Comparison of Different Techniques for Tropospheric Wet Delay Retrieval Over South America and Surrounding Oceans

A. Calori, G. Colosimo, M. Crespi, and M.V. Mackern

Abstract

Water vapour (WV) plays a fundamental role in several weather processes that deeply influence human activities. Satellite based radiometers, Ground based Global Navigation Satellite Systems (GNSS) and Numerical Weather Models (NWM) permit to obtain either measurements or estimates or forecasts of WV. This work presents a 2 years systematic comparison to address the agreement on the tropospheric wet delay retrieved by the three mentioned independent techniques over permanent stations belonging to SIRGAS (Sistema de Referencia para las Américas) GNSS network. SIRGAS tropospheric total delay estimations are compared with the official International GNSS Service (IGS) ones, with the measurements from the Jason-1 satellite radiometer (JMR) in terms of Zenith Wet Delays (ZWD) and, finally, with the ZWD computed from ERA Interim, the last reanalysis dataset from the European Center for Medium-Range Weather Forecasts (ECMWF). All the differences between the techniques, which were considered in order to yield a reliable comparison, are discussed. The statistical results of mean (μ), standard deviation (σ) and correlation (ρ), show that the highest agreement is reached between SIRGAS and IGS products ($\mu = -0.5$ mm, $\sigma = 5.6$ mm, $\rho = 0.98$), whereas slightly worse values are obtained in the comparisons with the JMR measurements ($\mu = -7.4$ mm, $\sigma = 15.4$ mm, $\rho = 0.91$), and the ERA Interim data ($\mu = -1.5$ mm, $\sigma = 16.6$ mm, $\rho = 0.91$).

Keywords

GNSS • Jason-1 radiometer • Numerical Weather Model • SIRGAS • ZWD retrieval

1 Introduction

Water Vapour (WV) plays a fundamental role in several weather processes that deeply influence human activities and it has been recognised as the most important among the greenhouse gases (Mitchell 1989). Several studies have confirmed how deeply water vapour is bound to climate changes, for instance by showing the high correlation between the yearly temperature variation and the WV content in the atmosphere (Wentz and Schabel 2000). It has been clearly understood that the knowledge of high accurate WV content and its distribution in the atmosphere improves short term weather forecasts significantly. At the same time, WV reveals very rapid changes both in the temporal and in the spatial domains such that, at present, there are no theoretical models that can reliably predict its behaviour.

Retrieving WV content in the atmosphere can be performed in different ways using independent techniques: starting from the more traditional and established ones, such as radiosondes and ground-based microwave radiometers, up to the more recent ones, such as satellite based techniques

AQ1 A. Calori (✉) • M.V. Mackern
AQ2 Facultad de Ingeniería, Universidad Nacional de Cuyo, Mendoza, Argentina

G. Colosimo • M. Crespi
DICEA-Area di Geodesia e Geomatica, University of Rome "La Sapienza", Roma, Italy
e-mail: gabriele.colosimo@uniroma1.it

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like satellite radiometers (Christensen et al. 1994), Global Navigation Satellite Systems (GNSS) (Bevis et al. 1992), Radio Occultation (Kursinski et al. 1997) and Numerical Weather Models (NWM). Since each of these techniques presents advantages and limitations, researchers' efforts have been recently focused on comparing the different approaches with the aim of combining them to retrieve WV content with the highest possible accuracy. The issues addressed in this work are related to the research activities promoted by the International GNSS Service (IGS) Troposphere Working Group.

Satellite based radiometers can provide integrated water vapor (IWV) measurements at different epochs. However, their application is limited over sea and ocean surfaces, the revisit time on the same location is rather low and reliable measurements are obtained only at certain weather conditions (e.g., no rain). Ground based GNSS stations can be used to estimate the signal delay caused by tropospheric refraction (Hogg et al. 1981). This delay, which is referred to as Zenith Total Delay (ZTD), can be unfolded into two components: the Zenith Hydrostatic Delay (ZHD) and the Zenith Wet Delay (ZWD), which are due to the contribution of the hydrostatic gases and to the water vapour, respectively. The GNSS technique has been proven capable of estimating the ZTD and then using these estimates to infer the IWV with accuracies of few millimetres (e.g., Rocken et al. 1997). Moreover, thanks to its dense station networks and to the very high temporal resolution of the estimates (up to few minutes) the interest in GNSS as IWV data source is continuously increasing. NWM, such as the European Center for Medium-Range Weather Forecasts (ECMWF), exploit data from many different sources and can be used to compute and forecast IWV all over the world with a medium-high temporal resolution (i.e., a few hours).

This work presents the results of a 2 years (i.e., June 2008–2010) comparison of the three described techniques for the determination of the tropospheric wet delay ZTD and the IWV over the South and Central American region. Initially, in order to assess the performances of SIRGAS estimations, the results were compared with the official ZTD distributed by the IGS. Then, the consistency of the products was evaluated with respect to: (1) ZWD measured by Jason-1 satellite mission; (2) ZWD computed from data of the ECMWF ERA-Interim reanalysis model. Following this introductory section, Sect. 2 describes the main features of the used techniques. The results from the comparison are discussed in Sect. 3. Finally, conclusions and future research prospects are outlined in Sect. 4.

2 Data Processing: Retrieving the ZTD from the Different Techniques

2.1 Ground Based GNSS Stations

2.1.1 ZTD from the SIRGAS Network

SIRGAS-CON is the regional densification of the International Terrestrial Reference Frame (ITRF) over Latin America and Caribbean, it spans a huge extension $-65^\circ < \phi < 20^\circ, -109^\circ < \lambda < -2^\circ$, with altitudes up to 3.770 m and, at present, it encompasses about 250 continuously operating GNSS reference stations, 48 of them belonging to the global IGS network (Brunini et al. 2012).

Within this research work, the site-specific ZTD_{SIR} were estimated for approximately 100 GNSS SIRGAS stations (SIRGAS-CON-D-SUR) (Mackern et al. 2009) with a global formal precision of few millimeters, as described in detail in Calori et al. (2013). Figure 1 shows the overall distribution of the used GNSS stations over the South American region.

The main processing features which are relevant for the next sections are as follows:

- Software: Bernese GPS Software 5.0 (Dach et al. 2009)—Differential positioning
- Elevation angle cutoff: 3°
- Mapping function: Niell (1996) for hydrostatic and wet component
- A priori values: (Berg 1948; Saastamoinen 1973)
- Temporal resolution of ZTD estimates: 15 min (tropospheric gradients not estimated)

2.1.2 IGS Tropospheric Products

Ever since 2003, a precise point positioning (PPP) approach is used within IGS to estimate ZTD values using raw GPS range measurements and the IGS Final Orbits and Clocks. This process produces one file per site per day containing a time series of ZTD with temporal resolution of 5 min and a formal precision of few millimetres (Buyn and Bar-Sever 2009). The main processing features relevant for the comparison are detailed:

- Software: GIPSY—Precise Point Positioning
- Elevation angle cutoff: 7°
- Mapping function: Niell (1996) and GMF (Böhm et al. 2006)
- A priori values: Hydrostatic delay based on altitude (2.3 m at sea level), and 0.1 m for the wet delay
- Temporal resolution of ZTD estimates: 5 min (tropospheric gradients estimated)

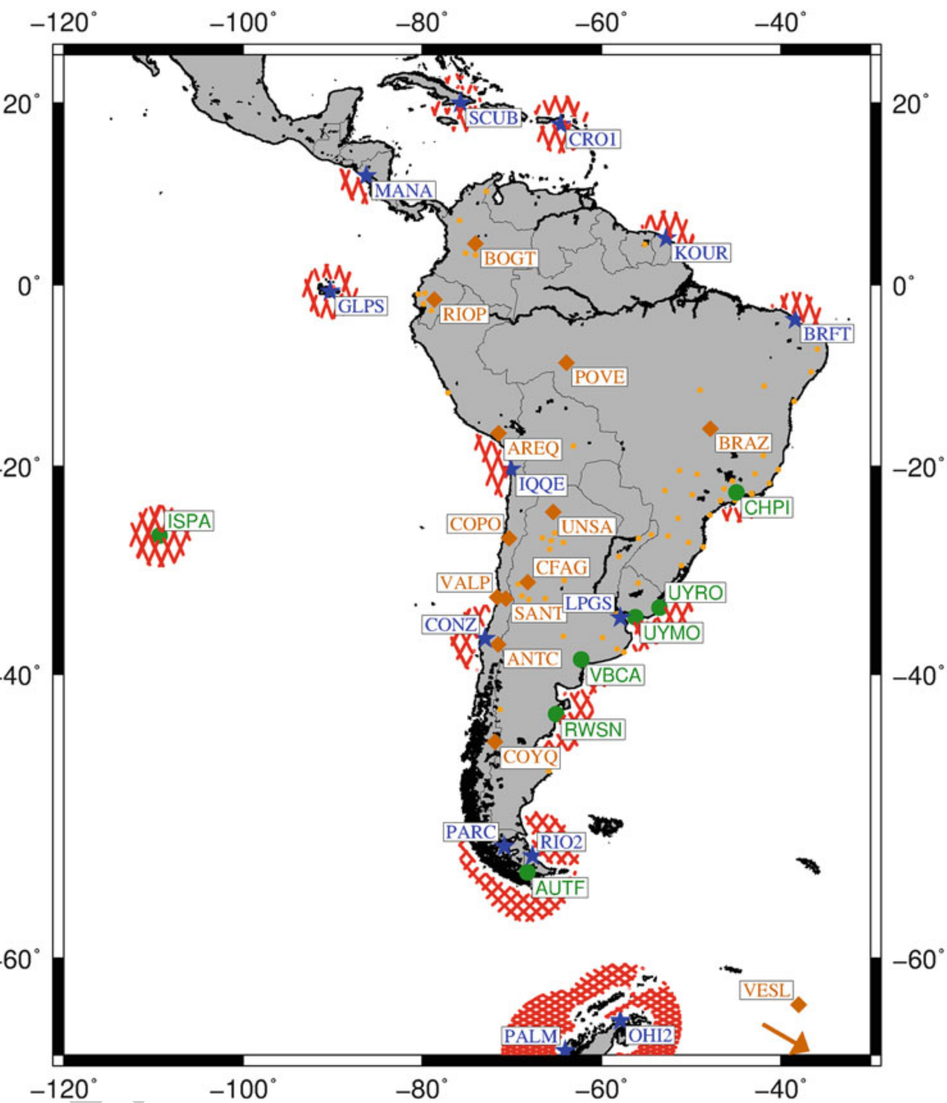

Fig. 1 Overall distribution of stations of SIRGAS-CON-D-SUR network processed within this work (*small orange circles*). Stations used in the comparison with only Jason-1 radiometer, are displayed as *green circles*. Stations used in the comparison with only IGS official products are displayed as *brown diamonds*. *Blue stars* represent stations that were used in the comparison with IGS and Jason-1 products. *Red* pattern displays the results of the automatic procedure implemented to select Jason-1 measurements that lie inside a circular area of a certain radius (1°) centred on the station

The comparison between the ZTD_{SIR} and ZTD_{IGS} was carried out over 27 sites common to both networks (Fig. 1, blue stars and brown diamonds).

2.2 Jason-1 and Satellite Radiometry

Jason-1 has been an altimetry satellite mission jointly operated by the French aerospace agency—Centre National d'Etudes Spatiales (CNES) and the United States National Aeronautics and Space Administration (NASA).

To retrieve the ocean topography with an accuracy of a few centimeters, Jason-1 was equipped with a Microwave Radiometer (JMR) used to measure the delay caused by the water vapor along the altimeter beam. JMR measures the brightness temperatures in the nadir direction over a circular footprint approximately between 20 and 30 km (Picot et al. 2003). Using a combination algorithm (described in p. 155 Kheim et al. 1995), the brightness temperatures can be coupled to retrieve the delay caused by the water vapor in the atmosphere (i.e. the ZWD) with a Root Mean Square Error (RMSE) of 1.2 cm that is, however, limited to open ocean areas (Ruf et al. 1994).

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For the present work, we have chosen to utilize the Geophysical Data Records (GDR) version c. Besides the altimeter measurements, GDR contain as ancillary information the hydrostatic meteorological correction (ZHD) provided by the ECMWF, which are then used to obtain the ZTD according to the standard equation

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

For this research, Jason-1 GDR version c binary data corresponding to the period from June 2008 to June 2010 were downloaded from the web. Then, a tuned software was implemented to filter out only those measurements which are close to the GNSS sites. Since JMR provides reliable measurements only over open ocean areas, 20 stations were

Table 1 Statistical results (compared product, number of stations, size of the dataset, average bias and standard deviation of the differences, correlation coefficient between the products) of the comparisons performed

Product	Stations (#)	Samples (#)	μ (mm)	σ (mm)	ρ
IGS–SIR	27	1,309,868	−0.5	6.9	0.98
ERA–SIR	30	65,534	−1.5	16.6	0.91
JMR–SIR	14	1,052	−7.4	15.4	0.93
ERA–IGS	27	67,638	−2.4	14.8	0.92
JMR–IGS	11	983	−5.6	14.9	0.93
JMR–ERA	14	958	−8.5	15.5	0.94

Different techniques have been compared in terms of ZWD whereas GNSS intra-comparison refers to ZTD

selected which fulfil the geographical criteria being located within a limited distance from coastline and the height of the station. Figure 1 shows the distribution of the selected stations (green dots and blue stars) subset and the Jason-1 ground tracks (red lines) for orbit cycle 275. As described in detail in Calori et al. (2013), the differences between the radiometer measurements and the GNSS estimates were addressed to yield a reliable comparison between the techniques.

2.3 ERA Interim

ERA-Interim is the latest global atmospheric reanalysis product computed by the ECMWF. This contains gridded data that describe the weather as well as ocean-wave and land-surface conditions together with upper-air parameters covering the troposphere and stratosphere (Dee et al. 2011). With the purpose of retrieving the ZWD at the GNSS sites from meteorological information, the binary data in *grib* format of 3 meteorologic parameters (i.e. the mean sea level pressure (P_{atm}), the total column water vapour (TCWV) and the 2 m temperature (2T)) were downloaded from the ECMWF web site for the time frame of the present analysis. These grids have a spatial resolution of 0.75° × 0.75° and a temporal resolution of 6 h (i.e. at 0, 6, 12 and 18 UTC). Here, it is also worth noting that both the TCWV and 2T are referred to the orography height (h_o), so that some height corrections were needed to retrieve the tropospheric delays (ZHD and ZWD) at the GNSS station height. As first step, the atmospheric pressure was computed at the GNSS station height (h) according to the standard pressure model of Berg (1948)

$$P_h = P_{atm}(1 - d \cdot h)^{5.225} \tag{2}$$

where $d = 0.0000226$. Then, the ZHD at the GNSS station height (i.e., $ZHD_{ERA,h}$) was retrieved following Davis et al. (1985)

$$ZHD_{ERA,h} = a\frac{P_h}{(1 - b \cdot cos(2\phi) - c \cdot h)} \tag{3}$$

where $a = 0.0022768$, $b = 0.00266$, $c = 0.28 \cdot 10^{-6}$, ϕ is the station latitude. The mean temperature of the troposphere (T_m) was modelled using the 2T according to Mendes et al. (2000, Eq. 17), model *UNB98Tm1*. This step was necessary in order to retrieve the ZWD at the orography height ZWD_{ERA,h_o} using the relation between the TCWV and the ZWD introduced by Askne and Nordius (1987, Eq. 25). To refer the ZWD retrieved by the ECMWF to the GNSS station height, the empirical relation proposed by Kouba (2008) was applied

$$ZWD_{ERA,h} = ZWD_{ERA,h_o} \cdot e^{-(h-h_o)/2000} \tag{4}$$

Finally, according to Eq. (1), we computed ZWD_{SIR} using ZHD_{ERA}. The comparison with ZWD_{SIR} was performed for all sites at which a comparison with either IGS or JMR values was already available (displayed as blue stars and brown diamonds in Fig. 1). At this stage of the research, no temporal interpolation was introduced so that GNSS and ECMWF were analysed only at identical times (i.e., 4 times per day).

3 Results and Discussion

The accuracy of the tropospheric estimations retrieved from SIRGAS network was assessed in terms of consistency with three different products: (1) the official ZTD generated by IGS; (2) the ZWD computed using meteorological information provided by ERA-Interim, ECWMF; (3) the ZWD measured by the JMR aboard the Jason-1 satellite altimetry mission. The comparison was carried out from June 2008 to 2010 and, because of the inter-techniques differences, it involved separate clusters of SIRGAS stations: 27 sites for comparison 1, 30 sites for comparison 2 and 14 sites located along the coastline for comparison 3. In each comparison, the agreement between the techniques was evaluated using the bias (μ), the standard deviation (σ) of the differences and the correlation coefficient (ρ) of the time series as statistical indexes.

Table 1, which reports the statistical inter-techniques indicators averaged over the whole set of stations, reveals

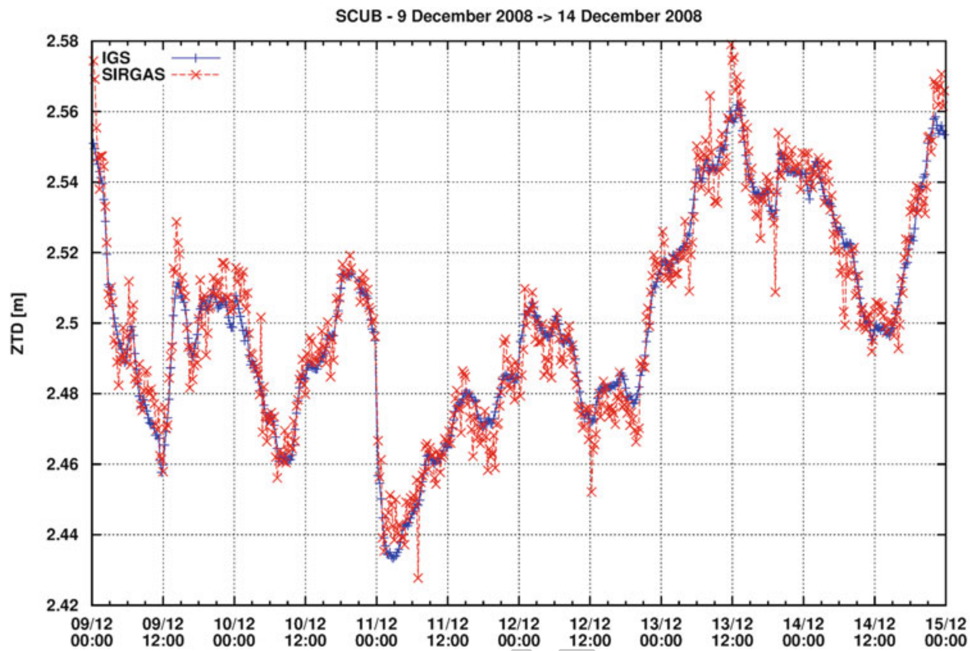

Fig. 2 5 days (9–14 December 2008) time series of IGS (*blue*) and SIRGAS (*red*) ZTD estimations

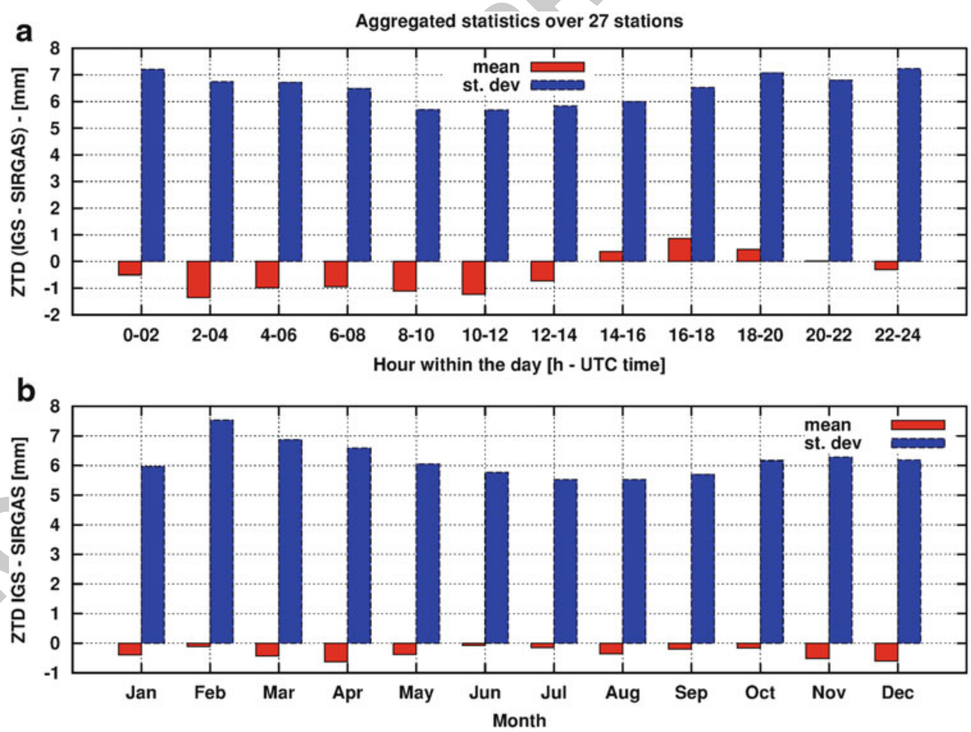

Fig. 3 Mean and standard deviation of the differences between IGS and SIRGAS ZTD grouped every 2 h (**a**) and every month (**b**). Here, it has to be underlined that hours of the day refer to UTC time

that SIRGAS GNSS tropospheric delays agree with those obtained from the different techniques (i.e., with a bias in the difference varying from a minimum of 0.5 mm for the IGS values up to a maximum of 7.4 mm for the JMR measurements). As expected from using the same technique, the best agreement is found between SIRGAS and IGS ZTD. Nonetheless, the different strategies used to process the GPS observations (Sect. 2.1) influence the ZTD estimations: in particular, a refined analysis showed that ZTD_{SIR} are characterized by a higher estimation noise, as it is shown in Fig. 2. Further, to investigate possible dependencies either on the epoch of the day or on the month of the year, the differences for the whole period have been grouped every 2 h and every month, respectively. Figure 3, which displays the results of the hourly and monthly comparison, does not highlight any degradation of the ZTD_{SIR} neither with the epoch of the day nor within the whole year.

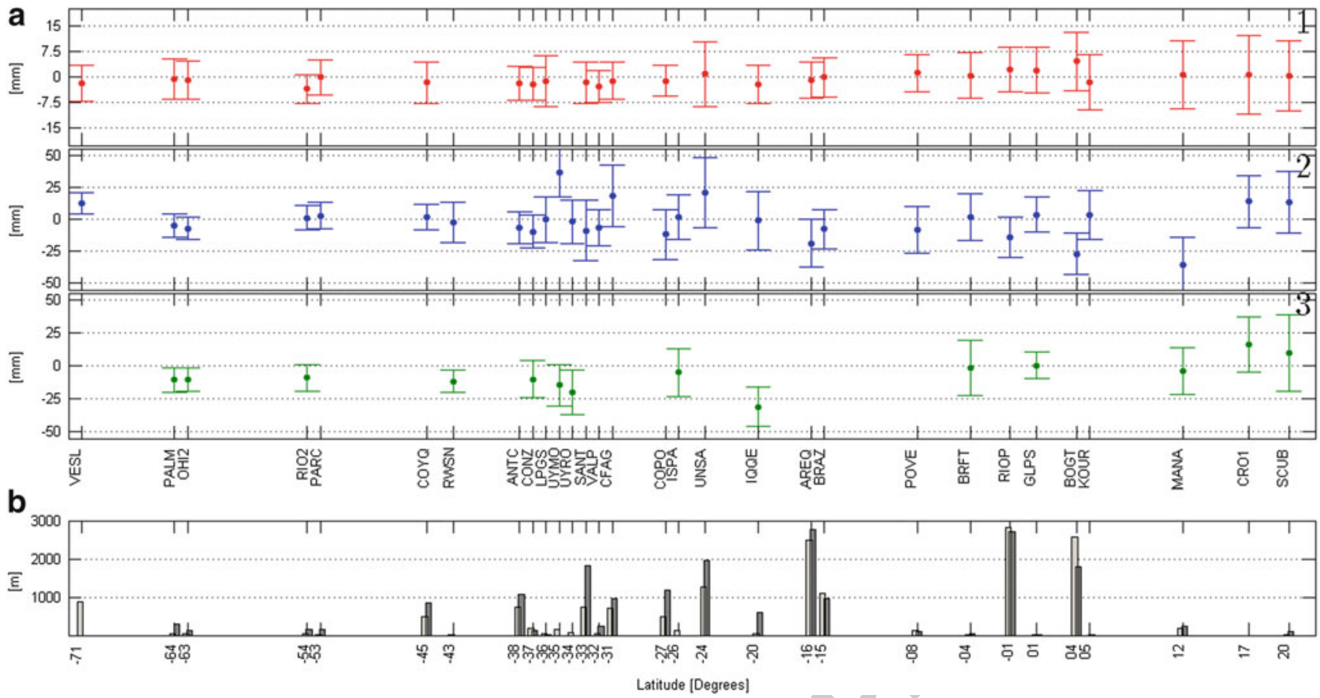

Fig. 4 (**a**) Bias and standard deviation over the 2 years of analysis on each SIRGAS site used in the 3 comparisons: (*1*) $ZTD_{IGS} - ZTD_{SIR}$ in *red*; (2) $ZWD_{ERA} - ZWD_{SIR}$ in *blue*; (3) $ZWD_{JMR} - ZWD_{SIR}$) in *green*. (**b**) The height in meters of each SIRGAS site: ellipsoidal height in *light grey*, orography height from ERA-Interim in *dark grey*

Table 1 shows that SIRGAS estimates agree to a high extent both with JMR measurements and with ERA-Interim weather data and the achieved results are fully consistent with Fernandes et al. (2013), Edwards et al. (2004), Bock et al. (2010). For each station, the results of the three comparisons are summarized in Fig. 4a; here, to investigate any latitudinal dependency of the results, the stations are sorted from north to south. Importantly, Fig. 4b displays the difference between the ellipsoidal height of the GNSS stations and the orography height of the ERA-Interim grid (i.e., h and h_o).

Although no clear latitudinal dependency in terms of bias is visible, Fig. 4a shows a slow decrease of standard deviation in the southern regions. The same situation is described by Teke et al. (2011) in their multi-technique comparison of ZTD and is most probably related to the lower content of WV in the colder regions as compared to the hotter regions, where the evaporation is dominating. Such effect is clearly visible in the inter-technique comparison 2 and 3. From the results of comparison 2 it is important to notice that large biases are obtained both for large and for little height differences (e.g., *BOGT*, *UNSA* and *UYMO*, *MANA*, respectively); therefore it appears difficult to infer a clear dependency between the results and the height differences.

4 Conclusions and Perspectives

In the period from June 2008 to June 2010, the ZTD of approximately 100 permanent stations belonging to SIRGAS network were estimated and then compared with the official ZTD distributed by the IGS. Then, the accuracy of the products was assessed in terms of consistency with respect to 2 independent techniques: (1) ZWD measured by Jason-1 satellite mission; (2) ZWD retrieved from observations data of the ECMWF ERA-Interim reanalysis model. The best agreement is reached between SIRGAS and IGS products ($\mu = -0.5$ mm, $\sigma = 6.5$ mm), whereas slightly worse statistical values are obtained in the comparisons with the JMR measurements ($\mu = -7.4$ mm, $\sigma = 15.4$ mm), and the ERA Interim data ($\mu = -1.5$ mm, $\sigma = 16.6$ mm).

A more detailed comparison undertaken with the IGS products confirmed that SIRGAS estimations quality is constant, independent from the local time or season of the year; at the same time, to mitigate the higher estimation noise in the final ZTD a further refinement of the processing parameters is required (e.g., using tighter constraints for parameters estimation). Overall, the achieved results are in accordance with previous researches. On one hand this testifies that the inter-technique differences were correctly accounted for, on the other, it further confirms SIRGAS capabilities to contribute to short and long term meteorological studies.

Future investigations are oriented to evaluate the impact of including other GNSS (GLONASS, Compass, Galileo) constellation in ZTD estimation to derive reliable near real-time short weather forecast over the whole South and Central American region.

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AUTHOR QUERIES

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