Investigation of Regional Troposphere Processes Using EPN Data

J. KRYNSKI, Y.M. ZANIMONSKIY[1]

Abstract

Networks of continuously operating GPS receivers are set up by geodesists, geophysicists, government and military agencies to implement a wide range of positioning capabilities and atmospheric investigations. Microwave radio signals transmitted by GPS satellites are delayed by atmosphere. An improvement in modelling atmosphere is needed for developing and spatial extension of real time GPS positioning technology. It might also be useful for precise processing of GPS data. Complexity of spatial and temporal dynamics of tropospheric processes makes them difficult to model. Applying statistical methods to the analysis of data from continuous GPS arrays can substantially reduce the regular effects of troposphere on GPS solutions. Tropospheric delay data obtained for Central and East European permanent EPN stations was analysed. The structure of atmospheric variations above the region along 50º parallel in that part of 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. Relatively simple structure of motion of such atmospheric fronts as compared with West European fronts allows their effective investigation.

1. Introduction

Precise processing of GPS data for geodesy and geodynamics as well as developing and spatial extension of real time GPS positioning technology require further improvement in modelling atmosphere. Numerous research groups are involved in both theoretical and experimental works on the subject. Investigation of atmospheric impact on the results of GPS positioning is carried out by the authors of this paper already for a few years. The research concerns both ionospheric and tropospheric effects. The effect of ionospheric disturbances on GPS solutions has been extensively analysed (Krynski et al., 2002a), (Krynski et al., 2002b), (Krynski and Zanimonskiy, 2002). Ionospheric data is already used in geodetic surveying to generate corrections to GPS positioning with single-frequency receivers. Total zenith delay data determined by processing GPS data from permanent GPS stations, similarly to the information provided by global maps of TEC, is so far mainly used by meteorologists (Douša, 2001; Reigber, et al., 2002) and practically is not applied in precise GPS positioning. Moreover, TZD data is not widely used in practical GPS surveying.

The investigation of regional tropospheric processes using EPN data is the aim of the paper. Preliminary results concerning the use of TZD, available on web pages for IGS and EPN permanent GPS stations, for the determination of corrections to GPS solutions, were obtained with widely used software packages such as Bernese and Pinnacle. Numerous long time series of vector components, derived from processing GPS data from chosen European permanent GPS stations, were generated. They provide extremely rich information on variability of GPS solutions that together with the external data enables qualitative and quantitative analysis of those variations as well as their reliable statistical estimate.

The experiments performed concerned the investigation of the response of the measuring system to ionospheric as well as tropospheric disturbances. The new approach of data analysis was conducted to check the repeatability of the response. It is based on the analysis of GPS solutions obtained from the overlapped segments of data (Krynski et al., 2002a). 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.

2. Correlation Analysis of TZD

Large uncertainty in weather prediction, despite of growing access to meteorological data in terms of scale, quality and quantity, indicates a complexity of temporal dynamics of tropospheric processes and difficulty of its modelling. Different types of data acquired using different techniques contribute to determination of different components of tropospheric models. Total zenith delay (TZD) that describes the delay of electromagnetic signal when passing troposphere, mapped onto the vertical path is one of such components. TZD is easily accessible as a by-product of the analysis of data from continuous GPS arrays.

[1] Jan Krynski, Yevgen M. Zanimonskiy: 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, yzan@poczta.onet.pl

Worldwide IGS network that consists of more than 200 permanent GPS stations, besides typical GPS and geodynamics products provides TZD data with 1 h temporal resolution and spatial resolution corresponding to the distribution of GPS stations participating in the program. TZD data files are accessible on IGS and EUREF web pages. Information on spatial distribution of TZD and its temporal variability is undoubtedly valuable for meteorologists to improve models used for weather prediction. In order, however, to calculate corrections that allow the extension of real time satellite positioning systems, a prediction of TZD using suitable models is required. The main disadvantage is that the TZD modelling accuracy gets worse with growing distance between the user and the permanent GPS station.

An extended research on variability and predictability of TZD in space and time domain is needed to efficiently derive such models. The analysis of correlation function of TZD is one of the simplest ways to study the phenomenon. Such a correlation function of TZD over a number of Central European permanent GPS stations was investigated using TZD data series with 1 h temporal resolution from April 14 until June 16, 2002, stored on EUREF web pages. Calculated correlation functions as well as the spectra of TZD variations over the stations are given in Fig. 1. The rms of correlation coefficient determined increases almost linearly from 0 to 0.2 with time lag varying from 0 to 24h.

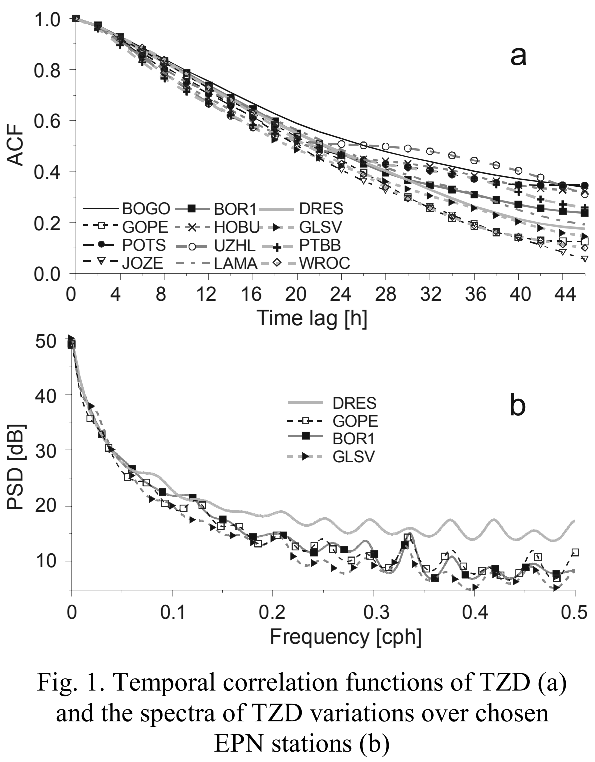

Fig. 1. Temporal correlation functions of TZD (a) and the spectra of TZD variations over chosen EPN stations (b)

Correlation functions of TZD over the individual GPS permanent stations investigated are only slightly dispersing within 24h interval; beyond that interval dispersion becomes substantial. It could result from purely geographical reasons or eventually technical constraints since, for example, a relatively large discrepancy of correlation functions for data over BOGO and JOZE stations that are only 42 km apart from each other, cannot be explained in terms of geography. The analysis of that phenomena exceeds however the research discussed in the paper.

Correlation coefficients of TZD decrease to the level of 0.5 after about 24h, practically for all stations investigated. However, for 3-5h intervals, correlation remains at the level of 90% what indicates a possibility of efficient interpolating TZD at arbitrary epoch when its data series is provided with a few hours temporal resolution.

Also the spectra of TZD at different stations are quite similar. Regular waves at higher frequencies of TZD spectra occur due to discretisation of TZD function and are associated with its sampling. Due to simplicity of the model used to generate TZD from GPS data, the estimated values of TZD represent the average over a sampling interval and they are tagged to the mean epoch of that interval. It results in an apparent smoothness of TZD series as well as in its apparent regularity.

Variations of TZD in space domain were also investigated. Correlation coefficient of TZD computed for the pairs of EPN stations shown in Fig. 2b versus a distance between the corresponding stations is given in Fig. 2a.

Distances between the permanent GPS stations in Poland do not exceed 300 km while in Ukraine they are still much larger. The map of contour lines of the correlation function of TZD in space domain, derived from data associated with EPN stations is given in Fig. 2c. It shows that the correlation coefficient within Poland reaches at least a level of 80%. It indicates the possibility of efficient interpolation of TZD for most locations within Poland using the data estimated for EPN stations. Calculation of TZD in the regions of Baltic Sea coast and the mountains in southern Poland is much more complicated due to the specifics of troposphere over sea and mountainous regions.

3. Correcting GPS Solutions with Use of Empirical Models

It is well known that the variations of troposphere parameters affect the results of GPS surveying and further the GPS solutions. The problem was already quite widely discussed in the literature and to add up anything new to it seems difficult, however possible. For example one could consider the determination of the corrections to vertical component of a vector calculated from GPS data without modelling troposphere by using correlation between that component and TZD difference. Such a correlation could efficiently be determined with use of time series of GPS solutions with sufficiently high temporal resolution that can be obtained by processing overlapped segments of GPS data. The method makes possible a combined analysis of TZD with 1h temporal resolution and vectors components obtained from GPS sessions longer than 1h (ordinary from 3 up to 24h) with 1h temporal resolution owing to the overlapping procedure.

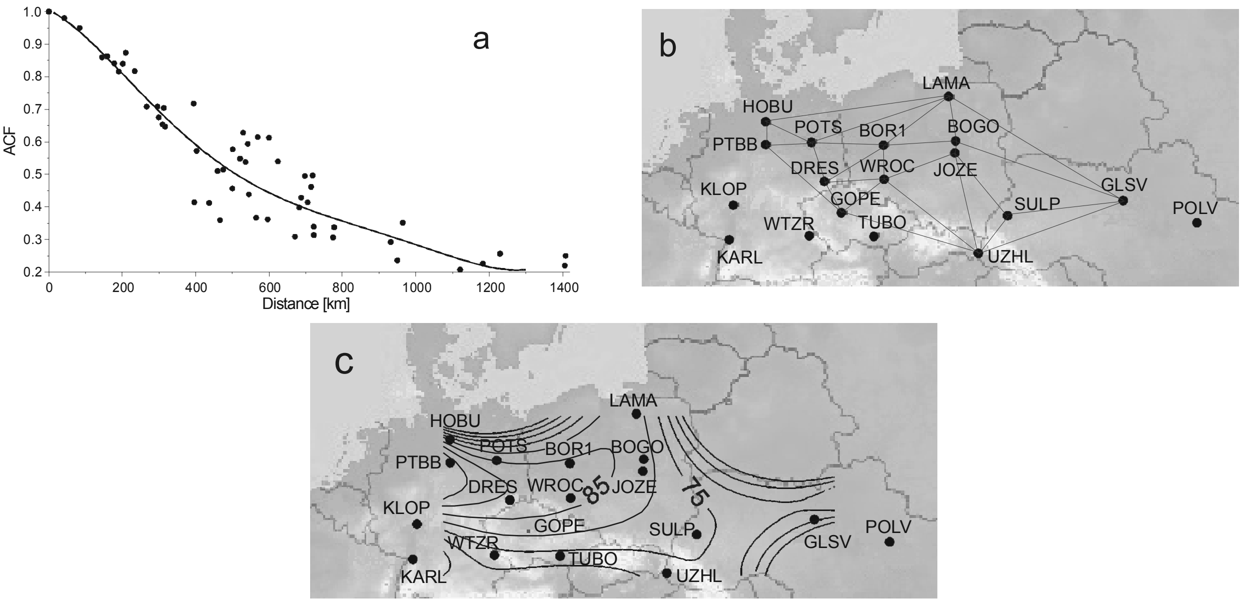

Fig. 2. Correlation function of TZD in space domain for a section of Central Europe (a) with the map of vectors investigated (b) and with interpolated contour lines of correlation coefficient (c)

Variations of TZD were analysed for numerous EPN stations. The results for BOGO and BOR1 stations as representative for Central Europe region are presented. Time series of TZD for BOGO and BOR1 stations (Fig. 3a) have a similar structure. Time series of GPS solutions for a vertical component of BOGO-BOR1 vector (~300 km length) calculated with use of Pinnacle software by processing 3h GPS sessions, together with time series of differences of TZD corresponding to those stations, are given in Fig. 3b. Both series are evidently correlated (Fig. 3d) what allows calculation of the correction δH to the vertical component using a simple relationship, i.e. δH = R×δ(TZD) where R is the regression coefficient. Residual variations of GPS solutions for a vertical component, after applying corrections δH, are shown in Fig. 3c.

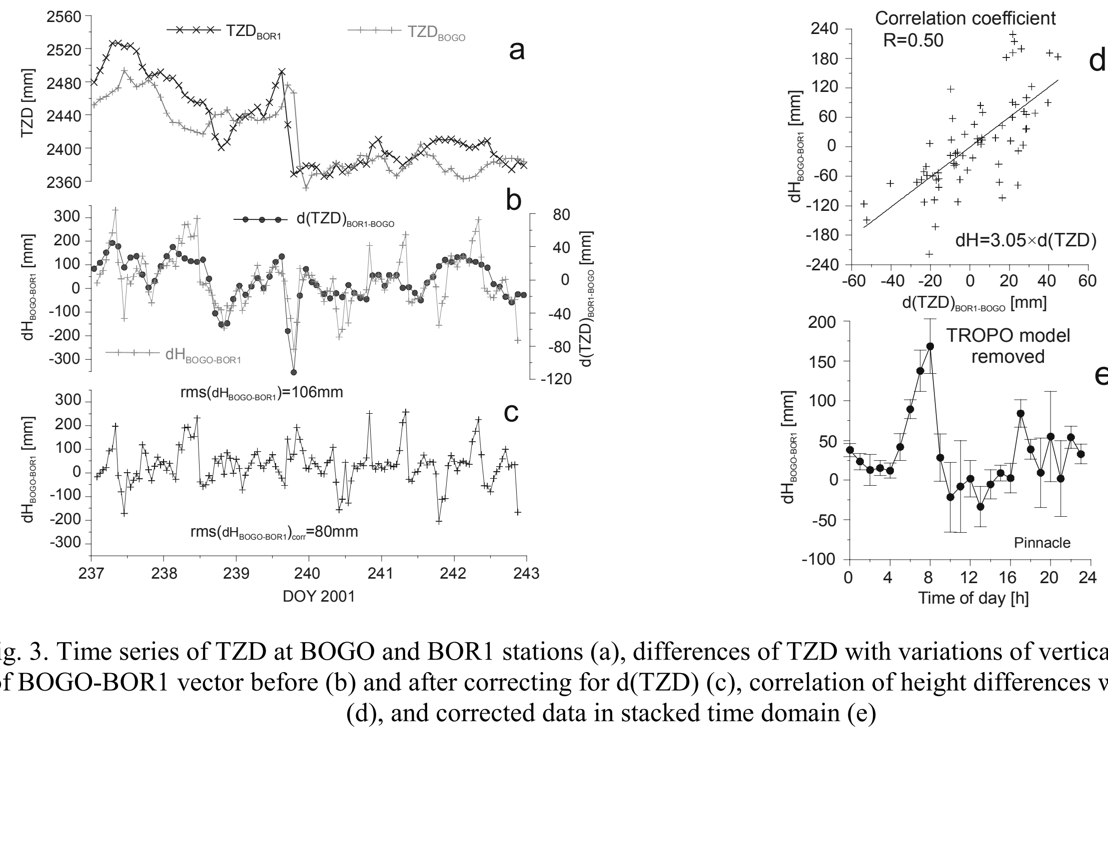

Fig. 3. Time series of TZD at BOGO and BOR1 stations (a), differences of TZD with variations of vertical component of BOGO-BOR1 vector before (b) and after correcting for d(TZD) (c), correlation of height differences with d(TZD) (d), and corrected data in stacked time domain (e)

Employing correcting terms to GPS solutions results in reduction of standard deviation of variations by up to 20%. Similar results were obtained for other vectors between the EPN stations investigated (Krynski et al., 2002b). The residual variations reflect the reaction of the GPS solutions to non-modelled ionospheric terms. Such a correction due to tropospheric effect is a linear function of TZD difference. Tropospheric effect does not affect the estimated height difference averaged over a long period of time, since TZD difference averaged over such a period equals to zero. That positive feature comes from the randomness of meteorological processes. Corrected height differences in stacked time domain are shown in Fig. 3e.

Joint analysis of time series of TZD together with time series of GPS solutions, in particular investigation of mutual correlation of δ(TZD) with height differences for Central European region, clearly shows its practical as well as cognitive aspects. It addresses the approach of correcting GPS solutions obtained with commercial software for tropospheric effects. It also contributes to the general knowledge on tropospheric processes in the region.

4. Structure of Atmospheric Variations Above the Region Along 50º Parallel in Central Europe

Time series of TZD for six stations of the investigated region that were used to generate correlation functions and spectra shown in Fig. 1 are given in Fig. 4. Similar terms are the bases of all signals presented. Also time shift of some terms is observed. The existence of such time shift in time series of TZD from permanent GPS stations of Central European region was already reported (Kruczyk and Rogowski, 2002).

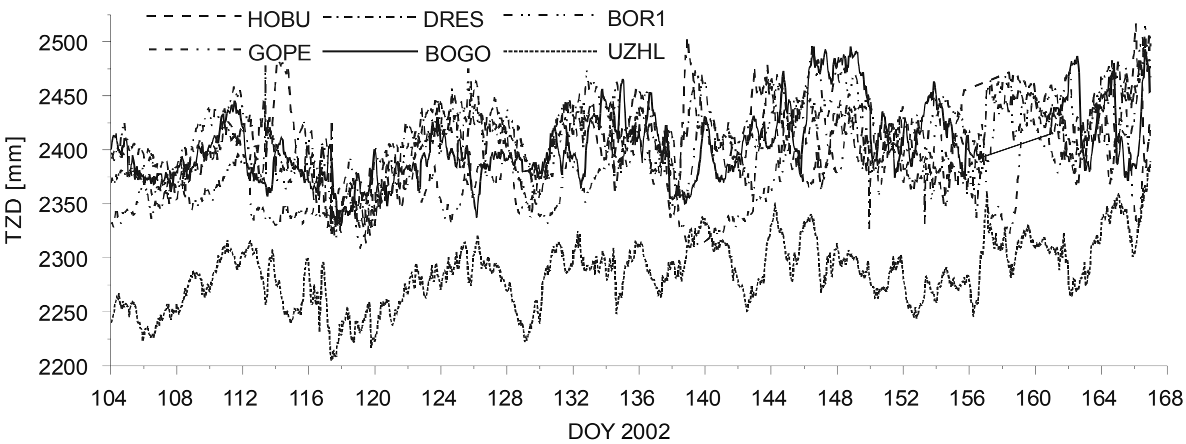

Fig. 4. Typical time series of TZD

Let us consider a 2D correlation coefficient of TZD in time and West-East distance between permanent GPS station in the region along 50º parallel. The coefficient was calculated using the TZD data series considered. Contour map and the 3D image of correlation coefficient are shown in Fig. 5. The larger the distance the larger time delay that corresponds to the movement of tropospheric events from west to east with speed of about 30 km/h is observed. Circulation of air masses from west to east in the form of atmospheric fronts is rather typical for Central Europe.

One of the main targets of this research is to investigate possibilities of correcting GPS/GLONASS solutions for the effect of dynamic tropospheric processes. Such a research requires first of all an extended analysis of large amount of data. High temporal resolution of TZD data that is already available on the IGS and EUREF web pages (1h resolution) enables to investigate the high-frequency terms in TZD time series. Several numerical examples were conducted considering regularity of atmospheric fronts circulation. Typical characteristics of them are discussed in the paper.

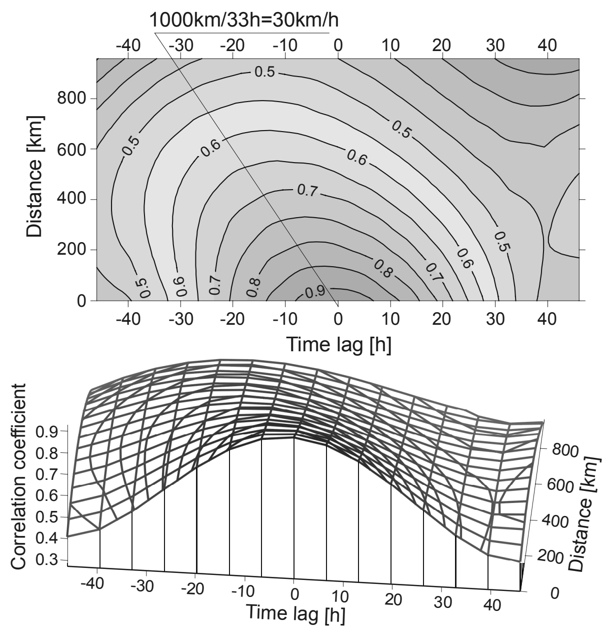

Fig. 5. Correlation coefficient of TZD in time and West-East distance between permanent GPS station in the region along 50º parallel

Time series of TZD for six stations in the investigated region over a period when the atmospheric front passes from west to east over Central Europe are given in Fig. 6a. Variations of TZD at all stations investigated are similar but mutually shifted in time. The shifts correspond to mutual location of the stations. Removing the shifts in time by fitting the curves to get their common characteristics can be considered as referring TZD time series at each station to its "local time" (Fig. 6b). Thus Fig. 6b illustrates the intensity of the atmospheric front when passing stations considered.

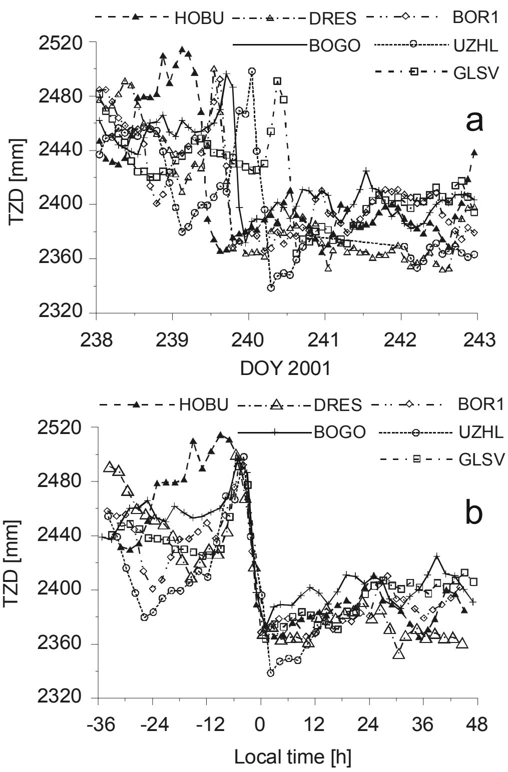

Fig. 6. Time series of TZD for six stations in the investigated region over a period when the atmospheric front passes from west to east over Central Europe (a) and after referring TZD time series at each station to its "local time" (b)

Some permanent GPS stations, besides standard GPS data, provide records of meteorological parameters that are also available on web pages. Time series of those parameters and their rates as well as TZD for BOGO and GOPE stations for August 27, 2001 when the atmospheric front was passing over those stations, are shown in Fig. 7a and Fig. 7b, respectively. There is an evident relationship between the variations of meteorological parameters and variations of TZD, although due to relatively sparse temporal resolution of TZD data available that equals to 2h (for 2001), correlation could not be well estimated. Recent availability of TZD with 1h temporal resolution will enable to investigate those correlations in future analyses. Variations of meteorological parameters and TZD at the remaining stations investigated have similar characteristics to those shown in Fig. 7.

Such a clear image of mutual correspondence of dynamics of variations of meteorological parameters, including TZD, was not always obtained at all EPN stations investigated. Distinguished rapid change of TZD in time at the station is the indicator of the existence of the large atmospheric disturbance. Data preceding together with data following such an event was processed toward estimation of time delay of the atmospheric front with respect to the epoch of its forming. The epoch of the atmospheric front formation corresponded to time of rapid change of TZD occurrence at the most westerly station in the region investigated. List of time delays of chosen atmospheric fronts at EPN stations investigated is given in Table 1.

Regularly, once a month approximately, cold atmospheric fronts form a soliton structure and as such pass two thousand kilometres with practically no change in shape. Large-scale tropospheric solitons were obviously observed by meteorologists earlier. Developed arrays of permanent GPS stations enable recently to conduct more advanced investigation of those interesting meteorological phenomena.

Table 1. Time delays of chosen atmospheric fronts at Central European stations investigated

Station	Longitude [deg]	Latitude [deg]	27Aug2001 delay [h]	21Jan2002 delay [h]	28Jan2002 delay [h]	8Feb2002 delay [h]
KARL	8.4	49.0		0.0	2.0	
KLOP	8.7	50.2		1.0	1.0	0.9
PTBB	10.4	52.3	1.7	3.8	1.0	0.9
HOBU	10.5	53.0	0.0	6.2	0.0	0.0
WTZR	12.9	49.1		6.2	4.8	3.9
POTS	13.1	52.4	2.6	9.1	2.1	1.8
DRES	13.7	51.0	7.7	7.7	4.0	1.9
GOPE	14.8	49.9	8.9	7.2	5.0	4.0
TUBO	16.6	49.2		13.0	6.0	5.9
BOR1	17.1	52.1	7.0	14.9	4.0	3.9
WROC	17.1	51.1	7.4	14.4	6.0	4.9
LAMA	20.7	53.9	5.8	24.5	5.0	8.2
BOGO	21.0	52.5	10.1	24.0	7.0	8.2
JOZE	21.0	52.1	9.6	22.6	7.0	
UZHL	22.3	48.6	16.8	25.9		8.2
SULP	24.0	49.8		26.4		
GLSV	30.5	50.4	25.9	47.5		
POLV	34.5	49.6		52.8		

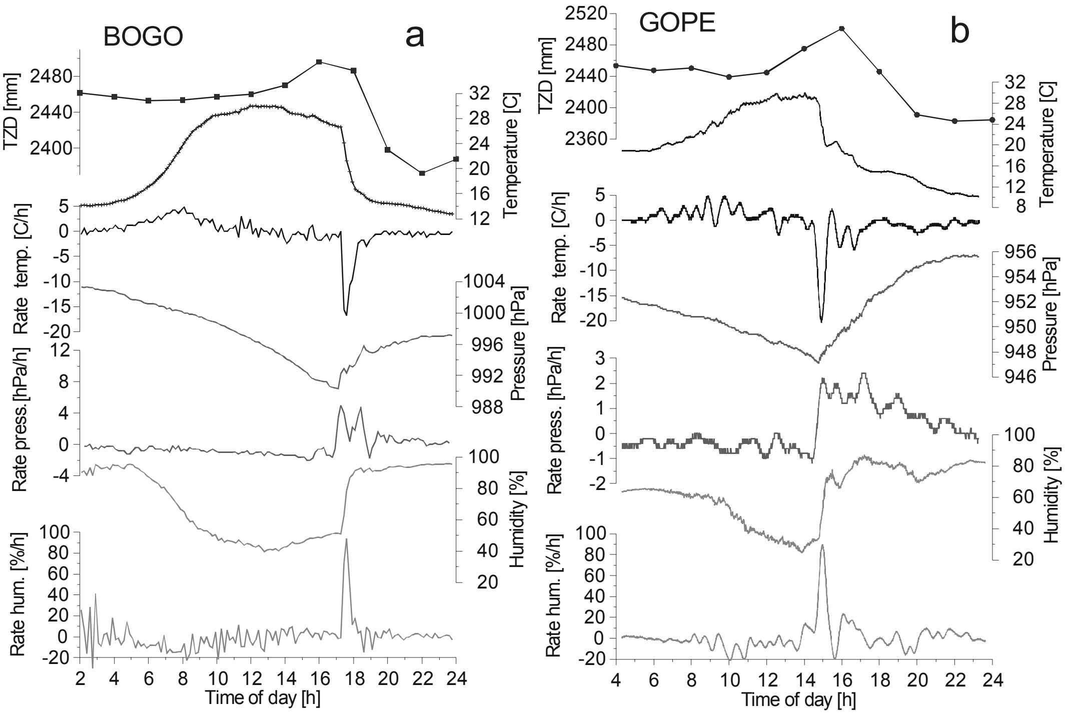

Fig. 7. Dynamics of variations of meteorological parameters and TZD when the atmospheric front was passing over BOGO (a), and GOPE (b) stations in August 27, 2001

The maps of dynamics of the atmospheric fronts passing over Central Europe in August 27-29, 2001 and in January 21-22, 2002 are shown in Fig. 8a and Fig. 8b, respectively. The contour lines are given with 2h resolution. The line of change the colour of contour lines indicates the location of the front after 24h following its forming in the region of HOBU station. Processes of forming and moving of solitary tropospheric waves were qualitatively modelled similarly to soliton modelling in water.

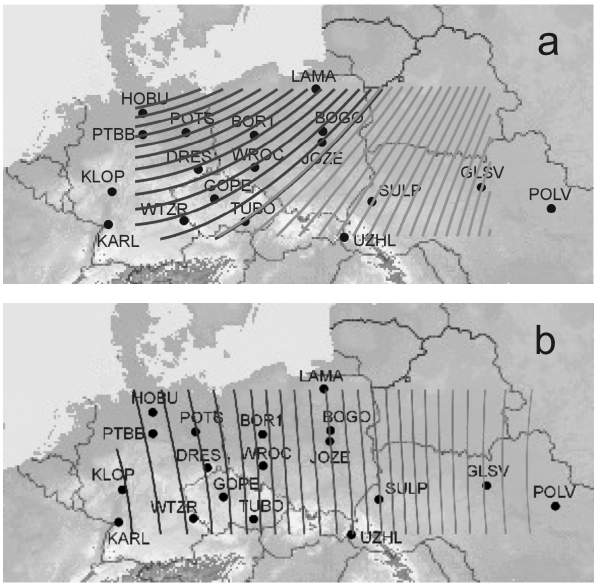

Fig. 8. Contour lines of the atmospheric fronts of August 27-29, 2001 (a), and of January 21-22, 2002 (b) on the background of the map of EPN stations used

Conclusions

Numerical experiments conducted indicate that the potentiality of GPS positioning is not fully exploited in surveying and geodesy. Analysis of time series of GPS solutions can result in improvement of modelling of GPS observations.

Quality of improvement of GPS solutions increases with the increase of periods of actual atmospheric disturbances. In the case of passing tropospheric front those periods are close to 1h or even shorter. An increase of temporal resolution of GPS solution series by processing overlapped sessions is an effective tool for detecting biases and reducing errors in the solutions.

Obtained models of biases may be applied for the increase of a quality of GPS solutions derived from short sessions as well as for upgrade of GPS data processing strategy.

Processing of GPS solutions with the use of the tools of statistical analysis enables

- to estimate actual quality of data;
- to model the influence the environmental effects and internal errors of GPS system;
- to correct GPS solutions using the derived models;
- to obtain maximum of information from input data (receivers files) by means of re-calculating same data using the same strategy;
- to investigate short term variations of the environmental effects, internal errors of GPS system and their mutual relationship.

The last mentioned possibility was illustrated in this presentation at the example of detection of the large-scale troposphere process such as cold front. On the basis of the data from EPN an attempt to reconstruct the scheme of the movement of some of atmospheric fronts was made.

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. Relatively simple structure of motion of such atmospheric fronts as compared with West European fronts allows their effective investigation using GPS-derived and meteorological data.

Acknowledgements

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 (grant No 9T12E01918). The authors express special gratitude to Mr. L. Zak from the Institute of Geodesy and Cartography, Warsaw, for processing GPS data.

Bibliography

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.

Douša J., (2001): *GOP Analysis Center Report*, EUREF Permanent Network: 3rd Local Analysis Centers Workshop, 31 May – 1 June 2001, Warsaw Poland, Reports on Geodesy, No 3 (58), 2001, pp. 43-48.

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

Kruczyk M., Rogowski J.B., (2002): *GPS derived integrated precipitable water – some remarks and proposed applications*, Reports on Geodesy, No 1 (61), 2002, pp. 183-195.

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., Wielgosz P. (2002a): *Modelling biases in GPS Positioning Based on Short Observing Sessions,* Presented at the XXVII General Assembly of European Geophysical Society 2002, Nice, France, 21-26 April 2002.

Krynski J., Cisak J., Zanimonskiy Y.M., Wielgosz P., (2002b): *Variations of GPS Solutions for Positions of Permanent Stations – Reality or Artifact*, Symposium of the IAG Subcommission for Europe (EUREF) held in Ponta Delgada, Portugal, 5-7 June 2002, EUREF Publication No 8/2, Mitteilungen des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main (in print).

Krynski J., Zanimonskiy Y., (2002): *Quality Structure of Time Series of GPS Solutions*, Proceedings of the 14th General Meeting of the Nordic Geodetic Commission, Espoo, Finland, 1-5 October 2002, pp. 259-264.

Reigber C., Gendt G., Dick G., Tomassini M., (2002): *Water Vapour Monitoring for Weather Forecasts*, GPS World, Vol.13, No 1, 2002, 18.