Variations of GPS Solutions for Positions of Permanent Stations
– Reality or Artefact –

J. KRYNSKI[1], Y. M. ZANIMONSKIY[2], J. CISAK[3], P. WIELGOSZ[4]

Abstract

Solutions for positions or vector components obtained from processing precise GPS observations are affected by numerous factors. Time series of such solutions indicate the existence of number of regular periodic biases that are not modeled in data processing stage. Processing of as long as daily observing sessions allows to substantially reduce the effect of a number of regular biases. Modeling the biases is required to get better accuracy of positioning with the use of shorter observing sessions. Separation of periodic biases onto three groups depending on ground segment (receiver, antenna and software), space segment (orbits and satellites configuration) and environmental segment (troposphere and ionosphere models) and eventual real displacements of the sites is needed to work on modeling the biases. Some of the biases detected seem to be artefacts.

1. Introduction

Solutions for positions or vector components obtained from processing precise GPS observations are affected by numerous factors. Time series of such solutions indicate the existence of number of periodic components and trends that are not modeled in data processing stage (BRUYNINX, 2001). Slow tectonics and other processes cause long-term trends in the solutions. There may also be abrupt offsets in the data due to seismic events or equipment changes. Periodic effects may exist at a variety of frequencies. They include annual rainfall and vegetation cycles, atmospheric pressure loading, long-term droughts, and other virtual effects due to the GPS system design or data processing procedure. Virtual changes of vector components, or in other words, substantial instrumental and numerical artefacts, are the subjects of this paper. In particular, an environmental segment (troposphere and ionosphere modeling errors) was investigated.

Considerable efforts have recently been made to investigate an impact of atmosphere on the errors of GNSS measurements, both systematic and random ones. Variations in the time series of GPS solutions are investigated at the Institute of Geodesy and Cartography, Warsaw, using conventional approaches as well as newly developed processing techniques. The research is carried out in several directions. Substantial effort is given to an increase of time resolution of GPS solutions time series with simultaneous reduction of random errors. To efficiently deal with those two intrinsically incompatible problems the method based on the analysis of GPS solutions obtained from overlapped segments of data from permanent GPS stations, e.g. the EPN stations, has been developed. The concept of overlapped segments is conventionally used to process the time series of data. Its advantages and disadvantages are widely discussed in the literature (e.g., HARRIS, 1978; NUTTALL and CARTER, 1982; WEBLEY et al., 2002). The larger an overlap, the higher time resolution of the series and more complete use of input information, but simultaneously the larger correlation between the parameters estimated. An increase of correlation coefficient due to an overlap of data segments is not a serious problem as long as it is taken into consideration when estimating statistical parameters, e.g. standard error of the mean. Rigorous analysis of the series of solutions obtained by processing satellite data from overlapped segments requires the modification of the computing procedure within the existing software packages by additional tools for correlation estimation.

These procedures are much more complex than those used in classical statistical toolboxes. The number of degrees of freedom is limited for the user of the programs to the choice of parameters and eventually the choice of software packages. The choice of appropriate parameters is, however, quite effective and the user can implement the refined enough approach to obtain GPS solutions (scientific software packages, e.g. Bernese - a representative high-end package or even commercial package - PINNACLE). The further processing of GPS solutions is rather a routine procedure. Time series of coordinates or components of vectors between stations do not exactly represent a random process. It is rather similar to an outcome of combined generators of random and chaotic numbers as well as periodic and polynomial trends (KRYNSKI et al., 2002). At the present stage of research it was not possible to obtain such a close mathematical formula for a correlation coefficient between the solutions obtained with the use of overlapped intervals that is known in the literature for random numbers. Some efforts in that direction were performed when the results of numerical experiments with the use of PINNACLE package are investigated.

[1] Jan Krynski, Institute of Geodesy and Cartography, Jasna 2/4, PL 00-950 Warsaw, Fax: +48 22 8270328, Tel.: +48 22 8280269/113, E-mail: krynski@igik.edu.pl

[2] Yevgen M. Zanimonskiy, Institute of Geodesy and Cartography, Jasna 2/4, PL 00-950 Warsaw, Fax: +48 22 8270328, Tel.: +48 22 8280269/121, E-mail: astro@igik.edu.pl

[3] Jan Cisak, Institute of Geodesy and Cartography, Jasna 2/4, PL 00-950 Warsaw, Fax: +48 22 8270328, Tel.: +48 22 8280269/121, E-mail: jcisak@asrecity.net

[4] Pawel Wielgosz, Institute of Geodesy, University of Warmia and Mazury, Michala Oczapowskiego 1, PL 10-957 Olsztyn, Fax: +48 89 5234768, Tel.: +48 89 5233279, E-mail: polix@uwm.edu.pl

The first results obtained with the use of overlapped segments have appeared rather impressive. It became possible to reliably separate periodic variations of vector components in a diurnal range and, moreover, to divide them into the effects of varying configuration of GPS satellites, with a fundamental period equal to a sidereal day (Krynski and Zanimonskiy, 2001a) and the effects of varying meteorological (Krynski and Zanimonskiy, 2001b) and ionospheric (Krynski and Zanimonskiy, 2002) parameters, with a period equal to a solar day. Due to the excellence of output data provided by the Bernese scientific package, such separation, quantitatively sufficient, was achieved on the basis of GPS data covering 4 months. More reliable qualitative estimation of spectral parameters would obviously require the analysis of longer time series of GPS solutions. Application of phenomenological models of variations of vector components in a sidereal time scale results in reduction of dispersion in time series of GPS solutions obtained from the 3 h long sessions by up to 20 % (Krynski et al., 2002). The obtained results are based on the analysis of variations of the components of vectors formed by Polish and also some Ukrainian permanent GPS stations.

One of the well-known sources of errors in geodetic positioning using satellite techniques comes from the modeling of atmospheric delay of the signal. Different models of ionosphere and troposphere, from quite simple to sophisticated ones, are implemented into different software packages for GPS data processing. The experiments described in the literature, e.g. (Gregorius and Blewitt, 1998), show that the errors due to atmospheric impact depend on a used software package and chosen parameterization (Krankowski et al., 2002). The atmospheric impact on GPS solutions was until now estimated under the assumption of stability of vectors between permanent stations (stable within the range of periods characteristic for variations of atmospheric parameters). The more developed program used and the more skillful its operator the smaller dispersion of results, in particular in conditions of passing atmospheric front (Gregorius and Blewitt, 1998) or ionospheric storm (Baran et al., 2002).

2. Numerical tests and results

Time series of GPS solutions based on processing observations from overlapped data segments allows for investigation of atmospheric impact on GPS measurements in a new dimension. Such a series can be considered as a record of the process of variations of vector components during varying atmospheric disturbances. The experiments performed concerned the investigation of the response of the measuring system to tropospheric perturbations when atmospheric front was passing the region as well as the response of the measuring system to an ionospheric storm.

It is quite natural that the first experiment was performed with the use of the PINNACLE program since it provides solutions affected by the atmosphere much stronger than those of Bernese program. Calculations were conducted using overlapped observing sessions of the length varying from 2 to 26 hours. The shift of 1 hour between the consecutive sessions processed was applied, i.e. two-hourly sessions were overlapped by 50%, and 24 hourly - accordingly by 96%. Three-weeks data, from August 12 until August 29 2001, from BOGO and JOZE EPN stations was processed. TZD data for the Central and East European EPN stations available at web sites of EUREF was analysed. The structure of atmospheric variations above the region along 50 parallel in Europe is quite specific. The atmospheric fronts that pass from west to east keep frequently the same structure when moving along 1-2 thousand kilometres during one or two days. Time dependence of TZD at several sites within 50-th parallel zone of the Central and Eastern Europe, from BOR1 up to GLSV, obtained for two independent epochs of 2001 clearly reflects an eastward traveling of the atmospheric fronts with the average speed of 18 km/h and 50 km/h, respectively (Fig. 1a, 1b). Passing front causes noticeable change of a measured height difference of two sites: BOGO and JOZE that are located almost along a meridian, 42 km apart from each other. Variations of height differences obtained from processing 3 h long GPS sessions practically coincide with the rate of variations of corresponding TZD (Fig. 1c). Unfortunately the 2 h time resolution of TZD data accessible on the web sites is lower than the one for GPS height differences determined (1 h) and makes it insufficient for correct description of such, rather fast process, as passing atmospheric front (recent TZD data are available with 1h resolution).

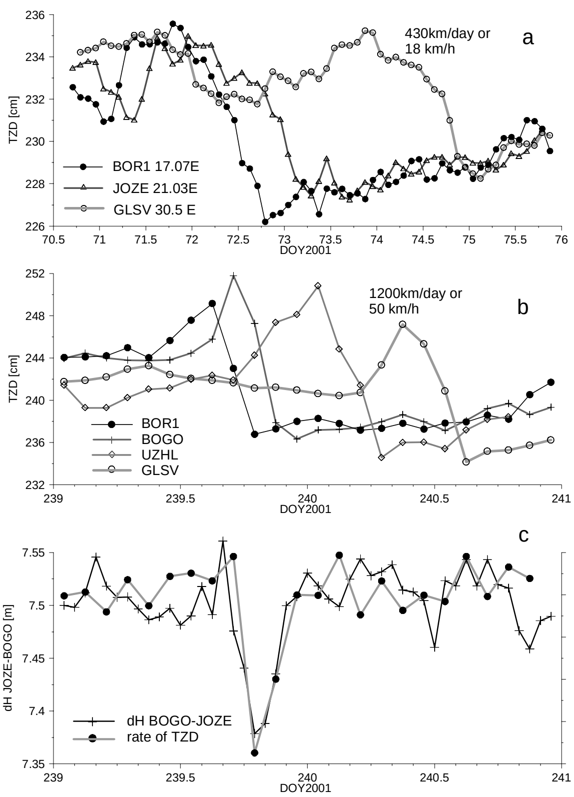

Fig. 1. Effect of atmospheric fronts traveling from west to east

Time series of the same vector components obtained with the use of the Bernese program, as expected, does not show significant variations during atmospheric front passing over the region. Certainly, different strategies of calculation and modeling of tropospheric effects provide different results in terms of remaining errors both random and systematic ones that affect GPS derived positions (FIGURSKI et al., 2000). Similar conclusion concerns the choice of strategies and modeling of ionosphere effects (BOSY et al., 2002).

The obtained results seem to confirm a widely spread judgement on a rather simple relation between an error in height estimation and an error of TZD (CUCURULL et al., 2002; FIGURSKI, 2002). Cucurull writes: "Accordingly, an error of 1 cm in TZD corresponds to an error of -3.4 cm in the clock correction, respectively, -2.5 cm in the height estimate, i.e., both the clock bias error and the station height error have the opposite sign with respect to the TZD error." The results of analysis do not confirm such a conclusion. It could be so but only under well-determined conditions. The correlation of the two errors can during several hours get switched to anti-correlation. An example of such a change was detected after the rainfall when analysing the time series of GPS solutions obtained from processing 2 h long sessions as well as TZD data from August 2001 (Fig. 2). The quantitative description of the phenomena is as follows. From August 12 until August 21 each millimetre in TZD increase corresponded to the increase of the height difference by 0.36 mm with correlation coefficient of 0.5, and from August 22 until August 29 1 millimetre increase of TZD corresponded to a decrease of height difference by 0.47 mm with correlation coefficient of 0.7.

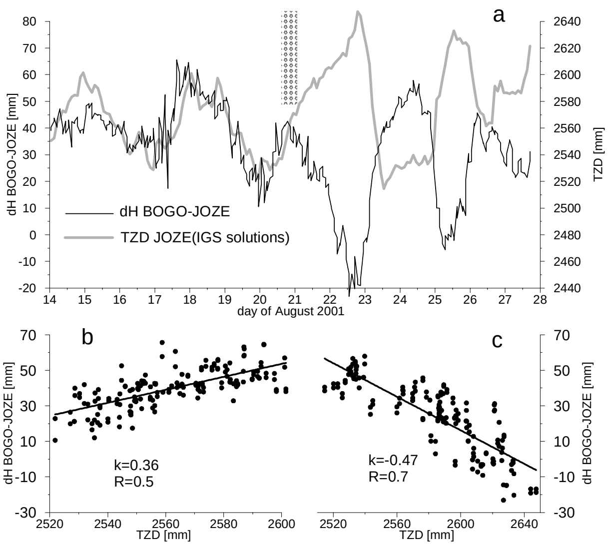

Fig. 2. Change of correlation of TZD and height variations to anti-correlation after the rainfall in August 2001

The experiments show possibilities of investigating circulation of atmospheric fronts in both time and space domain (apparently not in height) with the use of data from the network of permanent GPS stations. Unfortunately the number of GPS permanent sites that operate in Ukraine is insufficient for efficient monitoring of atmospheric fronts with GPS in Central and Eastern Europe. The sites located within 50 parallel zone, including the one in Kharkov that will start operating soon will apparently enable to monitor a central part of the fronts. Information on the processes at the edges of the atmospheric front can be obtained, in addition, from meteorological data provided by the network of stations that operate in the region. Thus the analysis of GPS solutions together with tropospheric and weather data at the beginning of eastwardly moving fronts in Western and Central Europe is required for "calibration" of a weather data (e.g. REIGBER et al., 2002).

Most of the recent publications on GPS and ionosphere (e.g. Baran et al., 2002) are focused on two problems. First one concerns modeling the ionosphere and determination of its parameters for real time positioning in global and regional scales (WAAS, LAAS) particularly with the use of single frequency receivers. The second direction is to investigate ionosphere in purely physical sense. The intension of the authors of this paper was to give an attention to one more, quite important and interesting topic that concerns ionosphere and top accuracy satellite positioning. The problem could be named the ionosphere and high-end satellite positioning. It could further be divided into two parts: a "discrete" one and a "continuum" one. The discrete part covers the problems of phase ambiguity resolution, cycle slips and change of satellite configuration during data acquisition. Long-term efforts of mathematicians and programmers in that matter are reflected in numerous publications and in developing more and more advanced scientific and commercial programs.

As it was already mentioned, the user in general has no access to the core of the program, but he can change parameters and computing strategies, in particular, when considering ionospheric effects. One of the main purposes of the conducted investigations was to use to a maximum degree the potentiality of software packages for suppression of discrete errors to try to estimate continuum.

The problem of continuum refers to errors related to non-linearity of computing algorithms and to second order effects of signal propagation in ionosphere. The non-linearity of algorithms used to process data from satellite geodetic systems and their linearization is already quite widely discussed in the literature (TIBERIUS, 1998). To add up something new to it seems difficult, however, it is possible. Namely, a weak non-linearity results in a well-known effect of detection, i.e. conversion of variations of parameters of the process or input signals into biases in output data. Qualitative and quantitative assessments of such conversion of a random error into a systematic one are indispensable when estimating metrological properties of the measuring system. An increase of a random error during ionospheric storms (BARAN et al., 2002) could be used as a test signal for testing the hypothesis on detection.

It is possible to show that the errors of single layer model (SLM) of ionosphere result in appearance of non-linearity in a total electron content (TEC) that affect the estimate of pseudo-ranges (BRUNNER and GU, 1991). It can further affect the estimates of other quantities, e.g. TZD and vector components. The present maxima of solar activity give a good chance to test numerous hypotheses related to continuum errors.

The numerical experiment was conducted using four months GPS data from February until May 2001. The use of Bernese software provided a high-end standard. The data from four Polish (BOR1, BOGO, JOZE, LAMA) and one Ukrainian (UZHL) EPN stations was processed. Processing of 24 h long GPS sessions is widely used as a standard for high precision monitoring of station positions as well as for Earth rotation and atmospheric parameters determination (Fig. 3a). Such observing sessions with an overlap (shifted by 1 h with respect to each other) were processed and used as reference (Fig. 3b).

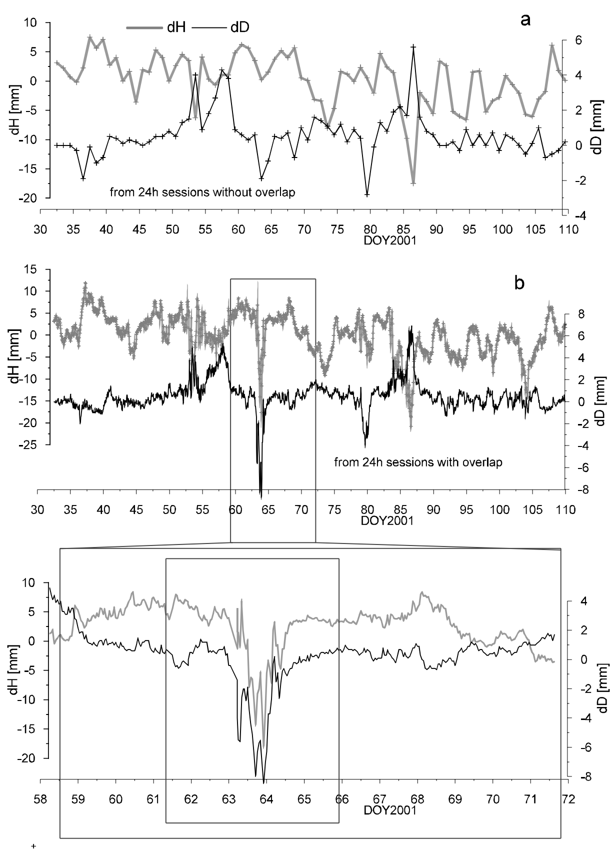

Fig. 3. Components of BOGO-JOZE vector from 24h sessions without and with overlap

In addition, to investigate short-term effects, computations were conducted using data from 4 h and 3 h long overlapped sessions shifted with respect to each other by 1 h and 0.5 h, respectively (Fig. 4). Data was processed with CODE (Centre for Orbit Determination in Europe) final orbits and CODE global ionosphere model (SCHAER, 1999) using the following strategy (WIELGOSZ, 2002)

- L3 ambiguity free solution for checking the accuracy of the coordinates,
- troposphere parameters estimation with no a priori model and Dry-Niell mapping function (one parameter per hour for 24 h long sessions, one parameter per 2 h for 4 h long sessions and one parameter per 3 h for 3 h long sessions),
- wide-lane (L5) ambiguity resolution (with CODE ionosphere model) fixing all coordinates (HUGENTOBLER et al., 2001),
- new L3 ambiguity resolution introducing the resolved wide-lane ambiguities and solving for the narrow-lane ambiguities,
- final vector's coordinates from fixed solution.

Data on TZD and TEC was selected from the web sites for the same period.

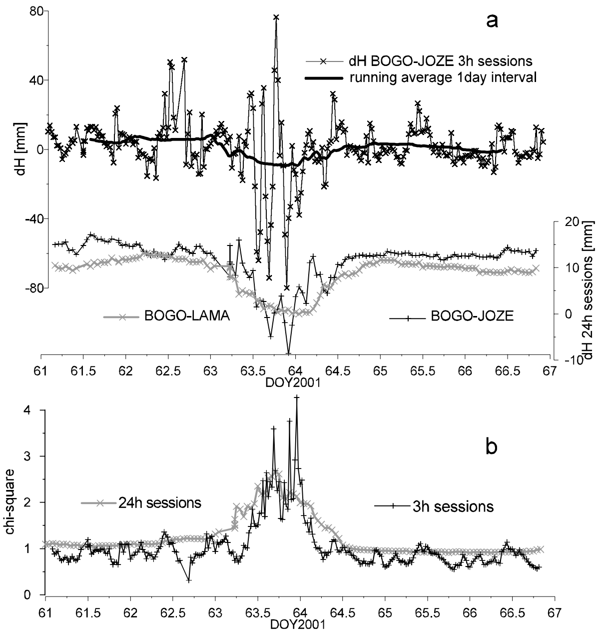

Fig. 4. Variations of the estimations of height components (a), as an eventual consequence of the internal errors in GPS data processing (b)

Time series of height component of BOGO-BOR1 vector and its length derived from GPS solutions spanned over 2 months together with an internal error estimate (P^2) and with time series of Kp index that is the measure of solar activity as well as of filtered TEC and rms of TZD for the respective period are presented in Fig. 5. The values of TEC shown in the graph was obtained from the IGS solutions using a bandpass filter in order to smooth its diurnal variations and filter out seasonal effects.

It is well known that variations of solar activity generate state transitions in ionosphere. Ionospheric storms can be both positive and negative that is reflected correlation or anti-correlation of Kp with TEC, respectively. In many time intervals in Fig. 5 an anti-correlation of Kp with TEC is observed. The polar ionosphere at the greatest degree reacts to solar activity variations. Thus ionospheric variations over DAV1 station are more expectable then those over BOGO or BOR1. Moreover, perturbations in a polar ionosphere are much more distinguished than the respective variations of Kp index. Variations of TEC above Australia (TIDB) and above Europe (BOGO) are slightly different, but they in general correspond to variations of Kp.

Time series of GPS solutions in Fig. 5 show that not all variations in the state of ionosphere are significant in the computed height differences or vector lengths. The response of the measuring system (for example, change of the estimate of distance dD) is not proportional to changes in ionosphere (TEC) and changes of an index of solar activity. On the other hand such response is characteristic for non-linear systems. Note that the change of the computed distance is followed by an increase of P^2, that is the measure of the internal stochastic processes in computing sessions. It should be noted, however, that not every increase of P^2 corresponds to a change of the estimate of vector length.

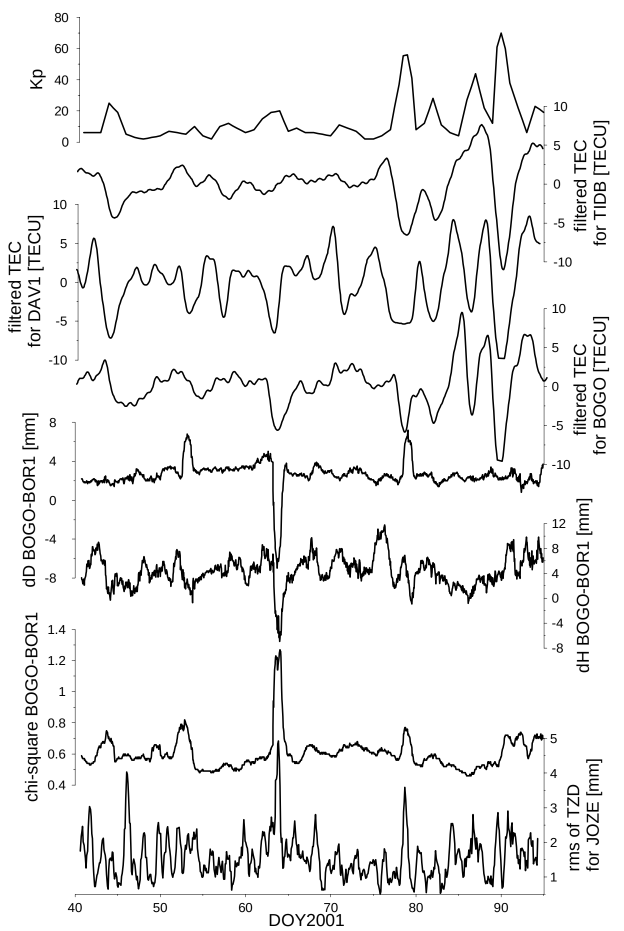

Fig. 5. Solar activity and atmospheric parameters versus variations in height component, vector length and P^2 estimate

Variations of height difference as well as vector lengths reflect the processes in both ionosphere and in troposphere that hampers their interpretation.

The lowest graph in Fig. 5 shows a system response in the mode of tropospheric measurements. It is visible that the estimated error of tropospheric delay increases at some ionospheric agitations. The response to ionospheric agitations is not seen in the estimated TZD because of the effect of strong meteorological variations.

3. Conclusions

Changes in the state of ionosphere and troposphere cause respective variations in the geodetic measurements obtained with the use of the satellite navigation systems. Short-term effects, such as ionospheric storms and atmospheric fronts could be detected and investigated when processing overlapped observing sessions that provide appropriate temporal resolution. Numerical experiments conducted with the use of a chosen data show that not all ionospheric disturbances reflect in variations in vector components estimated with high-end computing strategy. An increase of dispersion shown by P^2 estimate can be considered as an indicator of artefact. It could be interpreted as a result of a weak non-linearity of a measuring system, including data processing algorithm. If random errors due to e.g. uncertainties in ambiguity resolution (MERVART, 1995) substantially increase during ionospheric storm then a weak non-linearity affects the results with biases. Estimated biases in vectors lengths and their vertical component obtained form 24 h long sessions reached several millimetres. Unbiased results are obtained when ionosphere disturbances do not cause the increase of random errors. Weekly averages of GPS solutions over time interval that included ionosphere disturbances show a bias of one millimetre.

Investigations are continued with the use of large data sets from middle and high latitude regions, in particular Northern Europe and Antarctica, processed with different strategies.

Time series of GPS solutions obtained with the use of PINACLE package do not reflect any non-linearity due to respectively high level of modeling errors. Reaction of a measuring system to passing atmospheric fronts seems quite predictable. Height differences estimated from GPS data are correlated with gradients of TZD and their rates of change. The use of processing strategy based on Bernese software leads to a smooth solution free of atmospheric front impact.

Acknowledgments

The research was supported by the Institute of Geodesy and Cartography in Warsaw and was partially financed by the Polish State Committee for Scientific Research (grants No 9T12E01918, 8T12E05321 and 8T12E04520).

References

BARAN, L.W., ROTKIEWICZ, M., SHAGIMURATOV, I.I., WIELGOSZ, P., (2002): *Ionospheric effects during a geomagnetic storm*, International Association of Geodesy Symposia, Springer-Verlag Berlin Heidelberg, Vol. 125, pp 291-296.

BOSY, J., FIGURSKI, M., WIELGOSZ, P., (2002): *The strategy of GPS data processing in precise local networks during rising solar activity*, GPS Solutions (in print).

BRUNNER, F.K., GU, M., (1991): *An Improved Model for Dual Frequency Ionospheric Correction of GPS Observations*, manuscripta geodaetica, 16, pp 205-214.

BRUYNINX, C., (2001): *Overview of the EUREF Permanent Network and the Network Coordination Activities*, EUREF Publication, Eds. J. Torres, H. Hornik, Bayerischen Akademie der Wiessenschaften, München, Germany, 2001, No 9, pp 24-30.

CUCURULL, L., SEDO, P., BEHREND, D., CARDELLACH, E., A. RIUS, A., (2002): *Integrating NWP products into the analysis of GPS observables*, Physics and Chemistry of the Earth, 27 (2002), pp 377-383.

FIGURSKI, M., (2002): *Determination of chosen parameters of atmosphere with the use of permanent GPS observations and their impact on accuracy of satellite solutions* (in Polish), BEL Studio, Warsaw.

FIGURSKI, M., WIELGOSZ, P., BOSY, J., (2000): *Reduction of ionospheric refraction in local geodynamic networks,* Reports on Geodesy, No. 8 (54), 2000, pp 75-79.

GREGORIUS, T., BLEWITT, G., (1998): *The effect of weather fronts on GPS measurements*, GPS World, May 1998, pp 52-60.

HARRIS, F.J., (1978): *On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform*, Proc. IEEE, Vol. 66, pp 51-83, January 1978.

HUGENTOBLER, U., SCHAER, S., FRIDEZ, P., (2001): *Bernese GPS Software Version 4.2*, Astronomical Institute, University of Berne.

KRANKOWSKI, A., BARAN, L.W., SHAGIMURATOV, I.I., CISAK, J., (2002): *Influence of Ionosphere in Antarctic Region on GPS Positioning Precision*, Collection of Papers and Viewgraphs of IGS/IAACs Ionosphere Workshop, ESOC Darmstadt, Germany, January 17-18, 2002.

KRUCZYK, M., ROGOWSKI, J.B., LIWOSZ, T., (2001): *On Accuracy of IPWV Determined from GPS Networks*, Reports on Geodesy, No 3 (58), 2001.

KRYNSKI, J., ZANIMONSKIY, Y., (2001a): *Contribution of Data from Polar Regions to the Investigation of Short Term Geodynamics. First Results and Perspectives,* SCAR Report, Publication of the Scientific Committee on Antarctic Research, Scott Polar Research Institute, Cambridge, UK.

KRYNSKI, J., ZANIMONSKIY, Y., (2001b): *Common Features of Time Series of Superfluous Gravity, GPS Derived Positions and Meteo Data within Diurnal Interval*, Proceedings of the IAG 2001 Scientific Assembly, Vistas for Geodesy in the New Millennium, 2-7 September, 2001, Budapest, Hungary.

KRYNSKI, J., ZANIMONSKIY, Y., (2002): *Diurnal variations in gravity data and GPS solutions. Facts and artefacts* (in Russian), Paper presented at the International Conference on Modern Progresses of Geodetic Sciences and Industry, 28-30 March, Lvov, Ukraine.

KRYNSKI, J., ZANIMONSKIY, Y.M., WIELGOSZ, P., (2002): *Modelling biases in GPS positioning based on short observing sessions*, Presented at XXVII General Assembly of European Geophysical Society, Nice, France, 25-29 April 2002.

MERVART, L., (1995): *Ambiguity Resolution Techniques in Geodetic and Geodynamic Applications of the Global Positioning System,* Geodätisch-geophysikalische Arbeiten in der Schweiz, Schweizerische Geodätische Kommission, PhD thesis, Vol. 53.

NUTTALL, A.H., CARTER, G.G., (1982): *Spectral Estimation Using Combined Time and Lag Weighting*, Proc. IEEE, vol. 70, pp 1115-1125, September 1982.

REIGBER, C., GENDT, G. DICK, G., TOMASSINI, M., (2002): *Water Vapour Monitoring for Weather Forecasts*, GPS World, Vol.13, No.1, 2002, 18.

SCHAER S., (1999): *Mapping and Predicting the Earth's Ionosphere Using the Global Positioning System*, PhD Thesis, Astronomical Institute, University of Berne.

TIBERIUS, C., (1998): *Recursive data processing for kinematic GPS surveying*, Publications on Geodesy 45, Delft, July 1998.

WEBLEY, P.W., BINGLEY, R.M., DODSON, A.H., WADGE, G., WAUGH, S.J., JAMES, I.N., (2002): *Atmospheric water vapour correction to InSAR surface motion measurements on mountains: results from a dense GPS network on Mount Etna*, Physics and Chemistry of the Earth, Vol.27, No.4-5, 2002, pp 363-370.

WIELGOSZ, P., (2002): *Problem redukcji wp»ywu refrakcji jonosferycznej na wyniki opracowania pomiarów GPS* (in Polish), Ph.D. thesis, Institute of Geodesy, University of Warmia and Mazury, Olsztyn, 2002.