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Comparison of atmospheric parameters derived from GPS, VLBI and a ground-based microwave radiometer in Italy

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Abstract

Integrated Precipitable Water Vapor (IPWV) derived from GPS, water vapor radiometer WVR-1100 and RAdiosonde OBservation (RAOB) have been compared for the Cagliari site (Italy) on a seasonal and annual bases. The comparison analysis on estimating IPWV among the three independent techniques (GPS, WVR-110 and RAOB) has shown high accuracy equal to 0.136 cm with a bias of −0.049 cm throughout 1999. Furthermore, a comparison has been made between the estimated atmospheric parameters, equivalent zenith tropospheric delay (ZTD) and horizontal gradient, as resulting from independent analyses of GPS and VLBI data for the three Italian collocated stations: Matera, Medicina and Noto. We have realized that VLBI ZTD estimates are lower than that obtained by GPS of about 1.0–1.5 cm, while the standard deviations range from 0.5 to 2.0 cm.

Keywords: GPS; Microwave radiometer; VLBI; Zenith tropospheric delay; Integrated Precipitable Water Vapor

1. Introduction

Water vapor is the main greenhouse gas of the atmosphere and it is important in weather and climate processes. It is the source of the tropospheric delays effecting both Global Positioning System (GPS) and Very Long Baseline Interferometry (VLBI) observations, moreover it is responsible for most of the atmospheric absorption and emission processes at which the sky brightness temperature, directly measured by a ground-based water vapor microwave radiometer (WVR), is mainly related. In the last decade, ground-based GPS receivers have been developed as all-weather and low-cost remote sensing systems of the atmosphere (Bevis et al., 1992; Rocken et al., 1995), as compared to conventional techniques such as satellite radiometer sounding (Allishouse, 1983; Grody et al., 1980), ground-based microwave radiometer, radiosondes (Westwater, 1993), and sun-photometer (http://aeronet.gsfc.nasa.gov). The amount of water vapor contained in the neutral atmosphere is strongly related to the propagation delay of both GPS and VLBI observations. For many years such delay has been considered by geodesists as a nuisance parameter which has to be removed for precise positioning applications. Beside water vapor radiometer and radiosondes, VLBI geodetic technique can be used as an independent source of information to assess the reliability of GPS atmospheric information.

Since January 1999, in the framework of the European Community project MAGIC (Meteorological Applications of GPS Integrated Column Water Vapor Measurements in the Western Mediterranean) at Centro di Geodesia Spaziale of the Italian Space Agency in Matera, GPS zenith tropospheric delay (ZTD) are routinely produced and monitored for all the available Italian permanent stations. Few of these GPS permanent stations (Matera, Noto and Medicina) are collocated with VLBI antenna. During 1999 a ground-based dual-channel microwave radiometer (WVR-1100)

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owned by Fondazione "Ugo Bordoni" was collocated with a permanent GPS receiver at Cagliari Astronomical Station for the Sardenia Radio Telescope (SRT) Project.

The paper includes two main sections. In Section 2 we describe the comparison of Integrated Precipitable Water Vapor (IPWV) derived from GPS, from the ground-based microwave radiometer (WVR-1100) and from the RAdiosonde OBservation (RAOB) profiles at the Cagliari Astronomic Station for the whole 1999 SRT Project (see Fig. 1 for the geographical location and Table 1 for the coordinates). The IPWV is the height of liquid water that would result from the condensation of all the water vapor in a column from the surface to the top of the atmosphere. Section 3 shows the results of the comparison of GPS and VLBI estimated atmospheric parameters for the Italian stations: Matera, Medicina and Noto (see Fig. 1 for the geographical locations and Table 1 for the coordinates). For these comparisons all the VLBI experiments occurred during 1999 have been considered.

2. GPS, WVR and radiosonde IPWV

In 1999 a radiometric station was located in Cagliari (Fig. 1) a few meters away from the GPS receiver. This

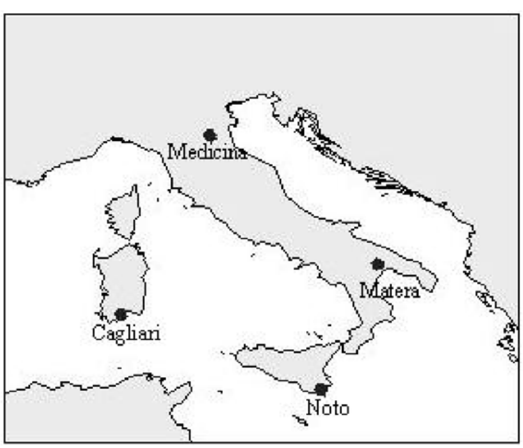


Fig. 1. Geographic map of Italy indicating the location of Cagliari, Matera, Medicina, and Noto.

Table 1
Cagliari, Matera, Medicina and Noto latitude, longitude and height with respect to WGS-84 ellipsoid, at epoch January 1, 1997

	Latituzade	Longitude	Height
Cagliari	39°8′9.278″	8°8′21.902″	238.370
Matera	40°38′56.868″	16°42′16.046″	535.650
Medicina	44°31′11.841″	11°38′48.525″	50.054
Noto	36°52′33.991″	14°59′23.309″	126.233

They are obtained using the International Terrestrial Reference Frame (ITRF97). Units are degree, minute and seconds for latitude and longitude, meter for height.

GPS receiver belongs to ASI (Agenzia Spaziale Italiana) Italian GPS Fiducial Network. The type of the receiver is ROGUE SNR-8100, the antenna type is AOAD/M_T. The GPS data acquired during 1999 are analysed with the GIPSY-OASIS II software (Webb and Zumberge, 1997) using the Precise Point Positioning strategy (Zumberge et al., 1997) in the framework of the European Community Project MAGIC (Haase et al., 2001; Pacione et al., 2001; http://geodaf.mt.asi.it/GDHTL/gps/gps_browse. html).

The GPS ZTD, i.e. the excess path length due to the signal travel in the troposphere measured in the zenith direction, can be divided into two components, the hydrostatic delay (ZHD) and the wet delay (ZWD) caused by water vapor

$$\mathrm{ZTD} = \mathrm{ZHD} + \mathrm{ZWD}. \tag{1}$$

If surface air pressure is known with an accuracy of 0.3 hPa or better, ZHD can be estimated by means of a simple model (Saastamoinen, 1972), to an accuracy better than 1 mm (Elgered et al., 1991). By subtracting the ZHD value from the GPS solution given in (1), ZWD is obtained. Moreover, it is possible to transform ZWD time series into IPWV (in cm) using

$$\mathrm{IPWV} = \Pi * \mathrm{ZWD}, \tag{2}$$

where the dimensionless "constant" of proportionality Π (Bevis et al., 1994) is a function of various physical parameters and of the weighted mean temperature of the water vapor (Askne and Nordius, 1987; Elgered et al., 1991; Davis et al., 1985). In this analysiswecalculated monthly means of Π by using the historical data base of radiosonde profiles available for Cagliari containing 5170 profiles within 15 years. We performed two parallel GPS analyses applying two different cut-off angles of 15° and 21.7°, respectively. The first angle is the standard cut-off angle used for GPS geodetic applications; the second one corresponds to the minimum elevation angle observed from the WVR.

The ground-based microwave radiometer is a portable scanning dual-channel type, model WVR-1100, manufactured by the Radiometrics Corporation, Boulder (CO), USA. Table 2 shows the main technical features of WVR-1100. It has two channels with the first at 23.8 GHz, near the water vapor spectral line centered at 22.235 GHz, and a second one at 31.4 GHz, within the almost transparent window band. More details on the WVR-1100 features, on the calibration procedure, and on the quality control processing data are reported in (Barbaliscia et al., 1998). For a non-scattering atmosphere in local thermodynamic equilibrium, the emission, mainly due to water vapor content and oxygen, can be quantified by a ground-based microwave radiometer through the well-known brightness temperature (T_B in Kelvin). The output of the WVR-1100 are T_B values with a data sampling rate of 45 s at the two operating

Table 2
Ground-based microwave radiometer (WVR-1100) features

Specifications	Value
Operating frequencies	23.8, 31.4 GHz
Viewing angle	All sky
Antenna beam width	5.7° (at 23.8 GHz) 4.4° (at 31.4 GHz)
Sidelobes	< -25 dB
Gain	31 dBi (at 23.8 GHz) 33 dBi (at 31.4 GHz)
Sampling time	45 s
Resolution	0.25 K
Accuracy	0.30 K
Double side band	400 MHz
Output	RS-232 at 1200 baud
Pointing slew rate	3 deg/s, azimuth greater than 90 deg/s, elevation
Dimensions	$50 \times 28 \times 76$ cm^3
Weight	21 kg with azimuth steering mount

channels. The T_B is the key-parameter describing atmospheric microwave emission depending on frequency (f), polarization and viewing angle. For simplicity in the following formulations, we are not indicating all these dependencies. At the ground surface level, by observing the sky at the zenith angle, T_B is related to the emission process of the medium by the linearized form of the radiative transfer equation (Chandrasekhar, 1950; Ulaby et al., 1982).

$$T_B(f) = T_C e^{-\tau_f(0,\infty)} + \int T(z)\alpha(f,z)e^{-\tau_f(0,z)}\,dz, \tag{3}$$

where T_C is the cosmic back-ground radiation, commonly assumed as 2.73 K; $\tau_f(0,\infty)$ is the total absorption; $T(z)$ is the absolute physical air temperature in Kelvin; z is the zenithal spatial position of the emitting air volume (km); $\alpha(f,z)$ is the atmospheric volume absorption coefficient or attenuation coefficient. The argument of the second exponential is the optical depth

$$\tau_f(0,z) = \int_0^z \alpha(f,z')\,dz'. \tag{4}$$

The use of the definition of the mean radiating temperature T_m (in Kelvin) (Wu, 1979),

$$T_m(f) = \frac{\int_0^\infty T(z)\alpha(f,z)e^{-\tau_f(0,z)}\,dz}{\int_0^\infty \alpha(f,z)e^{-\tau_f(o,z)}\,dz}, \tag{5}$$

in Eq. (3) allow to derive the total atmospheric attenuation in decibels from measurements of emission

$$\tau\ (\text{dB}) = 4.343\ln\left(\frac{T_m(f)-T_C}{T_m(f)-T_B(f)}\right). \tag{6}$$

In case of a dual-channel ground-based radiometer with one frequency mainly sensitive to water vapor (subscript 1) and the other to the liquid water (subscript 2), IPWV can be derived according to

$$\text{IPWV} = a_0 + a_1\tau_1 + a_2\tau_2, \tag{7}$$

where the retrieval coefficients a_i convert atmospheric opacities τ_1 and τ_2 into IPWV (Westwater and Guiraud, 1980). Using Eq. (7), the monthly statistical coefficients a_i have been estimated by applying algorithms based on the radiative transfer theory for a non-scattering atmosphere to the large historical database of 15 years of RAOB profiles from 1980 to 1997 (Shroeder and Westwater, 1991). In this framework, the model MPM92 of Liebe (1992) has been used to compute water vapor and oxygen absorption. Furthermore, the same RAOB database was used for climatological characterization, including theoretical propagation delays (Thayer, 1974), and retrieval algorithm developments.

During the 1999 SRT Project, RS-80 Vaisala radiosondes were launched by the Italian Air Force Service four times daily (at 00, 06, 12, 18 GMT) from the Cagliari-Elmas airport, approximately 15 km away from the GPS and WVR-1100 site. Moreover, standard measurements of surface air pressure, temperature and humidity were collected at the GPS and WVR-1100 site.The accuracy of the sensor measuring the surface air pressure is 0.5 hPa.

2.1. GPS IPWV sensitivity analysis to different cut-off angles

The bias and standard deviation of the IPWV derived from the two GPS solutions with integration times of 30 min and cut-off angles of 15° and 21.7°, respectively, are compared. Table 3 reports the calculated statistical parameters of the IPWV comparison with respect to the seasons and the year 1999. This comparison has been performed on 1208 estimates (referred to as NPTS in Table 3) obtained during the 1999 SRT Project. The yearly standard deviation of the GPS IPWV is equal to 0.106 cm and the correlation coefficient between the two GPS time series is 0.991. Table 3 shows that the GPS IPWV obtained with a cut-off angle of 15° is less than one standard deviation lower than that at 21.7°. This is in agreement with Fang et al. (1998) who found that ROGUE SNR-8100 (commonly called TurboRougue) receivers are not very sensitive to cut-off angle changes.

Table 3
Seasonal statistical parameters of the IPWV comparisons between GPS (cut-off: 15°) and GPS (cut off: 21.7°), with an integration time of 30 min

Period	Bias (cm)	Std. Dev. (cm)	Corr. coef.	NPTS
Winter	−0.040	0.100	0.977	315
Spring	−0.016	0.090	0.987	329
Summer	−0.004	0.093	0.989	229
Autumn	−0.088	0.115	0.987	335
Year	−0.040	0.106	0.991	1208

Bias is the difference between GPS (cut-off: 15°) and GPS (cut off: 21.7°), NPTS is the number of points.

In the following sections, we only consider the GPS IPWV derived using the cut-off angle of 15°.

2.2. GPS, WVR and RAOB IPWV comparisons and results

Here we compare the IPWV values obtained with the three different techniques considering all the available data acquired during the 1999 SRT Project. For this analysis, the GPS and the WVR IPWV values have been averaged over a time interval of 30 min with respect to the radiosonde launch-time. The bias and standard deviations of the monthly means of GPS IPWV, WVR-1100 IPWV, as well as RAOB IPWV are reported in Figs. 2 and 3, respectively. To quantify the different estimations more details can be found in Table 4, which shows the bias and the standard deviations for each of the four seasons of the year 1999. The bias has submillimeter values which seem to decrease during cold months, when the water vapor content of the atmosphere is normally small, see Fig. 2. Fig. 3 shows a seasonal behaviour of the standard deviations. The largest standard deviation of all the comparisons is recorded in summer. This is in agreement with Haase et al. (2000). It can be noticed that the largest standard deviation occurs for those involving RAOB (Westwater et al., 2000). By comparing WVR-1100 IPWV to GPS IPWV lower standard deviations are obtained, ranging on seasonal bases from 0.112 to 0.141 cm, see Table 4. Considering the whole year, we have found an average accuracy in estimating IPWV (0.136 cm of standard deviation and a correlation coefficient of 0.986 for WVR-100 and GPS comparison) in agreement with those presented in the literature (Rocken et al., 1993; Duan et al., 1996; Westwater et al., 1998; Tregoning et al., 1998; Emardson et al., 2000).

3. GPS and VLBI comparison of the estimated atmospheric parameters

The microwave signals of the GPS satellite and of a quasar in the case of the VLBI technique are delayed by the ionosphere and the neutral atmosphere (Bevis et al., 1992; Seeber, 1993). While the ionospheric refraction is eliminated through observations at two different frequencies (namely at around 1.5 and 1.2 GHz for GPS,

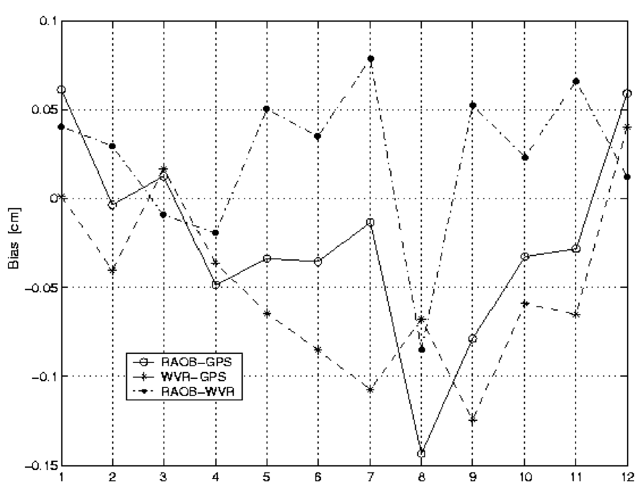


Fig. 2. Monthly bias values of IPWV of the comparisons among the GPS, WVR-1100, and RAOB for Cagliari, 1999.

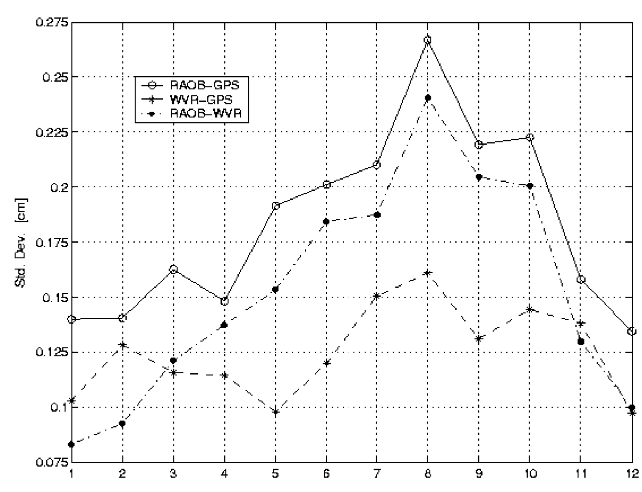


Fig. 3. Monthly mean, standard deviations of the IPWV differences RAOB − GPS, WVR − GPS and RAOB − WVR GPS for station Cagliari, 1999.

Table 4
Seasonal statistical parameters of the IPWV comparisons between WVR-1100 and GPS, RAOB and GPS with an integration time of 30 min

Period	WVR minus GPS				RAOB minus GPS			
	Bias (cm)	Std. Dev. (cm)	Corr. coef.	NPTS	Bias (cm)	Std.Dev. (cm)	Corr. coef.	NPTS
Winter	0.008	0.112	0.967	242	0.041	0.141	0.954	316
Spring	−0.026	0.115	0.975	292	−0.023	0.170	0.948	330
Summer	−0.088	0.151	0.970	226	−0.069	0.240	0.920	229
Autumn	−0.086	0.141	0.981	297	−0.048	0.205	0.957	341
Year	−0.049	0.136	0.986	1057	−0.022	0.193	0.968	1216

Definitions as in Table 3.

Table 5
GPS and VLBI analysis characteristics

	GPS	VLBI
Data	89 days	31 sessions of 24 h performed in 1999
Software	GIPSY-OASIS II	CALC/f-SOLVE
Strategy	Precise point positioning, batch of 24 h starting at 00:00 UT	Sessions analysed independently
Elevation cut-off angle	15°	None
ZHD calibration model	$1.013 \times 2.27e^{-0.116\times10^{-3}\ h}$	Saastamoinen model
Dry and wet mapping functions	Niell	Niell
Gradient mapping function	Niell dry	Niell dry
Data sampling rate	5 min	All observations are used
ZWD estimation model	Random walk with 5 min estimation interval	piecewise linear function with duration of the linear section of 1 h
ZWD constraint	$3.0\ \mathrm{mm}/\sqrt{(h)}$	50 ps/h
Gradients estimation model	Random walk with 5 min estimation interval	1 estimate every 3 h
G_N, G_E constraint	$0.3\ \mathrm{mm}/\sqrt{(h)}$	None
Phase post-fit residuals rejection criterion	2.5 cm	None

2.3 and 8.4 GHz for VLBI) the influence of the neutral atmosphere cannot be eliminated due to its non dispersive nature but it has to be adequately modelled. According to Bar-Sever and Kroger (1998) and MacMillan (1995), the mathematical model adopted for the propagation delay in these two geodetic techniques is

$$\mathrm{ZTD} = m_h(\varepsilon)\mathrm{ZHD} + m_w(\varepsilon)\mathrm{ZWD} + m_\Delta(\varepsilon) \times \cot\varepsilon[G_N\cos\phi + G_E\sin\phi], \quad (8)$$

where ε is the satellite/quasar elevation angle, ϕ is the satellite/quasar azimuth angle measured eastward from the north, $m_h(\varepsilon)$, $m_w(\varepsilon)$, $m_\Delta(\varepsilon)$ are the mapping functions, $\underline{G} = (G_N, G_E)$ is the gradient vector with G_N and G_E the components in the north and east directions, respectively. As far as the mapping functions are concerned, we chose $m_h(\varepsilon)$, $m_w(\varepsilon)$, $m_\Delta(\varepsilon)$ equal to Niell's dry, wet and dry mapping functions, respectively (Niell, 1996). The gradient vector takes into account the non homogeneity of the atmosphere in the azimuth direc-

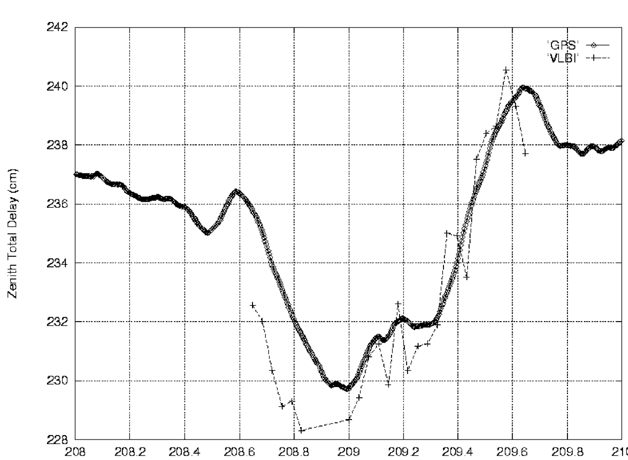


Fig. 4. Two-day (28, 29 July 1999) GPS and VLBI ZTD time series for Matera station. The error bars are not reported in the figure, GPS error bars are about 3 mm, while VLBI ones 5 mm.

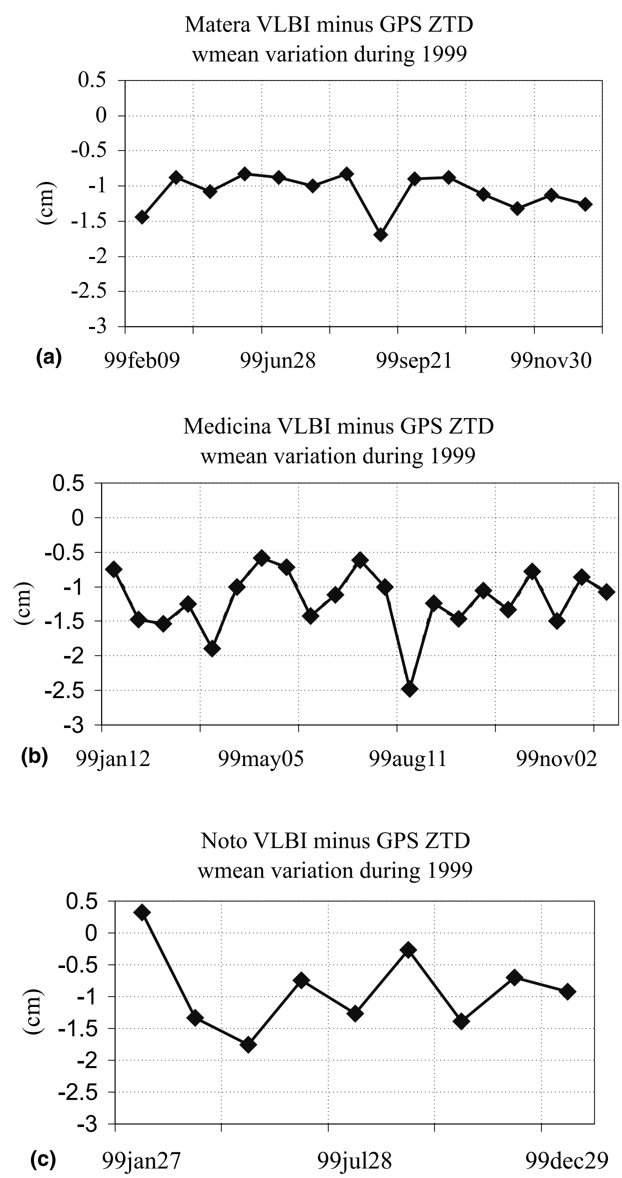


Fig. 5. Weighted mean (wmean) of VLBI–GPS ZTD time series of 1999 computed at Matera (a), Medicina (b), and Noto (c).

tion. The $\cot g(\varepsilon)$ factor accounts for the increase in horizontal change of refractivity along the signal path as the elevation decreases (MacMillan, 1995). It was shown that data from low elevation angles (MacMillan, 1995; Bar-Sever and Kroger, 1998) are required in order to separate the gradients components from the azimuthally homogeneous ones. We focused our attention on the Italian stations Matera, Medicina and Noto; the distance between the stations ranges from about 400 to 900 km. Table 5 reports the characteristics of the GPS and VLBI analyses.

We compared the ZTD and horizontal gradients derived from an independent analysis of simultaneous GPS and VLBI observations. The comparison is done in terms of weighted mean (wmean) and standard deviation of the differences, computed with a linear regression considering one hour of GPS estimates centered on the VLBI one. In Fig. 4 an example of GPS and VLBI ZTD time series for Matera is reported. Figs. 5(a)–(c) show that ZTD VLBI estimates are lower than the GPS ones of about 1.5 cm, while the standard deviations (Figs. 6(a)–(c)) range from 0.5 to 2.0 cm. Furthermore, the correlation coefficients between VLBI and GPS ZTD, calculated considering only estimates occurred at the same epoch, are 0.92, 0.95, 0.84 for Matera, Medicina and Noto, respectively (Figs. 7(a)–(c)). For the north and east components of the horizontal gradients wmean is about 0.2 cm and the standard deviations range from 0.05 to 1.0 cm. In Figs. 8(a) and (b) examples for Matera are reported. Similar results have been found by Niell (2001), Gradinarsky et al. (1999) and Behrend et al. (2001).

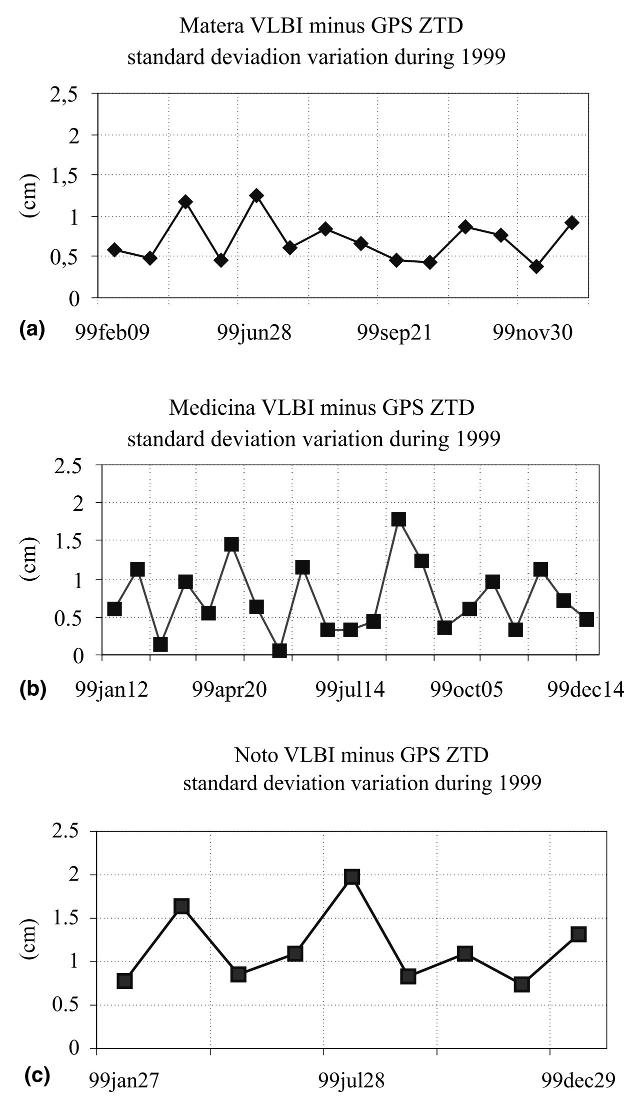


Fig. 6. Standard deviation of VLBI–GPS ZTD time series of 1999 computed at Matera (a), Medicina (b), and Noto (c).

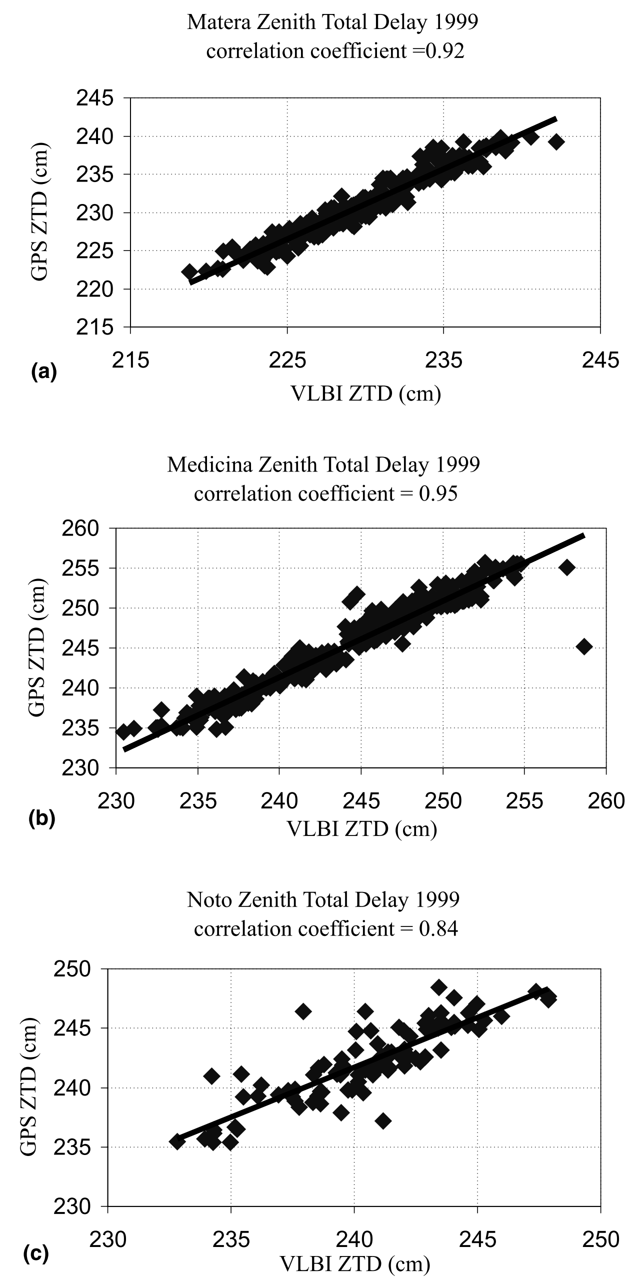
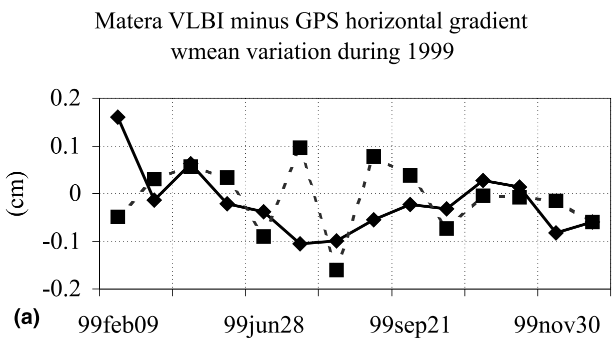


Fig. 7. Scatter plot of 1999 ZTD values from VLBI and GPS computed at Matera (a), Medicina (b), and Noto (c).



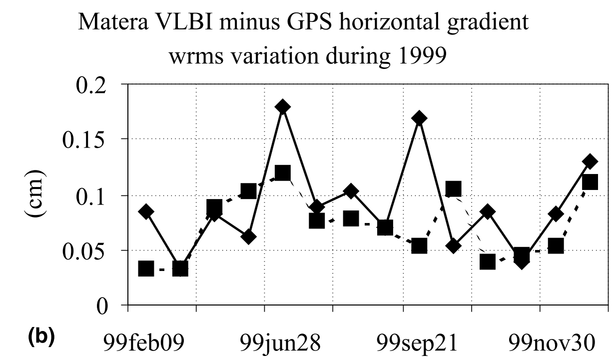


Fig. 8. Weighted mean (wmean) (a) and Standard deviation (b) of VLBI–GPS gradients components G_N (solid line and rhomb), G_E (dash line and square) time series computed at Matera during 1999.

4. Summary

Experimental analyses are presented in order to quantify the accuracy of different techniques and algorithms to estimate zenith IPWV present in the Earth's atmosphere. The experimental campaign called 1999 SRT Project took place throughout the year 1999 at Cagliari (Fig. 1).

By using GPS, a ground-based microwave radiometer (WVR-1100) and RAOB the IPWV estimates have been calculated and the results have been compared. The GPS data have been analysed with GIPSY-OASIS II producing ZTD estimates. The GPS IPWV has been derived from GPS ZWD by using the linear relationship of Eq. (2). ZWD has been calculated by subtracting the hydrostatic term from ZTD, according to the Saastamoinen model. The corresponding WVR-1100 IPWV values have been derived from atmospheric opacity (τ), as estimated by Eq. (7). Another source of independent IPWV values has been the RAOB which provides four profiles per day.

The comparisons have shown that GPS can estimate zenith IPWV with a millimetric accuracy with respect to conventional techniques such as ground-based microwave radiometer and radiosondes. The largest correlation has been found comparing results from the two electromagnetic sensors, WVR-1100 and GPS. On a seasonal basis for Cagliari site, the comparison of WVR-1100 to GPS has shown a standard deviation ranging from 0.112 to 0.141 cm. We have found an IPWV mean standard deviation accuracy of 0.136 cm for WVR-1100 and GPS.

A comparison of GPS and VLBI estimated atmospheric parameters (ZTD and horizontal gradient) obtained from independent analysis has been performed for the three Italian collocated stations: Matera, Medicina, and Noto and considering one year (1999) of VLBI experiments. Based on our results, GPS ZTD and VLBI ZTD values are highly correlated even if a bias of about 1 cm between them is present, that could be due to the influence of the different cut-off angles used by the two geodetic techniques.

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References

Allishouse, J.C., 1983. Total precipitable water and rainfall determinations from Seasat scanning multichannel microwave radiometer. J. Geophys. Res. 83, 1929–1935.

Askne, J., Nordius, H., 1987. Estimation of tropospheric delay for microwaves from surface weather data. Radio Sci. 22, 379–386.

Bar-Sever, Y., Kroger, P.M., 1998. Estimating horizontal gradients of tropospheric path delay with a single GPS receiver. J. Geophys. Res. 103 (B3), 5019–5035.

Barbaliscia, F., Fionda, E., Masullo, P.G., 1998. Ground-based radiometric measurements of atmospheric brightness temperature and water vapor contents in Italy. Radio Sci. 33, 697–706.

Behrend, D., Pino, D., Haas, R., Cucurrul, L., Gradinarsky, L.P., Keihm, S.J., Schwarz, W., Rius, A., Atmospheric parameters from VLBI, GPS WVR and a NWP model: a comparison, presented at EGS XXVI, 2001.

Bevis, M., Businger, S., Herring, T.A., Rocken, C., Anthes, R.A., Ware, R.H., 1992. GPS meteorology: remore sensing of atmospheric water vapor using the global positioning system. J. Geophys. Res. Lett. 97 (D14), 15.787–15.801.

Bevis, M., Businger, S., Chiswell, S., Herring, T.A., Anthes, R.A., Rocken, C., Ware, R.H., 1994. GPS meteorology: mapping zenith wet delays onto precipitable water. J. Appl. Meteorol. 33, 379–386.

Chandrasekhar, S., 1950. Radiative Transfer. Oxford University Press, New Jersey.

Davis, J.L., Herring, L.T.A., Shapiro, I.I., Rogers, A.E., Elgered, G., 1985. Geodesy by radio interferometry: effects of atmospheric modelling errors on estimates of baseline length. Radio Sci. 20, 1593–1607.

Duan, J., Bevis, M., Fang, P., Bock, Y., Chiswell, S., Businger, S., Rocken, C., Solheim, F., Hove, T., Ware, R., McClusky, S., Herring, T.A., King, R.W., 1996. GPS meteorology: direct estimation of the absolute value of precipitable water. J. Appl. Meteorol. 35, 830–838.

Elgered, G., Davis, J.L., Herring, T.A., Shapiro, I.I., 1991. Geodesy by radio interferometry: water vapor radiometry for estimation of the wet delay. J. Geophys. Res. 96, 6541–6555.

Emardson, T.R., Johansson, J., Elgered, G., 2000. The systematic behaviour of water vapor estimates using four year of GPS observations. IEEE Trans. Geosci. Remote Sensing 38, 324–329.

Fang, P., Bevis, M., Bock, Y., Gutman, S., Wolfe, D., 1998. GPS meteorology: reducing systematic errors in geodetic estimates of zenith delay. Geophys. Res. Lett. 25, 3583–3586.

Haase, J., Vedel H, Ge, M., Calais, E., 2000. Radiosonde and GPS zenith tropospheric delay (ZTD) variability in the Mediterranean. Presented at COST Action 716 Workshop, Oslo.

Haase, J., Calais, E., Talaya, J., Rius, A., Vespe, F., Santangelo, R., Huang, X.-Y., Davila, J.M., Ge, M., Cucurull, L., Flores, A., Sciarretta, C., Pacione, R., Boccolari, M., Pugnaghi, S., Vedel, H., Mogensen, K., Yang, X., Garate, J., 2001. The contributions of the MAGIC Project (meteorological applications of GPS integrated column water vapor measurements in the western Mediterranean) to the COST 716 objectives of assessing the operational potential of ground-based GPS meteorology on an international scale. Phys. Chem. Earth (A) 26 (6–8), 433–437.

Gradinarsky, L.P., Haas, R., Johansson, J.M., Elgered, G., 1999. Comparison of atmospheric parameters estimated from VLBI, GPS and microwave radiometer. In: Proceedings of the 13th working Meeting on European VLBI for Geodesy and Astronomy, Viechtach.

Grody, N.C., Gruber, A., Shen, W.C., 1980. Atmospheric water content derived from the Nimbus-6 scanning microwave spectrometer over the tropical Pacific. J. Appl. Meteorol. 19, 986–996.

Liebe, H., 1992. Atmospheric spectral properties between 10 and 350 GHz: new laboratory measurements and models. In: Westwater, E.R. (Ed.), Proceedings of Specialist Meeting on Microwave Radiometry and Remote Sensing Applications. Wave Propagation Laboratory, NOAA, Boulder, CO, pp. 189–196.

MacMillan, D.S., 1995. Atmospheric gradients from very long baseline interferometry observations. J. Geophys. Res. 22 (9), 1041–1044.

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

Niell, A.E., 2001. Private communication.

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

Rocken, C., Ware, R., Van Hove, T., Solheim, F., Alber, C., Johnson, J., 1993. Sensing atmospheric water vapor with the global positioning system. Geophys. Res. Lett. 20 (23), 2631–2634.

Rocken, C., Hove, T., Johnson, J., Solheim, F., Ware, R., Bevis, M., Chiswell, S., Businger, S., 1995. GPS/STORM-GPS sensing of atmospheric water vapor for meteorology. J. Atmos. Oceanic Technol. 12 (3), 468–478.

Saastamoinen, J., 1972. Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites. In: Henriksen, S.W. (Ed.), The Use of Artificial Satellites for Geodesy. Geophysics Monograph Series, vol. 15. AGU, Washington, DC.

Seeber, G., 1993. Satellite Geodesy. Walter de Gruyter, Berlin–New York.

Shroeder, J.A., Westwater, E.R., 1991. Users' guide to WPL microwave radiative transfer software, Boulder, CO, NOAA Tech. Memo., ERL-WPL 213.

Thayer, G.D., 1974. An improved equation for the radio refractive index of air. Radio Sci. 9, 803–807.

Tregoning, P., Boers, R., O'Brien, D., Hendy, M., 1998. Accuracy of absolute precipitable water vapor estimates from GPS observations. J. Geophys. Res. 103, 28701–28710.

Ulaby, F.T., Moore, R.K., Fung, A.K., 1982. In: Microwave Remote Sensing: Active and Passive, vol. I. Addison-Wesley, Reading, MA.

Webb, F.H., Zumberge, J.F., 1997. An Introduction to GIPSY/OASIS II, JPL D-11088.

Westwater, E.R., Guiraud, F.O., 1980. Ground-based microwave radiometric retrieval of precipitable water vapor in the presence of clouds with high liquid content. Radio Sci. 15, 947–957.

Westwater, E.R., 1993. Ground-based microwave remote sensing of meteorological variables (Chapter 4). In: Janseen, M.A. (Ed.), Atmospheric Remote Sensing by Microwave Radiometry. Wiley Incorporation, New York, USA, pp. 145–214.

Westwater, E.R., Han, Y., Gutman, S.I., Wolfe, D.E., 1998. Remote sensing of total precipitable water vapor by microwave radiometers and GPS during the 1997 water vapor intensive operating period. In: Proceedings of IGARSS'98, Seattle, USA.

Westwater, E.R., Stankov, B.B., Han, Y., Shaw, J.A., Long, C.N., Lesht, B.M., Shannahoff, J., 2000. Comparison of microwave radiometers and radiosondes during the Nauru-99 experiment. In: Proceedings of IGARSS'00, Honolulu, USA, July.

Wu, S.C., 1979. Optimum frequencies of a passive microwave radiometer for tropospheric path-length correction. IEEE Trans. Antennas Propag. 27, 233–239.

Zumberge, J.F., Heflin, M.B., Jefferson, D.C., Watkins, M.M., Webb, F.H., 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks. J. Geophys. Res. 102 (B3), 5005–5017.