

**CONCEPTS AND SOLUTIONS TO OVERCOME THE REFRACTION  
PROBLEM IN TERRESTRIAL PRECISION MEASUREMENT****Hilmar Ingensand***Swiss Federal Institute of Technology, ETH Zurich, Switzerland  
E-mail: ingensand@geod.baug.ethz.ch**Received 13-09-2007; accepted 12-03-2008*

**Abstract.** Refraction is a detrimental problem in terrestrial optical measurements and can be regarded as major source of systematic errors in the precise determination of distances and directions. In general, refraction is a function of the density inhomogeneities of the propagation medium. As the “classical” method of temperature-gradient determination does not meet the requirement of a representative integral determination of the refractive index gradient field, at the Institute of Geodesy and Photogrammetry of the ETH Zürich, two methods to determine and correct the refraction influence have been developed further during the last few years. One approach focuses on the determination of the refractive index gradient in measuring the turbulence of the air by scintillometry or CDD-based image processing, which is presently the key technology in tracking tachometers and digital levels. Turbulence is a measure of the energy in the heat exchanging process and can be converted by the Monin-Obukov-Similarity into temperature gradients. The advantage of optical scintillation measurements is to derive line averaged turbulence parameters of the atmospheric surface layer. Another challenging approach was the successful development of a compact laser-dispersometer at the ETH, which could be a component of actual geodetic instruments in the future. A dispersometer theodolite, based on the dual-wavelength method for dispersive air, is capable of refraction-free direction measurements. The results of both technologies, turbulence determination and dispersometry, will be presented and discussed in this paper.

**Keywords:** refraction, dispersometry, scintillometry, temperature gradient.

**1. Motivation**

Induced by the challenging project AlpTransit, which generates the longest railway tunnel of the world with a length of 57 km, the requirement of precise optical navigation of tunnelling machines was requested. In order to have an indication of the presence of refraction effects, additional loop misclosure calculations determine the influence. There is also a growing demand for refraction-free measurements in geodetic monitoring, industrial metrology as well as in aircraft production lines and precise alignment tasks of magnets in accelerator plants.

**2. Concepts and solutions**

To meet the requirement of refraction-free or refraction-indicated direction measurements, respectively, several approaches of refraction-determining methods were followed at the IGP/ETHZ during the last five year period (Fig. 1).

These are:

- temperature gradient measurements with aspirated PT-1000 temperature sensors;
- turbulence based methods causing the effect of image distortion, image dancing, intensity variations using Charge-coupled device-based geodetic instruments or scintillometers;

- the dual-wavelength dispersion method encompassing the development of a laser-dispersometer.

**2.1. Temperature gradient determination**

Vertical and horizontal temperature gradient measurements were carried out in order to map the temperature gradient in railway tunnels (Hennes *et al.* 1999). These temperature measurement devices using PT1000 sensors have been applied to compare and confirm the results of the new refraction determining methods to the actual temperature gradient. One disadvantage of temperature measurements is the rather bulky equipment and the so-called footprint effect which points to the problem of the representativeness of single temperature gradient measurements along the path of light.

In addition to temperature gradient measurements, we concentrate at present on two different approaches at the ETHZ. One approach is based on the propagation through a turbulent medium using the effect that the turbulence quantities are related to the refractive index gradient. This method can be regarded as an indirect method, as it uses the Monin Obukhov Similarity Theory (MOST) to evaluate the vertical temperature gradient and thus to calculate a refraction correction. The other approach with less hypotheses is the dispersion method which leads to

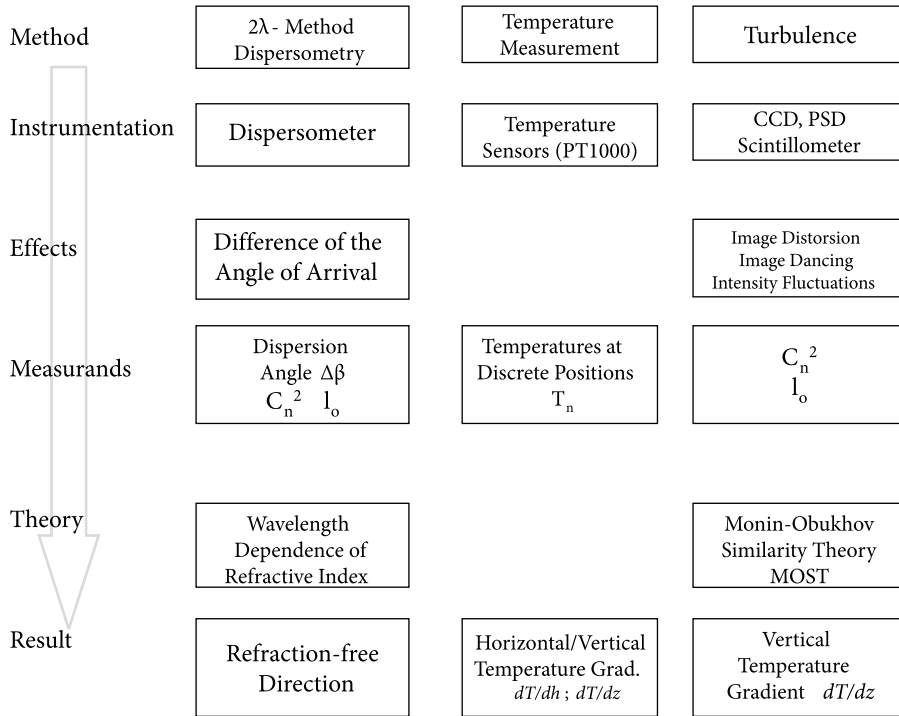


Fig. 1. Refraction determining methods

the development of a laser dispersometer to exclude the density dependence of the refractive index widely.

2.2. Optical turbulence

The propagation of electromagnetic waves is influenced by the turbulence of the atmosphere, where thermally as well as mechanically produced eddies influence the beam. The aforementioned effects as scintillation image distortion and image dancing can be used to derive characteristic turbulence parameters, the structure function of the refractive index  $C_n^2$  and the inner scale of turbulence  $l_0$ . The scintillometric method is based on the intensity variation of a laser beam after its propagation through the turbulent atmosphere. Experiments using the displaced-beam scintillometer SLS20 are described in detail in Weiss (2002). The other turbulence method uses the effect of image dancing which is determined by image processing.

In the image processing method the standard deviation  $\sigma_y^2$  of the positions of image structures, for example, codes of digital level, is a measure of the angle fluctuation of arrival which is caused by refraction-induced phase fluctuations of light waves, when light beams propagate through a turbulent medium. Among a wide number of formulae, we used the approach of Brunner (1980) for determining  $C_n^2$  which has provided the most plausible results:

$$C_n^2 = \frac{\sigma_\alpha^2 a^{1/3}}{1.05 \cdot R}, \quad \sigma_\alpha^2 = \frac{\sigma_y^2 p^2}{f^2},$$

$\sigma_\alpha^2$  – variance of angle of arrival [rad];  $R$  – distance;  $a$  – aperture;  $f$  – focal length;  $p$  – pixel size.

The variance of angle of arrival can be derived from the standard deviation  $\sigma_y^2$  of the positions of the edges in the image. The inner scale  $l_0$  is calculated by the depen-

dence of the intensity fluctuations  $\sigma_I^2$  of light waves propagating through a turbulent medium on the refractive index spectrum  $\Phi_n(\kappa)$ , where  $\kappa$  is the spatial frequency of the fluctuations. Hereby the refractive index spectrum of Hill (1978) can be applied which is parameterised by  $l_0$  and  $C_n^2$ . If this spectrum is integrated according to the log-amplitude variance,  $\sigma_\chi^2$  depends on  $l_0$  and  $C_n^2$ . The relation between the log-amplitude-variance  $\sigma_\chi^2$  and the intensity fluctuations  $\sigma_I^2$  follows the equation:

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

If the distance  $R$ , the wave number  $k$  of the radiation, and the structure constant  $C_n^2$  are known, an one-to-one relation between the intensity fluctuations  $\sigma_I^2$  and the inner scale  $l_0$ , allows to calculate the inner scale  $l_0$ . Based on the Monin-Obukhov Turbulence Theory (MOST), the turbulent sensible heat flux  $H$  and the turbulent momentum flux  $M$  can be derived from the structure constant of temperature  $C_T$  and the dissipation rate of turbulent kinetic energy  $\epsilon$ . This can be performed by setting up dimensionless equations of  $C_T$  and  $\epsilon$ , which lead to the Obukhov Length  $L$  by a numerical iteration scheme.  $L$  is an indicator of the stability of the atmosphere and necessary to determine the turbulent fluxes. From the sensible heat flux the temperature gradient  $dT/dz$  and refractive index gradient  $dn/dz$  can be derived to correct atmospheric induced deviations in precise geodetic measurements (Fig. 2).

2.3. ETH test results of the turbulence effect-based methods

Several tests have been carried out to evaluate and compare the different methods during last years. Fig. 3 de-

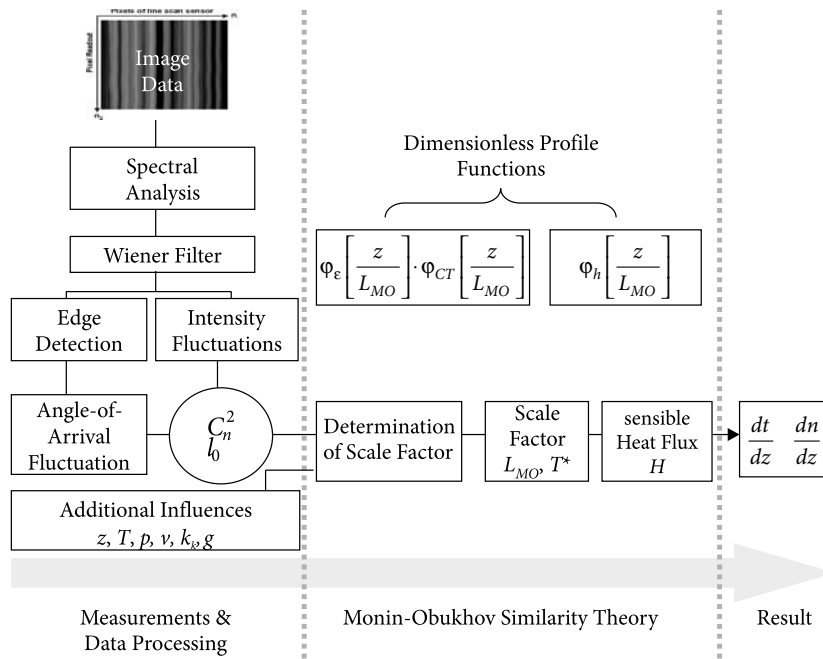


Fig. 2. Flow chart of turbulence measurements, theories and calculations to get the refractive index gradient

picts the comparison of the scintillometer results versus the image processing results of  $C_n^2$  and  $l$ .

A comparison of the temperature gradient measurements versus scintillometer and versus image analysing method has shown a large coincidence of all methods and an accuracy of 0.05 K° could be obtained (Fig. 4). The image processing method can be regarded as a promising method, as CCD-based geodetic instruments become a standard in geodetic metrology. There is almost no instrumental additional effort to implement this method in geodetic instruments as tacheometers and digital levels.

### 3. The developments of a geodetic field-useable laser

#### 3.1. Forerunners of the ETH experiments

The direct forerunner of the presented experiments and developments at the ETHZ was a feasibility study of the so-called Rapid Precision Levelling System (RPLS) under contract of NOAA. This study was carried out at WILD/LEITZ during 1986-89. These RPLS experiments have shown that a dispersometer with a geodetic focal length of less than 30 cm is feasible (Ingensand 1990) (Fig. 5). These experiments were stopped in 1989 because of the non-availability of portable adequate blue or green light sources and the appearance of GPS height determination techniques.

The dispersion method is mainly a metrological solution and bases on experienced atmospheric physics. The physical background of this dual-wavelength method follows the dispersion-effect which means the dry-air wavelength-dependence function for wavelength  $\lambda$  (Owens 1967) (Fig. 6).

$$n - 1 = \mu(\lambda)F_1(p, T) + \mu'(\lambda)F_2(p_{wv}, T),$$

$\mu, \mu'$  – dispersive coefficients;  $F_1, F_2$  – functions of temperature  $T$ ; air pressure  $p$ , partial pressure for water vapour  $p_{wv}$ .

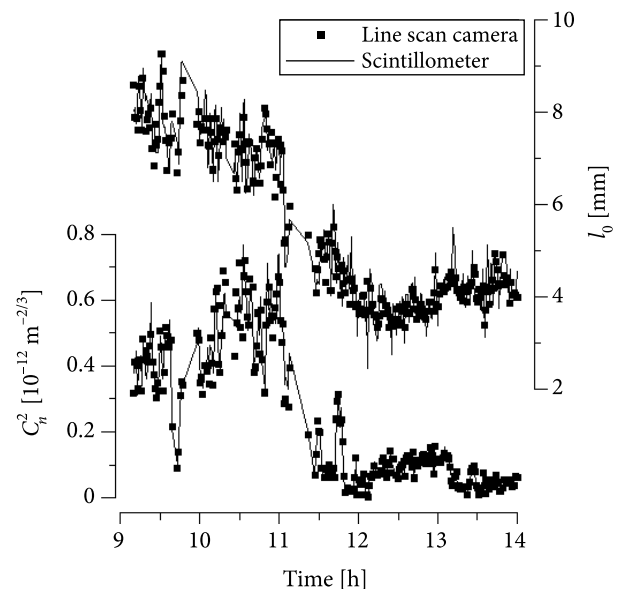


Fig. 3. Image processing versus scintillometry (Flach 2001)

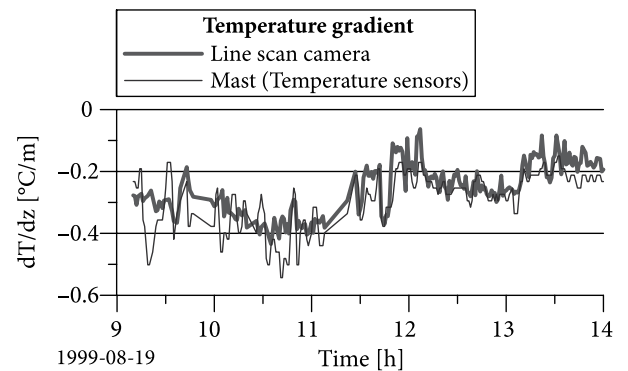


Fig. 4. Temperature gradient measurements versus temperature gradients derived from image processing (Flach 2000)

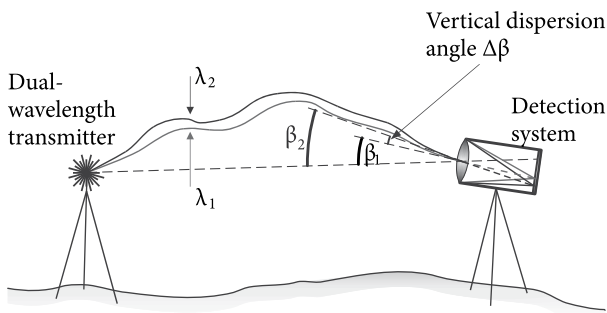


Fig. 5. Configuration of the dispersometer set-up

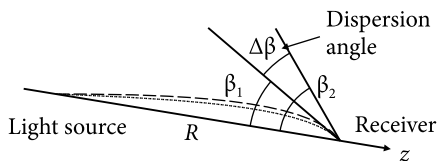


Fig. 6. Dispersion angle

Dispersion effects are related to absorption (deviation) of light. The difference between both angles is called the dispersion angle  $\Delta\beta$  and is approximately proportional to the refraction angle  $\beta$ . The larger the difference of angle-of-arrival will differ. The wavelength, dependent constant  $v$ , calculated by the dispersion formula for the used wavelengths 430 nm and 860 nm, respectively,  $\beta_{IR} = v(\beta_{blue} - \beta_{IR}) = v\Delta\beta$ , has a value of  $\sim 42$ .

Thus the dispersion angle has to be detected about 42 times more accurate than the refraction angle itself (Huiser, Gächter 1989). If the refraction angle is assumed in the order of  $1 \mu\text{rad} \triangleq 0.06 \text{ mgon}$ , related to the two wavelengths, the dispersion angle has to be resolved better than  $0.03 \mu\text{rad} \triangleq 0.00018 \text{ mgon}$ . The consequence is that in the focal plane of a geodetic telescope of a focal length of about 30 cm the position of the two spots blue and infrared have to be detected with all resolution of a few  $\mu\text{m}$ .

3.2. The light emitting device

The core of the light source is dual-wavelength laser generating blue light by frequency doubling of an IR-laser diode in Potassium Niobate (KNbO3)-crystal. This light source is a development of the Laboratory of Solid State Physics of the ETHZ (Fluck *et al.* 1996). The exact emitting wavelengths of the laser are  $\lambda_1 = 859.2 \text{ nm}$  and  $\lambda_2 = 429.6 \text{ nm}$ .

The two wavelengths are alternatively emitted by a rotating filter disc (Fig. 7). A microscope lens system focuses the beam into a fibre-optics which generates, after winding around a coil with a defined diameter, to generate the required monomode Gaussian beam profile.

3.3. The receiving system

The telescope of the ETH dispersometer was taken from the Leica RPLS experiment and has a focal length of 30 cm. The aperture can be tuned by a diaphragm in a range of 75 mm down to 30 mm to examine the sensitivity of the turbulence compensation on the aperture size. In the focal plane of the afore-mentioned telescope, a UDT SPOT-2D diode is mounted. As the regular position detection method using segmented diodes does not meet the required accuracy of a few nanometers, a special position detection method – the so-called gap technology – has been used. The gap area which is the space between the light sensitive areas, works similarly to a lateral-effect diode (Huiser, Gächter 1989).

In the aforementioned experimental set-up it could be demonstrated that the power spectrum of the dispersion corrected angle is more or less white after an optimisation of the aperture diameter. Another result of the experiments has shown the dependence of the aperture and the power spectrum. This has been proved according to the results of the RPLS experiment (Huiser, Gächter 1989). As an optimal aperture for this experiment we found a diameter  $d = 30 \text{ mm}$  (Fig. 8).

As depicted in Fig. 9, the accuracy of the refraction angle amounts to  $\sigma = 0.2 \mu\text{rad}$  after an integration time of 12 s. According to the Leica RPLS experiment, the results show the same behaviour as the accuracy of the refraction angle improves faster than the precision of the angles of arrival at both wavelengths. Additional results of these experiments have shown that dispersometry is nearly insensitive to the turbulence.

4. Conclusions

Both methods of the turbulence-imaging procedure and the dispersometer approach have shown that both are capable to calculate real-time corrections. In comparison with temperature gradient measurements, both methods are valid for the whole path length, because the data give line-averaged values. The turbulence-based method has the advantage of being simply implemented into geodetic instruments by using the existent CCD sensors

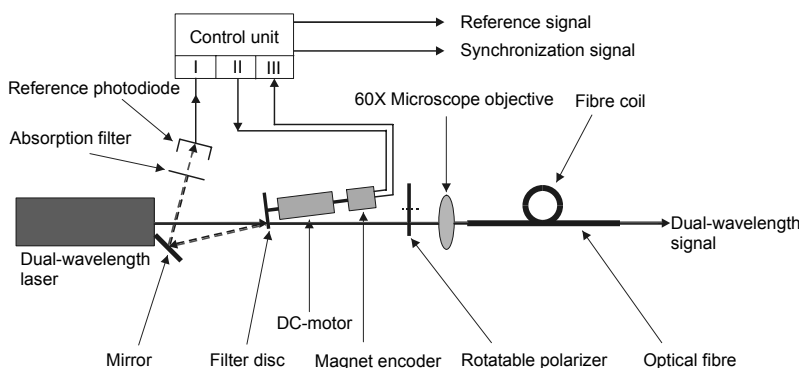


Fig. 7. Optical scheme of the two wavelengths-emitting unit (Böckem 2001)

and the micro-processing power of the instrument. Tests with Leica ATR technology has shown the capabilities of the turbulence technique using unmodified tachymeters (Troller 2001). But, based on Monin-Obukhov theory, the turbulence models are restricted to a horizontal homogenous surface. Further studies will be carried out in order to evaluate models for inclined terrain situations (Weiss 2002).

The dispersometer method has the advantage in being nearly free of hypotheses and other assumptions. The results of the ETH development have shown a high accuracy of refraction-free direction determination. But the investment in instruments is very high up to now. New technologies as blue-light emitting diodes will give new opportunities in implementing dispersometry into high-precision geodetic instruments.

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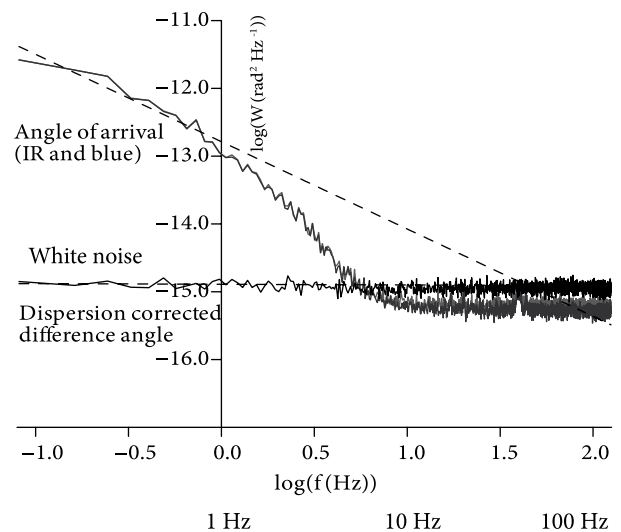


Fig. 8. Power spectra of the observed and dispersion corrected angle (Böckem 2001)

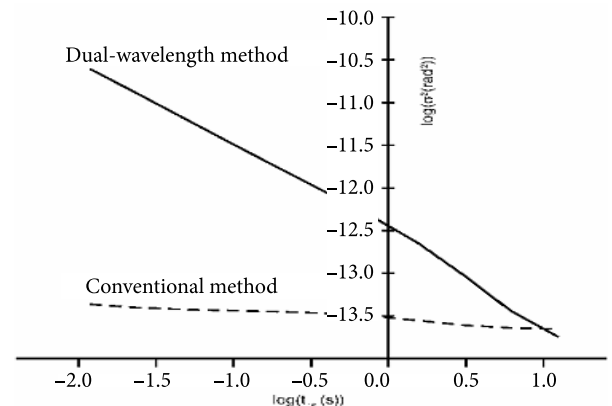


Fig. 9. Performance of the dispersion method (Böckem 2001)

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