Journal of the Meteorological Society of Japan, Vol. 82, No. 1B, pp. 587–596, 2004

Characterization of Atmospheric Parameters using a Ground Based GPS Network in North Europe

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(Manuscript received 18 April 2003, in revised form 15 November 2003)

Abstract

We characterize the temporal and spatial variation of the Zenith Wet Delay (ZWD) and the Zenith Total Delay (ZTD), estimated using a network of Global Positioning System (GPS) receivers. This characterization is important for the improvement and validation of atmospheric water vapor models, applicable in GPS meteorology, as well as in the navigation.

We treat the estimates of Zenith Hydrostatic Delay (ZHD) and ZWD as realizations of random walk stochastic processes and we derive the corresponding parameters for different locations and measurement techniques for data acquired at intervals of 1 to 3 hours. The monthly standard deviation (StD) of the ZTD is less than 50 mm and does not exhibit a strong seasonal signature over the period 1997–1998 for any of the studied GPS sites. However, the StDs of the pairwise-differenced ZTD time series show a seasonal dependence, mainly due to the spatial variations of the ZWD, which should be considered when GPS data are assimilated in weather prediction models.

We show the differences in typical spatial characteristics of ZHD and ZWD for the winter and summer seasons in North Europe. Finally, we describe the use of temporal structure functions for detection of rapid changes in ZTD.

1. Introduction

The radio signals transmitted from GPS satellites experience a delay as they propagate through the neutral atmosphere. By convention, the delays along the line of sight to each satellite are mapped to one single parameter—the zenith total delay (ZTD). The ZTD can be split into two parts: the zenith hydrostatic delay (ZHD), and the zenith wet delay (ZWD), i.e.

$$l = l_h + l_w. \tag{1}$$

The ZHD is due to the refractivity associated with the 'dry' gases and the induced dipole moment of the water molecule, while the ZWD is related to its permanent dipole moment. The ZHD can be estimated from atmospheric pressure data, acquired on the ground, as opposed to the ZWD; furthermore, in most weather conditions the ZWD experiences much faster variations compared to ZHD. Hence the ZWD is an important source of error in GPS positioning and geodesy (Emardson and Jarlemark 1999).

Other independent techniques are often used for comparison and calibration purposes (Keihm et al. 2002). Among these are the profiles of relative humidity acquired with radiosondes (RS), and wet delay estimates from water vapor radiometers (WVR). These techniques, however, lack the spatial and/or temporal resolution of the GPS approach, which makes GPS a very attractive data source for numerical weather prediction (NWP). The data from RS also suffer from problems related to sensor calibration and aging issues (e.g., Lesht 1999).

GPS data can be used in the development and evaluation of global models for atmospheric-path correction. Such models may

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Fig. 1. Map presenting the network of GPS receivers on the territory of North Europe.

be utilized in hand-held GPS receivers as an alternative to other systems, e.g., incorporating radio-broadcasted corrections—especially in remote geographical regions. The validation and use of such models requires good understanding of both the spatial and temporal characteristics of the atmospheric water vapor.

For the description of the temporal and spatial variation of water-vapor related parameters, we have used data from a network of GPS receivers (see Fig. 1), which has continuously operated during the years 1997–2002. A comprehensive study of the long term trends in integrated water vapor (IWV) time series, using the same data set, has been carried out by Gradinarsky (2002). A characterization of the diurnal cycle of IWV was done by Bouma (2002). An overview of the relation between spatial and temporal scales of the atmospheric variations can be found in Daley (1991).

We proceed with a discussion on GPS data quality in Section 2. In Section 3 we characterize the short term variability (periods up to 3 hours) of ZHD and ZWD. These results describe the change in the uncertainty of a model estimate with time. Section 4 presents the monthly and seasonal behavior of the ZTD/ZWD variability, which should be taken into account in atmospheric models for both weather prediction and positioning in North Europe. The spatial characteristics of ZTD/ZWD are described in Section 5, and show the uncertainty of a model estimate as a function of distance and season. Rapid changes in the ZTD, related to forecasting of severe weather, are discussed in Section 6. The conclusions follow in Section 7.

2. Estimating ZTD using GPS data

The estimated ZTD is an average of the integrated refractive index along all the propagation paths from the observed GPS satellites to the receiver on the ground referred to the zenith direction. When relating the estimated ZTD to the meteorological parameters, we introduce an uncertainty from the equation used for the refractivity. This is normally written

$$N = k_1 \frac{p_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}, \qquad (2)$$

where p_d is the partial pressure of all the dry gases; e is the partial pressure of water vapour; T is the absolute temperature, and the coefficients k_1, k_2, and k_3 are empirically determined from laboratory experiments.

A commonly used value for k_1 is 77.691 K/hPa which is based on a CO_2 content of 300 ppm. The expected average value in 2004 is 375 ppm which will imply a value of k_1 equal to 77.695 K/hPa (Rüeger 1999). The change in the ZHD, caused by this updated value of the CO_2 content, is only 0.1 mm. The largest uncertainty is in k_3, and is approximately 1% (Boudouris 1963).

The accuracy of the ZTD estimates depends on many other parameters. Most important are the uncertainties in the orbit parameters of the satellites, the model used for the receiver coordinates, and the minimum elevation angle used for the observations.

The orbit uncertainties are reduced by using a large tracking network. The International GPS Service for Geodynamics (IGS) provides different products of various quality, where the most accurate orbit parameters are available many days after the time of the data acquisition (Beutler et al. 1996). The ZTD errors caused by orbit uncertainties are correlated both temporally and spatially, meaning that observed rapid changes and differences between nearby GPS sites have a high common mode rejection of orbit induced errors. Uncertainties in the orbit parameters are the main difficulty encountered in the application of the ZTD in weather forecasting, where the requirement of data availability in near real time often means within 1–2 hours from data acquisition. The ZTD obtained from post-processing, using the most accurate orbit parameters, have a value as an independent source of information for validation purposes.

In continuously operating GPS networks the site coordinates are often well known, and by fixing the position to these values the formal uncertainties of the ZTD are improved. Physical phenomena causing variations in the ZTD estimates, such as tides, ocean and atmospheric loading effects, need to be modeled.

Changing the elevation cut-off angle is not an error source in itself but it introduces systematic biases due to multipath effects, a changing phase pattern of the antenna, and a different satellite constellation. The mapping from the observed elevation angles to the zenith value of the total delay can be performed using various mapping functions (Spilker 1996; Niell 1996). The Niell mapping functions, which are utilized here, introduce an rms error in total delay of less than 6 mm at satellite elevation angles larger than 10° (Bisnath et al. 1997).

The processing of GPS data has been carried out using the GIPSY data analysis software, developed at the Jet Propulsion Laboratory (Webb and Zumberge 1993). This setup utilizes the Final orbits released by IGS in a post-processing mode (Beutler et al. 1996). The elevation cut-off angle was set to 10°.

Let us conclude this background discussion by noting that the absolute accuracy of ZTDs estimated from ground-based GPS networks is affected by the used elevation-dependent models for antenna phase center, multipath, etc., which introduce a model-dependent bias. However, a major part of this unknown bias type of error should be possible to keep constant over time scales of years, as long as the used models, and the elevation cut-off angle are not changed. The strength of the method is the possibility to observe continuously with a good temporal resolution; the horizontal resolution is simply determined by the distance between the GPS sites.

3. Short term variation

If atmospheric corrections, calculated using an NWP model, are applied by a GPS user, one needs to consider how the uncertainty of these corrections changes with time. In this section we consider the time series of ZWD and ZHD to be realizations of a *random walk* process (Brown and Hwang 1997). Such a process is described statistically by the StD of its driving white noise sequence, known as the random walk parameter (rwp). The ground pressure measurements are needed for the estimation of ZHD, and hence for the calcualtion of ZWD and IWV from GPS data. ZWD data can be independently acquired using a WVR. We describe the corresponding rwp's in order to characterize the temporal behavior of the ZWD and the ZHD.

Spatially interpolated pressure data sampled every 3 hours are delivered by the Swedish Meteorological and Hydrological Institute (SMHI) for each of the GPS sites. Davis et al. (1985) proposed an approximate formula for estimating the ZHD at a given site with latitude θ in degrees, and height H in km above the ellipsoid (Fowler 1990), from ground pressure measurements:

$$l_h = (2.2768 \pm 0.0024)\frac{P}{f(\theta, H)}, \tag{3}$$

$$f(\theta, H) = 1 - 0.00266\cos(2\theta) - 0.00028H, \tag{4}$$

where l_h is in mm and the pressure P is in hPa. This formula aided the calculation of the rwp for a year long time series of pressure and the corresponding ZHD data. The results are presented in Table 1.

The technique for deriving zenith wet delay with the aid of a WVR has been used extensively (Elgered et al. 1991 and Jarlemark 1997). We performed an estimation of the rwp for the ZWD data acquired by a WVR, operating at the Onsala Space Observatory, for the years 2000 and 2001. The algorithm for deriving ZWD from WVR data experiences problems when data are acquired during rainfall. Therefore, the time series have been edited, and

Table 1. Random walk parameters estimated from pressure data for both atmospheric pressure and ZHD. Pressure data are sampled every 3 hours.

Site	Pressure rwp, $hPa \cdot \sqrt{s^{-1}}$ 2000	Pressure rwp, $hPa \cdot \sqrt{s^{-1}}$ 2001	ZHD rwp, $mm \cdot \sqrt{s^{-1}}$ 2000	ZHD rwp, $mm \cdot \sqrt{s^{-1}}$ 2001
ONSA	$1.3 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$
HASS	$1.3 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$	$2.9 \cdot 10^{-2}$	$2.7 \cdot 10^{-2}$
JONK	$1.3 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$	$2.7 \cdot 10^{-2}$
KIRU	$1.2 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$	$2.7 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$

Table 2. ZWD random walk parameters estimated from WVR(*) and GPS data for the years 2000 and 2001. The ZWD data were selected at intervals of 1 and 3 hours, respectively.

WVR/ GPS site	1-hourly ZWD rwp, $mm \cdot \sqrt{s^{-1}}$ 2000	1-hourly ZWD rwp, $mm \cdot \sqrt{s^{-1}}$ 2001	3-hourly ZWD rwp, $mm \cdot \sqrt{s^{-1}}$ 2000	3-hourly ZWD rwp, $mm \cdot \sqrt{s^{-1}}$ 2001
Onsala*	$1.2 \cdot 10^{-1}$	$1.5 \cdot 10^{-1}$	$1.2 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$
ONSA	$1.1 \cdot 10^{-1}$	$1.1 \cdot 10^{-1}$	$1.3 \cdot 10^{-1}$	$1.3 \cdot 10^{-1}$
HASS	$1.1 \cdot 10^{-1}$	$1.2 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$	$1.2 \cdot 10^{-1}$
JONK	$1.1 \cdot 10^{-1}$	$1.1 \cdot 10^{-1}$	$1.3 \cdot 10^{-1}$	$1.2 \cdot 10^{-1}$
KIRU	$1.0 \cdot 10^{-1}$	$1.0 \cdot 10^{-1}$	$1.0 \cdot 10^{-1}$	$9.4 \cdot 10^{-2}$

the noisy data, implying liquid water content greater than 0.7 mm, have been removed prior to the analysis (Elgered and Jarlemark 1998). We carried out the corresponding calculations for the rwp of the ZWD derived from GPS. In order to compare the two techniques, we analyzed the data at the rates of 1 sample per hour, and 1 sample each 3 hours. Emardson (1998) has shown that for the short time scales, less than one hour, the radiometer time series are affected by white noise (increasing the estimated rwp values). The results for the ZWD derived from WVR and GPS are presented in Table 2. The apparent variability of the ZWD is higher than that of the ZHD (cf. Table 1). This shows that the ZWD dominates the variability of ZTD in the atmosphere for time periods up to 3 hours, which is a typical update-interval of short-range weather forecasts. We also note that, averaged over a whole year, the short term variability of ZWD (the estimated rwp) is almost the same for the years 2000 and 2001.

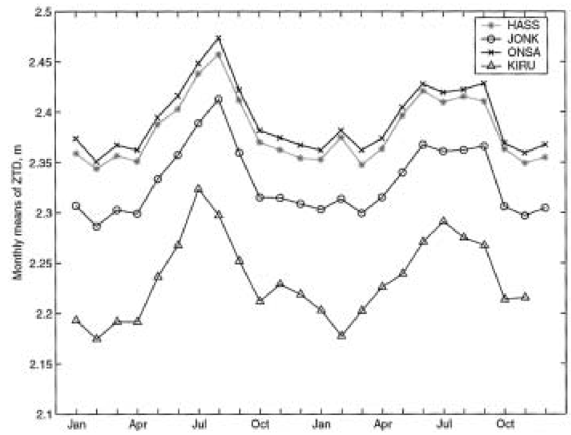

Fig. 2. Monthly means of the ZTD estimates from 1997 and 1998 for the four GPS sites at Hässleholm, Jönköping, Onsala and Kiruna.

4. Monthly and yearly characteristics

The comparison of biases and rms differences between estimates of integrated water vapor from WVR, GPS and radiosondes has been a subject of previous short term studies (Emardson et al. 1998). In this section, we attempt to characterize the behavior of ZTD and ZWD on the monthly and seasonal scales.

Using the network of GPS receivers described earlier (see Fig. 1), we calculated the monthly means and standard deviations of the ZTD data for the years 1997 and 1998. Fig. 2 shows the monthly means of the ZTD estimates for the four GPS sites Hässleholm (HASS), Kiruna (KIRU), Jönköping (JONK), and Onsala (ONSA). There exists a dependence of these values on the physical position of the corresponding GPS site. The biases between the sites are explained by the fact that KIRU has a height above sea level of 469 m and is in the north (latitude 68 degrees), whereas the other three sites are at lower altitudes (JONK = 228 m, HASS = 78 m, and ONSA = 10 m) and in the south (latitude 56–58 degrees). Even though the seasonal variations differ significantly between the two years, it can be seen that there is a rather strong spatial correlation (the distance between KIRU and HASS is 1362 km, while HASS and ONSA are only 181 km apart).

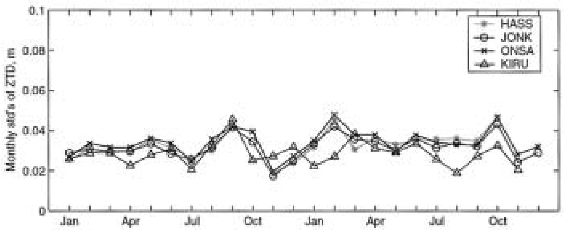

Fig. 3. Monthly standard deaviations of the ZTD estimates from 1997 and 1998 for the four GPS sites at Hässleholm, Jönköping, Onsala and Kiruna.

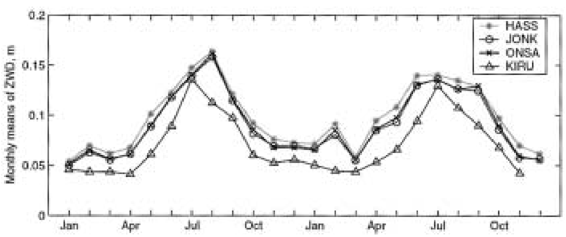

Fig. 4. Monthly means of the ZWD estimates from 1997 and 1998 for the four GPS sites at Hässleholm, Jönköping, Onsala and Kiruna. Note the sharper summer-time signature for Kiruna which is located much further north and experiences longer winters.

The standard deviations about each monthly mean of the ZTD throughout the same period can be seen in Fig. 3. There is no strong signature in the monthly StDs for any of the sites. However, we note that KIRU, in the north, on the average shows slightly less variation, and that the summer months are slightly more variable compared to the winter months. The monthly StDs of the ZTD time series do not exceed 0.05 m.

The monthly means of the ZWD are shown in Fig. 4. The dependence of the ZWD monthly means on the site location (height and altitude) is not as pronounced as for the ZTD (see Fig. 2). This can be explained with the small relative contribution of the ZWD estimates, compared to that of the ZHD. For the studied geographical area, the ZWD has typical values of about 0.1 m, while the ZHD, which is related to atmospheric pressure, takes values around 2.2 m, depending on the location and weather conditions (Webb and Zumberge 1993).

5. Spatial characteristics

In the following we assume that the ZWD/ZHD/ZTD fields are stationary within the studied periods. This assumption ensures that the variances of the individual time series remain constant, while the means are removed in the site-pairwise differencing described below. We do not assume, however, that these fields are homogeneous, because the variabilities of the ZWD and ZHD depend on the altitude of the observing station. This approach is related to the spatial structure functions (Tatarskii 1971), which describe the spatial variability of atmospheric parameters in turbulence after the data means are removed. For a study of the random fields related to water vapor under the assumption of homogeneity we refer to Stoew et al. (2001).

To describe the spatial characteristics of the ZWD estimates, we calculated the standard deviations of the differences between time series for each pair of GPS sites. The results are shown in Fig. 5. The ZWD estimates were taken for one winter month (January), one summer month (July), and the whole year of 1998.

The ZWD (and hence the water vapor content) is more spatially variable in the summer than in the winter; this is also seen in a comparison with the results for the whole year. It is a consequence of the higher convective activity in the troposphere in the summer; the water vapor content is also related to the air temperature, which may introduce variations within the diurnal cycle. Moist convection occurs over a large spectrum of spatial scales, ranging from microscale turbulence to systems that span hundreds of kilometers (Emanuel 1994). Conversely, the winter-time atmosphere is colder and more advective, rendering the smaller range in the variability of ZWD.

In all three cases shown in Fig. 5, we notice a limit in the site separation, beyond which the StD of the differences does not increase. We relate this to the spatial scales at which the atmospheric water vapor processes are no longer correlated, and the StDs of the pairwise differences become dominated by the local variations of the ZWD.

In Fig. 6, we show a plot constructed in a similar way from ZTD data. Together with

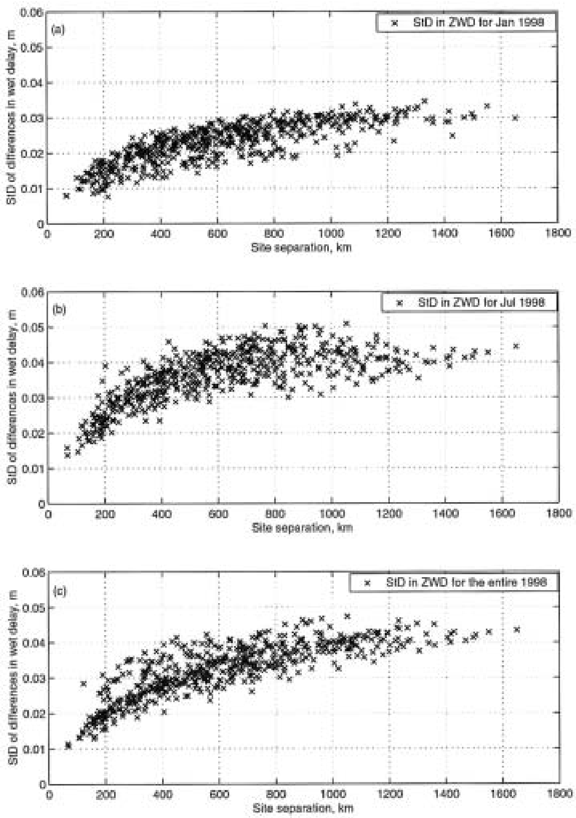

Fig. 5. Standard deviations of the pairwise differences in the ZWD time series derived from GPS data from 1998. The results were calculated for (a) one winter month (January), (b) one summer month (July), and (c) for the whole year.

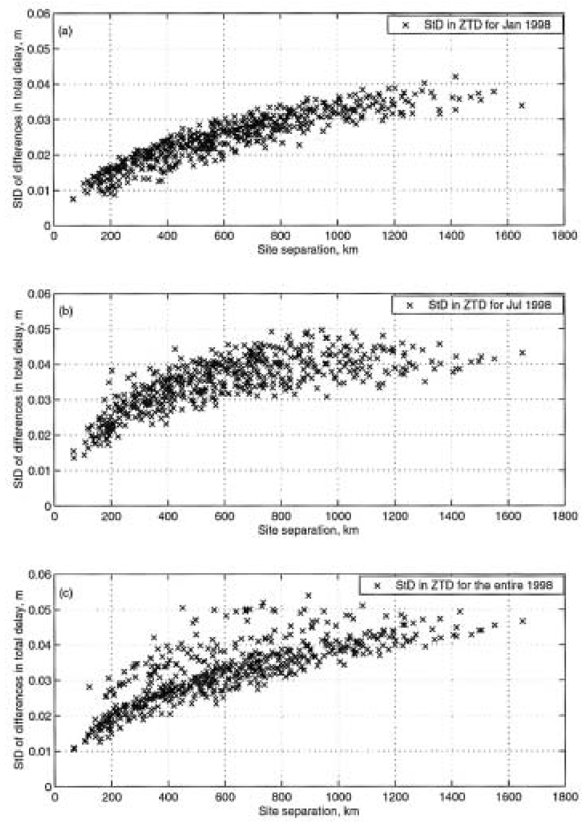

Fig. 6. Standard deviations of the pairwise differences in the ZTD time series derived from GPS data from 1998 for (a) January, (b) July, and (c) the entire year.

Fig. 7, this demonstrates the effects of the higher variability of the ZWD (compared to that of the ZHD) on the ZTD estimates.

The StDs of the pairwise differenced ZHD time series are plotted against site separation in Fig. 7. The ZHD data are derived from atmospheric pressure using the method described in Section 3. The apparent spatial variability of the ZHD estimates is much lower than that of the ZWD. Note that the pressure fields used in (3) and (4) were resampled from the original 3-hour- to a 5-minute sampling interval, using piecewise cubic spline interpolation (e.g., Press et al. 1992). The interpolation partly lowers the scatter of the ZHD StDs in Fig. 7, compared to the results shown in Figs. 5 and 6. In the process, a small portion of the short-term variations in the *true* ZHD is removed and is effectively attributed to the GPS-estimated ZWD; a signature from the spatial interpolation of the pressure field is also introduced to the ZWD estimates through (3) and (1). We compared time-interpolated pressure data to actual measurements at Onsala, and found that the StD of the differences between the two is less than 1 mm equivalent zenith delay. To reduce this effect, one of two approaches is in order: (a) use pressure data sampled at the same rate as the GPS data, or (b) use directly the ZTD estimates for assimilation into NWP models.

Note that data from ‘windy’ months are going to introduce higher variability in the ZHD fields, compared to the ‘quiet’ months during a given season, due to the advective nature of the processes. It is well established that the mean pressure fields above Scandinavia are more variable during the winter than the summer.

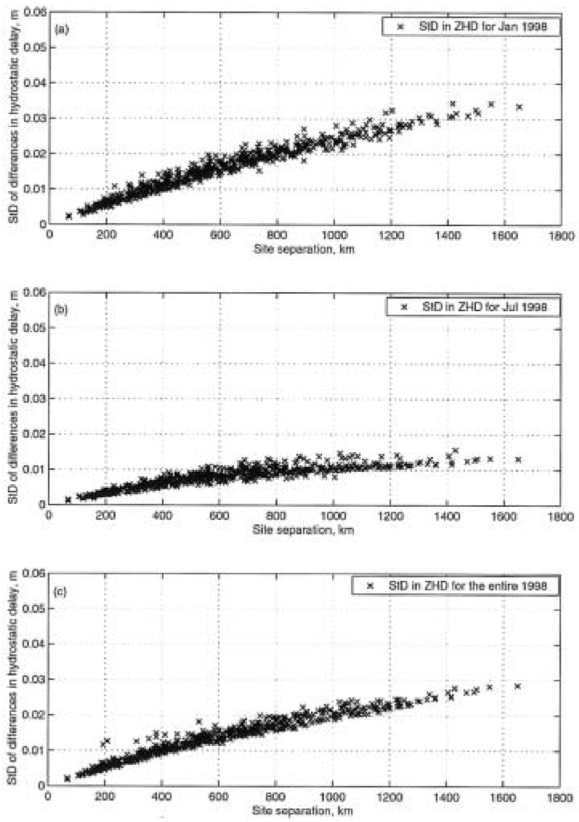

Fig. 7. Standard deviations of the pairwise differences in the ZHD time series derived from pressure data from 1998 for (a) January, (b) July, and (c) the whole year.

Typical average winter conditions are shown in Fig. 8. Stormy weather dominated in January 1995, while in January 1996 there was a high pressure formation east of the Scandinavian peninsula, characteristic for low variability of the mean pressure. In Fig. 9 we show the calculated StDs of the differenced time series of ZHD for the corresponding months.

The mean pressure fields for the months of July 1997 and July 1998 are presented in Fig. 10. July 1997 was dominated by a high pressure system over Scandinavia, which kept the conditions rather stable; July 1998 had a low pressure system centered over the region, hence the higher variability in ZHD for this period. In Fig. 11 we compare the StDs in ZHD from these two months. To conclude, the pairwise StDs in the ZHD field during winter/summer months of high atmospheric activity

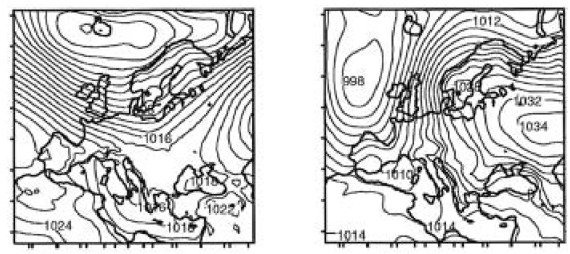

Fig. 8. Mean pressure fields over Scandinavia for a characteristic pair of winter months. January 1995 (left) was governed by westerly flows, low pressure structure in the North, and storms; January 1996 (right) was governed by a high pressure formation in the East and the weather was more stable. Courtesy C. Jones (personal communication, 2002).

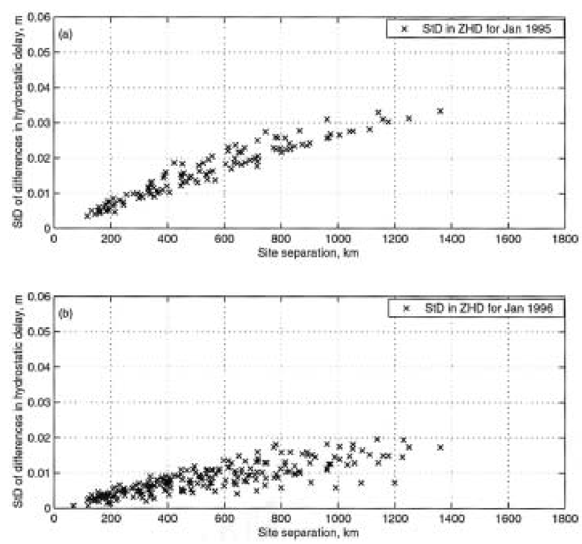

Fig. 9. Standard deviations of the pairwise differences in the ZHD time series derived from pressure data from (a) January 1995, and (b) January 1996. January of 1995 had dominating westerly flows and storm activity, and shows much higher spatial variability in the ZHD time series.

can be 50% higher than those during the corresponding low-activity months.

6. Searching for extreme events

In Section 3 we treated the time series of the atmospheric path delay above a given site as a random walk. This, however, is a first

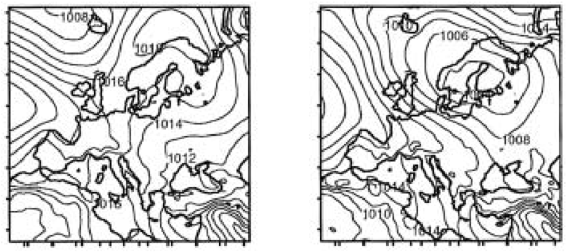

Fig. 10. Mean pressure fields over Scandinavia for a characteristic pair of summer months—July 1997 (left) and July 1998 (right). Courtesy C. Jones (personal communication, 2002).

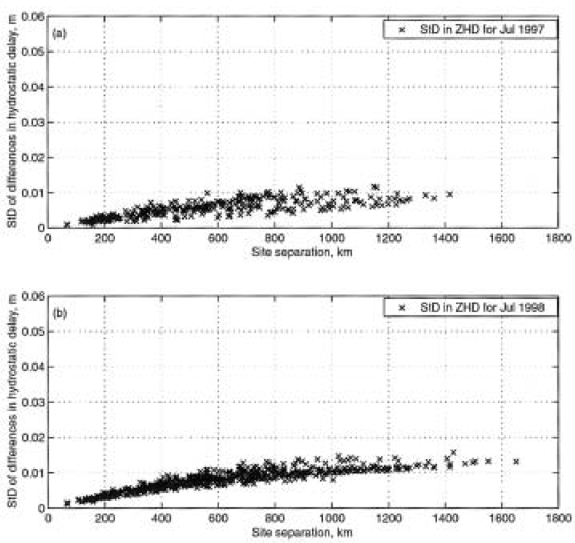

Fig. 11. Standard deviations of the pairwise differences in the ZHD time series derived from pressure data from (a) July 1997, and (b) July 1998. July of 1997 was more stable in terms of air pressure than July 1998 (see text).

order approximation, needed for comparisons between different measurement techniques. One could extend the treatment of the random process by using a *random walk with absorbing barriers* model (e.g., Grimmett and Stirzaker 1992). We consider meteorological phenomena related to local variations in the ZWD/ZTD. These variations can be used for detection/monitoring of passing atmospheric fronts. One relatively new use of GPS data is in the emerging GPS tomography (Elósegui et al. 1999; Flores et al. 2001). GPS data may aid the prediction of extreme weather conditions, such as thunder storms, night-time fog, or intense precipitation/flooding. Therefore, we need to describe statistically the ZTD variations on temporal scales of up to 1 hour.

Depending on the meteorological conditions, the ZTD can have properties differing from those of the random walk. For the statistical description of the process in the general case Jarlemark et al. (1998) used a *structure function*:

$$D_{\mathrm{ZTD}}(\tau) \stackrel{\mathrm{def}}{=} E\{[l(t+\tau) - l(t)]^2\}, \qquad (5)$$

which describes the changes over time of the zenith total delay l depending on the time lag τ. Note that the special case of a random walk yields linear dependence between $D_{\mathrm{ZTD}}(\tau)$ and τ. Similar functions can be defined also for ZHD/ZWD. Analytical approximations of the structure functions are presented by Treuhaft and Lanyi (1987).

We derived daily estimates of $D_{\mathrm{ZTD}}(\tau)$ for the year of 1998, for each of the GPS stations presented in Fig. 1. The values of the structure function were calculated for three different values of the time lag τ: 5, 15, and 60 minutes. The calculated $D_{\mathrm{ZTD}}(\tau)$ for all GPS sites were then used to produce a histogram. Rare, extreme changes in the ZTD contribute to the right tail of the histogram, while low variability amounts to the left tail, as shown in Fig. 12. A threshold can be suitably chosen, using such a histogram, in order to monitor rapid changes of ZWD in the vicinity of any given GPS site in near-real time.

7. Conclusions and future work

The importance of the knowledge of the biases and rms errors in the GPS estimates of ZTD cannot be overstated, especially when these data are to be used in operational forecasting. The overestimation of the water vapor content in the atmosphere leads to unrealistic precipitation levels in the weather forecast after the GPS data are assimilated into the NWP model (Cucurull 2001).

The seasonal changes in the short term variations of ZTD/ZWD, discussed in Sections 3 and 4, indicate the type and magnitude of fluctuations which should be taken into account when GPS data are assimilated. When mobile GPS users perform atmospheric correction to their position estimates, these seasonal

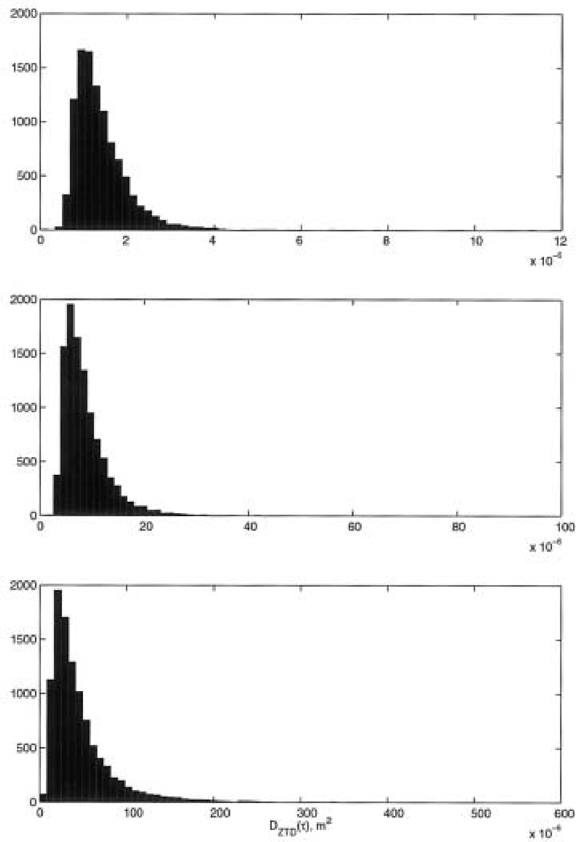

Fig. 12. Histograms of the structure function $D_{\mathrm{ZTD}}(\tau)$ calculated from ZTD values acquired in 1998. The selected sample intervals (τ) are 5, 15 and 60 minutes in the top, middle and lower graph, respectively. Note the different scales on the corresponding x-axes.

changes should be considered also as *variations in the uncertainty* of the correction models. The spatial characteristics of the type discussed in Section 5 also describe the uncertainties of atmospheric corrections (in the case when the corrections are being broadcasted to GPS users in a given geographical area).

Thus the analysis of long time series of GPS data over a certain area can be used to derive the design parameters for some applications of GPS-derived ZTD, namely weather forecasting and an improved GPS positioning.

The prediction of extreme weather, such as thunderstorms and floods, is a complex problem that requires accurate and timely information about many physical parameters and the spatial scales of their variations. Because of the relation between the scale of an atmospheric system and the time needed for it to move over a geographic area (Daley 1991), a large regional network of GPS receivers can be used to improve the monitoring of the atmosphere.

Acknowledgements

We are grateful to Colin Jones (SMHI) for the valuable comments on choosing representative periods of synoptic activity, and to Lars Meuller (SMHI) for interpolating the pressure fields to the GPS site locations. Our gratitude goes also to the two anonymous reviewers for helping improve the quality of our presentation.

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