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Precise Point Positioning with GPS data and some of its applications

Theses of the PhD Dissertation

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Background

Our country has well based geodetic system. It has a quite dense control network since decades, and a fully operational active GNSS network since ~10 years, which consists of more than 30 permanent GNSS stations. Thus in this area the double-difference positioning spread, because one can use these permanent stations as a reference point. In my studies, I started to examine the Precise Point Positioning (PPP) technique, which is quite a new field in satellite positioning. PPP does not require such a well-developed GNSS infrastructure. Nowadays this method has been used in territories lacking an appropriate control network, in offshore surveys and in the orbit determination of low Earth orbiter satellites.

The positioning using the double differenced phase ranges could be realized more easily than PPP, because it does not require the knowledge of all of the errors caused by different effects. This method summarize all of these effects into a lump sum. When the receivers are close to each other, this lump sum has somewhat the same value, therefore it can be eliminated with the differencing technique. The scientific literature calls it Observation Space Representation (OSR).

In the case of PPP we have to know all of these disturbing effects. The scientific literature calls this approach the State Space Representation (SSR). The modelled systematic error sources are (in the order from the satellite to the receiver): the differential code biases, the error of the satellite clock, the exact position of the satellite, the effect of the ionosphere and troposphere finally the phase centre offset and phase centre variations of the antenna. In order to consider all of these effects correctly, we have to use some precise products from a global organizations (eg. IGS – International GNSS Service, CODE – Center of Orbit Determination in Europe, NOAA – National Oceanic and Atmospheric Administration) or we have to produce it ourselves.

Objectives

My theses focuses on the neuralgic points of the PPP technique, and I examine theirs effects to the achievable accuracy. Thus the main objectives are:

- Evaluation of the precise orbit products (Ultra Rapid, Rapid, Final – IGS)
- Determining the minimal observation time regarding to the achievable accuracy
- Ionospheric effects on single-frequency observations. Introducing different ionosphere models to the PPP processing
- Examining different troposphere models regarding to the achievable accuracy and reliability in extreme meteorological conditions.
- Processing kinematic data with high accuracy on territories without suitable geodetic control network.

During the investigations I used the Swiss Bernese v5.0 scientific GPS software. To estimate different parameters during the processing (not only the coordinates) I created the appropriate scripts. Additional data is required to the processing, which were obtained from the following organizations:

- International GNSS Service (IGS) provided me with the investigated observations of the European permanent stations, the precise orbit and satellite clock parameters, the different code bias data and the earth rotation parameters.
- FÖMI Satellite Geodetic Observatory (SGO) provided me with the observation of the Hungarian national permanent network, and the proper station coordinates.
- European Permanent Network Central Bureau (EPNCB) and Institut Géographique National (IGN) provided me with the proper ITRF coordinates of the European permanent stations.
- To avoid the effect of phase center offset and phase center variation, the National Geodetic Survey (NGS) from National Oceanic and Atmospheric Administration (NOAA) provided me with the calibration data to every used type of antenna.
- Hungarian meteorological data were provided by the National Meteorological Service (OMSZ).
- Additional essential data to the processing were provided by the University of Bern (developer of Bernese).

Thesis 1.

I evaluated the available precise orbit and clock products and their usability. I determined that positioning with geodetic accuracy using Ultra Rapid orbit data would be feasible, because the difference compared to Final orbits were under 5 cm. The Ultra Rapid clock data has the standard deviation of 0.3-1.3 nanosecond (~10-40 cm), therefore geodetic accuracy cannot be achieved with these clock corrections. In Rapid products both of the orbit and clock data provide less than 5 cm difference compared to Final products. Thus the application of Rapid orbit solution is appropriate for geodetic positioning, furthermore this solution is available much sooner (in 17-41 hours) than the Final (in 8-17 days) products.

I evaluated the necessary duration of the observations, too. My results showed that the minimum two hours of observation is needed, without any cycle-slip, in order to have coordinates with an accuracy better than 5 cm. Longer observation time does not decrease the standard deviation of the coordinates, but we have a better opportunity to avoid the effects of a cycle-slip.

To evaluate the orbit and clock products I choose 3 different days with approximately 2880 data in each day (~30 satellites/15 minutes).

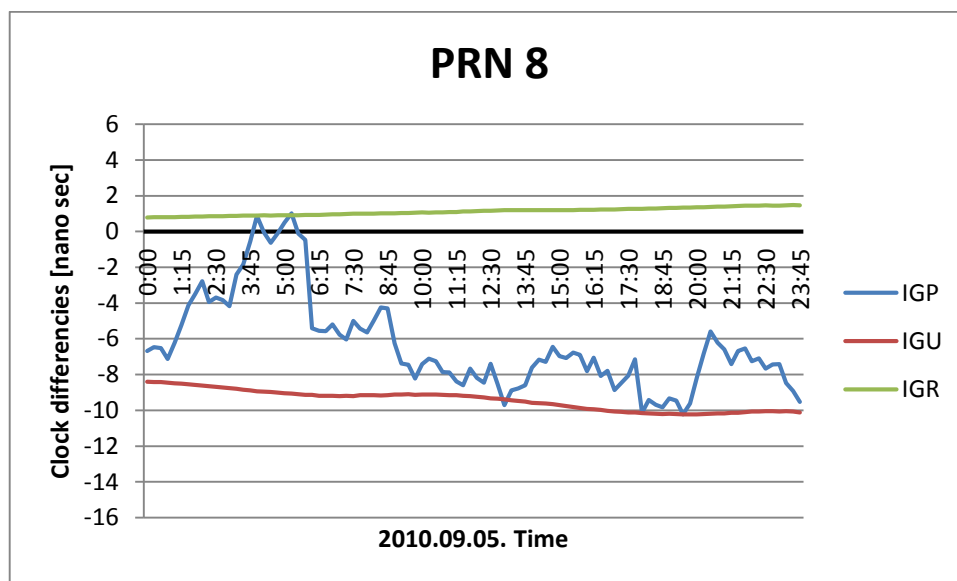


Figure 1. Clock differences compared to Final clock data on the given day

After the observation, the precise products are published in different time. One have to wait for the most proper Final (8-17 days) products, or using Rapid (17-41 hours) perhaps Ultra Rapid data (real time or near real time) is enough to reach geodetic accuracy. Instead of the differences of clock values, their high standard deviations cause more problem during the processing. The result show, that Rapid products can be used successfully, thus the waiting time for precise products is highly decreasing.

To determine the minimum observation time in order achieve the geodetic accuracy, I processed different precise orbit and clock products (Final (IGS and IGF), Rapid (IGR) and Ultra Rapid (IGU

– near real time (based on observations) and IGP – real time (modelled part), clock data with 5 minute resolution (IGS, IGR, IGU and IGP) and clock data with 30 second resolution (IGF)). Coordinates from processing daily observations were compared to their proper ITRF coordinates. The differences were in order of some millimetres

After the daily data process I started to decrease the observation time to 24, 22, 20,...3, 2.5, 2, 1.5, 1, 0.5 hours. The results of the coordinate differences are shown on Figure 2., the standard deviations can be found on Figure 3.

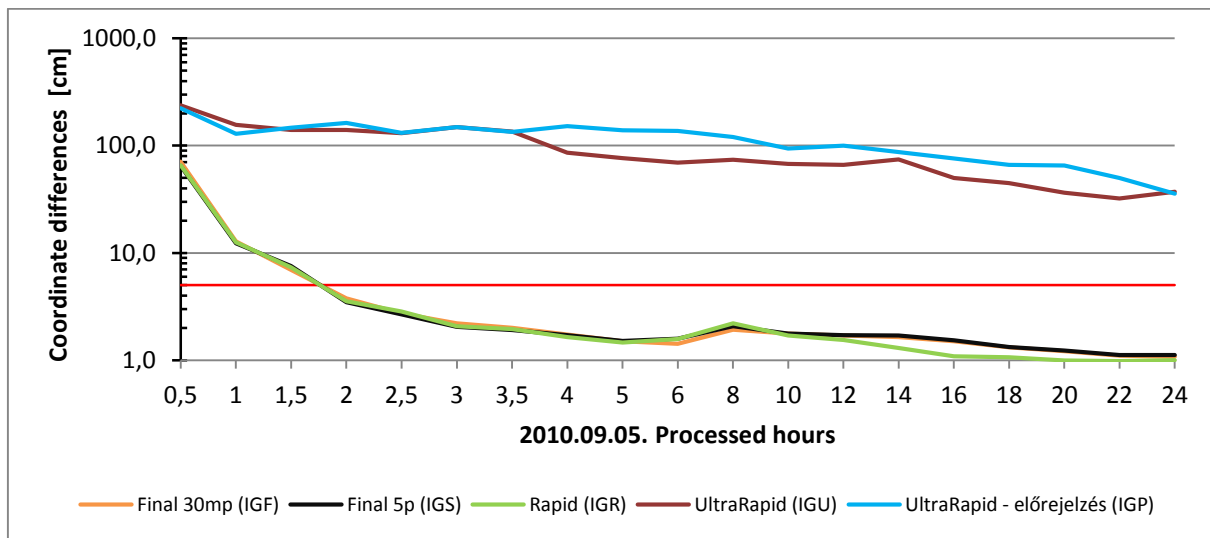


Figure 2. 3D coordinate differences [cm] compared to the proper ITRF coordinates with each precise products in a function of observation time

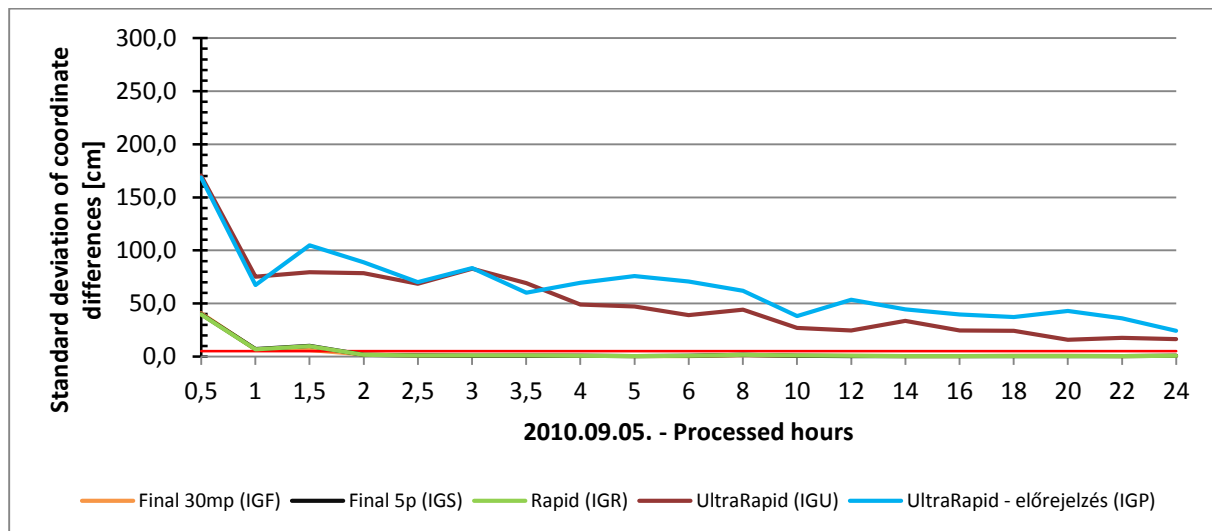


Figure 3. Standard deviation [cm] of coordinate differences in a function of observation time.

The minimum required observation time for a geodetic positioning is two hours according to the results. Increasing the observation time will not increase the standard deviation significantly. It must be noted that increased observation time provides better opportunity to avoid cycle-slips.

Thesis 2.

I evaluated different ionosphere models using single-frequency observations. I created local ionosphere models based on the code measurements of 52 permanent stations of the Hungarian active network. Using these local models I successfully processed permanent station observations in a distance of 1300 km in East-West direction. Coordinate differences after processing single-frequency measurements without any ionosphere model were in the order of 2-3 metres. Introducing these local models these residuals decreased to a 30-40 cm and in some cases to a 10-20 cm level. Based on these results I proved that geodetic accuracy cannot be achieved using single-frequency receivers in PPP applications, but using local ionosphere models the accuracy can be increased to a submeter level.

My objective was to increase the accuracy of single-frequency (L1) observations introducing different ionosphere models.

Generated/used ionosphere models:

- Local (derived from 52 Hungarian permanent stations – figure 4.)
- Global (published by CODE based on worldwide IGS permanent stations)

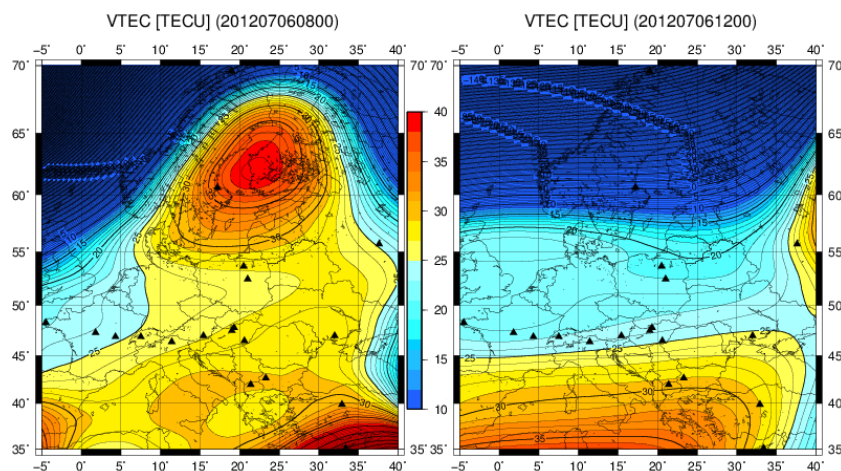


Figure 4. Ionosphere map derived from the code measurements of the Hungarian active network and their gross errors due to the extrapolation

I analysed permanent stations observations taken at different stations with an increasing distance from Hungary. I examined the efficiency of the ionosphere-free (L3) linear combination, the single-frequency (L1) observations without any ionosphere model, the L1 observations with local ionosphere model (L1 – local) and the L1 observations with global ionosphere models. The coordinate residuals between my process and the proper ITRF coordinates are shown on Figure 5.

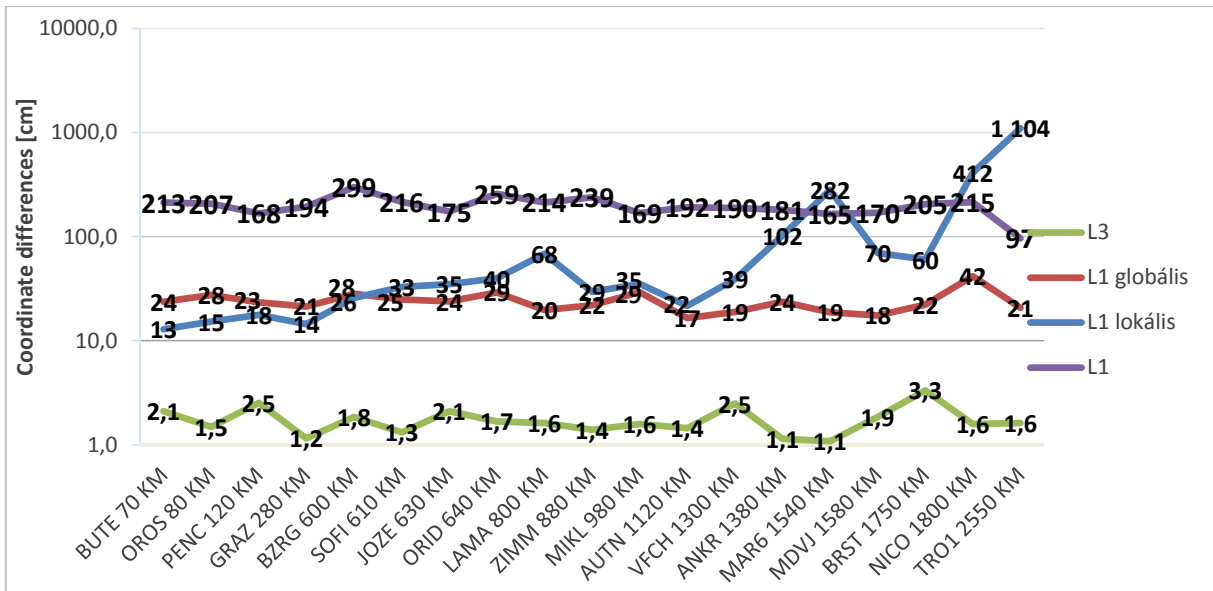


Figure 5. Coordinate differences compared to ITRF in each cases [cm] in a function of distance (logarithmic scale)

The L3 ionosphere-free linear combination provides the geodetic accuracy (~2 cm) unlike the L1 case (2-3 m), where no ionosphere model were used. Introducing global models these differences can be decreased to a 30 cm level (with ~10 cm standard deviation). Using local ionosphere models, the results can be divided into three sections. **1.:** Under the concerning area of the local model coordinate differences can be decreased under 20 cm (with the standard deviation of ~10 cm). **2.:** Increasing the distance from the local model, the coordinate residuals could be improved to te level of 30-40 cm (with ~20 cm standard deviation). These results could be achieved up to 1300 km in East-West direction, while the respective distance in North-South direction was 640 km, because the ionosphere total electron content depend on the magnetic latitude. **3.:** The local models have a limited coverage in terms of positioning accuracy, since the poor accuracy of the total electron content at the boundaries of the model coverage can cause artifacts in the positioning solution. These results are shown on Figure 6.

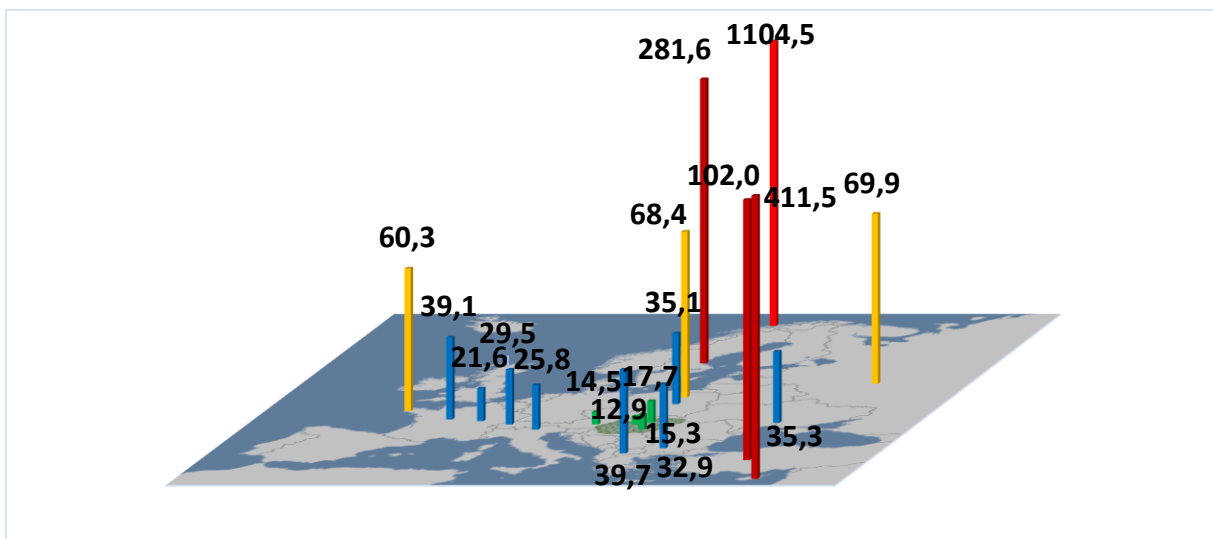


Figure 6. Coordinate differences using Hungarian local ionosphere models in each stations [cm] – daily observations

Theses 3.

I evaluated state-of-the-art troposphere models (Niell and Hopfield) and a regression troposphere model based on Hungarian meteorological radiosonde observations and their impact in PPP applications. In the calculation of a priori Zenith Total Delay (ZTD) the global models showed approximately 3 cm bias, while the regression model has only the half of this value. In a rainy summer and in a still winter period the regression model resulted ~2 cm differences compared to the estimated ZTD values of the PPP process. It has been overestimated by the Niell model in winter, and by the Hopfield model in summer while the respective estimates performed stable in case of the regression model. Based on the results I suggest to use the regression model at the computation of the a priori ZTD values.

I chose a quite rainy and a still meteorological period to examine two global model (Saastamoinen model with Niell mapping function and Hopfield model) and a local regression troposphere model (RM) which is based on more than 10,000 Hungarian radiosonde observations. Permanent stations close to Budapest were used, because meteorological data were available only in this area.

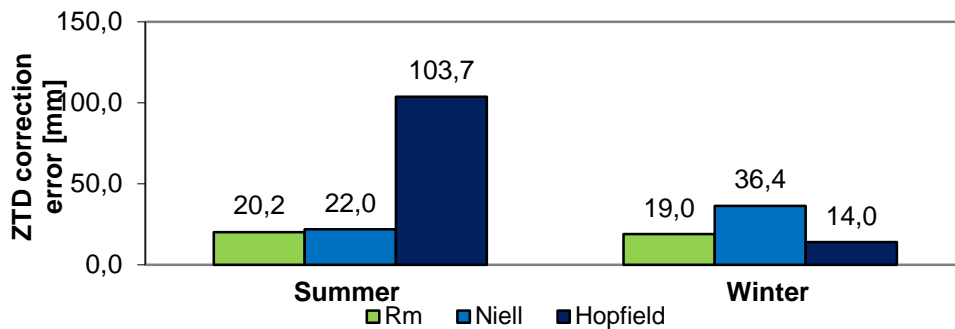


Figure 7. ZTD correction error in each a priori cases compared to the estimated values of the PPP process

A priori ZTD values computed with different troposphere models were compared to the estimated values of the PPP process. Figure 7. contains these corrections both in the summer and winter period. It is visible that the correction error is approximately 2 cm using the regression model, while the Hopfield model values has bigger differences in summer period. In winter these corrections are somewhat reduced, but the Niell values contains slightly larger errors. Figure 8. shows the a priori values from the troposphere models beside the estimated ZTD values at station JASZ.

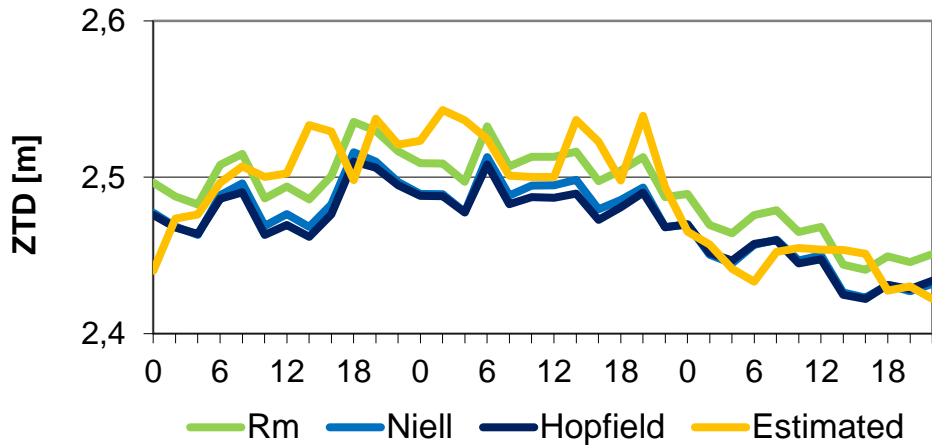


Figure 8. A priori ZTD values [m] and the estimated values of the PPP process 19-21. 08. 2006. at station JASZ

The real (estimated) and the a priori ZTD values from the different models can be seen during a three-day-period. Values of the regression model are slightly closer to the estimated values than the values of the global models. During GPS observations meteorological instruments are usually not available therefore these values can be estimated from standard atmosphere models. I compared ZTD values based on these standard values to the real values provided by radiosonde. These values have been measured twice a day in Budapest and once a day in Szezed (Figure 9.).

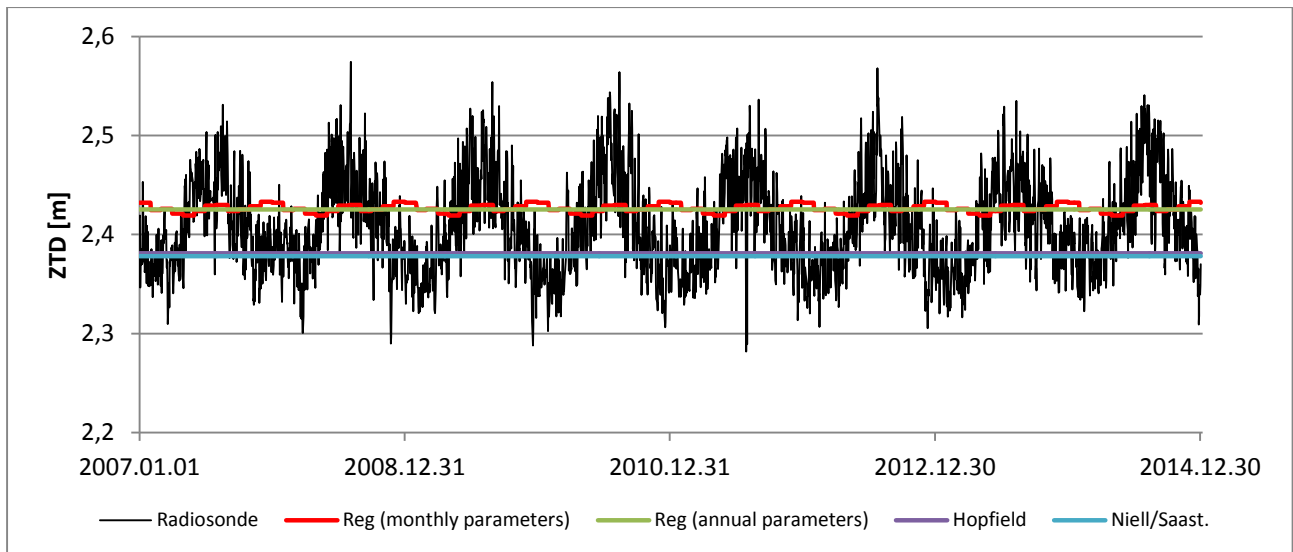


Figure 9. A priori ZTD values [m] from different models and ZTD values provided by the radiosonde - Budapest

The regression model fits better to the mean of the real values while the global models underestimate the ZTD values. The mean bias of the global models are in the 3 cm level, while the application of the regression model reduced this bias to the 1-2 cm level. Although the improvement is just a few centimetres, it could be important in real time applications.

Thesis 4.

I evaluated the feasibility of the PPP using kinematic data with two different technique. These techniques were: the post-processing technique using the kinematic PPP method and a combination of the traditional RTK technique with the static PPP method. An accuracy below 5 cm could be achieved using both techniques, in order to mitigate the effects of cycle-slips and to improve the height determination, the combination of the RTK and static PPP technique is suggested instead of the kinematic PPP method (which can produce decimetre errors). I demonstrated that this method can achieve geodetic accuracy in areas without any control network while the avoidance of cycle-slips is guaranteed.

I derived the empirical function for the estimation of the standard deviation of the computed coordinates as a function of the observation time from field observations. This formula can be used to estimate the necessary observation time during the planning of a field observation.

In 2009 an archaeological excavation was made in the Egyptian desert. It was a great opportunity to test PPP applications under real circumstances. The main aim of the field work was to create a digital terrain model in the vicinity of a pyramid. These field works lasted more than 15 days on an area without any geodetic basis. The PPP technique could provide the geodetic accuracy of positioning. It was really important for the further excavations, since a control network could not be established there. In order to process kinematic observations taken by a rover receiver, two different methods have been studied.

When a single rover receiver is available, one can use the post-processed kinematic PPP method. In this case after a quite long initialization time, the positions can be stored even in every seconds, due to the 1 Hz observation frequency. Weakness of this method is the need for post-processing. When a cycle-slip occurs during the observations, it can be discovered only during the post-processing. Moreover the initialization time is unknown therefore it can be estimated from the former observations. On Figure 10. the initialization time is clearly visible in case of a stationary receiver. The average initialization time lasted 300 epochs.

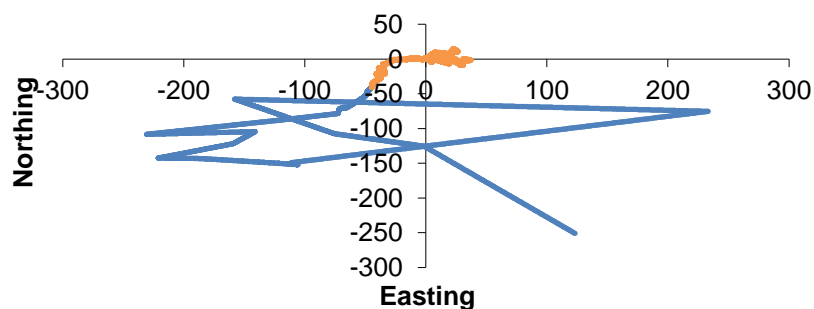


Figure 10. Horizontal coordinate alteration of a stationary receiver [mm]

The other tested method was to use the traditional RTK technique for the detail points. In this case, the base receiver does not have proper coordinates thus it should save the raw observations for a later post-processing. Processing these measurements with static PPP method can provide geodetic coordinates of the base station (depending on the observation time). Afterwards the corrections can be computed between the proper PPP coordinates and the preliminary base coordinates. Applying these corrections to all of the detail points, their positions can be corrected, thus every detail points can achieve almost the same accuracy as the base point. It is advisable to recalculate the detail point coordinates again with a GNSS software if the rover receiver stores the raw observations as well. This method is quite protected against cycle-slip, furthermore the base station is stationary instead of the moving rover receiver like in the first method.

Two formulas have been derived from the observations of the base station in Egypt. Processing the collected data with PPP I could derive two formula between the observation time and the RMS values of the coordinate processing. Using these functions one can estimate the expected RMS of horizontal and vertical coordinates at the preparation of a field work. These functions are shown on Figure 11. and 12.

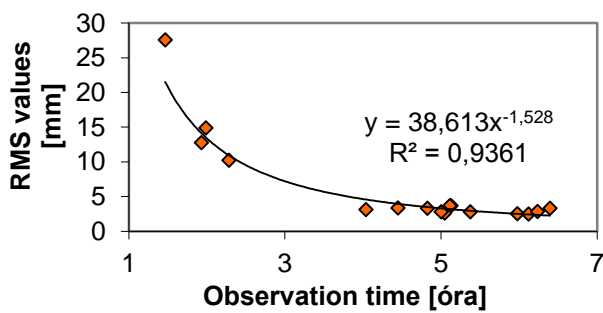


Figure 11. RMS values of the horizontal coordinates in a function of the observation time

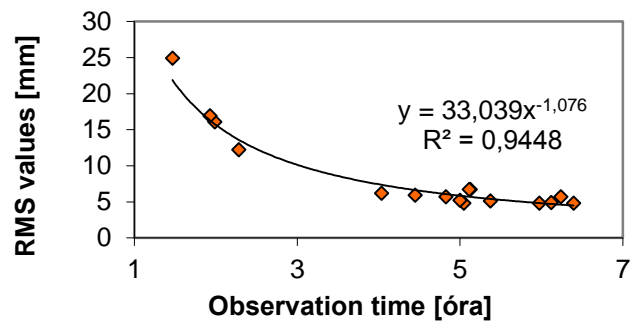


Figure 12. RMS values of the vertical coordinates in a function of the observation time

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