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Accuracy and variability of GPS tropospheric delay measurements of water vapor in the western Mediterranean

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The refractive delay of radio waves in the atmosphere is a large source of error for precise positioning using space geodetic measurement techniques, contributing a range error in the zenith direction on the order of 2.4 m. This motivated the early work on methods to model the error source (Saastamoinen 1972; Davis et al. 1985; Askne and Nordius 1987; Elgered et al. 1991) in order to remove it and, thus, increase the accuracy of space geodetic positioning estimates. Herring (1990) and Tralli and Lichten (1990) developed methods to include the zenith delays as unknown parameters to be simultaneously estimated in the positioning calculation. Bevis et al. (1992) proposed the use of these estimated delays as a means for studying the atmosphere.

Ground-based GPS receivers are an attractive source of humidity data for weather prediction in that they are portable, are economic, and provide measurements that are not affected by rain and clouds. They cannot independently provide a humidity profile as do radiosondes (RS), but they have the advantage of providing automated continuous data whereas operational radiosondes usually provide two or four measurements per day. Other ground-based measurements, such as water vapor radiometers or photometers, are affected by rain and clouds.

Many authors carried out studies to increase the accuracy of the technique, typically using a small number of stations. Rocken et al. (1993) were the first to demonstrate agreement between water vapor radiometer (WVR) and GPS-derived relative estimates of integrated water vapor (IWV), with a level of agreement of about 1 kg m^{-2} . Evaluation of absolute rather than relative IWV was made possible by extending the horizontal extent of the network, which also reduced biases in the estimates (Duan et al. 1996; Tregoning et al. 1998). Systematic errors were reduced by using improved mapping functions relating the delay observed at a given satellite elevation to the zenith delay, and by using improved antenna phase-center correction models (Niell 2000; Fang et al. 1998; Mader 1999). Tests that included gradients as a first approximation for laterally varying refractivity structure around the sites demonstrated that the estimation of zenith delays is robust with or without including these gradients (Ruffini et al. 1999; Bar-Sever et al. 1998). One long-term study (Emardson et al. 2000) detected instrumental biases due to antenna radomes and the resulting contamination of network solutions. This study used independent data from other instruments, in particular water vapor radiometers, to demonstrate the accuracy of the data. It has been demonstrated that the integrated water vapor can be retrieved using ground-based GPS observations with the same level of accuracy as radiosondes and microwave radiometers (Elgered et al. 1997; Bevis et al. 1992; Rocken et al. 1995; Duan et al. 1996; Emardson et al. 1998; Tregoning et al. 1998).

As the technique has improved, the potential of this method has been realized as an important source of humidity observations for numerical weather prediction

(NWP) models (Kuo et al. 1996; Zou and Kuo 1996) and for climate studies (Yuan et al. 1993). There have been efforts in North America and Europe dedicated to exploiting the data to improve forecasting. The first study of its kind was the "GPS/STORM" experiment, which took place in the high-tornado-risk area of the midwestern United States (Rocken et al. 1995). This experiment compared GPS water vapor measurements with radiosonde measurements during a time period that included more than six major storms and demonstrated the validity of the method. Since then, the U.S. National Oceanic and Atmospheric Administration (NOAA) has installed an operational network to further research the use of a ground-based GPS-integrated water vapor observing system for weather forecasting (Smith et al. 2000; Gutman and Benjamin 2001). GPS IWV data from an extensive network of stations in the Baltic region were compared with NWP model delayed-mode assimilation reanalyses and forecasts for a 4-month period (Yang et al. 1999). The difference between the NWP reanalyses and GPS IWV for 25 sites had a bias of -0.1 kg m^{-2} and a root-mean-square (rms) error of 2.3 kg m^{-2} . For some sites the bias was as high as 2.4 kg m^{-2} and the rms was as high as 3.4 kg m^{-2} , though the data that were used were later found to contain errors due to the site-specific radome equipment and have since been improved (Emardson et al. 2000). In general, the level of agreement between the GPS and the NWP reanalyses was approximately the same as the agreement of the reanalyses with the radiosondes. An extensive array of GPS receivers installed in Japan for earthquake research is now being used by the Japan Meteorological Agency (JMA) to retrieve IWV for planned assimilation in NWP models. In preliminary comparisons with the JMA objective analyses, the IWV was shown to track incoming storm fronts, but the data had some biases on the order of $2\text{--}4 \text{ kg m}^{-2}$ (Iwabuchi et al. 2000).

Concurrent with efforts in the United States to incorporate the GPS zenith tropospheric delay (ZTD) data into NWP models, the Meteorological Applications of GPS-Integrated Column Water Vapor in the Western Mediterranean (MAGIC) project was begun in Europe with similar objectives (Haase et al. 2001). MAGIC was a 3-yr project financed in part by the European Commission. The project objectives were to test the usefulness of the GPS data for NWP model validation, to develop the assimilation algorithms necessary for incorporating this data into NWP models, and to study the long-term use of these data in climate model validation.

The focus of this paper is the presentation of error statistics from the comparison of the GPS ZTD with radiosonde data and the HIRLAM 6-h forecasts. This will provide the necessary input for determining the error covariance matrix of the observation operator in the three-dimensional and four-dimensional variational assimilation algorithms in the HIRLAM forecasts. The comparison among the three datasets has been carried out continuously over a time period greater than two

annual cycles. The present study provides a comparison in a region that is climatically very different from the Baltic (Yang et al. 1999) and the midwestern United States (Smith et al. 2000), and, thus, provides additional important insight for effective use of the data.

2. GPS data processing

a. Network design, station distribution, and data flow

The data processing carried out for the MAGIC project includes data from 51 permanent GPS stations (Fig. 1). In order to reduce the computational load of the network geodetic solution, we divided the GPS network into three subnetworks—one in France, one in Italy, and one in Spain—with each subnetwork containing six common International GPS Service (IGS) reference stations. The three estimates of tropospheric delay at the common IGS stations are used to monitor the consistency of each subnetwork solution and are used for testing the sensitivity of the ZTD solutions to the network geometry.

The GPS data are collected daily in the receiver-independent exchange (RINEX) format with a 30-s sampling rate from the IGS data centers and other agencies responsible for permanent regional station archives. Surface meteorological data taken at the GPS sites (pressure, temperature, relative humidity) are also downloaded where they are available. The RINEX data are quality checked and stored until the final precise IGS orbits (Kouba and Mireault 1998) become available, approximately 2 weeks later.

The GPS data are processed at three institutions involved in the MAGIC project to ensure consistent results independent of the software used. The Centre National de la Recherche Scientifique (CNRS) Géosciences Azur laboratory in France processes all MAGIC stations, using the GPS at Massachusetts Institute of Technology (GAMIT) software (Bock et al. 1986; King and Bock 1999). The Institute for Space Studies of Catalonia (IEEC) in Spain processes a subset of IGS stations using the GPS Inferred Positioning System (GIPSY) software point-positioning strategy (Webb and Zumberge 1997; Zumberge et al. 1997; Ruffini et al. 1999; Flores et al. 2000). The Italian Space Agency (ASI) in Italy processes the Italian stations using the GIPSY software and has tested both a network-processing and a point-positioning strategy (Pacione et al. 2001). The ZTDs estimated by the three centers are then archived so that an ongoing, routine comparison among subnetworks, processing centers, and radiosonde and HIRLAM data can be used to validate the results. The entire procedure has been automated and runs routinely with very limited user input. Here, we present the results from the CNRS Géosciences Azur data-processing center.

b. Zenith tropospheric delay retrieval

The quantity observed by the GPS receiver is the interferometric phase measurement of the distance from

the GPS satellites to the receiver. The processing software must resolve or model the orbital parameters of the satellites, solve for the transmitter and receiver positions, account for ionospheric delays, and solve for phase cycle ambiguities and clock drifts, in addition to solving for the tropospheric delay parameters of interest. This requires the same type of GPS data-processing software as that which is used for high-precision geodetic measurements. We use the GAMIT software (Bock et al. 1986; King and Bock 1999), which solves for the ZTD and other parameters using a constrained batch least squares inversion procedure.

The tropospheric delay for a zenith path is the integral of the refractivity N over height in the atmosphere. The refractivity can be described as a function of temperature T , the partial pressure of dry air P_d , and the partial pressure of water vapor e (Smith and Weintraub 1953; Thayer 1974; Davis et al. 1985):

$$N = k_1 \frac{P_d}{TZ_d} + k_2 \frac{e}{TZ_w} + k_3 \frac{e}{T^2 Z_w}, \quad (1)$$

where k_1 , k_2 , and k_3 are constants that have been determined experimentally, and Z_d and Z_w are the compressibilities of dry air and water vapor, respectively. The best statistical estimates of the constants based on published results (Bevis et al. 1994) are $k_1 = 0.7760 \text{ K Pa}^{-1}$, $k_2 = 0.704 \text{ K Pa}^{-1}$, and $k_3 = 0.03739 \times 10^5 \text{ K}^2 \text{ Pa}^{-1}$.

The ZTD is, therefore,

$$\begin{aligned} \text{ZTD} &= 10^{-6} \int_{z_{\text{ant}}}^{\text{toa}} N \, dz \\ &= 10^{-6} \int_{z_{\text{ant}}}^{\text{toa}} k_1 \frac{P_d}{TZ_d} + k_2 \frac{e}{TZ_w} + k_3 \frac{e}{T^2 Z_w} \, dz, \quad (2) \end{aligned}$$

where z_{ant} is the height of the GPS antenna and toa is the top of the atmosphere.

Using an equation of state of the form $P_i = \rho_i R_i Z_i T$, for the i th component of a mixture of gases, this can be rewritten as

$$\begin{aligned} \text{ZTD} &= 10^{-6} k_1 R_d \int_{z_{\text{ant}}}^{\text{toa}} \rho \, dz \\ &\quad + 10^{-6} R_v (k_2 - \varepsilon k_1) \int_{z_{\text{ant}}}^{\text{toa}} \rho_v \, dz \\ &\quad + 10^{-6} R_v k_3 \int_{z_{\text{ant}}}^{\text{toa}} \frac{\rho_v}{T} \, dz, \quad (3) \end{aligned}$$

where ρ is density, ρ_v is the contribution of water vapor to the density of the air, R_d is the gas constant for dry air, R_v is the gas constant for water vapor, and $\varepsilon = R_d/R_v$ is the ratio of the gas constants for dry air and water vapor.

The ZTD may now be considered as the sum of two terms,

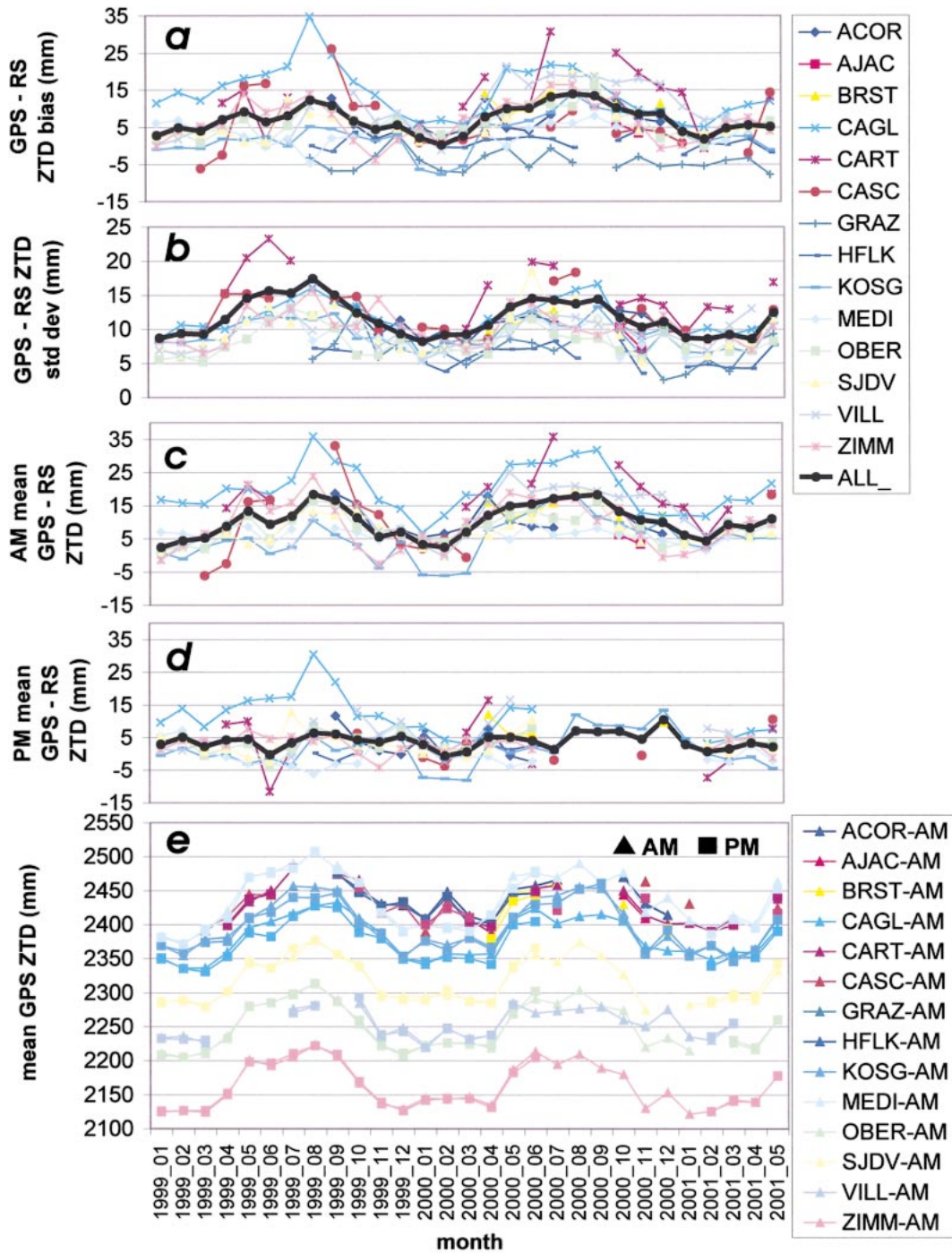


FIG. 7. (a) Time-dependent behavior of the mean GPS–radiosonde ZTD difference over a 2.5-yr time period, (b) std dev of the GPS–radiosonde ZTD difference, (c) mean GPS–radiosonde ZTD residuals for midday radiosonde launches, (d) mean GPS–radiosonde ZTD residuals for midnight radiosonde launches, and (e) mean GPS ZTD values for each site with midday launches (triangles) and midnight launches (squares). The mean residuals are much lower for midnight launches and have no annual variation even though the mean humidity (represented by mean GPS ZTD) is the same for midday and midnight.

TABLE 3. Comparison of the zenith tropospheric delay derived from the GPS measurements with those calculated from the HIRLAM 6-h forecasts. The Alt is the altitude of the GPS antenna relative to mean sea level, and dz is the difference between the GPS antenna altitude and HIRLAM orography. This height difference is taken into account by an interpolation or extrapolation of the model fields.

Station	Lat (°N)	Lon (°E)	Alt (m)	dz (m)	ZTD bias (mm)	Std dev (mm)	No. of data points	Correlation
ACOR	43.364 38	-8.398 93	14.9	-120.9	1.7	19.8	16 153	0.88
ALAC	38.338 92	-0.481 23	14.3	-215.9	6.7	19.9	19 417	0.89
AQUI	42.368 84	13.350 34	667.2	-419.4	0.7	16.8	15 661	0.90
BELL	41.599 62	1.401 14	803.6	309.0	3.8	17.0	29 230	0.92
BZRG	46.499 02	11.336 80	279.5	-1162.4	-2.6	19.2	29 856	0.94
CAGL	39.135 91	8.972 75	191.8	57.1	5.1	19.3	32 138	0.89
CART	37.586 75	-1.012 04	43.5	-5.0	5.4	20.0	13 562	0.88
CASC	38.693 41	-9.418 52	22.8	-8.6	0.8	24.4	23 042	0.82
CHAT	45.304 14	6.358 56	799.3	-959.4	3.6	17.7	16 969	0.90
COSE	39.201 42	16.310 41	618.2	-11.0	5.6	22.6	10 173	0.81
CREU	42.318 84	3.315 60	83.8	65.8	5.4	19.9	26 521	0.92
EBRE	40.820 89	0.492 36	57.7	-239.1	2.8	21.6	31 037	0.92
ESCO	42.693 57	0.975 66	2455.2	916.8	3.5	11.3	18 749	0.93
FCLZ	45.643 00	5.985 68	1308.7	542.9	6.4	12.6	29 519	0.95
GENO	44.419 39	8.921 14	110.8	-164.5	5.2	20.1	33 185	0.93
GINA	43.675 72	5.786 98	331.5	-128.9	3.4	16.7	31 161	0.94
GRAS	43.754 74	6.920 57	1269.4	561.3	2.0	15.0	26 093	0.94
GRAZ	47.067 13	15.493 48	490.9	-79.8	2.1	13.8	31 524	0.96
HFLK	47.312 90	11.386 09	2336.0	809.5	2.9	9.7	30 175	0.96
KOSG	52.178 43	5.809 64	53.5	36.1	1.1	12.8	32 264	0.97
LAMP	35.499 77	12.605 66	19.9	19.4	8.6	25.0	27 847	0.81
LLIV	42.478 13	1.973 05	1415.8	-121.7	6.7	13.9	16 913	0.93
MAHO	39.897 36	4.268 50	50.1	40.2	-4.0	23.1	9613	0.81
MARS	43.278 77	5.353 79	12.4	-93.8	1.4	18.7	24 441	0.92
MASI	27.763 74	-15.633 28	155.4	35.8	0.1	24.2	22 562	0.78
MATE	40.649 13	16.704 46	490.0	265.7	1.0	17.8	32 231	0.91
MEDI	44.519 96	11.646 81	9.7	-76.0	1.3	17.2	32 835	0.95
MELI	35.289 90	-2.939 24	11.5	-63.3	-3.1	23.0	12 404	0.82
MICH	43.924 16	5.717 35	577.4	-30.2	3.3	15.4	30 659	0.94
MODA	45.213 78	6.710 08	1129.1	-1009.9	7.2	16.9	30 425	0.92
MTPL	43.637 44	3.864 84	91.3	-15.6	11.1	17.8	14 446	0.93
NOTO	36.876 11	14.989 81	85.2	-77.1	5.8	25.7	26 681	0.83
OBER	48.086 17	11.279 87	595.7	18.5	3.6	12.9	32 787	0.96
SFER	36.464 34	-6.205 65	39.5	12.6	1.9	21.8	30 476	0.82
SJDV	45.879 08	4.676 57	382.4	20.9	3.7	14.8	28 720	0.94
TORI	45.063 37	7.661 28	262.7	-151.0	2.4	17.2	30 864	0.96
TOUL	43.560 77	1.480 76	158.6	-7.6	3.6	17.8	27 669	0.93
UNPG	43.119 39	12.355 70	303.4	-93.6	8.5	17.7	22 641	0.92
UPAD	45.406 72	11.877 93	39.4	16.7	0.3	15.9	26 553	0.96
VILL	40.443 59	-3.951 98	595.3	-174.6	0.6	17.4	31 627	0.89
WTZR	49.144 20	12.878 91	619.2	72.4	2.5	12.2	32 741	0.96
ZIMM	46.877 10	7.465 28	907.5	22.2	7.7	13.2	31 719	0.95
OVERALL	—	—	—	—	3.4	18.1	1 073 283	0.99

is less than 0.3 at greater than 600-km separation, but there are not enough data from the 14 GPS stations to determine with confidence the distance dependence of the error correlation at short distances.

The same is done for the GPS-HIRLAM 0-6-h forecast residuals (Fig. 14). Once again, the residuals are calculated at each time for a given pair of GPS stations, and the correlation coefficient between the residuals is calculated. The correlation coefficients are plotted as crosses in Fig. 14 as a function of the distance separating the pair of GPS stations. Here there are enough data to average the correlation coefficients over bins in 25-km distance ranges, shown as circles. The correlation drops off quickly and on average is below 0.3 at less than 200-km distance, but there are a significant number of

station pairs that have a correlation greater than 0.3 between 200 and 400 km. An e -folding scale on the order of 200 km is not unrealistic for error correlations near the ground for HIRLAM variables, but further studies are needed to clarify how much of the correlation can be attributed to the GPS data.

7. Discussion

In this section we discuss the implications the error characteristics of the data have for ongoing and future assimilation tests. Then, we discuss the main problems in handling the data: carrying out the processing within a short delay and handling the relatively large biases that vary significantly over the timescale of 1 month.

licated that GPS ZTD data are sensitive enough to reliably show spatial variations in average upper-air integrated water vapor over yearly timescales. Comparisons with midnight radiosonde launches show that these data are as reliable as radiosondes and with only a small but stable bias. These are promising conclusions for the potential use of GPS ZTD data for studying climatic variations of integrated water vapor and validation of regional climate models. However, the biases, which have some seasonal variation and some coherent regional variation on monthly timescales, must be further investigated before their use in climate studies.

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