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ABSOLUTE SEA LEVEL CHANGES AT THE TIDE GAUGE STATION IN WŁADYSŁAWOWO USING DIFFERENT TIME SERIES SOFTWARE PACKAGES

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This paper presents geocentric sea level changes at the tide gauge station in Władysławowo, Poland. These changes have been calculated from the time series of GNSS and tide gauge observations. For the estimation of the geocentric sea level trend computer software packages Hector, GITSA, GGMatlab, and Statistica have been used. The results show that all the software packages give a similar value of absolute sea level changes in Władysławowo and it is estimated at a rate of around 3 mm/year. The examined computer programs are featured by a different degree of visualization and the simplicity of use. A significant difficulty is to prepare the ***required data format*** and the installation of the computer program in the software environment e.g. Matlab. Finally, it can be concluded that the Hector software package, due to the simplicity of input data preparation, that the possibility of on-line calculations and the selection of different error models are very useful for the analysis of time-series of geophysical phenomena like sea level changes. The least recommended for this type of analysis of time series is the Statistica software package.

Key words: mean sea level, tide gauge, satellite GNSS observations.

Introduction

Sea level is a unique indicator in the study of the climate impact on any changes going on the Earth's surface. In the 21st century, rising sea levels will affect the infrastructure, ecosystems, and lives of hundreds of millions of people around the world. The study of previous and future sea level changes is essential for understanding the Earth's climate evolution e.g. (IPCC 2014), (Fu and Cazenave 2000).

Currently, there are two methods for determining trend in the sea level; from tide gauge and satellite altimetry data e.g. (Grgić et al. 2017). Tide gauges allow sea level observations but only at certain places. These observations are related to a point (benchmark) located on land, and thus determined trend of sea level are so-called relative sea level trend v_t. Satellite altimetry determines the sea level in a global system with respect to a released version of the (secular) International Terrestrial Reference Frame (ITRF), (Altamini et al., 2002) which refers to CM (Centre of Mass) frame (Blewitt, 2003). This sea level trend is so-called absolute sea level trend v_o. In order to compare trends of sea level obtained from different techniques, the tide gauges records should also refer to the center of the CM. Thus, the vertical movements of the earth's crust (vertical surface displacement) have to be taken into account (Cazenave et al. 2002).

Vertical crust displacement (trend) on tide gauge stations, until recently, have been estimated from repeated (every 20 years) measurements of precise levelling. The values determined in this way have been featured by a low reliability. Nowadays, continuous GNSS observations at tide gauge stations provide vertical movements of the earth's crust with high accuracy (Bitharis et al., 2017), (Wöppelmann and Marcos, 2016). Finally, geocentric sea level trend, in a consider span of time, is calculated from the following simple expression e.g. (Bitharis et al., 2017)

$$n_0 = n_t + n_s \qquad (1)$$

where v_o is a geocentric sea level trend, v_t is a local sea level trend calculated from tide gauge observations, and v_s is the vertical movement of the earth's crust derived from GNSS observations.

There are many research publications considering trend in the mean sea level along the Baltic Sea coast, (Montag, 1968), (Dziadziuszko & Jednorał, 1987), (Kalas, 1993), and others.

For example, the authors of the paper (Vermeer et al., 1988) have used 64 years of observations from 13 Finnish tide gauge stations to obtain precise relative changes in the Baltic sea level. The results show that the sea level change on the Finnish west coast is from 1 to 7 mm/year.

Łyszkowicz, (1995) used annual mean tide gauge data for the years 1951–1994, and the mean sea level and relative changes (linear trend) have been estimated on six Polish tide gauge stations. The value of the linear trend varies from 1.1 to 2.6 mm/year. In this paper, tide gauge observations in Władysławowo are characterized by a linear trend of +2.6 mm/year.

In the paper (Richter et al., 2012), based on tide gauge observations for almost 200 years, homogeneous series of changes in the mean sea level for nine tide gauge stations of the southern Baltic coast have been computed.

A valuable work is the paper (Wöppelmann et al. 2002) where the analysis of tide gauge data from 66 tide gauge stations, located mainly on the Baltic Sea coast, is presented. The regression analysis shows that the mean sea level changes from one millimeter to 2.3 mm/year. For example, for the station in Władysławowo the changes are 0.28±0.65 mm/year, in Helsinki -2.49±0.17 mm/year, and at the station in Stockholm -3.89±0.17 mm/year.

Similarly in (Pajak and Kowalczyk, 2018) sea level trend was estimated from the satellite altimetry and tide gauge time series for five tide gauge Polish stations.

Due to a lack of continuous GPS observations in those days, all the mentioned above publications concern the determination of only relative trend in sea level.

The main goal of this study is to estimate the applicability of computer programs like Hector, GITSA, GGMatlab and Statistica to determine absolute trend in mean sea level from GNSS and tide gauge observations at the station in Władysławowo.

GNSS data

The time series of daily position of the tide at the gauge station in Władysławowo from continuous GNSS observations has been taken from the web site of Nevada Geodetic Laboratory (NGL) see (Blewitt et al. 2018). These series have been elaborated by GIPSY/OASIS_II software package in the Earth frame IGS80. The package is developed by the Jet Propulsion Laboratory (JPL). More details of the elaboration of the series can be found on the website http://geodesy.unr.edu/gps/ngl.acn.txt.

Data set for Władysławowo tide gauge station, named WLAD.IGS08.tenv3, contains computed station's positions from April 2003 to February 2011 with a single day interval. The total number of computed positions is 2546. There are 7 gaps in the series from 2 to 13 days and a large gap between May 2010 and February 2011 (Fig. 1.). Therefore, in the following analyzes only the time series from the period 2003–2010 has been considered. Sorry, but it is clear. GPS times series give position of the earth crust to which the tide gauge is fixed. See introduction.

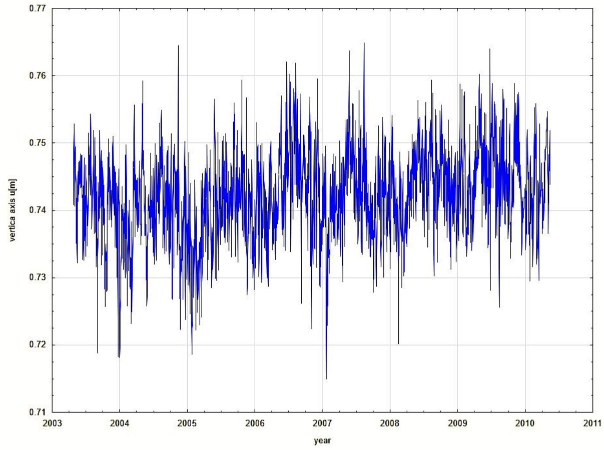


Fig. 1. Plot of daily changes in the height of the tide at the gauge station in Władysławowo calculated from GNSS observations

Tide gauge data

The tide gauge station in the port of Władysławowo, placed at the end of the Danish pier (Fig. 2), was established in 1938 (Dziadziuszko and Jednorał, 1987). The approximate geodetic coordinates of the station are: 54° 47' N', 18° 25' E.

In April 2003, in the tide gauge station building, the Department of Planetary Geodesy Polish Academy of Science launched a permanent GNSS station. In 2010–2011, it was included in the national ASG-EUPOS network.

In this study, the tide gauge mean records in Władysławowo from 1951–2017 have been analyzed. The mentioned time series consist of observations from 1951–1999, that is average monthly records of the tide gauge, and daily observations of the station from 1980–2013 (six records per day). They have been obtained from the Institute of Meteorology and Water Management Sea Department in Gdynia. A set of monthly mean records from 2013–2017 has been published in the Bulletin of the South Baltic[1].

There have been no observations during November and December 2002 in the given time series. These values have been interpolated. Finally, a file with monthly average observations (in mm) has been created for the years of 1951–2017 and it consists of 800 observations.

[1] http://old.imgw.pl/extcont/biuletyn_baltyk/

Fig. 2. Tide gauge station in Władysławowo and its location on the Polish part of Baltic Sea coastline (red dot)

The graph of monthly mean observations of the tide at the gauge station in Władysławowo is shown in Fig. 3.

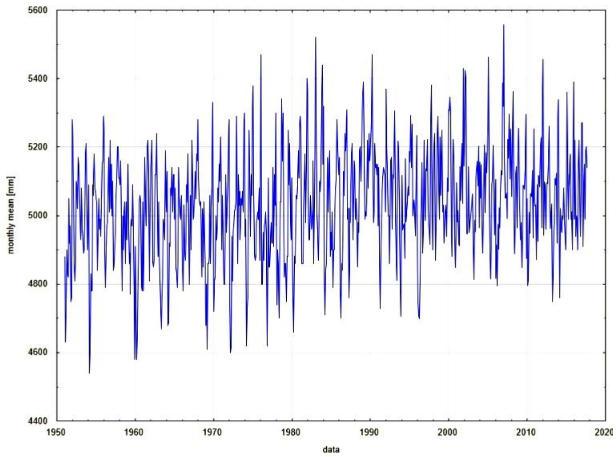


Fig. 3. Plot of monthly mean tide gauge observations at Władysławowo in the years 1951–2017

One factor causing the sea level changes is caused by the attraction by the Moon and the Sun masses of the seas and oceans. Tides in the Baltic Sea are almost imperceptible. In the southern Baltic Sea, where the depth does not exceed 100 meters, the water level due to tides only rise by one centimeter (Ekman, 1984).

Due to the very low tide value at the tide gauge at Władysławowo station and the fact that monthly averages are almost free of this effect, no corrections have been made to the calculated monthly tide gauge means.

Problems of analyzing GNSS and tide gauge time series

The analysis of time series assumes that the observations contain a factor describing the studied phenomenon (usually a few parameters) and a measurement error which make it difficult to identify the model.

Most time series models can be described by using two factors: trend and periodic changes. The trend is usually linear and never repeats itself, the second factor is repeated at regular intervals (Box et al., 2015).

In order to analyze the time series, it is first necessary to determine jumps or discontinuities and outliers. The following must be performed: interpolation of missing data, examination the linear relationship between variables (correlation), trend determination, and periodic signals (changes) in order to estimate the quality of the fitted model for observations (Gazeaux et al., 2013).

Detection and removal of jumps. In a series of continuous GNSS and tide gauge observations, jumps or gaps are mainly caused by changing the reference point of the antenna or the tide gauge rod (Bos et al. 2008). The detection of jumps in a series of observations is an ambitious attempt and is performed visually or mathematically.

Outliers detection and removal. Observations which significantly deviate from other observations are affected by outlier (gross error) (Baarda, 1968). In all the criteria for the study of outliers, suspected observations are included in the estimation of appropriate statistics in a given sample and then compared to the limit values in order to decide whether to reject it or not.

Data interpolation. Irregular distribution of data over time is a very common case in earth sciences. Also in the case of GNSS and tide gauge data, the observations are irregularly distributed. In this case, interpolation methods become important because, for example, spectral analysis methods require data that is distributed regularly over time. Data interpolation techniques x (t) have a tendency to estimate the value of x, at evenly spaced t-points from irregularly distributed real measurements (Bronsztejn et al., 2004). There are many methods of data interpolation such as the closest proximity interpolation, linear interpolation, and the spline method. However, interpolation methods bring various artificial effects.

Correlation. The purpose of correlation analysis is to examine the relationship between two quantitative variables using one parameter. The parameter is also known as the "correlation coefficient" and is often used at the early stage of the statistical linear compound analysis. There are many different types of correlation coefficients that are common used, namely the Pearson's R, the Kendall's tau, and the Spearman's Rho coefficient (Bronsztejn et al., 2004, p. 848).

Regression. In the case when for two variables, by calculating the correlation coefficient it was possible to determine their dependence. The next problem is to define the functional form, in the simplest form, the so-called linear regression. Linear regression is the relation between the variable y, which depends on the input data x, called the independent variable. Simple regression has the form (Bronsztejn et al., 2004, p. 848):

$$y = ax + b + \varepsilon \qquad (2)$$

where a and b are parameters and ε is an error.

Residual analysis. Data with small variability can be modeled in the following way: "data = fit + residual". Residuals are considered a new data set: residual = new match + new residuals and so on. In other words, residual statistics provide valuable information about the quality of the model that has been fitted to the data. Residuals that have an ideal Gaussian distribution with an average of zero means that they are only random variables. Based on this fact, the model does not describe the data very well when a significant tendency occurs in the residuals. Thus, in the residual analysis, using the $\chi 2$ test, it can be stated whether the residuals have a Gaussian distribution or not.

Software and computations

Hector package

Hector is a software package[2] that can be used to estimate the trend in time series with correlated errors (noise) (Bos et al., 2013). The package consists of a set of simple programs that allows to go, step by step, through the entire analysis process. The analysis of time series begins with removal of jumps, removal of outliers, properly deals with missing data, and possible consideration of annual and semi-annual and other periodic signals in the process of estimating the linear trend. The package enables a number of further analyzes that have not been used in this paper and have therefore been omitted. The input data are stored in the form of a simple ASCII text file. Each row of the file contains the Modified Julian Day (MJD), eastern component (e), north component (n) and a vertical component (u). The file can be edited with any text editor.

The Hector package assumes that the user is conscious of the type of temporal correlated noise contained in the observations. This computer program estimates both the linear trend and the parameters of the chosen noise model using the Maximum Likelihood Estimation (MLE) method. The chosen noise models are a combination of power-law noise and a white noise. Otherwise the model could be chosen from: Power law Approx, Flicker GGM, Random Walk GGM, 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). In order to choose the best model the Akaike (AIC) and Bayesian (BIC) criteria described in (Akaike, 1974), (Schwarz, 1978) were applied.

Based on the results of GNSS observations (par. 0) and tide gauge data (par.0), using on-line [3] Hector package, the vertical movements of the

[2] http://segal.ubi.pt/index.php?option=com_content&view=article&id=73&Itemid=78

[3] http://segal.ubi.pt/index.php?option=com_content&view=article&id=73&Itemid=78

earth's crust, mean sea level change, and annual signals (Fig. 4) have been determined. Assuming the GGM error model (Generalized Gauss Markov noise model), the following results have been obtained: v_s = +0.98 mm/year with an error of ±0.15 mm/year and v_t = +2.01 mm/year with an error of ±0.38 mm/year.

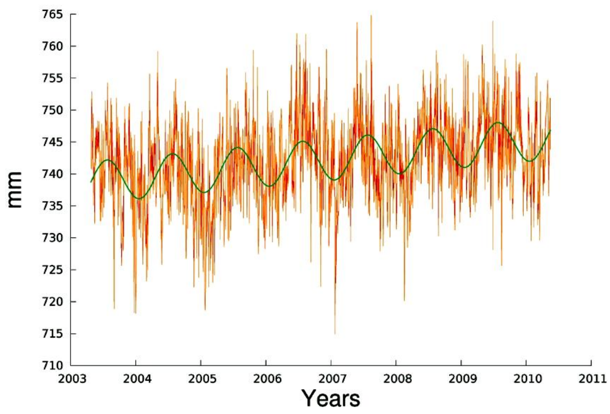


Fig. 4. Example of annual signal of GPS time series at Władysławowo

GITSA software package

GITSA software package has been developed using language of the MATLAB with Graphical User Interface (GUI). The most productive software environment has been developed during the last decade, and has become very popular in earth sciences. GITSA is an open source software and can be downloaded from the GITSA website[4] because this package is available on the Internet without any restrictions. GITSA package computes basic statistics, imports and visualizes different formats results of GNSS observations[5], determines and removes jumps and outliers, and interpolates missing data.

The results of GITSA are numerical and graphic files. The program also performs correlation analyses, regression analysis, and spectral analysis. Detailed information on the GITSA program can be found at work (Goudarzi et al. 2013) and the "GITSA user's Manual" attached to the help panel in GITSA.

GITSA can read and process a series of GPS observations only in its native GTS format intended for this computer program. The GTS files are loaded and displayed by double clicking on the analyzed file in the navigation pane (Fig. 5).The main window of GITSA shows the North (n), East (e) and Vertical (u) components of the estimated positions in the time series obtained from GNSS observations at the Władysławowo station. The left side pane shows the available GTS files in the current directory. The upper right side table presents basic descriptive and statistical information about the observations series.

After loading the GNSS observations series file (par. 0), no jumps were found. Then, it has been examined that all data was evenly distributed over time and there have been two gaps in data. These gaps were filled using linear interpolation. Further, at the 99 % confidence level, the possibility of outliers has been examined and 35 of them have been detected (Fig. 6). In the last step, the regression coefficient was calculated. Only the linear regression model has been selected from the other available regression models and the value of the earth's crust displacement was estimated as +0,88 mm/year with an error of ±0.06 mm/year.

Afterwards, the residual analysis has been performed by removing the observations trend. If the trend model has been correctly selected, residuals should have a Gaussian distribution with zero mean. GITSA allows to evaluate the model by estimating the practical and theoretical values of χ^2 statistics. In our case, the theoretical value of χ^2 for the confidence interval of 95 % is 292.17 and the estimated value of the statistic χ^2 is 131.94. This means that residuals have a normal distribution and the linear trend model has been chosen correctly. Introduce figure 6. There is Fig 6. See fist line.

After a number of complex transformations, tide gauge data from par. 0 have been prepared in the GTS format. No discontinuities in position have been found after loading these observations in the native format. The issue of an equal data distribution has been omitted. At a 99.5 % confidence level, 7 outliers have been detected. For the linear regression model, coefficients have been calculated and v_t = +2.0 mm/year with an error of ±0.29 mm/year has been obtained.

GGMatlab toolbox

GGMatlab is a set of MATLAB tools elaborated for use with the GAMIT/GLOBK GPS data analysis system (King, 2002), (King and Herring, 2002), which allow interactive viewing and handling of the velocities from GPS data using a MATLAB graphical user interface (GUI). This program is available and described on the web page[6].

[4] http://sourceforge.net/projects/gitsa

[5] Preparation of tide gauge data in .gts format is a little complicated

[6] http://www-gpsg.mit.edu/tah/GGMatlab

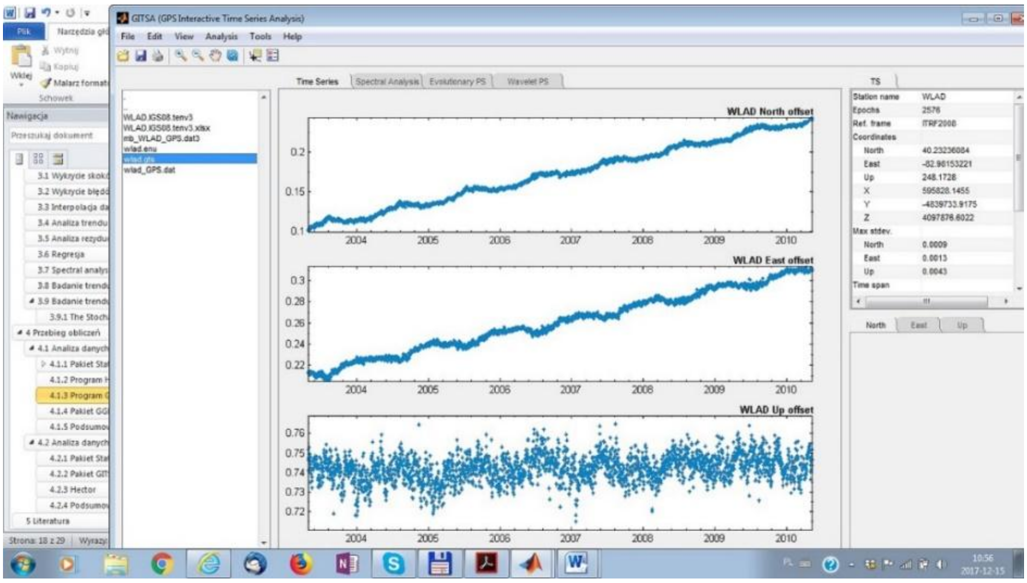


Fig. 5. Main window of GITSA

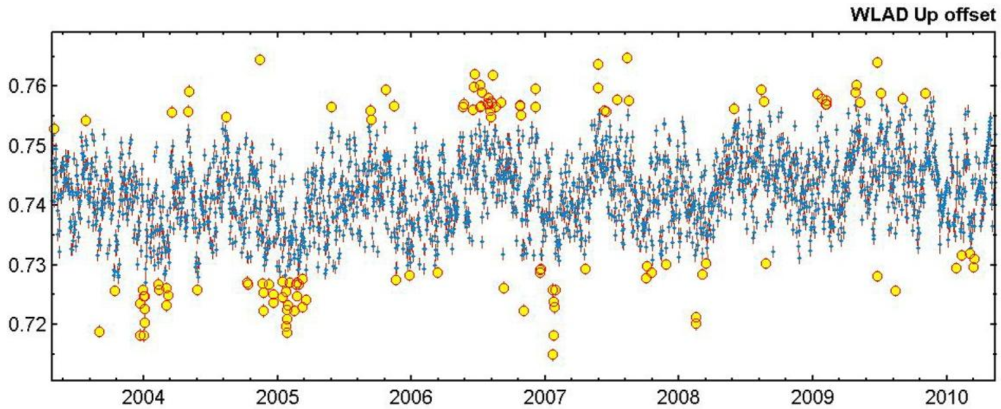


Fig. 6. Graph of the time series of GNSS observations at the station Władysławowo with marked observations with outliers (wheels)

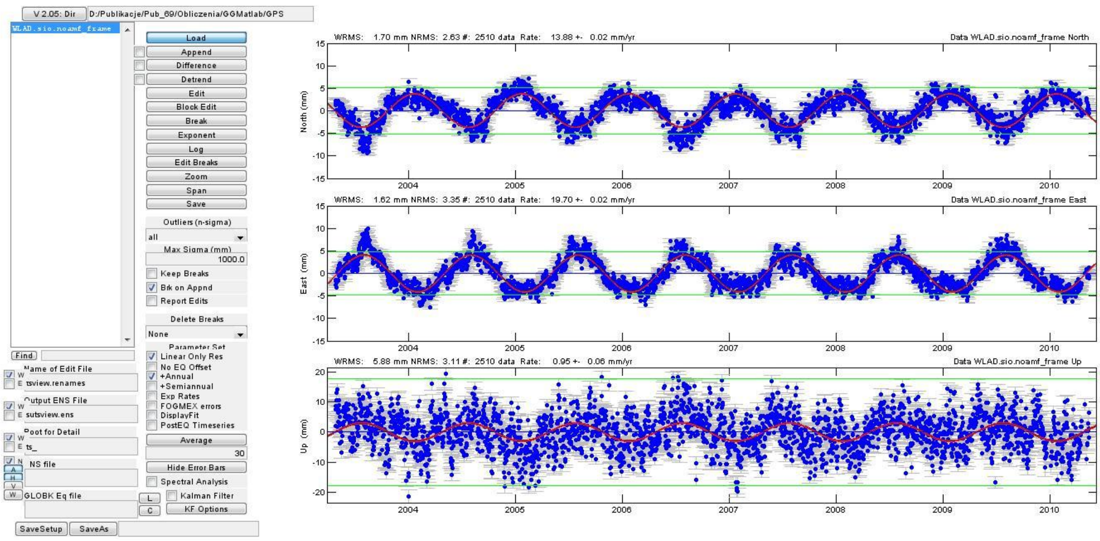


Fig. 7. The result of the analysis of the components n, e, u in the time series of GNSS observations at Władysławowo

The current version of this set of tools, used in this work, is marked as ver. 2.05. The GGMatlab consists of two independent tools, namely the *Velview* that allows viewing and analyzing changes in the deformation of the earth's crust; and *Tsview* that allows time series viewing and analyzing. The main goal of the *Tsview* tool is to assess the quality of the time series.

Data file formats used by this set of tools are simple ASCII files in SIO format and can be created from other file formats.

The main *Tsview* startup screen contains many functions and in our case "Detrend" option has been used. For the purpose of analysis, the time series (par.0) has been converted into the SIO format and then loaded into the *Tsview* module in the GGMatlab toolbox. After selecting the option counting seasonal signals, and taking the confidence level of 99 % to eliminate outliers, the "Detrend" function has been used.

This function removes the linear trend, jumps, and interruptions. During this operation, a certain confidence level is being assumed and the trend determination is repeated until all outliers are removed. The results of parameter estimation are saved in the MATLAB environment and are displayed in the upper right pane of the screen. As a result of the analysis, the vertical movements of the earth's crust have been estimated at +0.99 mm/year with an error of ±0.06 mm/year. A graphical illustration, after detrending the time series, for the three components of East (e), North (n) and Up (u) coordinate is shown in Fig. 7.

Similar operations have been performed for tide gauge observations and v_t = 1.95 mm/year with an error of ±0.25 mm/year has been obtained. The description of other *Tsview* GGMatlab functions, e.g. "Linear Only Resid", "RealSigma" (realistic sigma calculation), "DisplayFit", etc. can be found, for example, in a paper (Herring, 2003).

Statistica software package

Statistica is a popular analytics software package. It offers a set of the most important statistical methods, procedures and tools for data analysis, including time series analysis tools.

In this paper the time series of tide gauge observations given in par.0.have been examined. At first no jumps, based on visual assessment, in the tested series were found. Then, outliers that occurred in the time series were detected. For this purpose a linear trend has been estimated (option: linear regression) and in the next step the trend has been subtracted from the observations. Residuals obtained in this way have been standardized. The standardized values greater than 3.0 (99 % confidence level) as outliers have been removed from the input file. This procedure has been repeated several times until all outliers have been removed. In total, 5 observations have been removed. The determined trend v_t = +1.96 mm/year has been obtained with an error of ±0.28 mm/year. Introduce figure 8 here. Fig. 8

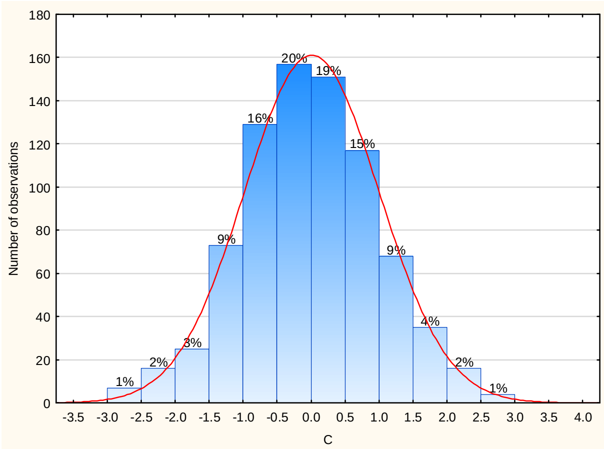


Fig. 8. Histogram of standardized residuals

If the model has been well-defined, residuals should be random and have normal distribution). This paper has checked whether the hypothesis, that residuals do not have a normal distribution, can be rejected. The p-value = 0.534 and the value of the statistic χ^2= 6.080 has been calculated and because $p > 0.05$, where 0.05 is the significance level, there is no reason to reject the hypothesis about the normal distribution of the studied residuals.

An analogous analysis has been made for the results of GNSS observations (par.0) and 21 outliers have been rejected. The determined trend has a value of v_s = +0.95 mm/year with an error of ±0.12 mm/year.

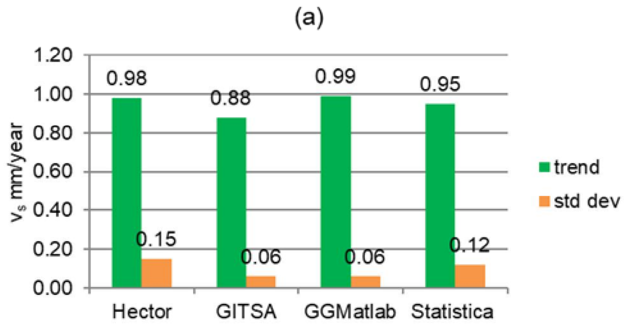
In this case no annual signals were computed in the tide gauge and GNSS time series.

Summary

In this paper, the time series of tide gauge and GNSS observations at the station in Władysławowo was analyzed. The analysis was conducted using the programs Hector, GITSA, GGMatlab, and Statistica. Using these programs jumps, outliers, correlations, and trend, were analyzed. Not all of these features are included in these programs. Table llustrates what actions were performed in each program.

Characteristic of tested software's

Software	Jumps	Outliers	Data interpolation	Correlation	Regression	Annual signal	Residual analysis
Hector	yes	yes	yes	yes	yes	yes	no
GITSA	yes	yes	yes	yes	yes	no	yes
GGMatlab	yes	yes	yes	yes	yes	yes	no
Statistica	yes	yes	no	yes	yes	no	yes



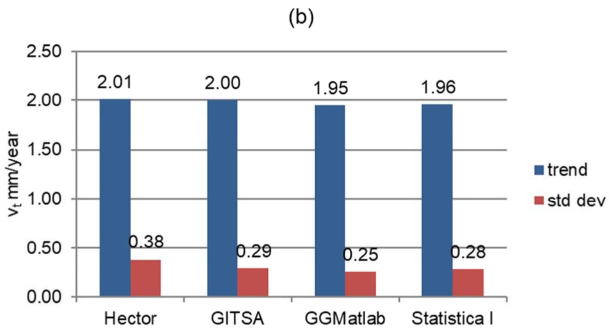


Fig. 9 (a). Vertical movements of the earth's crust from GNSS observations, (b) trend in sea level from tide gauge observations

Fig. 9(a) shows the movements of the earth's crust at Władysławowo station calculated from permanent GPS observations using four computer programs. An astonishingly good agreement of results at the level of 1 millimeter for three computer programs has been obtained. Only the results obtained from GITSA give slightly lower values. Similar comparison has been done with mean sea level changes (Fig. 9 (b)). Slightly lower values obtained from GITSA software may be due to the fact that probably the installed version did not work with the option "outliers removal". It is surprising that the results obtained from the Statistica package are consistent, where a somewhat simplified analysis has been realized.

The sketch shows that the linear trend in the earth's crust from GNSS observations is more accurately determined than from tide gauge observations. In the case of GNSS observations, the Hector and Statistica programs gives trend with a mean error about 0.15 mm / year and the GITSA and GGMatlab programs 0.06 mm / year. Similarly, in case of tide gauge observations trend is determined with mean error about 0.30 mm / year. Fig. 9.

Finally, absolute trend of the sea level v_o at the Władysławowo station, according to equation (1), is the sum of the movements of the earth's crust and sea level changes (Fig. 10). The estimated changes of absolute mean sea level are almost 3 mm/year.

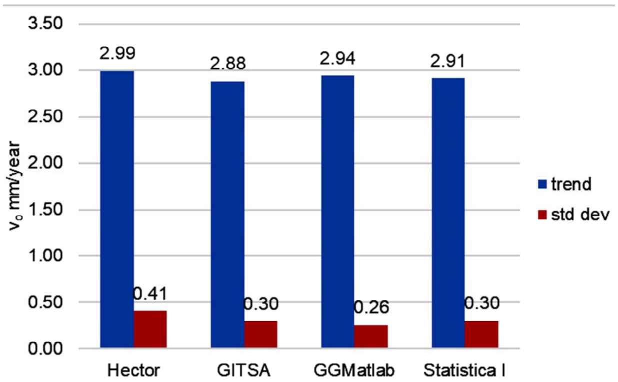


Fig. 10. Absolute trend of sea level station in Władysławowo

It is extremely difficult to verify the correctness of determining absolute sea level changes along the Southern Baltic Sea coastline. The nearest tide gauge station with continuous GPS observations is Sassnitz[7], where the estimated movements of the earth's crust is v_s=+0.83 mm/year with an error of ±0.55 mm/year, changes in the sea level are 1.31mm/year, and absolute changes in v_o are 2.14 mm/year. Thus, it can be stated that the values

[7] http://www.sonel.org/-Sea-level-trends-.html?lang=en

estimated for the station in Władysławowo are acceptable.

Conclusion and further investigations

In considering the advantages and disadvantages of the programs used in this study, the following can be stated. Preparing data for time series analysis with the Hector package is very easy and on-line calculations are very fast. The final results are given in a very concise form which do not allow tracking of particular stages of time series analysis.

The GITSA software requires the MATLAB environment installed on the computer. Input files must be prepared in the appropriate GTS format, which is quite complex and is a disadvantage of this software. The positive features of GITSA are interface, which in an accessible way allows to evaluate possible jumps, outliers, and determine the linear trend.

Another GGMatlab program, as the name suggests requires MATLAB environment installation. The principle of time series analysis is analogous to the GITSA program. The format of input file is a simple ASCII format and it is easy to prepare it in any editor.

Statistica software package like the MATLAB package, requires a purchase and sufficient funds. The data of input file is a simple text file in ASCII format that can be easy prepared in any editor.

Finally, it can be stated that due to the simplicity of input data preparation, on-line calculations as well as the selection of error model, the Hector software package is very useful in analyzing the time series of phenomena such as mean sea level changes and crustal movements at Baltic Sea tide gauge stations. In contrast, Statistica software package is the least recommended for the analysis of this type of time series because, among other problems, the removal of outliers is very labor-intensive.

This work is limited to determining the trend of sea level changes from tide gauge and GNSS data. Furthermore satellite altimetry provides consistent accuracy data which can be used to monitoring changes in sea levels. Therefore further study should focus on the estimation sea level trend from combination GNSS, tide gauge and altimeter data

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ЗМІНИ АБСОЛЮТНОГО РІВНЯ МОРЯ НА МАРЕОГРАФІЧНІЙ СТАНЦІЇ У ВЛАДИСЛАВОВІ НА ОСНОВІ ДАНИХ ЧАСОВИХ РЯДІВ З ВИКОРИСТАННЯМ РІЗНИХ ПАКЕТІВ ПРОГРАМНОГО ЗАБЕЗПЕЧЕННЯ

У цій статті представлено геоцентричні зміни рівня моря на мареографічній станції у Владиславові (північний захід Польщі). Ці зміни були розраховані на основі даних часових рядів GNSS та мареографічних спостережень. Для оцінки геоцентричного тренду зміни рівня моря використовувалися різні пакети програмного забезпечення, такі як Hector, GITSA, GGMatlab та Statistica. Результати показують, що зазначені

програмні пакети дають подібні значення абсолютних змін рівня моря у Владиславові і оцінюються приблизно в 3 мм на рік. Розглянуті комп'ютерні програми характеризуються різним ступенем візуалізації та простотою використання. Найбільшою складністю при використанні програм є підготовка необхідного формату даних та їх інсталяції в програмному середовищі, наприклад, Matlab. Загалом, можна зробити висновок, що програмний пакет Hector, завдяки простоті підготовки вхідних даних, можливості обчислень в он-лайн режимі та вибору різних моделей похибок вважається найбільш оптимальним для аналізу часових рядів геофізичних явищ, таких наприклад, як зміна рівня моря. Найменш рекомендованим для цього типу аналізу часових рядів є програмний пакет Statistica.

Ключові слова: середній рівень моря, мареограф, супутникові GNSS-спостереження.

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