

## MODELS OF VERTICAL MOVEMENTS OF THE EARTH CRUST SURFACE IN THE AREA OF POLAND DERIVED FROM LEVELING AND GNSS DATA

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### ABSTRACT

The known models of recent vertical movements of the Earth crust surface in the area of Poland were processed in the form of contour line map on the basis of the data of the first and second class geometric state levelling network. Second map done by Wyrzykowski (1985) was based on the results of measurements made in 1871-1882, 1926-1937, 1952-1956 and 1975-1977. The newest results of assignment of recent vertical movements of the Earth surface in the territory of Poland were published by Kowalczyk in 2006. The map of the contemporary vertical movements velocities has been processed using the least squares collocation method on the basis of repeated measurements of state precise levelling, executed mainly in 1974-1982 and 1997-2003. Presently, after about 3 years of satellite observations at about one hundred of permanent GPS stations of the ASG-EUPOS network, a verification of the mentioned models is possible on the basis of independent (satellite) measurements. As the resolution of the stations in Poland is sufficient, the model processed using satellite data was determined for the whole area of Poland and it was confronted with earlier (levelling) models. There are some differences in the analyzed models. A comparison of levelling and satellite models indicates defect of reference distinctly resulting from sea level variability.

**KEYWORDS:** maps of vertical movements, levelling, GPS, ASG-EUPOS, regional vertical velocity field

### INTRODUCTION

A precise geometrical levelling is characterized by the best accuracy within all current geodetic methods of determination of the Earth's crust vertical movements. The method is based on cyclically repeated measurements of the height of benchmarks situated on levelling lines. The mean error of the measurements of the first class national levelling network in the area of Poland is within 1.3-2.0 mm/km, for measurements performed in seventies of the 19th century, and 0.4-1.0 mm/km, for measurements performed in the fiftieth and seventieth of the 20th century and on the turn of the recent and current century. Taking into consideration that measurements of the precise levelling are repeated on average every 20 years, it is possible to determine relative velocities of the vertical movements with the accuracy of 0.1-0.3 mm/yr for every kilometre of the distance between the benchmarks.

Permanent GPS observations at the EPN (EUREF Permanent Network) stations in Europe began in 1996. The fifteen years long period of satellite observations enables to determine vertical velocity of the stations with the accuracy of about 0.1 mm/yr, practically irrespective of distances between the stations. However, the density of the EPN stations is very low and uneven. On average, distances between neighbouring stations in Central Europe are 100-200 km. This does not enable creating the model of vertical movements for the area of Poland with

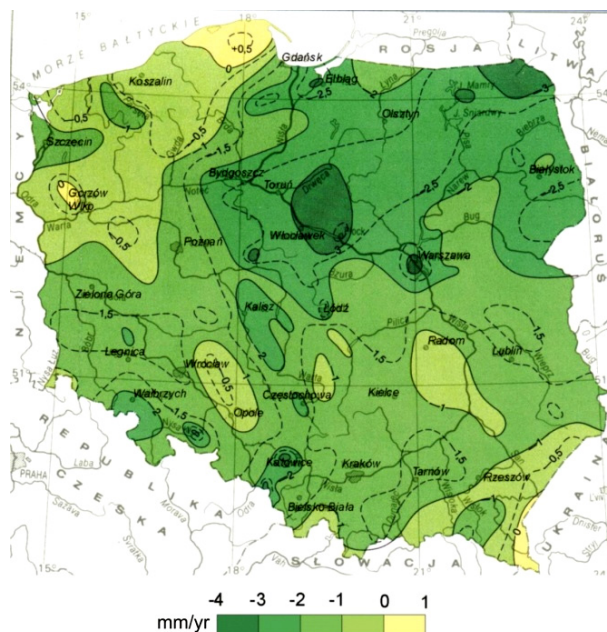
resolution comparable with models obtained from the levelling data. The Polish Active Geodetic Network ASG-EUPOS has been in use since 2008, including about 130 permanent GNSS stations located in the area of Poland and in the border areas of the neighbouring countries. Location density of these stations is not considerably different from the density of the nodes of the precise first-class levelling network. The three-year period of observations gives the basis for making an attempt to create the model of vertical movements in the area of Poland from satellite data and comparing it with the levelling models.

### MAPS OF THE VERTICAL CRUSTAL MOVEMENT VELOCITIES IN THE AREA OF POLAND

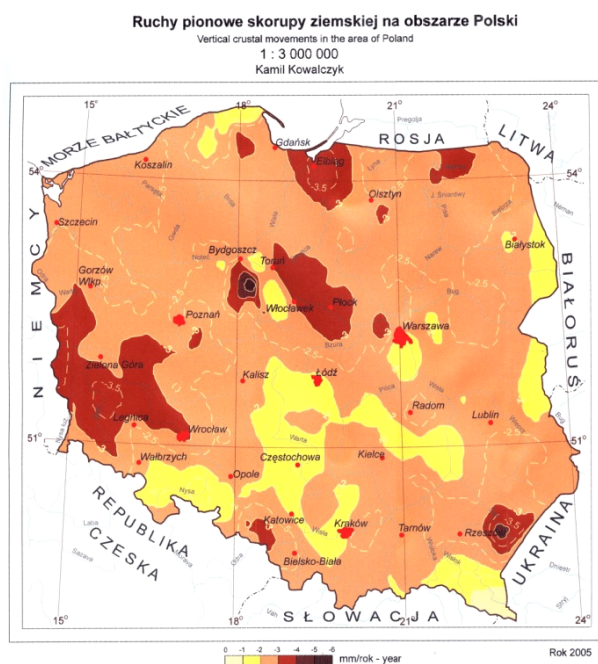
Repeated measurements of the precise levelling network of the first and second classes, made in the period since seventies of the 19th century to date, constituted the basic data for determining surface vertical movements of the Earth's crust for the area of Poland, presented in the form of maps of vertical velocity contour lines. Detailed description of available levelling data may be found in Kowalczyk (2009). By now, they made three such maps, two maps by Wyrzykowski in 1971 and in 1985 (Wyrzykowski, 1971, 1987), and one map by Kowalczyk (Kowalczyk, 2006). The map from 1971 was based on the results of measurements from 1871-1882, 1926-1937 and 1952-1956. The newer map



**Fig. 1** First class levelling network (Kowalczyk, 2006).



**Fig. 2** Map of vertical movements of the Earth crust surface in Poland (Wyrzykowski, 1987).



**Fig. 3** Map of vertical movements of the Earth crust surface in Poland (Kowalczyk, 2006).

from 1985 takes also into account the measuring cycle from 1975-1977. Lines of first-class levelling network with location of network nodes are presented in Figure 1. Vertical velocities appointed in these nodes constitute the basic data for the interpolation of the surface model.

Contour lines of the vertical movement velocities for the area of Poland interpolated by Wyrzykowski in 1985 are presented in Figure 2. According to Wyrzykowski, almost the entire area of the country is subject to subsiding with the speed of up

to -4 mm/year, but the Earth's crust uplift was recorded at its northern and south-eastern ends only.

Kowalczyk (2006) gave the newest, so far, results of estimating contemporary vertical movements of the Earth's crust surface in the area of Poland. He plotted the map of the vertical velocities interpolated from point data using the method of collocation of the smallest squares on the basis of repeated measurements in the national precise levelling lines, made in 1974-1982 and 1997-2003. The copy of the map by Kowalczyk is shown in Figure 3.

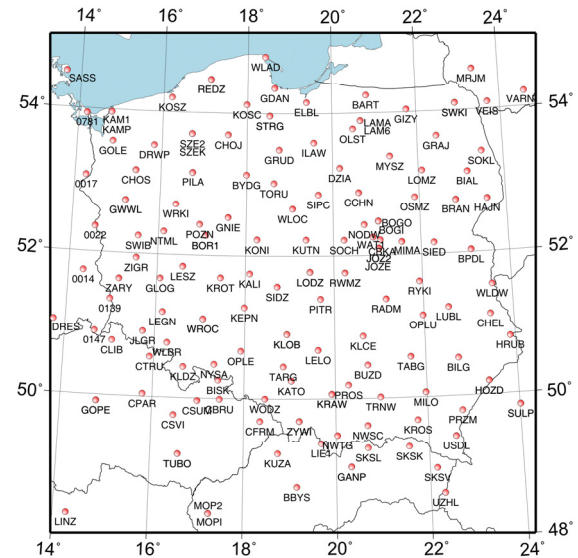
Results presented on the map are characteristic of a surface distribution of vertical movements with reference to the tide gauge located on the Polish Baltic coast in Władysławowo. According to this study the contemporary Earth's crust surface vertical movements in the area of Poland changed from -1.5 mm/year to -5.0 mm/year. Unlike the results of Wyrzykowski, local anomalies were not shown in the Nysa area in the south-western part of the country. However, they showed significant anomalies (subsidence) in the salt exploitation area in Inowrocław surroundings and natural gas exploitation area in Przemyśl surroundings.

#### VERTICAL VELOCITY DETERMINATION FROM GPS DATA

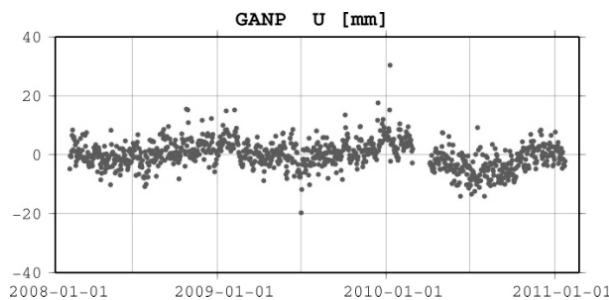
EPN and ASG-EUPOS stations location is presented in Figures 4 and 5. Vertical velocities of the EPN stations determined from cleaned time series were downloaded from the online service: <http://www.epncb.oma.be/>. The vertical velocities of the ASG-EUPOS stations in the ITRF2005 reference frame (Altamimi et al., 2007a) were calculated in the



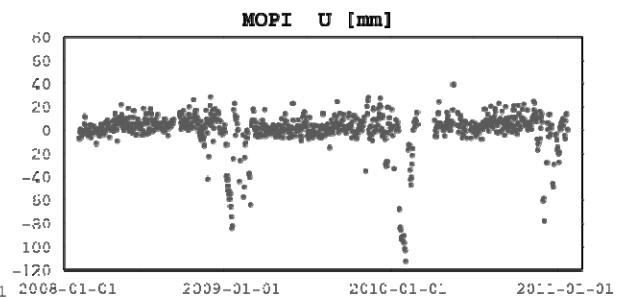
**Fig. 4** Location of the EPN sites.  
(<http://www.epncb.oma.be/>)



**Fig. 5** Location of the ASG-EUPOS sites.



**Fig. 6** Up coordinate time series of GANP (Ganovce, Slovak Republic) site.



**Fig. 7** Up coordinate time series of MOPI (Modra-Piesok, Slovak Republic) site.

Centre of Applied Geomatics, Warsaw Military University of Technology by means of the CATREF software (Altamimi et al., 2007b) using daily solutions of the GNSS network for the period from the beginning of February 2008 to the end of January 2011 (three years). This processing was performed within the geodynamical module, being a part of the "ASG+" project (Figurski et al., 2011).

Vertical velocities estimated on the basis of such a short time series may not be of very high credibility. In general, the effects which could decrease the velocity estimation reliability may be grouped into the following categories:

- annual oscillations due to real (atmospheric or hydrologic) or artificial (unmodelled diurnal and semidiurnal tidal displacements could propagate to spurious longer signals existing in the daily GPS solutions) effects (see Fig. 6);
- seasons-related changes, winter or summer (see Fig. 7);
- non-linearity (see Fig. 8);
- jumps (see Fig. 9);

- noise (see Fig. 10).

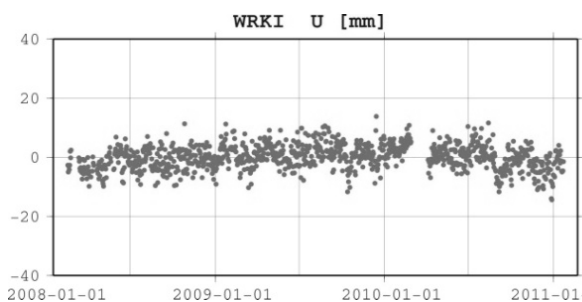
Figures 6 through 10 present time series (daily solutions) of the selected permanent sites (vertical component) in which the mentioned above effects reflect.

Figure 11 presents local vertical velocity vectors of the ASG-EUPOS sites in ITRF2005 frame determined on the basis of daily solutions using CATREF.

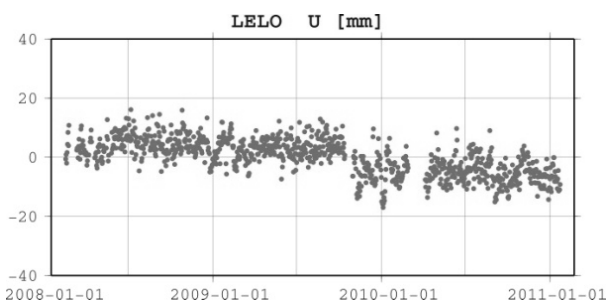
#### MODEL OF VERTICAL MOVEMENT VELOCITIES BASED ON THE EPN DATA

The surface model of the Earth's crust vertical movement velocities in the area of Europe was plotted using the EPN stations' velocities in the ITRF2005 reference frame. A kriging method with the linear semivariogram was applied to interpolation (mgStat, 2011). The model in the form of contour lines of equal velocities is shown in Figure 12.

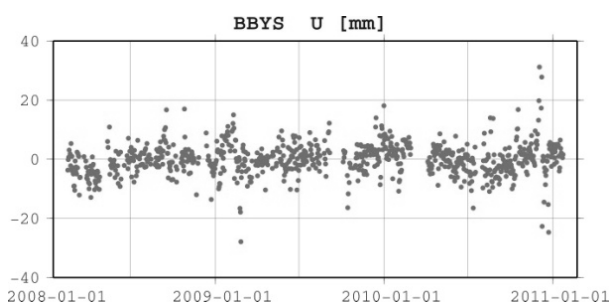
In the model created from the EPN data, zones of subsidence are noticeable in the area of Poland, clearly determined by stations exposed onto subsidence triggered by anthropogenic factors



**Fig. 8** Up coordinate time series of WRKI (Wronki, Poland) site.



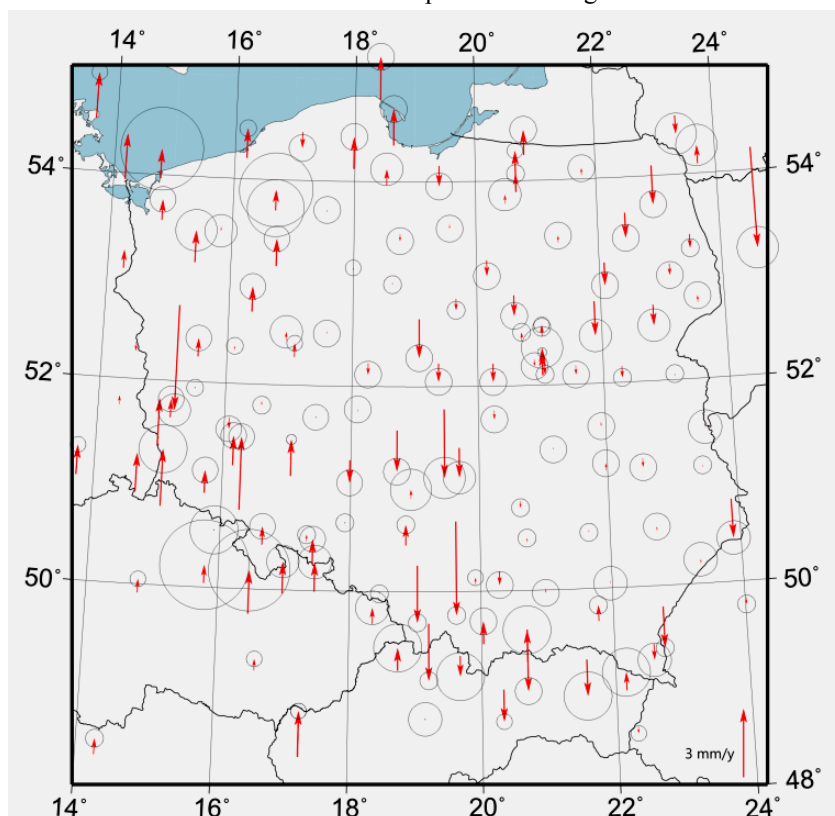
**Fig. 9** Up coordinate time series of LELO (Lelow, Poland) site.



(subsidence of mining areas - KATO (Katowice, Poland) station, and intensive exploitation of underground water - LODZ (Lodz, Poland) station). Apart from that, small vertical movements are characteristic of the area of Poland, in the range from -1 mm/yr to +1 mm/yr. Due to insufficient density of the stations, the model is generalized and useless for interpretation.

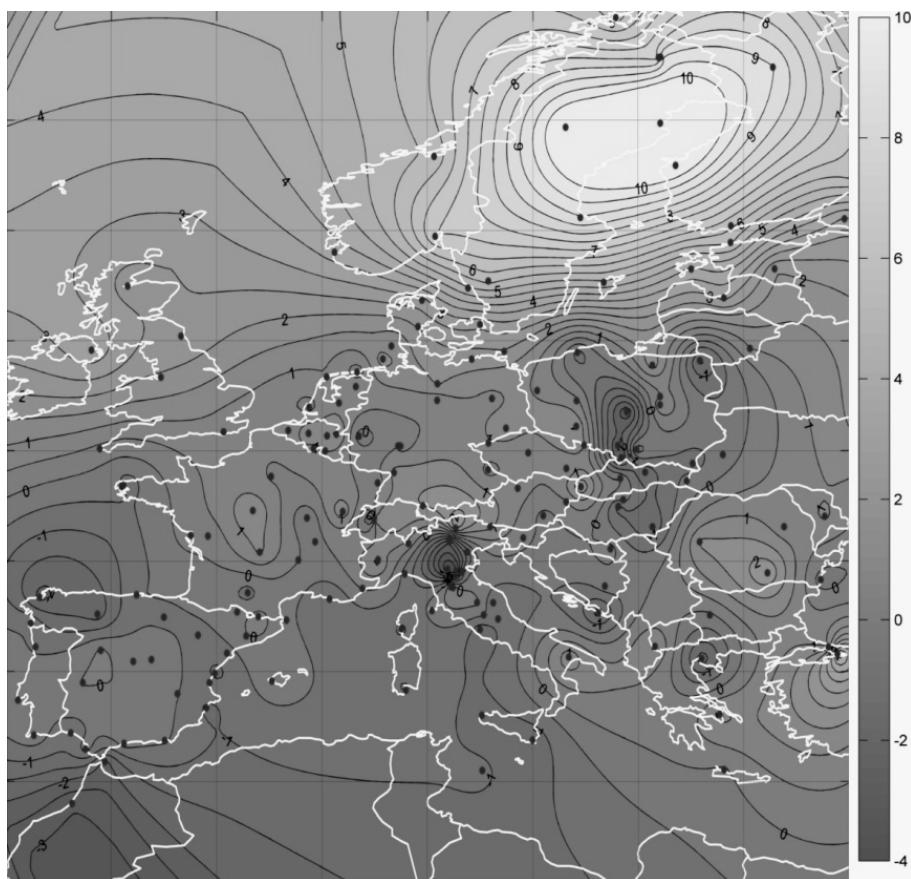
#### MODEL OF VERTICAL MOVEMENT VELOCITIES BASED ON THE ASG-EUPOS DATA

Much better density of the ASG-EUPOS stations in comparison with the EPN stations allows to create a model with resolution comparable with the levelling data. The model of vertical velocity contour lines created by means of the kriging method with linear semivariogram using satellite ASG-EUPOS data is presented in Figure 13.

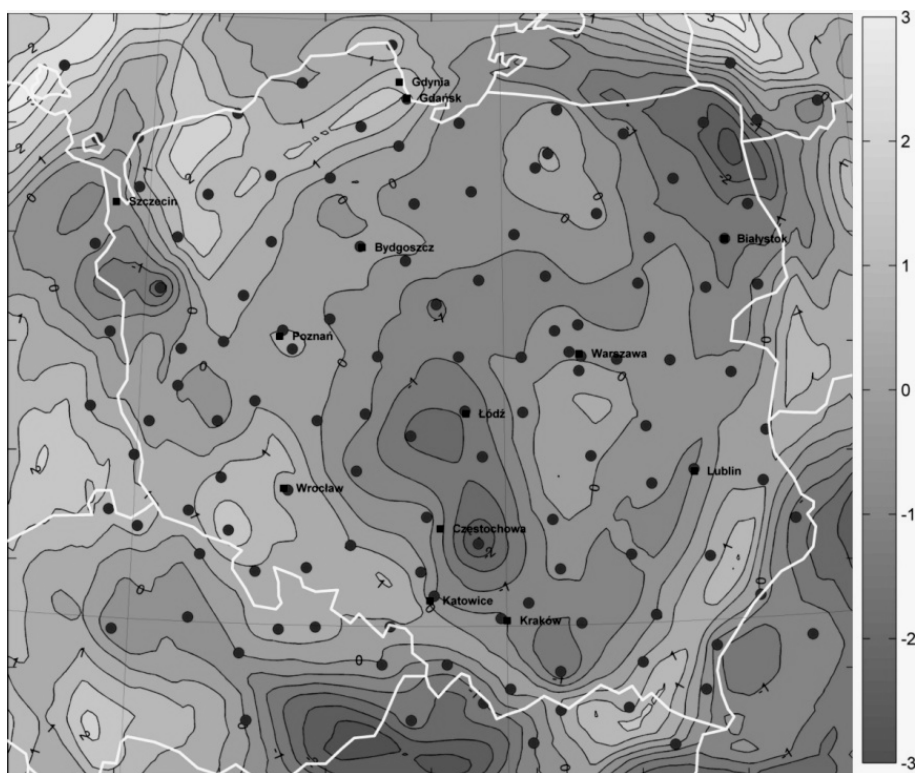


**Fig. 11** Vertical velocity vectors of the ASG-EUPOS sites.

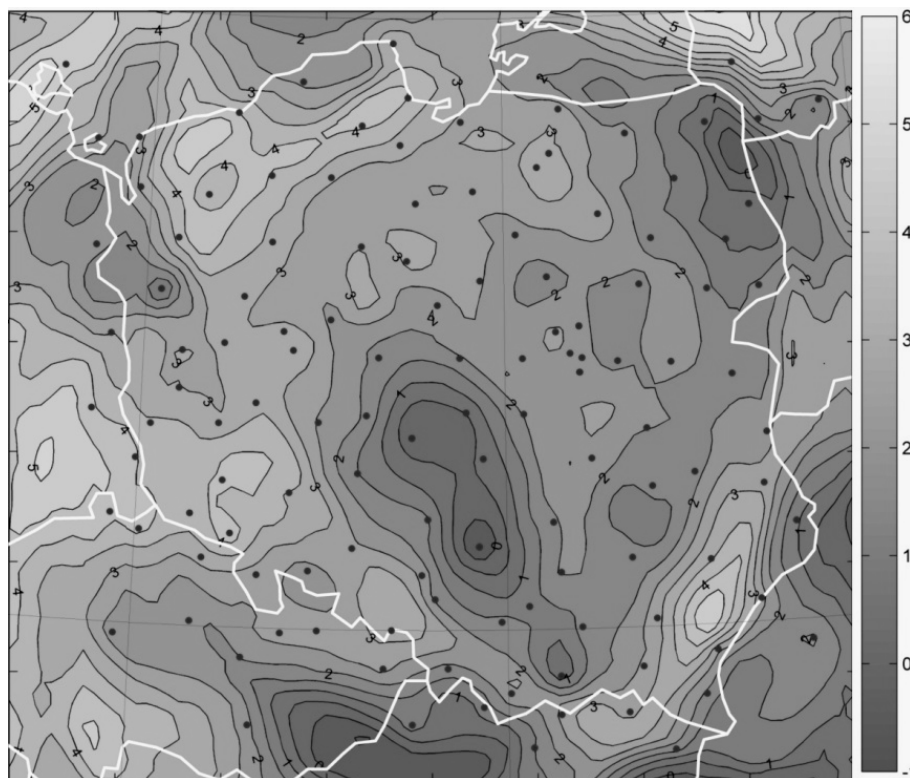




**Fig. 12** Contour lines of vertical movement velocity (mm/yr) of the Earth's crust in the area of Europe derived from the EPN data.



**Fig. 13** Contour lines of vertical movement velocity (mm/yr) of the Earth's crust in the area of Poland based on the ASG-EUPOS data.



**Fig. 14** Contour lines of the difference between the velocity models: the ASG-EUPOS model minus the model by Kowalczyk (mm/yr).

Like in the model interpolated from the EPN data, the model created using the ASG-EUPOS data indicates small vertical movements in the range from +1 to -1 mm/yr in the predominating area of the country. Bigger subsidence is shown in areas influenced by stations with anomalous values of vertical velocities: GWWL (Gorzów Wielkopolski) - 4.4 mm/yr, LELO (Lelów) - 4.9 mm/yr, ŁÓDŹ (Łódź) - 2.4 mm/yr, SIDZ (Sieradz) - 2.7 mm/yr, SWKI (Suwałki) - 2.1 mm/yr. Mean errors of these velocities should shape up to the level of  $\pm 0.5$  mm/year to  $\pm 0.8$  mm/year, because with this assumption changes in distance from the geoid to ellipsoid can be omitted (Sjöberg, 1983). The reasons of the anomalous subsidence require specialized analysis and interpretation.

#### COMPARISON OF THE „SATELLITE” AND „LEVELLING” MODELS

Differences between the „satellite” (ASG-EUPOS) and the „levelling” (Kowalczyk) models of the vertical movement velocity of the Earth crust surface in the area of Poland are presented in the form of the contour lines map in Figure 14.

The differences change within the range of -0.5 to +4.5 mm/yr with anomalies quite congruent with the previous model. The average difference of +2.5 mm/yr is exactly the same as the mean sea level velocity for the Władysławowo tide gauge averaged using data from various authors presented by

Kowalczyk (2006). To determine the vertical crustal movements relative to the mean sea level it is necessary to connect the levelling network with the sea level one. According to (Kowalczyk, 2006), the tide gauge station in Władysławowo was used for the „levelling” model.

#### CONCLUSIONS

Present day density of GNSS permanent stations in Poland is quite sufficient for reliable determination of a local (national) model of vertical Earth crust movements with resolution similar to the levelling network. However, the GPS coordinate time series of the ASG-EUPOS stations are still too short for reliable velocity estimation. Vertical velocities determined on the basis of the GNSS (GPS) data are not influenced by the sea level variability (contrary to the levelling models) but they are strongly influenced by geophysical and other unmodelled loadings. Analysis of observations from the permanent GPS stations indicates that the accuracy of heights determined on the basis of daily observations is ranging from 7 to 9 mm (Ihde and Augath, 2001). While analyzing the observations from the period of three years by linear regression showed that the ellipsoidal height differences have an error of about 0.5 mm/yr (Ihde and Augath, 2001). This means that from a statistical point of view the vertical crustal movements velocity of 1.0 mm/yr should be easily determined from three years of GPS observations.

Significant differences between the individual models derived from the levelling and the satellite data occur particularly in the vicinity of GNSS stations strongly influenced by anthropogenic factors. More reliable verification of the existing models will be possible after a few years of GNSS observations at the ASG-EUPOS sites. Obtained results should be treated as a contribution to the further study.

#### ACKNOWLEDGMENTS

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