TROPSY: Assessment techniques of tropospheric effects for local augmentation systems

TROPSY

Executive Summary Report

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1 Introduction

Galileo is the European initiative for a state-of-the-art Global Navigation Satellite Systems (GNSS), interoperable with other GNSS such as GPS or GLONASS and providing highly accurate, guaranteed global positioning under civilian control. The European Geostationary Navigation Overlay Service (EGNOS) delivers corrections and integrity information to GPS and GLONASS (augments these systems). It interoperable with other augmentation systems such as WAAS, MSAS and complies with standards defined by the International Civil Aviation Organization (ICAO). GNSS are based on the broadcasting of electromagnetic ranging signals. Those signals are located in the L-band and suffer from the signal delay in the atmosphere (troposphere and ionosphere). For the stand-alone user (e.g., user computing navigation solution without base station) it is important to remove such atmospheric delays. While ionospheric delay can be successfully removed by using multi-frequency receivers, tropospheric delay correction can be done exclusively by correction algorithm driven by meteorological parameters or using differential techniques.

Usually tropospheric correction models compute the tropospheric delays in a two-step procedure. At first, the tropospheric delay is computed in zenith direction. This value is called Zenith Total Delay (ZTD). ZTD's are typically in the order of 2-2.5 m. The slant total delay (STD), in the direction to the satellite, is computed by multiplying the ZTD with a coefficient obtained from a mapping function. The mapping function has a value of 1 in zenith and increase to the value of about 5 for elevation angles of about 10 degrees. It should be noted that modern tropospheric error correction models usually work for elevation angles of 3° to 5°. In case of lower elevation angles the modelling error increases extremely fast.

The tropospheric delay is split into two parts: hydrostatic (or dry) and wet delay. The hydrostatic delay is caused by dry gases and water vapour, which is considered to be in hydrostatic equilibrium. The remaining water vapour causes the wet delay. Normally both delays are modelled separately including zenith delay and mapping functions. The hydrostatic part is the largest part of the total delay (about 95%), and this part is modelled with a RMS of sub-centimetre level in zenith direction. The wet delay is much smaller, however the modelling is difficult due to more complicated nature effects and unpredictable behaviour of the distribution of water vapour. The error of the wet delay in zenith direction is about 2.4-4 cm for the recent models.

The tropospheric error correction model can be operated in the blind mode – when there is no external data available, but only climatological grid from the model itself. The site mode is a mode when there are meteorological data (temperature, pressure and relative humidity) from nearby sensors available. The model operates in a site-augmented mode if beside meteorological data additional data like mapping function coefficients, total tropospheric zenith delay at user position etc. are available.

Recent improvements of tropospheric error correction models concentrate on an improved modelling of the wet component. The Global Temperature and Pressure (GPT2) model was developed by the Vienna University of Technology and is widely used by GNSS and VLBI data analysis as a priori model. The proposed new model GPT2w (wet) is developed as an evolution of GPT2 and improves the modelling of the wet component. This improvement is achieved by processing the recent numerical weather products (NWP) and introducing the new climatological parameters (water vapour lapse rate and mean temperature). Introducing the new climatological parameters allows a more precise modelling approach of the wet component.

The project "TROPSY: Assessment techniques of tropospheric effects for local augmentation systems" aims at the improvement of accuracy of tropospheric correction algorithms for design, verification, and operations of GNSS systems.

This document represents the executive summary report and starts with an introduction of the new developed tropospheric error correction model GPT2w. Followed by a description of the data used to create this model.

The performance of GPT2w is assessed globally and locally (at the Austrian territory) using estimated zenith tropospheric delays from International GNSS Service and zenith and slant delays calculated with ray-tracing.

Afterwards, the GPT2w tropospheric error correction model performance is compared to the performance of current Galileo model (GALTROPO) and standard SBAS model (RTCA-MOPS). The model performance analysis and comparison with the recent geodetic tropospheric error correction models are assessed using radiosonde data as well.
This report is based on the work performed by TeleConsult Austria GmbH, Vienna University of Technology, Central Institute for Metrology and Geodynamics, Vienna, Austria and Budapest University of Geodesy and Surveying, Budapest, Hungary as part of contract awarded by European Space Agency.

2 GPT2w model

2.1 Model Description

The GPT2w is an enhancement of the two empirical models GPT (Global Pressure and Temperature) and GMF (Global Mapping Function). The development and validation of GPT2 as well as the comparison with GPT/GMF have been described in detail by [LAGLER 2013].

The input parameters for the GPT2w model are user position (i.e., longitude, latitude and ellipsoidal height), satellite elevation angle (angle between local horizon and zenith direction) and current epoch (in the form of Modified Julian Date). The GPT2w has the set of climatological and additional parameters computed at a global grid. Most of the grid parameters are presented in the form of average values (A_0), annual (A_1,B_1) and semi-annual (A_2,B_2) amplitudes, and phases. The correspondent values can be computed for the current epoch using the following relationship:

$$r(t) = A_0 + A_1 \cdot \cos\left(2\pi \frac{doy}{365.25}\right) + B_1 \cdot \sin\left(2\pi \frac{doy}{365.25}\right) + A_2 \cdot \cos\left(4\pi \frac{doy}{365.25}\right) + B_2 \cdot \sin\left(4\pi \frac{doy}{365.25}\right),$$

where doy is the day of year. The computations of the slant tropospheric delay is accomplished in the following steps:

1) Interpolate from the climatologic grid meteorological parameters, user undulation above ellipsoid and coefficients a_h, a_w for the mapping function computation.
2) Compute zenith hydrostatic (ZHD) and wet (ZWD) delays using

$$ZHD[m] = \frac{0.0022768 \cdot p\,[hPa]}{(1 - 0.00266 \cdot \cos(2\varphi) - 0.00000028 \cdot h_{ell}\,[m])}$$
$$ZWD[m] = 10^{-6} \cdot \left((k_2' + \frac{k_3}{T_m}) \cdot \frac{R_d}{(1+\lambda)g_m} \cdot e[hPa]\right) \qquad (1)$$

   where p is the atmospheric pressure at the height of user, h_{ell} represents the ellipsoidal height of the user, $k_2' = 16.52[\mathrm{K/hPa}]$ is a constant, λ is a water vapour lapse rate, e is a water vapour pressure, R_d is the specific gas constant for air dry constituents.

3) Compute hydrostatic $m_h$and wet $m_w$mapping functions for the specified elevation angle E

$$m_h = \frac{1 + \cfrac{a_h}{1 + \cfrac{b_h}{1 + c_h}}}{\sin(E) + \cfrac{a_h}{\sin(E) + \cfrac{b_h}{\sin(E) + \cfrac{b_h}{\sin(E)} + c_h}}} + h_{corr}$$

$$m_w = \frac{1 + \cfrac{a_w}{1 + \cfrac{b_w}{1 + c_w}}}{\sin(E) + \cfrac{a_w}{\sin(E) + c_w}} \qquad (2)$$

   here a_h, a_w are the mapping function coefficients interpolated from the grid, rest of the constant a, b, c and height correction h_{corr} are the same as for Niell model and can be found in the [NIELL 1996],

4) Compute the total slant delay (STD) by applying the mapping function coefficient to the correspondent zenith delays:
$$STD = ZHD \cdot m_h + ZWD \cdot m_w \qquad (3)$$

The estimations of the tropospheric error can be improved, if there are meteorological measurements (i.e., temperature, pressure and humidity) from the nearby sensors available. In this case, the correspondent values from the climatological grid can be replaced by the actual values. If the model is receiving the meteorological data, it is said to operate in the site mode.

If meteorological data are accompanied with additional parameters like zenith delays interpolated at user position or/and mapping function coefficients, than the model is operated in site-augmented mode. These parameters also replace the ones calculated from grid, e.g., zenith delays and mapping function coefficients and should be substituted in (1).

2.2 Data used to create model

The data used are a series of monthly files derived from the numerical weather model ERA-Interim (37 levels) between 2001 and 2010. Each monthly "observation" file contains:

- Latitudes and longitudes in one degree steps [-89.5° 89.5°] x [0.5° 359.5°]
- Modified Julian days of the 15th of each month
- Hydrostatic and we mapping function coefficients
- ZHD and ZWD in meters
- Mean temperatures Tm in Kelvin
- Pressure on the ground in hPa
- Temperature on the ground in degrees Celsius
- Water vapour partial pressure in hPa
- Orthometric height of the grid point in meters

We apply the method of harmonic decomposition as already used by [LAGLER 2013] to create GPT2w. For each parameter we set up a mean value, two annual coefficients and two semi-annual coefficients which were determined in a least-squares approach for each point of the 1-degree grid – the same grid as used by GPT2. No weight matrix was used, because no a priori hypothesis could be reasonably made.

For the local test cases the climatological grid has been created for the Austrian territory. For this were used regional NWP ALARO provided by Central Institute for Meteorology and Geodynamics (ZAMG). ALARO is operated on a horizontal resolution of 4.8 km and uses 60 levels in the vertical. The model is run four times per day, whereas the integration is performed up to 72 hours lead-time. ALARO (the configuration run at ZAMG is also named ALARO5-AUSTRIA) is coupled to the global IFS model, which is run at ECMWF. For ALARO5-AUSTRIA, the initial state for the free atmosphere is provided by interpolation of the IFS model fields to 4.8 km model grid. A surface assimilation system is run at ZAMG and fed with SYNOP and high-density TAWES (Semi-automatic weather stations in Austria) data to produce the initial state for the surface fields using an optimum interpolation method. The blind Regional Tropospheric Correction Model GPT2w is based on climatological parameters derived (by a least squares approach) from 3-years' time series (2011-2013) of the ALARO NWP model operated by ZAMG. The spatial resolution of regional GPT2w model is 0.2° x 0.3°, which corresponds to 25 km both in latitude and in longitude (for the middle-European region).

2.3 Model Testing

GPT2w has been tested using following reference data:

- the tropospheric zenith delays computed by IGS (about 380 globally distributed stations see left part of Figure 2-1, estimation every 2 hours, test period – two years 2012-2013)

- ray-tracing results for specific elevation angles: 3°, 10°, 30°, 90° (estimation every 6 hours)
- radiosonde data from 11 stations
- tropospheric zenith delay estimated for 115 Austrian GNSS stations (test period May 2013 - October 2013, estimation every hour), see right part of the Figure 2-1.

The model has been tested in blind, site and site-augmented mode. For this purpose, ZAMG collected data from the global and Austrian networks of meteorological sensors. The distribution of stations used in model verification is shown at the Figure 2-1.

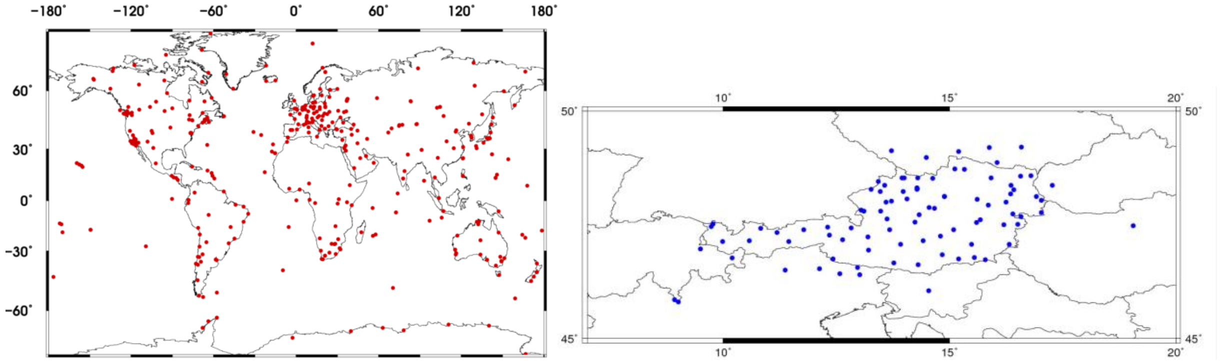

Figure 2-1: IGS and Austrian stations used for GPT2w verification

The GPT2w model has been tested in blind, site and site-augmented modes using the ZTD estimations from IGS as a reference. The network configuration is show at the left part of the Figure 2-1. A comparison (i.e. RMS and bias) of the results for the blind test is given in Table 2-1.

	RMS error, [mm]	Bias, [mm]
Minimum	16.1	-40.0
Maximum	64.0	29.2
Mean	37.4	-0.2

Table 2-1: Test Case 'blind' - RMS error and Bias of GPT2w ZTDs w.r.t. IGS ZTDs

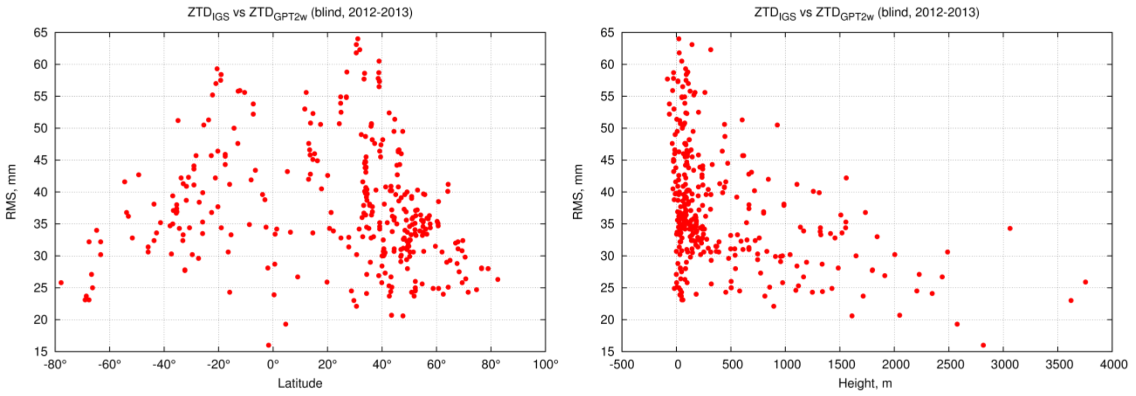

Figure 2-2: RMS of the differences between IGS ZTDs and GPT2w ZTDs w.r.t. station latitude (left) and height (right)

The tropospheric delay is highly dependent on the station latitude and height. The dependency of the RMS error on latitude and station height is shown in Figure 2-2. Furthermore, tropospheric delays obtained from the GPT2w blind model were compared with delays obtained from ray-tracing. The results are shown in Table 2-2:

	3°		**10°**		**30°**		**90°**	
	RMS error, [mm]	**Bias, [mm]**	**RMS error, [mm]**	**Bias, [mm]**	**RMS error, [mm]**	**Bias, [mm]**	**RMS error, [mm]**	**Bias, [mm]**
Min	287.7	145.5	100.2	58.3	35.3	20.2	17.7	10.1
Max	1740.8	-1242.9	609.6	-435.6	215.5	-154.0	107.9	-77.1
Mean	612.1	-149.6	212.9	-25.4	75.6	-8.8	37.9	-4.4

Table 2-2: Comparison of ZTD/STD (ray-tracing) and ZTD/STD (GPT2w blind)

Figure 2-3 shows the distribution of the differences ZTD(IGS) – ZTD(GPT2w) with the bins of 1 cm. In addition, the Gaussian distribution based on the calculated bias and standard deviation (blue line) is visualized.

ESA GALTROPO model has been also included into comparison. Figure 2-3 shows the distribution of the differences ZTD(IGS) – ZTD(GPT2w) and ZTD(IGS) – ZTD(ESA). In addition, the Gaussian distribution based on the calculated bias and standard deviation (red line) is visualized.

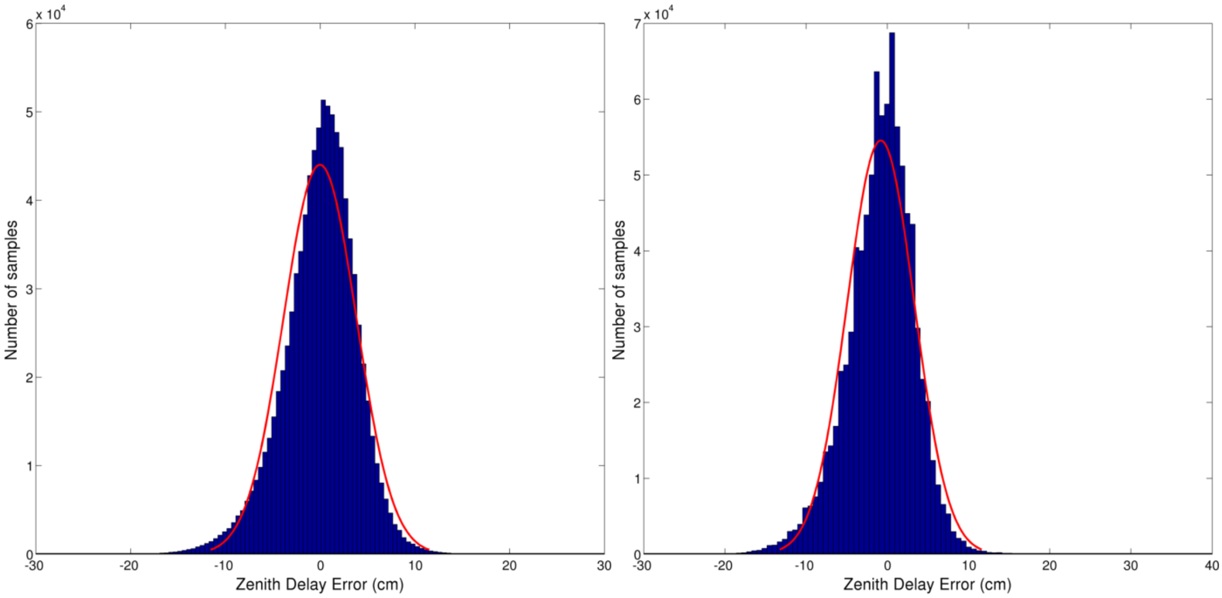

Figure 2-3: Gaussian distribution ZTD(IGS)-ZTD(GPT2w) (left), and ZTD(IGS)-ZTD(ESA) (right)

As it can be seen errors for the both GPT2w and ESA models are very well described by the normal distribution. The plot ZTD error w.r.t. reduced variate (Figure 2-4) shows in which range Gaussian distribution describes the model error. Plots indicate that characterising tropospheric delay errors using a Normal distribution is recommended in the following ranges GPT2w: [-2σ;+3σ], ESA GALTROPO: [-1σ;+3σ].

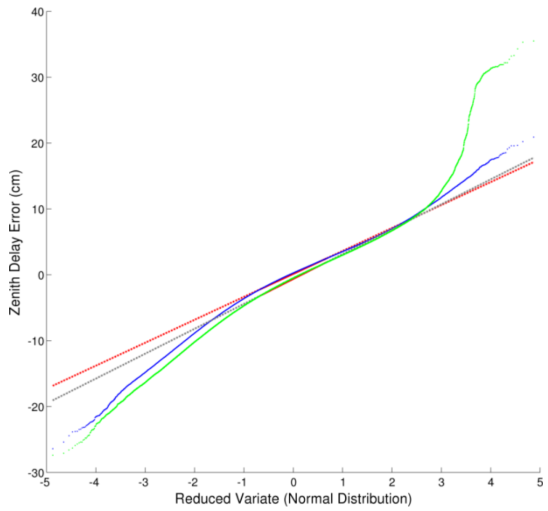

Figure 2-4: Gaussian plot of zenith delay residuals. (Solid blue line – GPT2; solid green line – ESA GALTROPO; dashed lines – best fit Normal distributions)

In site mode the test values were computed using GPT2w with actual meteorological parameters from near-by meteorological sensors. The zenith delays computed from GPT2w in site mode were compared with the delays obtained from the GNSS measurements at IGS stations. The RMS and the bias of the differences between ZTD(IGS) and ZTD(GPT2w_site) are shown in Table 2-3.

	RMS error, [mm]	Bias, [mm]
Minimum	10.2	-1.9
Maximum	65.7	-42.2
Mean	31.6	-1.9

Table 2-3: Comparison of ZTD(IGS) and ZTD(GPT2w site)

Furthermore, the ZTD(GPT2w site) was compared with the ray-traced ZTD. Figure 2-5 shows the RMS error of the differences between ZTD(GPT2 site) and ZTD(ray-tracing) w.r.t. latitude and station height.

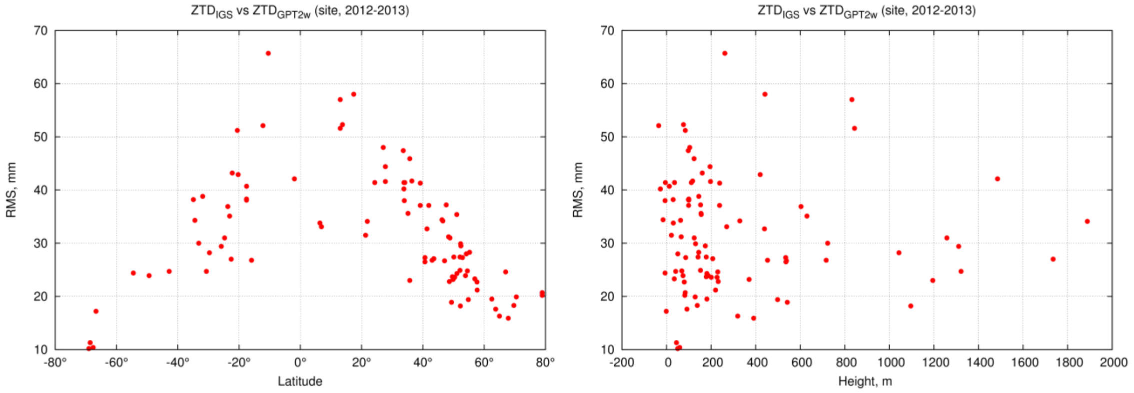

Figure 2-5: RMS of the differences between ZTD(GPT2w site) and ZTD(ray-tracing) w.r.t. station height (left) and latitude (right)

The ZTD(GPT2w site) was mapped to predefined elevation angles (3°, 10° and 30) using the blind mapping function coefficients ah and aw of the GPT2w. The resulting slant delays STD(GPT2w site) were compared with ray-traced slant delays STD(ray-tracing). The RMS error and the bias of the differences are shown in Table 2-4.

	3°		10°		30°		90°	
	RMS error, [mm]	**Bias, [mm]**	**RMS error, [mm]**	**Bias, [mm]**	**RMS error, [mm]**	**Bias, [mm]**	**RMS error, [mm]**	**Bias, [mm]**
Min	115.7	-1323.0	39.4	-442.8	14.5	-157.6	7.3	-79.0
Max	1521.6	362.3	519.7	142.9	184.8	50.9	92.6	25.5
Mean	523.9	-116.2	182.9	-9.2	64.9	-2.9	32.5	-1.4
Number of stations			109					
Number of data samples			286983					

Table 2-4: Comparison of STDs(ray-tracing) and STDs(GPT2w site)

The distribution of the differences ZTD (ray-tracing) – ZTD (GPT2w site) and reduced variate w.r.t. TZD error are shown in Figure 2-6. As in the case of blind model the differences in the range [-10 cm; 10 cm] distributed normally. A side peak at -22 cm is present. It can be seen that tropospheric delay errors as in the case of blind mode follows the normal distribution in the range of [-1σ; 2σ].

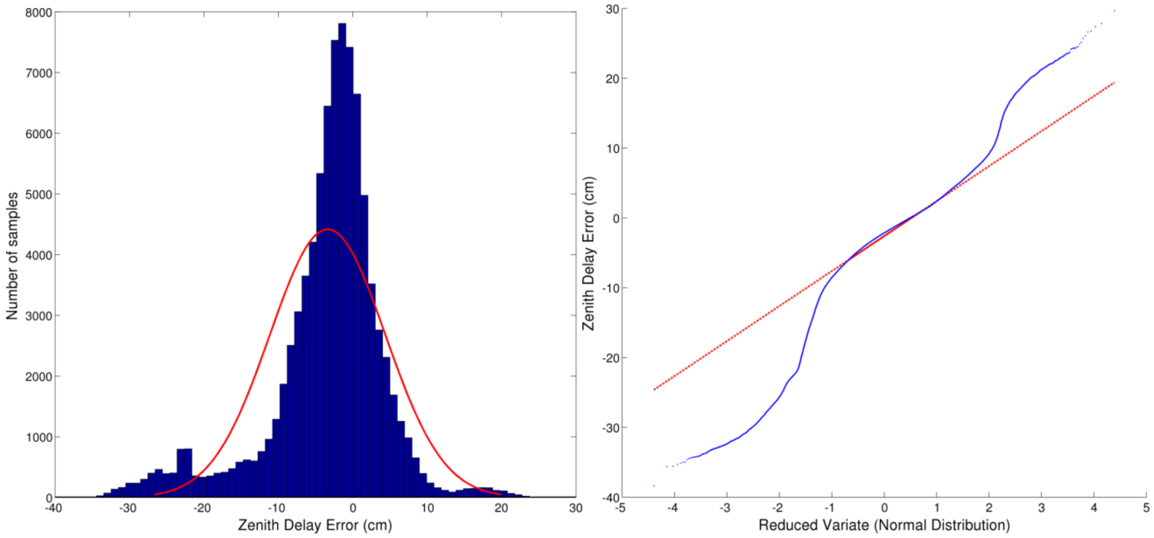

Figure 2-6: Distribution ZTD(VMF1) – ZTD(GPT2w site) and Gaussian distribution

In site-augmented mode tropospheric delays are computed with GPT2w using actual meteorological parameters (i.e., pressure, temperature, humidity and water vapour lapse rate computed from ray tracing). The slant delays are obtained using mapping function coefficients computed from ray-tracing.

The tropospheric delays are tested by comparing the values from ray-tracing and GPT2w for pre-defined angles (3°, 10°, 30°, and 90°). The RMS and the bias of the differences between STD(ray-tracing) and STD(GPT2w site-augmented) are given in Table 2-5.

Zenith hydrostatic and wet delays derived from GPT2w (blind) were also compared to the correspondent values obtained from radiosonde data, the results are shown at Table 2-5.

	Bias [cm]	RMS [cm]	σ [cm]
ZHD	0.2	2.0	1.7
ZWD	-0.1	3.9	3.5

Table 2-5: GPT2W model minus RS profiles – mean bias, mean RMS and mean sigma of the differences between these two models for the whole study period

The performance of the troposphere models in terms of slant tropospheric delays were validated using radiosonde and microwave radiometer observations. Two months of radiosonde profiles and a month of microwave radiometer atmospheric profiles in July to August of 2014 were used for this validation study. The profiles stemmed from the Hungarian radiosonde and microwave radiometer site in Szeged.

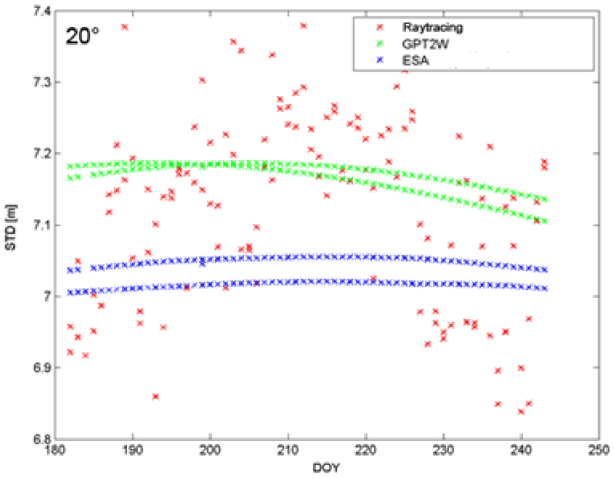

Figure 2-7: 20°STD estimated using GPT2W and ESA models wrt the raytraced STD in Szeged

Figure 2-7 show the STD estimates computed with GPT2W and ESA models for elevation angle of 20°. It can be clearly seen that GPT2W estimates show a smaller bias w.r.t the ESA model. Figure 2-8 shows the ZTD residuals for the GPT2w w.r.t. Gaussian distribution.

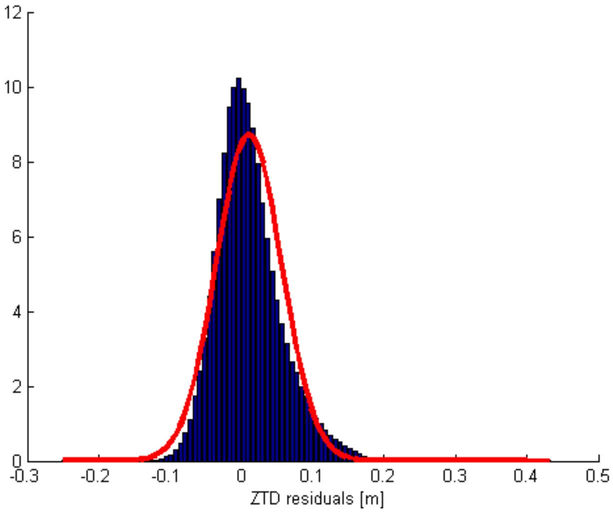

Figure 2-8: The histogram of the ZTD residuals for the GPT2 model and the fitted normal distribution

3 Conclusions

Concerning the global test cases it can be concluded that the tropospheric correction model developed in this project are able to describe globally the tropospheric delay in zenith direction with an RMS of about 37 mm (in blind mode), 31 mm (in site mode). The bias is in the both cases negligible. Most of the deviations can be allocated to the wet component while the modelled hydrostatic component deviates from the test data at the 1 cm level.

The derived slant delays in the global site mode deviate at 30^o elevation at the 1 dm level , while RMS of the slant delays at 10^o elevation reaches up to 2dm (max. 5dm) and up to 5dm at 3^o elevation (max > 1m). The numbers improve considerably in global site-augmented mode towards 5cm at 30^o elevation (max. 12 dm), 12 cm at 10^o elevation (max 30 cm) and 3 dm at 3^o elevation (max about 9 dm).

In the terms of accuracy the GPT2w overcome dramatically RTCA-MOPS and slightly current Galileo model GALTROPO.

GPT2w model errors distributed according to Gaussian distribution in the range of [-2σ;+3σ] which is better than GALTROPO ([-1σ;+3σ]), however worse than standard RTC-MOPS ([-4σ;+4σ]). The developed model is proposed to be used in various GNSS scenarios: in stand-alone user operation as an internal model of receiver, as a-priori model for post-processing GNSS measurements, in Local-Area and Satellite Based Augmentation Systems.

Comparing the RTCA MOPS, ESA and GPT2 models (in blind mode) with the radiosonde data the following results can be formulated:

- The RTCA MOPS model performs worse almost in all areas than the other two models. Since both the ESA and the GPT2 use more advanced meteorological models, the better performance can be easily justified.
- It can also be observed that GPT2 has a slightly worse performance in the equatorial region in terms of bias, while it performs better than the ESA model in higher latitudes in terms of the bias of both the hydrostatic and wet delays.
- It can be also seen that the GPT2w model improves the ZWD bias of the original GPT2 model in the equatorial region. Moreover, the ZHD bias is further improved in the higher latitude areas.
- In the site mode, the lapse rate models included in GPT2w improved the estimation of ZWD significantly with respect to the original GPT2 model. Moreover, GPT2w performs better than both RTCA and ESA models in terms of bias.
- GPT2w utilizes an individual mapping function which is superior to the regularly utilized Niell Mapping function.
- GPT2w is based on meteorological parameters and not on ZWD grids. This allows for an easy imbedding of external meteorological measurements.

In general, climatological models of the current complexity can describe the Zenith Total delay at the 3.5cm accuracy level with an insignificant bias. Ray-tracing across numerical forecast or nowcast models allows to establish the Zenith Total Delay at the 1cm level but is obviously processing and data exchange extensive.

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