DEVELOPMENTS IN SCINTILLOMETRY

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SECOND INTERNATIONAL WORKSHOP ON SCINTILLOMETRY

WHAT: Thirty scientists from five nations discussed developments in the growing field of scintillometry—the study of wave propagation in the atmospheric surface layer that can be used to measure and decipher low-level turbulence.
WHEN: 8 November 2007
WHERE: Wageningen, Netherlands

The shimmering view over a hot tarmac road is an example of scintillation. A scintillometer measures the intensity of this shimmering. It consists of a transmitter that emits a beam of electromagnetic (EM) radiation to a receiver over a more or less horizontal path at a height between 1 and 100 m above the surface—that is, within the atmospheric surface layer. As the EM waves propagate through the turbulent air the intensity of the radiation varies in time and space because the refractive index varies due to temperature and humidity fluctuations. For some users this information on wave propagation is what they are interested in; for others it is the starting point to derive properties of atmospheric turbulence, and from that derive surface fluxes of heat, water vapor, and momentum. The technique has become known as scintillometry.

Apart from celebrating Henk DeBruin's retirement (see sidebar for additional information about Henk DeBruin) as a festive reason for this workshop,[1] there was the desire to bring together scintillometry researchers who have varying interests. Those interests ranged from basic theory on wave propagation in the turbulent atmosphere, through opportunities for further instrument development, to applications in meteorology and hydrology. Having these people together in one room enabled unique communication. For instance, the theoreticians could learn about how their theories are used in areas like water management, the instrument developers heard about the latest developments in wave propagation theory, and the users of scintillometry could articulate their needs with respect to new sensors.

In his welcome address, Bert Holtslag, Chair of the Meteorology and Air Quality (MAQ) Group of Wageningen University, gave an overview of the scintillometer research performed at Wageningen in the last 15 years. It started with the building of opti-

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[1] The workshop was the successor to the First Workshop on Scintillometry held in autumn 2004 in De Bilt (Netherlands) and also of a scintillometry symposium at the fifth annual meeting of the European Meteorological Society in 2005.

cal large-aperture scintillometers (LAS) for sensible heat flux observations, focusing on the design choices for the instrument and testing it over heterogeneous terrain and under extreme (dry, wet, high vegetation, etc.) conditions. Second, the use of scintillometry in different applications focused on evapotranspiration monitoring in irrigated areas, validation of remote sensing estimates of surface fluxes, and validation of weather and climate models. The latter application has led to the installation of a network of six scintillometers in combination with ceilometers in the Netherlands and Germany to study boundary layer dynamics, as the latter is relevant for the study of greenhouse gas budgets. Apart from the optical LAS, research has been performed on the double-beam laser scintillometer and radiowave scintillometers.

BOUNDARY LAYER TURBULENCE AND SCINTILLOMETRY. To understand and analyze the signal of a scintillometer, knowledge on the properties of atmospheric turbulence is needed, in particular on the shape of the refractive index spectrum and on its variability in space and time.

The first keynote speaker was Rod Frehlich, who was a member of the National Oceanic and Atmospheric Administration (NOAA) scintillometer group that built and tested numerous scintillometer designs in the 1970s and 1980s. Whereas most users of scintillometers *make assumptions* on the turbulent spectrum of the refractive index to interpret their scintillometer data, Frehlich uses the scintillometer signal to *infer* information on the turbulent spectrum (see Fig. 1 for a sketch of the general shape). For that purpose he uses a scintillometer with a point source and many point receivers. The advantage of the scintillometer over other techniques for measuring turbulence is that the EM radiation propagating along a path of 10^2–10^4 m is affected by a large number of turbulent eddies such that the signal measured (even instantaneously) at the receiver already represents a statistical average of small-scale atmospheric properties (a so-called path average). This allows for very short averaging times. Furthermore, Frehlich obtains information on the *spatial* structure of turbulence directly, whereas most techniques rely on the conversion of *temporal* information to spatial information, making assumptions on how the turbulent field does—or does not—change in time. From his experiments, Frehlich found that the refractive index spectrum is highly variable in time and that the mean spectrum deviates from the generally accepted shape that is based on a few single-point time series of temperature (the so-called Hill spectrum). He attributed these differences to small-scale intermittency [variations of turbulence properties on small time scales and length scales (see Frehlich 1992; Frehlich et al. 2004)]. With the information gained on the properties of the refractive index spectrum and the variations therein due to small-scale intermittency, Frehlich returned to the application of the refractive index spectrum in scintillometry to pose (but not yet answer) the following question: What would be the *impact* of the uncertainty in the exact shape of the turbulence spectrum and the intermittent variations in the characteristics of that spectrum on the turbulence parameters derived from the scintillometer signal?

The second keynote speaker was Silvain Cheinet of the Institute of Saint-Louis, a cooperative French–German research institute for security and defense. His focus was on the impact of boundary layer turbulence on optical propagation, and more specifically on the propagation of a scintillometer beam. He used a large-eddy simulation (LES) model to study turbulence in the atmospheric boundary layer. From the subgrid turbulent kinetic energy computed by the model, Cheinet computed three-dimensional fields of the structure parameter of the refractive index, with which he could compute the optical propagation through his modeled turbulence. In that way he could study the signals of virtual scintillometers installed in his LES. One of his conclusions was that for scintillometers installed high above the ground (on the order of 80 m), the variability of the output due to large-scale turbulence can be significant (Cheinet and Siebesma 2007).

Finally, Arnold Moene from the MAQ Group of Wageningen University showed how information on the structure parameters of temperature

HENK DEBRUIN

The workshop was organized on the occasion of the retirement of Associate Professor Henk DeBruin from the MAQ Group of Wageningen University. In the past 15 years he played an active role in adopting and developing scintillometry to a routine method for meteorologists and hydrologists who want to monitor turbulent fluxes of sensible heat and water vapor. Research in scintillometry before that period was mainly focused on atmospheric wave propagation studies, but lost momentum after the end of the Cold War. Henk referred to the renewed interest in the subject as a renaissance of scintillometry (DeBruin 2002). He shares his thoughts on the subject in an essay online (http://dx.doi.org/10.1175/2008BAMS2704.2).

and humidity can be derived from in situ airborne turbulence measurements. The observations were performed (by the Italian Biometeorology Institute) in the vicinity of the Cabauw tower in the Netherlands on which an extra-large-aperture scintillometer (XLAS) is installed over a path of nearly 10 km. The aircraft measurements were performed along the same path but at a higher level. Moene used a wavelet analysis technique to derive local (for each location in the flight path) power spectra. In turn, local estimates of the structure parameter can be derived from these local power spectra (see Fig. 1). With this new technique the statistical distribution of the structure parameter, which turned out to be lognormal, as well as the spatial variability can be studied (Moene and Gioli 2008).

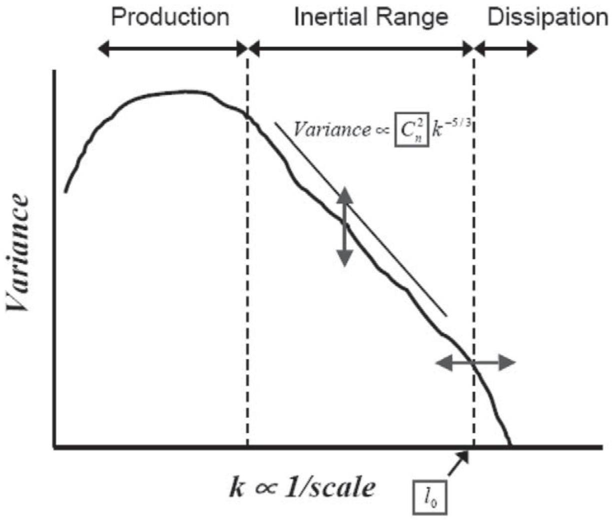

FIG. 1. Sketch of the power spectrum of the refractive index (*n*). the structure parameter of the refractive index (C_n^2) indicates the intensity of the fluctuations, whereas the inner scale (l_0) indicates at which scale the inertial subrange (where energy is only converted from fluctuations at larger scales to smaller scales) ends and the dissipation range begins (where molecular processes become important). The scale where production ends and the inertial subrange starts is called the outer scale.

INSTRUMENTAL ASPECTS AND NEW TYPES OF SCINTILLOMETERS.

Two talks focused on instrumental aspects of scintillometers and the design of new types of instruments.

Wim Kohsiek, formerly working at the Royal Netherlands Meteorological Institute (KNMI) gave a presentation on the possibility of using a large-aperture scintillometer to measure the inner scale of turbulence (usually small apertures are used to measure this smallest scale of the turbulent flow). This inner scale (see Fig. 1) is important since it can be used to estimate momentum transport and it is also relevant to estimate the degree of saturation of the scintillometer signal. If a stripe filter (with alternating opaque and translucent vertical stripes of about 1-cm width) is placed in front of a LAS, the scintillometer signal becomes more sensitive to the inner scale than for a normal LAS (see Churnside et al. 1988). However, experiments have shown that the information is largely buried in instrumental noise. Hence, Kohsiek explored options to reduce the noise by using better detectors, better radiation sources (more power), and better optics. He found that by transmitting at a wavelength where much less absorption occurs, the signal loss in the atmosphere may be reduced. The total reduction in noise should be sufficient to use this striped LAS as an inner-scale scintillometer.

Oscar Hartogensis (from MAQ of Wageningen University) discussed a recently started research and development project that focuses on the development of new scintillometer types for operational flux monitoring. On the one hand, a combined optical–radiowave system should enable the monitoring of both evapotranspiration and sensible heat flux. On the other, a field-scale scintillometer combining the merits of the LAS and laser scintillometers should yield observations of sensible heat flux and momentum flux on a scale of a few hundred meters. The first steps in this project were two field experiments. The first was held in the summer of 2007 at the Chilbolton Observatory [of Rutherford-Appleton Laboratory (RAL)] in the United Kingdom (see Hartogensis et al. 2008). This experiment, conducted in collaboration with the Center of Ecology and Hydrology, focused on the testing of the prototype of a radiowave scintillometer. A second experiment (Kleissl et al. 2008) was performed in collaboration with New Mexico Tech in Sevilleta National Wildlife Refuge, a park in New Mexico. This latter experiment focused on the issue of saturation of the scintillometer signal: Under which conditions does the simple relationship between scintillometer signal and the structure parameters of the refractive index no longer hold, and can we model those deviations? At the time of the workshop the data from both experiments were very fresh, hence few definite results could be shown.

APPLICATIONS OF SCINTILLOMETRY.

The last four talks focused on the application of scintillometry to monitor fluxes over different landscapes.

Frank Beyrich of the Meteorological Observatory Lindenberg, part of the German Meteorological Service, presented experiences from the long-term operation of a LAS. He showed an elaborate method to automatically check data (as is needed in operational applications). He explained that meteorological limitations to long-term operation encompass precipitation, poor visibility, and weak turbulence. On the other hand, methodological limitations are signal saturation, inner-scale dependence of the signal, and tower vibrations. The scintillometer at Lindenberg is an important part of the observatory's monitoring program because it provides an estimate of the sensible heat flux over an area of heterogeneous land the size of a grid box in a numerical weather prediction model (Beyrich et al. 2008).

For Wim Bastiaanssen of the Dutch remote sensing firm Waterwatch, scintillometry can be used to validate and calibrate remote sensing methods for determining spatial maps of actual evaporation (e.g., Bastiaanssen et al. 2005). The maps are used to clarify in which parts of a water management unit (a river basin or an irrigation district) most water is used. Since water use efficiency (kilogram harvested product per cubic meter of supplied water) is an important indicator of proper water use, Waterwatch has also developed methods to estimate crop yields from remote sensing data. For the validation of the evaporation estimates, the scintillometer fills the scale gap between lysimeter and eddy-covariance measurements on one hand and regional water balances on the other.

Dirk Schüttemeyer of the Meteorological Institute of Bonn University (Germany) studies urban meteorology. Against the backdrop of the warning by the Intergovernmental Panel on Climate Change (IPCC) of an increasing number of heat waves, the city of Bonn is working on a decision support system for health problems related to heat. To characterize the effect of the urban heat island, two scintillometers have been installed—one over the city center and the other over farmland. The analysis of the scintillometer data clearly shows that an upward sensible heat flux over the city continues longer in the afternoon than over the rural site. However, daytime maximum values in the sensible heat flux are comparable for both surfaces.

Jonathan Evans of the Center for Ecology and Hydrology (CEH) in Wallingford (United Kingdom) closed the day with a presentation on the use of scintillometry to determine evaporation on a landscape scale. The CEH experiment started with the use of LAS over a 2.3-km path. To determine evaporation, the LAS-derived sensible heat flux was supplemented with an estimate of the landscape-scale net radiation, determined from remote sensing data. The next step was to develop, in close collaboration with RAL, a new radiowave scintillometer. The design criteria and experiences reported in the literature (Lüdi et al. 2005) resulted in a scintillometer operating at 94 MHz at very low (solar) power (only 15 W) in the field for nearly 2 yr. Analysis of the raw data revealed that filtering is needed to remove both unwanted slow variations due to changes in the atmospheric opacity and high-frequency noise. The combined use of the optical LAS and the radiowave scintillometer (the so-called two-wavelength method) provides realistic estimates for the sensible and latent heat flux.

CONCLUSIONS. The one-day workshop on developments in scintillometry showed that scintillometry remains a unique field of research in which optics, turbulence, instrumental aspects and applications in meteorology and hydrology come together. People that do not regularly meet because their fields are too dissimilar found each other on this day in Wageningen.

It was clear from the workshop that there are still holes in our knowledge of the characteristics of atmospheric turbulence that preclude a full analysis of scintillometer signals. However, current scintillometers can be helpful to characterize the turbulent atmosphere, especially for applications of wave propagation. Progress in optical components and signal analysis techniques is leading to new and improved scintillometers. Scintillometry, too, is evolving as a method to monitor fluxes of heat, water vapor, and momentum on large spatial scales, and is becoming an increasingly common tool.

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