JPCE 491
DISK / 25/2/02

ARTICLE IN PRESS

No. of pages: 8
DTD 4.3.1/ SPS

PERGAMON

Physics and Chemistry of the Earth xxx (2002) xxx–xxx

PHYSICS and CHEMISTRY of the EARTH

www.elsevier.com/locate/pce

MM5 derived ZWDs compared to observational results from VLBI, GPS and WVR

D. Behrend [a,*], R. Haas [b], D. Pino [a], L.P. Gradinarsky [b], S.J. Keihm [c], W. Schwarz [d], L. Cucurull [a], A. Rius [a]

[a] Institut d'Estudis Espacials de Catalunya (IEEC), CSIC Research Unit, c/Gran Capital 2–4, 08034 Barcelona, Spain
[b] Onsala Space Observatory (OSO), Chalmers University of Technology, Sweden
[c] Jet Propulsion Laboratory (JPL), Pasadena, California, USA
[d] Bundesanstalt für Kartographie und Geodäsie, Fundamentalstation Wettzell, Kötzting, Germany

Abstract

Modelled values of zenith wet delay (ZWD) from the non-hydrostatic numerical weather prediction (NWP) model MM5 are compared to estimated values retrieved from observations by geodetic very long baseline interferometry (VLBI), global positioning system (GPS) receivers, and water vapour radiometers (WVRs). In addition, sparse radiosonde (RS) data are used to augment the available data sets. The comparison is done for three stations of the European geodetic VLBI network for six observing sessions during the year 1999. The stations (Madrid, Onsala, and Wettzell) were primarily chosen to have the maximum number of collocated measuring techniques. In general, the time series for the different techniques show a good agreement. The correlation values between the techniques amount to 75–95%. The RMS differences of MM5 with respect to the other techniques obtain values of ±1.3–1.6 cm. The bias between MM5 and VLBI lies at about 1.0 cm, the bias between MM5 and GPS varies in the range of 0.0–0.6 cm and appears to be station dependent.

1. Introduction and motivation

A crucial parameter in numerical weather prediction (NWP) models is the atmospheric humidity content. A good knowledge of the temporal and spatial distribution of the atmospheric water vapour together with the corresponding error information has a noticeable impact on the quality of the prediction results (e.g., Yang et al., 1999). Until recently the primary source for the determination of the distribution of the water vapour in the atmosphere has been radiosondes (RSs). Having the advantage of providing vertical profiles of water vapour, RS have the drawback of being launched only sparsely in time and space, i.e. once or twice a day with the launch sites some hundred kilometers apart. While NWP models have increased their horizontal and vertical resolution over the past decade, the number of observational sites for RS and ground meteorological data has stayed almost the same. This shortcoming may be cured or at least alleviated by the inclusion of additional water vapour measurements from independent techniques in order to be assimilated into the NWP models (e.g., De Pondeca and Zou, 2001). For improving the spatial coverage and providing a continuous monitoring of the atmospheric humidity, geodetic space techniques present themselves these days. Due to the favourable spatial distribution of stations, the low operational costs and near-real-time availability, the global positioning system (GPS) constitutes the obvious choice for improving NWP models. While very long baseline interferometry (VLBI) does not provide the temporal or spatial density of GPS, its accuracy and the distribution of its antennas over a wide range of climates makes it a potential additional source of important climate data (Niell et al., 2001). Nonetheless, as the geodetic space techniques only provide integrated water vapour values (instead of profiles), they will not replace RS observations but rather augment them.

In order to evaluate the claims for accuracy and precision by each of the techniques, campaigns with collocated instruments are needed (Niell et al., 2001). Numerous studies have been carried out to determine

* Corresponding author. Present address: Stanford Linear Accelerator Centre, 2575 Sand Hill Road M/s#21, Menlo Park, CA 94025, USA. Tel.: +34-93-280-6395; fax: +34-93-280-2088.
E-mail addresses: behrend@ieec.fcr.es, behrend@slac.stanford.edu (D. Behrend), .

1474-7065/02/$ - see front matter
PII: S1474-7065(02)00004-9

the accuracy of VLBI, GPS, WVR, and RS derived tropospheric parameters by intercomparing the different techniques among themselves and by comparing them, mainly GPS, to NWP models: e.g. (Behrend et al., 2000; Cucurull and Vandenberghe, 1999; Cucurull et al., 2000; Gradinarsky et al., 2000a,b; Haase et al., 2001; Niell et al., 2001; Pacione et al., 2001; Yang et al., 1999). The comparisons made using VLBI data (Behrend et al., 2000; Niell et al., 2001) are restricted to campaign style of data with 1–4 d of continuous VLBI observations restricted to a selected single station. Here we present a comparison between all of the aforementioned techniques for six disconnected days of VLBI observations for the arbitrarily chosen year 1999. With a session roughly every second month the observational data cover an annual cycle. For the same stations and times numerical simulations of the meteorological situation using the non-hydrostatic fifth-generation Mesoscale Model (MM5) were conducted.

2. Description and analysis of the observational data

Since 1990 the European geodetic VLBI community performs geodetic VLBI observations with the fixed-station VLBI-sites in Europe on a regular basis. While the main objective is the determination of crustal motion in Europe (Haas et al., 2000), the analysis of the observed VLBI data gives also results for atmospheric parameters at the respective stations. Several of the European geodetic VLBI network stations employ, aside from VLBI, also other geodetic space as well as remote sensing techniques. At the stations Madrid, Onsala and Wettzell facilities for VLBI, GPS, WVR, and RS are collocated at the same site, i.e. they are all within 100 m with the exception of the RS that are 40–80 km away. Fig. 1 depicts the geographic distribution of the stations, and Table 1 provides some general station information. The climatological situations of the investigated sites cover a range from a semi-arid continental (Madrid) over a temperate continental (Wettzell) to a temperate marine regime (Onsala).

For the three stations (Fig. 1) zenith wet delay (ZWD) values are derived from the various techniques for specific days of the arbitrarily chosen year 1999. We do not analyse the error sources that occur due to the conversion from the original observations to the common parameter ZWD. An exhaustive compilation of the errors involved can, for instance, be found in Niell et al. (2001). This implies that we neglect assumptions underlying the different conversion procedures and, thus, possible biases for each technique. We implicitly assume, therefore, that the sum of the conversion errors is negligible.

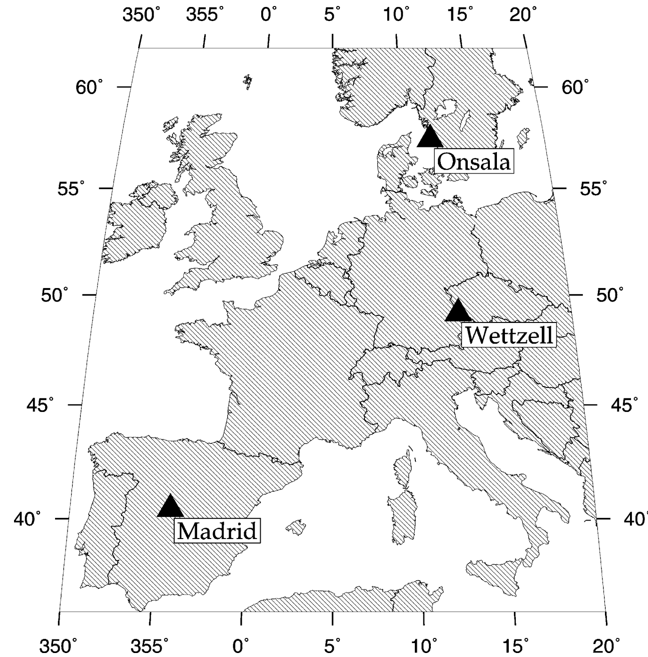

Fig. 1. Three sites of the European geodetic VLBI network with the collocated measurement techniques VLBI, GPS, WVR, and RS.

2.1. Space geodetic observations

In the year 1999 six geodetic VLBI experiments of the EUROPE series were observed (see Table 2). The experiments of this observing program are spread more or less homogeneously over the entire year with an experiment every second month. The experiments start at 1200 h UT and last for 24 h.

The VLBI data were analysed using the SOLVE software package (Ma et al., 1990). Atmospheric parameters for the VLBI stations involved were estimated as piecewise linear functions with an interval length of 90 min for the ZWD and horizontal gradient parameters. Constraints corresponding to a random walk variance of 100 mm^2/h for the ZWD and 1.0 mm^2/h for

Table 1
Station characteristics of the chosen sites (geodetic latitude φ, geodetic longitude λ, ellipsoidal height h, distance d to the neareast sea, and climatological regime)

Station	φ (°)	λ (°)	h (m)	d (km)	Climate
Madrid	40.4	−4.2	850	600	Semi-arid, continental
Onsala	57.4	11.9	25	0.5	Temperate, marine
Wettzell	49.2	12.9	550	400	Temperate, continental

Table 2
VLBI sessions of the EUROPE series for the year 1999

Session	Observation time	Days of year (doy)
EU-47	01-FEB 1200–02-FEB 1200	032.5–033.5
EU-48	26-APR 1200–26-APR 1200	116.5–117.5
EU-49	28-JUN 1200–29-JUN 1200	179.5–180.5
EU-50	16-AUG 1200–17-AUG 1200	228.5–229.5
EU-51	11-OCT 1200–12-OCT 1200	284.5–285.5
EU-52	13-DEC 1200–14-DEC 1200	349.5–348.5

the horizontal gradients were applied. These constraints were found by Gradinarsky et al. (2000a,b) to be reasonable from comparisons of an extensive VLBI, GPS and WVR data set observed at the Onsala Space Observatory.

The IVS (International VLBI Service for Geodesy and Astrometry) network stations Madrid, Onsala and Wettzell are also IGS (International GPS Service for Geodynamics) network stations performing permanent GPS observations. The data observed with the collocated GPS-antennas and receivers were analysed using the GIPSY software package (Webb and Zumberge, 1993) applying the precise point positioning method (Zumberge et al., 1997). For the Kalman filter analysis again random walk variance constraints of 100 mm^2/h for the ZWD and 1.0 mm^2/h for the horizontal gradients were used. The interval length for the update of the Kalman filter was adapted to the interval length chosen for the VLBI data analysis. For both, the VLBI and the GPS data analysis, the Niell mapping functions (Niell, 1996) were applied.

2.2. Radiometric and radiosonde observations

The three sites are equipped with continuously observing collocated water vapour radiometers (WVRs). Three different instrument types are employed: a JPL type D2 (Madrid), a Chalmers type Astrid (Onsala), and an ETHZ type White (Wettzell). The radiometers perform continuous and repeating sky scanning observations at different elevation and azimuth angles. Each sky-scan takes about 12–15 min. Different analysis software packages corresponding to the individual instruments were applied to analyse the WVR observations and the ZWD parameters were determined for the same interval length as from the VLBI and GPS observations. For instrument maintenance reasons and due to rainy weather it was not possible to observe all of the six sessions for all three stations.

RSs are launched not directly at the stations but at dedicated launching sites, usually airports, twice a day. For Madrid the closest launch site is the Barajas airport at about 40 km distance, for Onsala it is the Landvetter airport at about 38 km, and for Wettzell the RS launch site chosen is at Kümmersbruck some 80 km away. In Landvetter there were four launches a day during the investigation period; the two other stations just had one launch per day.

3. Numerical weather prediction modelling

For the same stations and days a numerical simulation using the non-hydrostatic fifth-generation Mesoscale Model (MM5) was performed. MM5 was developed at Penn State University (PSU) and the National Center for Atmospheric Research (NCAR) (see e.g. Dudhia et al., 2001). We set up four (two-way nested) domains with resolutions of 27, 9, 3, and 1 km. For the used 31×31 grid this translates into domain sizes of about 850, 300, 100, and 30 km side length. The smallest domain was centered approximately at each site. The initial and boundary conditions were updated every six hours with information obtained from the $0.5° \times 0.5°$ ECMWF model. The resolution of the topography and land-use data bases for each domain were: $5'$, $1'$, $1'$, and $30''$. High vertical resolution was prescribed in the atmospheric boundary layer (ABL) with 27 levels of around 100 m grid spacing.

The soil parameterizations used have differences with regard to the drag, heat and moisture coefficients, and in the degree to which roughness length depends on surface wind speed. Soil temperature was predicted at six different levels by means of the diffusion equation. The model surface properties (albedo, roughness length, moisture availability and heat capacity) are specified according to the 24 USGS land-use categories, which are then reduced to one of the 13 land-use MM5 categories and a summer–winter season.

The same physical descriptions are prescribed for all simulations. We have calculated the boundary layer processes using the Medium Range Forcast scheme based on Troen and Mahrt (1986); a Kain-Fritsch scheme has been used for the cumulus parameterizations and a simple ice model for the explicit moisture schemes.

4. Results and comparisons

The 24 h ZWD time series resulting from the analyses described in Sections 2 and 3 are depicted in Figs. 2–4. For the sake of visualisation and comparison of the time series we do not show error bars in these figures. The simulation results from MM5 have a precision of 2 mm for precipitable water (PW) (Cucurull and Vandenberghe, 1999) corresponding to a precision of 15 mm for the ZWD (Behrend et al., 2000). The ZWD values obtained from GPS and VLBI have formal errors in the order of 5 and 4–8 mm, respectively. Results from WVR can be expected to have a precision of 2 mm plus 5% of the measurement and results from RS of 5% of the measurement (Niell et al., 2001). These error values are used in the statistical analysis.

In general, there exists a good agreement between the simulations from MM5 and the results of the different observational techniques. The deviations are usually contained in the margins given by the formal errors of the involved techniques. Making the crude classification into summer and winter seasons, one notices the low moisture values for the winter sessions (EU-47, EU-48, EU-52), whereas the summer sessions (EU-49, EU-50, EU-51) show a higher moisture content. Only the station Madrid (Fig. 2) has high moisture values also during one of the winter experiments (EU-52).

There are basically two occasions in which the ZWD estimation differences exceed the formal error margins significantly. One is connected with instrumental respectively data analysis problems: the ZWD time series of the WVR of Wettzell fluctuates quite strongly (see e.g. day of year 229 in Fig. 4). Probably observations that are contaminated by rainfall events and thick clouds have not been removed correctly in the data editing process. Still, the complete removal of such observations is a prerequisite to obtain a clean data set (Gradinarsky et al., 2000a,b).

The other occasion is with the winter experiments EU-47 (day of year 33) and EU-52 (day of year 348) at the station Onsala (see Fig. 3). Here the MM5 derived ZWDs do not coincide with the measurement techniques: on day of year 33 MM5 describes a peak for midnight, which is not seen with the measurement techniques, and on day of year 348 the MM5 simulation shows a similar divergence for the second half of the observation session. In both cases MM5 tends to overestimate the ZWD values, i.e. it overestimates the water vapour content in the atmosphere. Still, comparisons of NWP model with GPS derived ZWD values over a longer time span (more than one year) have shown that such occurrences are not uncommon (e.g., Haase et al., 2001). Yang et al. (1999) found discrepancies of up to 5 mm PW (3 cm ZWD) for a comparison between GPS and the NWP model HIRLAM from 20 stations in Scandinavia over a time period of 4 months.

The synoptic weather situation during the two observation sessions could provide – in this special case – a possible explanation for the divergence of the MM5 derived ZWDs from the measured time series. In both cases a winter frontal system moves from the Atlantic towards Scandinavia bringing cold and wet air into the domain. The mesoscale model reproduces the synoptic situation reasonably well. However, since MM5 does not predict precipitation for the Swedish west coast, the humidity influx reflects itself in an overall increase of the water vapour content as simulated by the model. The measurement techniques, on the other hand, observe only the local moisture content of the atmosphere which might differ from the regional results. Therefore, it is possible that the introduction of another model parameterization reduces the deviations significantly.

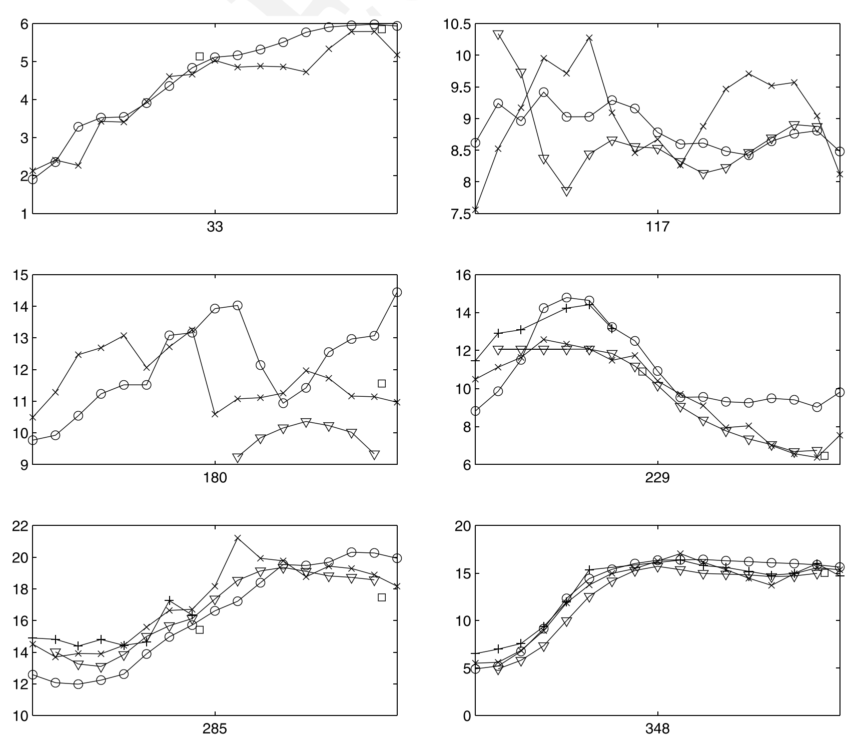

Fig. 2. Time series of ZWD for the station Madrid. Shown are: MM5 (◯), VLBI (▽), GPS (×), WVR (+) and RS (□). The *x*-axis covers 24 hours centered around midnight of the respective day of year in 1999, the *y*-axis is in units (cm).

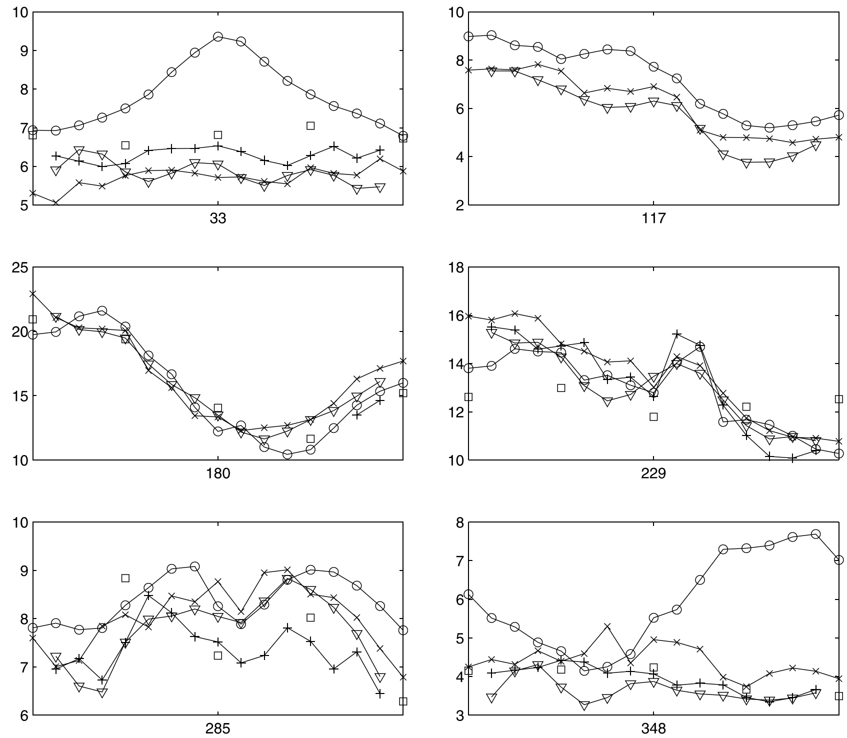

Fig. 3. Time series of ZWD for the station Onsala. Shown are: MM5 (◯), VLBI (▽), GPS (×), WVR (+) and RS (□). The *x*-axis covers 24 hours centered around midnight of the respective day of year in 1999, the *y*-axis is in units (cm).

However, since the RS data are usually assimilated into the ECMWF data, MM5 should reproduce the RS derived ZWD values quite closely. As this is not the case, it cannot be excluded that for EU-47 and EU-52 the corresponding ECMWF weather fields do not contain the RS data for Landvetter.

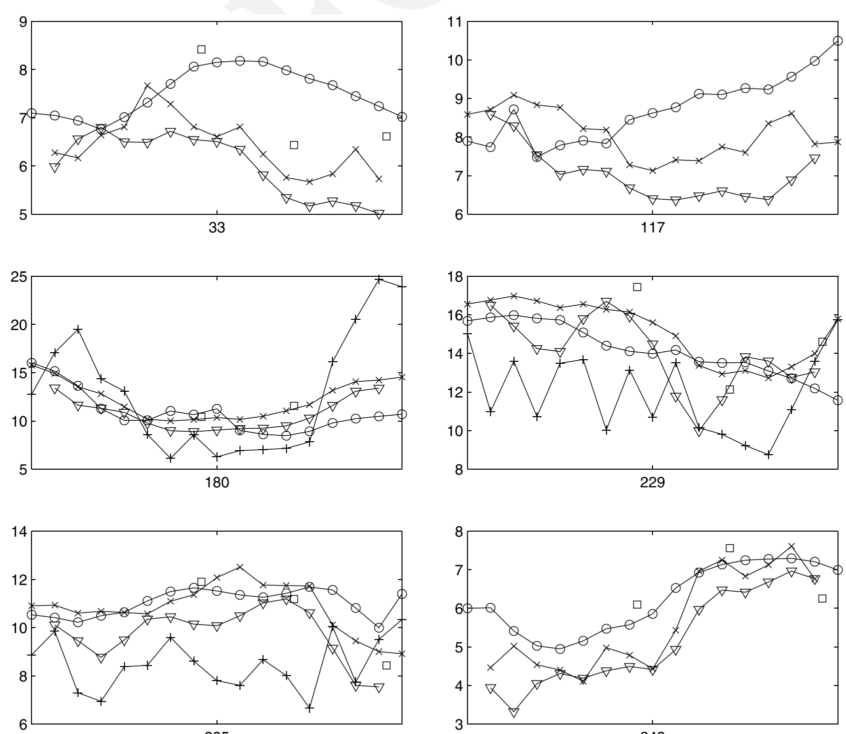

Fig. 4. Time series of ZWD for the station Wettzell. Shown are: MM5 (◯), VLBI (▽), GPS (×), WVR (+) and RS (□). The *x*-axis covers 24 hours centered around midnight of the respective day of year in 1999, the *y*-axis is in units (cm).

Table 3
Statistical parameters for the independently derived ZWD values

Meth. 1	Meth. 2	# Points	Bias (cm)	RMS diff. (cm)	Corr. (%)
VLBI	GOS	255	−0.75	±0.96	81.1
	WVR	146	−0.18	±2.28	83.6
	WVR*	86	−0.39	±0.87	98.0
	MM5	255	−1.03	±1.43	91.1
GPS	WVR	211	0.68	±3.02	75.8
	WVR*	90	0.04	±0.94	97.7
	MM5	302	−0.27	±1.43	75.3
WVR	MM5	158	−0.52	±2.85	78.4
WVR*	MM5	90	−0.53	±1.56	94.1

The bias value is taken in the sense Meth. 1 minus Meth. 2. Given are the combined values of all three stations. WVR* excludes the Wettzell data.

The results of a statistical analysis are summarised in Tables 3 and 4 and are depicted in the scatter plot of Fig. 5. WVR represents the water vapour radiometer data of all three stations, whereas WVR* has the Wettzell data excluded. The smallest scatter and, thus, the best agreement is obtained with VLBI vs. GPS, WVR* vs. VLBI, and WVR* vs. GPS. GPS vs. MM5 and VLBI vs. MM5 have a similar scatter that is slightly larger than the VLBI vs. GPS; WVR vs. MM5 has an unrealistic scatter due to the inclusion of the Wettzell data.

The overall comparison (Table 3) gives correlation values between 75% and 95%. Lowest correlation values are obtained in comparisons with WVR data (Wettzell included) and, surprisingly, for the comparison GPS vs. MM5. The highest correlations are found for WVR* vs. VLBI, WVR* vs. GPS, and VLBI vs. MM5. The RMS difference values of VLBI vs. MM5 and GPS vs. MM5 amount to 14.3 mm confirming the accuracy values given above. For GPS and WVR the biases appear to be station dependent respectively instrument dependent (see also Table 4). VLBI and MM5 seem to be independent of the conditions at the station; thus an averaging over the three stations is permissible. This gives an overall bias between VLBI and MM5 of $\mathrm{ZWD(VLBI - MM5)} = -1.0 \pm 1.4$ cm.

The bias for GPS vs. MM5 takes values of 0.0, −0.2, and −0.6 cm (Table 4). The RMS differences, however, take values of ±1.4–1.6 cm indicating that the precision of the GPS data is consistent whereas the accuracy has a dependence on the station and observational conditions. The slightly larger scatter for Madrid hints at a minor

Table 4
Stationwise statistical parameters for the independently derived ZWD values

Meth. 1	Meth. 2	# Points	Bias (cm)	RMS diff. (cm)	Corr. (%)
Madrid					
VLBI	GPS	75	−0.99	±1.37	91.9
	WVR	24	−1.18	±0.79	90.8
	MM5	75	−1.14	±1.61	91.2
GPS	WVR	28	−0.66	±0.82	74.8
	MM5	102	−0.20	±1.32	88.2
WVR	MM5	28	0.76	±1.35	90.4
Onsala					
VLBI	GPS	90	−0.39	±0.57	90.8
	WVR	62	−0.08	±0.69	95.4
	MM5	90	−1.03	±1.34	94.3
GPS	WVR	62	0.35	±0.81	86.8
	MM5	102	−0.60	±1.47	85.2
	RS	39	0.46	±1.25	90.8
WVR	MM5	62	−1.11	±1.27	90.3
Wettzell					
VLBI	GPS	90	−0.90	±0.74	85.9
	WVR	60	0.12	±3.38	52.4
	MM5	90	−0.94	±1.35	85.2
GPS	WVR	121	1.15	±3.84	74.8
	MM5	98	0.01	±1.43	88.8
WVR	MM5	68	−0.52	±3.95	39.3

The bias value is taken in the sense Meth. 1 minus Meth. 2.

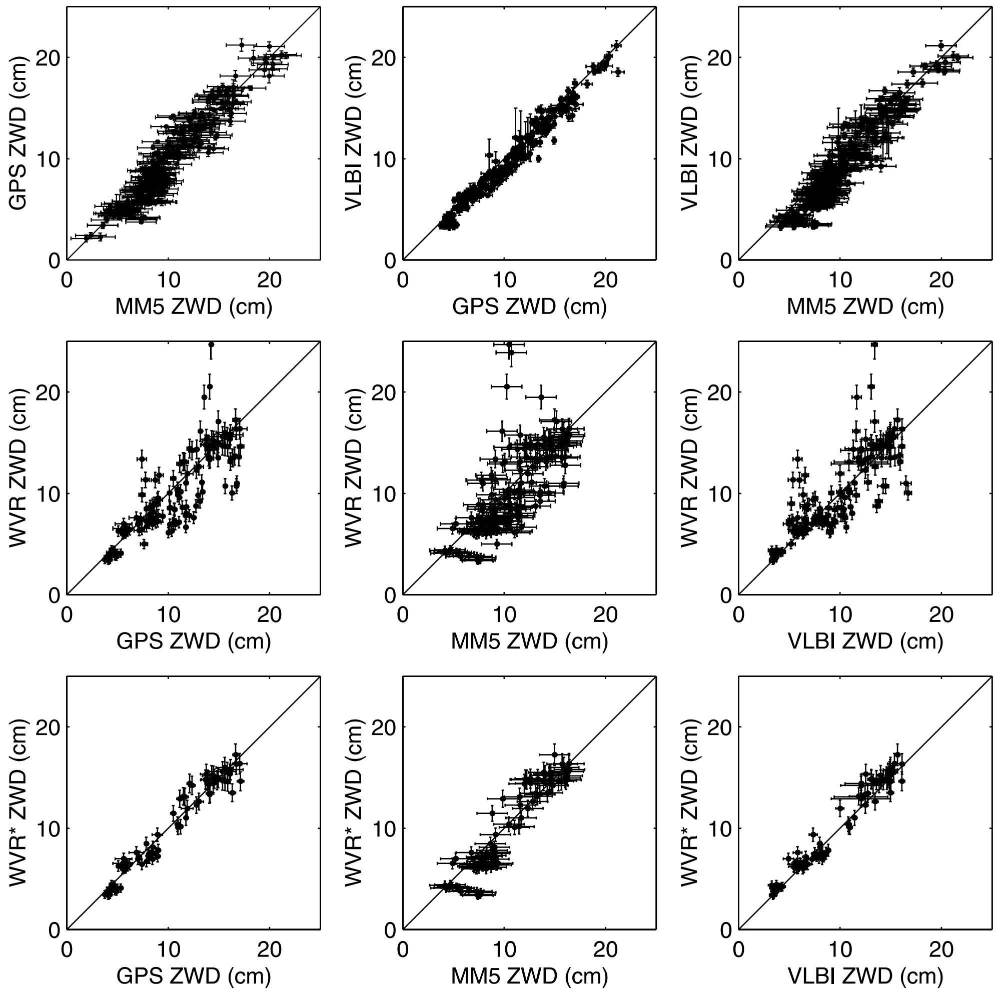

Fig. 5. Scatter plots for pairs of techniques. Top row: GPS vs. MM5 (left), VLBI vs. GPS (center), VLBI vs. MM5 (right). Middle row: WVR vs. GPS (left), WVR vs. MM5 (center), WVR vs. VLBI (right). Bottom row: WVR* vs. GPS (left), WVR* vs. MM5 (center), WVR* vs. VLBI (right). WVR* excludes the Wettzell data.

problem of the GPS data at this station in the year 1999. A similar finding holds true for the WVR vs. MM5 comparison. Thus, for assimilating GPS data into NWP models station dependent biases need to be determined and accounted for.

5. Conclusions and outlook

We compared ZWDs simulated from MM5 with values retrieved from VLBI, GPS, WVR, and RS for three stations of the European geodetic VLBI network where the different techniques are collocated. In general we find good agreement between the different and independent techniques with correlation coefficients in the range of 75–95%. Best agreement in terms of RMS difference, bias, and correlation is found between VLBI and GPS. This was to be expected as both techniques share common error sources. When the WVR data for Wettzell are being excluded in the comparisons (WVR* data set), the agreement with the other three techniques is at least as good as between VLBI and GPS. It has to be kept in mind, however, that the amount of comparison data is reduced significantly by excluding Wettzell and that the exclusion implies some degree of arbitrariness. In contrast to GPS, VLBI does not show a dependence on the conditions at the station, at least for the three VLBI stations used in our study, probably mainly due to the absence of multipath effects and the lesser near-field scattering in the vicinity of the VLBI antennas. Thus, for assimilating GPS data into NWP models it is necessary to determine the station dependent bias value, whereas VLBI furnishes absolute ZWD values that is biased for the entire system, but not for a single station. Still, this needs to be confirmed by the analysis of larger data sets. The bias between VLBI and MM5 derived from three stations and six observational sessions spread over the year 1999 amounts to -1 cm (VLBI$-$MM5). Due to this feature VLBI appears to be a highly useful ground truth calibration technique for climate studies and NWP models.

Acknowledgements

Dirk Behrend and Rüdiger Haas are supported by the European Union (EU) within the Training and Mobility of Researchers (TMR) programme under contract FMRX-CT960071. David Pino is financially supported by the project IMMPACTE (CIRIT, DME, Barcelona, Spain).

References

Behrend, D., Cucurull, L., Vilà, J., Haas, R., 2000. An intercomparison study to estimate zenith wet delays using VLBI, GPS, and NWP models. Earth Planets Space 52, 691–694.

Cucurull, L., Vandenberghe, F., 1999. Comparison of PW estimates from MM5 and GPS data, MM5 Workshop'99, Boulder, CO, USA.

Cucurull, L., Navascues, B., Ruffini, G., Elósegui, P., Rius, A., Vilà, J., 2000. The use of GPS to validate NWP systems: the HIRLAM model. J. Atmos. Ocean. Tech. 17, 773–787.

De Pondeca, M.S.F.V., Zou, X., 2001. A case study of the variational assimilation of GPS zenith delay observations into a mesoscale model. J. Appl. Meteor. 40, 1559–1576.

Dudhia, J., Gill, D., Guo, Y.-R., Manning, K., Wang, W., 2001. PSU/NCAR Mesoscale Modeling System Tutorial Class Notes and User's Guide (MM5 Modeling System Version 3), Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research, p. 300, Boulder, CO, USA.

Gradinarsky, L.P., Elgered, G., Xue, Y., 2000a. Using a micro-rain radar to assess the editing of ground-based microwave radiometer data. In: Pampaloni, P., Paloscia, S. (Eds.), Microwave Radiometry and Remote Sensing of the Earth's Surface and Atmosphere. Proceedings of the 6th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment, Firenze, Italy. Publisher VSP, Netherlands, pp. 183–191.

Gradinarsky, L.P., Haas, R., Elgered, G., Johansson, J.M., 2000b. Wet path delay and delay gradients inferred from microwave radiometer, GPS and VLBI observations. Earth Planets Space 52, 695–698.

Haas, R., Gueguen, E., Scherneck, H.-G., Nothnagel, A., Campbell, J., 2000. Crustal motion results derived from observations in the European geodetic VLBI network. Earth Planets Space 52, 759–764.

Haase, J.S., Vedel, H., Ge, M., Calais, E., 2001. GPS Zenith Tropospheric Delay (ZTD) Variability in the Mediterranean. Phys. Chem. Earth 26, 439–443.

Ma, C., Sauber, J.M., Bell, L.J., Clark, T.A., Gordon, D., Himwich, W.E., 1990. Measurement of horizontal motions in Alaska using very long baseline interferometry. J. Geophys. Res. 95 (B13), 21991–22011.

Niell, A., 1996. Global mapping functions for the atmosphere delay at radio wavelength. J. Geophys. Res. 101 (B2), 3227–3246.

Niell, A.E., Coster, A.J., Solheim, F.S., Mendes, V.B., Toor, P.C., Langley, R.B., Upham, C.A., 2001. Comparison of measurements of atmospheric wet delay by radiosonde, water vapor radiometer, GPS, and VLBI. J. Atmos. Ocean. Tech. 18, 830–850.

Pacione, R., Sciarretta, C., Vespe, F., Faccani, C., Ferretti, R., Fionda, E., Ferraro, C., Nardi, A., 2001. GPS meteorology: validation and comparisons with ground-based microwave radiometer and mesoscale model for the Italian GPS permanent stations. Phys. Chem. Earth 26 (3), 139–145.

Webb, F.H., Zumberge, J.F., 1993. An Introduction to GIPSY/OASIS-II. JPL Publication D-11088. Jet Propulsion Laboratory, Pasadena, CA.

Yang, X., Sass, B.H., Elgered, G., Johansson, J.M., Emardson, T.R., 1999. A comparison of precipitable water vapor estimates by an NWP simulation and GPS observations. J. Appl. Meteorol. 38, 941–956.

Zumberge, J.F., Heflin, M.B., Jefferson, D.C., Watkins, W.W., Webb, F.H., 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks. J. Geophys. Res. 102, 5005–5017.