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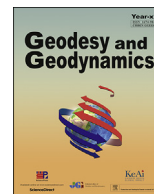
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Monitoring Zenithal Total Delays over the three different climatic zones from IGS GPS final products: A comparison between the use of the VMF1 and GMF mapping functions

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ABSTRACT

The International GNSS Service (IGS) final products (ephemeris and clocks-correction) have made the GNSS an indispensable low-cost tool for scientific research, for example sub-daily atmospheric water vapor monitoring. In this study, we investigate if there is a systematic difference coming from the choice between the Vienna Mapping Function 1 (VMF1) and the Global Mapping Function (GMF) for the modeling of Zenith Total Delay (ZTD) estimates, as well as the Integrated Precipitable Water Vapor (IPWV) estimates that are deduced from them. As ZTD estimates cannot be fully separated from coordinate estimates, we also investigated the coordinate repeatability between subsequent measurements. For this purpose, we monitored twelve GNSS stations on a global scale, for each of the three climatic zones (polar, mid-latitudes and tropical), with four stations on each zone. We used an automated processing based on the Bernese GNSS Software Version 5.2 by applying the Precise Point Positioning (PPP) approach, L3 Ionosphere-free linear combination, 7° cutoff elevation angle and 2 h sampling. We noticed an excellent agreement with the ZTD estimates and coordinate repeatability for all the stations w.r.t to CODE (the Center for Orbit Determination in Europe) and USNO (US Naval Observatory) products, except for the Antarctic station (Davis) which shows systematic biases for the GMF related results. As a final step, we investigated the effect of using two mapping functions (VMF1 and GMF) to estimate the IPWV, w.r.t the IPWV estimates provided by the Integrated Global Radiosonde Archive (IGRA). The GPS-derived IPWV estimates are very close to the radiosonde-derived IPWV estimates, except for one station in the tropics (Tahiti).

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1. Introduction

The radio signals transmitted from the Global Positioning System (GPS) satellites are delayed while they propagate through the

neutral atmosphere and this delay affects the accuracy of the estimated coordinates of the receiving stations [1]. The mathematical model that defines the neutral delay is based on the mapping of the delay at a given elevation angle to the zenithal direction by means of a so-called mapping function. The Zenithal Total Delay (ZTD) can be divided into two components: Zenith Wet Delay (ZWD) and Zenith Hydrostatic Delay (ZHD) [2] as

$$ZTD = ZHD + ZWD \quad (1)$$

Three mapping functions are now in wide use: the Niell Mapping Function (NMF) [3], the Vienna Mapping Function 1 (VMF1) [4] and the Global Mapping Function (GMF) [5]. The continued fraction model [6] is the common base of these three mapping functions:

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$$f_i(e, a_i, b_i, c_i) = \frac{1 + \frac{a_i}{1 + \frac{b_i}{c_i}}}{\sin e + \frac{a_i}{\sin e + \frac{b_i}{c_i}}} \quad (2)$$

where f_i is the mapping function, e is the elevation angle, (a_i, b_i, c_i) are coefficients and $i = (w, d)$ stands for, respectively, wet and dry mapping function. These coefficients are strictly speaking site-dependent, but very often they only depend on the latitude and day of the year. The VMF1 and GMF mapping functions are using the same (b_i, c_i) coefficients, by estimating value of (b_i, c_i) for 23 pressure levels (from 1000 hPa to 1 hPa), 10 different elevation angles (from 3.2° to 90°), from the global grid of the European Center for Medium-Range Weather Forecasts (ECMWF), with a resolution of $(2.0^\circ \times 2.5^\circ)$ [7]. The (a_i) coefficients are considered as the mapping function dominant components, and the VMF1 (a_d, a_w) mapping function coefficients are fitted w.r.t. the ray-tracing of the Numerical Weather Model (NWM) of the ECMWF with a grid resolution of $(0.25^\circ \times 0.25^\circ)$, four times a day for each station (0 h, 6 h, 12 h, 18 h, UTC). The GMF (a_d, a_w) mapping function coefficients (mean values and annual variations) are obtained through an expansion of the VMF1 mapping function parameters in spherical harmonics up to degree and order 9, from the NWM global grid ECMWF of monthly means from September 1999 to August 2002 [5]. All of these two mapping functions are dependent on external data, but the GMF mapping function is only dependent on the day of the year and the station coordinates, which makes it easier to implement.

The ZHD estimate, that is necessary to separate the ZWD from the ZTD (Eq. (1)), can be calculated with an accuracy of 0.2 mm by using surface pressure measurements [8]:

$$ZHD = \frac{0.0022768 \cdot P_s}{1 - 0.00266 \cdot \cos(2\varphi) - 0.00028H} \quad (3)$$

where φ is the station latitude in rad, H is the geoid height in km and P_s is the surface pressure in hPa.

The ZWD estimate from Eq. (1) is then converted into an IPWV estimate through a linear relationship [9]:

$$IPWV = ZWD * \Pi_{T_m} \quad (4)$$

where Π_{T_m} is a dimensionless factor function of the so-called T_m , the weighted mean temperature of the atmosphere with respect to its water vapor contents. This is not the purpose of this paper to dive into the intricacies of Eq. (4), so we refer to Zhang et al. [10] for a full discussion of all the metrological aspects.

We will now investigate any systematic differences coming from the particular choice of the VMF1 or GMF mapping functions, as implemented in the Bernese GNSS Software Version 5.2 (BSW 5.2). Our comparison is based on the use of the PPP method [11], for relevant subsets of the twelve IGS stations over three climatic zones, for the three following points: a) the estimated ZTD; b) the coordinate repeatability; and c) the estimated IPWV. We did a coordinate repeatability check as the receiver coordinate estimates and the ZTD estimates are highly correlated.

2. Data description

The IGS network contains more than 400 stations distributed around the world. We selected twelve well-distributed stations (Fig. 1), w.r.t. the three climatic zones, for the whole year 2014. The choice of these stations was based on the following criteria:

- Four stations in each climatic zone: see Table 1;
- Data availability: see Table 2. In our case, we used six stations with a concomitant availability of meteorological data and radiosonde IPWV (see Table 3);
- Approximately the same elevation, close to the sea, to maximize the ZTD values [12].

As already mentioned, we divided our dataset into.

- The input data: GPS observations, GPS satellite precise orbits and clocks as well as the Earth-rotation parameters (EOP) and the meteorological data provided by the Center for Orbit Determination in Europe (CODE) (<ftp://ftp.aiub.unibe.ch>, including temperature and pressure at the station level, used to estimate the IPWV);
- The reference data: used to assess the results obtained in the processing part. The ZTD estimates provided by CODE are generated by applying a wet and dry VMF1 mapping function at 3 elevation cutoff angle, based on a relative positioning approach and the Bernese 5.2 package. The ZTD estimates provided by USNO are generated by applying a wet and dry GMF

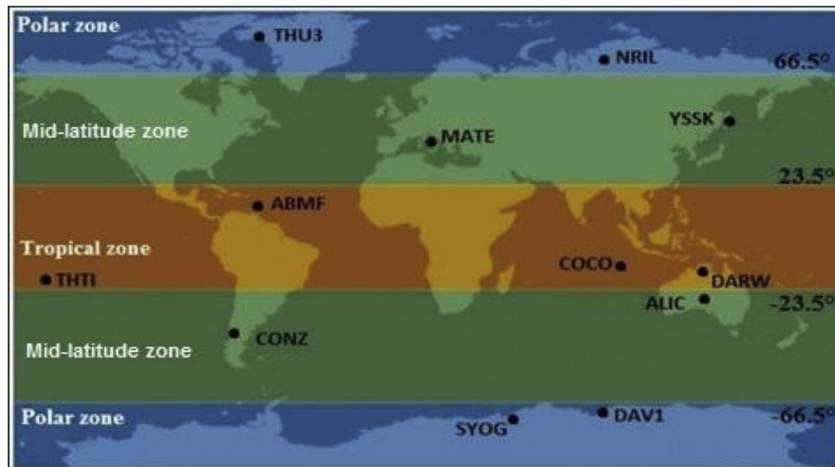


Fig. 1. Distribution of the twelve selected IGS stations (black dot), through the different climatic zones (orange: tropics ($23.5^\circ S \sim 23.5^\circ N$), green: mid-latitudes ($23.5^\circ S \sim 66.5^\circ S$ and $23.5^\circ N \sim 66.5^\circ N$), blue: polar, Arctic ($66.5^\circ N \sim 90^\circ N$) and Antarctic ($66.5^\circ S \sim 90^\circ S$)).

Table 1

Names and coordinates of the twelve selected stations (see Fig. 1) from the worldwide IGS network.

Station name	City name	Country	Longitude °	Latitude °	Ellipsoidal Height (m)
THU3	Thule Airbase	Greenland	−68.825	76.537	36.1
NRIL	Norilsk	Russian Federation	88.359	69.361	47.89
YSSK	Yuzhno-Sakhalinsk	Russian Federation	142.717	47.030	91.29
MATE	Matera	Italy	16.705	40.649	535.6
ABMF	Les Abymes	Guadeloupe	−61.528	16.262	−25.00
COCO	Cocos “Keeling” Island	Australia	96.834	−12.188	−35.22
DARW	Darwin	Australia	131.133	−12.844	125.19
THTI	Papeete	French Polynesia	−149.606	−17.577	98.49
ALIC	Alice Springs	Australia	133.885	−23.670	603.36
CONZ	Concepcion	Chile	286.974	−36.844	181.2
DAV1	Davis	Antarctica	77.973	−68.577	44.5
SYOG	East Ongle Island	Antarctica	39.584	−69.007	50.09

Table 2

Data availability in 2014 for the twelve selected IGS stations of Table 1. (“/” means no data).

Station name	GPS observations	CODE ZTD	USNO ZTD	Meteorological data	Radiosonde PWV
THU3	365	364	365	362	/
NRIL	343	333	330	340	334
YSSK	361	358	356	361	352
MATE	365	364	364	363	/
ABMF	364	355	348	/	/
COCO	364	357	362	363	/
DARW	365	359	363	365	361
THTI	364	359	363	364	363
ALIC	365	363	361	359	233
CONZ	359	360	356	262	/
DAV1	365	363	357	365	352
SYOG	359	326	345	/	/

Table 3

Comparison between our VMF1/GMF ZTD estimates and CODE/USNO ZTD estimates, in terms of biases and standard deviations (STD), for the whole year 2014, for six relevant stations from Table 1, all over the globe.

Station Name	Climate Zone	VMF1 (BSW5.2-CODE)		GMF (BSW5.2-USNO)	
		STD (mm)	Bias (mm)	STD (mm)	Bias (mm)
THU3	Polar,Artic	2.46	0.18	2.32	−1.87
MATE	Mid-latitudes	4.62	1.28	4.86	−0.26
DARW	Tropics	5.83	−1.04	4.36	−0.12
THTI	Tropics	5.88	2.10	4.51	0.58
CONZ	Mid-latitudes	5.08	1.29	5.51	−0.77
DAV1	Polar, Antarctic	2.05	−0.20	4.77	−8.45

mapping functions at 7° elevation cutoff angle, based on a PPP approach and the Bernese 5.0 package (BSW 5.0). The CODE products are sampled every 2 h and the USNO products are sampled every 5 min. We averaged the USNO products down to a 2 h sampling for comparison purposes. The Radiosonde Soundings (RS)-derived IPWV (mostly 12 h sampling) are archived by IGRA (Integrated Global Radiosonde Archive: <ftp://ftp.ncdc.noaa.gov/>) [13,14].

3. Data processing

All our processing (Table 3) was done twice on the Bernese 5.2 GNSS software package (BSW5.2), w.r.t the same parameters (PPP method, Ionosphere free linear combination L3, 7° cutoff elevation angle, CHENHER gradient estimation model [15]), ITRF08 reference frame, 2 h sampling, daily coordinate estimation), but first by using the VMF1 and secondly the GMF mapping function.

3.1. Errors filtering

We removed all the outliers by applying, for each station, a 3-sigma filter (about 1.5 cm for the North and East components (N, E), and 2.8 cm for the vertical component (U) on the residual coordinates. Our data flow is summarized in Fig. 2.

3.2. Quality assessment

In Table 3 we present our ZTD results (VMF1 and GMF mapping functions) compared to the IGS ZTD results (CODE and USNO), for six relevant stations: a) from the polar zones, Thule (Greenland, THU3) and Davis (Antarctic, DAV1); b) the mid-latitudes zones, Matera (Mediterranean, MATE) and Concepcion (South America, CONZ); and c) from the tropical zone, Darwin (Australia, DARW) and Tahiti (THTI, French Polynesia). The results are quite similar, with differences attributable to the fine tuning of the different

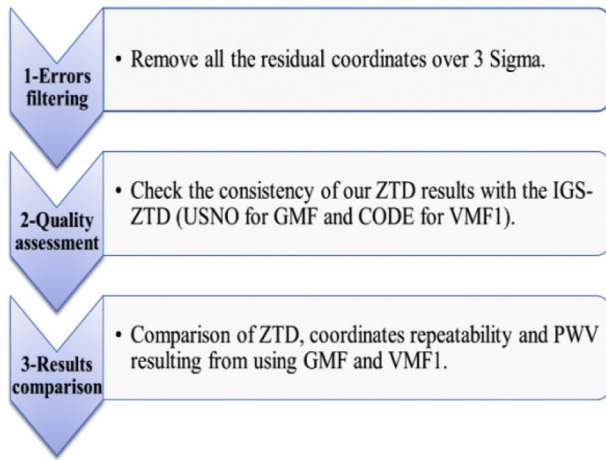


Fig. 2. The main stages of the comparison between our processing (VMF1 and GMF mapping functions), by using the Bernese 5.2 software and the IGS products (CODE and USNO).

processing, knowing that IGS is claiming that the accuracy of their ZTD estimates is around 4 mm (<http://www.igs.org>).

We noticed a very large systematic bias of -8.45 mm (Fig. 3a) for the Antarctic Station Davis (DAV1) when we compare our BSW 5.2 GMF/ZTD estimates to the BSW 5.0 USNO GMF/ZTD estimates. A similar shift (Fig. 3b), for the same station, appears if we compare the ZTD estimates provided by the two IGS analyses centers; CODE (VMF1) and USNO (GMF) (Bias = -6.56 mm, STD = 4.05 mm). According to reference [7], the particular choice between the VMF1 and GMF mapping function should cause biases of about 1 mm or less, but USNO and CODE results differ for this station by a bias of more than 8 mm. Both of our results based on VMF1 and GMF mapping function are close to the CODE products (biases less than 2 mm). This indicates that the bias of 8.45 mm is not coming from the particular choice of mapping function or our processing. A positive bias can also be noted for the Tahiti (THTI) station in the tropical zone (see paragraph 3.3.2 and reference [10]).

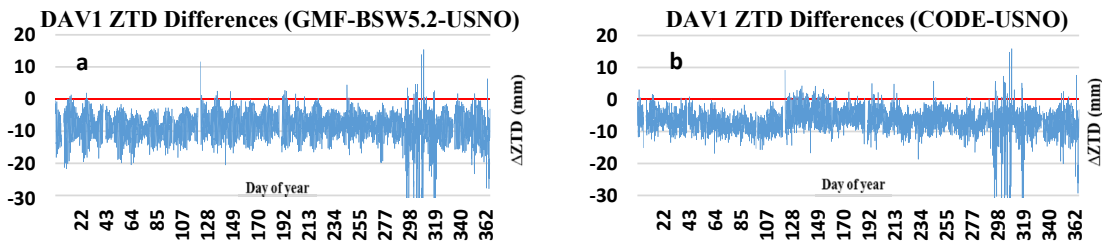


Fig. 3. (a) Differences between our Bernese 5.2 GMF-ZTD estimates and USNO-ZTD-estimates for the Polar Antarctic Davis (DAV1) station, and (b) Differences between USNO GMF-ZTD and CODE VMF1 ZTD estimates for the same station.

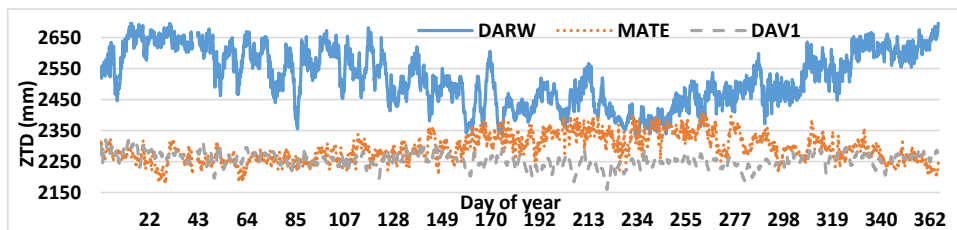


Fig. 4. Our time series of the VMF1-ZTD estimates over three different climatic zones stations: Darwin (DARW, tropics, continuous line), Matera (MATE, mid-latitudes, dotted line) and Davis (DAV1, Polar Antarctic, discontinuous line).

3.3. Results comparison

As already said, we will now do a comparison consisting of the three following steps:

- Consistency of our ZTD estimates w.r.t the choice of the mapping function and the different climatic zones;
- Repeatability of coordinate estimates of our station w.r.t the choice of the mapping function and the different climatic zones;
- Consistency of the IPWV estimates w.r.t. the IGRA archive, as a function of the choice of the mapping function.

3.3.1. Comparison of ZTD estimates

Fig. 4 shows our VMF1/ZTD time series estimates for the stations Darwin, Matera and Davis (DARW, MATE and DAV1), each one pertaining to a different climatic zone. We notice the influence of the climatic zones on the amplitude of the ZTD estimates, exceeding 2.7 m for the tropical zone, around 2.4 m for the mid-latitudes zones and no more than 2.3 m for the polar zones. A seasonal modulation is also clearly seen for the tropical and mid-latitudes stations.

Although our VMF1/ZTD estimates and the GMF/ZTD estimates are quite similar, Fig. 5 shows that the ZTD estimates relative to the polar stations are the most impacted by the particular choice of the mapping function. We note a correlation between the standard deviations (STD) of the ZTD differences between our Bernese 5.2 GMF/ZTD estimates and VMF1/ZTD estimates and the station's latitudes. The further we get from the equator, the more STDs rise.

3.3.2. Coordinates repeatability comparison

In this second part, we investigate the impact of the choice between the two mapping functions on the coordinate repeatability, with a one-day sampling, by using a program of coordinate comparison called COMPAR. The results are expressed in a “reference” topocentric coordinate system related to the station, which is the mean value of the estimated coordinates over one year of observations. The components North (N), East (E) and Up (U) represent the deviations from this mean value, the RMS (Root Mean

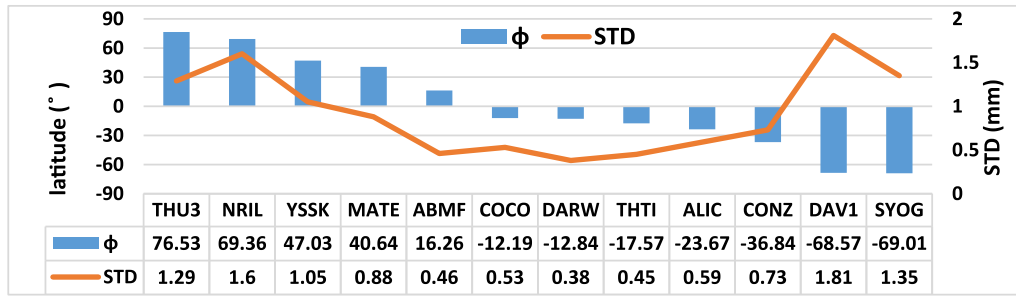


Fig. 5. Relationship between the station's latitude (ϕ , blue bars) and the standard deviations (STD, orange line) of the ZTD differences between our Bernese 5.2 GMF-ZTD estimates and VMF1-ZTD-estimates. The minimum value is recorded at the Darwin (DARW) tropical station (0.38 mm), and the maximum value at the Davis (DAV1) Polar Antarctic station (1.81 mm).

Squares) represents the average of the daily deviations for the whole year 2014.

Fig. 6a shows that the horizontal North East (N, E) coordinates repeatability RMSs obtained by using the GMF and VMF1 mapping functions are almost similar for all the stations (RMS differences min = 0 mm, max = 0.06 mm). All the polar stations RMS results show that the GMF related RMS are smaller than the VMF1 related RMS (min = 0.30 mm, max = 0.89 mm). On the other hand, the vertical components (U) show more variability (RMS differences slightly larger, but still at the sub-millimeter level). Even if the RMS differences between the two vertical components are at the sub-millimeter level (min = 0.03 mm, max = 0.89 mm), one can see in Fig. 6b that the RMS differences are larger for the stations close to the poles.

3.3.3. IPWV comparison

In this section, we investigate the impact of the choice of the mapping function on the GPS/IPWV estimates, w.r.t. the IPWV values archived by IGRA. As this type of data acquisition is expensive (typically around 200 USD per balloon launch or even more), and with poor temporal resolution (usually twice a day at 00 h UTC and 12 h UTC), only a few IGS and RS stations are collocated around

the world. In our case, when applying the collocation conditions found in [16] (distance less than 50 km and height difference less than 500 m), we ended up with only six collocated stations (see Table 5).

The IGRA RS/IPWV values are estimated from the ground up to the 500 hPa level (around 5.5 km). In reference [17] the author argues that RS missing data above the 300 hPa level introduce a bias at the level of 0.61%. Nevertheless, a recent study indicates that the bias can be up to 10% in tropical areas [10], in the case of very high IPWV values.

We can draw from Table 6 two important conclusions: firstly, the results obtained by applying the VMF1 and GMF mapping functions are similar; secondly our GPS/IPWV estimates basically agree with the RS/IPWV estimates; but of course we have to keep in mind that the IPWV in the atmosphere varies from essentially zero at the Earth Poles to about 60 mm and more in tropical areas [10]. This appears clearly in Table 6 for the Tahiti station (THTI). We have also to note that the ECMWF products used by both mapping functions are more precise in the North hemisphere than in the South hemisphere, as most of the surface stations assimilated in this model are located in populated areas [4].

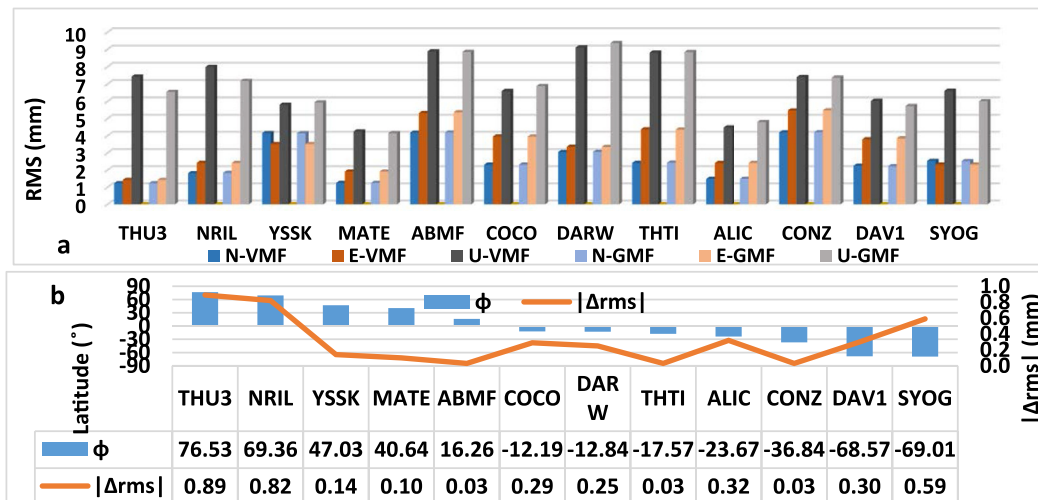


Fig. 6. (a) RMS errors for the coordinate repeatability, for the twelve IGS stations of Table 1, and for the whole year 2014 (VMF1 related values in deep color, GMF related values in light color). (b) Relationship between the RMS errors and station latitudes for the vertical (Up) component (the notation $|\Delta rms|$ means the difference between the VMF1 and GMF RMSs). See paragraph 3.3.2 for a precise definition of the RMS.

Table 4

Statistical comparison between our VMF1/ZTD and GMF/ZTD estimates for the twelve IGS stations of Table 1.

Station name	STD (mm)	Bias (mm)
THU3	1.29	−0.03
NRIL	1.6	0.83
YSSK	1.05	0.05
MATE	0.88	−0.01
ABMF	0.46	0.05
COCO	0.53	−0.11
DARW	0.38	0.00
THTI	0.45	−0.26
ALIC	0.59	−0.32
CONZ	0.73	−0.01
DAV1	1.81	−1.46
SYOG	1.35	−1.39

Table 5

The six collocated GPS and RS stations used in this study and their distance in terms of horizontal and vertical separation.

Station name	Radiosonde name	ΔHeight (m)	Distance (km)
NRIL	RSM00023078	9.36	4
YSSK	RSM00032150	69.29	9
DARW	ASM00094120	93.79	53
THTI	FPM00091938	96.49	2.5
ALIC	ASM00094326	58.36	14
DAV1	AYM00089571	26.50	0.2

Table 6

Comparison between our GPS/IPWV estimates (VMF1 and GMF) and the RS/IPWV estimates in terms of STD and biases, for the six collocated stations of Table 5.

Station name	GMF-RS (mm)		VMF-RS (mm)	
	STD	Bias	STD	Bias
NRIL	1.02	0.55	1.04	0.44
YSSK	2.33	−0.18	2.30	−0.18
DARW	3.59	−0.24	3.59	−0.29
THTI	4.56	−1.45	4.57	−1.46
ALIC	2.02	1.87	2.05	1.98
DAV1	0.66	−1.04	0.64	−0.84

4. Conclusions

In this paper we studied the modeling of GPS neutral atmospheric zenithal delays (ZTD) and coordinate repeatability on a global scale, over twelve GNSS stations, with four stations for each climatic zones (polar, mid-latitudes and tropical, see Fig. 1, Tables 1 and 2). For this purpose, we considered PPP precise orbits and IGS final products, by using the Bernese GNSS Software Version 5.2 as a processing tool. We had a closer look at the impact of the choice of the VMF1 versus the GMF mapping functions, with comparisons with the CODE and USNO results. We conclude that:

- 1) The choice between the GMF and VMF mapping functions (to be precise about the particular implementations of the GMF and VMF1 mapping functions in the Bernese 5.2 software) has no influence on the estimates of the ZTD, especially for the tropical and mid-latitudes zones, but we have to pay more attention to the polar zones (Figs. 3–5, Tables 3 and 4);
- 2) The choice between the GMF and the VMF1 mapping functions has no influence on the repeatability of the station's horizontal components (E, N) for all the climatic zones. On the other hand, at the polar stations, there is a small improvement on the vertical components repeatability when using the GMF mapping function instead of the VMF1 mapping function (Fig. 6). This must be taken into account for high precision positioning purposes;

- 3) For the GPS/IPWV estimates (Tables 5 and 6), the particular choice of the GMF or VMF1 mapping functions has no impact, w.r.t. the RS/IPWV IGRA reference, for polar and mid-latitudes zones. However, this is not true for the tropical zone. It is clear that the assumptions and approximations made for mid-latitudes areas [9] to translate the GPS wet delays into IPWV estimates must be revisited in tropical areas, in accordance with [10].
- 4) From the two firsts conclusions (points 1 and 2) it is clear that the VMF1 and GMF mapping functions also lack reliability in the polar zones. This is certainly caused by the lack of data to constrain by ray tracing the continued fraction model built in the mapping functions, and especially over the Antarctic.
- 5) As a general conclusion we couldn't say that one choice of the mapping function (VMF1 versus GMF), with respect to their implementation in the Bernese Software Version 5.2, is "better" than the other, at least in mid-latitudes areas. In other climatic zones, both of them may need to be revisited. From a practical point of view, the GMF mapping function is easier to use, and as a result, the GMF mapping function is widely implemented in most of the current GNSS software packages. But the fact that the GMF mapping function implementation is based on average values of seasonal variations prevents it to take into account unusual meteorological variations, which is not the case for the VMF1 mapping function implementation [5].

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