Péter Braunmüller: The evaluation of troposphere models applied in the Hungarian Active GNSS Network

Abridged version of my MSc degree thesis at the *Budapest University of Technology and Economics* written in 2011; the thesis defence was in January 2012. The thesis was written in the *Satellite Geodetic Observatory* of the *Institute of Geodesy, Cartography and Remote Sensing*.

1. Introduction

The GNSS (**G**lobal **N**avigation **S**atellite **S**ystem) technique is the second most widely used space-born application after telecommunications. The absolute accuracy of single point positioning is about 2 – 10 m, depending on the user equipment. It is caused by unmodelled or imperfectly modelled GNSS errors including satellite-, and receiver clock biases, errors of the broadcast satellites orbits, the effect of the atmosphere (ionospheric effect on the signal propagation and delays caused by the troposphere), multipath effect, phase center variation (PCV) of the transmitting and receiving antennas, etc. In several fields (e.g. surveying/geodesy/geodynamic investigations) more precise positioning is required, so the accurate modelling of the error budget is necessary. To be able to carry out GNSS measurements with centimetre accuracy additional information from some forms of augmentation systems are required. Such corrective information can come for example from ground-based augmentation systems, which consist of permanent stations observing 24 hours a day.

In Hungary the GNSS Service Centre established and maintains a system – modelling the error budget – consisting of 35 Hungarian stations extended with 19 stations integrated from the neighbouring countries. On the basis of the permanent station's observations real-time services provided for the whole area of Hungary. Using network RTK solutions (FKP, MAC or VRS can be chosen) centimetre level accuracy can be achieved. Beside that the registered users can get real-time single base RTK and DGNSS corrections in different formats and can also download RINEX or Virtual RINEX data for post-processing. (*www.gnssnet.hu*)

2. Troposphere modelling

Troposphere is where the inhabitants of our planet live, it starts on the surface of the Earth and goes up to height of 9 to 18 km. The depth of it varies with the latitude, it is greatest at the equatorial regions (approximately 18 km) and minimal near the poles (about 9 km). Approximately 75-80 % of the mass of the whole atmosphere is in the troposphere including nearly all water vapour (about 99%) and dust particles. (*Russel,* 2010) The refractive index – showing the ratio of the vacuum speed of light and the real speed of the signal – is always bigger than 1. It means that the signals emitted by the satellites reach the receiver later, therefore a greater satellite-to-receiver range is measured. Troposphere is a non-dispersive medium for radio frequencies below 15 GHz, hence its effect is independent of GNSS frequencies. It causes delay in both GNSS carrier and code observations. (*Ádám-Rózsa, 2011*)

The value of the delay caused by the troposphere basically depends on the followings: air-pressure, air temperature and the partial pressure of water vapour. It can be separated into two parts: hydrostatic and wet part. Although the wet part is only approximately 10 % of the total value it can be derived less accurately, because it varies quickly with the change of the amount of water vapour. The average total zenith delay in Hungary is about 2.3-2.4 m. The modelling of the troposphere is based on the above mentioned factors. (*Ádám-Rózsa, 2011*)

During my evaluations I dealt with the following models: Hopfield model, Black model, Saastamoinen model, Niell model and the Global Mapping Function (GMF). The first two models derives nearly the same values for the hydrostatic part, the difference is less than 1 %. The deflection is greater in case of the wet part, because the Black model uses average values depending on the climate and season. For the continental climate area (just like Hungary) the value of the wet delay is only defined for winter, so I calculated the average monthly wet delays on the basis of radiosonde measurements performed at Budapest and Szeged every day (*Figure 1*). I used these values for further evaluations.

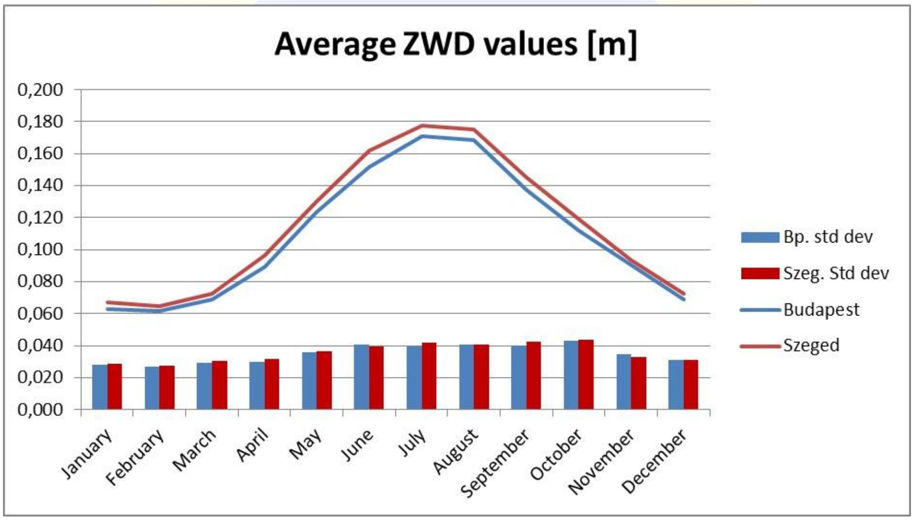

Figure 1 – Average monthly zenith wet delay values

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Both Hopfield and Black models calculate the zenith delays, but not the delays for the direction of the satellite. To get these values a mapping is required. The mapping functions handle the dry and wet parts of the delay separately. However the Saastamoinen model gives directly the delays in the satellite direction as a fraction of the zenith angle. As input parameters it also needs the air-pressure, the air temperature and the partial pressure of water vapour. The Saastamoinen model has a modified or refined version having two additional correction factors. The effect of them is very small, therefore these are rarely applied. (*Ádám-Rózsa, 2011*)

The so called Niell model is a mixture of the Saastamoinen model and the Niell Mapping Function (NMF). In the troposphere model the dry and wet components are separated and calculated for the zenith direction. The second step is the estimation of the satellite direction tropospheric delay with the NMF. There are two slightly different versions of this model. One is depending on the day of the year (DOY) and the other is independent of it. (Note that it does not cause significant offset.) The Global Mapping Function (GMF) is very similar to the NMF but the coefficients are calculated in another way. (*Boehm et al., 2006*)

Beside the troposphere models described here shortly, the Vienna Mapping Function (VMF) is also notable, but during my evaluations I could not deal with it.

Note that the satellite direction delays derived from these troposphere models only depend on the elevation angle and not on the azimuth, so it assumes that the atmosphere is symmetric around the stations.

3. Description of the performed evaluations

During my evaluations I compared the zenith delay values estimated by the networking software of the Hungarian Active GNSS Network (GNSSnet.hu) using various troposphere models to results of a priori models, two processing with Bernese and with values derived from radiosonde measurements. In case of the a priori models the input meteorological data stemmed from the ground observations taken during the launch of the radiosonde. One of the processing carried out with Bernese was a near real-time solution, where the total zenith delay values are calculated using observations of the previous 12 hours of 86 permanent stations (including nearly all stations of GNSSnet.hu). (*Rózsa et. al., 2011*) The other processing if carried out by the SGO Analysis Centre of EUREF. In both cases the delay values were available in hourly resolution and estimated using Niell troposphere model.

Radiosonde is a small and light (usually weighting 250 g), expendable package of sensors measuring various atmospheric parameters. These parameters are: temperature, air-pressure, dew point and a few others. It is attached to a weather balloon and rises up at least to 20 km. The collected data are sent back on radiofrequency. Every day approximately an hour before 00:00 and 12:00 UTC (official observation times) radiosondes are launched from hundreds of meteorological sites globally. (*Dabbert et al., 2002*) In Hungary only one sonde is launched a day to reduce the costs, because after falling back to the ground these instruments are usually never discovered. One radiosonde cost about 160 €, plus the launching and data collection has extra charges. In Hungary Vaisala RS92-D radiosondes are used, which provided the best performance on the *WMO Intercomparison of high quality radiosonde systems* in 2010 (*Nash et. al., 2011*). Beyond the measurements of the radiosonde, surface observations are made in part of the launch procedures.

The basis of the comparison was the zenith total delay values (ZTD) and in some cases the two separated parts of the delay. I used the networking software of GNSSnet.hu in a post-processing mode, which meant that a network simulation is carried out using the observations of 21 permanent stations (*Figure 2*). The tropospheric delay values were saved in a 2 minutes resolution. The test network was set up around Budapest and Szeged (two cities where radiosonde measurements are performed in Hungary). I also tested two smaller separate networks around the two cities, but that solution had a less reliable result. (In some cases there has been approximately 5 cm error of ZTD.)

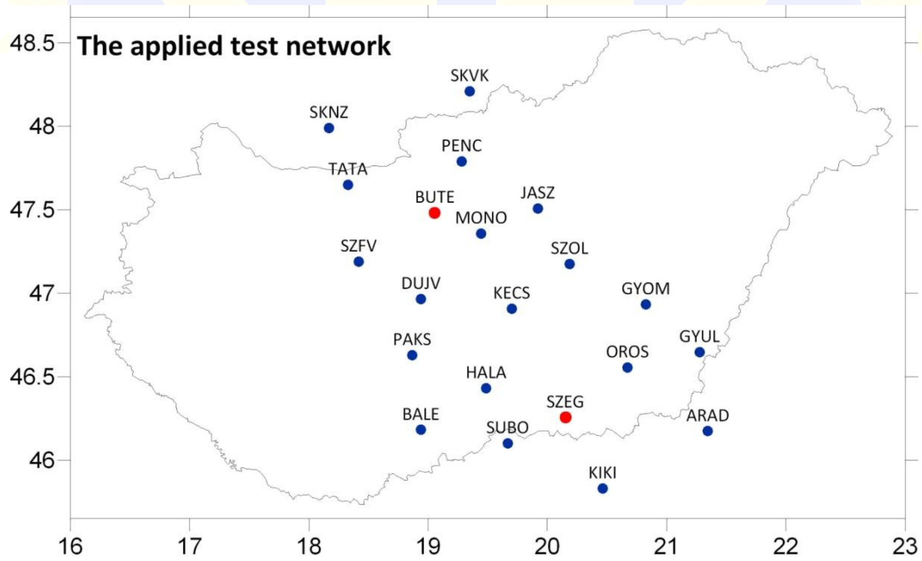

Figure 2 – The applied test network

I have investigated the performance of the various troposphere models in two test periods. The first period was at the middle of April 2011, when several heavy, but local storms occurred, especially around the capital city of Hungary. During the test I post-processed the data of network stations starting at 21:00 UTC and finishing at 01:00 UTC the next day. I did this because I was mainly interested on the differences between the estimated ZTD values of the test network and the zenith total delays derived from radiosonde measurements. The second, shorter test period was a weekend at the end of July 2011, when a new maximum of daily rainfall was recorded in Hungary. The rainfall during 24 hours was more than 100 mm in the Eastern part of the country on 30 July. (In comparison, the earlier measured maximum was 77.8 mm in 1969.) During this second test period I post-processed not only the late evenings like earlier, but the whole days as well. I started it on 27 July at 21:00 UTC and finished on 31 July at 01:00 UTC. With this solution I could get a better view of the troposphere changes caused by the actual weather.

Before the comparison of ZTD values from different resources, the data considered as reference had to be analyzed. In case of the radiosonde measurements the data can be corrupt if the sonde cannot fly up to the height of 21 km. It can cause decimetre level error in the ZTD values. In case of the Bernese solutions I investigated the ZTD differences between them. The usual offset was very small, during the investigated periods the maximum offset was 1.2 cm. Presumably it is caused by the different ephemeris data and station coordinates used by the two solutions. Additional difference can originate from the epochs of the known ZTD values.

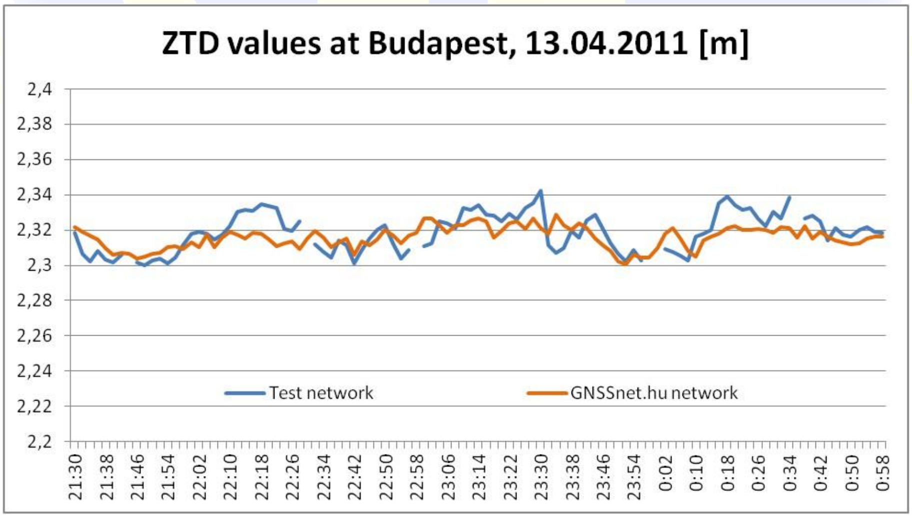

Figure 3 – ZTD values at Budapest, 13.04.2011

I compared the ZTD estimated in post-processing method with the real-time estimation of GNSSnet.hu to see if there is any error in the method of the tests. Part of this comparison is showed only small differences (always less than 2 cm), which can be caused by the slightly different input data, but all together the two values had a good conformity (*Figure 3*).

4. Results of the test periods

Comparing the ZTD values of radiosonde measurements and the networking software of GNSSnet.hu in the first test period it can be seen that the trends are the same for all models but the modified Hopfield/Black model gives systematically 2-4 cm greater values than the others, which perform the calculations on the basis of the Saastamoinen model (*Figure 4*). It is interesting to see that the Niell model without day of year dependency and the Global Mapping Function perform very similarly. It is due to the fact that the main difference between these models is in the mapping function, which is the reduction of the zenith delays to the elevation of the satellites. Notable difference between the two Niell models occurred only once at Szeged, where there was rain unlike in the capital city. The greater differences experienced on the rainy days at BUTE can be caused by the approximately 10 km distance between the permanent station and the launch site of the radiosonde. (In comparison at Szeged this distance is much smaller.) On those days there was a strong wind which could cause a great drift in the flight of the radiosonde. Note that the relative ZTD values were greater than the radiosonde measurements when there was rain over the whole network. The absolute values had a relevantly bigger offset on 13 April at Budapest when rainfall was just west of the test network.

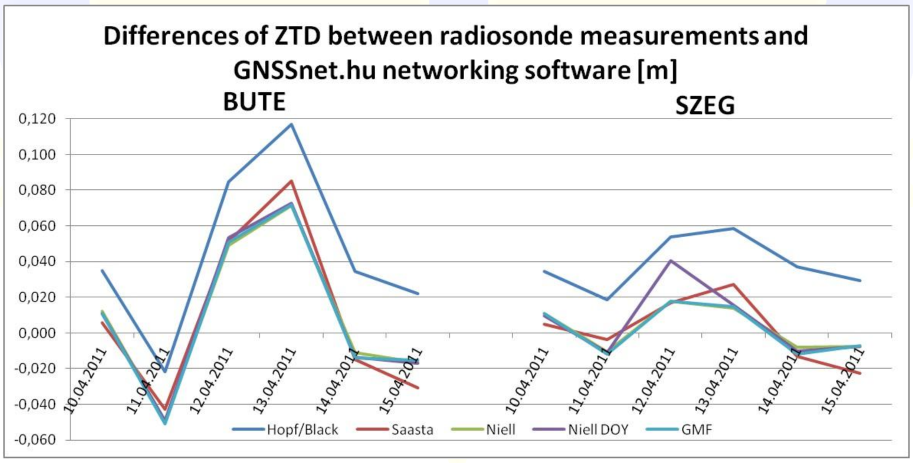

Figure 4 – ZTD differences between radiosonde measurements and GNSSnet.hu networking software

If we compare the delay values estimated by the networking software and Bernese (EUREF solution) the same trend appears (*Figure 5*). It is notable that this time the differences are smaller than earlier. The Niell models and the GMF had the least offset. This can be caused by the fact that the input data was nearly the same for the two GNSS software packages and Bernese also use the Niell troposphere model. The Saastamoinen model also showed a quite good conformity and the Hopfield/Black model had the greatest differences.

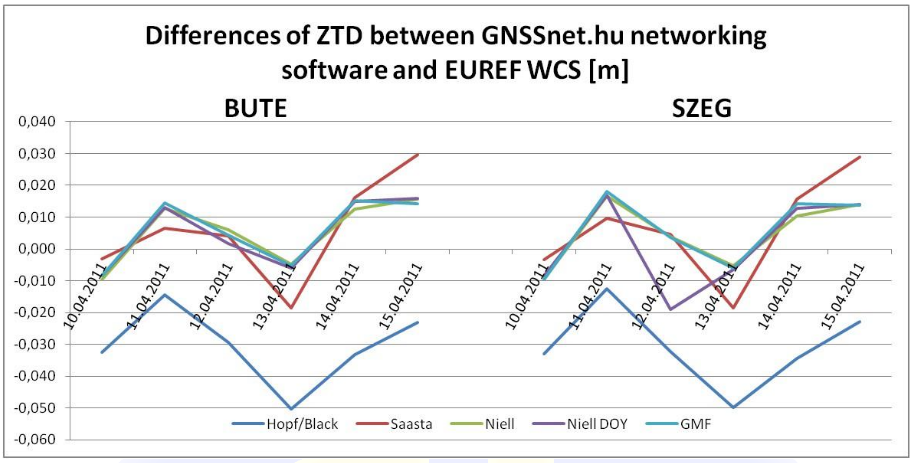

Figure 5 – ZTD differences between GNSSnet.hu networking software and EUREF solution

I compared the results of the networking software to the values of the a priori models (Hopfield, Black, Saastamoinen and the modified Saastamoinen as these give zenith delays in closed formulas). The Hopfield and Black were compared to the modified Hopfield/Black model and the Saastamoinens to each other. The Hopfield- and the Saastamoinen-based models gave very similar results and the trends were always the same. The Saastamoinen model in the networking software gave almost always smaller differences compared to the matching a priori model than the Hopfield/Black model. It is interesting that the latter offset was significantly smaller when there was rain over the whole test network.

I also compared the delay values calculated with a priori models to radiosonde measurements. This comparison is especially interesting, because the hydrostatic and the wet part of the delay can be analyzed separately (*Figure 6*). Even the wet part is only approximately 10 % of the dry delay, the calculation of the latter is less reliable as it quickly varies with the actual weather. That is why greater differences occurred in the wet part in comparison to the values of radiosonde. It is also interesting that all models calculated nearly the same values for the wet part except for the Black, which uses pre-defined values for the zenith wet delays. On rainy days the zenith wet delays of the radiosonde were greater than the a priori models and the opposite can be noticed on the days when there was no rainfall. The wet part of the Black model was always smaller than the wet part of the other models. This trend suggests that during the test period the amount of water vapour in the troposphere was not typical for April.

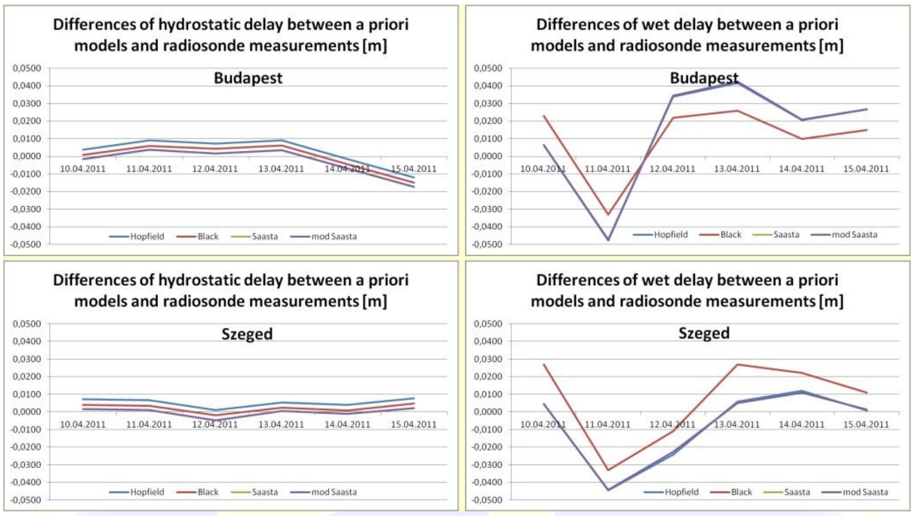

Figure 6 – Tropospheric zenith delay differences between a priori models and radiosonde measurements

During the second test period (end of July 2011) I did not focus only on the time of radiosonde measurements but processed the whole days. This way I could get a better overview of the weather changes and could compare longer periods. I also made the same comparisons like in case of the first test period, described earlier. Even the meteorological circumstances were different the two periods showed quite the same trends, therefore not described here in details.

This longer analysis was disturbed by a probably false measurement of the radiosonde deployed near Szeged on 28 July, because it resulted in a zenith total delay 15 cm less than the values calculated by the Bernese software or with the a priori models. This error is in the wet part of the delay, because the hydrostatic part of the zenith total delay is within 1 cm of the values of the a priori models.

Analyzing the differences between the models applied in the networking software of GNSSnet.hu and the solution of Bernese and the radiosonde measurements there are no major differences. On *Figure 7* the arrival of a Mediterranean cyclone can be seen on the afternoon and evening of 28 July. On 30 July as the amount of rain decreased a several centimeters difference appeared between the estimation of the networking software and Bernese. The trend was the same at Szeged also. On the longer time series graph no significant difference can be seen between the two types of Niell model and the Global Mapping Function. Usually the modified Hopfield/Black model resulted in smaller zenith total delay values than the others and in several cases the Saastamoinen model derived greater values. These periods were usually before the rain.

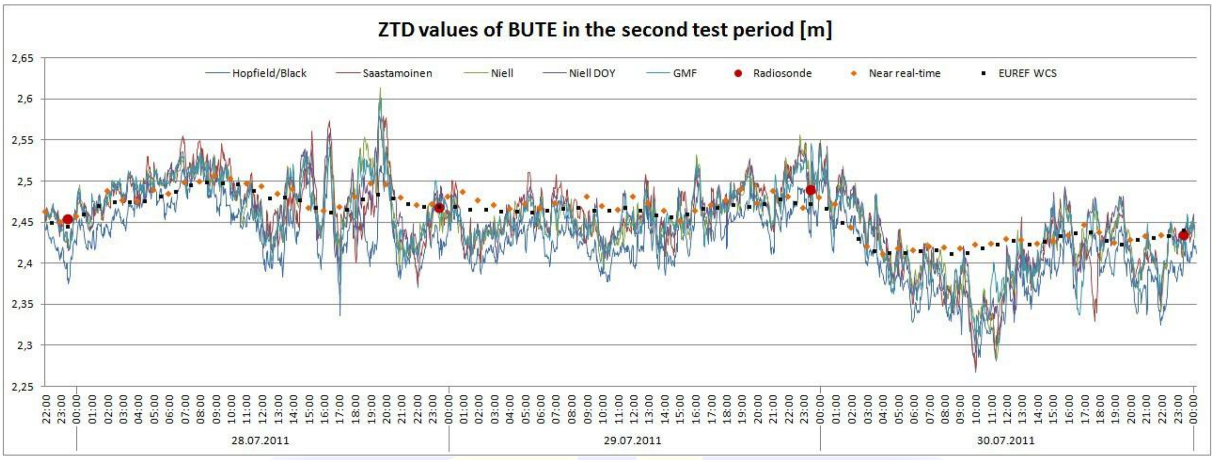

Figure 7 – ZTD values in the second test period, BUTE

After 29 July midnight (00:00 UTC) the quantity of rain decreased and after 07:00 there was rain only east of the network. At the same time the zenith total delays decreased. During the period when the difference was remarkable no rain fell over the test network. This difference decreased as the persistent rain moved eastwards and a few local, but quite heavy storms appeared in the southwestern part of the network. This figure also shows that the difference between the ZTD values of the near real-time solution and the EUREF weekly combined solution are small and usually the latter gives the smaller values. These differences are possibly caused by the different satellite ephemerides and station coordinates used in the two processes.

5. Analysis of long time series of Niell model

As the Niell model is applied in the GNSSnet.hu real-time network, I could analyze the performance of it compared to radiosonde measurement in a longer time period. For every day I calculated the average ZTD values of the real-time estimation (the sampling rate was 2 minutes) for the flight time of the radiosonde (one hour starting at 23:00 UTC). There is a seasonal fluctuation in the zenith total delay values; the differences are usually smaller in the winter and greater in the summer (*Figure 7*). This variation shows a good conformity with the amount of precipitation over Hungary.

During the analysed 1014 days the differences of the absolute values exceeded 10 cm only 7 times, which is less than 0.7 %. Three of these occurrences were probably caused by the error of the radiosonde measurements. The average difference and the standard deviations were less than 2 cm in case of both stations. These values prove that the Niell model can perform well under various meteorological circumstances for a long time and in the Hungarian permanent network it can provide reasonable accuracy.

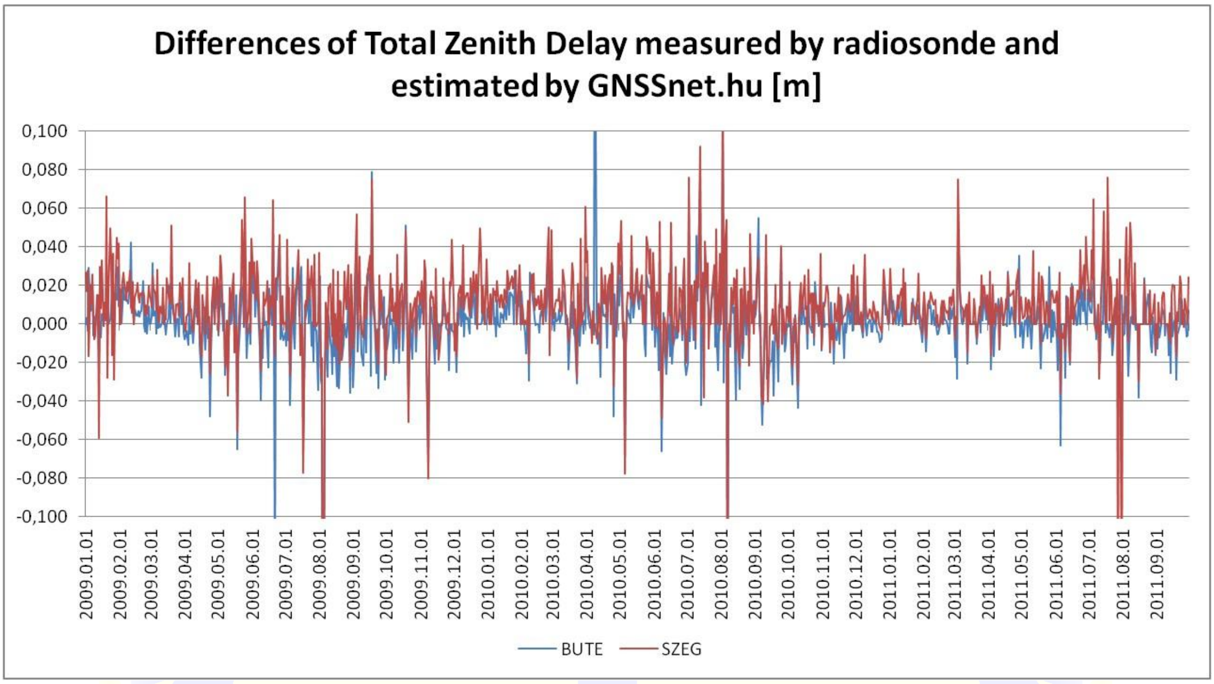

Figure 8 – ZTD differences between radiosonde measurements and real-time estimation of GNSSnet.hu

6. Feasibility of the test network

I investigated the feasibility of the test network extension using stations of the EUREF Permanent Network (EPN). (Four of the Hungarian stations are part of the EPN.)

Every station added to the post-processing test network had to have 1 Hz data, because some of the post-processing options require it. (1 Hz data means that the input RINEX file should contain observations for every second.) Less than half of the EPN stations (49 %) provide 1 Hz data in real-time, but none of the stations of neighbouring countries. In my opinion the data of permanent stations several 100 kilometres away from Hungary would not have a significant effect on the tropospheric zenith delay estimation especially in case of the stations in Budapest and Szeged, examined in details. Without the required 1 Hz data the extension of the test network is not possible, therefore the effect of a widely extended network was not investigated in the thesis.

7. Summary

During my diploma work I tested various troposphere models applied in the networking software of GNSSnet.hu. I compared the zenith total delay estimates to radiosonde measurements; and analyzed the performance of various a priori troposphere models; plus I compared all of these delays to the results of a near real-time process and with the EPN combined solution carried out with Bernese.

In the first test period greater absolute differences occurred between the estimation of the networking software and the radiosonde measurements. These can be in connection with the increased wind speed observed at both sites of radiosonde launch on 12 and 13 April, when the greatest differences occurred. The results compared to the EUREF weekly combined solution did not show significant differences.

The various a priori models gave nearly the same values for the hydrostatic part of the tropospheric delay, with a constant offset to each other. Greater differences appeared in the calculation of the wet part. Here the Black model was the least reliable, although the monthly pre-defined values were computed on the basis of the radiosonde measurements.

According to these evaluations, the Niell model is a reasonable choice. The application of the Hopfield, the Black or the Saastamoinen model is not advised, because these showed greater differences in comparison to the reference data. Usually the two types of the Niell models provided nearly the same results. The detailed investigation of the Niell model based on the archived data of GNSSnet.hu real-time processing showed a seasonal fluctuation in the residuals of the comparison with radiosonde measurements. The average difference was less than 2 cm at both sites. As the Global Mapping Function derived nearly the same ZTD values as the Niell models, further investigation is needed to determine whether the application of it is worthwhile.

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