Tropospheric Refraction Estimation Using Various Models, Radiosonde Measurements and Permanent GPS Data

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Key words: GPS, atmosphere, zenith troposheric delay, mapping function, Radiosonde

SUMMARY

The basic idea of this study is the estimation of Tropospheric delay with all of possible observations and methods available in the surround area of EUREF GPS station (AUT1) of the Aristotle University of Thessaloniki. The tropospheric delay is estimated in situ from three different data sources. We estimate the tropospheric delay using 3 days of GPS pseudorange observations (days 157, 158, 159 in 2005), and the Total Zenith delay derived from the EUREF analysis centre. We compare the estimated delay from the permanent GPS data with that measured from radiosonde measurements which carried out at Thessaloniki airport, located near to GPS station. In addition, the tropospheric delay is estimated using three known tropospheric models, Ifadis, Niell and Saastamoinen. The tropospheric delay from Ifadis and Niell models is computed using the corresponding mapping functions with the calculated Total Zenith delay from radiosonde data. In Saastamoinen model surface meteorological data was used.

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1. INTRODUCTION

The neutral atmosphere, calling troposphere in the next, is the lowest part of the earth's atmosphere up to about 80 km altitude. The neutral atmosphere consists of a combination of several gases. The signal propagation on this layer depends on the temperature, the pressure and the water vapour. The factor that describes the variability of troposphere is the refractive index (n), which strongly depends on space and time, the wave, trace a curve analogously to the variability of refractive index.

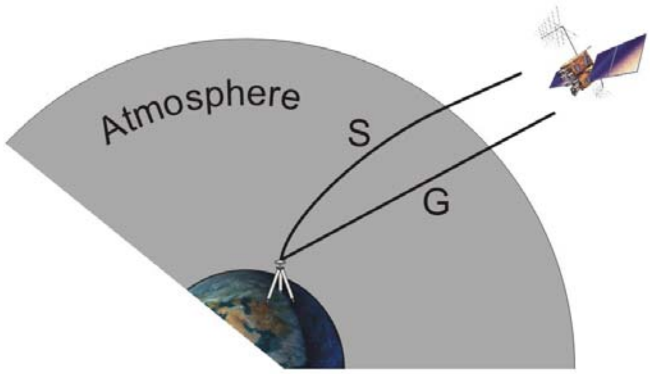

Fig. 1 Simple representation of the atmospheric effect in radiowave propagation.

$$\Delta L = \int_s n\, ds - G \qquad (1.\ 1)$$

On the above equation n is the refractive index and G is the direct path using the real length **S** of the ray path in equation 1 we get the following equation:

$$\Delta L = \int_s [n-1] ds + [S - G] \qquad (1.\ 2)$$

Where S is the length of the true ray path, n is the refractive index along the ray path S. Equation (1.2) gives the total delay of the electromagnetic wave caused by the neutral part of the atmosphere. The term [S-G] represents the difference in the distance between the straight line path G (that a radiowave could follow in the absence of atmosphere) and the real curved path S and it is called geometrical error. As long as the refractive index gets very small values it is not used in the calculations and it is replaced by another quantity, the refractivity N, that is $N = 10^{-6}$ (n-1), and Equation (1.2) gives:

$$\Delta L = 10^{-6}\int_s N \cdot ds + [S - G] \qquad (1.3)$$

The refractivity is divided in two components, the term N_h is the refractivity due to the gases of air, except the water vapour, and called "hydrostatic" refractivity and the term N_w which is the refractivity due to the water vapour and it is called "wet" refractivity, given the division of refractivity the equation (1.3) for the total delay is rewritten as:

$$\Delta L = 10^{-6}\int_s N_h ds + 10^{-6}\int_s N_w ds + [S - G] \qquad (1.4)$$

Or

$$\Delta L = \Delta L_h + \Delta L_w + \Delta L_{geom} \qquad (1.5)$$

The equation of the air refractivity is given by Smith and Weintraub (Smith & Weintraub 1953) and with greater accuracy by Thayer (Thayer 1974):

$$N = k_1\left(\frac{P_d}{T}\right)Z_d^{-1} + k_2\left(\frac{P_w}{T}\right)Z_w^{-1} + k_3\left(\frac{P_w}{T^2}\right)Z_w^{-1} \qquad (1.6)$$

The "hydrostatic" refractivity N_h and the wet refractivity N_w (due to water vapour) respectively are equal to:

$$N_h = k_1\left(\frac{P_d}{T}\right)Z_d^{-1} \quad \text{and} \quad N_w = k_2\left(\frac{P_w}{T}\right)Z_w^{-1} + k_3\left(\frac{P_w}{T^2}\right)Z_w^{-1}$$

Where,
k_1 = (77.604 ± 0.014) K/mbar
k_2 = (64.79 ± 0.08) K/mbar
k_3 = (3.776 ± 0.004) x10^5 K^2/mbar

P_d is the partial pressure of the dry air (in mbar), P_w is the partial pressure of the water vapour (in mbar), Z_d and Z_w are the compressibility factor for the dry air and the water vapour respectively. Several investigators proposed empirical models to describe the delay, especially in lower elevation angle where the delay is taken greater values, because in lower elevation angles the signal covers a longer part of atmosphere. The Tropospheric Delay in slope measures is mapped with a function, called mapping function, for each ray trace in a total delay from zenith (ZTD - Zenith Tropospheric Delay). Using the mapping function equation (1.5) is modified as:

$$\Delta L = \Delta L_h^z \cdot m_h(\upsilon) + \Delta L_w^z \cdot m_w(\upsilon) \qquad (1.7)$$

Where ΔL_h^z is the total hydrostatic zenith delay, ΔL_w^z is the total wet zenith delay, υ is the elevation angle, $m_h(\upsilon)$ is the hydrostatic mapping function and $m_w(\upsilon)$ is the wet mapping function. In 1972 Marini proposed a mapping function in a continuously fractional form as:

$$m(\upsilon) = \cfrac{1}{\sin(\upsilon) + \cfrac{a_1}{\sin(\upsilon) + \cfrac{a_2}{\sin(\upsilon) + \cfrac{a_3}{\sin(\upsilon) + \cdots}}}} \qquad (1.\ 8)$$

2. DATA AND MODELS USED IN THIS STUDY

In the present analysis we use radiosonde observations and GPS pseudorange observations from the EUREF permanent GPS station (AUT1) of the Aristotle University of Thessaloniki. Radiosounding is available twice daily and take place in Thessaloniki airport. The data is available for downloading from British Atmospheric Data Centre (BADC / Met Office). Analytically the test data covers 3 days of time span and separate to the following sets:

Observations in days 6 -8 / 6/05 or 156, 157 and 158 doy in 2005

- Radiosondes from Thessaloniki airport (BADC / Met Office).
- Troposheric zenith delay derived from EUREF analysis centre for AUT1.
- GPS P code pseudoranges from AUT1

Also, three tropospheric models with known accuracy are used and described in paragraphs 2.2 , 2.3 and 2.4.

2.1 Radiosonde data

Ray tracing technique assumes a spherically stratified and homogeneous atmosphere. In order to calculate the delay at GPS permanent station the pressure, temperature, and dew point temperature from each sonde is used. The distance between airport and AUT1 it's about 6 Km, thus we assume that the troposphere conditions are the same for two sities (Table 1).

Table. 1 Station's Coordinates

Station	**Lat**	**Lon**	**H (m)**
AUT1 – GPS station	40°34'00.54376''	23°00'13.37808''	108.50
Airport (Radiosonde station 16622)	40°31'12''	22°58'12''	8.0

To estimate the tropospheric delay we use the equation (1.4) and double exponential transform for the arithmetic integration (Nakamura, 1991).

2.2 Saastamoinen Model

Saastamoinen (Saastamoinen, 1972) computed the total delay from zenith distance z =90°-υ as :

$$\Delta L = \frac{2.277 \cdot 10^{-3}}{\cos(90^{\circ} - \upsilon)} \left(P_0 + \left(\frac{1255}{T_0} + 0.05 \right) \cdot e_0 - 1.16 \cdot \tan^2(90^{\circ} - \upsilon) \right) \qquad (2.\ 1)$$

Where, P_0 is the total surface pressure in mbar , e_0 the partial water surface pressure in mbar and T_0 the surface temperature in degrees Kelvin. The results are given in meters.

2.3 Ifadis Mapping Function

Ifadis (Ifadis, 1986, 1993) used a third order fraction form as the basis for the development of his models in the form of global and climate solutions with versions for the prediction of both the wet and hydrostatic delay.

$$m_h(\upsilon) = \frac{1}{\sin(\upsilon) + \frac{a_1}{\sin(\upsilon) + \frac{a_2}{\sin(\upsilon) + a_3}}} \qquad (2.\ 2)$$

Where **m (90) =1** by definition and the parameters, a_3 is constant and equal to 0.078 and a_1, a_2 of mapping function can estimated from surface pressures and temperature, as:

$$a_i = k_1 + k_2(P - 1000) + k_3(t - 15.0) + k_4\sqrt{e}, \quad i = 1, 2 \qquad (2.\ 3)$$

P is the total surface pressure in mbar, e the partial water surface pressure in mbar and t the surface temperature in Celsius degrees.

2.4 Niell Mapping Function (NMF)

Niell, (Niell, 1996) kept the basic form of the Herring (MTT model, - Herring, 1992) mapping function adding a height correction term and assuming that the elevation dependence is a function of only geographical parameters (if we accept that in a way the day of the year is also a constant and independent parameter) and proposed the function.

$$m(\upsilon) = \frac{1 + \frac{a}{1 + \frac{b}{1 + c}}}{\sin(\upsilon) + \frac{a}{\sin(\upsilon) + \frac{b}{\sin(\upsilon) + c}}} + \Delta m(\upsilon) \qquad (2.\ 4)$$

The wet delay parameters a_w, b_w, c_w are given at tabular latitude φ_i 15°, 30°, 45°, 60° and 75° . The hydrostatic parameters a_h , b_h and c_h at time t in UT days is calculated as:

$$a_h(\phi_i,t)=a_{avg}(\phi_i)-a_{amp}(\phi_i)\cos\left(2\pi\frac{t-T_0}{365.25}\right) \quad (2.5)$$

Where a_{avg} and a_{amp} are given at tabular latitude φ_i 15°, 30°, 45°, 60° and 75°, and the T_0 is the adopted phase, DOY 28 as described in Niell (1996).
The height correction is given by:

$$\Delta m(\upsilon)=\frac{1}{\sin(\upsilon)}-\frac{1+\frac{\alpha_h}{1+\frac{b_h}{1+c_h}}}{\sin(\upsilon)+\frac{a_h}{\sin(\upsilon)+\frac{b_h}{\sin(\upsilon)+c_h}}}\times H \quad (2.6)$$

Where H the orthometrical height in Km and
$a_h=2.53\times10^{-5}$, $b_h=5.49\times10^{-3}$, $c_h=1.14\times10^{-3}$.

3. TROPOSPHERIC DELAY ESTIMATION

The tropospheric delay is calculated from above models is compared to the one taken from the radiosonde data, which is accepted at the present study as absolute precise. In the first step we examine the behaviour of Niell and Ifadis mapping functions using zenith delay from radiosonde data. Also, the Saastamoinen zenith delay (wet and hydrostatic) with simple mapping function of $1/\cos z$ is used. Saastamoinen model is an option in many GPS software package, and is an efficient way to calculate the delay if there is no radiosonde or any precisely meteorological data. Based on radiosonde observations we compute differences between models and the radiosonde delay. The results are given in Table 2 for three typical days from 6 to 8 / 6/2005 (157, 158 and 159 of 2005).

3.1 Comparisons between Models.

We calculate the delay using the equation (1.7) and the ifadis and Niell mapping function.The zenith delays are derived from radiosonde observations

Table. 2 Comparison between models, mean values per day at elevation angle.

Model	**Elevation angle (Deg)**						
	5	**10**	**20**	**30**	**40**	**60**	**80**
DOY 157 Radiosonde	**25,913**	**13,878**	**7,187**	**4,935**	**3,844**	**2,856**	**2,512**
Ifadis	-0,718	-0,125	-0,019	-0,006	-0,003	-0,001	-0,001
Niell	-0,742	-0,115	-0,009	0,002	0,004	0,004	0,004

Saastamoinen	-2,035	-0,417	-0,165	-0,108	-0,083	-0,061	-0,054
DOY 158 Radiosonde	**25,712**	**13,755**	**7,121**	**4,890**	**3,809**	**2,829**	**2,489**
Ifadis	-0,526	-0,008	0,044	0,037	0,031	0,024	0,021
Niell	-0,815	-0,136	-0,017	-0,004	0,000	0,001	0,002
Saastamoinen	-1,652	-0,202	-0,052	-0,031	-0,023	-0,016	-0,014
DOY 159 Radiosonde	**25,432**	**13,601**	**7,041**	**4,835**	**3,766**	**2,798**	**2,461**
Ifadis	-0,794	-0,143	-0,025	-0,010	-0,006	-0,003	-0,003
Niell	-0,826	-0,134	-0,016	-0,002	0,001	0,002	0,002
Saastamoinen	-1,367	-0,046	0,029	0,025	0,021	0,016	0,014

Ifadis and Niell mapping functions show the same results. Ifadis' model gives a slightly better delay prediction in 5° elevation angle while Niell has a slightly better estimation for higher elevation angles. The Saastamoinen model gives over a meter of error in low elevation angles and a centimetre level in higher elevations.

3.2 Tropospheric Delay from GPS pseudoranges.

The basic idea on this step is to calculate the tropospheric delay from GPS pseudoranges when station coordinates with high accuracy is known, in our case from EPN solution. The pseudorange measurement (with P code) between point K and satellite i (Hofmann-Wellenhof et.al. 1997, Fotiou & Pikridas 2006) is modelled as:

$$P_K^i = \rho_{\mathrm{K}}^{\mathrm{i}} + \delta\rho_{mul} + \delta\rho_{rel} + c\delta_{\mathrm{K}} - c\delta^i + I_K^i + T_K^i + e_K^i \qquad (3.\ 1)$$

where P_K^i is the measured code pseudorange between the observing site K and the satellite i, $\rho_{\mathrm{K}}^{\mathrm{i}}$ is the geometric distance, c is the speed of light (c=299792458 m/s) I_K^i, T_K^i are the ionospheric and tropospheric delays , $c\delta^i, c\delta_K$ the satellite and receiver clock errors accordingly, $\delta\rho_{mul}$ the multipath effect for P code, $\delta\rho_{rel}$ the relativistic correction (Special and General Relativity) and e_K^i the random error. In order to calculate the tropospheric delay in station AUT1 we subtract from the pseudorange all the systematic errors and finally we have:

$$T_{AUT1}^i = P_{AUT1}^i - \rho_{\mathrm{AUT1}}^{\mathrm{i}} - \delta\rho_{mul} - \delta\rho_{rel} - c\delta_{\mathrm{AUT1}} + c\delta^i - I_{AUT1}^i + e_{AUT1}^i \qquad (3.\ 2)$$

The geometric distance $\rho_{\mathrm{AUT1}}^{\mathrm{i}}$ is calculated for each epoch using the accurate station coordinates and satellite's coordinates by:

$$\rho^i_{AUT1} = \sqrt{\left(X^i - X_{AUT1}\right)^2 + \left(Y^i - Y_{AUT1}\right)^2 + \left(Z^i - Z_{AUT1}\right)^2} \qquad (3.\ 3)$$

Where X^i, Y^i, Z^i are the satellite's position and $X_{AUT1}, Y_{AUT1}, Z_{AUT1}$ the three known point coordinates of our station in the ITRF00 system and presented in Table 3.

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Table. 3 Coordinates of AUT1 in ITRF 2000

Station	**X**	**Y**	**Z**	**System**
AUT1	4466283.420	1896166.885	4126096.780	ITRF00

The multipath effect $\delta\rho_{mul}$ is derived using Leica GNSSQC software. Ionospheric delay, satellite - receiver clock errors and the relativistic correction were calculated with NAVGPS (Papaparaskevas, 2002) software using the relevant information from RINEX navigation file. The mean delay value of each elevation angle is produced every 0,5 degrees approximately from all visible satellites.

$$T_\upsilon = \frac{1}{\mathrm{n}} \sum_{\upsilon - 0.25^\circ}^{\upsilon + 0,25^\circ} \sum_{i=PRN} T^i_{AUT1} \qquad (3.\ 4)$$

Where υ is the elevation angle and i is the PRN of available satellite in current elevation angle and n is the number of observations. For example the tropospheric delay for 40° elevation angle is:

$$T_{40^\circ} = \frac{1}{300} \sum_{\upsilon = 39,804^\circ}^{40,212^\circ} \sum_{\mathrm{i}} T^i_{AUT1} = 3,858m$$

This computation is done for satellites with PRN i=1, 3, 4, 5, 7, 8, 9, 10, 11, 13, 14, 15, 16, 18, 19, 20, 21, 22, 23, 24, 27, 28, 29, 30 and 31

Figure 2 presents the average tropospheric delay per day as a function of elevation angle for the days 157, 158 and 159. The results for the tropospheric delay using all available data/observations (from the three days 157, 158 and 159) are presented in figure 3. This scatter feature is that the delay which derived from three days (more that one) of observations are more close to those computed from Radiosonde measurements.

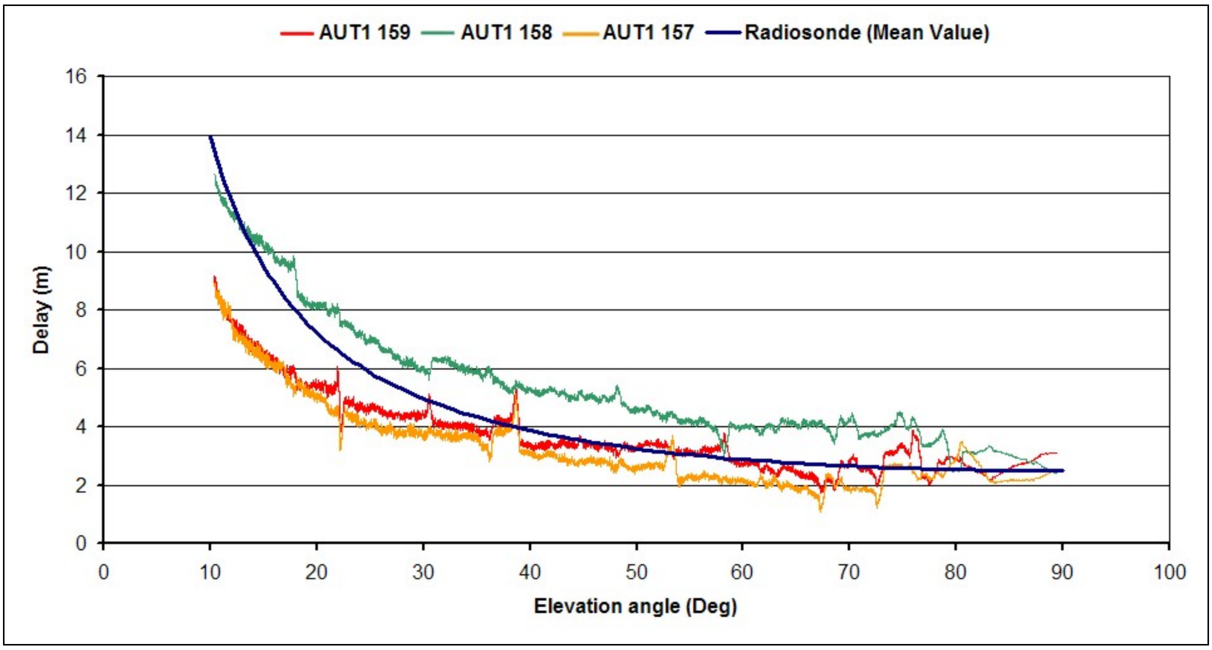

Fig. 2. Troposheric delay for days 157, 158 and 159

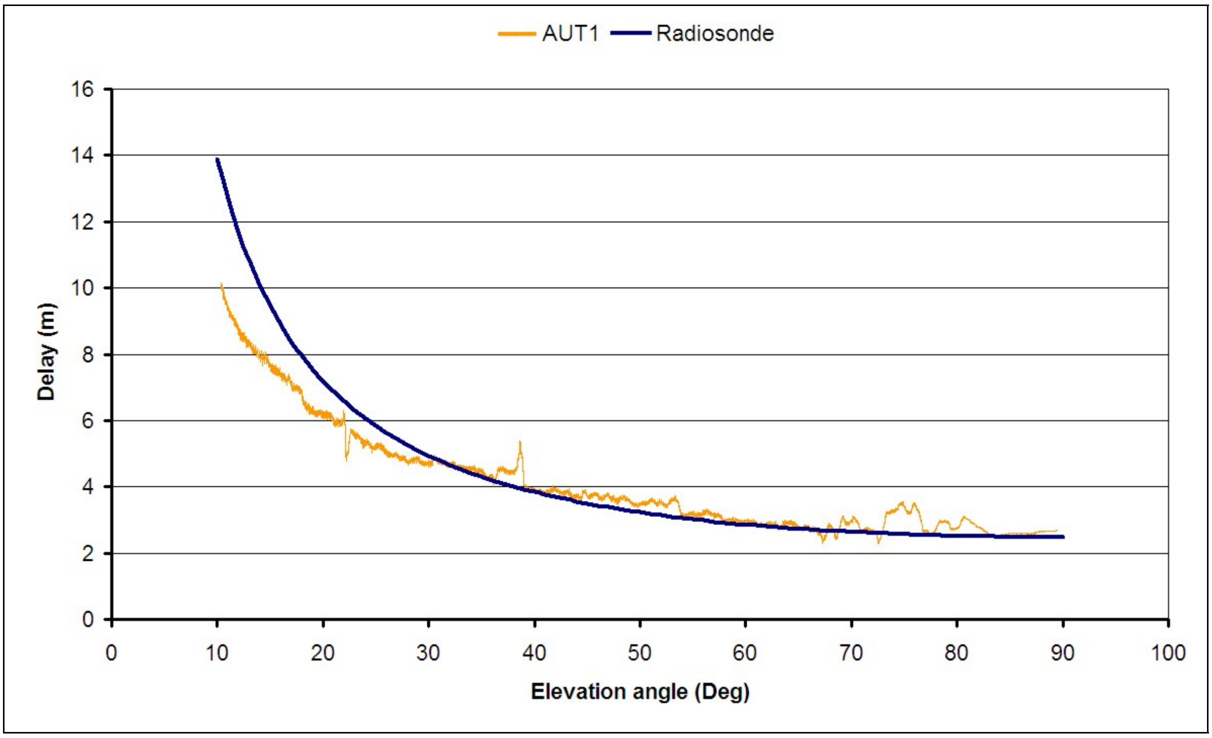

Fig. 3 Total troposheric delay from three day's observation

3.3 Tropospheric Zenith Delay from EUREF Solution.

In this step we compare the ZTD which is given from the EUREF data center with the ZTD from Radiosoundings (fig 4). The ZTD values estimated from the EUREF data center differ from those estimated from radiosonde up to 5 cm and from those of the Saastamoinen model up to 7,5 cm (Table 4).

Table. 4 Total Zenith delays.

Time	EUREF	Radiosonde	EUREF - Radiosonde (cm)	Saastamoinen	EUREF - Saastamoinen (cm)
157:18000	2,479	2,461	1,7	2,418	6,0
157:39600	2,500	2,489	1,1	2,424	7,5
158:18000	2,455	2,403	5,2	2,435	2,0
158:39600	2,506	2,475	3,1	2,432	7,4
159:18000	2,477	2,445	3,2	2,451	2,7
159:39600	2,479	2,466	1,2	2,449	3,0
159:82800	2,409	2,360	5,0	2,414	-0,4

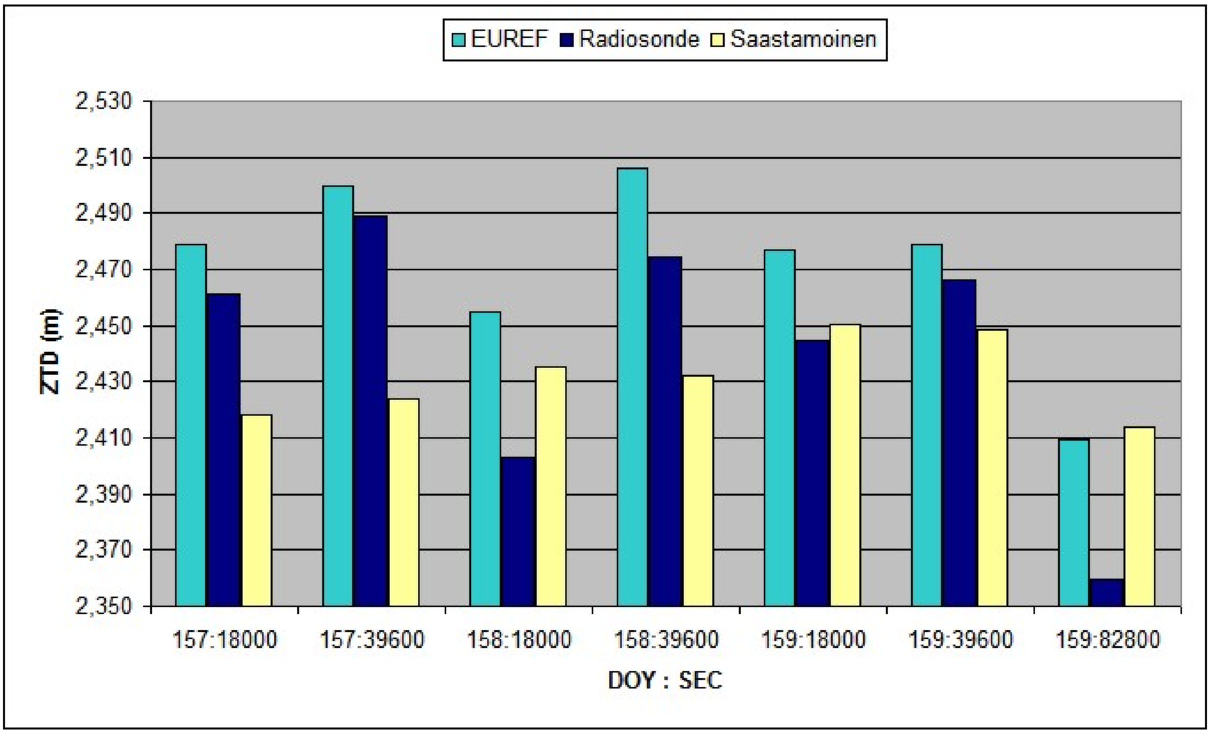

Fig. 4. Total Zenith delays.

3.4 Tropospheric Zenith Delay from Pseudoranges.

The delay in elevation angle υ is given from equation (1.7), using the simplest mapping function $m_h(\upsilon) = m_w(\upsilon) = \frac{1}{\sin(\upsilon)}$ and gives

$$\Delta L = \frac{1}{\sin(\upsilon)}\left(\Delta L_h^z + \Delta L_w^z\right) \tag{3. 5}$$

Following (Rocken, 2004) we can calculate the total zenith delay from pseudo ranges using a least squares solution where:

$$\hat{ZTD} = (\mathbf{A}^T \cdot \mathbf{P} \cdot \mathbf{A})^{-1} \mathbf{A}^T \cdot \mathbf{P} \cdot \mathbf{b} \tag{3. 6}$$

With arrays

$$\mathbf{A} = \begin{bmatrix} \frac{1}{\sin(\upsilon_1)} \\ \frac{1}{\sin(\upsilon_2)} \\ \vdots \\ \frac{1}{\sin(\upsilon_n)} \end{bmatrix} \quad , \quad \mathbf{b} = \begin{bmatrix} T_{\upsilon_1} \\ T_{\upsilon_1} \\ \vdots \\ T_{\upsilon_n} \end{bmatrix} \quad \text{assuming} \quad \mathbf{P} = \mathbf{I}$$

The troposphere delay T_{υ_i} is the average value according to equation (3.4) from all available satellites for all days. The ZTD is calculated only from the delays from elevation angles above 30° because the error in low elevation angles show high values (approximately 1-4 meters).

	ZTD (m)	**RMS (m)**	**SDev (m)**
AUT1 (Pseudoranges)	2,603	0,018	0,135

As a first approach we compare it with those estimated from the other methods and the computed differences varied from 13 to 17 cm.

	Pseudoranges	**EUREF**	**Saastamoinen**	**Radiosonde**
ZTD (m)	2,603	2,472	2,432	2,443
Difference (Pseudoranges- model)	-	-0,131	-0,171	-0,160

4. CONCLUSIONS

Estimation of the tropospheric delay is a crucial factor for accurate point positioning. Analysing 3 days of observation data we conclude that the zenith tropospheric delay derived from EUREF solution is given with high accuracy (1 cm approximately) and can be used with out any meteorological data. For any station not included in EUREF network the tropospheric delay can be computed using Niell or Ifadis mapping functions together with Saastamoinen ZTD with sufficient accuracy. At 5° elevation angle ifadis mapping function show a better behaviour than Niell while Niell mapping function show better results for elevation angle 20° and greater. On the other hand if surface meteorological measurements are not available we can produce a ZTD but with a limited accuracy, in our case was about 13-17 cm, using P code pseudoranges. This modelling could be useful for GPS code applications. As it concerns the Saastamoinen model it's a good and accurate method to compute for zenith tropospheric delay if surface meteorological data is available.

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