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Horizontal gradients in the wet path delay derived from four years of microwave radiometer data

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Abstract. We have analyzed four years of inferred wet path delay data from a microwave radiometer operating at 21.0 and 31.4 GHz. We have applied a four parameter gradient model to the wet delays, using different lengths of the time series for the gradient estimation. The mean gradient, averaged over 15 to 1440 minutes, varies between 0.9 and 0.4 mm and has a preferred direction towards the north-east. Increasing the averaging time causes the estimated gradient to decrease. The 15 minutes mean gradient is 1.3 mm for the summer months and 0.7 mm for the winter months. Structure function results are also presented.

Introduction

The refractive index due to water vapor in the atmosphere causes a propagation delay of the radio waves, called the wet delay [*Davis et al.*, 1985]. The large variability of the wet delay caused by the inhomogeneous water vapor distribution introduces a major error in the measurements of the space based geodetic techniques, such as Very Long Baseline Interferometry (VLBI), the Global Positioning System (GPS), and the Global Navigation and Satellite System (GLONASS). The wet delay data used in this paper were acquired from the dual frequency ground-based microwave radiometer located at the Onsala Space Observatory. The Onsala Water Vapor Radiometer (WVR) has been operating nearly continuously since 1994, which means that we can perform a statistical analysis of local phenomena and particularly horizontal gradients in the refractive index. Knowledge of the gradient magnitudes and their time scales provides valuable information for the processing strategies for the space based geodetic techniques [*MacMillan*, 1995] [*Bar-Sever et al.*, 1998]. We will briefly describe the observations and define the horizontal gradient before presenting the results and the conclusions.

Observations

The WVR measures the sky emission at two frequencies – 21.0 and 31.4 GHz. The sky emission at these frequencies depends on the amounts of water vapor, liquid water, and oxygen in the atmosphere. The measured brightness temperatures are used to infer the wet path delay [*Elgered*, 1993]. The WVR is fully steerable in azimuth and elevation, which provides a good coverage of the sky. A total of 40–50 observations in different directions on the sky are acquired during 10–12 minutes which sets a lower limit for the time scales of the gradients to be studied. An example of a relatively strong horizontal gradient observed by the WVR is shown in Figure 1. Using the model presented in the next section, this gradient corresponds to a value of 2.7 mm in the 246^o direction.

All available WVR data from 1994 to 1997 have been analyzed. The minimum elevation angle in this period was 22.5°. The instrument has acquired data for approximately 90% of the total time. The data were edited for instrumental errors and data obtained during rain or only from a limited area of the sky were ignored. The useful amount of data for gradient estimation was 65% of the total four years of observations.

Atmospheric Gradients

We apply a gradient model, where four parameters are estimated from the available wet delay data [*Davis et al.*, 1993]. The model for the observed equivalent zenith wet delay $\Delta\tilde{L}^z$ is a function of the elevation angle ϵ, the azimuth angle ϕ, and the time lag Δt from a time epoch for which the model parameters will be referred to. It is written as

$$\begin{aligned}\Delta\tilde{L}^z(\epsilon,\phi,\Delta t) &= \Delta L^z + V_L\Delta t + \\ &\cot\epsilon\left[1-10^{-6}N_s\csc^2\epsilon\right]\times \\ &\left[\Xi_n\cos\phi+\Xi_e\sin\phi\right] \qquad (1)\end{aligned}$$

The estimated model parameters are: ΔL^z is the zenith delay, V_L is the zenith delay rate, Ξ_n and Ξ_e are the north and the east delay gradients respectively, N_s is the ground refractivity. The delay gradient is defined as

$$\Xi_i = 10^{-6}\int_0^\infty \xi_i\ (z)\ z\,dz \qquad (2)$$

where ξ_i is the horizontal gradient of refractivity, defined as the first order term of the Taylor expansion, along the two horizontal directions (e.g. north and east), of the refractivity at altitude z [*Davis et al.*, 1993].

In the following we will concentrate on the estimated horizontal gradients, the total gradient as well as its components Ξ_n and Ξ_e, using subsets of the data acquired over intervals from 15 minutes to one day. We required at least 2/3 of such a time interval to contain data in order to estimate the model parameters. The statistical uncertainty of the estimated gradient is typically at the 0.1–0.2 mm level for the 15 minute estimates.

Results and Discussion

The consistency of the data is studied by comparing the yearly probability density functions (PDF) [*Leon-Garcia*, 1993] of the total gradient for the four years. Figure 2 shows these distributions for gradients estimated using 30 minute

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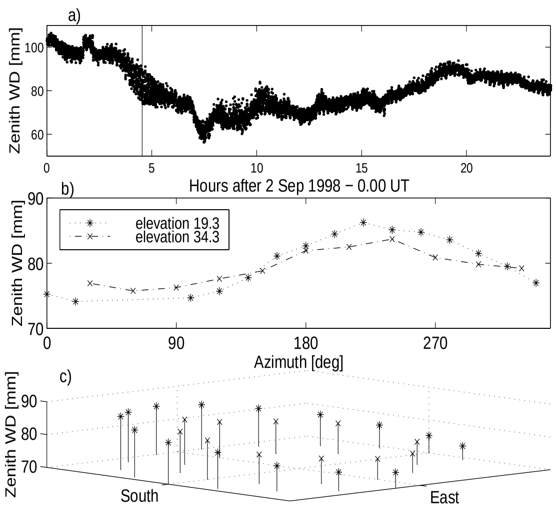

Figure 1. Example of an observed wet delay gradient, where (a) contains the WVR wet delay time series and the vertical line indicates the time of a scan at a constant elevation of 19.3° followed by a scan at 34.3°, (b) and (c) show the wet delay in these two scans as a function of the azimuth. Note that in 1998 a lower limit for the elevation angle was used.

long subsets of the WVR data. A good agreement between the years is observed, where the lower mean and standard deviation (std) for 1996 can be explained by missing data in the summer period, when the atmosphere is most variable.

The gradient distributions obtained for summer and winter for the 30-minutes gradients data are shown in Figure 3a. The mean and the std for the summer values are nearly twice as large as the winter values. Figure 3b shows the mean gradient for each month and for different lengths of the time interval used for each individual estimation.

The gradient magnitude depends on the length of the time series for which the gradient is estimated. This is in agreement with expectations that the atmosphere has a turbulent structure. Figure 4a shows a comparison of the gradient distributions for the time intervals 15, 90, 360 and 1440 minutes. The corresponding cumulative distribution functions (CDF) [*Leon-Garcia*, 1993] of the estimated gradients are shown in Figure 4b. Table 1 presents the mean gradient values for different gradient estimation time lengths. The mean value and the standard deviation decreases when the averaging time increase.

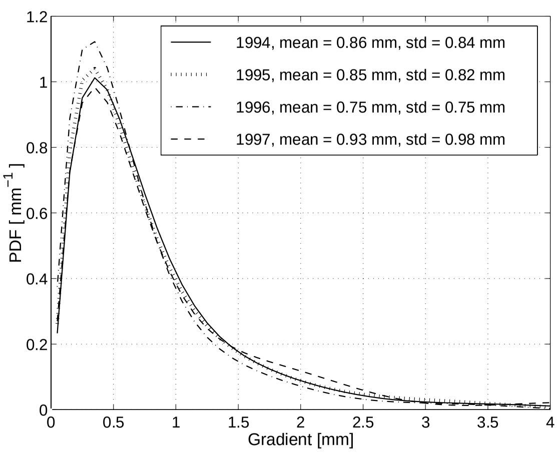

Figure 2. Annual gradient PDF for 1994–1997. Given are also the mean and the standard deviation (std) of the distributions.

Table 1. Mean gradient and std (in mm) as a function of the estimation time length (in minutes)

time length	15	30	90	180	360	1440
mean	0.92	0.84	0.72	0.65	0.56	0.43
std	0.94	0.80	0.68	0.62	0.49	0.30

The preferred directions of the estimated gradients are shown in Figure 5. We used different limits for the gradient size to select different subsets of the gradients. We find a common effect for the different gradient sizes, where the highest probability of finding a gradient is in the north–east direction.

A systematic behavior such as in Figure 5 can for small gradients be caused by a tilt in the plane of the bearing of the azimuth drive in the WVR. Measurements of the WVR foundation give an estimate of the tilt angle of 0.22° in northern direction. Using the mean value of the zenith wet delay of

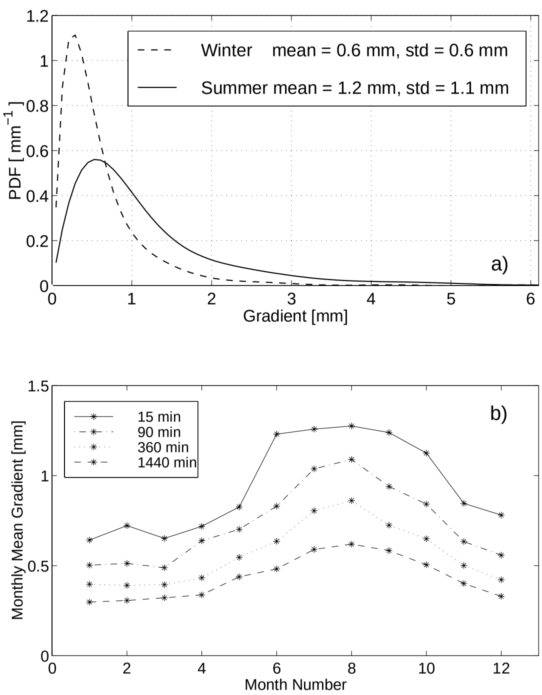

Figure 3. Annual variability of the gradients: (a) 30-minute gradient PDF for winter (Dec.–Feb.) and summer (Jun.–Aug.) periods, and (b) seasonal variability of the gradient estimated for different time lengths using all four years of data.

83 mm we find that a maximum total gradient of 0.3 mm will arise from this tilt when using a regular scanning–mode schedule of the WVR. The direction of the tilt would however give a gradient direction towards the south, which is clearly not present in Figure 5.

Examination of the systematic behavior of the gradient direction on a yearly and seasonal basis showed consistent results through the years and no seasonal dependence was present. An argument against the importance of the tilt of the WVR is that the very strong gradients (see Figure 5b and 5c) definitely have the same preferred direction. This is consistent with earlier results based on a much smaller data set [*Davis et al.*, 1993].

We have identified one major cause for the horizontal gradients, namely the passage of weather fronts which are frequent in the north-western parts of Europe. *Gregorius and Blewitt* (1998) discuss their influence on GPS measurements. *Hanssen et al.* (1999) present examples of similar weather conditions with strong horizontal gradients in water vapor obtained from interferometric radar measurements.

The horizontal gradient can also be characterized by using structure functions. We define a temporal structure function (SF) as:

$$\Upsilon_\Xi(\tau) = < [\Xi(t+\tau) - \Xi(t)]^2 > \qquad (3)$$

where τ is a time lag. The SF of the north, the east, and the total horizontal gradient for the 15 minute data subsets are shown in Figure 6. The SF for the total gradient is smaller in magnitude because it does not contain negative values as do the north and the east gradients. We note that for time differences larger than half a day the gradient has a white noise behavior. The stochastic behavior of the gradients can be studied and modeled based on the structure function results, in a similar way as described by [*Herring et al.*, 1990], where the statistical properties of the equivalent zenith wet delay were studied in order to determine the model to be used in the data analysis.

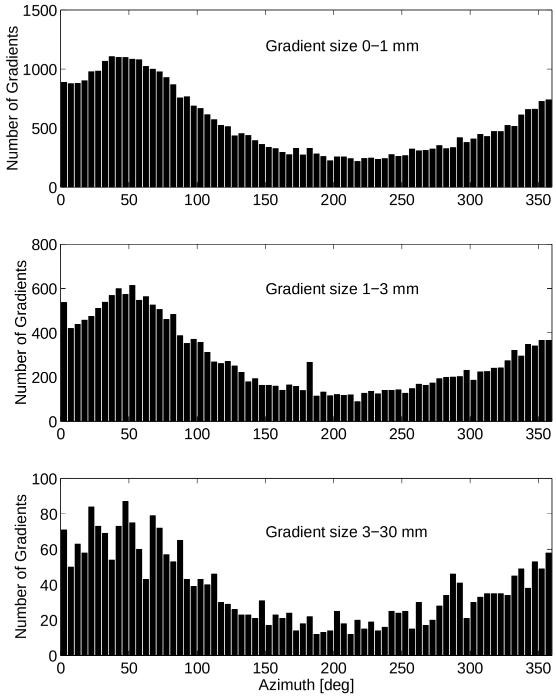

Figure 5. The gradient azimuth distribution for three different intervals of gradient sizes.

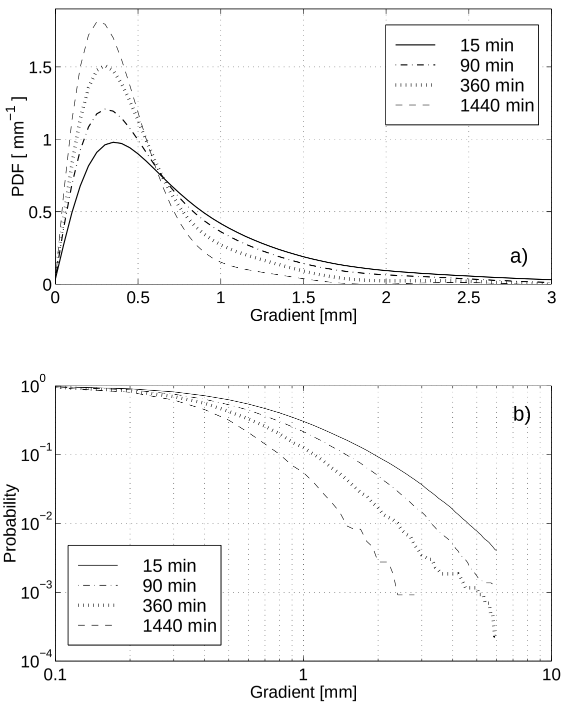

Figure 4. Distribution of gradients estimated for different time lengths. Shown are: (a) the PDF for time intervals from 15 minutes (lowest peak, highest gradients) to one day (maximum peak), and (b) the CDFs for the PDFs in (a).

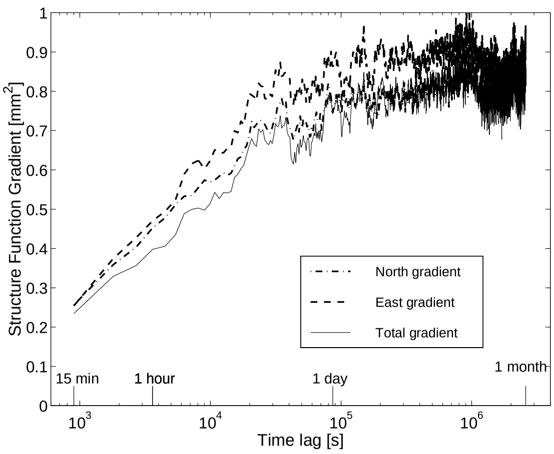

Figure 6. Gradient structure function.

Conclusions

The characterization of horizontal gradients is an important additional information when estimating atmospheric parameters in the analysis of space geodetic data and can result in a reduced uncertainty in the estimated geodetic parameters [*Bar-Sever et al.*, 1998]. Characterization of horizontal linear atmospheric gradients in the wet delay using WVR data shows that gradients are short lived. For example, there is a 30% probability to find a mean gradient larger than 1 mm for 15 minutes, whereas it is only 5% probability that the mean gradient is larger than 1 mm averaged over 24 hours (see Figure 4). The change in the statistics from year to year is small but a strong seasonal variation exists. The mean value for the 15 minute gradient in the summer is 1.3 mm, whereas it is only 0.7 mm in the winter (see Figure 3b). The decorrelation time of the observed gradients was found to be of the order of half a day. Important future work will be to compare these results with similar data from other sites in other climatic zones.

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