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Abstract. We discuss aspects of how to derive precise estimates of zenith total delays (ZTD's) of the neutral atmosphere (its non-ionized constituents) from meteorological data in order to validate ZTD's derived from ground based GPS (Global Positioning System) observations. The goal is that a later stage GPS ZTD's may conversely be used in numerical weather prediction (NWP) model validation and forecasting. We determine ZTD by numerical integration over modeled or measured profiles of the atmosphere. Doing so, we find it is necessary to discriminate between geopotential and geometric heights. A term is added for the delay arising above the known atmospheric profile. Results obtained for the dry delay by numerical integration and by the Saastamoinen compare well, offsets being of sub millimeter scale only. The offsets we attribute to the time variations of the atmospheric temperature and humidity profile not being accounted for in the Saastamoinen formula. It is found that conversion of the dewpoint temperatures appearing in radiosonde (RS) reports to relative humidities may constitute a problem, and give an estimate of the maximum error associated with that. The GPS sites are in general not co-located with the RS sites nor with the grid-points of the model fields. Before deriving and comparing ZTD's it is necessary to correct for such positional offsets. We find that the correction for vertical offsets between GPS and RS sites or model orography is ambiguous, which can introduce errors.

Using our ZTD calculation algorithms we compare ZTD's based on data from the first one and half year of the MAGIC project. The results are:

$$\begin{aligned}\langle ZTD_{GPS} - ZTD_{RS} \rangle &= 6.0 \pm 11.7 \text{ mm}, \\ \langle ZTD_{GPS} - ZTD_{model} \rangle &= 3.2 \pm 17.1 \text{ mm}, \\ \langle ZTD_{RS} - ZTD_{model} \rangle &= -1.6 \pm 14.7 \text{ mm}, \\ \langle ZHD_{RS} - ZHD_{model} \rangle &= 1.2 \pm 3.7 \text{ mm}.\end{aligned}$$

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1 Introduction

The MAGIC project (Meteorological Applications of Global Positioning System Integrated Column Water Vapor Measurements in the Western Mediterranean) is an EU funded project concerned with the potential use of ground based GPS observations in weather forecasting and climate monitoring. In the project we are mainly focusing on the production and use of ZTD's. (Further information about MAGIC can be obtained via www.acri.fr/Magic).

Our concern in this article is primarily the development of tools for validation of the GPS derived ZTD's against ZTD's derived from meteorological data, both from RS's as well as from the NWP model HIRLAM (high resolution limited area model) used at the Danish Meteorological Institute (DMI).

The MAGIC data bank contains an overwhelming amount of GPS and meteorological data, rendering statistical comparisons of the data sensitive to small variations in the way in which ZTD is calculated and to the way in which one corrects for the offsets in position between RS and GPS sites or between NWP model grid and GPS sites prior to making the ZTD comparisons. Consequently we have been attempting to develop ZTD calculating software which utilises the meteorological information to the fullest, avoiding, whenever possible, the use of assumptions based on average atmospheric properties. It may turn out that the use of such assumptions is not a source of significant errors, but we find a precise understanding of this does not exist at present.

This article describes some of our findings regarding the calculation of ZTD from meteorological data. A full, more detailed and comprehensive description is being made for publication elsewhere. Further we describe some of the results of a preliminary comparison of the ZTD data currently available in the MAGIC data bank. Other aspects of the comparison are described in Haase et al. (2001). The article is arranged as follows: Section 2 describes the data sets, section 3 describes aspects of the ZTD derivation, section 4 presents a statistical comparison of the data sets, while section 5 contains a discussion and section 6 the conclusion.

2 The Data

The NWP local area model HIRLAM (see e.g. Sass et al. (1999) for details) has been run for the region bounded by -33 to 39.3 in longitude and 24 to 55.5 in latitude (the ‘MAGIC region’) at 0.3 degrees resolution with 31 vertical levels, for the period 1998-11-15 to 2000-04-30. Data assimilation was performed at 00, 06, 12, and 18 UTC. No satellite data were assimilated. The forecasts ran for 12 hours, but here we consider only data of forecast age zero to six hours. Comparisons with older forecasts will be presented elsewhere. The boundary data came from ECMWF (European Center for Medium-Range Weather Forecasts), twice daily and in the form of 0, 6 and 12 hour forecasts, valid at 00, 06, 12, 18 UTC. At each time-step (3 minutes in most cases) vertical atmospheric profiles were extracted from the HIRLAM model for the locations corresponding to GPS and RS sites for which we have observational data. From these model estimates of ZTD and other delay measures were calculated with a 15 minute resolution and distributed to the MAGIC data bank. See the next sections for details about the delay calculations.

All radiosonde reports available at DMI coming from the MAGIC region have been extracted from 1998-11-15 to 2000-06-25. The conversion of dewpoint temperatures to specific humidities was done using the procedure detailed in section 3.2. In general an RS is launched once or twice a day at the RS sites, but some of the RS sites in the sample have been reporting irregularly.

The GPS ZTD data are calculated by the CNRS (Centre National de la Recherche Scientifique/Geoscience Azur) (e.g., Ge et al., 2000) based on data from both their own GPS stations and from MAGIC partners exchanging GPS data with the CNRS. Depending on the GPS station such data will cover a large or small fraction of the above mentioned periods. The time resolution of the GPS ZTD data is 15 minutes.

3 Derivation of zenith delays from meteorological data

The ZTD is the integral of the refractivity over a vertical column of the neutral atmosphere, commonly written as

$$ZTD = 10^{-6} \int_{z_{site}}^{z_{top}} \{k_1 R_d \rho_d + (k_2 + k_3/T) R_w \rho_w\} \delta z, \quad (1)$$

(see e.g., Bevis et al. (1994)). Here ρ means density, z geometric height, R gas constant, whereas subscripts d and w mean dry and wet. The k 's are empirically determined constants quantifying the refractivity of the lower neutral atmosphere for radio-waves in the GPS range, they may contribute to the uncertainty of derived ZTD's on the millimeter level. See Bevis et al. (1994) for estimates of the k 's. In this article we shall be using $k_1 = 7.76 \cdot 10^{-1} \text{ K/Pa}$, $k_2 = 7.04 \cdot 10^{-1} \text{ K/Pa}$ and $k_3 = 3.739 \cdot 10^3 \text{ K}^2/\text{Pa}$ when deriving delays from meteorological data. Further one should notice that some constituents, like liquid water and ice, are

not included, but the effects of those are in general expected to be minor (e.g., Elgered (1992)).

In an NWP model like HIRLAM the useful variables for calculation of ZTD are pressure (p), temperature (T) and specific humidity (q). Expressed in those the above integral for ZTD turns into

$$ZTD = 10^{-6} \int_0^{p_{site}} k_1 \frac{R_d}{g} \delta p + 10^{-6} \int_0^{p_{site}} \frac{R_d}{g\epsilon} q ((k_2 - k_1\epsilon) + k_3/T) \delta p, \quad (2)$$

with ϵ being the ratio of the molecular weight of water vapour to that of dry air. The two expressions 1 and 2 are identical provided the atmosphere is in hydrostatic equilibrium. The first integral in Eq. 2 is called the hydrostatic or dry delay (ZHD), the latter the wet delay (ZWD). g is the local vertical acceleration due to gravity and non inertial forces. The contribution to the integral from above 80 km is negligible, thus the lower limit of the integral can safely be set to zero in Eq. 2.

We calculate ZTD by numerical integration of the right hand side of Eq. 2, using data from either the HIRLAM model or RS's, the latter after conversion of dewpoint temperatures to specific humidities.

Using Eq. 2 it is important to include the variation of g with height. That corresponds to using proper, geometric heights for z in Eq. 1 rather than the geopotential heights widely used in meteorology and occurring in, for example, RS reports. See Vedel (2000) for details. We find the effect of *not* doing so is around -5 mm in ZTD at mid latitudes. In our numerical integration we utilise the relations $\delta \ln p \propto \delta z$, $\delta z \propto \delta T$, and $\delta \ln p \propto \delta q$ when having to interpolate.

The ZHD integral contains significant contributions up to about 80 km above the geoid, far beyond the top level of both the HIRLAM model (top level for T and q is 12.5 hPa) and standard radiosondes. We have derived an expression for the contribution to the dry delay from the top of the known profiles and further up, which is added to the numerical integral of the profile data when calculating the delays. The expression is based on an assumption of hydrostatic equilibrium, of the temperature being constant upwards the top of the known profile, and of $g(r) = g_1(r_1/r)^2$, r being the distance to the center of the Earth, in which case

$$\Delta ZHD \approx \frac{k_1 R_d p_1}{g_1} \left\{ 1 + 2 \frac{R_d T_1}{r_1 g_1} + 2 \left(\frac{R_d T_1}{r_1 g_1} \right)^2 \right\}, \quad (3)$$

with T_1 , g_1 , r_1 , and p_1 being the values at the top of the known profile. We derive g_1 using the procedures outlined in Vedel (2000). The approximation is found to work very well on US standard atmosphere data, even from rather low levels, and to be stable against offsets in temperature, which is important – the assumption of the temperature being constant in that part of the atmosphere is far from true. The contribution to ZWD from above the model and RS profiles is negligible.

Radiosonde launch sites and GPS sites are rarely co-located. Similarly the NWP model orography has a finite resolution.

Comparing ZTD's from sources with position offsets it is of vital importance to correct for these. (Very roughly, an altitude difference of 8 m corresponds to 1 hPa which corresponds to 2.3 mm in ZHD). The vertical correction is non trivial, as no 'correct' solution exists. In a preliminary study we have found offsets in ZTD of 0.8 ± 5.8 mm between ZTD's based on different, yet both widely used, vertical shifting algorithms for meteorological profiles (Vedel, to be finished, the two corrections methods compared are those described in 4.1 and 4.2).

3.1 The Saastamoinen formula versus direct integration

Adopting a standard atmospheric temperature profile and a function describing the variation of the gravitational acceleration with height, the hydrostatic delay becomes a function solely of location and local pressure. The well known formula by Saastamoinen (1972) is one such example. We have compared ZHD's based on that formula and on numerical integration of atmospheric profiles in order to assess the precision of the Saastamoinen formula and the importance of the temperature variations for the dry delay. For the Saastamoinen formula we use $ZHD = k_s p_{site} / f(\theta, H)$, where $k_s = 2276.8 \cdot 10^{-5}$ mm/Pa and $f(\theta, H) = 1 - a_1 \cos 2\theta - a_2 H$, with θ being the latitude and H the altitude with respect to the ellipsoid, and the constants taking the values $a_1 = 2.66 \cdot 10^{-3}$ and $a_2 = 2.8 \cdot 10^{-4}$ km $^{-1}$ (from Emardson et al., 1998, p 1809).

The results are shown in Fig. 1, in terms of mean offset and standard deviation, for radiosonde profiles. For most of the sites the data covers more than a full year.

The Saastamoinen formula provides on average a very fine estimate of ZHD. The effect upon ZHD of the time variations of the temperature profile and humidity profile, which both effect the relation between pressure and proper height, are of sub millimeter scale only for the data in our sample.

3.2 Derivation of humidity from radiosonde data

Radiosondes measure the relative humidity, rh , during their ascent. These are converted to dewpoint temperatures, T_{dew} , prior to the profiles being broadcast via the GTS network to the meteorological institutes. A precise conversion (rh, T) to T_{dew} requires precise knowledge of the function *esat* describing the relation between the water vapour saturation pressure and temperature. The real *esat* is very complicated however, the radiosonde ground equipment apply an approximation, resulting in dewpoint temperatures which are not fully correct. Further the function used for the conversion is equipment specific (John Elms, 2000, personal communication). Thus, obtaining the correct specific humidities for the integration of Eq. 2 for a RS profile it is therefore, at least in theory, necessary first to apply first the inverse of the function used at the particular RS site, to get back to the measured rh , and secondly to use a precise *esat* to convert (p, T, rh) to specific humidity. Is this of importance in practice for ztd comparisons?

We do not have information about the conversion formulas used at the individual sites. However, using two different conversion formulas for conversion of T_{dew} to rh , a very precise one (based on *esat* from the HIRLAM model), here named $rh1$, and the one used in the most widespread RS equipment in Europe (Digicora), here called $rh2$, we can assess the importance of using the correct conversion formula. We find $\langle ZTD_{rh2} - ZTD_{rh1} \rangle = 2.3 \pm 1.0$ mm for the radiosonde profiles extracted for MAGIC. This is large enough to be of importance in our statistical comparisons.

It is likely, however, that the conversion formulas used at the different radiosonde sites are similar enough that using the conversion formula from one type of equipment on data from another type of equipment yields much smaller offsets. But this should be tested. It is very unlikely that the problem is particular to Digicora equipment, and Vaisala is thanked for providing information about the formula used in their ground equipment.

Notice also that the offset is only of the order one per mille of the total ZTD signal. Given the much larger errors of NWP model humidities and single RS humidity measurements the discrepancy is not of similar importance in day to day comparisons of ZTD's, nor when assimilating humidities into NWP models.

As a consequence of the above the specific humidities deduced for the RS profiles extracted for the MAGIC project has been deduced as, $q = e\epsilon / (p - e(1 - \epsilon))$, where $e = rh \text{ esat}_{HIRLAM}(T)$ and rh is derived from (T_{dew}, T) by use of the inverse of a function similar to that used in Digicora equipment.

4 Comparison of delays

4.1 Comparison of GPS and radiosonde ZTD's

A comparison of GPS and RS ZTD's have been made for station pairs with small horizontal separations, ≤ 50 km. No correction was made for the horizontal offsets in location, but a correction was done for the offset in altitude, interpolating upwards, extrapolating downwards assuming constant temperature lapse rate, $\delta T / \delta z = -0.0065$ K/m, and constant relative humidity equal to that of the lowest RS level. A 3 sigma clipping was applied to the ZTD offsets at each pair of sites in order to remove incorrect GPS and RS data. We find $\langle ZTD_{GPS} - ZTD_{RS} \rangle = 6.0 \pm 11.7$ mm. The results are shown site wise in Fig. 2. There appears to be a systematic bias, the GPS ZTD being larger than the RS ZTD. The reason for the bias is currently unknown.

It may be related to the fact that the sites compared are not co-located, introducing by chance a systematic effect in our small sample of pairs. It may be related to the k 's used in Eq. 2 being incorrect, but the error is likely smaller than the effect we find here. Another problem is the difficulties which arise due to the rather poor resolution of the RS reports, in particular of humidity, and the lack of a high level quality screening, something which is routinely applied before util-

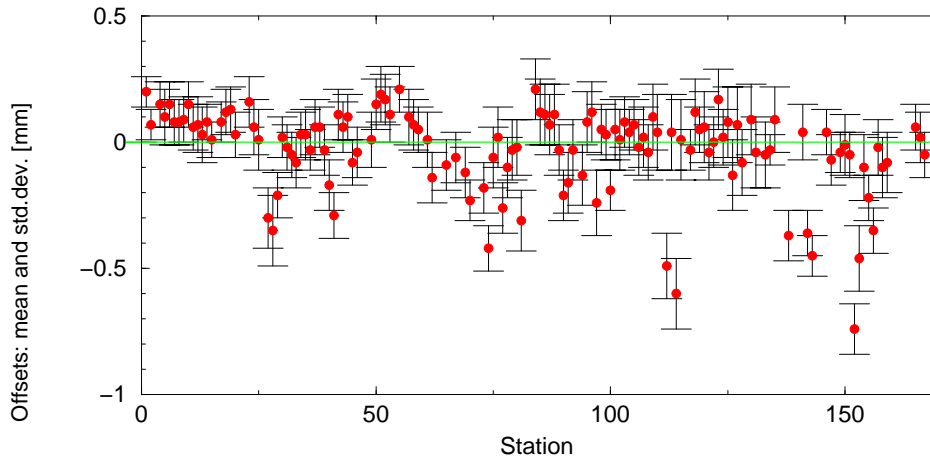


Fig. 1. $\langle ZHD_{saas} - ZHD_{integration} \rangle$. Line represents mean of all offsets.

ising such data in NWP modeling. However, we find it very unlikely such problems will result in systematic offsets of the magnitude found in our GPS RS ZTD comparison. Because NWP model HIRLAM may itself be biased the lack of a similar bias in the RS HIRLAM ZTD comparison presented below does not allow us to draw any conclusions regarding this problem. Comparisons of ZTD's from high and low resolution RS profiles have been started in EU COST ACTION 716.

Liljegren et al. (1999) have reported an improved correlation between the integrated water vapour measured by means of integration RS profiles and by microwave radiometers when the RS humidity measurements were corrected for an offset in RS relative humidity depending on the time between the calibration of the RS and its launch. The correction increases the rh inferred from the RS observation, and thus would act to diminish the GPS-RS ZTD bias for our sample. More work is needed to resolve this issue.

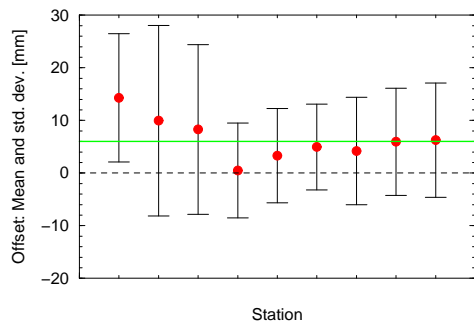


Fig. 2. $\langle ZTD_{GPS} - ZTD_{RS} \rangle$. Full line: mean of all ZTD offsets.

4.2 Comparison of radiosonde and HIRLAM delays

A comparison has been made between delays derived from RS's and from HIRLAM data. Horizontal interpolation and vertical shifts have been performed in the HIRLAM model fields to the location of the radiosonde sites. The vertical

shifts were done using the method by Majewski (1985), using a version and parameters similar to those used in the HIRLAM model. Figure 3 is for data to which a 3 sigma clipping was applied to the ZTD offsets at each site in order to remove incorrect RS reports. Over the whole dataset, comprising more than 90000 RS reports, the average offsets are: $\langle ZTD_{RS} - ZTD_{HIRLAM} \rangle = -1.6 \pm 14.7$ mm and $\langle ZHD_{RS} - ZHD_{HIRLAM} \rangle = 1.2 \pm 3.7$ mm, respectively.

There is a much better agreement between hydrostatic delays, which depends (nearly) solely on pressure, than wet or total delays, which depends also on humidity.

We attribute this mainly to the NWP model having problems predicting humidity, based on the humidity verifications of the HIRLAM model performance routinely carried out at DMI.

However, as the verification of the HIRLAM humidities is to some extent based on RS data, it is difficult to fully disentangle to which degree the ZWD scatter is due to the HIRLAM model being in error or due the differences in representativeness between the very local RS measurements and the large grid-boxes of the model.

The fact the scatter found in the GPS RS comparison is smaller than for the RS HIRLAM comparison indicates the model has humidity errors. This argument is based on the fact that the GPS ZTD measure is in this context semi local, somewhere between the RS ZTD and the NWP ZTD in representativeness. It is a special type of average over a number of delays measured towards the GPS satellites visible to the GPS receiver at the site. Further the GPS and RS sites compared have horizontal distances comparable to the grid-box size of the HIRLAM model simulations, and the observations are not simultaneous (an RS ascent takes more than one hour). Based on this we would expect to see a relatively larger spread for the GPS RS ZTD offsets than for the RS HIRLAM ZTD offsets if the offsets were dominated by representativeness effects, contrary to our findings.

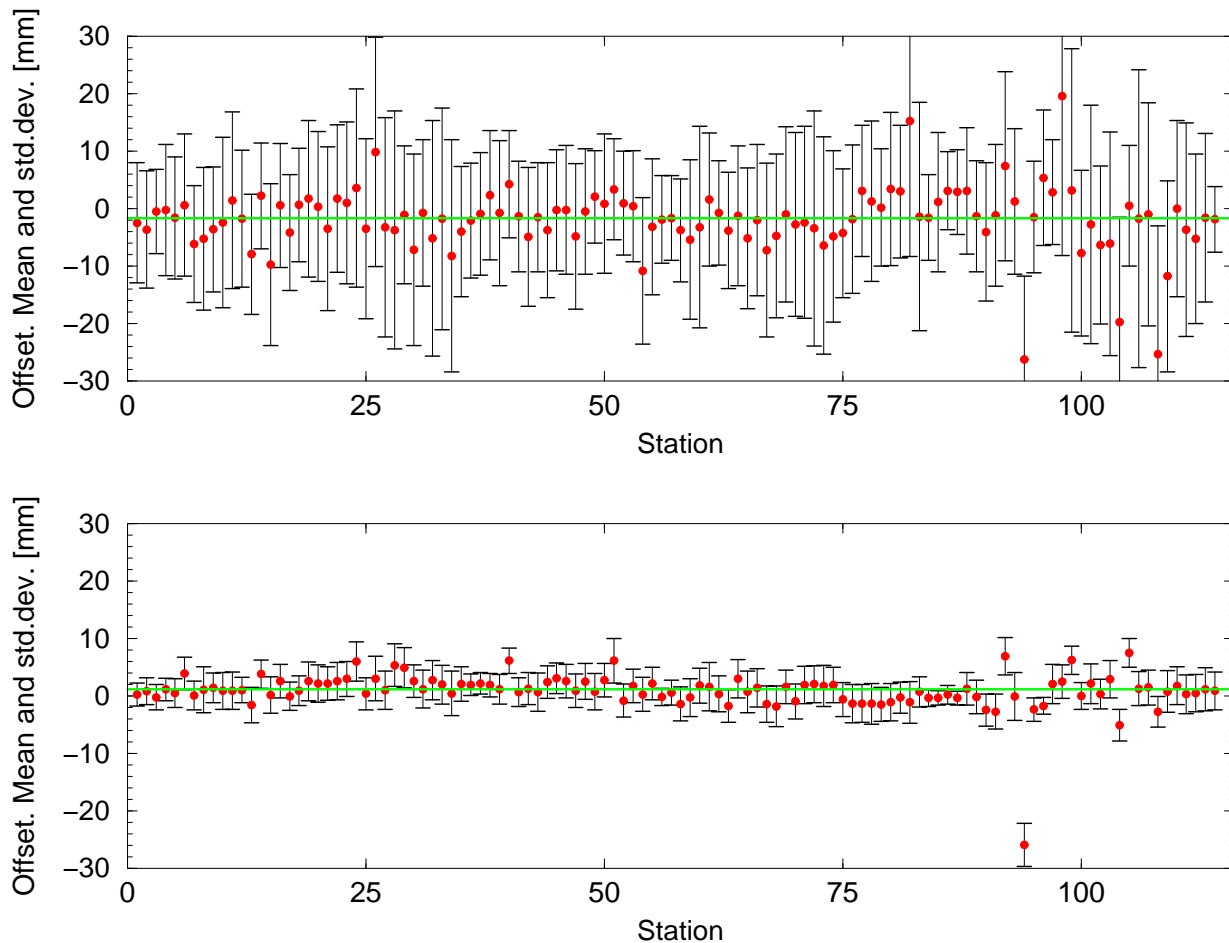


Fig. 3. Top: ZTD offsets, mean and standard deviations, from radiosonde and HIRLAM data. Bottom: similar, but for the hydrostatic delays. Lines represent means of all offsets of respective type.

4.3 Comparison of GPS and HIRLAM ZTD's

The GPS ZTD's from CNRS have been compared against ZTD's deduced from HIRLAM data. Horizontal interpolation and vertical shifts were made on the HIRLAM fields to the locations of the GPS antennas. The vertical shifts were done using the method by Majewski (1985). Results are shown in Fig. 4, for data to which a 3 sigma clipping has been applied to the offsets at each site. The sigma clipping is necessary to remove incorrect GPS delays which have escaped the GPS ZTD quality control effective at the current stage of the MAGIC project. The average offsets are: $\langle ZTD_{GPS} - ZTD_{HIRLAM} \rangle = 3.2 \pm 17.1$ mm, deduced on the basis of about 1360000 pairs of ZTD's. (The data are not all independent though, due to the way in which the GPS ZTD data are deduced and the way in which an NWP model work.) These results are in line with previous studies by other groups (e.g. Yang et al. (1999) and Cucurull et al. (2000)) Spin-up effects were found not to be of importance in a preliminary comparison against ZTD's based on HIRLAM 6 to 12 hour forecasts.

Using the same data Haase et al. (2001) find that the de-

viation of the GPS HIRLAM ZTD offsets decrease with site altitude, despite the vertical shifts being on average larger for the high altitude stations, and further that there exists a seasonal variation, the deviation being largest in the warm, humid summer months.

Given that the HIRLAM model assimilates the RS data and not the GPS delays our result indicates that measured against HIRLAM data the GPS delays are of a quality more or less comparable to the radiosonde delays.

5 Discussion

Measured against the HIRLAM model we find the GPS and RS ZTD's to be of comparable quality. Further we find that the offsets in ZHD between HIRLAM and RS are much smaller than for ZTD, and we have argued that this is partly due to model having problems predicting humidities. Further there is strong correlation between the GPS and meteorological ZTD's in our dataset (Haase et al., 2001), similar to what has been found in a number of previous studies of other datasets when comparing integrated water vapour estimates based on GPS, RS and NWP model data (e.g., Yang et al. (1999) and

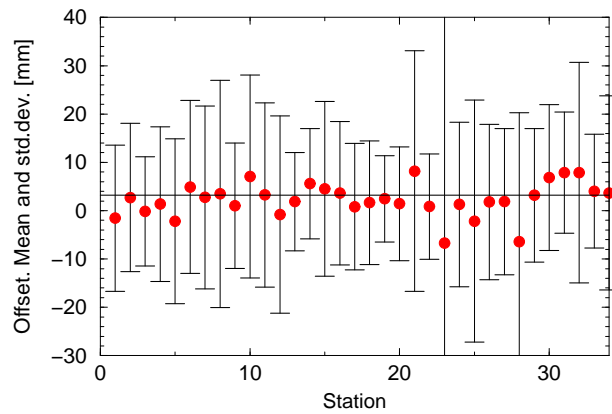


Fig. 4. ZTD offsets, mean and standard deviations, from GPS and HIRLAM data. Line represents mean of all offsets

Cucurull et al. (2000)). Together this is an indication that GPS ZTD's can provide valuable extra humidity observations for NWP models like HIRLAM.

On the other hand it also means that care is required when constructing assimilation algorithms for ground based GPS delays, in order not to disturb the pressure field of the models as a result of the models much poorer handling of humidity (in a ZTD sense in this context), when assimilating GPS ZTD data. Similarly the correlations of the errors of the GPS ZTD estimates (inherited from the GPS data reduction) is a problem not to be forgotten, as most current data assimilation software relies on the errors of the observations being un-correlated.

Within MAGIC we have now started assimilation experiments where GPS ZTD's are utilized in NWP model simulations. Similar tests are being carried out by other groups.

6 Conclusion

We have developed software for calculation of ZTD's based on meteorological data from NWP models and radiosondes by means of numerical integration. We find it is important to discriminate between geometric and geopotential heights in the integration. An expression is given for the small additional part of the ZHD which arises above the known atmospheric profile. In a comparison we find that the so-called Saastamoinen formula for ZHD works well, offsets being of sub millimeter scale only. The proper conversion of radiosonde dewpoint temperatures to specific humidities may constitute a problem. Ignoring the problem can lead to ZTD biases on the millimeter level. For ZTD comparisons between sites which are not co-located a correction for the offset in altitude between sites, or between model orography and sites, is necessary. This may well add to ZTD uncertainties on the millimeter level.

Using data from the MAGIC project we compare ZTD's based on GPS, radiosonde and NWP model HIRLAM data. We find $\langle ZTD_{GPS} - ZTD_{RS} \rangle = 6.0 \pm 11.7$ mm, $\langle ZTD_{GPS} - ZTD_{model} \rangle = 3.2 \pm 17.1$ mm, $\langle ZTD_{RS} - ZTD_{model} \rangle =$

-1.6 ± 14.7 mm and $\langle ZHD_{RS} - ZHD_{model} \rangle = 1.2 \pm 3.7$ mm.

The GPS ZTD's appear to be systematically high relative to the ZTD's based on meteorological data, in particular relative to the RS ZTD's. No indication is found that this is due to the GPS ZTD being in error, and the GPS ZTD's appear a promising new source of humidity information for NWP models.

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