the measurement of H and the fourth part gives experimental results with additional values of evapotranspiration calculated with different analytical models and meteorological data.

2. Measurement of the refractive index structure parameter

2.1. Fluctuations of intensity

The fluctuations of atmospheric refractive index, or optical turbulence, are due to the temperature changes and perturbations like water vapor. The irradiance fluctuations in the receiver plane resulting from optical turbulence are commonly described as '*scintillation*', and they are estimated by the refractive index structure parameter C_n^2. Turbulence's eddies with sizes at the scale of the order of the first Fresnel zone are the primary cause of irradiance fluctuations. These fluctuations include the temporal variation in the received irradiance, such as star twinkle, and spatial variations within a receiver aperture, such as speckle. In the weak fluctuation regime, it is natural to work with the *log amplitude* variance $\sigma_{\ln A}^2$ rather than the irradiance variance itself σ_I^2, because the logarithm of the amplitude of an optical wave is assumed to follow a Gaussian statistical law in this regime. The log amplitude of a spherical wave is related to the refractive index structure parameter C_n^2 [$m^{-2/3}$] through [4,5]:

$$\sigma_{\ln A}^2 = 0.031\, k^{7/6} L^{11/6} C_n^2 \tag{1}$$

where L is the beam path length (m), k is the optical wave number (m^{-1}) defined for the wavelength λ as: $k = 2\pi/\lambda$. In this equation, we assume a statistically homogenous and isotropic turbulence. Moreover, in the far-field lowest-order Gaussian-beam wave is considered as a spherical wave.

Under the condition of Rytov theory, the normalized variance of irradiance σ_I^2 is approximately equal to the log-irradiance variance i.e. $\sigma_I^2 \cong \sigma_{\ln I}^2$, and allows us writing [6] the relation between the log-irradiance variance and the log amplitude of a spherical wave:

$$\sigma_{\ln A}^2 = \frac{1}{4} \ln(1 + \sigma_I^2) \tag{2}$$

where σ_I^2 is the scintillation index defined by:

$$\sigma_I^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} \tag{3}$$

This notation leads to the well-known formula for the refractive index structure parameter C_n^2:

$$C_n^2 = \frac{\ln(1+\sigma_I^2)}{0.124\, k^{7/6} L^{11/6}} \tag{4}$$

2.2. Fluctuations of beam wandering

The propagation of a laser beam in a free-space produces angular spread in the far-field due to natural diffraction, of the order of λ/D, where D is the beam diameter. In presence of optical turbulence, however, a finite optical beam will experience random deflections as it propagates, leading further spreading of the beam by large-scale inhomogeneity of the atmosphere, therefore the 'hot spot' or *instantaneous center* of the beam will be randomly displaced in the receiver plane, producing what is commonly called *beam wandering*. Beam wandering at the receiver plane can be modeled as a random tilt angle arising at the transmitter plane, similar to angle-of-arrival fluctuations of a reciprocal propagating wave with the receiver diameter replaced by the transmitter beam diameter. Moreover, beam wandering is mostly caused by a large-scale turbulence near the transmitter where the *outer scale* of turbulence forms an upper bound on the inhomogeneity size. For this reason, the analysis often follows the Geometrical Optics conditions, where natural diffraction effects are neglected.

This phenomenon can be characterized statistically by the variance of the hot spot displacement along an axis or by the variance of the magnitude of the hot spot displacement. Beam wandering can then be used to get the value of refraction index structure parameter C_n^2 through the variance of the point of maximum irradiance. For a collimated beam in the case of infinite outer scale, the following equation [7] will give the value of C_n^2:

$$C_n^2 = 0.328\, \langle r_c^2 \rangle\, D^{1/3} L^{-3} \tag{5}$$

where D is the diameter of the beam [m], L is the propagation path [m] and $\langle r_c^2 \rangle$ represent the mean value of the beam wandering over the measurement time [m]. We can write $\langle r_c^2 \rangle$ according to the mean square of the beam position on the detector:

$$\langle r_c^2 \rangle = \langle x^2 \rangle + \langle y^2 \rangle \tag{6}$$

providing that we assume locally homogeneous fluctuations. In our case, the position (horizontal x and vertical y from a zero reference) is monitored by the mean of a position sensing detector. This detector can be a lateral effect photodiode (LEP), which is a two-dimension detector that generates photocurrents proportional to the position and the intensity of the centroïd of light on the active area. The current carriers generated in the illuminated region are divided between the electrodes in proportion to the distance of the current paths between the illuminated region and the electrodes. Or it can be also a quadrant (4Q) photodiode, which consist of four photodiodes separated by a small gap (few dozen micrometer), the position being deduced from the difference of photocurrent between the right and left side or the top and bottom side. The noise sensitivities of the 4Q detector and the LEP are roughly 0.2 and 0.5 [8]. In case of low background illumination, the noise level of an LEP is typically more than ten times higher than that of the 4Q receiver due to the low (typically 10 kΩ) interelectrode resistance. Consequently, in electrical sense the achievable SNR and accordingly the resolution of the 4Q detector are