www.czasopisma.pan.pl PAN www.journals.pan.pl

GEODESY AND CARTOGRAPHY
Vol. 68, No. 1, 2019, pp. 65–86

DOI: https://doi.org/10.24425/gac.2019.126094

Review paper

Research on Earth rotation and geodynamics in Poland in 2015–2018

Janusz Bogusz[1*], Aleksander Brzezinski[2,3], Jolanta Nastula[3]

[1*]Military University of Technology
Faculty of Civil Engineering and Geodesy
2 Urbanowicza St., 00-908 Warsaw, Poland
[1]e-mail: janusz.bogusz@wat.edu.pl; ORCID: http://orcid.org/0000-0002-0424-7022

[2]Warsaw University of Technology
Department of Geodesy and Geodetic Astronomy
1 Pl. Politechniki., 00-661 Warsaw, Poland
[2]e-mail: alek@cbk.waw.pl; ORCID: http://orcid.org/0000-0002-0553-8913

[3]Space Research Centre
Polish Academy of Sciences
18A Bartycka St., 00-001 Warsaw, Poland
[3]e-mail: nastula@cbk.waw.pl; ORCID: http://orcid.org/0000-0002-1136-5609

[*]Corresponding author: Janusz Bogusz

Received: 19 March 2019/ Accepted: 5 April 2019

Abstract: This paper summarizes the activity of the chosen Polish geodetic research teams in 2015–2018 in the fields of Earth: rotation, dynamics as well as magnetic field. It has been prepared for the needs of the presentation on the 27th International Union of Geodesy and Geodynamics General Assembly, Montreal, Canada. The part concerning Earth rotation is mostly focused on the use of modelling of diurnal and subdiurnal components of Earth rotation by including low frequency components of polar motion and UT1 in the analysis, study of free oscillations in Earth rotation derived from both space-geodetic observations of polar motion and the time variation of the second degree gravitational field coefficients derived from Satellite Laser Ranging (SLR) and Gravity Recovery and Climate Experiment (GRACE) observations, new methods of monitoring of Earth rotation, as well as studies on applications of the Ring Laser Gyroscope (RLG) for direct and continuous measurements of changes in Earth rotation and investigations of the hydrological excitation of polar motion. Much attention was devoted to the GRACE-derived gravity for explaining the influence of surface mass redistributions on polar motion. Monitoring of the geodynamical phenomena is divided into study on local and regional dynamics using permanent observations, investigation on tidal phenomena, as well as research on hydrological processes and sea level variation parts. Finally, the recent research conducted by Polish scientists on the Earth's magnetic field is described.

Keywords: Earth rotation, geodynamics, Earth magnetic field, GNSS

1. Introduction

In the research concerning Earth rotation and geodynamics carried out by Polish scientists in a period of 2015–2018 many research institutions were involved, listed in Acknowledgments part. The investigations on Earth rotation in Poland have been performed mostly by the scientists of the Space Research Centre of the Polish Academy of Sciences (SRC PAS). The main concern of the work was the use of the Gravity Recovery and Climate Experiment (GRACE) data for modeling time variations of Earth orientation parameters (EOP) due to surface mass redistributions. The research on Earth rotation variations due to the influence of geophysical fluids has been extended by including other geodynamic phenomena, such as sea level change and hydrological processes on different scales, from local and regional to global ones.

Thanks to Earth's artificial satellites the new possibilities of providing the Vertical Land Motion arise. The changes of the permanent Global Navigation Satellite Systems (GNSS) stations' positions along with precise levelling data allow to monitor the present dynamic of the Earth's surface. They may also be supported by other satellite (Satellite Laser Ranging – SLR and Doppler Orbitography and Radiopositioning Integrated by Satellite – DORIS) techniques. On the other hand, tidal observations support the geodynamic research to a very significant extent. Since 2016 first Polish observatory was equipped with superconducting gravimeter, being able to observe temporal changes of Earth's field of gravity with unprecedented reliability.

2. Earth rotation

In a period of 2015–2018 Polish researchers working on Earth rotation participated in the scientific programs of the international organizations, like the IAG (International Association of Geodesy), IAU (International Astronomical Union), IERS (International Earth Rotation and Reference Systems Service). In particular they contributed to the activity of the IAU/IAG Joint Working Group on Theory of Earth Rotation and Validation; see the report by Brzezinski (2015) for details. Short summaries of the most important publications concerning Earth rotation will be given below.

2.1. Modeling diurnal and subdiurnal components of Earth rotation

The high frequency signals in polar motion, with periods from a fraction of day to daily, are small – at the submilliarcsecond level, nevertheless important for understanding the dynamics of Earth rotation. There is also a need for high quality models of diurnal and semidiurnal effects in polar motion and UT1 for reduction of GNSS data. Brzezinski et al. (2015) applied the complex demodulation (CD) technique, originally developed for extracting the subdiurnal signals in Earth orientation parameters (EOP), for analysis of the retrograde diurnal component of polar motion (PM) and the low frequency component of dUT1. By comparison to the results based on the celestial pole offsets and dUT1 series from the combined solutions provided by the IVS (International VLBI Service) and IERS they could demonstrate consistency of the CD parametrization with the standard approach. This research was extended by Wielgosz et al. (2016) who included in the analysis the low frequency components of PM and UT1 estimated by CD version of the VieVS (Vienna VLBI Software). They could conclude that the CD parametrization applied for analysis of VLBI observations does not change those EOP components which are included in standard adjustment, while enabling simultaneous estimation of diurnal and semidiurnal components from standard VLBI (Very Long Baseline Interferometry) measurements. The authors suggested also implementation of the CD algorithm for data analysis of other space geodetic techniques, like GNSS and SLR, which can help to retrieve of subdiurnal signals from past data.

2.2. Studying the free oscillations in Earth rotation

The most important free oscillation in Earth rotation is the Chandler wobble (CW), the largest component of polar motion, discovered at the end of XIXth century and monitored on regular basis since that time. Several aspects of the Chandler wobble have been studied by the researchers from the SRC PAS since 1990-ties, including determination of the resonance parameters and explanation of the excitation mechanism of CW. Recently, Nastula and Gross (2015) estimated the period T and quality factor Q of CW after imposing the minimum condition on power of the difference between the observed and modeled excitations in the vicinity of the resonance frequency. The observed excitation was derived from both space-geodetic observations of polar motion and the time variation of the second degree gravitational field coefficients derived from SLR and GRACE observations. The modeled excitations were computed from the output parameters of the global circulation models of the surficial fluids, the atmosphere, the oceans and the hydrology. The preferred values of CW resonance parameters were $T = 430.9$ solar days and $Q = 127$, with the 95% confidence intervals (430.2, 431.6) and (56, 255), respectively.

The second rotational mode of the Earth is the Free Core Nutation (FCN) which affects both Earth rotation and body tide. The FCN parameters are usually estimated from VLBI estimation of nutation or from the tidal gravity observations by the superconducting gravimeters. Rajner and Brzezinski (2017) reported an attempt to determine the FCN parameters from gravity record collected with the use of a spring LaCoste & Romberg Earth Tide gravimeter, located at Jozefoslaw observatory near Warsaw. They estimated the FCN period $T = 430$ sidereal days, which is in good agreement with the VLBI nutation results, and the quality factor $Q = 1300$ which is roughly consistent with other determinations from gravimetry but significantly smaller than the VLBI nutation estimate.

2.3. Research on the methods of monitoring Earth rotation

VLBI plays an important role in monitoring changes in Earth rotation. There is one VLBI station in Poland, in Piwnice near Torun, but it does not participate in geodetic programs. There are plans to adapt the old VLBI antenna in Piwnice to the VLBI2010 standards and to join with this instrument the VGOS (VLBI Global Observing System) network. In a frame of preparation, several research works have been performed. One is the study reported by Wielgosz et al. (2016). They considered the problem of the simultaneous estimation the Earth Orientation Parameters (EOP) and station coordinates by the networks of VLBI stations. Several tests have been performed using the VLBI analysis software VieVS. The main problem considered was the method of weighting the results from the stations having bigger post-fit residuals. Several weighting strategies have been considered and evaluated using different statistical indicators.

Polish researchers have been also involved in the studies on applications of the Ring Laser Gyroscope (RLG) for direct and continuous measurements of changes in Earth rotation. This technique has been considered since about two decades as a complement of the space geodetic techniques for monitoring Earth rotation. So far there is only one instrument, the G-ring at the Wettzell Observatory in Germany, which has sufficient sensitivity for this purpose, but according to our knowledge other instruments are under construction. Tercjak et al. (2015) investigated the application of RLG for estimation of nutation rates. They considered one instrument with parameters of G-ring, but also simulated results from several RLG's and their combination with actual VLBI data. The conclusion of this study was basically negative, showing that for improvement of the VLBI estimates at least 3 RLG are needed having relative level accuracy by at least 2 orders of magnitude higher than the G-ring. In the next study, Tercjak and Brzezinski (2017) performed detailed analysis how the known diurnal and subdiurnal signals in polar motion and UT1 are reflected in the observations of G-ring. They considered the available models of so-called diurnal polar motion, diurnal and semidiurnal ocean tide effects in polar motion and UT1 and librations, prograde diurnal in polar motion and semidiurnal in UT1. As a next step, the effects of changing the geographic location of a horizontally mounted instrument, or changing its orientation with respect to the crust, have been considered.

2.4. Investigations of the hydrological excitation of polar motion

Polar motion is almost entirely excited by the global geophysical processes taking place in the external fluid layers of the Earth, the atmosphere, the oceans and the land hydrosphere commonly designated as hydrology. The excitation of polar motion is usually studied by comparing the so-called geodetic excitation function derived by applying the deconvolution procedure to the polar motion series determined by the space geodetic techniques, to the geophysical excitation series which are derived from geophysical models. Significant progress in polar motion excitation studies could be achieved in recent years due to the availability of the time variable coefficients of the Earth's gravity field, determined by the satellite experiment GRACE as well as by the Satellite Laser Ranging (SLR) observations. The reason is that the mass term of polar motion excitation components (χ_1, χ_2) is proportional to time variable gravity coefficients $(C_{2,1}, S_{2,1})$. The mass term of polar motion excitation, derived from GRACE and SLR data, usually called the gravimetric excitation function, can be used to improve the excitation balance of polar motion, particularly at seasonal frequencies, but also to constrain the global hydrology models. The investigations of the hydrological excitation of polar motion using the excitation data from hydrological models and GRACE/SLR gravity data have been performed by researchers from the SRC PAS in cooperation with the scientists from JPL (Jet Propulsion Laboratory) and AER (Atmospheric and Environmental Research) in USA. Nastula et al. (2015) made an analysis of the Hydrology Angular Momentum (HAM) functions derived from 11 solutions based on GRACE/SLR data, including comparison to the geodetic excitation (Geodetic Angular Momentum – GAM) based on the IERS C04 series after removal of the Atmospheric Angular Momentum (AAM) series based on the NCEP/NCAR reanalysis model and the Oceanic Angular Momentum (OAM) series based on the ECCO-JPL ocean model (so-called geodetic residuals G-A-O). Different HAM series have been compared to the G-A-O residual that was a base of assessment of the quality of gravimetric solutions. In the next stage of research, Nastula et al. (2016) performed analysis of the HAM functions derived from the GRACE RL05 solutions provided by three GRACE processing centers, the Center for Space Research (CSR), the Jet Propulsion Laboratory and the GeoforschungsZentrum (GFZ). Comparison with the G-A-O residuals revealed significant differences between the three RL05 solutions which were attributed by the authors to different treatment of gravity signals over ocean areas. The best agreement with the observed (geodetic) excitation was found for the CSR solution. The impact of continental hydrology on polar motion had been investigated in a comprehensive study by Winska et al. (2016). The HAM functions were estimated from the GRACE RL04 and RL05 data and from different models of global hydrology like the Climate Prediction Center (CPC), Global Land Data Assimilation System (GLDAS), National Oceanic and Atmospheric Administration (NOAA), and Land Surface Discharge Model (LSDM). The authors considered not only the global values of HAM but also the regional hydrological excitations of polar motion. They found that the maximum values of the excitation functions derived from hydrological models and GRACE data have similar geographical patterns but the amplitudes are different. Final conclusion from the comparison of geodetic residuals and global hydrological excitation functions of polar motion was that none of the considered HAM functions has enough energy to significantly improve the agreement between the observed geodetic and geophysical excitations. In the associated paper by Winska (2016), the hydrological excitations of polar motion determined from different variables of FGOALS-g2 climate model from CMIP5 project have been compared to geodetic residuals G-A-O at decadal, inter-annual and multi-annual time scales. This analysis was completed by the consideration of GLDAS global hydrological excitation functions and GRACE gravimetric excitations. In the following work Winska et al. (2017) considered hydrological excitation of polar motion using different variables from the GLDAS models. The main purpose of the research was to check the individual contributions from different hydrological processes such as evapotranspiration, runoff, snowmelt and soil moisture, to polar motion excitations at seasonal and subseasonal periods. In addition, they used time variable gravity field solution from the GRACE experiment to estimate the hydrological mass component of polar motion excitation. A comparative analysis had been done for different regional and global estimates of the HAM functions. Finally, the hydrological excitations were compared with the geodetic residuals G-A-O to check how well the polar motion excitation budget can be closed. Sliwinska et al. (2018) investigated hydrological excitation of polar motion using the global and regional estimates of Terrestrial Water Storage computed on the base of Coupled Model Intercomparison Project Phase 5 climate models, GLDAS land hydrology models and observations from the GRACE satellite mission. The hydrological excitation functions estimated from models were compared to those based on GRACE data and to the geodetic residuals G-A-O. The comparison demonstrated that the GLDAS models of seasonal and non-seasonal TWS change are closer to GRACE data than the climatic models, however, no one of the considered models is fully consistent with GRACE results or with geodetic residuals. From analysis of different TWS components to the HAM function it could be concluded about the dominant role of soil moisture.

3. Geodynamic phenomena

In 2013 the International Association of Geodesy celebrated its 150th anniversary at the Scientific Assembly held in Potsdam. At this occasion the special issue of the IAG Symposia Series has been issued. Among the others, Kolaczek and Nastula (2016) presented very interesting overview on developments of geodynamical studies related to the Earth rotation in the XX century. They pointed the important scientific milestones and gave the information about developments and organizational achievements in the considered field.

3.1. Study on local and regional dynamics using permanent observations

The research related to the local and regional dynamics of the Earth were presented in two review papers (Brzezinski et al., 2016a and Brzezinski et al., 2016b). They described in details engagements of two institutions (namely, Department of Planetary Geodesy, Space Research Centre, Polish Academy of Sciences and Department of Geodesy and Geodetic Astronomy, Warsaw University of Technology). Moreover, Pasik et al. (2016) presented current state of the art of polar research carried out by the employees and students of the Faculty of Geodesy and Cartography, Warsaw University of Technology. Remaining in polar research, Rajner (2018) presented a comprehensive study of the present-day uplift rates of GNSS with geophysical predictions at the chosen stations in Spitsbergen obtained height changes related to ice mass loss in Svalbard of 6 Gt/yr.

For many years equipment which has permanently been working at the Geodynamic Laboratory of the Space Research Center in Ksiaz has been given very valuable data concerning the dynamics of the Sudeten area. Kaczorowski et al. (2015) presented a novel concept explored in the Laboratory by means of new techniques: short-range laser scanning, precise electronic tachometric and interferometric measurements, precise geometric levelling as well as gap gauges to complement currently working instruments. All those activities are aimed at providing a complete information of the dynamic processes in the Ksiaz Massif: deformation of tectonic origin, tilts of the bed rock, vertical movements and displacements on faults.

Several case studies concerning local geodynamics have been conducted. Among the others, Szafarczyk and Gawalkiewicz (2016) performed a tensor analysis of ground deformation in a landslide area. With the use of geodetic methods they measured and analyzed the deformation on a landslide of a natural slope in Milowka and landslide of the open cast mine Belchatow obtaining the values of the extreme deformations in the GPS-based rosettes. Szafarczyk and Gawalkiewicz (2018) researched the industrial chimney in the Bochnia Salt Mine. They analyzed changes in the deviation of the chimney's axis from the vertical with the use of bisector methods surrounding the tangential and laser scanning with total station. Szczerbowski and Piatkowska (2015) performed research involving the linking of the results of Interferometric Synthetic Aperture Radar (In-SAR) with those of levelling measurements, arising certain opportunities for interpretation by means of the determination of the vertical displacements: between levelling measurement campaigns and areas or spots uncovered by levelling. Their case study denoted Inowroclaw Salt Dome. Szczerbowski et al. (2016) found the horizontal displacements and deformation of shafts in Bochnia to be corresponding to similar effects observed in the Wieliczka Salt Mine with a northward tendency despite the differences between the geological and mining environments. Wajs and Milczarek (2018) presented the observations of surface subsidence in the open pit mining area by Synthetic Aperture Radar (SAR) active remote sensing technique. They found that the post-proceed satellite Line of Sight (LOS) displacement indicates vertical changes of the surface within the dumping and excavation area. Szczerbowski and Jura (2015) presented the results from the GPS/GNSS permanent stations of Legnica-Glogow Copper District (LGCD). Referring to the Polish Active Geodetic Network (ASG-EUPOS) they observed the subsidence basin being shaped after mining tremors with the center located near the area of epicenter. They found a vertical displacements of c.a. 10 mm at maximum. Milczarek et al. (2017) presented the results of surface displacements calculated with the Persistent Scattered Satellite Interferometry (PSInSAR) technique for the area of the former Walbrzych Hard Coal Basin (WHCB) in SW Poland. According to the analysis of the ENVISAT-acquired radar images for the 458 track and for the 2002–2009 period they presented continuous surface displacements for the entire former mining site. Blachowski et al. (2018) extended the area of interest to the selected zones from Czech Republic and Poland presenting the comparative analysis of secondary deformations in two former mining areas in the first period after cessation of underground hard coal mining. Blachowski and Herkt (2018) enhanced the Walbrzych Hard Coal Mines Geographic Information System (GIS) for deformation research purposes. As the result, the interactive maps with precise information on location and characteristics of underground mining were developed. The system was also supplied by the query tools streamline preprocessing operations necessary for geospatial analyses. Blachowski (2016) investigated the mining induced land subsidence with the use of weighted spatial regression method.

The study concerned the former Walbrzych coal mine area and very long 1886–2009 observational period. The modelling has been performed in GIS with Geographically Weighted Regression (GWR) method that allows for spatial variability of subsidence factors. The four of the considered parameters (namely, thickness, inclination and depth of coal levels and surface slope) turned out to be significant.

Two different areas of interest of Polish researchers covered two most dynamic orogens: Sudeten and Tatra Mountains. Walo et al. (2016) studied the Pieniny Klippen Belt (PKB), which is situated in Southern Poland, being one of the main fault zones on the boundary of the Outer and Inner Carpathians. The history of the geodetic measurements in this region reach early 60's last century. They determined the horizontal displacement in the PKB area based on GNSS as well as gravity (absolute) measurements. Szczerbowski (2016) searched for disturbances in daily GPS solutions possibly sourced at tectonic stress. He used the ASG-EUPOS coordinates, drawing conclusions that spatio-temporal evolution of horizontal displacements of ASG-EUPOS stations in the Sudety Mts. and in adjacent areas are determined by expressions of underlying geological structures. Kaczmarek et al. (2016) summarized the epoch satellite GPS/GNSS and gravimetric measurements from last 25 years in the regional research network GEOSUD, SILESIA, SUDETY and the local geodynamic polygons ("Snieznik", "Stolowe Mts."). The data from crack-gauges on several tectonic faults were also included. As the results they provided maps of vertical movements, with special attention being put on the levelling lines which intersect Sudeten main tectonic faults.

The models of crustal movements play essential role not only in recognition of the dynamic processed in the Earth's interior, but also for constructing the kinematic reference frames for geodesy, which should follow the Earth's dynamics. Kraszewska et al. (2016) used the Satellite Laser Ranging (SLR) coordinates for analysis of the accuracy of estimated parameters, which define the tectonic plate motions finding a remarkable concurrence agreement between their solutions and the APKIM 2005 model. The similar research has been conducted for global Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) network (Kraszewska et al., 2018). Klos and Bogusz (2017) analyzed the International GNSS Service (IGS) "repro2" contribution to the ITRF2014. They employed the GPS position time series of 115 European stations between 1995 and 2015 with the minimum length of 10 years and estimated their velocities with associated uncertainties. The determination of those uncertainties was followed by noise analysis to take power-law dependencies in the position time series into consideration. Special attention was paid to the Vertical Land Movement (VLM). Kowalczyk (2015) used data from Polish Active Geodetic Network for the construction of a model of relative vertical crustal movements in the Polish territory. In this research he focused on the changes of vertical velocity between the chosen ASG-EUPOS stations. As a result, several models of relative vertical movements were evaluated and compared each other. Kowalczyk and Bogusz (2017) gave 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 (LSE), the VSED method detects the discontinuities in time series and determines the values of jumps at the same time. They used the time series from Precise Point

Positioning (PPP) solution obtained in the Nevada Geodetic Laboratory (NGL) using satellite data gathered at more than 50 permanent stations located in Latvia, Lithuania and northeastern Poland. The obtained vertical velocities gave an overview of a possibility of the proposed method to be used and the ongoing vertical movements. Kowalczyk and Kuczynska-Siehien (2018) examined the relationship between vertical movements of the Earth's crust and variation in geoid heights. They used data from the Gravity Recovery and Climate Experiment (GRACE), precise levelling, tidal gauge observations and GNSS stations providing the model of the vertical crustal movements of the Sudeten area together with geoid height variation. They concluded, that variations in geoid heights do not exceed one-tenth of the vertical movements of the Earth's crust in the considered area, what coincides with other determinations. The similar study was performed for northeastern Poland (Kowalczyk and Kuczynska-Siehien, 2017). Kowalczyk (2017) tested the correlation between the vertical crustal movements and temperature changes on the example of selected vectors between permanent GNSS stations. As an example he took two permanent ASG-EUPOS stations corelating the time series of height and temperature concluding that the influence of thermal expansion of materials holding the GNSS antenna on the estimated vertical crustal movements between the stations are of 0.1 mm/yr magnitude. Finally, Bednarczyk et al. (2018) solved the problem of identification of fiducial point in the subsequent levelling campaigns (precise and GNSS) by providing coherent database containing attributes of both types of data and automatization of the joint point identification process. They presented the results of such identification process, depending on the amount of data, on the example of the area of Poland.

Several numerical analysis on the geodetic time series aimed at reliable determination of the velocity (horizontal or vertical) were performed. Bogusz et al. (2016) proposed the methodology of reliable determination of the velocities of permanent GNSS stations. They showed, that proper treatment of either deterministic or stochastic part of the position time series will lead to the most reliable velocities along with their uncertainties. Rapinski and Kowalczyk (2016) proposed a new method for detection of discontinuities in the height component of GNSS time series. They proposed the Switching Edge Detection (SED) algorithm based on the detection of the epochs in which step occurs and estimation of either vertical movement parameters or magnitude of steps by preparing the model and Least Squares Estimation of the parameters. The performance of this approach was shown using the ASG-EUPOS time series. Kowalczyk and Rapinski (2018) continued the verification of a GNSS time series discontinuity detection approach to support the estimation of vertical crustal movements. Using several triangles formed from the GNSS permanent stations on the area of Poland and their loop misclosures they confirmed the efficiency of the provided method. Finally, Kowalczyk and Rapinski (2017) applied the Vertical Switching Edge Detection algorithm to all permanent GPS station included in the ASG-EUPOS network. They found, that in the process of identification based on the loops misclosure criterion, there were 35 time series that fulfilled the previously assumed criteria. Then, they performed the network adjustment of height time series showing, that the accuracy of VLM of 0.5 mm/yr can be obtained from the processing of GNSS navigation data.

The time series analysis aimed at reliable determination of either velocity or its uncertainty is an inseparable part of kinematic modelling of the Earth's dynamics. The incorrect interpretation of coordinate time series may provide the misinterpretation of the geophysical processes in the Earth's interior. Bogusz (2015) dealt with non-linear long term trend revealing that many of GNSS stations experience the non-linear movement. He used the final approximation of wavelet decomposition to mathematically describe the long term trend of Precise Point Positioning solutions provided by the Jet Propulsion Laboratory (JPL) using the GIPSY-OASIS software. He stated, that GPS-derived velocity inversions using wavelet approximation could be successfully compared to the elastic deformation that was predicted e.g. with finite elements modelling aimed at approximating the geometry of the subduction, spreading or transition zones. Bogusz and Klos (2016) analyzed another part of the functional model of the GNSS position time series by means of seasonal changes. They proposed that the deterministic part should include all periodicities from 1st to 9th harmonics of residual tropical, Chandler, and draconitic periods and compared this approach with frequently used assumptions of the tropical annual and semi-annual-only curves. They found that this approach to the subtraction of seasonals caused the Akaike Information Criterion (AIC) values to decrease in the median value of 30%. Finally, they noticed that there are some of the GPS stations that improved their velocity uncertainty even of 56%. Several research concerned the considering of the amplitudes of oscillations as being time-variable. Bogusz et al. (2015a) proposed to use non-parametric methods. They stacked 3D position times series from JPL into data sets according to year (from January to December) and applied wavelet decomposition using Meyer's symmetric wavelet to prove that amplitudes of the annual curve change in time. Following this idea Gruszczynska et al. (2016) and Gruszczynska et al. (2018) proposed the Singular Spectrum Analysis (SSA) as well as its multivariate variant (MSSA) to be optimal method for description of this variability, but with non-significant influence to the stochastic part as previously applied methods (e.g. wavelet decomposition, Chebyshev polynomials, or Kalman filtering – numerical experiments presented in details in the paper by Klos et al. (2018a)). Klos et al. (2018b) found that the effects of insufficiently modeled seasonal signals will propagate into the stochastic model and falsify the results of the noise analysis, in addition to velocity estimates and their uncertainties. They provided the General Dilution of Precision (GDP) as the ratio of velocity uncertainties determined from two different deterministic models while accounting for stochastic noise at the same time. Klos et al. (2018c) proposed a two-stage method of subtraction of environmental (atmosphere, non-tidal part of ocean changes and continental hydrosphere) loadings. They proved, that previous attempts failed by changing the stochastic part significantly along with uncertainties of the permanent station velocity. Application of the Improved Singular Spectrum Analysis (ISSA) solved this problem, which was demonstrated on the height changes of 376 permanent IGS stations, derived as the official contribution to International Terrestrial Reference Frame (ITRF2014). Kaczmarek and Kontny (2018) proposed to estimate the seasonal signals in GNSS position time series and environmental loading models with iterative Least-Squares Estimation (iLSE) approach. They used the Center for Orbit Determination in

Europe (CODE) "Repro2013" coordinates revealing the high (0.5-0.8) correlation between Up component of GNSS-derived position and deformations from loading models.

Subtraction of the deterministic part from original position time series leads to obtain the residual part, being almost purely stochastic. However, this ideal case occurs rare, so the residuals still contain some useful information to be extracted. Bogusz et al. (2015b) used a 5-year span time series (2008-2012) of daily solutions in the ITRF2008 from Bernese 5.0 processed at the Military University of Technology EPN Local Analysis Centre (MUT LAC) to evaluate using L1 and L2 norms the so-called Common-Mode Error (CME). It is defined as the superposition of the technique-dependent and environmental systematic errors in GPS-derived position time series. Consequently, Gruszczynski et al. (2016) proposed to use orthogonal transformation to subtract CME. They studied the Principal Component Analysis (PCA) with the existence of a non-uniform spatial response in the network to the CME being assumed. They found improvement (by means of better credibility) of accuracy of the determined velocity being accompanied by the spatio-temporal filtering of position time series. Gruszczynski et al. (2018) introduced for the first time in geodesy the probabilistic Principal Component Analysis (pPCA). It is a method which allow the spatio-temporal filtering aimed at estimation and subtraction of CME, but with no interpolation of the missing values. The efficiency of the proposed algorithm was firstly tested on the simulated incomplete time series, then CME was estimated for a set of 25 permanent stations located in Central Europe. They found, that more than 36% of the total variance represented by time series residuals can be explained by the 1st Principal Component (PC). Since the other PCs variances turned out to be less than 8%, they concluded that that common signals stored in the 1st PC are significant in GNSS residuals. Finally, Kaczmarek and Kontny (2018) modelled the position time series with the use of Least-Squares Estimation (LSE) and the inverse continuous wavelet transform (CWT).

3.2. Investigations of tidal phenomena

It's been a tradition of the International Association of Geodesy to take patronage over the so-called "Tidal Symposium". The 18th Geodynamics and Earth Tides Symposium 2016 "Intelligent Earth system sensing, scientific enquiry and discovery" was held in Trieste, Italy with more than 110 attendants from all over the World. It was organized by the scientists worked under the umbrella of IAG Sub-Commission 3.1 "Earth tides and geodynamics", being currently chaired by Prof. Janusz Bogusz. The classical Earth Tide Symposia were held since 1957, the 18th was the first with the word "Geodynamics" being attached. The 2016 Symposium addressed a wide range of scientific problems in geodynamical research and chose the interactions of geophysical fluids with Earth tidal phenomena and observations as a specific focus (Braitenberg et al., 2018).

The gravimetric infrastructure of the Borowa Gora Geodetic-Geophysical Observatory of the Institute of Geodesy and Cartography, equipped so far with four LaCoste&Romberg model G gravimeters (three of them with modern feedback systems) and the A10-020 field absolute gravimeter was enhanced in 2016 with a new iGrav-

027 superconducting gravimeter. It was delivered to the Observatory at the beginning of February 2016 and became fully operational in late April 2016. Sekowski et al. (2016) presented major aspects of installation, preliminary results of initial data analysis as well as a comparison with A10 measurements. The reliable results of tidal data processing are expected soon.

After several years of break Borowiec laser station is back again to satellites tracking with new possibilities and new perspectives. At the beginning of 2016 station completed the quarantine procedure of the International Laser Ranging Service (ILRS). First results from BORL station confirmed a high quality of observations (Lejba et al., 2016).

Concerning the determination of the tidal parameters from permanent observations Jagoda et al. (2017a) estimated h_2 and l_2 (Love and Shida numbers of second degree) parameters based on the analysis of the Satellite Laser Ranging data from the period January 2013 to January 2015. The solution has been computed using the LAGEOS-1 and LAGEOS-2 data with two different approaches: separately and jointly for the two satellites. The obtained values of tidal parameters are equal to: $h_2 = 0.6140 \pm 0.0005$ and $l_2 = 0.0876 \pm 0.0002$. Consequently, Jagoda et al. (2017b) determined the values of k_2 and k_3 Love numbers using the same LAGEOS satellites and the period from January 2014 to January 2016. Moreover, in the paper the potential sources of the differences in the values of the determined parameters are discussed. In the paper by Jagoda et al. (2018) the considerations about obtained differences in the k_2 and k_3 values were continued.

3.3. Research on hydrological processes

In Sec. 2 we reported on the investigations concerning the impact of hydrological processes on polar motion using data from global hydrology models and GRACE-based satellite gravimetry data. However, also the regional effects due to the hydrological processes have been studied in a period of 2015–2018 by Polish researchers, mostly from the University of Warmia and Mazury (UWM). Birylo et al. (2015a) attempted to evaluate local hydrosphere conditions using the data from satellite gravimetry mission GRACE and GOCO gravity model, with the purpose of prediction the flood and drought events in Poland. They concluded that a combination of gravimetric and meteorological models yields more reliable modeling of water flow than the contributing individual models. Birylo et al. (2015b) further extended this research by including geological data into the combination model of water flow. They developed a combined geopotential model, expressed by the equivalent water thickness – EWT, from GRACE data, meteorological WGHM model and geological data over the area of Poland. This model served in turn as a base for a map of water risk for Poland. Rzepecka et al. (2016a) applied the global land data assimilation system GLDAS for determination of groundwater changes in Poland. They evaluated two GLDAS parameters which are essential for the context, namely the snow water equivalent (SWE) and the soil moisture (SM), using four GLDAS sub-models, and then compared their estimates at two locations in Poland. They found that the differences between the parameters estimated from the sub-models are quite large, comparable to the size of the parameters themselves. This research was extended by Rzepecka et al. (2016b) by including the GRACE-derived EWT and direct measurement of ground water level (GWL) variations in the estimation. Preliminary comparison between the GWL determined using GRACE data augmented with GLDAS output parameters and direct measurements led the authors to the conclusion that the method applied yield promising results and will be validated in future studies. In the next stage of research, Rzepecka et al. (2017) performed extensive analysis of groundwater level variations, water balance and all the associated hydrological parameters, like precipitation, evapotranspiration, surface run-off and subsurface run-off. This analysis was done for the area of Sudety Mountains in the South-Western Poland, and for the period between 2002 and 2015. The GWL variations were estimated by the use of TWS values determined from the GRACE observations and GLDAS model with a spatial resolution one by one degree and temporal resolution of one month. The authors found in the Sudety area a high average stability of total water storage over the period considered with simultaneous decrease of groundwater level at a rate of about 1 cm/year. Birylo at al. (2018a) developed an algorithm for water budget prediction using the Autoregressive Integrated Moving Average (ARIMA) models. A comparison between a 12-month prediction and actual budget data provided a satisfactory assessment of the prediction method. The same statistical approach was applied by Birylo and Pajak (2018) for analysis of geoid variation in the region of Three Gorges Dam on the Yangtze River in China, computed as difference between the static gravity field model EGM2008 and the time variable gravity observed by GRACE. The main purpose of the paper was determination of the trend in data and short-term prediction based on ARIMA modeling. Birylo et al. (2018b) computed the water budget for the whole territory of Poland from the GLDAS model by considering all the relevant parameters including precipitation, surface run-off and evapotranspiration. Detailed tests were performed for the two areas adjacent to Lamkowko and Wroclaw stations and for the period 2009–2015. The estimated water budget was presented in a graphic form and interpreted.

The influence of hydrology on GNSS observations has been investigated by researchers from the Warsaw University of Technology (WUT). Zygmunt et al. (2016) performed analysis of vertical displacement of 23 IGS stations divided into three groups: inland stations, near shoreline and islands. The observed vertical displacements have been compared to the modeled deformation computed from the surface loading caused by continental water. A satisfactory agreement between the modeled and observed deformations could be found only for the inland stations. In case of other two groups of stations the modeled values were much lower and weakly correlated with the observed values. Rajner and Liwosz (2017) investigated seasonal signals in position time series for selected eight GNSS sites in Poland. They used for the analysis the weekly GNSS time series taken from homogeneously reprocessed global network solution and from regional solutions performed by WUT. The modeled deformations were computed from the GRACE-derived Total Water Equivalent (TWE) and from the output of Water GAP Hydrology Model (WGHM). Comparison of the observed and modeled deformations confirmed that the major part of observed seasonal variations for GNSS vertical components can be attributed to the hydrosphere loading. The horizontal displacements were found about three times smaller than the vertical ones, and the conclusions their origin were ambiguous.

3.4. Research on sea-level variations

Polish researchers continued during the term 2015–2018 investigations on modeling sea level variations in both the global scale (mostly the members of the group of the University of Wroclaw) and the regional scale limited to Baltic Sea (researchers from UWM). In the first case the research was a continuation of earlier studies leading to implementation at the University of Wroclaw of the near-real time system and service "Prognocean" for sea level prediction. Recently, a new science-oriented version of this service, called "Prognocean Plus", based on the high performance supercomputing structure had been developed at the Wroclaw Centre for Networking and Supercomputing of Wroclaw University of Technology. Swierczynska et al. (2016) compared predictive skills of these two sea level forecasting systems and the third one called MyOcean which is a part of the European Copernicus Marine Environment Monitoring Service. The predictions from each of three systems have been compared with Sea Level Anomaly (SLA) data using various statistical indicators. The conclusion was that the data-based approaches used by Prognocean and Prognocean Plus show better performance in forecasting sea level variability than the physically-based model of MyOcean. On the other hand, MyOcean resolves irregular SLA changes better because its prognoses highly correlate with data. Niedzielski (2017) presented review on modeling and prediction of various features of marine environment. He focused on several empirical time series methods (like data transformations, polynomial-harmonic models, autoregressive processes, prediction equations) and some physical approaches (general circulation models and coupled air-sea models). He also discussed common statistical measures used to evaluate models and the resulting predictions. The reasons of imperfections in forecasting the sea level anomaly variations were investigated by Kosek et al. (2016). After performing detailed analysis of seasonal and subseasonal signals in the weekly SLA maps they could conclude that the main cause of the increase of the SLA prediction errors is the phase variation of the annual oscillation, which exhibits a random character to certain extent. Finally we should mention two works of the Wroclaw University team on estimation of the ocean reference depth, its present-day value (Jurecka et al., 2016) and the depth-age relationship over the geological time scale (Niedzielski et al., 2016).

A series of papers concerning sea level changes observed over the Baltic Sea basin has been published by researchers from UWM. Pajak (2017) performed analysis of 5-years long series of sea level anomaly data derived from the satellite observations for three points of the Baltic Sea, two inshore points and one open sea point. The work focused on seasonal variations using different statistical indicators. Further results concerning the estimation of sea level rise over the Baltic Sea from satellite altimetry data was reported by Pajak and Birylo (2016). An extensive analysis of seasonal Baltic Sea level changes was performed by Pajak and Birylo (2017) using the combination of satellite altimetry data, time variable gravity observations from GRACE mission, and terrestrial water storage estimates from GLDAS hydrology model. The estimation had been done for three offshore locations in Poland. Pajak and Kowalczyk (2018) reported detailed analysis of the dynamics of sea level and of the associated physical phenomena over the 5-year period 2010–2014 and for five Baltic Sea stations, Swinoujscie and Wladyslawowo in Poland, Helsinki in Finland and two open sea stations. They used in analysis the data of water temperature, salinity, sea level anomaly from satellite altimetry and equivalent water height from GRACE observations.

4. Earth magnetic field

Systematic (continuous or repeated) magnetic measurements are the key element to understand and properly predict the changes in the Earth's magnetic field. The elements to be measured are: absolute geomagnetic field magnitude (F), magnetic inclination (I) and magnetic declination (D). Welker (2015) presented the history of magnetic measurements in the Baltic Sea from the very beginning (the mid-1800s) to the present. The discovered anomalies in a geomagnetic field in the form of charts were stored in the Atlas of the Baltic Magnetic Charts. Welker and Reda (2016) presented the metrology of magnetic measurements with recent apparatuses. They described the checking and testing of the instruments for geomagnetic measurements performed in a geomagnetic observatory which holds trusted apparatus that participated in the relevant international comparison campaigns organized by the International Association of Geomagnetism and Aeronomy (IAGA). The Earth's magnetic field distribution – both onshore and offshore – is complicated and variable in time, so it is essential to know the secular variation on the area of interest. That is why, Welker et al. (2017) proposed a new project of the Baltic network of repeat stations and gave a solution for the instruments usable for quasi-absolute magnetic measurements.

5. Summary

In this review article an outline of researches concerning Earth rotation and geodynamics carried out by scientists from Polish scientific institutions from 2015 to 2018 is given. Most of the research works on Earth rotation focused on the use of time variable gravity data from GRACE satellite mission for constraining the hydrological excitation function HAM and improving the excitation balance of the observed polar motion. That includes research on seasonal components of polar motion but also the 14-month free Chandler wobble. Also the regional effects due to the hydrological processed have been investigated using the output parameters from global hydrology models and GRACE-derived time variable gravity data. Polish researchers continued also during the term 2015–2018 investigations on modelling sea level variations in both the global scale and the regional scale limited to the Baltic Sea.

In 2016 the Borowa Gora Geodetic-Geophysical Observatory was equipped with superconducting gravimeter as the first of the Polish research station. After a couple of years of inactivity the laser station at the Borowiec Astrogeodynamic Observatory started to track the satellites. These were two unquestionable successes related to the geodetic equipment. Plans related to the retrofitting of the Observatory in Ksiaz are advanced. Several measurements and analyses concerning local geodynamics in the Southern Poland were done, especially on the geodynamic network of the Sudety and Tatra Mts. Furthermore, several Vertical Land Motion models of the area of Poland and the adjacent areas were provided which were based on the GNSS and levelling measurements. Finally, the research on the Earth's magnetic field in Poland with a special focus on the Baltic Sea was performed.

Acknowledgements

This paper was prepared according to the activities of the scientists from the following institutions (in alphabetical order):

- Borowiec Astrogeodynamic Observatory, Space Research Centre of the Polish Academy of Sciences in Borowiec;
- Department of Geodesy and Geodynamics, Institute of Geodesy and Cartography in Warsaw;
- Department of Planetary Geodesy, Space Research Centre of the Polish Academy of Sciences in Warsaw;
- Faculty of Civil Engineering and Geodesy, Military University of Technology in Warsaw;
- Faculty of Earth Sciences and Environmental Management, University of Wroclaw;
- Faculty of Environmental Engineering and Geodesy, Wroclaw University of Environmental and Life Sciences;
- Faculty of Geodesy and Cartography, Warsaw University of Technology;
- Faculty of Geoengineering, Mining and Geology, Wroclaw University of Technology;
- Faculty of Geodesy, Geospatial and Civil Engineering, University of Warmia and Mazury in Olsztyn;
- Faculty of Mining Surveying and Environmental Engineering, University of Science and Technology in Cracow.

The work of Janusz Bogusz on the report was supported by the Faculty of Civil Engineering and Geodesy MUT statutory research funds.

References

Bednarczyk, M., Kowalczyk, K. and Kowalczyk, A. (2018). Identification of pseudo-nodal points on the basis of precise leveling campaigns data and GNSS. *Acta Geodynamica et Geomaterialia*, 15(1), 5–16, DOI: 10.13168/AGG.2017.0028.

Birylo, M., Nastula, J. and Kuczynska-Siehien, J. (2015a). The creation of flood risks model using a combination of satellite and meteorological models – the first step. *Acta Geodynamica et Geomaterialia*, 12(2), 151–156. DOI: 10.13168/AGG.2015.0018.

Birylo, M., Sienkiewicz, J., Nastula, J. and Kuczynska-Siehien, J. (2015b). Combined model of gradiometric, meteorological and geological data for the purpose of water flow observation. 15th International Multidisciplinary Scientific GeoConference SGEM 2015 Conference Proceedings. ISBN 978-619-7105-36-0/ISSN 1314-2704, 3(1), 145–152, DOI: 10.5593/sgem2015B31.

Birylo, M., Rzepecka, Z., Kuczynska-Siehien, J. and Nastula, J. (2018a). Analysis of water budget prediction accuracy using ARIMA models. *Water Science & Technology: Water Supply*, 18.3, 819–830. DOI: 10.2166/ws.2017.156.

Birylo, M., Rzepecka, Z. and Nastula, J. (2018b). Assessment of the water budget from GLDAS model. Proceedings of the 2018 Baltic Geodetic Congress (BGC Geomatics). DOI: 10.1109/BGC-Geomatics.2018.00022.

Birylo, M. and Pajak, K. (2018). Statistical approach to the computation of an influence of the Yangtze Dam on gravity fluctuations. Proceedings of the 10th International Conference "Environmental Engineering", Lithuania, 27–28 April 2017, eISSN 2029-7092, DOI: 10.3846/enviro.2017.165.

Blachowski, J. (2016). Application of GIS spatial regression methods in assessment of land subsidence in complicated mining conditions: case study of the Walbrzych coal mine (SW Poland). *Natural Hazards*, 84(2), DOI: 10.1007/s11069-016-2470-2.

Blachowski, J. and Herkt, P. (2018). Enhancement of the Walbrzych Hard Coal Mines Geographic Information System for its application in studies of mining deformations. XXIIIrd Autumn School of Geodesy E3S Web of Conferences 55, 00002(2018). DOI: 10.1051/e3sconf/20185500002.

Blachowski, J., Jirankova, E., Lazecky, M., Kadlecik, P. and Milczarek, W. (2018). Application of satellite radar interferometry (PSInSAR) in analysis of secondary surface deformations in mining areas. Case studies from Czech republic and Poland. *Acta Geodynamica et Geomaterialia*, 15(2), 173–185. DOI: 10.13168/AGG.2018.0013.

Bogusz, J. (2015). Geodetic aspects of GPS permanent stations non-linearity studies. *Acta Geodynamica et Geomaterialia*, 12(4), 323–333. DOI: 10.13168/AGG.2015.0033.

Bogusz, J. and Klos, A. (2016). On the significance of periodic signals in noise analysis of GPS station coordinates time series. *GPS Solutions*, 20(4), 655–664. DOI: 10.1007/s10291-015-0478-9.

Bogusz, J., Gruszczynska, M., Klos, A. and Gruszczynski, M. (2015a). Non-parametric estimation of seasonal variations in GPS-derived time series. International Association of Geodesy Symposia, 146, 227–233. DOI: 10.1007/1345_2015_191.

Bogusz, J., Gruszczynski, M., Figurski, M. and Klos, A. (2015b). Spatio-temporal filtering for determination of common mode error in regional GNSS networks. *Central European Journal of Geosciences*, 7, 140–148. DOI: 10.1515/geo-2015-0021.

Bogusz, J., Klos, A., Gruszczynska, M. and Gruszczynski, M. (2016). Towards reliable velocities of permanent GNSS stations. *Reports on Geodesy and Geoinformatics*, 100(1), 17–26. DOI: 10.1515/rgg-2016-0003.

Braitenberg, C., Rossi, G., Bogusz, J., Crescentini, L., Crossley, D., Gross, R., Heki, K., Hinderer, J., Jahr, T., Meurers, B. and Schuh, H. (2018). Geodynamics and Earth Tides Observations from Global to Micro Scale: Introduction. *Pure and Applied Geophysics*, 175(5), 1595–1597. DOI: 10.1007/s00024-018-1875-0.

Brzezinski, A. (2015). Report on activities of the Sub-Working Group 2 "Polar Motion and UT1" of the IAU/IAG Joint Working Group on Theory of Earth Rotation. Proc. Journées 2014 *Systèmes de référence spatio-temporels*, (eds.) Z. Malkin and N. Capitaine, Pulkovo Observatory, pp. 135–138.

Brzezinski, A., Wielgosz, A. and Böhm, S. (2015). On application of the complex demodulation for monitoring Earth rotation: analysis of the nutation and long periodic UT1 data estimated by VieVS CD. Proc. Journées 2014 *Systèmes de référence spatio-temporels*, (eds.) Z. Malkin and N. Capitaine, Pulkovo Observatory, pp. 171–174.

Brzezinski, A., Jozwik, M., Kaczorowski, M., Kalarus, M., Kasza, D., Kosek, W., Nastula, J., Szczerbowski, Z., Winska, M., Wronowski, R., Zdunek, R. and Zielinski, J.B. (2016a). Geodynamic research at the Department of Planetary Geodesy, SRC PAS. *Reports on Geodesy and Geoinformatics*, 100(1), 131–147. DOI: 10.1515/rgg-2016-0011.

Brzezinski, A., Barlik, M., Andrasik, E., Izdebski, W., Kruczyk, M., Liwosz, T., Olszak, T., Pachuta, A., Pieniak M., Prochniewicz, D., Rajner, M., Szpunar, R., Tercjak, M. and Walo, J. (2016b). Geodetic and geodynamic studies at Department of Geodesy and Geodetic Astronomy WUT. *Reports on Geodesy and Geoinformatics*, 100(1), 165–200. DOI: 10.1515/rgg-2016-0013.

Gruszczynska, M., Klos A., Gruszczynski, M. and Bogusz, J. (2016). Investigation on time-changeable seasonal components in the GPS time series: case study of Central Europe. *Acta Geodynynamica et Geomaterialia*, 13(3), 281–289. DOI: 10.13168/AGG.2016.0010.

Gruszczynska, M., Rosat, S., Klos, A., Gruszczynski, M. and Bogusz, J. (2018). Multichannel Singular Spectrum Analysis in the estimates of common environmental effects affecting GPS observations. *Pure and Applied Geophysics*, 175(5), 1805–1822. DOI: 10.1007/s00024-018-1814-0.

Gruszczynski, M., Klos, A. and Bogusz, J. (2016). Orthogonal transformation in extracting of common mode errors from continuous GPS networks. *Acta Geodynamica et Geomaterialia*, 13(3), 291–298. DOI: 10.13168/AGG.2016.0011.

Gruszczynski, M., Klos, A. and Bogusz, J. (2018). A filtering of incomplete GNSS position time series with probabilistic Principal Component Analysis. *Pure and Applied Geophysics*, 175(5), 1841–1867. DOI: 10.1007/s00024-018-1856-3.

Jagoda, M., Rutkowska, M. and Kraszewska, K. (2017a). The evaluation of time variability of tidal parameters *h* and *l* using SLR technique. *Acta Geodynamica et Geomaterialia*, 14(2), 153–158. DOI: 10.13168/AGG.2016.0036.

Jagoda, M., Rutkowska, M. and Kraszewska, K. (2017b). Evaluation of time change of the Love k_2 and k_3 numbers using LAGEOS SLR data. *Biuletyn WAT*, LXVI(3). DOI: 10.5604/01.3001.0010.5393 (in Polish with English abstract).

Jagoda, M., Rutkowska, M., Kraszewska, K. and Suchocki, C. (2018). Time changes of the potential Love tidal parameters k_2 and k_3. *Studia Geophysica et Geodaetica*, 62(4), 586–55. DOI: 10.1007/s11200-018-0610-8.

Jurecka, M., Niedzielski, T. and Migon, P. (2016). A novel GIS-based tool for estimating present-day ocean reference depth using automatically processed gridded bathymetry data. *Geomorphology*, 260, 91–98. DOI: 10.1016/j.geomorph.2015.05.021.

Kaczmarek, A., Cacon, S. and Weigel, J. (2016). Recent relative vertical movements in the tectonic zone of the Sudety Mts. *Acta Geodynamica et Geomaterialia*, 13(2), 177–184. DOI: 10.13168/AGG.2015.0055.

Kaczmarek, A. and Kontny, B. (2018a). Estimates of seasonal signals in GNSS time series and environmental loading models with iterative least-squares estimation (ILSE) approach. *Acta Geodynamica et Geomaterialia*, 15(2), 131–141. DOI: 10.13168/AGG.2018.0009.

Kaczmarek, A. and Kontny, B. (2018b). Identification of the noise model in the time series of GNSS stations coordinates using wavelet analysis. *Remote Sensing*, 10(10), 1611. DOI: 10.3390/rs10101611.

Kaczorowski, M., Borkowski, A., Zdunek, R., Goluch, P., Kuchmister, J. and Cmielewski, K. (2015). Integrated tectonic studies: a new concept explored in the Geodynamic Laboratory of the Space Research Center in Ksiaz. *Acta Geodynamica et Geomaterialia*, 12(2), 169–179. DOI: 10.13168/AGG.2015.0012.

Klos, A. and Bogusz, J. (2017). An evaluation of velocity estimates with a correlated noise: case study of IGS ITRF2014 European stations. *Acta Geodynamica et Geomaterialia*, 14(3), 255–265. DOI: 10.13168/AGG.2017.0009.

Klos, A., Bos, M.S. and Bogusz, J. (2018a). Detecting time-varying seasonal signal in GPS position time series with different noise levels. *GPS Solutions*, 22(1). DOI: 10.1007/s10291-017-0686-6.

Klos, A., Olivares, G., Teferle, F.N., Hunegnaw, A. and Bogusz, J. (2018b). On the combined effect of periodic signals and coloured noise on velocity uncertainties. *GPS Solutions*, 22(1). DOI: 10.1007/s10291-017-0674-x.

Klos, A., Gruszczynska, M., Bos, M.S., Boy, J.-P. and Bogusz, J. (2018c). Estimates of vertical velocity errors for IGS ITRF2014 stations by applying the Improved Singular Spectrum Analysis method and environmental loading models. *Pure and Applied Geophysics*, 175(5), 1823–1840. DOI: 10.1007/s00024-017-1494-1.

Kolaczek, B. and Nastula, J. (2016). Outline of the chronology of the developments of geodynamic investigations connected with earth rotation studies in the twentieth century: Authors' perspective. International Association of Geodesy Symposia Series, 143, 503–511. DOI: 10.1007/1345_2015_86.

Kosek, W., Niedzielski, T., Popinski, W., Zbylut, M. and Wnęk, A. (2016). Variable seasonal and subseasonal oscillations in sea level anomaly data and their impact on sea level prediction accuracy. [In:] Sneeuw N., Novák P., Crespi M., Sansò F. (eds.), VIII Hotine-Marussi Symposium on Mathematical Geodesy, International Association of Geodesy Symposia Series, 142, 47–50, DOI: 10.1007/1345_2015_74.

Kowalczyk, K. (2015). The creation of a model of relative vertical crustal movement in the Polish territory on the basis of the data from Active Geodetic Network EUPOS (ASG EUPOS). *Acta Geodynamica et Geomaterialia*, 12(3), 215–225. DOI: 10.13168/AGG.2015.00220039.

Kowalczyk, K. (2017). Testing the Correlation Between the Vertical Crustal Movements and Temperature Changes on the Example of Selected Vectors Permanent GNSS Stations. Proceedings of the 10th International Conference "Environmental Engineering", Lithuania, 27-28 April 2017, eISSN 2029-7092, DOI: 10.3846/enviro.2017.205.

Kowalczyk, K. and Bogusz, J. (2017). Application of PPP solution to determine the absolute vertical crustal movements: case study for northeastern Europe. Proceedings of the 10th International Conference "Environmental Engineering", Lithuania, 27–28 April 2017, eISSN 2029-7092, DOI: 10.3846/enviro.2017.222.

Kowalczyk, K. and Kuczynska-Siehien, J. (2017). Testing Correlation between Vertical Crustal Movements and Geoid Uplift for North Eastern Polish Border Areas. Proceedings of the 10th International Conference "Environmental Engineering", Lithuania, 27–28 April 2017, eISSN 2029-7092, DOI: 10.3846/enviro.2017.206.

Kowalczyk, K. and Kuczynska-Siehien, J. (2018). Testing the relationship between vertical crustal movement and geoid uplift for the Sudetes area. *Annales Societatis Geologorum Poloniae*, 88(1), 47–57. DOI: 10.14241/asgp.2018.004.

Kowalczyk, K. and Rapinski, J. (2017). Robust network adjustment of vertical movements with GNSS data. *Geofizika*, 34(1), 45–65. DOI: 10.15233/gfz.2017.34.3.

Kowalczyk, K. and Rapinski, J. (2018). Verification of a GNSS Time Series Discontinuity Detection Approach in Support of the Estimation of Vertical Crustal Movements. *International Journal of Geo-Information*, 7(4), 149. DOI: 10.3390/ijgi7040149.

Kraszewska, K., Jagoda, M. and Rutkowska, M. (2016). Tectonic plate parameters estimated in the International Terrestrial Reference Frame ITRF2008 based on SLR stations. *Acta Geophysica*, 64(5), 1495–1512. DOI: 10.1515/acgeo-2016-0072.

Kraszewska, K., Jagoda, M. and Rutkowska, M. (2018). Tectonic plates parameters estimated in International Terrestrial Reference Frame ITRF2008 based on DORIS stations. *Acta Geophysica*, 66(8), 509–521. DOI: 10.1007/s11600-018-0169-3.

Lejba, P., Suchodolski, T., Schillak, S., Bartoszak, J., Michałek, P. and Zapaśnik, S. (2016). New face of the Borowiec Satellite Laser Ranging Station. Proceedings of the 20th International Workshop on Laser Ranging. GFZ Potsdam, Germany.

Milczarek, W., Blachowski, J. and Grzempowski, P. (2017). Application of PSInSAR for assessment of surface deformations in post-mining area – case study of the former Walbrzych hard coal basin (SW Poland). *Acta Geodynamica et Geomaterialia*, 14(1), 41–52. DOI: 10.13168/AGG.2016.0026.

Nastula, J., Winska M. and Birylo M. (2015). Comparison of polar motion excitation functions computed from different sets of gravimetric coefficients. Proc. Journées 2014 "Systèmes De Référence Spatio-Temporels", 187–190.

Nastula, N. and Gross, R. (2015). Chandler wobble parameters from SLR and GRACE, *Journal of Geophysical Research: Solid Earth*, 120(6), 4474–4483. DOI: 10.1002/2014JB011825.

Nastula, J., Salstein, D.A. and Popinski, W. (2016). Hydrological excitations of polar motion from GRACE gravity field solutions, C. Rizos, P. Willis (eds.). International Association of Geodesy Symposia Series, 143, 513–519. DOI: 10.1007/1345_2015_85.

Niedzielski, T. (2017). Basic prediction methods in marine sciences. [In:] Green D.R., Payne J. (eds.), *Marine and Coastal Resource Management – Principles and Practice*. Routledge, Taylor & Francis Group, 121–141.

Niedzielski, T., Jurecka, M. and Migon, P. (2016). Semi-Empirical Oceanic Depth – Age Relationship Inferred from Bathymetric Curve. *Pure and Applied Geophysics*, 173(5), 1829–1840. DOI: 10.1007/s00024-015-1204-9.

Pasik, M., Adamek, A., Rajner, M., Kurczynski, Z., Pachuta, A., Woźniak, M., Bylina, P. and Próchniewicz, D. (2016). Participation of employees and students of the Faculty of Geodesy and Cartography in polar research, *Reports on Geodesy and Geoinformatics*, 100(1), 235–252, DOI: 10.1515/rgg-2016-0016.

Pajak, K. (2017). Seasonal Baltic Sea level change from altimetry data. Proceedings of the 10th International Conference "Environmental Engineering", eISSN 2029-7092 / eISBN 978-609-476-044-0, DOI: 10.3846/enviro.2017.223.

Pajak, K. and Birylo, M. (2016). Evaluation of the Baltic Sea basin using satellite altimetry data. 16th International Multidisciplinary Scientific GeoConference SGEM 2016 Conference Proceedings, ISBN 978-619-7105-59-9/ISSN 1314-2704, 3(1), 297–304. DOI: 10.5593/SGEM2016/B31/S12.039.

Pajak, K. and Birylo, M. (2017). Seasonal Baltic Sea level changes in coastal zone. Proceedings of the 10th World Congress on Water Resources and Environment At: "Panta Rhei", Athens, Greece, Volume: European Water 59: 185–192, ISSN:1792-085X.

Pajak, K. and Kowalczyk, K. (2018). Assessment of the Dynamics of Sea Level and Physical Phenomena in the Baltic Sea. *Geodetski Vestnik*, 62, 430–444. DOI: 10.15292/geodetski-vestnik.2017.03.373-386.

Rajner, M. (2018). Detection of ice mass variation using GNSS measurements at Svalbard. *Journal of Geodynamics*, 121, 20–25. DOI: 10.1016/j.jog.2018.06.001.

Rajner, M. and Brzezinski, A. (2017). Free core nutation period inferred from the gravity measurements at Józefoslaw. *Studia Geophysica et Geodaetica*, 61(4), 639–656. DOI: 10.1007/s11200-016-0174-4.

Rajner, M. and Liwosz, T. (2017). Analysis of seasonal position variation for selected GNSS sites in Poland using loading modelling and GRACE data. *Geodesy and Geodynamics*, 8(4), 253–259. DOI: /10.1016/j.geog.2017.04.001.

Rapinski, J. and Kowalczyk, K. (2016). Detection of discontinuities in the height component of GNSS time series, *Acta Geodynamica et Geomaterialia*, 13(3), 315–320. DOI: 10.13168/AGG.2016.0013.

Rzepecka, Z., Birylo, M. and Nastula, J. (2016a). Evaluation of the global land data assimilation system (GLDAS) data products essential for determination groundwater in Poland. 16th International Multidisciplinary Scientific GeoConference SGEM 2016 Conference Proceedings, ISBN 978-619-7105-59-9 / ISSN 1314-2704, 3(1), 313–320. DOI: 10.5593/SGEM2016/B31/S12.041.

Rzepecka, Z., Birylo, M. and Nastula, J. (2016b). Assessment of resultant groundwater calculated on the basis of GRACE and GLDAS models. 16th International Multidisciplinary Scientific GeoConference SGEM 2016 Conference Proceedings, ISBN 978-619-7105-59-9/ISSN 1314-2704, 2(2), 125–132. DOI: 0.5593/SGEM2016/B22/S09.017.

Rzepecka, Z., Birylo M., Kuczynska-Siehien, J., Nastula, J. and Pajak, K. (2017). Analysis of groundwater level variations and water balance in the area of the Sudety mountains. *Acta Geodynamica et Geomaterialia*, 14(3), 313–321. DOI: 10.13168/AGG.2017.0014.

Sekowski, M., Dykowski, P. and Krynski, J. (2016). New iGrav superconducting gravimeter station in Central Europe at the Borowa Gora Geodetic-Geophysical Observatory. *Geoinformation Issues*, 8, 5–17.

Sliwinska, J., Winska, M. and Nastula, J. (2018). Terrestrial water storage variations and their effect on polar motion. *Acta Geophysica*, 67(1), 17–39. DOI: 10.1007/s11600-018-0227-x.

Swierczynska, M., Mizinski, B. and Niedzielski, T. (2016). Comparison of predictive skills offered by Prognocean, Prognocean Plus and MyOcean real-time sea level forecasting systems. *Ocean Engineering*, 113(2016), 44–56. DOI: 10.1016/j.oceaneng.2015.12.023.

Szafarczyk, A. and Gawalkiewicz, R. (2016). Case study of the tensor analysis of ground deformations evaluated from geodetic measurements in a landslide area. *Acta Geodynamica et Geomaterialia*, 13(2), 213–222. DOI: 10.13168/AGG.2015.0003.

Szafarczyk, A. and Gawalkiewicz, R. (2018). The Impact of the Rock Mass Deformation on Geometric Changes of a Historical Chimney in the Salt Mine of Bochnia. POL-VIET 2017 E3S Web of Conferences 35, 04002 (2018). DOI: 10.1051/e3sconf/20183504002.

Szczerbowski, Z. (2016). Investigation on reflection of tectonic pattern in ASG EUPOS data in the Sudetes and adjacent areas. *Reports on Geodesy and Geoinformatics*, 102, 32–51. DOI: 10.1515/rgg-2016-0026.

Szczerbowski, Z. and Piatkowska, A. (2015). Towards data integration and analysis in the detection of terrain surface deformation in the case of the Inowroclaw salt dome. *Geomatics and Environmental Engineering*, 9(4), 95–110. DOI: 10.7494/geom.2015.9.4.85.

Szczerbowski, Z. and Jura, J. (2015). Mining induced seismic events and surface deformations monitored by GPS permanent stations. *Acta Geodynamica et Geomaterialia*, 12(3), 237–248. DOI: 10.13168/AGG.2015.0023.

Szczerbowski, Z., Kaczorowski, M., Wiewiórka, J., Jóźwik, M., Zdunek, R. and Kawalec, A. (2016). Monitoring of tectonically active area of Bochnia. *Acta Geodynamica et Geomaterialia*, 13(1), 59–67. DOI: 10.13168/AGG.2015.0044.

Tercjak, M. and Brzezinski, A. (2017). On the Influence of Known Diurnal and Subdiurnal Signals in Polar Motion and UT1 on Ring Laser Gyroscope Observations. *Pure and Applied Geophysics*, 174(7), 2719–2731. DOI: 10.1007/s00024-017-1552-8.

Tercjak, M., Böhm, J., Brzezinski, A., Gebauer, A., Klügel, T., Schreiber, U. and Schindelegger, M. (2015). Estimation of nutation rates from combination of ring laser and VLBI data, Proc. Journées 2014. *Systèmes de référence spatio-temporels*, (eds.) Z. Malkin and N. Capitaine, Pulkovo Observatory, 167–170.

Wajs, J. and Milczarek, W. (2018). Detection of surface subsidence using SAR SENTINEL 1A imagery and the DInSAR method – a case study of the Belchatow open pit mine, Central Poland. XXIIIrd Autumn School of Geodesy, E3S Web of Conferences 55, 00004 (2018). DOI: 10.1051/e3sconf/20185500004.

Welker, E. (2015). Polish magnetic measurements in the Baltic – history and prospects. *Scientific Journal of Polish Naval Academy*, 2(201), 75–85. DOI: 10.5604/0860889X.1172075.

Welker, E. and Reda, J. (2016). Magnetic measurements, apparatus and meteorology. *Geoinformation Issues*, 8(1), 19–24.

Welker, E., Reda, J. and Palka, A. (2017). Magnetic repeat station network on the Baltic Sea – why so needed? *Annual of Navigation*, 24(2017), 19–30. DOI: 10.1515/aon-2017-0002.

Wielgosz, A., Tercjak, M. and Brzezinski, A. (2016a). Testing impact of the strategy of VLBI data analysis on the estimation of Earth Orientation Parameters and station coordinates. *Reports on Geodesy and Geoinformatics*, 101, 1–15. DOI: 10.1515/rgg-2016-0017.

Wielgosz, A., Brzezinski, A. and Böhm, S. (2016b). Complex demodulation in monitoring Earth rotation by VLBI: testing the algorithm by analysis of long periodic EOP components. *Artificial Satellites*, 51(4), 135–147. DOI: 10.1515/arsa-2016-0012.

Winska, M. (2016). Hydrological Excitations of Polar Motion Derived from Different Variables of *Fgoals – g2* Climate Model. *Artificial Satellites*, 51(4), 107–122. DOI: 10.1515/arsa-2016-0010.

Winska, M., Nastula, J. and Kolaczek, B. (2016). Assessment of the Global and Regional Land Hydrosphere and its Impact on the Balance of the Geophysical Excitation Function of Polar Motion. *Acta Geophysica*, 64(1), 270–292. DOI: 10.1515/acgeo-2015-0041.

Winska, M., Nastula, J. and Salstein, D.A. (2017). Hydrological excitation of polar motion by different variables from the GLDAS model. *Journal of Geodesy*, 91(12), 1461–1473. DOI: 10.1007/s00190-017-1036-8.

Walo, J., Próchniewicz, D., Olszak, T., Pachuta, A., Andrasik, E. and Szpunar, R. (2016). Geodynamic studies in the Pieniny Klippen Belt in 2004-2015, *Acta Geodynamica et Geomaterialia*, 13(4), 351–361. DOI: 10.13168/AGG.2016.0017.

Zygmunt, M., Rajner, M. and Liwosz, T. (2016). Assessment of continental hydrosphere loading using GNSS measurements, *Reports on Geodesy and Geoinformatics*, 101, 36–53. DOI: 0.1515/rgg-2016-0020.