FREQUENCY AND PHASE ANALYSIS OF DAILY REPROCESSED SOLUTIONS FROM SELECTED EPN STATIONS RELATING TO GEOLOGICAL PHENOMENA

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ABSTRACT
The main assumption of this research was to check and verify the behaviour of a few EPN (European Permanent Network) stations on both sides of the Teisseyre-Tornquist zone (T-T zone), which is located on Polish territory and crosses Poland almost in half. The selected EPN stations' time series were a subject of frequency and phase analysis. The main purpose of the research was to verify if there is any correspondence between stations located on one and on the other side of the T-T zone. The idea was also to check if any geological phenomena occurs on examined stations through the behaviour of the stations. The chosen period of research was between 2003 and 2008. The stations' selection is not coincidental, VLNS, LAMA, BOGO, JOZE, BOR1 and WROC were chosen, because they had the longest and constant solutions provided by EPN.
Using wavelets as a tool for analysis, the authors detected biases in time series on chosen EPN stations (near T-T zone). Applying multiresolution wavelet analyses on different stations in the component Up the frequency bands were achieved. The authors decided to analyze the low-frequency bias (wavelet approximation band). The reason of using this tool was to analyze the frequencies and also to compare the frequency phase, in order to have more complex analyses of physical phenomena of the T-T zone in Poland.

KEYWORDS: Teisseyre-Tornquist zone, reference stations, frequency analyses, phase analyses, EPN, wavelet analyses, Symlet, multiresolution analysis

INTRODUCTION

The authors' assumption was to observe the behaviour of a few EPN stations around the Teisseyre-Tornquist (T-T zone) zone and develop and describe any geological phenomena.

We wanted to check if the behaviour of the stations on East and West side of the T-T zone differs. If such assumption is correct, GNSS permanent sites could be used for precise localization of the zones determination. The stations selected for the investigation had the longest and constant solutions and were situated near the T-T zone. We chose: VLNS, LAMA, BOGO, JOZE, BOR1 and WROC.

The T-T zone is located in the Central portion of the Trans-European Suture Zone (*TESZ).* The *TESZ* is stretching from Denmark and the North German Lowlands, through Poland, Ukraine and Romania, running over a distance of 2000 km. It is documented by paleomagnetic data that this important geological boundary in Europe separates the mobile Phanerozoic terranes, in SW, from the ancient Precambrian structure of the East European Craton and Baltic Shield (Stanica et al., 1999). Poland's territory is a border for three main tectonic units forming European continent. They are: old Precambrian platform of Eastern Europe known as East European Craton (around milliard years old), Palaeozoic platform of Central and Western Europe (about 300 million years) and the youngest Carpathian (orogens) structure. The *TESZ* is an extremely interesting natural laboratory for tests over tectophysical processes occurring in Earth's centre. The T-T zone is a part of gigantic tectonic margin, running from North Sea to Black Sea. The name of the zone was taken from the first discoverers, a German scientist Alexander J. H. Tornquist (1868-1944) who confirmed the existence of such a zone and Polish geologist, who examined in 1893 the character of the zone, Wawrzyniec Teisseyre (1860-1939). The T-T zone divides the Europe and is considered to be the most important tectonic element in Europe. Similar zones around Europe are a source of earthquakes. We can give the Turkey territory as an example, which is situated between African and Euroaziatic plate, is such an example. However, tectonic plates of the T-T zone seem to be firmly "glued", that is why this territory does not suffer from any severe earthquakes. However, historically looking at that matter it is hard to state interchangeably that no earthquakes will occur in the future. The T-T zone separates West European platform from East European Precambrian platform. The thickness of the Earth crust is about 32-35 km for a Palaeozoic platform, 42-45 km for a Precambrian platform and in the region of the T-T zone it is about 50 km. At a first glance it may give an impression that it is a tectonic trench. The impression is even bigger if we take into consideration the thickness of aqueous rocks (even up to 20 km) in the T-T zone. The geological character of the T-T zone is a subject of countless discussions among geologists and geophysicists. The researches from the past (i.e. a one conducted in 1997 by, the Institute of Geophysics of Polish Academy of Science, the *POLONAISE* Project) proved that the T-T zone has a deep asymmetry (slant, inclination). In that process a hypothesis was coined, that there was a collision of two lithospheric plates (called *Baltica*- SW margin of the East European (Bayer et al., 2001) and *Avalonia*) which were partly pulled one on another. That is why it is thought that there was a mountainous range running through the whole of today's Poland territory, at a slant. Through the process of erosion the mountainous range was completely levelled and covered with aqueous. The collision hypothesis still needs to be validated. http://www2.mos.gov.pl/dgikg/programy_projekty/badania/index.html, (Wiejacz, 1991).

The *TESZ* and the T-T zone are wildly discussed in scientific literature and many different aspects of the zone were examined. The author's idea was to check stations' activity on East and West side of the T-T zone. According to our assumption, the behaviour should be almost identical as the T-T zones are firmly "glued". However, analyzing long time series (a few years' analysis) it was observed that the low-frequency biases are in anti-phase and they depend on station's placement. The tests need to be re-examined. One should remember that such tests are time occupying as we need long period of observations, and more points of observation such as ASG-EUPOS (Active Geodetic Network European positioning System) sites.

The paper concerns frequency and phase analysis of daily reprocessed solutions from a few EPN stations, which surround the T-T zone in Poland (Fig. 1). They are: VLNS, LAMA, BOGO, JOZE, BOR1 and WROC.

There was a question raised whether any geological movements might be detected through analyses of component Up time series from single stations or vector series estimated through X, Y, Z coordinates.

DATA

The least-squares method is usually employed to GNSS solutions analysis. As the result, it generates residuals, which contain both unmodelled systematic biases and random measurements noise.

In 2008 in Military University of Technology/Centre of Applied Geomatics (MUT/CAG) there was a test reprocessing conducted. The authors used different models and guidelines. (Dach et al., 2004), (Kenyeres et al., 2008), (Mervart et al., 2005), (Niell, 1996), (Ray et al., 2004), (Schaer, 1995). The results were presented during EUREF 2008 meeting in Brussels and published in (Figurski et al., 2009). Weekly and daily time series were the reprocessing products. In this paper the authors used daily time series solutions.

The diagram (Fig. 2) shows exemplary daily solutions of XYZ ITRF2005 coordinates after the reprocessing. Time series were obtained through elimination of linear trend and constant component from X,Y,Z axis (residuals). The residuals contain the signature of both unmodelled biases and random noises. Figure 2 shows that there are frequency biases and various noises in time series. The changes on some stations may include information associated with some physical phenomena in the surrounding area. In the signals we expect to find and try to describe local earth crust movements.

The examined stations tend to have simultaneous noise, which can be eliminated. The elimination of noise may be conducted through connection of the stations by spatial length vectors, which are estimated every day.

$$V(i)=\sqrt{\begin{aligned}&\left(X_{ST2}(i)-X_{ST1}(i)\right)^2+\\&+\left(Y_{ST2}(i)-Y_{ST1}(i)\right)^2+\left(Z_{ST2}(i)-Z_{ST1}(i)\right)^2\end{aligned}} \quad (1)$$

V – distance vector

$X_{ST1}, Y_{ST1}, Z_{ST1}$ - coordinates of first station; start vector

$X_{ST2}, Y_{ST2}, Z_{ST2}$ - coordinates of secend station; end of vector

i - day of solution

A configuration of length vectors *V (*formula 1) in time creates one-dimension time series of distances between two stations (Fig. 3). These time series do not have common characteristics such as frequency biases and velocities of the sites. In order to check if they move mutually a linear trend was determined and isolated. The similar problem was showed in (Figurski et al., 2007).

In Figure 3 vector time series of sites located on one side of the T-T zone (LAMA-BOGO) as well as the vector time series crossing the zone (VLNS-BOR1) do not show linear changes, mean distance is constant. The unimportant changes on these graphs (0.1 mm/per year) with standard time series deviation of 1.3-1.6mm should not be taken into extensive consideration. Since there were no mutual linear movements detected, the authors decided to use spectral analyses. The authors tried to find dominating frequency biases in vector time series. Continuous wavelet analyses was the chosen method. Figure 5 shows the exemplary results.

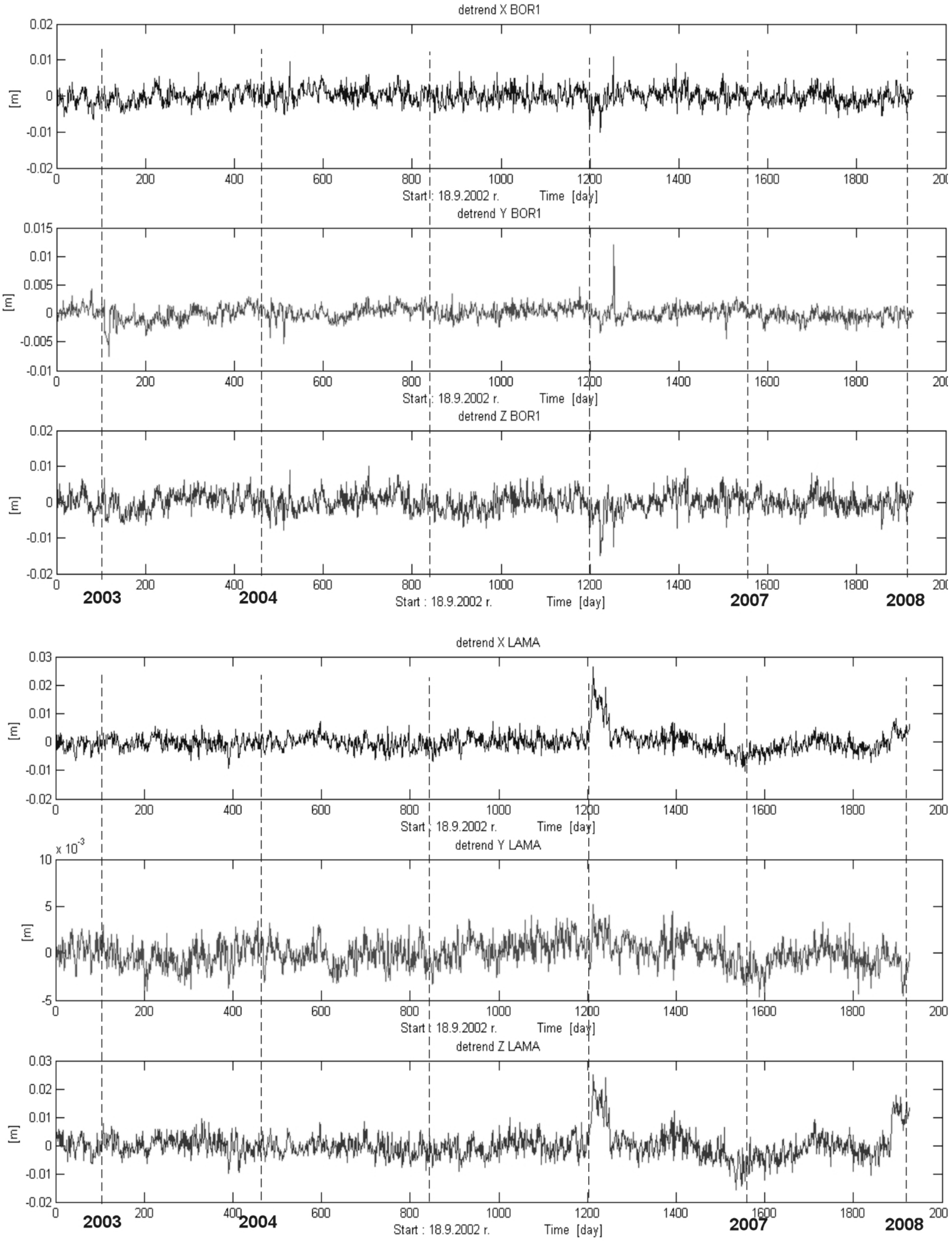

Fig. 2 Exemplary time series of coordinates changes without constant value and linear trend from BOR1 and LAMA stations.

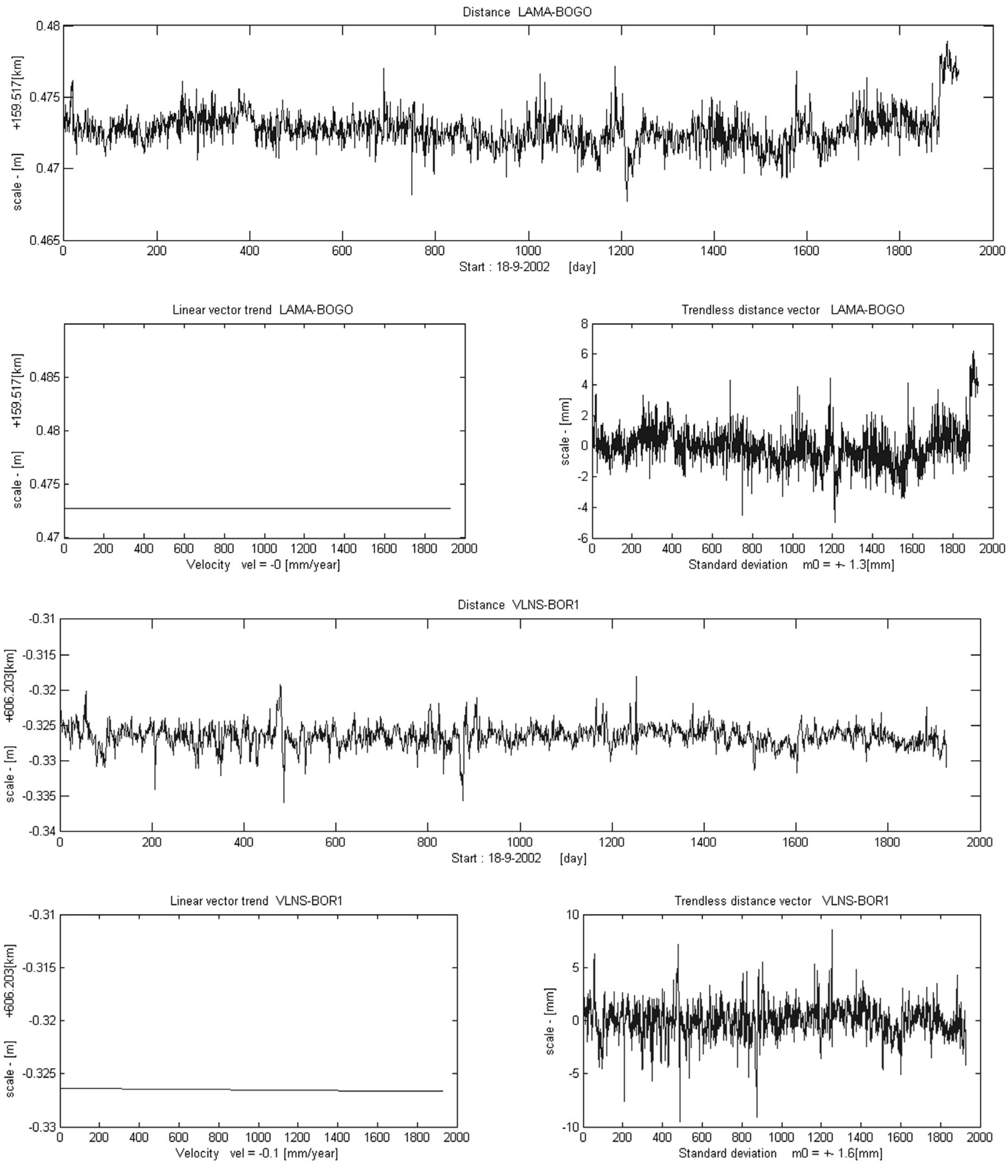

Fig. 3 Exemplary time series of vector changes between LAMA-BOGO and VLNS-BOR1 stations.

CONTINUOUS WAVELET TRANSFORM

In particular, the Wavelet Transform (WT) is of interest for the non-stationary analyses of signals such as GPS results, because it provides an alternative to the classical Fourier Transform (FT) which is adopted in case of stationary signals. Fourier analyses are known to have characterizing signals whose spectral character changes in time. Such signals are not well represented in time and frequency by the FT methods. The method of wavelet analysis is closely related to time-frequency analyses based on the Eiger-Ville distribution (Satirapod et al., 2007) A continuous wavelet transform was adopted, as shown in Figure 4, in order to check the contents of the spectrum. (Bialasiewicz, 2000; Zhang Yan et al., 2004).

The most popular method of spectral analyses of time series is a Fast Fourier Transform (FFT). The use of this method is restricted when we want to analyse

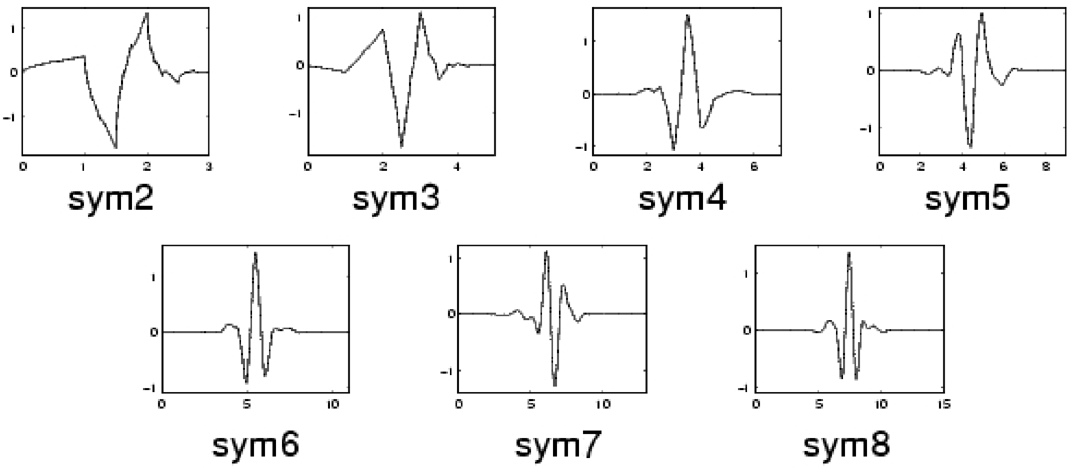

Fig. 4 Illustration of symlet mother family wavelets.

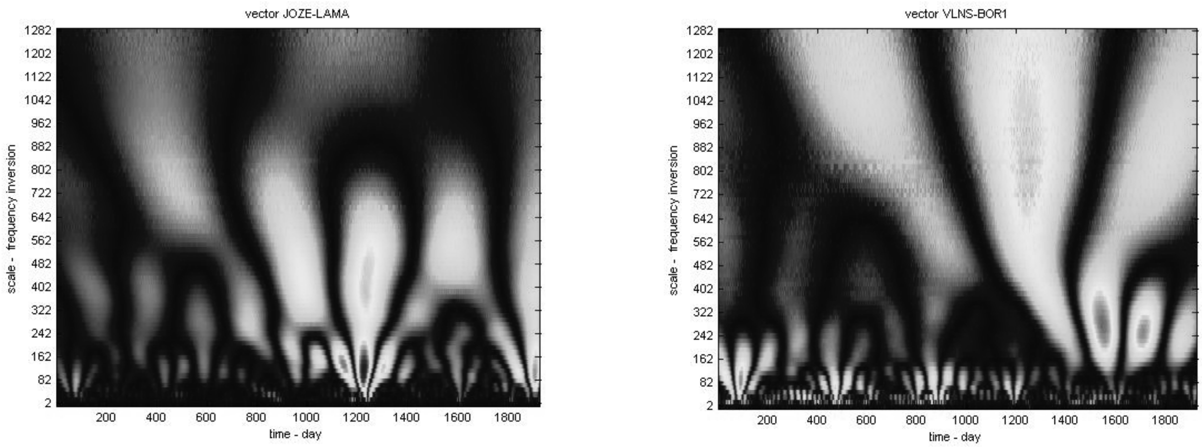

Fig. 5 Exemplary imagery of continuous wavelet analysis of length vectors between JOZE-LAMA and VLNS-BOR1 stations.

stationary time series (the ones which are not changeable in an analysed time). In case of non-stationary signals FFT should not be used.

On many occasions, not much attention is paid to this signal aspect and the signal is transformed by the FT method. Fourier Transform has an infinitely strong frequency, but no time localisation. The time series of analysed EPN stations are an example of non-stationary character of the signals. The frequency biases trends in time series appear in a given span of time and disappear in another, or their energy value is so insignificant that it vanishes in noise. To analyse frequency of coordinates we need different tools such as FFT and wavelet transform or any other. Wavelet transform is adopted in case of non-stationary signals, i.e. signals carrying components of frequency changing in time. To understand wavelet transform we need to use convolution of a given signal with the functions received by scaling and shifting a mother wavelet.

$$\gamma(s,\tau) = \int f(t)\psi^*_{s,\tau}(t)dt = \int \frac{1}{\sqrt{s}} f(t)\psi^*(\frac{t-\tau}{s})dt \qquad (2)$$

γ – two dimentional coefficient of wavelet transform function

ψ – mother wavelet

f – analized time function

τ – time shifting parameter

s – scale parameter

A coefficient of wavelet transform is the measure of correlation of investigated signals and analysing wavelet. '***s***' corresponds to the scale parameter (inversion of frequency), time lag mother wavelet described by parameter $\boldsymbol{\tau}$ and $\boldsymbol{s=1}$. Due to the factor $\boldsymbol{\tau=0}$, wavelet energy of $\sqrt{s}$ analysing wavelet is not changing with the scale. Mother wavelet is well concentrated as far as time and frequency are concerned. These conditions determine that this function has at least a few oscillations. That is why it is a ‘short wave’.

$$\int \psi(t)dt = 0 \quad \psi(\omega) = 0 \tag{3}$$

Scaling has fundamental importance for wavelet transform. Through scaling we can decide if we want to get good resolution in time or frequency (Heisenberg uncertainty principle).

To analyze the frequency of time series Fourier transforms or wavelet analyses might be used. Concerning the advantages of interpreting time and frequency at the same time, we chose wavelet analyses. More on this can be found on the following web pages:
http://www.amara.com/current/wavelet.html or
http://cas.ensmp.fr/~chaplais/wavetour_presentation/Wavetour_presentation_US.html,
http://www.mathworks.com.

The Wavelet Toolbox is a collection of functions built on the MATLAB® Technical Computing Environment. It provides tools for the analyses and syntheses of signals and images for statistical applications, using wavelets and wavelet packets within the framework of MATLAB.

The Symlets are nearly symmetrical wavelets proposed by Daubechies as modifications to the db family. The properties of the two wavelet families are similar. Here are presented the wavelet symlet family functions.

Daubechies (1990), for example, introduced a set of orthonormal wavelets, and more recently, a new family of non-orthogonal wavelets have been introduced by other authors. In general, the selection of the wavelet that best decomposes the data remains a research topic of its own. (Satirapod et al., 2007).

The choice of a mother wavelet is a very important step into further analysis and into obtaining good results. Regarding the choice of a mother wavelet, after several attempts we chose Symlet 8. Symlet 8 turned out to fit best to the method of analysing daily time series. Souza and Monico (2004) showed the advantage of symlets over Daubechies. Using Symlet 8 we got easier interpretation of the results. The images were clear and legible, than when using other wavelets types. The shape of this mother wavelet symlet best correlates with the analysed time series. The results are shown in Figure 5.

Analyzing image of continuous wavelet (Fig. 5) we cannot distinguish dominating frequencies in the whole of the testing period. Various frequencies appear in different time intervals.

MULTIRESOLUTION WAVELET ANALYSIS OF COMPONENT UP

As a tool for examination, multiresolution wavelet analysis was chosen (MRA). Multiresolution method is designed for most of the so called discrete wavelet transforms (DWT) and for the algorithm of the Fast Fourier Transform. e.g.; (Mallat, 1999; Charles and Chui, 1992; Primer et al., 1988).

A natural way of introducing wavelets is through the multiresolution analysis. Multiresolution analysis provides a natural framework for the understanding of wavelet bases, and for the construction of new examples e.g. (Daubechies, 1992)

Recently, some wavelet-based techniques have been introduced in the field of GPS solution analysis e.g. (Satipord et al., 1995; Fu and Rizos, 1997; Ogaja et al., 2003; Satirapod, 2001, 2003).

These methods have addressed some potential applications such as signal denosing, outlier detection, bias separation and data compression. The technique is first applied in order to decompose GPS double-differenced residuals into low-frequency bias and high-frequency noise terms. Our concept was to use multispectral analysis to compare phases of biases.

There were frequency biases detected in analysed vector series, which are probably caused by vertical changes (the most common ones). The main component characterizing vertical movement of the Earth crust is component Up. The next step for the analyses was to check the behaviour of component Up on all analysed stations. Amplitude’s frequency biases and phases on both sides of the T-T zone were checked. The tool for the spectral analyses was multispectral wavelet analyses based on Symlet8. Because of time series length the best effects were obtained through 8th degree of decomposition. The figures below present the results.

The initial time series coordinate Up (without linear trend) (on top of the Figure 6) was divided into 8 components (decomposition degree), responsible for each frequency band. The outcome of the analyses was approximation component A (first one) and 7 decomposition components (D8-D2). Decomposition D1 is considered to be a white noise.

The advantage of MRA over FFT is that the first method allows the analyses of phases and not only the analyses of frequencies.

In order to do the comparison of amplitude and phase of the signals, they should be grouped in analogous frequency bands. The comparison of approximation component A is presented in Figure 6. If we take a close look at the graphs with data from between 2006 and 2008 we can see an interesting occurrence. The stations of the East side of the T-T zone (LAMA, BOGO, VLNS) oscillate in anti-phase to stations of the West side of the T-T zone (BOR1, WROC). The exception is JOZE station, which behaves as if it was placed on West side of the T-T zone. More about JOZE station, its placement and surroundings can be found in (Rogowski, 2001) and (Bogusz et al., 2001). JOZE station is also discussed in “Reports on Geodesy” (published by Warsaw University of Technology, Institute of Geodesy and Geodetic Astronomy) where the authors widely describe other aspects of JOZE behaviour. JOZE station is monitored by the Astrogeodetic

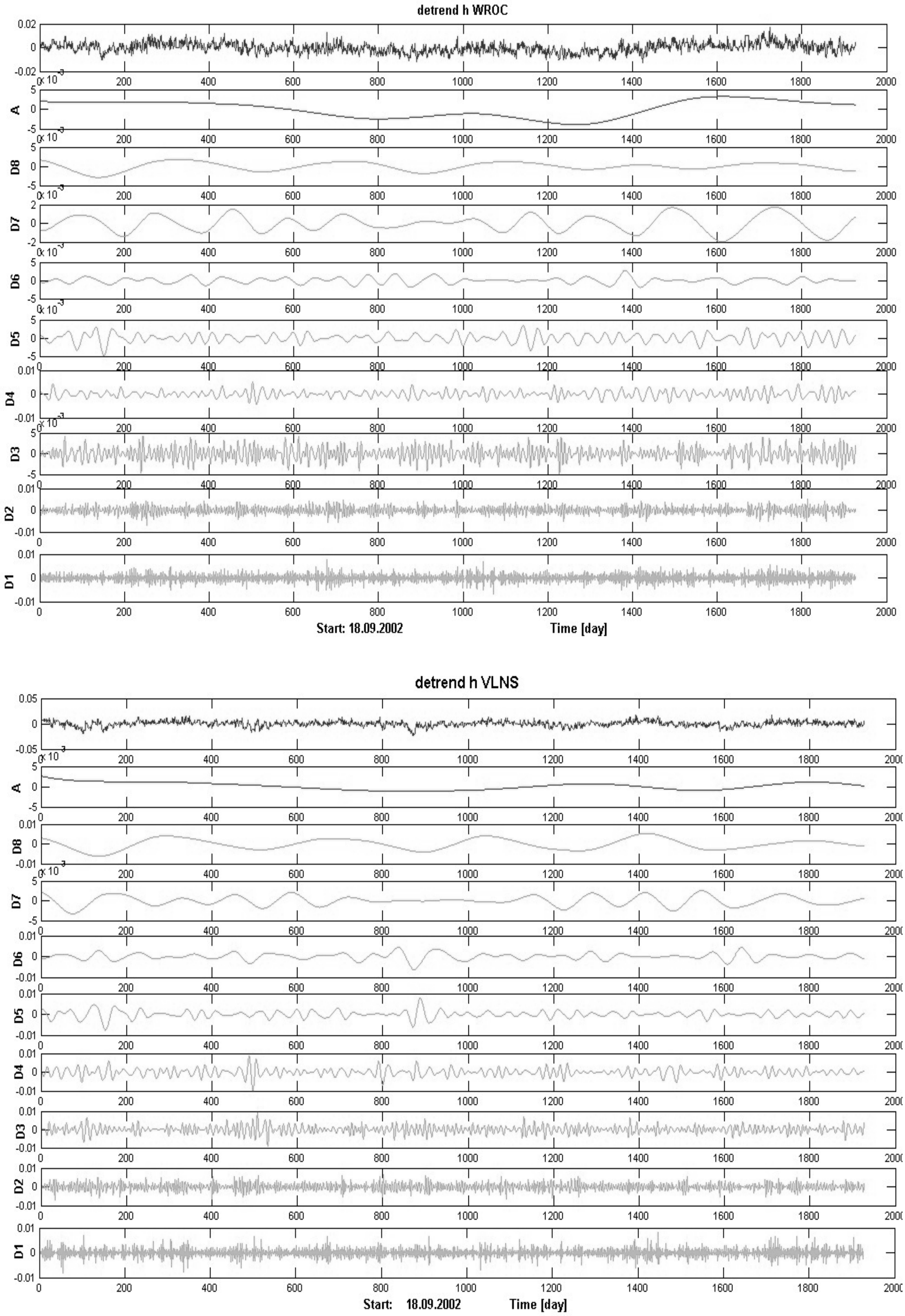

Fig. 6 Exemplary multispectral wavelet analysis of up component 'h" of WROC and VLNS stations. A wavelet analysis of symlet8; decomposition degree n=8.

Observatory of the Institute of Geodesy and Geodetic Atronomy of the Warsaw University of Technology.

The amplitude for frequency band (approximation A) is the highest on LAMA and WROC stations. The remaining stations have comparable amplitude for this frequency band (Fig. 7).

Figure 8 shows the next frequency band D8 of component Up. The biggest amplitude for this band is in VLNS.

SUMMARY

The tests of velocity vector were conducted. Linear trend analyses (velocity) and frequency analyses of time series did not show characteristic results.

Based on time series of coordinates of component Up of chosen stations frequency biases components were isolated. As a tool for examination, multiresolution wavelet analysis was chosen. Multiresolution method is designed for most of the so called discrete wavelet transforms and for the algorithm of the Fast Fourier Transform. After selecting a proper wavelet type, as well as a degree of decomposition (proportional to the length of analysed time series), an examined signal was divided into part A (approximation) and decomposition D1 to Dn, where 'n' is a degree of decomposition.

A set of decompositions is shown in Figures 7, 8 and 9. Using this set of decomposition we can cross examine the phases of detected frequencies.

The separation of analysed time series into components of decomposition describes the power of amplitude and allows the comparison of phase differences for chosen stations in an examined frequency band. We can also establish the time of component appearance and compare it with geological phenomena.

The authors noticed that there are a few circumstances that might influence the final results of the research. The most questions arise when analyzing the coordinates on JOZE station. JOZE station is located near the airport and on a instable grounds. These conditions may be the reasons for stations behaviour as if it was on the other side of the TT zone. Of course, it is only the authors' preliminary interpretation. Further research is needed in order to prove the idea. There must also be different stations chosen for this analysis. When this phenomena was detected, only a few stations had enough observation history for the examination (only EPN stations). The hypothesis about the anti-phase on East and West side of the T-T zone will be verified using data from ASG-EUPOS network in near future. However, the ASG-EUPOS network operates since 2 years and till now, we did not have long time series to obtain precise elaborations. This very day it is hard to tell if the supposed hypothesis is correct or not, and time series from polish sites are too short to obtain reliable results of elaborations. Polish satellite positioning system ASG-EUPOS is operational since June 2008, so in the near future there will be more stations to verify this phenomenon.

Multispectral analysis allows the division of examined time series into frequency bands as well as the use of phases of oscillations between the stations. This can be quite interesting when examining geological phenomena or when analysing the velocities of tidal waves.

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REFERENCES

Bayer, U., Grad, M., Pharaoh, T. C., Thybo, H., Guterch, A., Banka, D., Lamarche, J., Lassen, A., Lewerenz, B., Scheck, M. and Marotta, A.-M.: 2001, The southern margin of the East European Craton: new results from seismic sounding and potential fields between the North Sea and Poland. Tectonophysics, 360, Issues 1–4.

Bialasiewicz, Jan T.: 2000, Falki i Aproksymacje/ Wavelets and Approximations; WNT Warszawa, (in Polish).

Bogusz, J.: 2001, Activities of astro-geodetic observatory in Józefoslaw in 2001; Reports on Geodesy; No.2 (57).

Chui, Ch.K.: 1992, An Introduction to Wavelets; Academic Press, San Diego.

Daubechies, I.: 1992, Ten Lectures on Wavelets.

Figurski, M., Kroszczyński, K., Kaminski, P. and Gałuszkiewicz, M.: 2007, Monitoring of permanent GPS stations at the Sudety Mountains, Acta Geodyn. Geomater., 4, No. 4 (148), 141–144.

Figurski, M., Kaminski, P., Kroszczynski, K. and Galuszkiewicz, M.: 2009, Preliminary results of the complete EPN reprocessing computed by the MUT EPN local analysis centre. Bullettin of Geodesy and Geomatics, LXVIII – N. 2.

Fu, W.X. and Rizos, Ch.: 1997, Applications of the wavelet transform from GPS cycle slip correction and comparison with Kalman filter, Manuscripta Geodaetica, 20, 191–172.

Hugentobler, U., Dach, R. and Fridez, P.: 2005, Bernese GPS Software 5.0. Astron. Inst., Univ. of Berne, Switzerland. (Electronic version available at http://www.bernese.unibe.ch/docs/ DOCU50.pdf)

Legrand, A,J., Bruyninx, C., Habrich, H., Figurski, M. and Kenyeres, A.: 2008, Regional re-analysis: Expectations & experiences within the EPN. IGS Workshop;, Miami Beach, Florida, USA, 2-6 June.

Mallat, S.G.: 1999, A Wavelet Tour of Signal Processing; Academic Press.

Mervart, L.: 1995, Ambiguity resolution techniques in geodetic and geodynamic applications of the Global Positioning Systém. Geod. Geophys. Arb. Schweiz, 53, 155 pp.

Niell, A.: 1996, Global mapping functions for the atmosphere delay at radio wavelengths, Geophys. Res., 101(B2), 3227–3246.

Ogaja, C., Rizos, Ch. and Satirapod, Ch.: 2003, The applications of wavelets to GPS signal processing; 10th Int. tech. Meeting of the Satellite Division of the U.S. Inst. Of Navigation, Kansas City, Missouri, 16-19 September, 1385–1388.

Primer, A., Burrus, C.S. and Gopinath, R.A.: 1988, Introduction to Wavelets and Wavelet Transforms, H. Guo Prentice-Hall.

Ray, J., Dong, D. and Altamimi, Z.: 2004, IGS reference frames: status and future improvements. GPS Solutions, 8(4), 251–266, doi 10.1007/s10291-004-0110-x.

Satirapod, Ch., Ogaja, C., Wang, J. and Rizos, Ch.: 2007, GPS analysis with the aid of wavelets.

Satirapod, Ch., Rizos, Ch., Collin, F. and Warnant, R.: 1995, Multipath mitigation by wavelet analysis for GPS base station applications.

Satirapod, Ch.: 2003, Reduction of multipath effect at GPS base station with the use of wavelets; Proceeding of the National Conference on Mapping and Geo-Informatics, Bangkok, Thailand, 18-20 November.

Satirapod, Ch.: 2001, Improving the accuracy of static GPS positioning with a new stochastic modelling procedure;; 14 th Intl. Tech. Meeting of the Satellite Division of the U.S. Inst. Of Navigation GPS ION'2001, Salt Lake City, Utah, 11-14 September, 2196-2205.

Souza, E.M. and Monico, J.F.G.: 2004, Wavelet shrinkage: high frequency multipath reduction from GPS relative positioning; GPS Solutions. 8, 152-159; doi 10.1007/s10291-004-0100-z.

Schaer, S.: 1995, Mapping and predicting the Earth's ionosphere using the Global Positioniong Systém. Geod. Geophys. Arb. Schweiz, 59, 205 pp.

Stanica, M., Stanica, D. and Marin-Furnica, C.: 1999, The placement of the Trans-European Suture Zone on the Romanian territory by electromagnetic arguments. Earth Planets Space, 51, 1073–1078.

Rogowski, J.B.: 2001, Research conducted from the astro-geodetical observatory of Warsaw University of Technology at Józefoslaw – historical outline and present state. Reports on Geodesy, 56, No. 1.

Wiejacz, P.: 10/1991, Czy grozi nam trzęsienie Ziemi?/ Are we threaten with the earthquakes?; Wiedza i Życie, (in Polish).

Zhang Yan, Wu, Yun, Liu Yong-qi and Shi Shun-ying: 2004, Application of wavelet analysis to crustal deformation data processing. Acta Seismologica Sinica, 17, Supp., 110–116.

http://www.amara.com/current/wavelet.html

http://cas.ensmp.fr/~chaplais/wavetour_presentation/Wavetour_presentation_US.html

http://www.mathworks.com.

http://www2.mos.gov.pl/dgikg/programy_projekty/badania/index.html

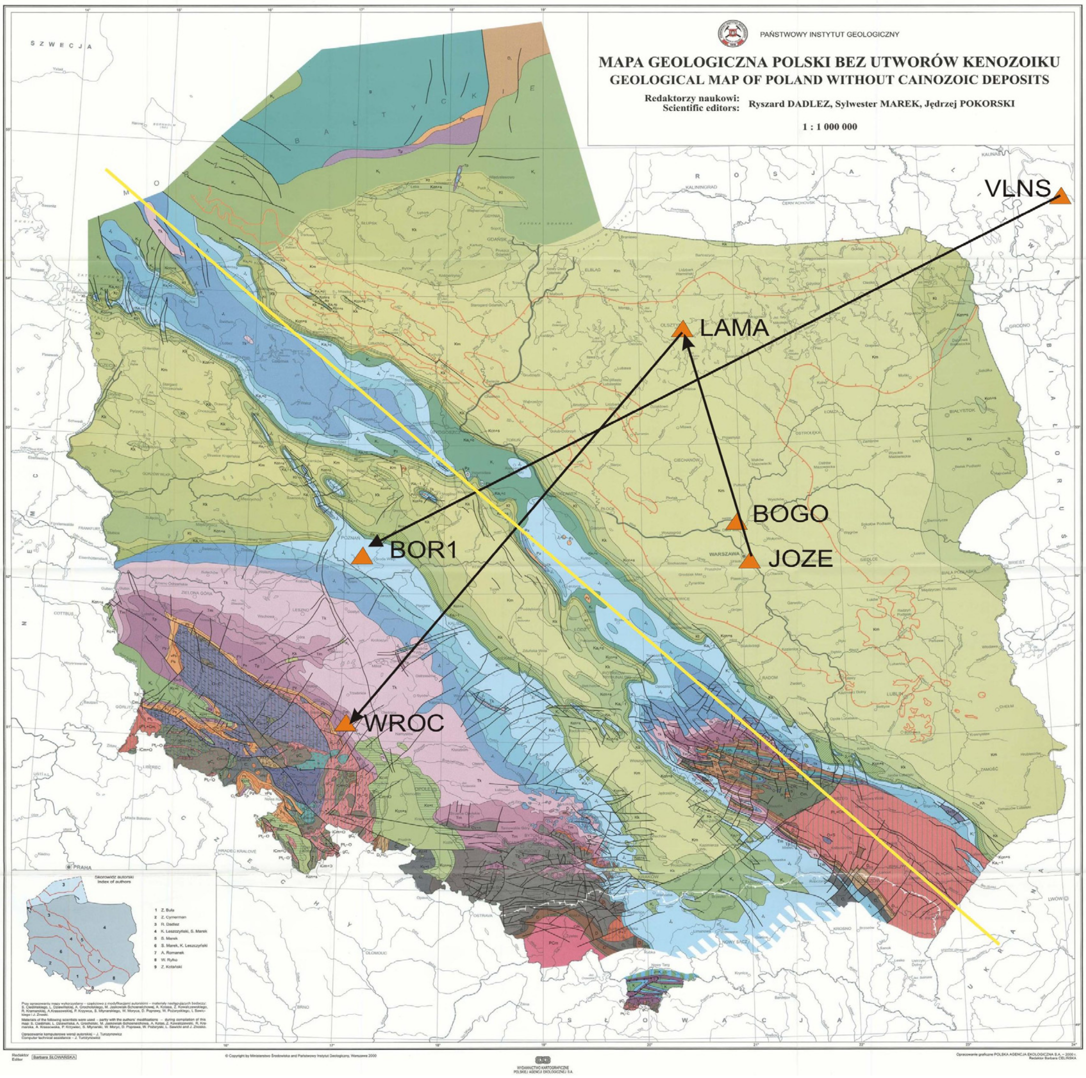

Fig. 1a Placement of analysed stations on Geological Polish Map, source: (http://www.pgi.gov.pl/pgi_en/index.php?option=news&task=viewarticle&sid=6&Itemid=2). Yellow colour – T-T zone.

Fig. 1b Legend of the Geological Map of Poland without Cainozoic deposits, source (http://www.pgi.gov.pl/pgi_en/index.php?option=news&task=viewarticle&sid=6&Itemid=2).

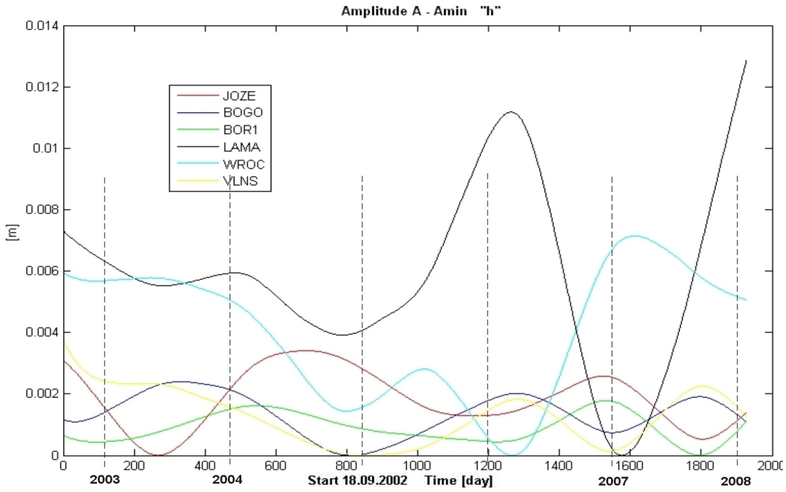

Fig. 7 A combination of approximation component A-Amin of analysed stations.

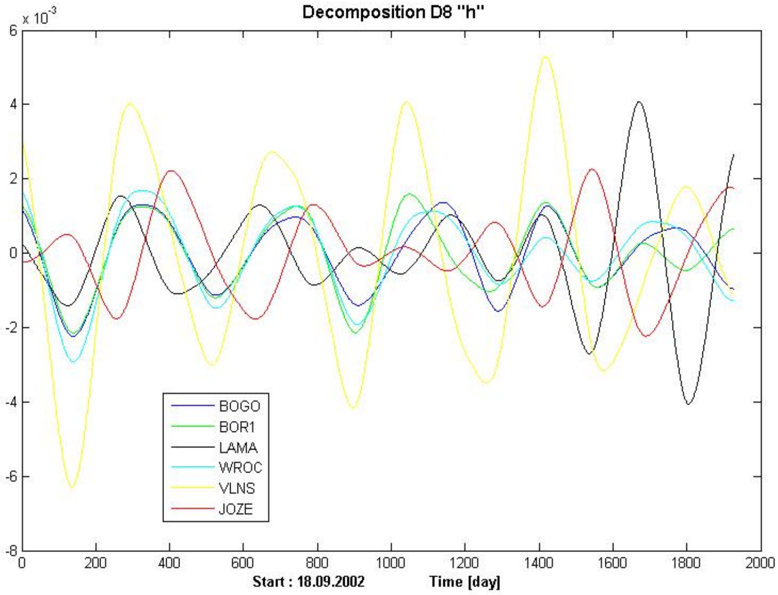

Fig. 8 A combination of decomposition component D8 of analysed stations.

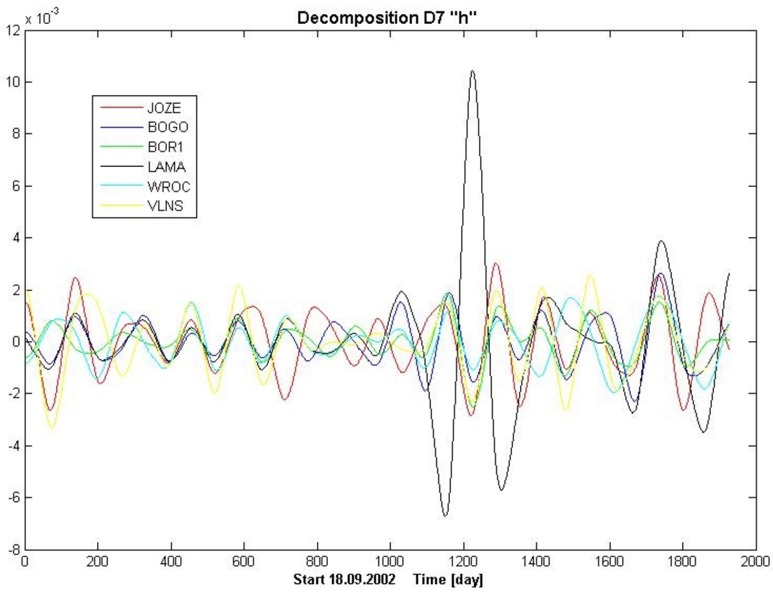

Fig. 9 A combination of decomposition component D7of analysed stations.