The use of GPS data at T-T Zone for the verification of the recent terrestrial reference frames considering possible geodynamic processes

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Abstract. The interpretation of the geodynamic phenomena with the use of GPS observations strongly depends on the quality of the terrestrial reference frame. The aim of this contribution is to verify station velocities from recent ITRF/ETRF solutions as well as to evaluate the possible geodynamic processes by using long time series of GPS data from four permanent GNSS stations operating in T-T zone. The components of four baselines were calculated with the use of the Bernese v.5.0 GPS software using GPS observation data from 2004–2012. Time variations of baseline components and baseline length were analysed and their linear trends were estimated by applying linear regression analysis. The obtained results have indicated that the variations are within the range from –0.2 to 0.3 mm/year in X–component, from –0.6 to –0.3 mm/year in Y–component, from –0.2 to 0.2 mm/year in Z–component and from –0.2 to 0.6 mm/year for the baseline length. The estimated linear trends of baselines components variations fit substantially better to the respective ones derived from ITRF2008/ETRF2000 (R8) than to the ones from ITRF2005/ETRF2000 (R5).

1. Introduction

Accurate and reliable terrestrial reference frame is extremely important in studying geodynamic processes using space-geodetic techniques. Since 1988, the International Terrestrial Reference Frame (ITRF) has been released and updated regularly, with most recent two releases being ITRF2005 (Altamimi et al., 2007) and ITRF2008 (Altamimi et al., 2011). Beside the ITRF, the IAG Sub-commission for the European Reference Frame (EUREF) has released the European Terrestrial Reference Frame (ETRF). The ETRF89 was defined as corresponding to the ITRF89 at epoch 1989.0, ETRF2000 (R5) to

ITRF2005 and ETRF2000 (R08) to ITRF2008 (Boucher and Altamimi, 2011).

Through the past years, many studies were performed to assess the accuracy of the terrestrial reference frames (TRF), e.g. (Altamimi et al., 2011; Collilieux et al., 2011; Wu et al., 2011). As a common conclusion they have indicated that the accuracy of the origin and scale of the TRF are one of the main factors limiting the determination of accurate velocities of the GNSS sites. Consequently, the evaluated accuracy of these velocities differs from site to site.

In the area of Poland, in particular, in the Teisseyre-Tornquist zone (T-T zone) area (Fig. 1), several

studies were devoted to examine the crustal defor-
mation and the existence of geodynamic processes
by using various geodetic tools and methods. For
example, daily reprocessed solutions from a few
EPN (EUREF Permanent Network) stations located
at both sides of the T-T zone have been analysed
using wavelet analysis in terms of biases of fre-
quency and phase (Kaminski et al., 2010). The re-
sults indicated the existence of frequency biases
in baseline's time series, which might result from
vertical changes. Moreover, the study has shown
there is anti-phase oscillation for GNSS stations of
the eastern side of the T-T zone and GNSS stations
of the western side of the T-T zone. Another approach
to detect geodynamic processes in the T-T zone
was the research based on the analysis of a series
of 10–day solutions from the same part of the year
from the period of 1997–2010, using GNSS data
from two GNSS stations located at T-T zone (Cisak
et al., 2011). Both commercial and scientific soft-
ware were applied. The results obtained indicated
that commercial software are insufficient to study
the geodynamic process at the investigated part
of T-T zone. The study also showed that processing
of a few days GNSS data, e.g. from 10 days, annu-
ally, using scientific software does not provide suf-
ficient basis to justify the geodynamic processes
at such area as T-T zone, that seems quite stable.
The other study concerned the review the impact and
importance of such sources like earth tides, ocean
tidal loading, atmospheric radiation tides loading,
polar motion and its oceanic indirect effect, and the
non-tidal ocean loading, in high-precision posi-
tioning with space geodetic techniques focusing
on Jozefoslaw station located in the T-T zone (Raj-
ner, 2012). It has indicted which sources are im-
portant to be considered to fulfil precision criteria
of positioning. Vertical movements of the Earth's
crust over Poland including the area of T-T zone
were investigated with the use of GNSS data from
the ASG-EUPOS (Active Geodetic Network EUPOS)
and European Permanent Network (EPN) as well
as geometrical levelling data (Kontny and Bogusz,
2012). This study has indicated a reference defect
due to the sea level variability, when comparing
the vertical motions from these three data sources
against each other. All those studies have addressed
the T-T zone as a potential subject for geodynamic
process, and their results obtained can be regarded
as a contribution to the further studies.

The purpose of this study is to verify velocities
from recent ITRF/ETRF solutions for the stations
in the T-T zone as well as to evaluate the possible
geodynamic processes by using long time series
of GPS data from four permanent GNSS stations
of IGS/EPN network operating in T-T zone.

2. Study area and GNSS stations used

The Teisseyre-Tornquist zone (T-T zone) boundary
region is situated in the collision zone between the
Precambrian Platform of Eastern Europe and the
Paleozoic Platform of Central and Western Europe.
It has been regarded as one of the seismo-tecto-
nically active areas of Europe (Grad et al., 2000).
This zone is crossing the area of Poland from
North-West to South-East (Fig. 1). Two permanent
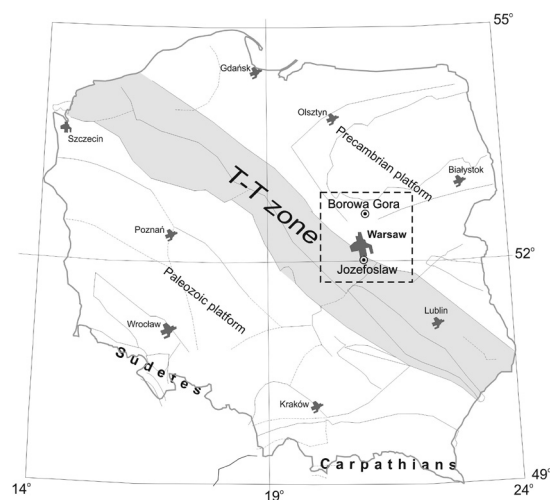GNSS stations, named JOZE and JOZ2 are located

Fig. 1. The Teisseyre-Tornquist zone (T-T zone) boundary
region and study area (dashed rectangle)

at Jozefoslaw Astrogeodetic Observatory in the
east boundary of the T-T zone, and two sites BOGO
and BOGI are located at Borowa Gora Observatory
outside the T-T zone. These stations operate within
the European Permanent GNSS Network (EPN) of
EUREF since mid 1990. Furthermore, stations BOGI,
JOZ2 and JOZE also operate within the Interna-
tional GNSS Service (IGS). There are few impor-

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tant reasons why those stations have been chosen for the following research: (1) their location can offer an appropriate baselines configuration to examine the geodynamic processes at T-T zone, (2) the velocities from the recent ITRF and ETRF have exhibited inconsistent slow motion at baselines of ~42 km lengths, (3) the availability of long-term continuous GNSS data. Table 1 summarizes the main characteristics of these stations.

3. GPS data processing

The GPS observation data from 2004–2012 with sampling rates of 30 seconds from the GNSS stations specified in Table 1 have been processed using precise ephemeris and Earth rotation parameters provided by the international GNSS service (IGS). Furthermore, Earth tides and Ocean tide loading model coefficients based on IERS and FES2004 models (Lyard et al., 2006), respectively, were implemented to eliminate the tide-loading effects. Antenna Phase Centre Variation (PCV) were modelled with the use of absolute PCV model. According to a double-differencing processing standards of the Bernese GPS software v.5.0 (Dach et al., 2007), and the EPN Local Analysis Centres (EPN LAC) recommendations (see http://www.epncb.oma.be), an optimal processing strategy was developed to process the data in daily session solution. The basic steps of this strategy can be described in brief as follows:

- The observed GPS data, precise ephemeris and Earth rotation parameters were converted to the Bernese format.
- The baselines JOZE-BOGO, JOZE-BOGI, JOZ2-BOGO and JOZ2-BOGI were created from single differencing files.
- Cycle slips were detected and corrected; and then outliers were detected and removed from the observations.
- Zenith path delays were estimated at 2h intervals for baseline stations. A priori values for the zenith path delays were obtained using the DRY NEILL model, and wet part of the troposphere was estimated with use of the WET NEILL mapping function (Neill, 1996).
- The phase ambiguities have been resolved using the SIGMA-dependent strategy. During this step, both frequencies L1 and L2 were used, the minimum elevation angle was set to 3°, and the elevation-dependent weighting was applied by using the $\cos^2(z)$ function.
- Finally, each baseline was adjusted by considering one of the baseline stations as fix station.

According to above steps, Processing Control File (PCF) was created. This PCF defines which scripts are to be in run, and in what sequence the processing will be conducted by means of the Bernese Processing Engine (BPE) tool (cf. Dach et al., 2007). With the use of BPE, the GPS data from each individual baseline were processed in daily batches.

Table 1. Characteristics of the chosen GNSS stations

Station	Domes No	Receiver	Antenna and radom Code	
BOGO	12207M003	Ashtech Z-XII3 TPS EUROCARD	ASH701945C_M	Snow
BOGI	12207M002	Ashtech Z18 JPS E_GGD JPS Legacy JAVAD TRE_G3T DELTA JPS EUROCARD	ASH701941.B	Snow
JOZE	12204M001	Trimble 4000SSI Trimble 4000SSE	TRM14532.00	None
JOZ2	12204M002	Ashtech Z18 Leica GRX 1200 GG Pro	ASH701941.B LEIAT504GG	Snow None

4. Results and analysis

The daily baseline components (ΔX, ΔY, ΔZ) were obtained for BOGI–JOZ2, BOGI–JOZE, BOGO–JOZ2 and BOGO–JOZE baselines. In order to reduce the white noise within the daily solutions, 7–days average solutions were obtained by applying moving average window with 7–day intervals. Figures 2−4 show the changes of baselines components with respect to their mean values of daily and 7–day average solutions. Moreover, the lengths of those baselines were calculated from daily solutions as well as from 7–days average solutions. Depicted in Figure 5 daily and 7–day average solutions centered with respect to their mean values show the variations of baseline lengths (reformulation). The histograms of differences between the daily solutions and 7–day average solutions are presented in Figure 6. About 95% of daily solutions agree with 7–day average solutions at the level of ±4 mm for the X and Y components, ±6 mm for the Z components, and ±4 mm for the baseline lengths.

The linear trends (V_X, V_Y, V_Z and V_D) of baselines components and baselines length variations were estimated from 7–days average solutions using linear regression analysis (Table 2). They are within the range from –0.2 ±0.27 to 0.3 ±0.36 mm/year in X–component, from –0.3 ±0.20 to –0.6 ±0.27

mm/year in Y–component, from –0.2 ±0.34 to 0.2 ±0.60 mm/year in Z–component and from –0.2 ±0.16 to 0.6 ±0.30 mm/year in the baseline length. It should be noted that during the GPS week 1470 the antenna of station JOZ2 was replaced, and therefore linear trends of baselines BOGO–JOZ2 and BOGI–JOZ2 variations were estimated in two steps before and after the replacement.

In order to verify the velocities of these sites obtained from the recent ITRF/ETRF solutions (see http://itrf.ign.fr/ITRF_solutions/ and http://etrs89.ensg.ign.fr/pub), the estimated linear trends of baselines components and lengths variations were compared with the respective ones obtained from recent ITRF/ETRF. The differences Δ between the velocities from recent ITRF/ETRF and the estimated linear trends of BOGI–JOZ2, BOGI–JOZE, BOGO–JOZ2 and BOGO–JOZE baseline components variations are presented in Figure 7.

The differences Δ shown in Figure 7 exhibit compatibility of all baselines investigated. They have revealed an agreement of about –0.1 to 0.5 mm/year at Y–component for all reference frames. The differences between linear trends of baseline components variations obtained from ITRF2005 and ETRF2000 (R5) and the corresponding ones obtained from 7–day average solutions can reach as much as 2.6 mm/year in X–component, 0.3 mm/year in Y–component,
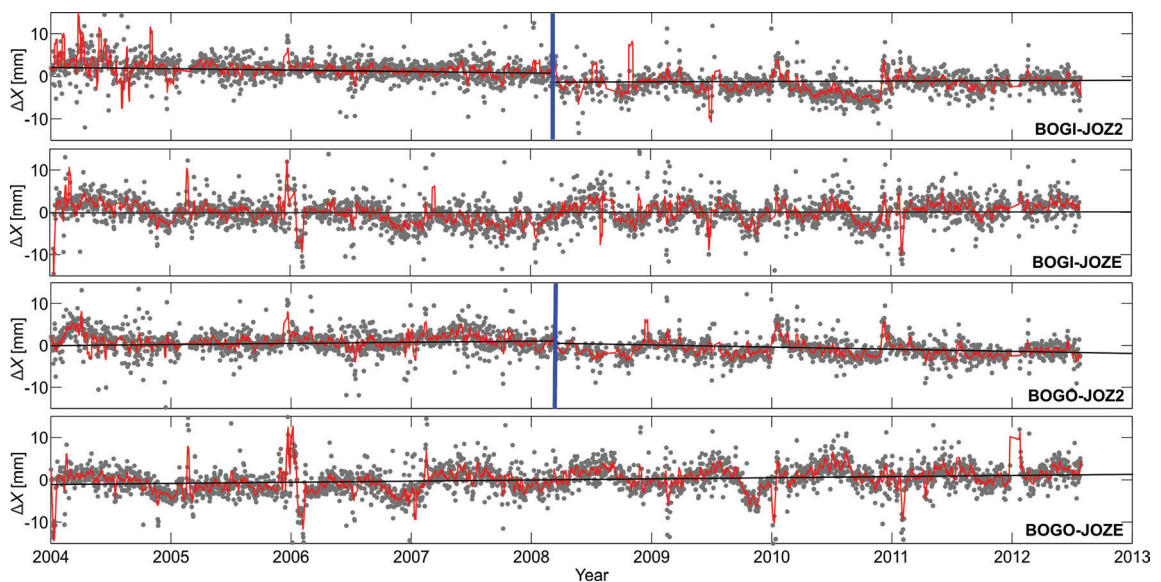

Fig. 2. Variations in X–component; daily solutions (grey dots) and 7–day average solutions (red line); linear trends (black line); blue vertical lines represent the period of antenna replacement at JOZ2

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3.8 mm/year in *Z*–component and 4.6 mm/year in the length of these baselines. This might be due to the relative antenna phase variation (PCV) models that was applied only when computing ITRF2005 and ETRF2000 (R5) (Bruyninx et al., 2011).

The ITRF2008 and ETRF2000 (R8) solutions coincide at sub millimetre level with the estimated linear trends of baseline components variations. Overall, the ETRF2000 (R8) has provided good agreement with respect to 7–day average solutions.
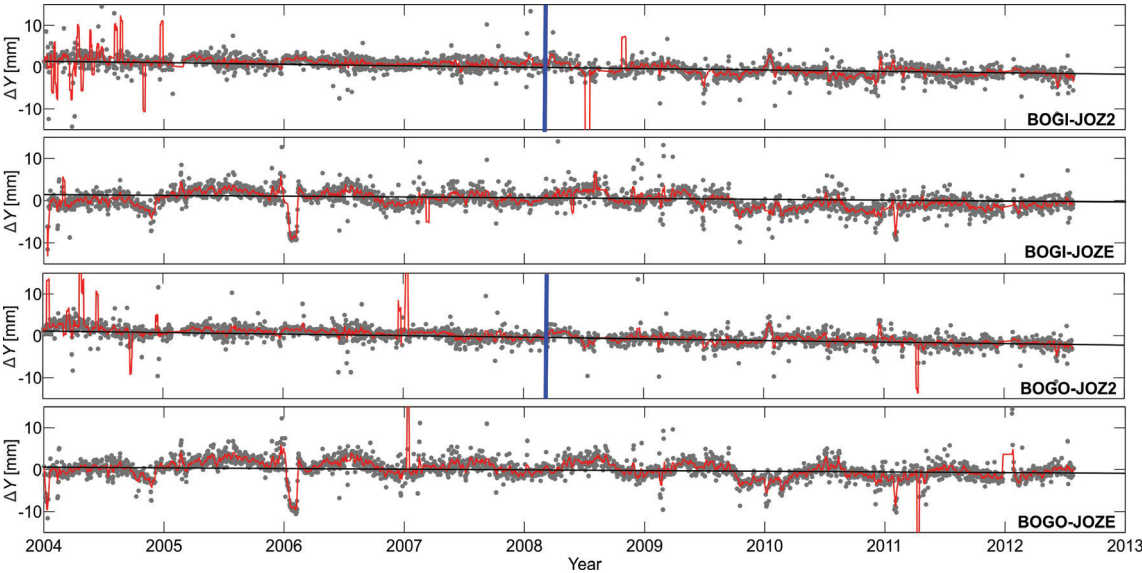

Fig. 3. Variations in *Y*–component; daily solutions (grey dots) and 7–day average solutions (red line); linear trends (black line); blue vertical lines represent the period of antenna replacement at JOZ2
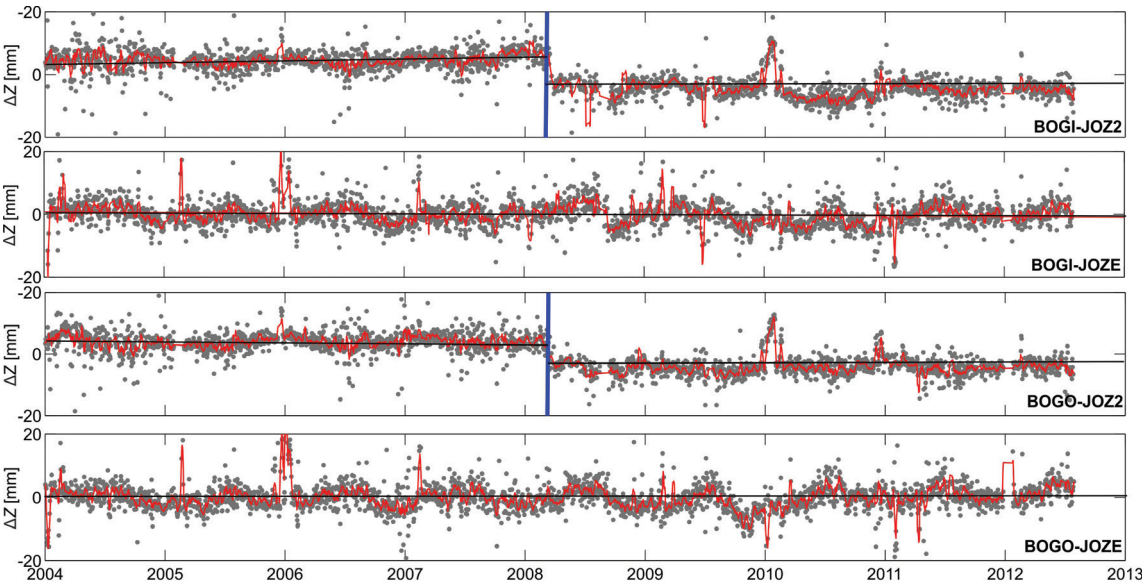

Fig. 4. Variations in *Z*–component; daily solutions (grey dots) and 7–day average solutions (red line); linear trends (black line); blue vertical lines represent the period of antenna replacement at JOZ2

Fig. 5. Variations in baseline lengths; daily solutions (grey dots) and 7–day average solutions (red line); linear trends (black line); blue vertical lines represent the period of antenna replacement at JOZ2
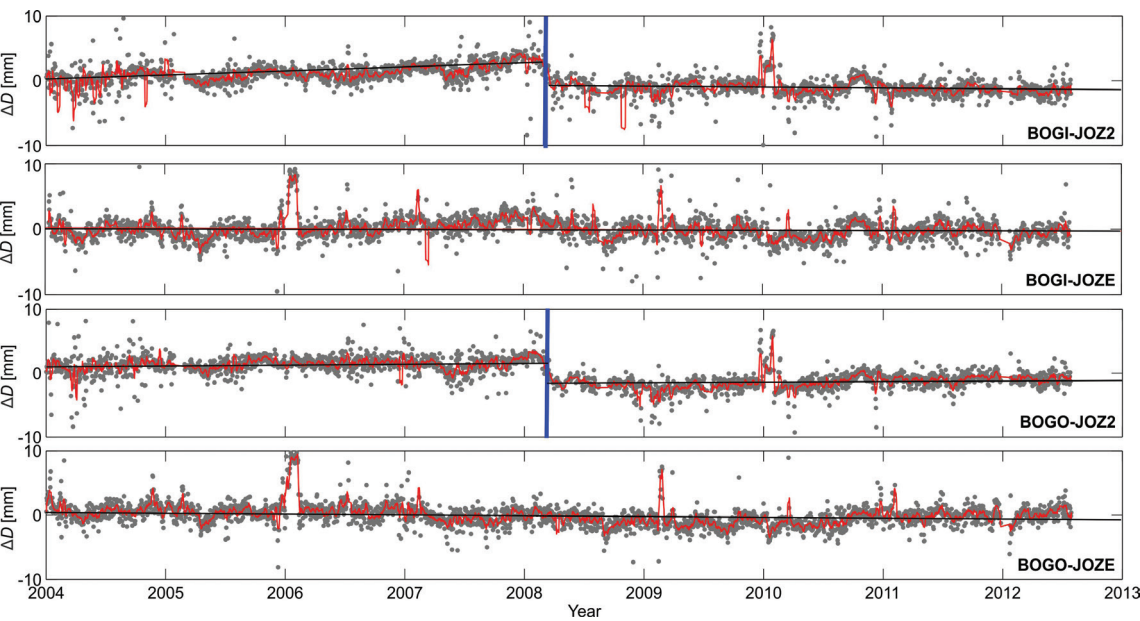
5. Summary and conclusions

Continuous GPS observations (from 2004.0 to 2012.9) of four Polish permanent GPS stations (BOGO, JOZE, JOZ2 and BOGI) located at the T-T zone area were processed to assess their relative tectonic motion as well as to examine the consistency of the recent ITRF/ETRF at T-T zone. With the use of Bernese GPS software v.5.0, daily solutions for components of four individual baselines BOGO–JOZ2, BOGI–JOZE, BOGO–JOZ2 and BOGO–JOZE have been obtained, then 7–day average solutions were estimated. From the varia-

tions of these 7–day average solutions, linear trends for each baseline were determined.

All investigated baselines have provided quite similar linear trends within the corresponding baseline components and baseline length. Generally, linear trends of the variations of these four baselines components have revealed that the relative motions of these GNSS stations are at sub-millimetre level. The estimated uncertainties of linear trends determined were also at sub-millimetre level. Therefore, in order to attribute such trend as the effect of the geodynamic process at the investigated part of T-T zone, and taking into consideration

Table. 2. The estimated linear trends of baselines components and baseline length variations from 7–day average solutions [mm/year]

Baseline	V_X	V_Y	V_Z	V_D
BOGI–JOZ2	0.3 ±0.36	−0.3 ±0.25	0.2 ±0.60	0.6 ±0.30
BOGI–JOZE	0.0 ±0.26	−0.3 ±0.20	−0.2 ±0.34	0.0 ±0.16
BOGO–JOZ2	−0.2 ±0.27	−0.6 ±0.27	0.1 ±0.55	0.5 ±0.32
BOGO–JOZE	0.3 ±0.29	−0.3 ±0.25	0.0 ±0.38	−0.2 ±0.16

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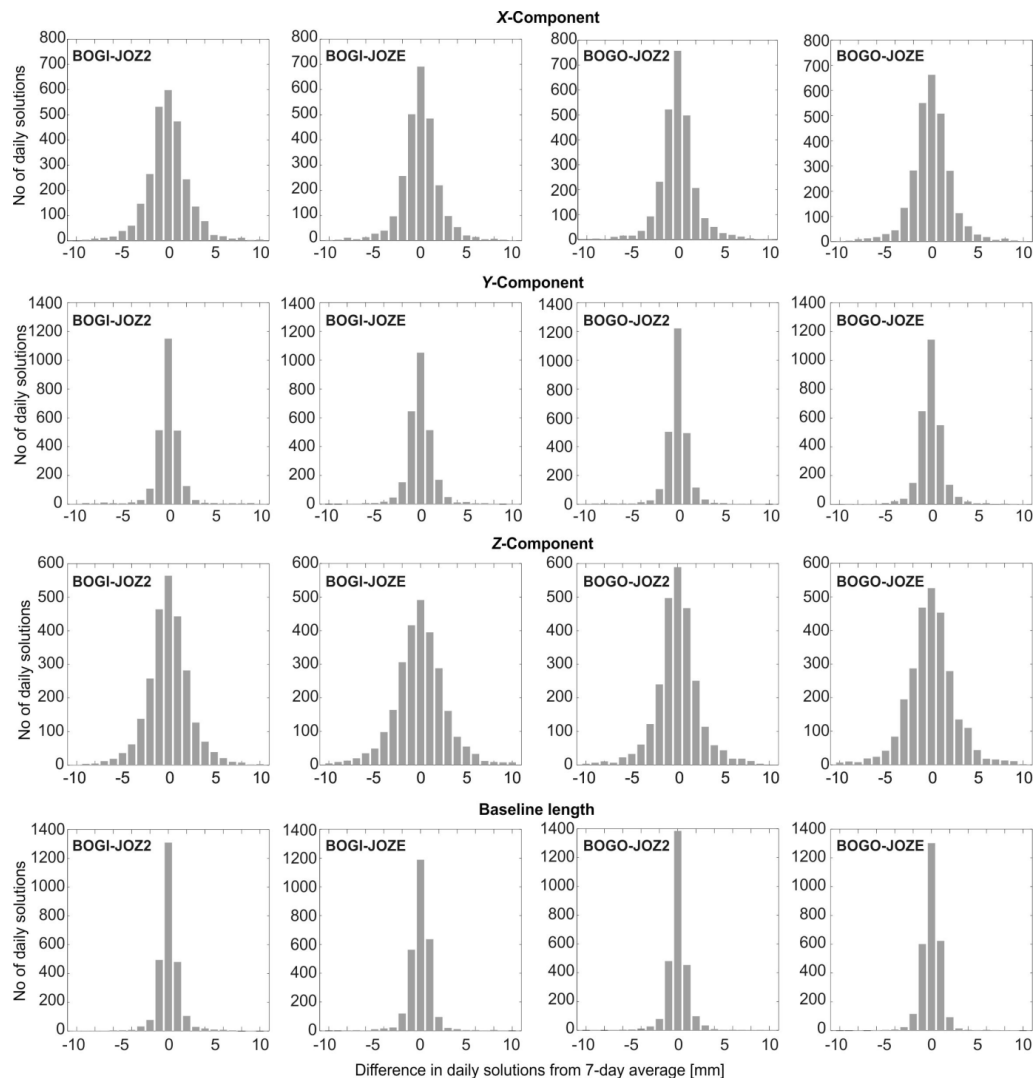possible geodynamic processes

Fig. 6. Histograms showing the difference between the daily solutions and the 7–day averages solutions
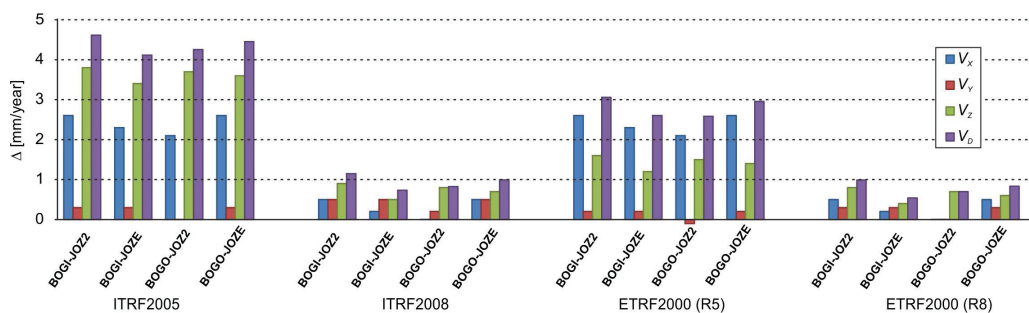

Fig. 7. The differences Δ between linear trends of baselines components variations from recent ITRF/ETRF and the estimated ones from 7–day average solutions

present accuracy of GPS data, long period of GPS monitoring data will be needed.

The linear trends of baselines components variations estimated from 7–day average solutions demonstrate much better agreement with the respective ones obtained from ITRF2008/ETRF2000 (R8) velocities than with those from ITRF2005/ETRF2000 (R5). This confirms the superiority of ITRF2008/ETRF2000 (R8) over ITRF2005/ETRF2000 (R5) addressed in the literature. It indicates that velocities of stations in the investigated area, provided by ITRF2008/ETRF2000 (R8) are more reliable than those from ITRF2005/ETRF2000 (R5). It also suggests ETRF2000 (R8) as the recommended reference frame at that part of T-T zone.

Acknowledgments

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Wykorzystanie obserwacji GPS w strefie T-T do weryfikacji współczesnych układów odniesienia z uwzględnieniem możliwych procesów geodynamicznych

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Streszczenie. Możliwość interpretowania zjawisk geodynamicznych na podstawie analizy obserwacji GPS w dużej mierze zależy od jakości ziemskiego układu odniesienia. Celem niniejszej pracy jest zweryfikowanie prędkości stacji uzyskanych ze współczesnych rozwiązań ITRF/ETRF, a także ocena ewentualnych procesów geodynamicznych przy użyciu długiego szeregu czasowego obserwacji na stacjach permanentnych GNSS położonych w rejonie strefy Teisseyre'a-Tornquista. Składowe czterech wektorów obliczono przy użyciu programu Bernese v.5.0 z obserwacji GPS z lat 2004–2012. Poddano analizie zmiany czasowe składowych tych wektorów oraz ich długości; przy wykorzystaniu analizy regresji wyznaczono trendy liniowe tych zmian. Rezultaty analiz wskazują na zmiany w przedziałach -0.2 do 0.3 mm/rok w składowej *X*, -0.6 do -0.3 mm/ rok w składowej *Y*, -0.2 to 0.2 mm/ rok w składowej *Z* oraz -0.2 do 0.6 mm/ rok w długości wektora. Wyznaczone trendy liniowe zmian składowych wektorów wykazują znacząco lepszą zgodność z odpowiednimi zmianami otrzymanymi z rozwiązań w układach ITRF2008/ETRF2000 (R8) niż ze zmianami z rozwiązań w układach ITRF2005/ETRF2000 (R5).

Słowa kluczowe: strefa Teisseyre'a-Tornquista, geodynamika, układ odniesienia, GPS, zmiany czasowe, trend liniowy

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Metoda poszukiwania wizualnego w badaniach percepcji map

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Streszczenie. Sposób zaprezentowania rzeczywistości na mapie wpływa na jej odbiór przez użytkownika, a więc rzutuje również na obraz rzeczywistości, jaki zostanie wytworzony w jego umyśle. Dlatego też mapy od wieków były i nadal są uznawane za narzędzia poznania, kształtujące wyobrażenia ludzi o świecie. Dwudziestowieczni kartografowie doszli do przekonania, że wielowiekowy, bazujący na intuicji, sposób opracowywania map nie tylko można, ale wręcz należy zmodyfikować, aby lepiej odzwierciedlały one rzeczywistość, wykorzystując w tym celu teorie i metody badawcze z innych dziedzin, w tym szczególnie z psychologii. Zaczerpnięcie metod z psychologii przyczyniło się do rozwoju kartografii poznawczej. Jej podstawowymi cechami, odróżniającymi ją od innych kierunków badawczych w kartografii, było zwrócenie się w stronę użytkownika mapy, analiza procesu jej czytania i interpretacji, stosowanie eksperymentu jako podstawowej metody badawczej oraz przenoszenie na grunt kartografii doświadczeń i metod, a często również samych problemów badawczych, zaczerpniętych z psychologii.

Sposób wykorzystania mapy oraz predyspozycje i ograniczenia poznawcze jej użytkownika należą do istotnych zagadnień podejmowanych przez kartografów od kilkudziesięciu lat. Problem efektywności map powinien być bowiem rozwiązywany dzięki wykorzystaniu wiedzy zarówno na temat zasad ich redakcji, jak również zdolności poznawczych użytkownika. Pierwsze badania psychologiczne w kartografii skoncentrowały się na jednej z subdyscyplin psychologii – psychofizyce. Jest to jeden z najstarszych obszarów badawczych psychologii, zajmujący się badaniem zależności między bodźcem fizycznym a zachowaniem, doznaniem psychicznym lub umysłowym, które ten bodziec wywołuje. Po okresie dużego zainteresowania badaniami eksperymentalnymi w latach 1970. już na początku lat 1980. badania te zaczęły spotykać się z narastającą krytyką. Do spadku zainteresowania badaniami nad percepcją map przyczynił się również rozwój i upowszechnienie technik komputerowych. Kiedy znacząca część podstawowych problemów dotyczących wdrażania technik komputerowych w kartografii została rozwiązana, to właśnie komputery przyczyniły się do ponownego wzrostu zainteresowania badaniem percepcji map. Ułatwiły bowiem badanie map oraz rozszerzyły zakres metod badawczych, a także umożliwiły powstanie wielu nowych rodzajów map, na przykład map animowanych, interaktywnych, prezentacji trójwymiarowych, które zmieniły sposób korzystania z mapy i wymagały przeprowadzenia odpowiednich badań. Dostosowanie nowych form opracowań kartograficznych do możliwości percepcyjnych człowieka zostało uznane za jedno z fundamentalnych zadań kartografii.

Jednym z rodzajów stosowanych percepcyjnych badań psychologicznych jest poszukiwanie wizualne (ang. *visual search*). Wymaga ono zaangażowania uwagi respondenta podczas wykonywania zadań, polegających na odnalezieniu i identyfikacji zadanych obiektów w złożonym układzie wizualnym, pełnym różnorodnych obiektów rozpraszających jego uwagę. Teorie poszukiwania wizualnego zajmują się wyjaśnianiem, w jaki sposób ludzie poszukują konkretnych obiektów i wyłapują je spośród wielu innych. Badania te są stosowane również m.in. w medycynie, marketingu oraz reklamie.

Słowa kluczowe: kartografia, poszukiwanie wizualne w percepcji map, teoria integracji cech, teoria zaangażowania uwagi, teoria poszukiwania kierowanego

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