Geocentric Sea Level Changes At Tide Gauge Station In Władysławowo

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Key words: mean sea level, land uplift, time series analysis.

SUMMARY

Knowledge of the changes in the mean sea level is important in geodynamic, climatology and other fields. The present work shows the geocentric changes of sea level at the tide gauge Władysławowo on the Polish coast of the Baltic Sea. Changes in sea level were estimated from tide gauge and permanent GNSS observations. We used the monthly mean tide gauge readings from 1951 -2017 obtained from Institute of Meteorology and Water Management[1]. Daily GPS time series of Władysławowo station were downloaded from the Nevada Geodetic Laboratory (NGL) from April 2003 to February 2011. Computed in this work the absolute mean sea level changes at the station Władysławowo was estimated as +2.99 mm/year with the error of ± 0.41 mm/year.

[1] http://www.imgw.pl/en/

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1. INTRODUCTION

The surface of the oceans and seas is not the ideal horizontal surface (the geoid). Temporary water level is the result of changes during the long-term factors, annual and short periodic. The mean surface area of the oceans and seas over a longer period of time, can be obtained by averaging sea level (mean sea level) for a given period. The average sea level can be calculated from observations of tide gauge, altimetry and oceanographic methods

Vertical movements of the Earth's crust calculated from observations of tide gauge are determined relative to the land and are called relative movements. If we want to compute absolute sea-level changes, the vertical movements of the Earth's crust have to be considered. Until recently, the determination of the vertical movement of the Earth's crust at tide gauge was possible only with repeated (every 20 years) precision levelling.

More recently, continuous GNSS observations at tide gauge stations allow determine the vertical movements of the Earth's crust with high accuracy Bitharis (2017), Wöppelmann and Marcos (2016). For that reason, continuous GNSS measurements at tide gauge are made and used to determine the vertical movement of the Earth's crust. Geocentric changes to sea level shall be calculated from the following simple formulae

$$v_o = v_t + v_s \qquad (1)$$

where v_0 is geocentric change in sea level, v_t is the change in sea level calculated from tide gauge observations of and v_s is vertical movement of the Earth's crust from GNSS observations.

There is a second reason to remove from tide gauge observations vertical movements of the Earth's crust. This reason is altimetry. Altimetry this is different from the traditional tide gauge that is determine the sea level in the global reference system referenced to the center of mass of the Earth. GPS observations not only removes the vertical movements from tide gauge observations but they referred sea level changes to the same reference system, usually the ITRF.

There are many publications concerning the investigation of variations to the mean level of the Baltic Sea. Ealier determinations of the Baltic mean sea level changing using tide gauge data have been done by e.g. Montag (1968), Dziadziuszko and Jednorał (1987) and Wyrzykowski (1987).

The purpose of this work is to define a linear trend of time series observations of GPS and the time series observation of tide gauge in Władysławowo to determine absolute Baltic sea level changes at the station in Władysławowo.

2. THE DATA
2.1 GPS data

Daily GPS time series Władysławowo station position were downloaded from the Nevada Geodetic Laboratory (NGL) organization that conducts research in the field of surveying satellite in order to resolve the problems at global and regional levels. This file is named WLAD. IGS08. tenv3 contains the computed station positions from April 2003-February 2011 the interval one day. The total number of computed positions is 2546. In the series there are 7 breaks from 2 to 13 days and a very long break between May 2010 and February 2011 (Fig. 1). The statistic of the vertical component u computed from the GPS observation at Władysławowo station is as follows (Table 1).

Table 1 Statistics (in mm) of the vertical component u computed from GPS observations at Władysławowo station

Number of observations	Mean	Minimum	Maximum	Std. dev.
2546	742.1	714.9	764.8	6.7

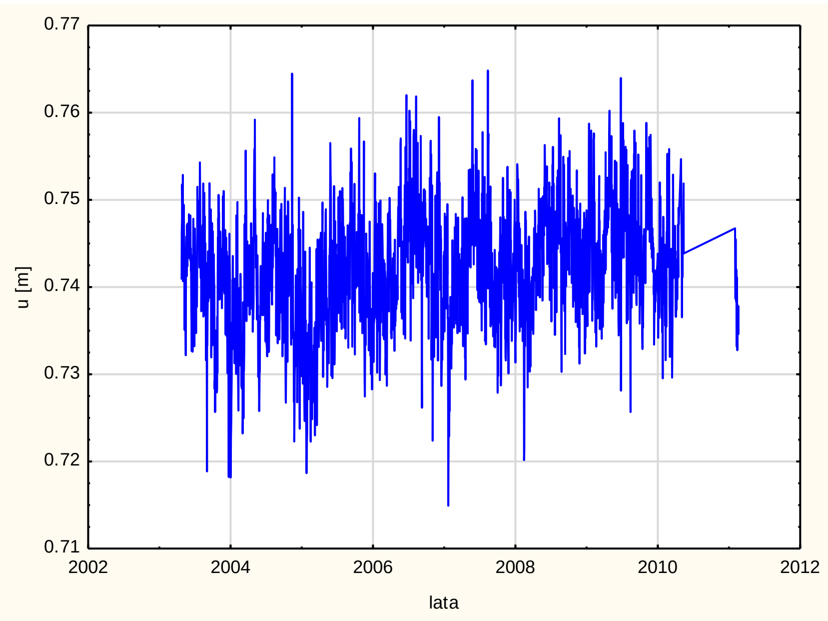

Fig. 1 Drawing of the daily changes of vertical component *u* computed from GPS observation

2.2 Tide gauge data

This work studied the mean readings of tide gauge in Władysławowo from 1951 -2017. The consider time series consist of mean monthly observations from years 1951-1999, obtained from IMiGW Branch Office in Gdynia, daily observations of the tide gauge from the years 1980-2013 (six readings per day), and a collection of monthly mean readings from the years 2013-2017 published in Bulletin of the South Baltic Area on the website: http://old.imgw.pl/extcont/biuletyn_baltyk/ . In a time series were missing observations from November and December 2002. These values were interpolated for the purpose of this work. Finally file of monthly mean values (in mm) for the years 1951-2017 consists of 800 elements and its statistical characteristics are as follows:

Table 2 Characteristics of the monthly mean sea level at Władysławowo(in mm)

Number of observations	mean	minimum	maximum	Std dev
800	5029	4540	5558	160

Diagram of monthly mean readings of tide gauge in Władysławowo, created for the purpose of this work, is shown in the Fig. 2. At the same time in this figure is shown the simple regression that indicates a clear change in the sea level over the period of time.

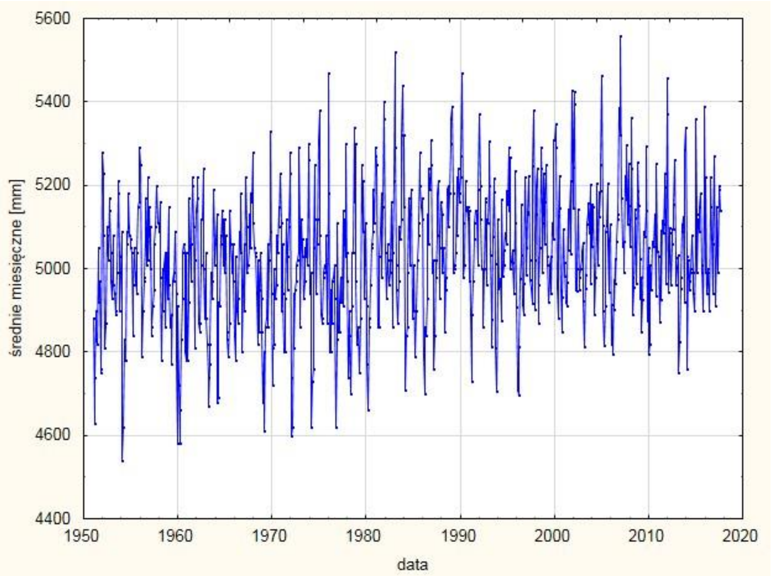

Fig. 2 Graph of mean monthly tide gauge readings in Władysławowo in the years 1951-2017

One of the factors causing changes in sea level are tides caused by effects of gravity of the Moon and Sun on the mass of the oceans and seas. The tides of the Baltic Sea are almost invisible. This is due to a lack of a wide connection with the ocean, the weight of the water in the sea much płytszym and smaller than the ocean. On the South Baltic areas, where the depth does not exceed 100 metres, the water level at high tide is rising just one centimeter.

Due to the very small tides at the tide gauge station in Władysławowo, and the fact that the mean monthly are nearly free from its impact, the monthly mean were not corrected due to tides.

3. CALCULATIONS

In this chapter GPS and tide gauge time series were investigated using the computer program Hector. The software package Hector can be used to estimate a linear trend in the geophysical time series. Iit is well known that in most geophysical time series "noise" is correlated in time, and it has a significant impact on the accuracy of the estimation of a linear trend. Therefore in our case it is reasonable to use a computer program, such as Hector.

Hector program Boss et al. (2013) assumes that you are familiar with the type of correlation time "noise" contained in observations and estimates both the linear trend and the parameters of the "noise" of the selected model using the method of maximum likelihood (MLE). The chosen noise models are a combination of power-law noise and a white noise. Otherwise the model could be chosen from: PowerlawApprox, FlickerGGM, RandomWalkGGM, ARMA, ARFIMA or GGM (Generalized Gauss Markov). The chosen method for the likelihood computation is 'AmmarGrag ' which is described in more detail in (Bos et al., 2013). To choose the best “noise” model are used criteria Akaike (AIC) and Baysian (BIC) described in Akaike (1974), Schwarz (1978).

3.1 Analysis of GPS data.

For analyses the source file data WLAD. IGS08. tenv3 containing daily solutions was used, from which the not complete observation done in year 2011 were removed. Finally this time series consists of 2576 elements. The calculation was carried out with the available models of "noise" and it was found that the smallest values of the AIC and BIC was obtained with the model error GGM. In this case, the calculated trend is + 0.98 mm/year with an error ± 0.15 mm/year. The annual term cos is equal to-3.050 and the annual term sin is:-1.182.

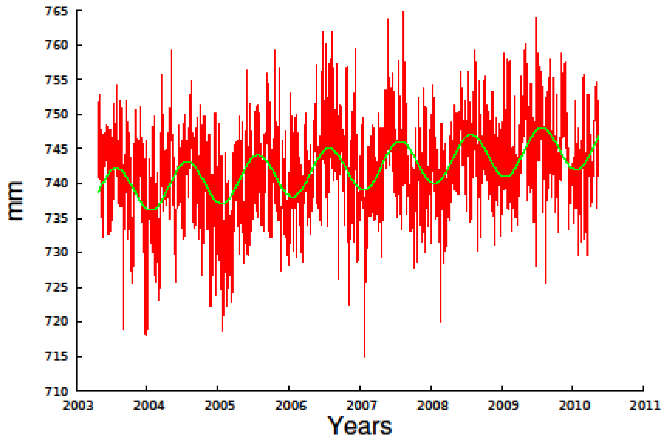

Fig. 3 Diagram of GPS time series at the station in Władysławowo with seasonal changes over time

3.2 Tide gauge data analysis

In the analyses of tide gauge data we used a set of monthly mean observation of tide gauge in Władysławowo from the years 1951-2017 containing of 798 observations.

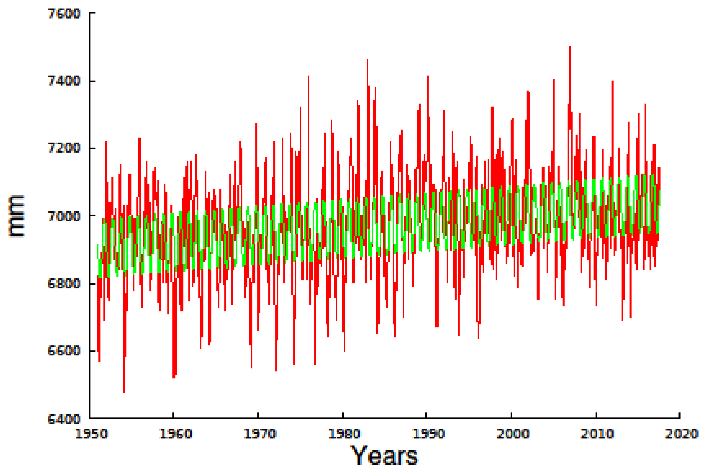

Fig. 4 The diagram of tide gauge time series in Władysławowo

The calculation was carried out with the available "noise" models and it was found that the smallest values of the AIC and BIC was obtained with the model error GGM. In this case, the calculated trend is + 2.01 mm/year with an error ± 0.38 mm/year. The annual term cos is equal to 30.031 and the term sin is 81.775.

4. SUMMARY

The station Władysławowo is a very good station to monitoring the absolute changes of mean sea level because the tide gauge and GPS antenna are separated only fee meters apart. Sea level changes computed from tide gauge data from the years 1951-2017 gives trend +2.01 mm/year. The crust is moving up and its trend computed from 8 year of continuous GPS data is +0.98 mm/year. Therefore the absolute mean sea level changes at the station Władysławowo was estimated as +2.99 mm/year with the error of ± 0.41 mm/year.

To check our results we compared them with the results obtained at the Sassnitz station which is in the SONEL network. SONEL[2] is providing high-quality continuous measurements of sea- and land levels at the coast from tide gauges (relative sea levels) and from modern geodetic techniques (vertical land motion and absolute sea levels) for studies on long-term sea level trends, but also the calibration of satellite altimeters.

A small number of SONEL stations are located at the Baltic Sea but there are any station at Polish sea coast. The near station Sassnitz is located in Germany about 500 km from Wladyslawowo. The SONEL service state that the change of the mean sea level computed from tide gauge data is +1.31 mm/year and the GPS land uplift is +0.83 mm/year. Combine velocity is +2.14mm/year with error ±0.55 mm/year. It means that our computations gives reasonable values, and the Władysławowo station could be very easily included in SONET network.

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Education and previous appointments:
1967 - Master of Science (M.Sc.), 1975 - doctor (Ph.D.), 1994 - habilitation, 1999, professor.

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Geodesy, gravity field, geodetic networks, surveying.

Selected publications: Łyszkowicz A.,1993, *The Geoid for the Area of Poland*, Artificial Satellites, vol. 28, No 2, Planetary Geodesy, No 19, pp. 75-150, ,Łyszkowicz A., Denker H.,1994, *Computation of Gravimetric Geoid for Poland Using FFT*, Artificial Satellites, Planetary Geodesy No 21, str.1-11, Łyszkowicz A., Forsberg R., 1995, *Gravimetric Geoid for Poland Area Using Spherical FFT*, IAG Bulletin d'Information N.77, IGES Buletin N.4, Special Issue, Milano, pp.153-161, Łyszkowicz A. Biryło M., Becek K., 2014, *A new geoid for Brunei Darussalam by the collocation method*, Geodesy and Cartography, Vol. 63, No 2, pp. 183-198, Łyszkowicz A., Bernatowicz A., 2017, *Current state of art of satellite altimetry*, Geodesy and Cartography, Vol. 66, No 2,

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