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Application of PPP Solution to Determine the Absolute Vertical Crustal Movements: Case Study for Northeastern Europe

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Abstract. To estimate the relationship between vertical movements of the Earth’s crust, geoid temporal changes and Mean Sea Level (MSL) variations, a knowledge about the absolute (determined from satellite and space techniques) height changes over time is required. In this paper, we give an idea of determining the height changes with a use of Vertical Switching Edge Detection (VSED) algorithm. On the basis of the least squares estimation, the VSED method detects the discontinuities in time series and determines the values of jumps at the same time. We used the time series from PPP (Precise Point Positioning) solution obtained in NGL (Nevada Geodetic Laboratory) using satellite data gathered at more than 50 permanent stations located in Latvia, Lithuania and northeastern Poland. The minimum time span of data was set up to 3 years. Data were pre-analyzed by removing outliers and interpolating small gaps. The obtained results give an overview of a possibility of the proposed method to be used and the ongoing vertical movements on the area we considered.

Keywords: GPS, PPP, vertical crustal movements.

Conference topic: Technologies of Geodesy and Cadastre.

Introduction

These days, the absolute variations of height in time are employed to estimate the relationship between vertical movements of the Earth’s crust and temporal changes of geoid and mean sea level (MSL) (e.g. Kowalczyk *et al.* 2014a, 2014b). The vertical crustal movements may be determined using precise levelling e.g. (Kowalczyk 2005; Kowalczyk, Rapiński 2013) or Global Navigation Satellite System (GNSS) e.g. (Kontny, Bogusz 2012). The vertical crustal movements are classified as relative or absolute. The relative vertical movements require the control points to be precisely appointed. These control points cannot change their position in time (they are very static in their position) or their movements needs to be precisely known and described (Kowalczyk 2015). If these control points were placed near a tide gauge with estimated mean sea level changes this movement is called “observed” (Kakkuri 1987). Vertical crustal movements determined with the use of GNSS permanent stations are called “absolute”.

Due to their rarity and temporal irregularity, data from precise levelling cannot be formed in the regular time series (Kowalczyk 2008; Lyszkowicz *et al.* 2015). On the contrary, GNSS observations formed in time series, allow, due to the long time span of records and variety of sampling, a wide range of statistical methods to be applied. However, the GNSS position time series are biased by numerous geophysical (Bogusz *et al.* 2011) or artificial (Penna, Stewart 2003; Bogusz, Figurski 2012) phenomena. Therefore, the estimates of trend interpreted as vertical or horizontal movement should be preceded by procedures that minimize the influence of the above-mentioned phenomena (Gazeaux *et al.* 2013; Klos *et al.* 2016).

In this research, we used Vertical Switching Edge Detection (VSED – Rapiński, Kowalczyk 2016) algorithm to simultaneously detect the offsets and estimate the changes in height. Basing on Least Squares Estimation (LSE), VSED detects the discontinuities in time series and determines the amplitudes of jumps at the same time. The vertical movement was estimated fixing one of the control points. Network adjustment was performed using weighted iterative robust estimation (Duchnowski, Wiśniewski 2006.). The results we obtained, give an overview of a possibility of the proposed method to be used as well as the ongoing vertical movements on the area of northeastern Europe.

Data

We used daily time series from the PPP (Precise Point Positioning) solution processed by NGL (Nevada Geodetic Laboratory). We employed satellite data gathered at 55 permanent stations located in Latvia, Lithuania and northeastern Poland (Fig. 1).

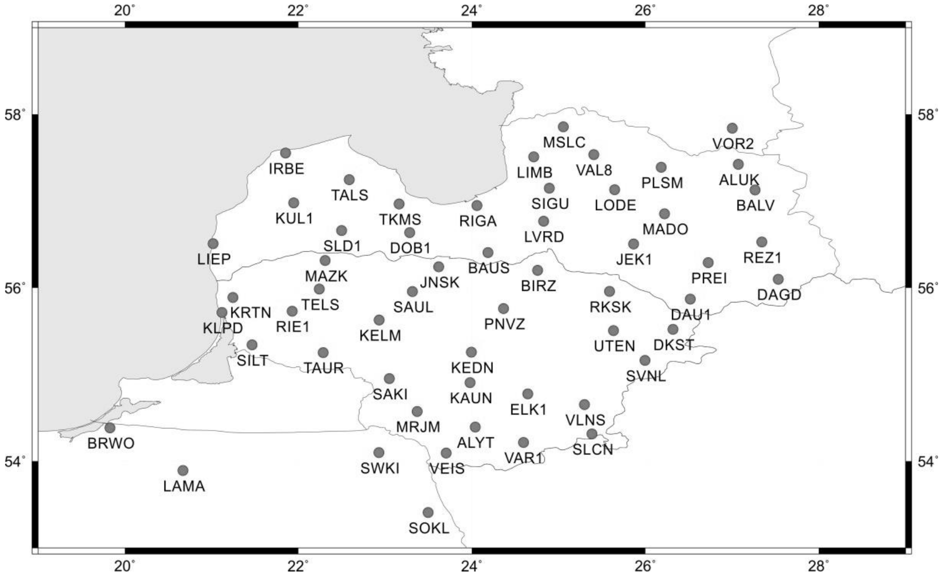

Fig. 1. The layout of the GNSS permanent stations used in this research

We used two types of data. The absolute vertical movements as well as height differences on the pre-defined baselines (Fig. 2). The Delaunay triangulation was applied, similarly to (Kowalczyk *et al.* 2014a; Kowalczyk, A., Kowalczyk, K. 2014).

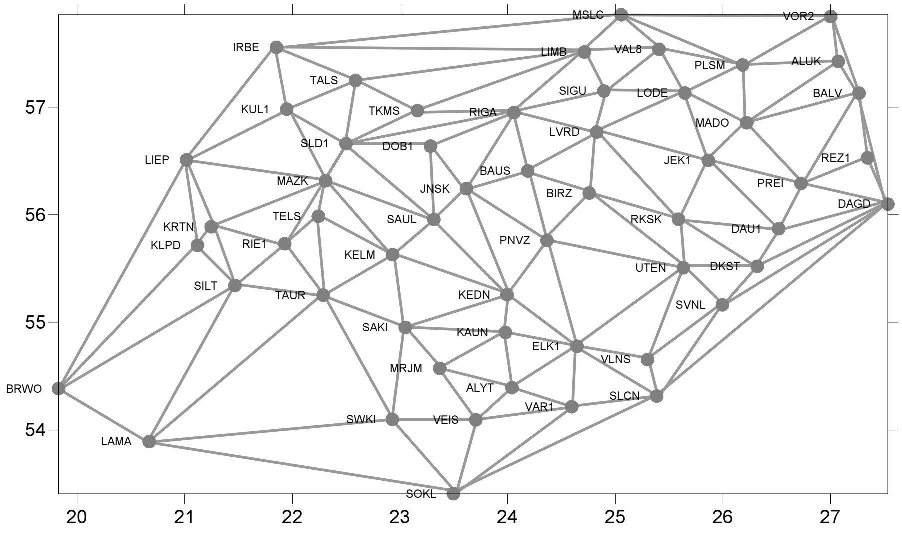

Fig. 2. Delaunay triangulation

As it was shown in (Kowalczyk 2015), the time span of the observed height changes is crucial. Therefore, the minimum time span on each baseline was set to 3 years (Table 1). However, to test the usefulness of the presented methods, the shorter time series were also included.

Table 1. Time spans of the time series on each baselines

Time span (years)	Number of stations	Percentage
0÷1	3	2.0%
1÷2	1	0.7%
2÷3	15	9.9%
3÷4	10	6.6%
4÷5	15	9.9%
5÷6	26	17.1%
6÷7	81	53.3%
7÷8	0	0.0%
8÷9	1	0.7%

Data was pre-analyzed by removing outliers and interpolating small gaps. Figs. 3 and 4 present exemplary time series from LAMA (Lamkówko, Poland) and ALYT (Olita, Lithuania) stations with relatively long time spans of the data.

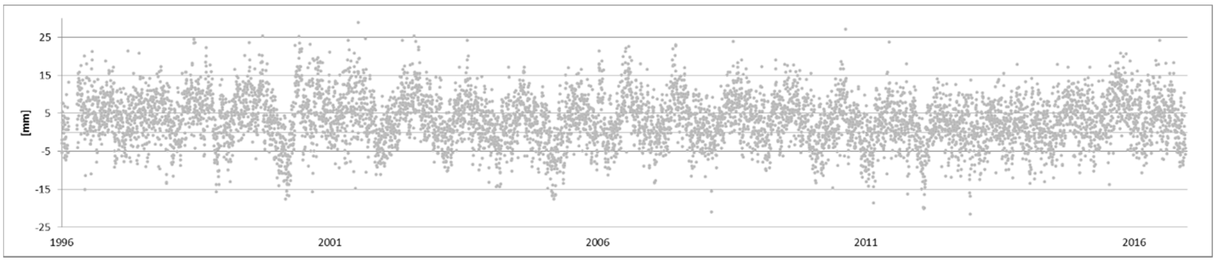

Fig. 3. LAMA vertical time series [mm]

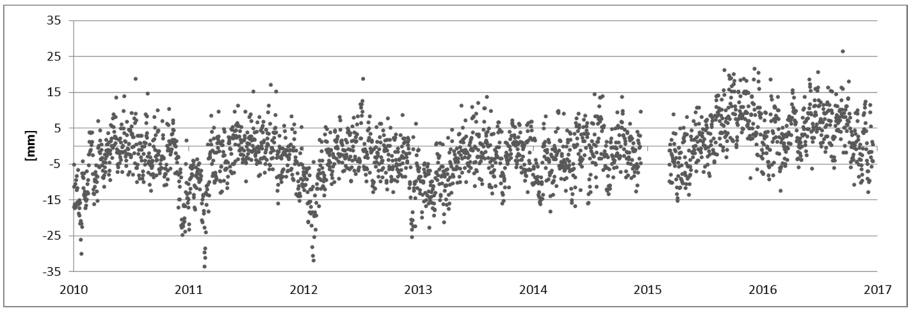

Fig. 4. ALYT vertical time series [mm]

Fig. 5 presents the residual time series after subtraction of the annual and semi-annual curved (commonly observed in GNSS time series – Bogusz, Figurski 2014) using LSE with clearly visible reduction of the scatter.

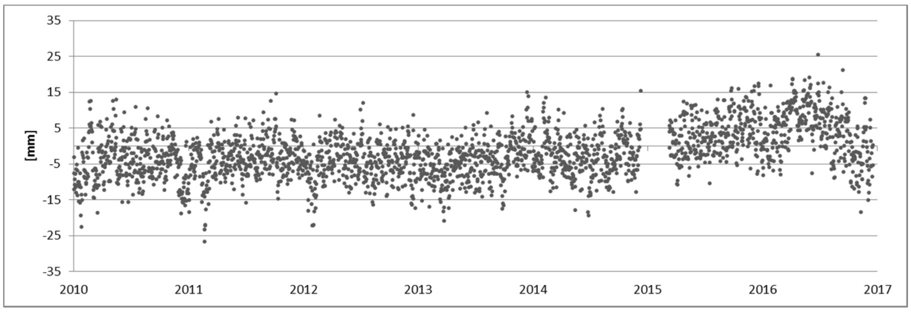

Fig. 5. ALYT residual vertical time series [mm]

The time series of height differences were formed using data collected at the ending points at the same moment of time. Fig. 6 presents the exemplary time series on the VLNS-SLCN baseline.

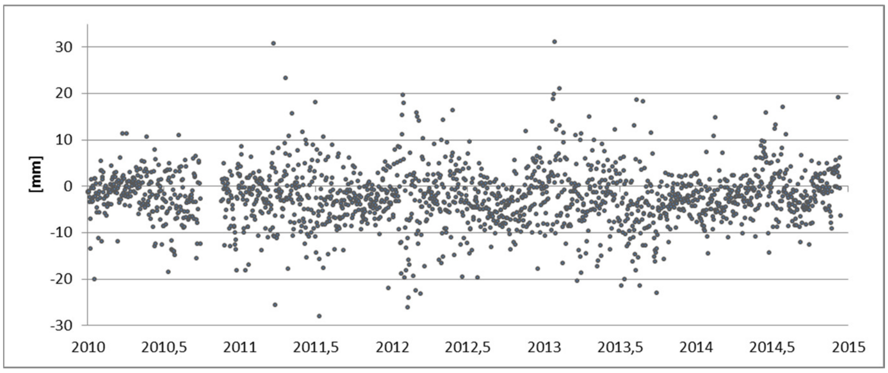

Fig. 6. VLNS-SLCN height differences [mm]

Determination of the absolute vertical motion

To assess the vertical velocity field in the considered area, the vertical trends were estimated (Fig. 7). Data were interpolated using minimal curvature method. The largest formal velocity errors were obtained at the: SLD1, LVRD, BRWO, PNVZ, TKMS stations, marked with white circles in Fig. 7.

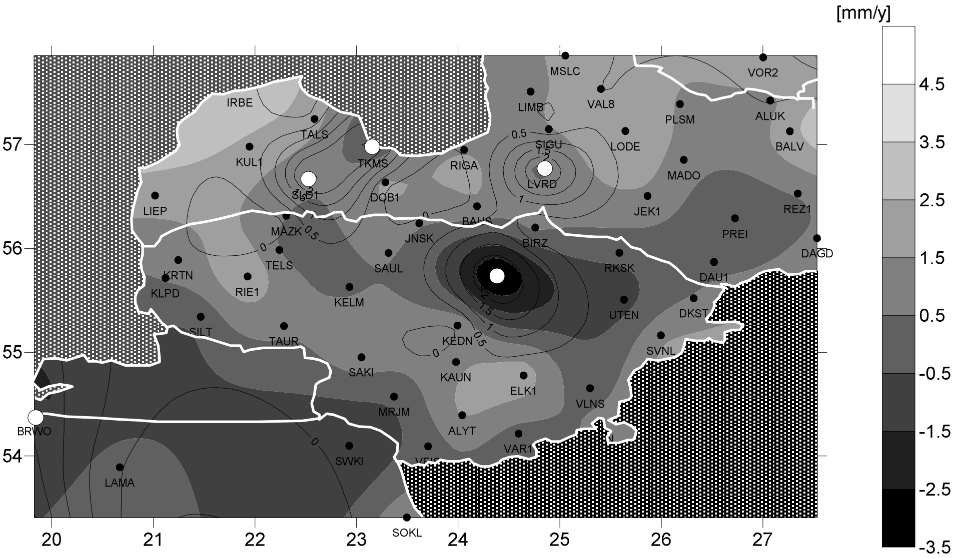

Fig. 7. GNSS-derived vertical velocities [mm/yr] with their one sigma errors (right)

Using baselines presented in Fig. 2, the non-adjusted height differences were determined. Basing on the conclusions from (Kowalczyk 2015), the SAUL (Szawle, Lithuania) station was set up as a basic one with the known movement and its uncertainty. The adjustment was carried out with robust estimation in 3 iterations with non-adjusted trends as observables.

Weights were determined as follows:

$$p_{\Delta v^N_{GNSS}} = \frac{\Delta T}{m_{p_{\Delta v^N_{GNSS}}}{}^2}, \tag{1}$$

where: $m_{p_{\Delta v^N_{GNSS}}}$ – a posteriori error of non-adjusted trend; ΔT – time difference between initial and final epoch.

Fig. 8 presents distribution of the weights on the individual baselines. The extreme weights were obtained on 7 baselines, which turned out to be the best in this network and located in the middle of the network as well as on their periphery. Most of the weights are diversed with relatively large amount of small values. This allows to reduce the influence of the theoretically worst baselines on the final vertical movements.

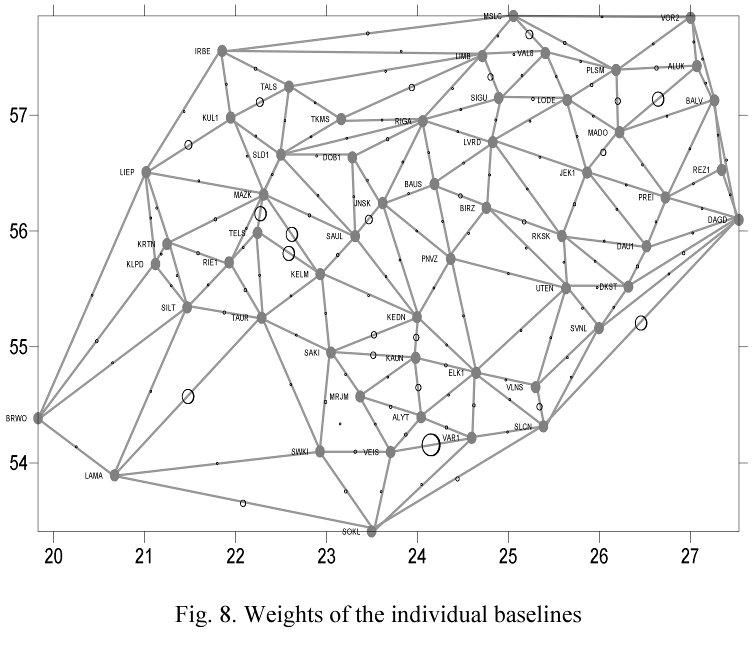

Fig. 8. Weights of the individual baselines

Fig 9 presents the absolute vertical movements determined from GNSS observations for the considered area. They vary from –1.0 to 1.5 mm/yr with clearly visible uplift in the north-western area due to Glacial Isostatic Adjustment. Distribution of errors is concentrated around vectors with largest weights assigned in the adjustments process.

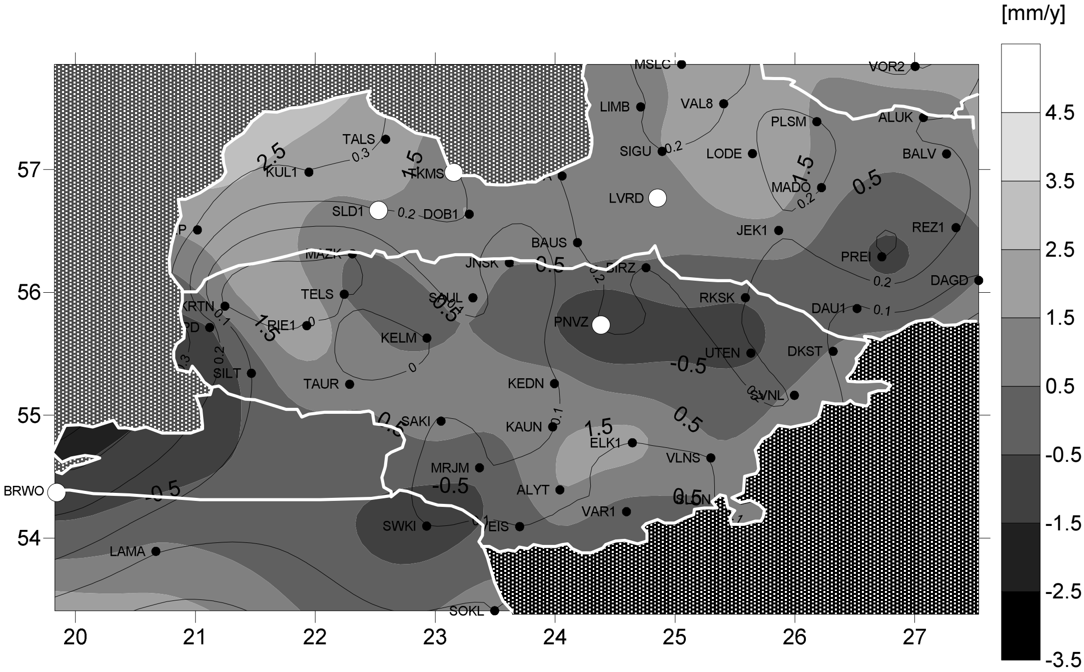

Fig. 9. Absolute vertical movements [mm/yr] with error isolines

Conclusions

The GNSS-based times series employed in this research, allowed to determine the absolute vertical movements with the uncertainty ranged from ±0.1 to ±2.5 mm/yr. These uncertainties strongly depend on the length of the data and its quality. This quality could be improved using some denoising methods, however this was not in the scope of this paper. Relative movements are determined using properly constructed set of connections (forming triangles) with known non-adjusted height differences. Prior to the adjustment, the appointment of weights is crucial. Those weights are able to help with additional assessment of the quality of obtained results. In our case, the obtained errors of the relative movements ranged from ±0.1 to ±0.3 mm/yr. Those numbers describe actual quality of the GNSS PPP solutions.

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GPS time series were downloaded from the Nevada Geodetic Laboratory, accessed from http://geodesy.unr.edu in December 2016.

Map was drawn in the Generic Mapping Tool (Wessel *et al.* 2013).

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