Real-Time GPS Network Analysis Using the IGS Ultra-Rapid Satellite Orbits Applied for Displacements Monitoring

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SUMMARY

The paper shortly describes the ultra-rapid orbits of GPS satellites and their potential applications in real-time monitoring of position variations. The processing procedure for near real-time network solution using precise orbits is explained. With the recent accuracy of the ultra-rapid ephemerides using their predictions the network in near real-time with unprecedented reliability can be processed and thus can be used for monitoring of stability of the individual stations or the whole network. These results can be further improved by Kalman filtering approach. The near real-time solution has been tested at Department of Theoretical Geodesy at the Slovak University of Technology. An experiment with a device which allowed performing antenna horizontal displacements with exactly measurable magnitude is discussed in the last chapter of the paper. Our approach enables to detect sub-centimeter displacement in several hours after the event at sites in distances of tens of kilometers from the nearest network station.

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1. INTRODUCTION

When the GOP (Geodetic Observatory Pecny) as the International GNSS Service (IGS) analysis center firstly introduced the ultra-rapid ephemerides in 2004 (Douša, 2005), the scientists was given a new instrument for precise near real-time GPS applications. Up to that time the only available products in real or near real time were the predicted GPS broadcast ephemerides with their accuracy level of 1 - 2 m. Final precise IGS ephemerides with the latency exceeding two weeks have been too delayed for many applications. Also the delay of the IGS rapid ephemerides (latency about 17 hours) became too large as the requirements for precise nearly real-time monitoring increased. The need for precise un-delayed satellite orbits quickly emerged. With accuracy dropping down of nearly 95% (compared to broadcast ephemerides) it is possible to use now the ultra-rapid IGS orbits for monitoring of structures, buildings or other hazardous areas. The near real-time solution of regional GPS monitoring network has been developed and tested at Department of Theoretical Geodesy at the Slovak University of Technology. An experiment with a device which allows performing antenna horizontal displacements with exactly measurable magnitude will be reported.

2. THE CONCEPT OF ULTRA-RAPID ORBITS

The IGS is an international collaboration of more than 200 independent organizations focused on providing the high quality GNSS products with free access to data for scientists and other users (IGS, 2008). One of the main products provided by the IGS are the satellite orbits obtained from processing of observations from permanent GNSS stations located all over the globe. There are three types of the IGS orbit products. The most precise are the final orbits. It takes more than two weeks to complete and process all observations from permanent stations and to compute the final satellite orbit parameters. Other type products are the rapid orbits, as they are produced much faster than final orbits with the delay about 17 hours.

The production of the last type of orbits became after several improvements of the algorithms even faster and therefore these products are named as ultra-rapid. The GOP analysis center has started the near real-time global processing for orbit determination in 1999. The first development was aimed to obtain the efficient hourly orbit product, but the update rate was later reduced to 3 hours using analysis method with better orbit predictions. The system was designed as robust, but extremely efficient (Douša, 2005). Ultra-rapid orbits consist of two parts – the first part contains fitted portion of observed data, the second part contains predicted data. These parts also slightly differ in terms of accuracy – predicted orbital data provides accuracy of approximately 10 cm in real-time, while observed part delivers accuracy of 5 cm with delay of several hours. Ultra-rapid ephemerides are updated four times a day – every 6 hours with delay of 3 hours. The first developments in early years aimed to generate efficient hourly solutions; the update rate was later reduced for better orbit prediction. The long-arc orbit determination (Beutler et al., 1996) is used for final combination of the orbits. It requires 6-hour normal equations combined into a 3-day global solution. The process is performed iteratively for the appropriate orbit parameterization (Douša, 2005).

3. USING ULTRA-RAPID ORBITS FOR PROCESSING OF PERMANENT NETWORK

The Department of Theoretical Geodesy (DTG) at Faculty of Civil Engineering at Slovak University of Technology (SUT) is one of 16 local analysis centers (LAC) of EUREF Permanent Network (EPN). It provides routinely weekly solutions of subnetwork consisting of approximately 45 permanent GNSS stations located all over European continent. The solutions are obtained using the Bernese GPS Software (Hugentobler et al., 2006). The standard latency of these solutions is about three weeks. The complete observation data from permanent stations are available in several hours after the end of the week. However, it is not possible to process the subnetwork immediately, as the precise IGS ephemerides are available with the delay of two weeks later.

At DTG we tested a near real-time processing of the permanent network in parallel. From the regularly analyzed EPN subnetwork several distant stations have been removed (e.g. QAQ1, Greenland or REYK, Iceland) where the baselines are approximately 2000 km long. The solutions with such long baselines and short observation spans were sometimes instable, therefore the network was truncated. After elimination of the most distant permanent stations, the subnetwork of 25 stations was used for near real time solution. All routines needed for a network solution will be shortly described in the next section.

The processing starts with raw data conversion to the independent exchange format RINEX. In general, it is possible to download RINEX data for majority stations directly from EPN data centers via the FTP protocol. As the uploading to the servers is not at some stations completely automated or there might be a power or computer failure or any other source of delay, the LACs should wait a while for delayed data. The length of an acceptable delay varies according to the kind of processing strategy. In case of precise solutions using final (precise) ephemerides, a day or two are acceptable. On the other hand, if the hourly solutions are processed, the delay should not exceed several tenths of minutes. In the near real time processing at DTG 20 minutes limit is allowed for downloading the hourly observation data. To decrease the volume of the data flow, the observation files are usually compressed by the Hatanaka RINEX compression method and the standard Unix Z compression. After the files are downloaded to DTG processing facilities they are uncompressed and are ready for the processing.

The observation files are not the only data needed to be downloaded. Besides, the IGS ultra-rapid orbits and up-to-date Earth rotation parameters (ERP) are transferred from IGS databases. Ultra-rapid solution is processed four times a day referenced to 0, 6, 12 and 18 h UTC with 3 hours delay. These files can be downloaded via FTP from IGS servers at any time.

Before processing gathered data the baselines should be created. This can be either done by Bernese Processing Engine (Hugentobler et al., 2006) or the operator chooses manually the best pairs of the stations. In LAC SUT solution the baselines are created automatically for each processing batch. The baseline definition routine checks integrity of observed data by program teqc. The critical parameter is the ratio of observed epochs to all possible observable epochs. However, there are more options to decide whether the observation file is acceptable, partly usable, or useless. In the LAC SUT processing mode acceptable files contain at least 80% of possible epochs observed; the usable files contain minimum 20% of possible epochs observed. The files with less than 20% of possible observations are considered to be completely missing. These values can be altered according to the importance of the processing, length of observation window and/or preference of user. The station with less than 80% of possible observations cannot be a considered as the "node station" (common for more than one baseline). If some node stations do not meet this criterion the network is reshaped.

The major results of the processing are the coordinates of every station and the relevant covariance matrix. These will be later used for further, near real time analysis. In LAC SUT the procedure based on Kalman filtering (Kalman, 1960) is used for the analysis. As the Kalman filter utilizes the previous estimate and the current observation are used for update of the solution, it was chosen as an effective procedure for repeated analysis of large sets of coordinates which are considered as time variable.

4. NEAR REAL-TIME MONITORING

The predicted part of ultra-rapid orbits delivers high precision orbit parameters in the real time, and they are sufficiently accurate also for the near future. It is a powerful tool for all applications focused on both timeliness and precision. Using appropriate processing method it is possible to extract high precise coordinate estimates in near real time for relatively long baselines (up to hundreds km). Such information can be used for monitoring of stability of important structures, buildings or other in hazardous areas in homogeneous robust network.

To evaluate the potential of the processing procedure mentioned, an experiment with simulated displacements has been performed. The GPS observations were processed in near real-time and coordinate analysis using Kalman filter algorithms was subject of continuous stability check. In this example the near-real time means less than 30 minutes delay. In fact, the first 20 minutes were spent by waiting for data, after the observations are downloaded; only 6-7 minutes were needed to perform all the processing and obtaining the final results. The waiting period can be shortened to get the solution faster, but there is a risk that insufficient number of stations is delivering the data within the deadline. The 20 minute delay was chosen as a compromise between timeliness and the need for correct and sufficient observation files. The experiment started with long-term monitoring of a stable test point, then a horizontal movement of the antenna about 35 mm in north-west direction was performed, and finally the antenna was returned back to its initial position after two days.

Permanent evaluation of the station coordinates is sufficient to get sub-centimeter accuracy. Several tests have to be performed before the results can be considered as the final (in the processed observation epoch).

The first is the “net-displacement” test. This is aimed to detect a reference station movement. In the LAC SUT solution, where the single reference station is used for initial referencing, there is a danger that the whole network shifts – it does not matter whether physically or it moves just due to wrong observation data. It has to be taken into account that the network is systematically shifted. The differential displacement are tested using simple quartile test (Mendenhall-Sincich, 1988)
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The “net-displacement” test detects the reference point (and thus the whole network) dislocation. Next test is aimed to detect the displacement of single monitoring stations. This test compares the evaluated a-priori residuals (difference between predicted and observed values) with RMS error resulting from network adjustment. However, as the RMS errors are in the GPS processing overvalued because of the correlations not included in solution algorithms, the RMS value must be factorized for each station separately to provide more realistic estimate. The RMS scale factor value is derived out from a-priori residuals set and is regularly updated.

Figure 1 shows an output from the experiment mentioned above. There are two basic sets of information data visualized; they are represented by black and colored points. The black ones represent the coordinates estimated (Bernese GPS Software output), while the colored are the estimates using the Kalman filter algorithm. Red points are estimates using a noise matrix with 0.1 mm level, the blue ones use the 0.5 mm noise. The vertical bars represent RMS errors for each epoch. The computation is performed in 4 hours intervals between epochs.

The graphs readily show that smaller noise applied for Kalman filtering provide smoother solution, while larger noise make estimates to be more noisy, but faster reacting for indication of sudden changes. The graphs confirm that displacement of 1-2 cm in both of the components can be detected quite easily with delay of several epochs only. The less smooth curve (blue) responds more quickly and depicts the position shift with more fidelity when compared to smoother (red) curve and is more appropriate for bias representation. The scatter of position from the network solution (black points) in individual 4-hour intervals is up to 0.06 m in horizontal coordinates and emphasizes the necessity of Kalman filtering of the solutions.

After analysis of the experiment the most appropriate value of noise for the observed process will be estimated and thus setting the Kalman filter to provide high precision with high effectivity. Note that the Kalman filtering is essential as the individual estimates are more scattered as is the amplitude of simulated bias.

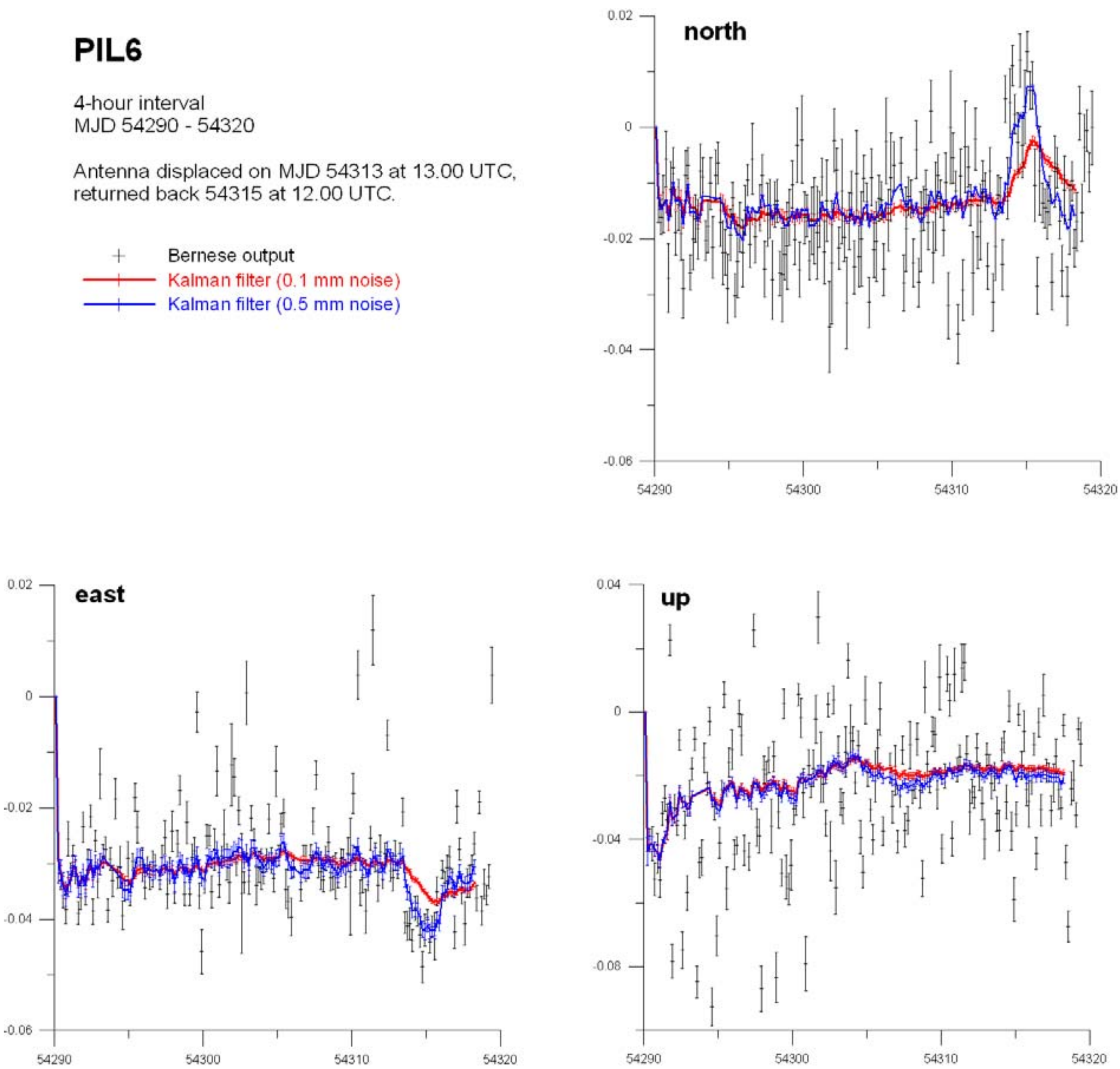

Figure 1: Displacement monitoring results in north-south, east-west and vertical components (in meters). The individual points and the error bars are the results of 4-hour processing intervals; the colored lines represent the position estimates with Kalman filtering.

5. CONCLUSIONS

The near real time coordinate evaluation algorithm using the ultra-rapid IGS GPS satellite orbits was developed at DTG SUT in Bratislava. The sub-centimeter accuracy of estimated horizontal coordinates is achieving in the network solution with baselines of several tenths to several hundreds of kilometers. This strategy is not influenced by possible biases of reference points close to monitored region. Kalman filtering approach helps to positive detection of eventual coordinate shifts due the various phenomena. The presented method is suitable for long-term continuous monitoring of stability of important structures, buildings or other hazardous areas.

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