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Derivation of refractive index and temperature gradients from optical scintillometry for the correction of atmospherically induced problems in highly precise geodetic measurements

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Abstract. Refraction effects are generally caused by an inhomogeneous propagation medium for an elctro-magnetic beam and are recognized as today's major source of systematic errors in the precise optical determination of angles and distances. In this contribution a method for deriving temperature- and refractive index- gradients from optical scintillation is presented. These gradients can be used for the correction of atmospherically induced errors in highly precise geodetic measurements. Field observations have been carried out over several sites and under different atmospheric conditions in order to test and improve this technique.

Keywords: refraction, scintillometry, refractive index, sensible heat flux, temperature gradient, refractive index gradient

1. Introduction

Geodetic measurements for construction and monitoring tasks, spanning over several hundred meters, usually determine the polar measurement elements with optical and electro-optical methods. The precision of these measurements is impaired by refraction effects of the turbulent atmosphere, because optical inhomogeneities in the propagation medium causes refraction effects as beam bending and time-of-flight variations. They are considered as today's major source of systematic errors in the precise determination of angles and distances. For the derivation of appropriate correction values for such measurements, the refractive index- or temperature gradients of the propagation medium must be known. The direct measurement of these gradients along the propagation path is still a problem, therefore new methods and set ups for its derivation are developed in the scope of the PEARL (Precise Elevation Angle measurements for Real-time Levelling) project. A goal of the PEARL project is to find effective methods for refraction compensation in real-time for the propagation path. In this paper we focus on a method, which uses the effect of optical scintillation for the compensation of deterministic refraction effects: Scintillation measurements with a displaced-beam scintillometer or with CCD-sensors yield line averaged turbulence parameters of the atmospheric boundary layer and can be used for the determination of temperature- and refractive index gradients.

2. Refraction Errors

According to the Fermat-principle, light travelling from a source to a receiver system, takes the path, which is related to the shortest travel time. Due to the fact, that the light speed depends on the refractive index of the propagation medium, the emitted beam seeks the path with the lowest refractive index. Besides wavelength, the refractive index depends on parameters describing the optical density, like temperature and the partial pressures of the components of the propagation medium. In the atmosphere, these parameters vary spatially and temporally, with the result that a ray is bent and fluctuating. For optical wavelengths, refraction effects are mainly caused by temperature fluctuations and gradients. The temperature influence amounts to approximately 1ppm/K. The vertical temperature gradient can vary in layers near the ground up to ± 1 K/m, depending on season, daytime, type of surface, height above ground etc.. For practical requirements, a temperature gradient of 1 K/m results in a lateral deviation of 10 mm for sights of 150 m, which exceeds the requirements of engineering surveying. Even when regarding all precise levelling observation rules, including a minimum ground distance of 1 m, a systematic derivation of 0.4 mm/km occurs, assuming a slope of 1 percent and a tempreature gradient of 0.3 K/m, which is a typical value for that height.

3. Optical scintillation method

The effect, that the propagation of an electromagnetic wave is influenced by the optical turbulence of the atmosphere, can be used to derive atmospheric turbulence parameters. The scintillation method is based on the detection of intensity fluctuations (also called scintillation) of a laser beam during its propagation through the turbulent atmosphere. Another possibility is the analysis of image dancing, which is also caused by the turbulent propagation medium. Both effects, intensity fluctuation and image dancing due to optical turbulence can be analyzed, and by using an atmospheric model, several turbulence parameters can be derived. Section 4 shows a comparison of results from both methods. In this section we will focus on the scintillation method with a displaced beam scintillometer, Section 3.1 gives a short description of the instrument and Section 3.2 a brief overview over the algorithm, on which both methods are based on.

3.1. Displaced-beam scintillometer

For the scintillation method, we use a displaced-beam scintillometer SLS20 (Thiermann, 1992), which emits two parallel, differently polarized laser beams, with the separation δ. After the beams propagate over a path of 50 m to 200 m, they are identified by their respective polarization at a receiver unit by two detectors of diameter D. During the propagation along a propagation path of total length R, the laser beams are scattered at refractive inhomogeneities of the atmosphere. The intensity fluctuations are measured at the receiver unit. With the assumption of the Rytov approximation, the variance of the logarithm of the amplitude of the received radiation at a point detector σ_χ^2, is given by (e.g. Lawerence and Strohbehn, 1970):

$$\sigma_\chi^2 = 4\pi^2 K^2 \int_{r=0}^{R} \int_{k=0}^{\infty} k\phi_n(k) sin^2(\frac{k^2 r(R-r)}{2kR}) dkdr \qquad (1)$$

where K is the optical wave number, ϕ_n the spectrum of refractive index inhomogeneitiies, k the spatial wave number and r a coordinate along the propagation path R. The covariance of the logarithm of the amplitude of two laser beams $B_{1,2}$ is given by:

$$B_{1,2} = 4\pi^2 K^2 \int_{r=0}^{R} \int_{k=0}^{\infty} k\phi_n(k) J_0(k\delta) sin^2[\frac{k^2 r(R-r)}{2kR}][\frac{4J_1^2(kDr/2R)}{(kDr/2R)^2}] dkdr \qquad (2)$$

where $J_{1,0}$ are Bessel functions of the first kind. From the variance and covariance of the logarithm of the amplitude it is possible to determine the structure parameter of the refractive index C_n^2 and the inner scale of turbulence l_o, because these are the only variables, beside known physical dimensions of the instrument (Thiermann, 1992).

3.2. Algorithm for the derivation of the refractive index and temperature gradient

The measurement with a displaced-beam scintillometer delivers the structure parameter of the refractive index C_n^2 and the inner scale of turbulence l_0, which are important quantities in the study of electromagnetic wave propagation in the atmospheric surface layer. Since for optical wavelengths, the fluctuations of the refractive index of the atmosphere are mainly due to temperature variations, the structure constants C_n^2 can be related to the structure parameter of the temperature C_T^2 by the formula (Wesely and Alcaraz, 1973):

$$C_T^2 = (\frac{T^2}{a_1 p})^2 C_n^2 \tag{3}$$

where T is the temperature in [K], p is the pressure in [hPa] and $a_1 = 7.89 * 10^{-5}$ [K/hPa] for a wave length of $\lambda = 670$ nm. Equation (3) neglects the moisture influence on the refractive index, but it was shown, that only under particular atmospheric conditions, with large latent heat flux E and small sensible heat flux H, (Bowen-ratio $Bo = H/E < 0.5$) relative errors of up to 20 % can occur (Weiss et al., 1999). For most analyzed cases the influence of moisture fluctuations on the refractive index fluctuations was negligibly small.

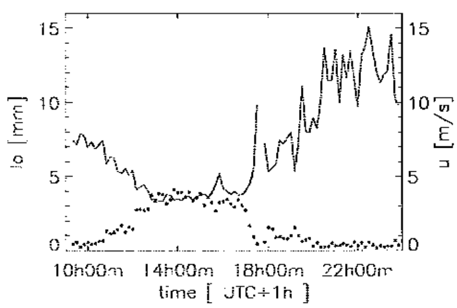

Figure 1. Time series of inner scale (solid line) and wind velocity (dots), 10 min. average, July 15. 1999, height 1.8m over grassland in San Vittore/Switzerland.

The inner scale of turbulence is a length scale which represents the size of the smallest eddies, which occur in the turbulent atmospheric boundary layer, maintaining against viscous dissipation. Hill and Clifford (1978) show, that l_0 can be related to the dissipation rate of kinetic energy ϵ by:

$$l_0 = 7.4 \nu^{\frac{3}{4}} \epsilon^{-\frac{1}{4}} \tag{4}$$

where ν is the viscosity of air. Figure 1 shows an example of a time-series of l_0 (solid line) and the wind velocity u (dots), measured under homogeneous conditions over grass land on July 15, 1999 in San Vittore/Switzerland. This figure indicates typical orders of l_0 and the inverse relation between l_0 and u. l_0 reaches values up to 15 mm at calm wind conditions and decreases with increasing wind velocity.

From a set of given C_T^2 and l_0 values, it is possible to derive sensible heat flux H and momentum fluxe M, in correspondence with the dissipation technique of Champagne et al. (1977). This technique is based on the Monin-Obukhov similarity theory. Using dimensionless equations for C_T^2 and ϵ (e.g. Thiermann and Grassl, 1992), leads to the Obukhov Length L and the characteristic scales of temperature T_* and velocity u_* by a numerical iteration scheme. Here L is an measure for the atmospheric stability and T_* and u_* are directly proportional to the turbulent fluxes of H and M . With dimensionless equations for the sensible heat flux ϕ_H for unstable ($z/L \leq 0$) and stable ($z/L \geq 0$) atmospheric conditions (e.g. Högström, 1988):

$$\phi_H = (1 - 12\frac{z}{L})^{-\frac{1}{2}} \text{ (unstable) and } \phi_H = 1 + 7.8\frac{z}{L} \text{ (stable) }, \quad (5)$$

where z is the measurement height, it is now possible to derive the mean potential temperature gradient by:

$$\frac{d\theta}{dz} = \frac{T_*}{kz}\phi_H \ , \quad (6)$$

where θ is the mean potential temperature, and k the van Karman constant, assumed as 0.4. The potential temperature gradient $d\theta/dz$ can easily be converted to the temperature gradient dT/dz. With dT/dz and the mean pressure gradient dp/dz, which can be achieved by using the hydrostatic approximation, the refractive index gradient for the employed optical wavelength can be calculated by:

$$\frac{dn}{dz} = a\frac{1}{T}\frac{dT}{dz} - \frac{p}{T^2}\frac{dT}{dz} \quad (7)$$

where a is a constant, depending on the wavelength.

4. Experimental data

Various experiments over flat agricultural terrain in Switzerland were made in summer 1998 and 1999, in order to improve the scintillation method and to test its accuracy. Figure 2 (left side) shows an example of the evolution of the refractive index gradient, measured over grass on Aug. 25, 1999. The time series of dn/dz shows 10 minutes averaged data for a height of 1.2 m. Length of the propagation path was $R = 78$ m. It can be seen, that the refractive index gradient increases until noon up to a value of $0.6 * 10^{-6}$/m and decrease in the afternoon until the evening and exhibits a similar shape as the global radiation G and the sensible heat flux H during that day, shown on the right side of Figure 2. The short, but strong decrease around 13:30h was caused by a cirrus cloud event, which decreases the incoming solar radiation, with the result that also the refractive index gradient decreases. This

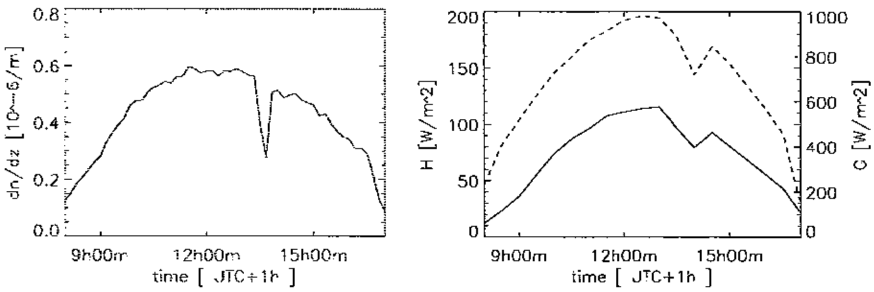

Figure 2. Time series of refractive index gradient dn/dz (left side), 10 min. average, Aug. 25, 1999. Right side: Time series of global radiation G (dashed line, right axis) and sensible heat flux H(solid line, left axis), 30 min. mean.

curve indicates that the optical turbulence was mainly thermally driven during this particular day.

The precision of the derived refractive index gradient is strongly dependent on the accuracy of the derived sensible heat flux. Therefore a comparison of sensible heat flux, optically sensed by scintillometry versus a direct measurement with the eddy correlation technique (instrument: sonic-anemometer), were analyzed. These measurements were made on an airport in San Vittore/Switzerland on flat, homogenous terrain, in July 1999. The homogeneous conditions allow a comparison of these two instruments (line-averaged measurement versus point measurement), because for a homogenous surface, it can be assumed, that both instruments have nearly the same source area conditions. Moreover, the homogeneity requirement of the Monin Obukhov theory

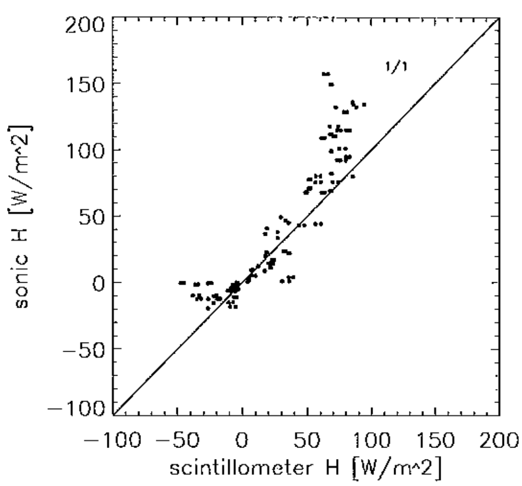

Figure 3. Comparison of sensible heat flux derived by scintillometer versus sonic-anemometer, data are 30 min. means.

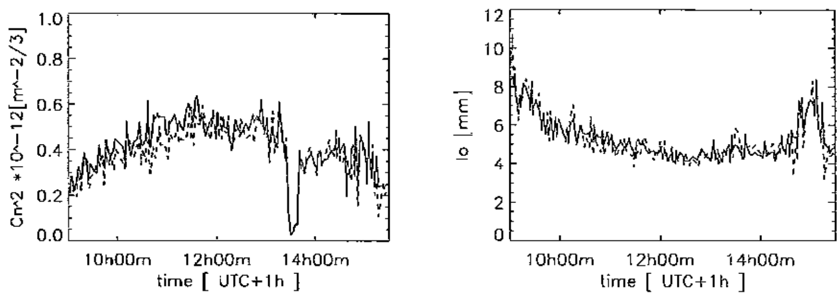

Figure 4. Comparison of structure parameter of refractive index and inner scale of turbulence, scintillometer (solid line) versus line scan camera (dashed line).

is fulfilled. Measurement hight was 1.8 m; data are 30 min. means. The comparison of the sensible heat fluxes in Figure 3 shows a good correspondence with a correlations coefficient of 0.91.

In order to investigate, whether the scintillation method can be implemented into standard geodetic systems, an experimental set up which consists of a digital line scan camera, which grabbed the image of a coded levelling rod, was made and the results are compared to these of the scintillometer. As mentioned in Section 3, image dancing can also be used to calculate the turbulence parameters l_0 and C_n^2 and with the algorithm described in Section 3.2 the refractive index gradient can be estimated. The required quantities can be determined with image processing techniques described by Böckem et al. (2000). The line scan rate was 330 Hz, hence, it took about 10 s to grab 3000 lines, which were compiled into an image. Figure 4 shows a comparison of C_n^2 (left side) and l_0 (right side) scintillometer (solid lines), versus line-scan camera (dotted lines), which were measured on Aug. 25, 1999. Measuring conditions are the same as described for Figure 2, data are 1 min. means. The results show a good correspondence, the correlation coefficients amounts to 0.94 for l_0 and 0.91 for C_n^2. The method of image analysis may be limited, if the illumination of natural light is to weak (e.g. during night) or too strong (e.g. disturbing back light).

5. Conclusion and outlook

The results of the scintillation method are promising with respect to calculating real-time corrections for beam bending, valid for the whole path length, because this method yields line-averaged values. New studies are being pursued, which examine the possibility of utilizing the data acquisition features of common surveying instruments. The algorithm for the derivation of the turbulence parameters is in principle restricted to homogenous surfaces, because it is based on the Monin Obukhov theory. Therefore further experiments with non ideal conditions are presently analyzed, in order to investigated that problem and to deepen the understanding of the restrictions of this method.

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