On the computation of Zenith Total Delay Residual Fields by using Ground-Based GNSS estimates

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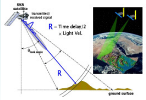
Abstract

Tropospheric refraction is one of the major error sources in satellite-based positioning. The delay of radio signals caused by the troposphere ranges from 2m at the zenith to 20m at low elevation angles, depending on pressure, temperature and humidity along the path of the signal transmission. If the delay is not properly modeled, positioning accuracy can degrade significantly. Empirical tropospheric models, with or without meteorological observations, are used to correct these delays but they are limited in accuracy and spatial resolution resulting in up to a few decimeters error in positioning solutions. The present availability of dense ground-based GNSS networks and the state of the art of GNSS processing techniques enable precise estimation of Zenith Tropospheric Delays (ZTD) with different latency ranging from real time to post-processing. We present a method for computing ZTD residual fields interpolating, through Ordinary Kriging, the residuals between GNSS-derived and model-computed ZTD at continuously operating GNSS stations, following the general lines of the method outlined in [9]. At a known user location, ZTD value (hereafter site-ZTD) can be obtained as the sum of site-ZTD residual and modeled-ZTD value. The performance of the method is assessed comparing site-ZTD values against IGS, radiosonde and Very Long Baseline Interferometry (VLBI) tropospheric products at some European stations. This work aims at assessing that empirical models can be improved if tropospheric corrections got from ground-based GNSS network are taken into account, since it is not possible for an empirical model to emulate tropospheric delay variations exactly.

Motivation

GNSS positioning is complicated by the presence of the tropospheric propagation delay. In current positioning services tropospheric delay corrections are not broadcasted, unlike ionospheric corrections, to the users but are corrected locally by the users using empirical tropospheric model, with or without meteorological observations. However residuals delay after modeling are at a few cm level in the zenith directions which may lead to positioning errors of a few dm. We tested [7] that the use of tropospheric delay corrections, computed following the method described below, for a fixed receiver of known coordinates gets an improvement up to 8cm (residual RMS) in the height determination.



Atmospheric effects are not negligible in accurate geolocation of SAR products (@1-m level) generated by the most advanced SAR satellite missions, as Cosmo-SKYMed (ASI) and Terrasar-X (DLR). At those frequencies (~10GHz), the SAR ray path is delayed by the troposphere, directly related to the ZTD that can be estimated by GNSS measurements. Even if on a global scale routine correction of SAR images can be more easily implemented by means of an empirical tropospheric model, specific and refined applications for a given area may profit of GNSS ZTD values, especially if they are dense enough in space to provide a reliable field [8].

From point-wise GNSS ZTD estimates to site-ZTD

Step 1: GNSS Data Collection and ZTD Processing

Figure 1. ASI E-GVAP Ground based GPS network

ASI-CGS is an E-GVAP (http://egvap.dmi.dk/) Analysis Center. On hourly basis GPS data covering the central Mediterranean area (Figure 1) are analyzed and NRT ZTD estimates are sent to a common ftp server at UK Met Office. GIPSY-OASIS II is used for GPS data reduction following the standard technique of network adjustment. A detailed description of the processing strategy is reported in [6]. The accuracy of ASI NRT ZTD products has been assessed by comparing them w.r.t. radiosonde ascents, HIRLAM NWP data and other GPS solutions [5].

Step 2: Ordinary Kriging Interpolation

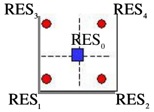
GNSS ZTD estimates as obtained in Step 1 are considered as true delays. The difference between the GNSS-derived ZTD and model-computed ZTD are defined as ZTD residual.

UNB3m [3] is used as reference model, which is capable of predicting ZTD with an uncertainty of 5cm [4].

It computes the hydrostatic and wet zenith delays according to the Saastamoinen model and a prediction of the meteorological parameters based on a look-up table with annual mean and amplitude for temperature, pressure and relative humidity. These parameters are calculated for a particular latitude and doy using a cosine function for the annual variation and a linear interpolation for latitude.

ZTD residuals between GNSS-derived and model-computed ZTD are interpolated through Ordinary Kriging (OK) with a geographical coverage spanning [35°, 55°] in latitude and [-10°. 20°] in longitude, both with 0.5° spacing. OK is a powerful spatial interpolation technique, especially for irregularly spaced data points, and is widely used throughout the earth and environmental sciences.

Step 3: ZTD correction at a user location



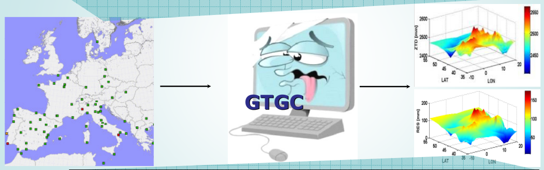
We get the residual at a given location by a bi-linear interpolation performed on the four nearest points in the grid:

$\mathrm{RES}_0 = \sum_{i=1}^{4} \omega_i RES_i$, **with the general weight function:** $\omega(x,y) = x^2 y^2 (9 - 6x - 6y + 4xy)$, **where *z* and *y*, positions of the point within the proper grid cell, are calculated from:** $x = \frac{\Delta\lambda}{\text{longitude grid interval}}$, $y = \frac{\Delta\varphi}{\text{latitude grid interval}}$

Site-ZTD can be obtained as the sum of site-ZTD residual and modeled-ZTD value.

GnssTropoGridCreator (GTGC)

Number of GPS sites	>60
GPS data	▪ L1/L2 phase/code pseudorange hourly batches ▪ RINEX format ▪ 1h latency
Ancillary data	IGS UR products
GPS data analysis SW	NASA/JPL GIPSY/OASIS
E-GVAP ZTD product	▪ Hourly batches ▪ 15' ZTD estimates for each site ▪ COST format ▪ 90min latency



GTGC Product (Ordinary Kriging)	▪ UNB3M reference model ▪ ZTD grids at 0-height layer ▪ ZTD residual grids ▪ [35°,55°] lat, spacing: 0.5° ▪ [-10°,20°]lon, spacing: 0.5° ▪ IONEX modified format ▪ <2h latency

Validation

We have set-up a processing chain implementing step 1 and 2 in a fully automatic way and on hourly basis. We use as input data ASI NRT ZTD estimates (blue sites in Figure 2). The performance of the method has been evaluated for 1-year period (January-December 2011) considering 25 European stations belonging to the EPN/IGS Network (red sites in Figure 2). At those 25 stations we compute site-ZTD as outlined in Step 3.

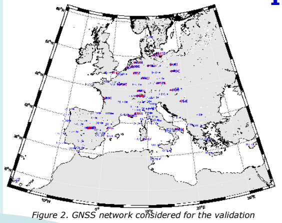


Figure 2. GNSS network considered for the validation

Intra-technique Validation: comparisons against IGS ZTD values

The intra-technique validation is done via a comparison to reference post-processing results as IGS tropospheric products [1 - 2].

Figure 3 shows statistical comparison of UNM3m-ZTD values (in red) and site-ZTD (in blue) with respect to IGS ZTD estimates for all the 25 test sites. The upper figure reports the absolute values of biases, while the bottom figure plots the standard deviation values.

An improvement of about 30% for the bias and 50% for the std is shown when site-ZTD, rather then UNB3m-ZTD values, are compared w.r.t. IGS.

On the basis of these results in the following plots we have considered only site-ZTD.

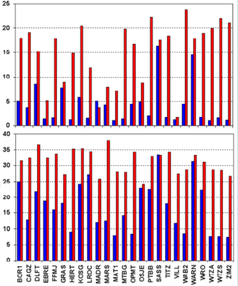


Figure 3. Statistical comparison. Absolute values of bias (top), std (bottom)

In Figure 4 the monthly variation of the IGS ZTD values for each test site vs site-ZTDs is shown. Sites are sorted according to increasing latitude (*left*), increasing orthometric height (*middle*) and increasing distances from the nearest GNSS input site (*right*).

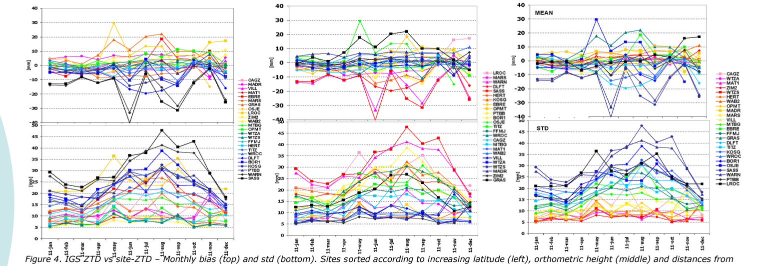


Figure 4. IGS ZTD vs site-ZTD – Monthly bias (top) and std (bottom). Sites sorted according to increasing latitude (left), orthometric height (middle) and distances from the nearest GNSS input site (right).

We find the largest std for sites in Northern Europe (*left*), for sites at lowest heights (*middle*) and for sites with major distances from the nearest GNSS input site (*right*).

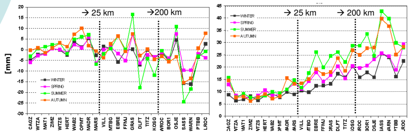


Figure 5. IGS ZTD versus site-ZTD – Seasonal bias (left) and STD (right). Sites sorted according to increasing distances w.r.t. the nearest GNSS input site.

In figure 5 seasonal bias and std between IGS-ZTD and site-ZTD are plotted. It can be noticed that the seasonal std increases with the distance being in the range of [5;15]mm till 25km, [10,30]mm till 200km and [15,45]mm till 300km.

The largest values in the std are found during the summer period, which can be related to the atmospheric seasonal cycle.

Validation against independent techniques: Radiosonde and VLBI

***Radiosonde versus site-ZTD*: The annual bias and std for 5 test sites is reported in table 1.**

Among them HERT is the closest to the radiosonde launch site (3,42 km) while ZIM2 is the most distant (41,02 km). The agreement, in terms of bias and std of the residual ZTD values, is good (see Table 1).

	RS code	BIAS [mm]	STD [mm]	# sample	Distances [km]
HERT	3882	10,6	10,6	386	3,42
WROC	12425	1,5	23,2	578	14,06
CAGZ	16560	-0,9	17,5	666	14,49
VILL	8221	3,5	14,2	545	29,56
ZIM2	6610	5,9	11,1	573	41,02

Table 1. Radiosonde vs site-ZTD - Annual statistics

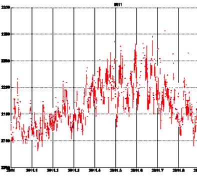


Figure 6. Site-ZTD (continuous red line) and Radiosonde ZTD (dotted blu line) at ZIM2.

***VLBI versus site-ZTD:* 3 test sites are co-located with VLBI radio-telescope antenna MAT1, WTZA and WTRS. The VLBI solutions used in this comparison are the ASI/CGS contributions to the IVS tropospheric services.**

	BIAS [mm]	STD [mm]	CC	# sample
MAT1	0,05	9,04	0,97	875
WTZA	-0,30	9,88	0,97	2092
WTZS	-0,14	9,88	0,97	2092

Table 2. VLBI vs site-ZTD- Annual statistics

Site-ZTD and VLBI estimates are very highly correlated, with an overall bias of –0,13mm (see table 2).

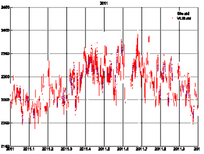


Figure 7. Site-ZTD (continuous red line) and VLBI ZTD (dotted blue line) at MAT1.

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