LONG RANGE SCINTLLOMETRY

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1. INTRODUCTION

In the verification of climate and weather models there is a need for experimental data on area-averaged fluxes of heat and water vapour. A scintillometer is very suitable to this purpose. When using incoherent transmitter and receiver apertures, a distance of several km can be covered. The basic equation for such a device is:

$$\sigma_\chi^2 = 0.223\, C_n^2\, D^{-7/3}\, L^3 , \qquad (1)$$

where σ_χ^2 the log amplitude variance of the received radiation, C_n^2 is the refractive index structure parameter, D the transmitter and receiver aperture (here taken equal) and L the distance between transmitter and receiver.

For the steps from C_n^2 to the surface heat flux the reader is referred to the existing literature, e.g. Andreas, 1990. Eq.(1) holds for weak scattering, which means that multiple scattering is not considered. However, when increasing the path length L a moment will be reached where this assumption is no longer valid and the linear relationship between $\sigma_\chi^2$and C_n^2 breaks down. In this region, called the saturation region σ_χ^2 levels off with increasing C_n^2, and eventually decreases. For a 15 cm aperture scintillometer mounted 40 m above the surface, and a path length of 5000 m saturation sets in at a heat flux of less than 100 Wm^{-2}. This puts a limitation on the maximum useful distance of a scintillometer.

There are several ways to extend the range of a scintillometer. One solution is the use of larger apertures. Another one is to mount the scintillometer at a higher level above the ground, since C_n^2 decreases with height in the lower unstable boundary layer. A third option is the use of a coherent radiation source in the mid infrared or even longer wavelength because σ_χ^2 generally decreases with increasing wavelength. In the following some aspects of these three solutions will be discussed, with emphasis on the use of larger apertures.

2. AN EXTRA LARGE APERTURE SCINTILLOMETER (XLAS)

2.1 *Technical aspects*

We built a 0.31 m scintillometer using the concept of the 0.15 m scintillometer (LAS) that was successfully used in many field projects. In this scintillometer Fresnel lenses are used instead of mirrors. This has the advantage of keeping the weight down, is cheaper and has larger flexibility in mounting the light emitter and the detector cell since these are not interfering with the optical path. We used 14” lenses with 200 groves per inch and a focal length of 0.61 m (Edmund Scientific, Barrington, N.J., USA) that were stopped down to 0.324 m. The light source is a TIES 16A gallium arsenide LED with 150 mW radiant output at a current of 2 A. This source was driven with a 7 kHz block wave. The detector is UDT-455 photodiode with 5.1 mm^2 surface (UDT sensors, Inc., Hawthorne, CA, USA). In the electronic circuitry following the detector the 7 kHz carrier is removed from the signal and the remaining modulation, that is caused by atmospheric refractive index turbulence, is amplified in such a way that a signal proportional to log C_n^2 is obtained as output. Also the magnitude of the carrier is available as output.

It is important to measure the effective apertures since these are usually less than the geometrical ones, due to the radiation pattern of the light source and other geometrical factors. To this purpose the XLAS was set up over a distance of approximately 400 m and the apertures were stopped down with annular masks of various sizes. The carrier signal is then analysed as function of the aperture area. A short distance is desirable to obtain a carrier signal with little variations. In Fig. 1 the result is shown. It is seen that the linear relation between the carrier and the aperture area levels off at the largest (full) aperture. From this

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plot an effective aperture of 0.306 m for the transmitter and 0.313 m for the receiver was derived. In Eq. (1) an aperture of 0.31 m was used subsequently.

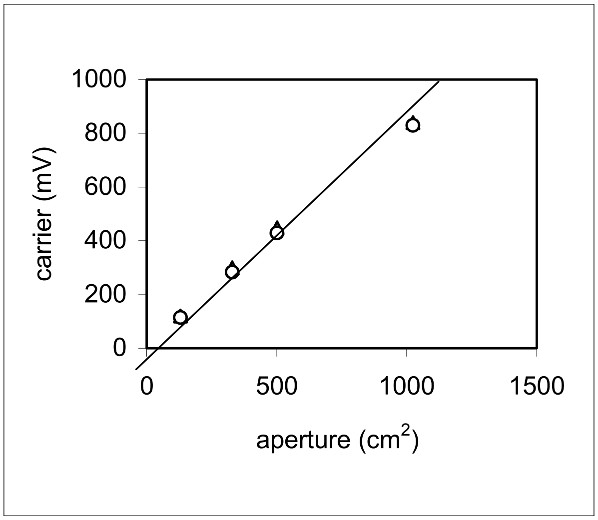

Fig.1 Received radiation versus aperture. The circles denote receiver stops, the triangles transmitter stops

Application of large apertures has the additional benefit of increasing the signal. If the optics were perfect, the emitted cone of light would be twice as narrow as that of the 0.30 m focal length, 0.15 m aperture scintillometer, thus giving four times the intensity at the receiver. Also, the receiver's surface is four times larger, thus leading to a signal gain of 16 over the LAS. In an experiment with a XLAS and a LAS operated side by side a gain of only 2 was found instead. We ascribe this result to the less perfect optical quality of the Fresnel lenses as compared to mirrors. This was also found in the pointing accuracy of transmitter and receiver, which was only little more stringent for the XLAS as for the LAS.

2.2 *Field experiment*

The XLAS was set up between the TV tower near the town of IJsselstein (transmitter) and the meteorological tower near Cabauw (receiver) at 9.8 km from the TV tower. The optical path covers mainly grassland, with some built-up area right near the TV tower and about 1.5 km from the Cabauw tower. The scintillometer was first installed in July 2000, dismantled in September 2000, and put in operation again in September 2001, with the aim to keep it running for a full year. In the first period the transmitter was at a height of 39.5 m above the surface, thereafter it is 43.3 m. The receiver was mounted at 46.5 m height. The area covered by the scintillometer is very flat. Giving account for the curvature of the earth, an average height of 41 m is taken for the first period, and 43 m for the second period of time.

2.3 *Saturation*

An introduction to this topic can be found in Andreas (1990). Here, we base ourselves on the analysis of Frehlich and Ochs (1990). The theory behind this phenomenon is fairly complex, even under the use of several approximations. In the analysis of the incoherent large aperture scintillometer it is useful to start with the subject of a coherent (point) source and detector, and then generalise to the incoherent case by integration over the apertures. In the theory important parameters are the field coherent length and the effective scattering radius. The first quantity can be regarded as the maximum distance between two points across the optical path where the radiation field is coherent. In case of a vacuum this distance is infinity for a point source, but turbulence degrades the optical phase front and reduces the coherence length. At the same time the effective scattering radius increases. This quantity relates to the area that effectively contributes to the scattering. For a point source, and far from saturation this is the Fresnel zone defined by $(\lambda L)^{1/2}$, where λ is the optical wavelength; for a LAS it is the aperture of the optics. When the scintillation becomes saturated, the effective scattering radius may get larger than the Fresnel zone or the radius of the aperture. Consequently, an increasing number of independently scattering areas contributes to the received radiation and the increase of σ_χ^2 is damped.

Frehlich and Ochs show that for a near-infrared incoherent scintillometer the effect of saturation also depends on the inner scale of the atmospheric turbulence. This quantity denotes the transition region where the inertial subrange ends and the dissipation range begins. In this way the shape of the temperature spectrum near the inner scale gets of importance. Hill (1978) showed that this spectrum has a bump near the inner scale.

In this experiment we have to be aware of saturation if $C_n^2 > 2x10^{-15}$. This corresponds to a sensible heat flux of about 50 Wm^{-2} in unstable conditions. In summer the sensible heat flux can go up to 200 Wm^{-2}. Consequently, we have to correct for saturation. Using the analysis of Frehlich and Ochs, a corrected sensible heat flux is calculated which in fair approximation can be represented as:

$$Hcorr = (1 + 0.002\ Hobs)\ Hobs, \qquad (2)$$

where Hobs is the sensible heat flux without taking account of saturation and Hcorr is the one including saturation. It follows that the correction is 20% at Hobs = 100 Wm^{-2} and 40% at Hobs = 200 Wm^{-2}. Given the uncertainties in the correction, this is about the upper useful limit of the XLAS in the present set-up. At this moment we are exploring the upper limit in more detail: in Eq. (2) no account is given yet for the dependency on the inner scale. Fig. 2 gives a comparison between the scintillometer sensible heat flux and the one from the eddy correlation station at Cabauw without correction for saturation, as published in Kohsiek et al. (2002), and including the correction represented by Eq. (2). It is seen that the saturation correction gives some improvement.

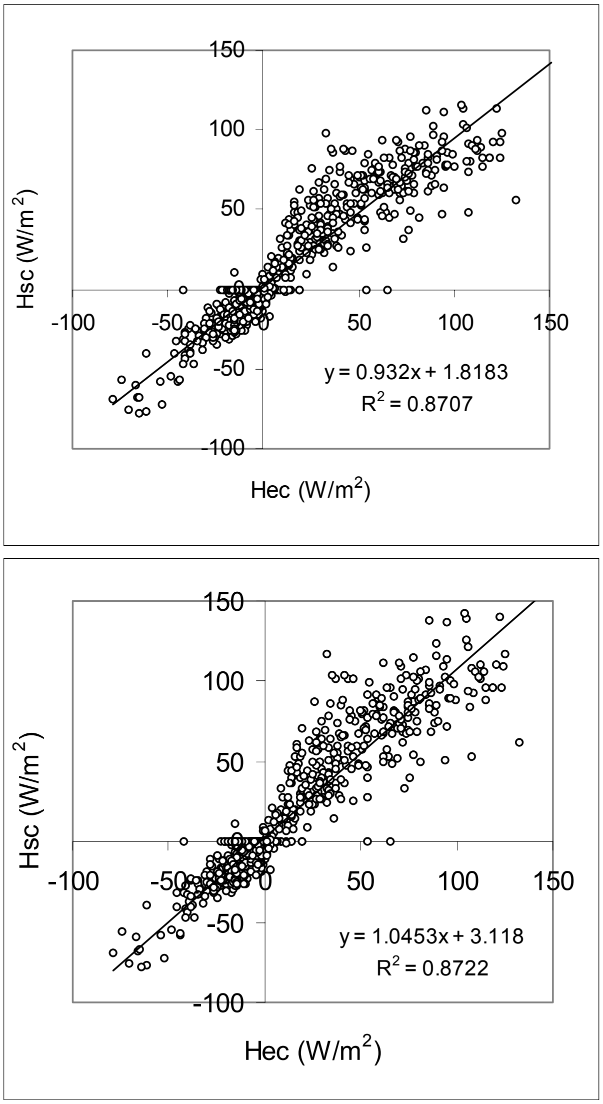

Fig.2 The sensible heat flux determined with the scintillometer (Hsc) versus eddy correlation measurement (Hec). The upper figure is without saturation correction, in the lower figure this correction is included. Only positive heat fluxes were corrected. Regression results are included.

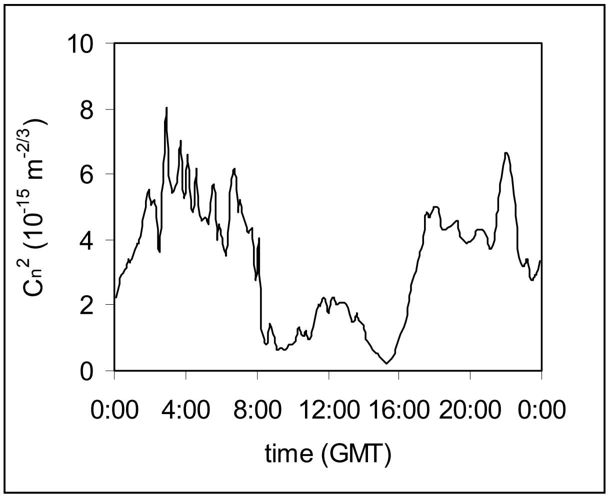

Fig.3 The refractive index structure parameter on 15 February 2002. Note the high values at night.

So far only positive sensible heat fluxes were considered. When the atmospheric boundary layer is stable σ_χ^2 can exceed the saturation limit by far. Fig. 3 gives an example. In this situation multiple path interferences may have occurred due to reflection by the inversion. However, Fig.2 suggests that also during night useful measurements are generally possible. We still have to sort out whether this a coincidence or not.

2.4 *Other ways to avoid saturation*

In the Introduction two other options were given: using a longer wavelength, and increasing the path height. We first discuss the effect of wavelength. It is not obvious from Eq. (1) how the wavelength of the radiation affects the performance of the scintillometer. One has to recall that Eq. (1) is only valid if $D>>(\lambda L)^{1/2}$. Going to a wavelength of say 10.6 μm, and using again L=9800 m, one finds $(\lambda L)^{1/2}$ = 0.32 m, thus about the size of the XLAS aperture. Aperture averaging is then little effective, and instead of using such large apertures, it is more practical to use much smaller ones. Then the source and detector can be regarded as having zero dimensions and the scintillation equation now reads:

$$\sigma_\chi^2 = 0.124\, C_n^2 k^{7/6} L^{11/6}, \qquad (3)$$

where $k=2\pi/\lambda$ is the optical wave number. Thus, in this situation an increase in wavelength results in a decrease of σ_χ^2. As an example: given a sensible heat flux of 200 Wm^{-2}, and a height of 40 m, C_n^2 is about 1.3×10^{-14} $m^{-2/3}$ and, with λ=10.6 μm and L=9800 m, one gets σ_χ^2 = 0.18. This value is smaller than the saturation limit of 0.3 quoted by Ting-i Wang et al. (1978), so it can be assumed that saturation is absent.

In going to mid-infrared wavelengths one has to keep in mind that the scintillometer becomes increasingly sensitive to moisture fluctuations. At a wavelength of 10.6 μm this is three times larger than at 0.94 μm. Depending on the Bowen ratio, the moisture correction can be sizeable.

The other option is increasing the path height. We have to discriminate between a stable and an unstable boundary layer here. In the latter (unstable) case the temperature structure parameter (C_T^2) has a $(z/z_i)^{-4/3}$ dependency, where z_i is the inversion height (Kohsiek, 1988). This relation is only valid in the lower part of the convective boundary layer, say $z/z_i<0.2$. The inversion layer height often shows a pronounced diurnal cycle, thus an increase in height of the scintillometer limits the time interval of useful measurements.

The behaviour of C_T^2 in the stable boundary layer is complex. Wyngaard and Kosovic (1994) argue that it depends on many factors, among which unsteadiness and gravity waves. Thus, deriving heat fluxes from a 40 m high scintillometer may be doubtful. Another complication is that, in case of the stable atmospheric surface layer, the form of the Monin-Obukhov relation that underlies the relation between C_T^2 and the sensible heat flux is not clear. A special situation, that of multiple path interference, was already mentioned. Summarising, from the point of view of applicability of the scintillometer in the stable boundary layer one would rather decrease than increase the height of the instrument.

3. FUTURE PLANS

So far, we have compared XLAS fluxes with a local eddy correlation measurement, thereby assuming that the terrain seen by the scintillometer is homogeneous. We will investigate this assumption with the help of thermal pictures taken by aircraft and by satellite. We will also study the heat budget of an imaginary box around the scintillometer path, where the sensible heat flux follows as a residual of the heat storage change and heat input at the sides and the top. The applicability of the scintillation method in the stable boundary layer will also be a topic of future investigation, as well as the saturation effect.

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