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PRECISE NEAR REAL-TIME GNSS ANALYSES AT GEODETIC OBSERVATORY PECNÝ – PRECISE ORBIT DETERMINATION AND WATER VAPOUR MONITORING

Jan DOUŠA

Research Institute of Geodesy, Topography and Cartography, Geodetic Observatory Pecný, 244, 251 65 Ondřejov, +420-323649235, +420-323649236
Corresponding author's e-mail: jan.dousa@pecny.cz

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ABSTRACT
This paper provides a summary of the Geodetic Observatory Pecný achievements within the Centre for the Earth Dynamics Research (CEDR, 2005-2009) project in the field of precise near real-time GNSS analyses. The GOP data centre supporting our own near real-time activities as well as those of various other institutes has been enhanced by including GLONASS data, real-time GNSS data and some other supporting products. The ultra-rapid GNSS orbits are routinely determined and predicted at GOP by analysing a global network of 60 stations. Significant improvements, which resulted in the fitted and predicted satellite position rms of 4 and 10 cm, respectively, were achieved within the CEDR project. The GOP orbit product is updated every 6 hours and it routinely contributes to the International GNSS Service (IGS). Based on these predicted precise orbits, the GOP near real-time regional GNSS network solution is routinely provided for monitoring water vapour in the atmosphere. Resulting zenith troposphere delays achieved a standard deviation of 3-5 cm compared to precise EUREF post-processing results or a standard deviation of 1-2 mm when converted to precipitable water vapour and compared to a nearby radiosonde. The troposphere delays estimated in GOP are operationally used in the Numerical Weather Prediction.

KEYWORDS: GPS, GLONASS, precise orbit prediction, troposphere delay, near real-time

1. INTRODUCTION

The Centre for the Earth Dynamics Research (CEDR) is a joint project of four contributing organizations, led by the Research Institute of Geodesy, Topography and Cartography (RIGTC), see Kostelecký (2010). The Geodetic Observatory Pecný (GOP) of the RIGTC contributes to the project with a number of activities. In this paper we summarise the achievements of the precise near real-time GNSS analysis developed and improved at GOP within the CEDR project. Three main activities are explained – near real-time data support (Sec 2), ultra-rapid orbit determination (Sec 3) and near real-time troposphere path delay monitoring (Sec 4). Most of these activities serve as a basis for long-term contributing to well-established international services and projects, such as the International GPS Service (IGS), the EUREF Permanent Network (EPN), the EUMETNET GPS Water Vapour Programme (E-GVAP) etc. The main achievements and interconnections of all these activities are emphasized. Due to the limited extent of the paper, we refer to detailed descriptions whenever other publications are available.

2. NEAR REAL-TIME DATA

Since 2002, a EUREF data centre has been operating at GOP with main focus on near real-time data and products. Hourly RINEX files (Gurtner and Estey, 2005) of more than 150 permanent GNSS stations are routinely available at ftp://ftp.pecny.cz/LDC. Besides providing public access for selected data, the GOP analysis centre uses global, regional and national data sets for the following activities: GPS-meteorology (Sect 4), precise GNSS orbit determination (Sect 3), near real-time and rapid coordinate monitoring for the Czech and EUREF Permanent networks (Filler, 2007; Douša and Filler, 2009) and contribution to the EUREF reference frame maintenance (Douša and Filler, 2003).

The data centre was completely re-designed during 2004 (Douša and Souček, 2004) and since that time the system has been extended with respect to the following features:

- concatenating hourly/daily global navigation GPS and GLONASS files
- concatenating daily GNSS observation files
- supporting GLONASS observation data and orbit product
- supporting real-time data input
- extracting the site-logs, GNSS information
- monitoring data quality and latency.

We will briefly address the testing and operational support of the real-time data flow, which have been particularly important for the results in Sections 3 and 4. More details can be found also in Douša and Bartošová (2007).

REAL-TIME DATA TESTING AND OPERATIONAL INPUT

The real-time data support for the GOP data centre has been implemented mainly for these reasons: a) to provide an alternative source of GPS and GLONASS data besides standard IGS data centres, b) to speed up hourly data, c) to support robust generation of hourly global broadcast navigation files and d) to gain experience with two real-time data dissemination schemes: EUREF-IP (http://epncb.oma.be) and RTIGS (http://www.igs.org).

We have set up two real-time clients - the open source BKG Ntrip Client (Weber and Mervart, 2008) using TCP/IP/NTRIP (Weber et al., 2003) protocol and the RTIGS Archiver using UDP/RTIGS protocol (Caissy et al., 2006). If real-time data input into GOP data centre is successful, hourly files are not downloaded using a standard ftp procedure. Before the real-time data is converted into standard 30s-RINEX hourly files, temporary 1s-RINEX hourly files are stored and checked for the presence of necessary header information and for data completeness (90 percent of all data is requested). Specific software 'RinexMonitor' has been developed for this reason. Daily reports of the number of missing epochs in a single hourly file together with marked erroneous events are plotted and fortnightly summaries of the percentage of observation and numbers of available satellites are shown on the GOP webpage (http://www.pecny.cz). More details can be found in Douša and Bartošová (2007).

The visualization proved that before a data centre can provide archived files from real-time data streams, it must check data integrity and volume. After implementing both real-time schemes in a testing campaign, finally the system based on NTRIP protocol has been adopted for the operational data centre support. The advantages of this approach can be summarised as follows:

- full support of GLONASS data and GLONASS navigation messages
- fewer missing observation epochs
- well designed open-source client (BNC)
- integrated handling of RINEX header information
- configuration of the streams on the user side

3. PRECISE ORBIT DETERMINATION

The International GNSS Service, IGS (Dow, 2007) is a collaborative effort of more than 200 individual organizations to provide precise GNSS products and free access to global GNSS data for a wide range of scientific and engineering applications. The IGS collects individual contributions and its purpose is providing precise combined products, such as orbits, Earth rotation parameters, satellite and receiver clocks, zenith troposphere delays, ionosphere maps etc. Other important roles of the IGS are coordination, standardisation and supervision of the activities for high-accurate GNSS solutions.

In 2000, the IGS initiated the specific product, ultra-rapid orbits, to support upcoming near real-time and real-time applications, e.g. GPS meteorology (Bevis et al., 1992). At the same time, at GOP we developed a precise orbit determination procedure for hourly mode (Douša and Mervart, 2001). Later in 2002, we improved the procedure and started a routine processing of a global network providing precise ultra-rapid orbits. Since 2004, this product has been officially contributing to the International GNSS Service. In 2006 and 2008 we enhanced the processing strategy and in 2009 we extended the processing to the GLONASS system.

Below, we briefly summarize the characteristics and improvements of the orbit product and we evaluate its quality. We also present our activities in monitoring the real real-time orbit quality and briefly introduce our proposal for precise orbit dissemination in real-time.

THE PROCESSING STRATEGY IN A NUTSHELL

Among many in-house developed scripts and programs of the whole GOP orbit determination system, the Bernese GPS Software (Dach et al., 2007) is the core analysing tool for batch processing of double-difference GNSS observations. Our system has been developed as highly efficient based on pre-processing of the last 6 hours followed by the combination with preceding solutions. For the combination, the Bernese GPS software was modified to support a stacking of orbit arcs from sub-daily solutions.

Only the GNSS navigation messages and observation and predicted Earth rotation parameters (ERPs) are needed to initiate the procedure. Through analysing navigation messages, we are also able to detect satellite manoeuvres, which is important in the pre-processing steps. In order to provide overall robustness, our solution consists of two orbit improvements (Fig. 1) wherefore either predicted precise IGS orbits or broadcast orbits could be then used as a priori orbit information.

Pre-processing is the main part of each of the two solution iterations. All steps are efficiently performed in five individual clusters in parallel (Fig. 1, black boxes). In all the steps, where the least square adjustment (LSQ) is applied (GPSxxx), a full normal equation matrix (NEQ) is saved as the result. It is followed by the NEQ combination applying

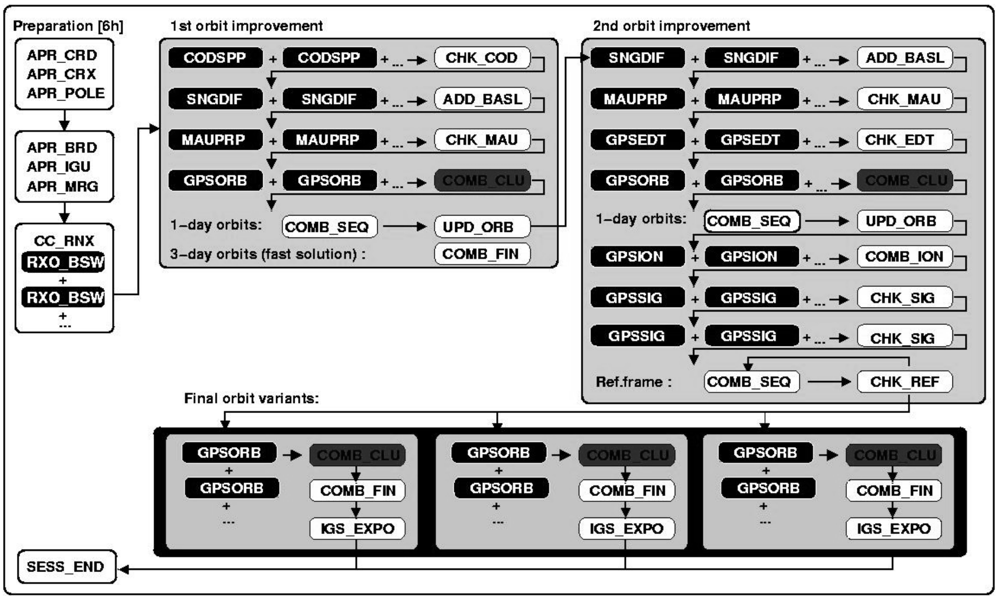

Fig. 1 GOP ultra-rapid orbit processing blocks. Black boxes are processed in paralel.

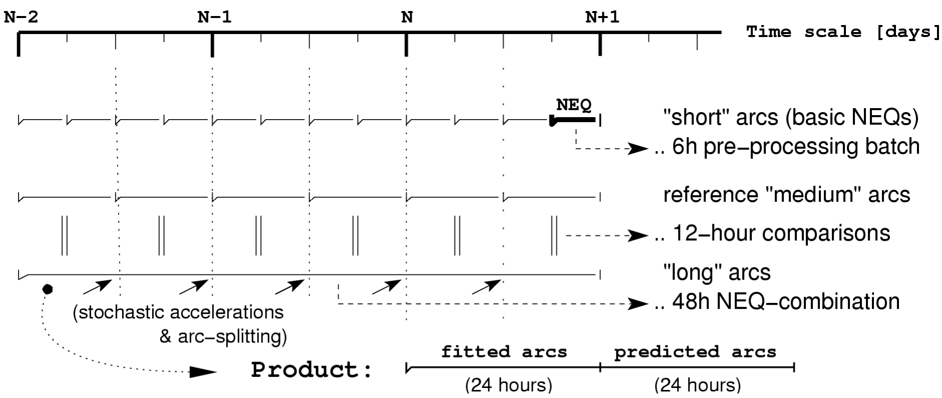

Fig. 2 Chart of the long-arc orbit combination procedure.

sequential LSQ – a) COMB_CLU step combines cluster-NEQs into a 6-hour global solution and b) COMB_SEQ step combines 6-hour global-NEQs into a daily solution. The latter is the product of the pre-processing and orbit improvement iteration step. After the second orbit improvement step is completed, the 6-hour NEQs are combined into a single 3-day final orbit product using different variants (Fig. 1, bottom three blocks). The orbit parameters (as well as the ERPs and coordinates) are stacked there for an interval of 3 days in order to provide the best 24h orbit prediction as the final product. The parameterization of final 3-day orbit model is a key part of the precise orbit prediction and thus the procedure will be briefly addressed, too.

In the best case, the six initial orbit parameters plus nine additional solar radiation parameters of the extended CODE model (Springer et al., 1999) are combined into a unique orbit arc over a 3-day interval. For various reasons like satellite manoeuvres, eclipsing events or data loss, the existing orbit model is not always satisfactory and the solution then does not provide the best results. The iterative procedure is provided in order to handle the best setup of the orbit parameters. The main goal is to identify the epoch, at which the individual satellite orbit arc should either be split into two (or more) pieces, or at which additional stochastic parameters representing a satellite velocity should be introduced. To recognize such epochs, the long orbit arc of every satellite is compared with the original short one as shown in Figure 2. The information about the satellite manoeuvre, obtained at the initial phase of the processing, is used in this procedure too.

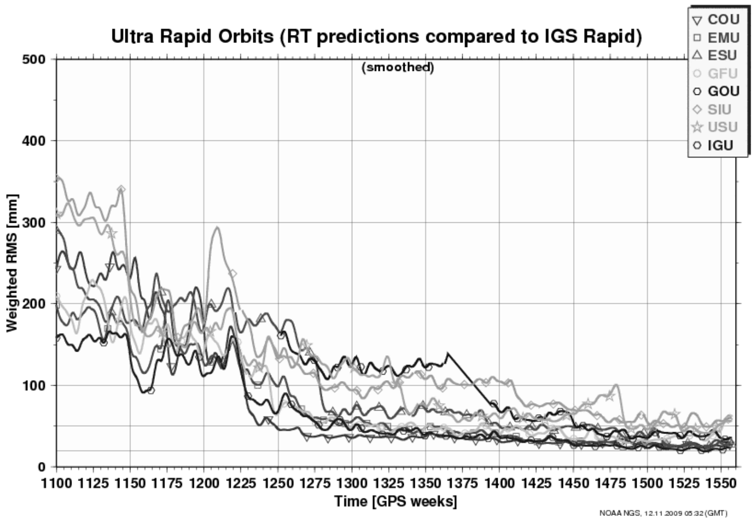

Fig. 3 A comparison of individual analysis centre contributions to the IGS ultra-rapid products (http://igs.acc.org).

Table 1 Our ultra-rapid product (GOU) compared to the IGS final product. The weighted RMS is reported for fitted and 12h predicted product as the first and the second number, respectively.

	Orbits [cm]	Pole motion [mas]	Pole rate [mas/day]	Length of a day [ns]
GOU (2005)	12 / 24	0.3 / 0.5	0.4 / 0.4	0.07 / 0.09
GOU (2009)	4 / 10	0.1 / 0.3	0.2 / 0.4	0.03 / 0.07

STRATEGY IMPROVEMENTS (2006-2008)

Many further developments in our orbit determination system were introduced in 2006 and 2008 (Douša, 2008):

- adapting new official Bernese software V5.0 with many advanced models (troposphere, IERS 2000 standards,...)
- re-designing the system to make it consistent with other GOP systems for daily and near real-time
- extending parallel processing to all possible steps
- estimating 6-hour ionosphere model for supporting the ambiguity resolution
- resolving integer ambiguities (60-70 %) within 6-hour data batch
- identifying satellite problems and manoeuvres during pre-processing
- weighting the problematic satellite observations to avoid any solution disruption
- enhancing the strategy of orbit accuracy code estimation in final product
- determining the reference datum in near real-time
- refining the solar radiation pressure parameters estimation
- supporting the stochastic parameter setting for satellites in eclipses
- single or combined processing of GPS and GLONASS

Some developments enhanced the overall procedure efficiency and robustness, others enabled easier routine maintenance. Most of the developments have had a direct impact on the quality of our product. Routine comparison of individual ACs' products to the IGS final product is shown in Figure 3. Table 1 shows the overall improvement in the quality of all products corresponding to changes from 2005 to 2009.

GLONASS ULTRA-RAPID ORBIT IMPLEMENTATIONS

In September 2009, the GLONASS constellation reached 20 (+1) satellites (R09 is excluded due to incomplete data). Because the global coverage of the GLONASS data from the IGS network is not yet optimal, we exploited some additional data from available non-IGS stations originally disseminated in real-time 1Hz streams (see Sect 2). Another problem is that some receivers in the IGS global network do not record all available satellites, mainly those GLONASS having a negative channel number.

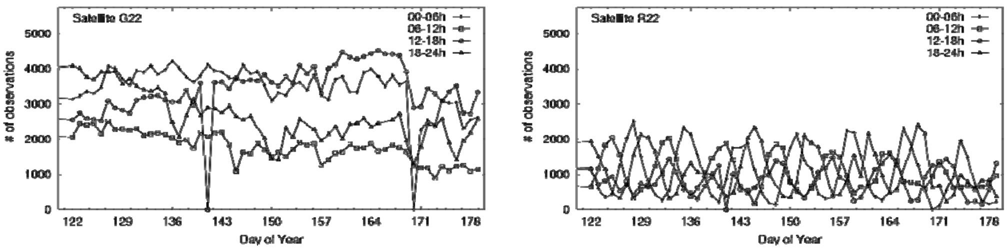

Fig. 4 Number of observations for satellites GPS 22 (left) and GLONASS 22 (right) plotted for four 6h batches during a day.

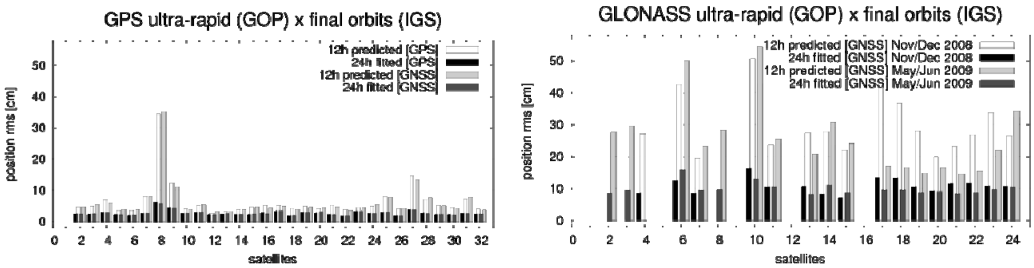

Fig. 5 The left figure shows the position RMS for GPS satellites from stand-alone GPS and GNSS solution for 12h-predicted and 24h-fitted interval. The right figure shows the position RMS for GLONASS satellites from GNSS solution in two periods.

Although a careful selection of the global stations for maximizing all GNSS observations has been carried out, the volume of available GLONASS observations is still substantially lower than GPS (Fig. 4). The figure also shows a strong fluctuation of GLONASS data within each six-hour data window.

A revision of all processing steps was necessary to reach the maximum robustness of the solution when the incomplete GLONASS system is included. The complete GLONASS navigation hourly files were provided in order to initialize the orbit determination. A standard checking procedure was improved to eliminate all incorrect messages. The GPS and GLONASS initial orbits are prepared individually and eventually they are merged together.

The original GOP processing scheme was extended with a simple option for switching between GPS, GLONASS or GNSS analysis. Accordingly, all the individual processing steps were enhanced to use combined data as well as to apply specific options for GPS or GLONASS only. For example, due to missing an integer ambiguity resolution strategy for GLONASS in Bernese 5.0, the relevant steps are not performed for GLONASS data. The global ionosphere model, estimated in near real-time for the ambiguity resolution is estimated from GPS pseudo-range data only and it is currently not provided in a stand-alone GLONASS solution.

The combined GNSS and stand-alone GPS, GLONASS orbit and ERP products were evaluated during two 60-day periods: Nov/Dec 2008 and May/Jun 2009. The important result was that GLONASS data have no negative impact on the determination of GPS orbits, see Figure 5 (left). We can thus immediately provide a single rigorous GNSS solution for a fully consistent GNSS orbit and ERP product. Figure 5 (right) shows the lower quality of GLONASS orbits from the GNSS solution. Further developments will be resolving the integer ambiguities, improving the global data coverage and possibly revising the estimation of the solar radiation pressure parameters for GLONASS. The stand-alone GLONASS solution resulted in approx. 20 % worse orbits compared to the GNSS solution. It is clearly due to the fact that GLONASS solution still benefits from the common parameters estimated predominantly with GPS data (station coordinates, troposphere path delays, Earth rotation parameters). More details can be found in Douša (2009).

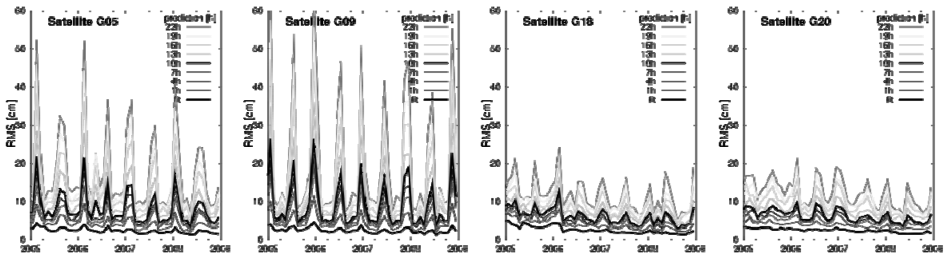

Fig. 6 The time-series of the satellite G05, G09 (Block IIA) and G18, G20 (Block IIR) IGS ultra–rapid orbit predictions (fit, 1h, 4h, 7h, 10h, 13h, 16h, 19h and 22h) compared to IGS final orbits (monthly average).

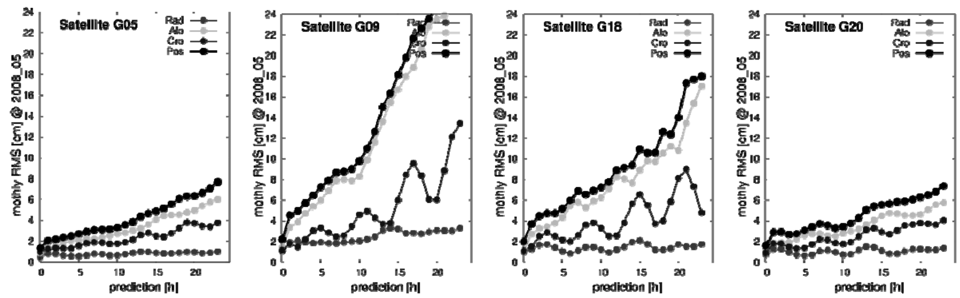

Fig. 7 Monthly IGS ultra-rapid orbit prediction errors for the satellites G05, G09 (Block IIA) and G18, G20 (Block IIR) plotted with respect to the prediction interval. Satellites G09 and G18 were affected by the eclipsing period, while satellites G05 and G20 were not.

REAL-TIME PRECISE ORBIT DISSEMINATION AND MONITORING

The ultra-rapid orbits are mainly used in near real-time and real-time applications. The prediction part of the product (3-9 hours) is thus very important. Because combined from more individual solutions, the most accurate and robust is the IGS product. We have developed an evaluation system for the predicted orbits to study the product performance. Figure 6 shows the results of the time-series of monthly RMS orbit prediction errors for two satellites selected because of the different block type - IIA (old) and IIR (new). The effect of a half-year periodic degradation of the product is caused by the Earth eclipsing the satellite orbit. The second aim of the evaluation was to study the dependency of the orbit accuracy with respect to the prediction interval, which is shown in Figure 7. Again, both satellite block types are represented during an eclipsing and a non-eclipsing period. The figure thus demonstrates much faster degradation for the satellite of block IIA during such an event.

The IGS ultra-rapid orbit product is updated every 6 hours. The continuity for the satellite position is not provided. We have developed specific software and procedure to support real-time applications with a continuous precise orbit stream. This consists of predicted satellite clocks, but it can be additionally supplemented with high rate satellite clocks from real-time filter. Our approach to distribute the orbit information is based on the polynomial representation of each component of the satellite position in terrestrial system within a limited interval. Various techniques to estimate the polynomial coefficients with respect to the guarantee of a continuity of the satellites' positions and velocities were developed and tested. The estimation by applying Lagrange form and by least-square polynomial fitting (with or without various continuity conditions) is demonstrated in Figure 8.

Different polynomial degrees and time-intervals were additionally evaluated in order to provide a sub-centimetre orbit reproducibility, see Figure 9. The errors from testing polynomials were estimated comparing down-sampled IGS orbit positions (900s) to the original positions (30s). The polynomials of degree 8 are clearly sufficient to represent precise orbits for hourly interval (i.e. using ±30 min from the reference epoch). The range of the polynomials has also been estimated to consider efficient encoding for real-time dissemination. The distribution of the GPS and GLONASS ultra-rapid orbit predictions via

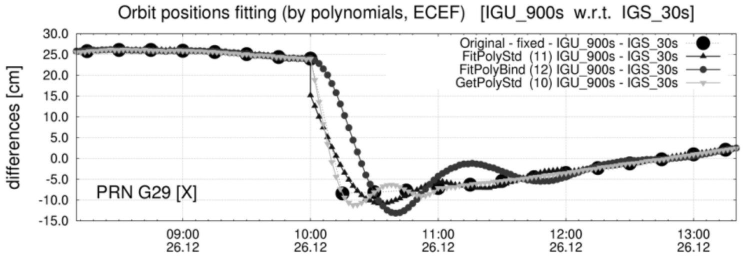

Fig. 8 Three methods of the polynomials estimation: GetPolyStd (Lagrange form), FitPolyStd (unconditional fitting), FitPolyBind (fitting conditional for the consistency in the coordinates and velocities).

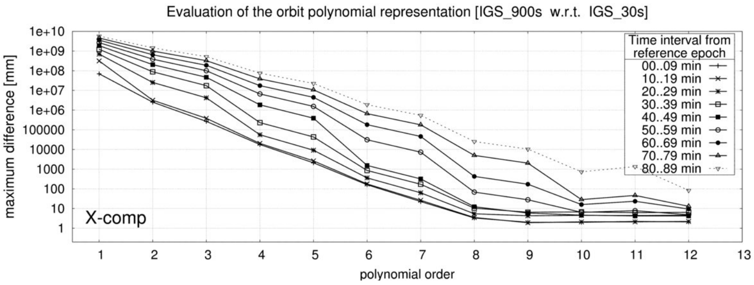

Fig. 9 Polynomial degree test with respect to the validity interval – IGS orbits sampled at 900s intervals were interpolated and compared with respect to the same orbits sampled originally at 30s intervals.

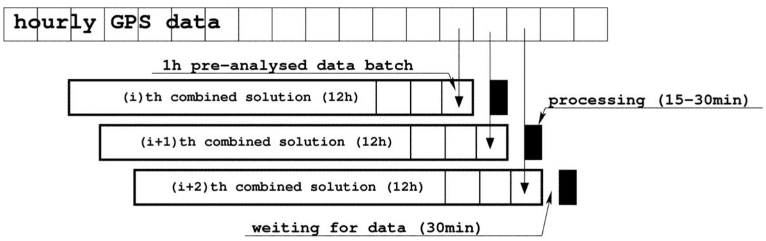

Fig. 10 Near real-time ZTD estimation scheme – hourly NEQs and 12-hour combination.

NTRIP streams has been implemented together with operational backward evaluation of the predicted orbits with respect to the IGS rapid orbits.

4. GNSS TROPOSPHERE MONITORING NEAR REAL-TIME ZTD ESTIMATION

The Bernese GPS software is also used for the near real-time (NRT) GPS estimation of zenith troposphere delays (ZTDs) for numerical weather prediction application. The double-difference GPS observations are reduced on an hourly basis. The station coordinates are estimated in near real-time as a produkt of sequential least square adjustment over a period of 28×24 hours. The ZTDs are then estimated using the same approach, but only over the last 12 hours, see Figure 10..

The IGS ultra rapid product (Springer et al., 2001) is a prerequisite in our solution (though alternatively we can apply our ultra-rapid orbits contributing to the IGS product). The predicted orbits are fixed, but for even higher robustness, an iterative quality checking is provided for the residual screening and any satellite is rejected from the solution or from the single baseline if identified as problematic for any reason. In 2006 and 2007, the original processing system was completely re-designed to include new features:

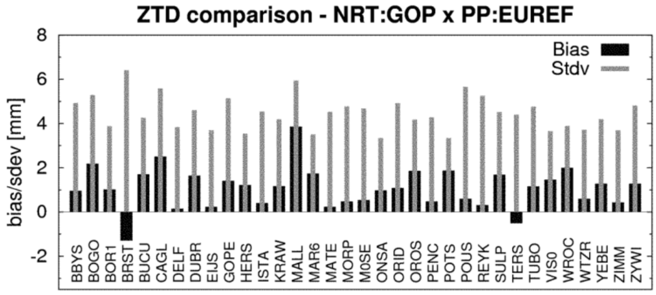

Fig. 11 The comparison of GOP near real-time ZTDs with EUREF combined ZTD produkt.

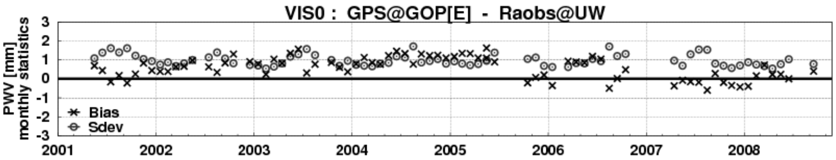

Fig. 12 Monthly statistics of the GPS and radiosonde PWV comparison (stationVIS0).

- Parallel processing for a) independent steps of the analysis and for b) network clusters, which are finally combined into a single solution. This scheme supports more stations processed in near real-time with the same hardware. Up to 80 stations are run on a multi-core Linux PC within 20 mins.
- Ambiguity resolution applying wide-lane and narrow-lane techniques (whenever possible using smooth code data). The two-hour batches are the basis and the ambiguities are fixed within the coordinate estimation (the 2-hour coordinate repeatability over 28 day-solution has improved from 10/25/25 to 6/6/16 mm in the North/East/Up components).
- Near real-time coordinate estimation and monitoring based on 2-hour solutions over the last 28 days.
- ZTD solution based on ambiguity-fixed hourly solutions (testing purpose).
- New ZTD model: a priori Saastamoinen model (Saastamoinen, 1972) with dry Niell mapping function (Niell, 1996) and estimated ZTD using wet Niell mapping function. The new ZTD model reduced the GPS-radiosonde bias.
- Piece-wise linear function for the troposphere estimation model.
- Filter for ZTD product - a minimal interval of continuous data for ZTDs (4 h) and coordinates (48 h) is requested.
- Graphical monitoring system, e-mail/SMS warning system.

GOP ZTD product has been continuously available since February 2001. The product contributed to the COST-716 (Elgered, 2001) and TOUGH (Vedel et al., 2003) projects in the past and it contributes to the E-GVAP (egvap.dmi.dk) project now. Since 2007 the product is operationally assimilated in MeteoFrance and UK MetOffice. In 2006, the GOP solution has been completed to include so called “supersites”, a selection of 13 stations in Europe. These hold a specific position among the other stations, since they are collocated to other water vapour monitoring techniques (e.g. radiosonde, radiometer, etc.). They are used for the external evaluation as well as for the individual contributing centres ZTD inter-comparisons.

EVALUATION OF GOP TROPOSPHERE ESTIMATES

We have compared our near real-time ZTDs with the EUREF combined ZTD product for all commonly available stations (Fig. 11). Only ZTDs after GPS week 1400 were used, before this time inconsistent troposphere models were applied for both products.

Additionally, thanks to EGVAP and TOUGH products, we have got our ZTDs converted into the Precipitable Water Vapour (IWV) and we compared those with radiosonde data available nearby, example shown in Figure 12. For close collocation, standard deviation seasonally fluctuates usually between 0.5-2 mm. In November 2006, a 1-2 mm bias was reduced thanks to applying a new troposphere model in GPS. The bias between old and new GPS troposphere models has been evaluated using two parallel product lines. Three - month results revealed variations of 1-5 mm depending on station location and time.

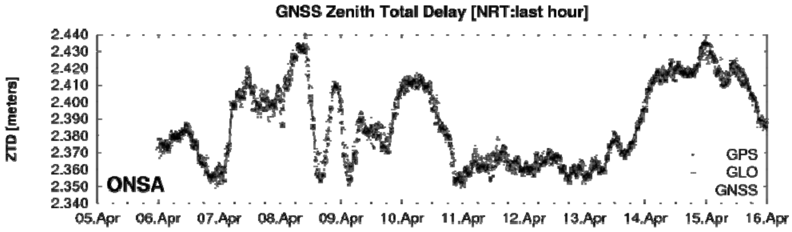

Fig. 13 Time-series for zenith total delay parameters estimated at stations ONSA (Onsala) using GPS, GLONASS or both data.

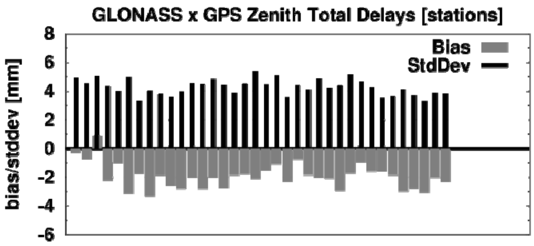

Fig. 14 Inter-comparisons of GLONASS and GPS based ZTDs for all processed stations (x-axis).

The ZTD results were also validated with the HIRLAM numerical weather model (www.hirlam.org). The agreement in ZTD was found at the level of 8-24 mm with very strong seasonal and rather significant sub-daily variation.

We also compared our ambiguity-fixed and ambiguity-free ZTD solution and identified an average bias of approx. 1 mm for most of the processed stations. In near real-time, the ambiguity resolution strongly depends on the station location within the network and on the data quality. The reason is not well understood, but a similar effect was observed even more clearly in the post-processing solution (Douša, 2003).

EXPLOITATION OF GLONASS DATA

In 2009, we have extended the near real-time ZTD estimation procedure towards the use of GLONASS data. This consisted of specific steps towards improving the robustness of the solution. Again, stand-alone GPS or GLONASS solutions were enabled besides the GNSS combined solution. For testing all the solutions, we set up a network of 38 European stations providing both GPS and GLONASS hourly data. The network was processed during 30 days for all three independent dataset variants. Common configuration and strategy were applied and to enable simple ZTD comparison between the solutions, the coordinates were kept fixed on the same values. More details can be found in Douša (2009).

Comparing near real-time ZTDs from each processing solution with respect to the post-processing results, we demonstrated a good consistency of the GLONASS, GPS and GNSS results. The standard deviations of ZTDs of the last processing hour are in the range of 4-6 mm for all 38 stations of the processed network. We didn't find a significant improvement in ZTD quality comparing GNSS to stand-alone GPS solution. On the other hand, Figure 13 demonstrates a very good quality of ZTDs from a stand-alone GLONASS solution despite occasional data problems and overall lower accuracy of the predicted GLONASS precise orbits. A systematic error in ZTDs from GPS and GLONASS has been identified. For all stations in the network, the GLONASS ZTDs resulted in approx. 1-3 mm lower values than ZTDs estimated by GPS only, see Figure 14.

In the future, the impact of GLONASS on ZTD estimation will increase with completing the system and with the increased number of observations, as well as when it is supported by the precise ultra-rapid orbit products from IGS. The higher benefit is expected mainly in gradient estimation or slant troposphere path delay estimation.

PRECISE PREDICTED ORBITS REQUIREMENTS FOR ZTD

The effect of errors in the predicted orbits on estimated ZTDs was studied in order to assess the relevant ultra-rapid orbit update cycle. Two different, widely applied strategies, were used in the study – the Precise Point Positioning (Zumberge, 1997) and the network solution (e.g. used at GOP). The capability of the compensation of the radial and tangential orbit errors in both techniques by various estimated parameters (satellite and receiver clocks, phase ambiguities) were assessed.

Assuming the compensation by ZTD only and admitting the error of 1 cm in ZTD, the marginal requirement for the maximum orbit error is 1 cm for radial- and 8 cm for tangential position components using PPP approach, versus 217 cm (radial) and 19 cm (tangential) using network solution. Nevertheless, in radial orbit position, an error of a few meters can be still absorbed by satelite clocks (96 %) and phase ambiguities (97 %) even in PPP technique. A tangential orbit position error up to 8 cm for PPP- and 38 cm for network solutions should not bias ZTD by more than 1 cm, but in general, a bigger error cannot be accepted. Its impact on ZTD further depends on the compensation ability of ambiguities and clocks (PPP) in specific constellations. More details are given in Douša (2009).

5 CONCLUSION

This paper summarises the developments of the near real-time GNSS solutions at the Geodetic Observatory Pecný within the CEDR project (2005-2009). After many improvements, the products achieved a level of maturity, which is proved by their operational use in various services and applications. The EUREF GOP data centre contributes to the distribution of near real-time GNSS data and products especially in Europe. The GOP precise near real-time orbits contribute to the IGS ultra-rapid product, which is combined from seven independent contributions, and which is the most precise GPS orbit product in real-time. The IGS product is exploited in numerous near real-time or real-time applications, both scientific and commercial. The zenith troposphere delays estimated at GOP in near real-time contribute to the EUMETNET GPS Water Vapour Programme and they are distributed to meteorological agencies worldwide. As of 2009, Meteo France and UK Met Office operationally assimilate our near real-time ZTDs in order to improve the numerical weather forecasting.

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