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Review paper

Research on Earth rotation and geodynamics in Poland in 2019–2022

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Abstract: This paper summarizes the activity of the chosen Polish geodetic research teams in 2019–2022 in the fields of the Earth rotation and geodynamics. This publication has been prepared for the needs of the presentation of Polish scientists' activities on the 28th International Union of Geodesy and Geodynamics General Assembly, Berlin, Germany. The part concerning Earth rotation is mostly focused on the estimation of the geophysical excitation of polar motion using data from Gravity Recovery and Climate Experiment (GRACE) and its follow-on (GRACE-FO) missions, and on the improvement of the determination of Earth rotation parameters based on the Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and Global Navigation Satellite System (GNSS) satellite techniques. The part concerning geodynamics is focused on geodetic time series analysis for geodynamical purposes and monitoring of the vertical ground movements induced by mass transport within the Earth's system, monitoring of the crustal movements using GNSS and newly applied Interferometric Synthetic Aperture Radar (InSAR), discussing the changes of the landslides and its monitoring using geodetic methods as well as investigations of seismic events and sea-level changes with geodetic methods. Finally, the recent research activities carried out by Polish scientists in the international projects is presented.

Keywords: time series analysis, deformation, Earth rotation, geodynamics, seismic events

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1. Introduction

In the research concerning Earth rotation and geodynamics carried out by Polish scientists in a period of 2019–2022 many research institutions were involved, namely (in the alphabetical order):

- AGH University of Science and Technology, Faculty of Mining Surveying and Environmental Engineering and Faculty of Geo-Data Science, Geodesy, and Environmental Engineering;
- Institute of Geophysics, Polish Academy of Sciences;
- Koszalin University of Technology, Faculty of Civil Engineering, Environmental and Geodetic Sciences;
- Military University of Technology, Faculty of Civil Engineering and Geodesy;
- Polish Air Force University;
- Polish Geological Institute – National Research Institute;
- Space Research Centre, Polish Academy of Sciences;
- University of Warmia and Mazury in Olsztyn, Faculty of Geoengineering;
- Warsaw University of Technology, Faculty of Civil Engineering and Faculty of Geodesy and Cartography;
- Wroclaw University of Environmental and Life Sciences, Faculty of Environmental Engineering and Geodesy;
- Wroclaw University of Science and Technology, Faculty of Geoengineering, Mining and Geology.

The main concern of the research related to the Earth rotation was the improvement of the geophysical excitation balance of the observed polar motion by the extensive use of different data products from Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) missions. Another important field of research was the estimation of global geodetic parameters, including those of Earth rotation and geocenter coordinates, from the analysis of observations from the satellite techniques.

The main concern of the research related to geodynamics was determination of the land motion with geodetic methods. The geodetic methods mainly used for these purposes were GNSS and InSAR with a focus of vertical land motion for determination of the relative sea-level changes as well as landslides and ground deformations caused by seismic tremors. Moreover, geodetic time series related to dynamic effects were carried out, paying attention to environmental loading sensed by GNSS and geocenter motion derived using SLR.

2. Earth rotation

In the period of 2019–2022 Polish researchers involved in the studies on Earth rotation took an active part in the programs of the international scientific organizations, such as the International Association of Geodesy (IAG), International Astronomical Union (IAU) and its Commission A2 Rotation of the Earth (Malkin et al., 2019), International Earth Rotation and Reference Systems Service (IERS). In particular, they made contributions to the activity of the IAU/IAG Joint Working Group on Theory of Earth Rotation and Validation (Ferrandiz et al., 2020), the IAG Inter-Commission Committee on "Geodesy for Climate Research" and its Joint Working Group C.1: Climate Signatures in Earth Orientation Parameters (http://iccc.iag-aig.org/joint-work-groups/215/), the IAU Division A Working Group on Time Metrology Standards (https://www.iau.org/science/scientific_bodies/working_groups/304/), and the IERS Working Group on the 2nd Earth Orientation Parameter (EOP) Prediction Comparison Campaign (https://www.iers.org/IERS/EN/Organization/WorkingGroups/Prediction Comparison/predictionComparison.html). The 2nd EOP Prediction Comparison Campaign, originally scheduled for 2021–2023, has been implemented and maintained by the Space Research Centre of PAS in Warsaw. A comprehensive summary of the research on Earth rotation will be given below.

2.1. Geophysical excitation of Earth rotation

The influence of continental water storage and cryosphere on polar motion (PM) excitation was investigated using different data products from GRACE and GRACE-FO missions. Such contribution was assessed by analysis of time series of GRACE/GRACE-FO-based hydrological and cryospheric angular momentum (HAM/CAM) (Nastula et al. 2019; Nastula and Sliwinska 2020; Sliwinska et al. 2020a, 2020b, 2021a, 2021b, 2022a; Sliwinska, 2022).

The achievements of 15 years of HAM/CAM research based on GRACE mission data were summarized in Nastula et al. (2019). HAM/CAM determined using GRACE solutions delivered by seven data centers were compared with hydrological angular momentum (HAM) estimates from hydrological models and climate data, and validated with time series of geodetic residuals GAO (sum of hydrological and cryospheric signal in observed PM excitation) taken as a reference.. Special emphasis was placed on the analysis of non-seasonal changes in PM excitation. A high correlation between GRACE-based HAM/CAM and the corresponding GAO series in this spectral band was found. The lack of realistic information about the ice cover may have contributed to the fact that the HAM series from hydrological and climate models were characterized by a much weaker correlation with the GAO than the series determined from gravimetric data.

HAM/CAM from the two most recent releases (RL05 and RL06) of the GRACE monthly solutions were compared by Nastula and Sliwinska (2020). The prograde and retrograde circular components in gravimetric excitation series were determined by applying complex Fourier transform, and analyzed in seasonal, non-seasonal short-term and non-seasonal long-term spectral bands. GRACE has been shown to be equally accurate in identifying prograde and retrograde oscillations in HAM/CAM. The highest correlation between HAM/CAM and GAO was found for seasonal and non-seasonal long-term oscillations.

A comprehensive assessment of HAM/CAM determined from the newest GRACE Level-2 solutions (degree-2 order-1 coefficients of geopotential, ΔC21, ΔS21) delivered by different data centers was conducted by Sliwinska et al. (2020a). Analysis of HAM/CAM in various spectral bands (oscillations with periods of 1000–3000, 450–1000, 100–450, and 60–100 days) and for several periods of GRACE measurements (data from the beginning, middle and end of experiment activity) showed that exploiting data from the University of Texas at Austin Center for Space Research (CSR) and the Institute of Geodesy of the Technical University Graz, Austria (ITSG) enables the greatest compatibility between HAM/CAM and GAO.

First estimates of HAM/CAM based on data from the novel GRACE-FO mission were analyzed and juxtaposed with GRACE results by Sliwinska et al. (2020b). The study showed that during the initial 19-month period of GRACE-FO measurements, the compatibility between HAM/CAM and GAO was in line with the accord achieved during the initial stage of GRACE activity, and superior to the corresponding compatibility achieved during the final months of GRACE operation. A detailed comparative analysis of HAM/CAM derived from three kinds of data from GRACE/GRACE-FO missions, i.e. ΔC21, ΔS21 geopotential coefficients, terrestrial water storage (TWS) maps based on coefficients of geopotential, and TWS maps obtained from mascon solutions, was conducted. These studies were continued in the subsequent paper (Sliwinska et al., 2021a), where the analysis was extended to include trends, seasonal and non-seasonal changes. A comparison with results from satellite laser ranging (SLR) was also provided. It was demonstrated that HAM/CAM series computed from GRACE/GRACE-FO mascon solutions were in higher consistency with GAO than the same series based on data from other types, particularly with regards to seasonal fluctuations. A detailed analysis of PM excitation derived from mascon data provided by different data centers proved that the choice of mascon solution has no noticeable impact on the level of compliance between HAM/CAM and GAO (Sliwinska et al., 2021b; Sliwinska, 2022). A summary of the research on the use of different types of GRACE and GRACE-FO data products to determine HAM/CAM was included in the PhD thesis of Justyna Sliwinska (Sliwinska, 2022). The thesis was defended with honors in April 2022.

In Sliwinska et al. (2022), several combined HAM/CAM series were computed from GRACE and GRACE-FO solutions using the three cornered hat (TCH) method, which allowed to minimize the noise in the combined series. Individual combined series were calculated as a weighted average of single solutions, in which the determined noise had an inverse relationship with the weights. A validation of combined series with the GAO as a reference showed that the proposed approach allows for increased compliance with GAO compared to exploiting single GRACE/GRACE-FO solutions.

The coefficients ΔC21, ΔS21 from temporal gravity field models based on kinematic orbits of several low-Earth-orbit satellites were exploited in (Sliwinska and Nastula, 2019) to determine HAM/CAM. The study revealed that the quality of HAM/CAM computed from data of this type is highly dependent on orbital altitude and inclination of satellite used. Models based on Swarm data were proved to be the most appropriate for analysis of PM excitation.

Historical simulations from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) were utilized to verify whether climate models offer plausible data for determining HAM (Nastula et al., 2022). Climate-based HAM series were compared with GAO, GRACE-based HAM/CAM and HAM obtained from the Land Surface Discharge

Model (LSDM). Overall, the agreement between GAO and HAM derived from CMIP6 was less than the previous agreement established with the GRACE scores, and the level of consistency varied depending on the model and oscillations considered. Nevertheless, some CMIP6 models may produce reliable HAM data, especially for annual variations.

Various datasets were used by Winska and Sliwinska (2019) and Winska (2022) to determine the geophysical excitation of PM. Winska (2022) focused on interannual oscillations in PM excitation calculated using different atmospheric and ocean models, GRACE/GRACE-FO data, and LSDM. Interannual oscillations in PM excitation were retained using the Multi Singular Spectrum Analysis method. The primary finding of the research indicates that adding hydrological considerations to the coupling of atmospheric and oceanic excitations enhances the consistency between geophysical and geodetic excitation in the interannual spectral band. However, the models still need some amelioration to reduce non-negligible differences between geodetic and geophysical estimates of PM excitation. Winska and Sliwinska (2019) focused on various estimates of GAO computed as differences between geodetic and joint atmospheric and oceanic excitation. It was shown that the choice of atmospheric and oceanic models has a considerable influence on amplitudes of GAO but affects the GAO phases to a much lesser extent.

Celestial pole offsets (CPO) predictions developed at the Jet Propulsion Laboratory (JPL) with the use of Kalman filter and smoother were evaluated by Nastula et al. (2020) for 90-day forecast horizon. The JPL predictions were compared with corresponding forecasts delivered by the IERS and with IERS observational data. JPL prediction errors have been shown to increase less rapidly with prediction day than errors of forecasts processed at IERS. When JPL predictions were employed instead of IERS predictions, the root mean square differences between forecasted and observed celestial pole offsets (CPOs) were reduced by 43% for dX and 33% for dY at 90th day of prediction.

2.2. Research on the methods of monitoring Earth rotation

Polish scientists contributed during 2019–2022 to the investigations concerning the methods of determination of global geodetic parameters including Earth rotation parameters and coordinates of the geocenter based on the satellite techniques: Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS).

Kosek et al. (2020) reported results of the determination and analysis of the common signals in the geocenter motion determined by GNSS, SLR, DORIS, and GRACE, with particular attention paid to seasonal components. The amplitude of the annual term was estimated at the level of 2 mm for the X coordinate, 2.4 to 3.6 mm for the Y coordinate and 2.8 to 5.6 mm for the Z coordinate components, while the semiannual term was found about 2 times smaller than the annual one. Detailed analysis revealed that the seasonal signals computed in the study were not stable in time and there were considerable divergences between the outcomes derived from various techniques.

The paper by Zajdel et al. (2020) discussed estimation of polar motion (PM) coordinates, rates of the pole coordinates, and Length-of-Day, commonly referred to as

Earth Rotation Parameters (ERP). The GPS, GLONASS, and Galileo daily estimates of ERP have been evaluated with a detailed search for system-specific signals. The ERP estimates have been compared to the IERS-C04 series and the products of IGS analysis centers. Zajdel et al. (2021a) derived the sub-daily polar motion series based on GPS, GLONASS and Galileo observations. The first empirical models of sub-daily PM have been developed with 38 main tidal harmonics, separately for each participating GNSS system and multi-GNSS solution. The solutions have been compared to other available sub-daily models, the Desai-Sibois model (based on hydrology), IERS 2010 Conventions model (mixed) and the Gibson model (from VLBI).

Yu et al. (2021) recomputed weekly time series of geocenter motion determined using SLR data. Observations from LAGEOS 1/2 satellites covering the period from 1994 to 2020 were processed with Bernese GNSS Software 5.2. For computing the GCM (Geocenter Motion) time-series, the network shift approach was used. To separate and research on the geophysical signal inside the series, the SSA method was applied. First two Principal Components (PCs) with large w-correlation were regarded as one periodic signal pair. With this method the substantial annual signal in X, Y and Z components were detected. Moreover, semi-annual oscillations were found to be significant in X and Z components. Moreover, other periodic signals were identified and explained by draconitic effects or/and aliasing of K1/O1, T2, and Mm tides. However, overlapping effects of the ground-track repeatability of SLR satellites data should also be considered. Systematic differences in X and Z components suggest a better distribution of SLR stations for recover the GCM in Y component.

Zajdel et al. (2021b) searched for common patterns in geocenter coordinates derived from GPS, GLONASS, and Galileo observations. Three years of data collected at the globally distributed stations were considered. They tested all individual solutions as well as combinations of data from the aforementioned GNSS constellations. They proved that using a box-wing model a priori information on forces related to the solar radiation pressure (SRP) acting on satellites mitigates most of the spurious signals in geocenter coordinates originated from the different navigation satellite systems. They concluded, that combination of Galileo and GPS solutions take the lead to the best geocenter estimates.

Drozdzewski et al. (2019) investigated the problem of how modeling of horizontal gradients in the SLR technique influences the determination of PM coordinates and Length-of-Day. So far, SLR was the only satellite geodesy technique in which the asymmetry of the atmosphere has been not accounted for in modeling the tropospheric delay. The model of horizontal gradients, developed in the paper, improves the consistency of SLR-derived and the IERS C04 PM series by reducing the offset for the pole coordinates by about 20 microarcseconds (μas).

The paper by Strugarek et al. (2019) discusses the determination of global geodetic parameters, including pole coordinates and UT1-UTC from the laser ranging to LEO satellites, Sentinel-3A and 3B as well as from the combined LAGEOS-1/2 and Sentinel-3A/B solutions. Sosnica et al. (2019) considered the estimation of global geodetic parameters including pole coordinates and Length-of-Day by the use of SLR observations to Galileo, GLONASS, BeiDou, GPS, and QZSS. The ERPs were derived by applying the approaches with the orbits based on the SLR observations and with orbits based on microwave GNSS observations. Finally, the ERP solutions based on the observations of LAGEOS-1/2 were compared to the GNSS-only solutions.

Bury et al. (2021a) applied the combination of SLR and GNSS observations for the determination of precise Galileo orbits and geodetic parameters including the Length-of-Day. The secular drift which is present in cumulated Length-of-Day series from GNSS-only solutions could be significantly reduced when using the combined GNSS-SLR solution with an equal weighting of GNSS and SLR observations. In the paper Bury et al. (2021b) the integration of SLR and GNSS techniques onboard the Galileo and GLONASS satellites was used for different realizations of the terrestrial reference frame. The paper investigated how the minimum no-net-rotation and no-net-translation network constraints influence the estimation of station coordinates and Earth rotation parameters including Length-of-Day variation.

Zajdel et al. (2019a) investigated the so-called GNSS network effect, the question of how the inhomogeneous distribution of GNSS stations influences the estimation of global geodetic parameters. In addition, the authors verified the influence of the network constraints and the realization of the origin of the terrestrial frame on the estimation of the pole coordinates and Length-of-Day variation. When accounting for the geocenter motion in GNSS solutions, the pole coordinates are changed by about 12 µas (in a sense of Weighed Root Mean Square – WRMS) and Length-of-Day by 1–2 µs. Zajdel et al. (2019b) addressed the problem of how the selection of SLR stations for the realization of no-net-rotation constraints influences the accuracy of estimation of the pole coordinates and Length-of-Day variation in the solutions based on the SLR observations to LAGEOS-1/2.

Polish researchers continued during 2019–2022 investigations on the application of the large Ring Laser Gyroscope (RLG) for continuous monitoring of variations in Earth rotation. Tercjak et al. (2020) studied in detail the impact of solid Earth tides, ocean tidal loading and non-tidal loading phenomena (influences of the atmosphere and continental hydrosphere) on the main RLG observable, the Sagnac frequency. They also discussed potential causes of existing discrepancies between the data reduced with the use of tiltmeter measurements and the data reduced with model-based signal. Recently, a four-component, tetrahedral laser gyroscope array ROMY has been constructed at the Geophysical Observatory Fuerstenfeldbruck near Munich (Gebauer et al., 2020). Preliminary analysis of the initial measurements of ROMY (ibid.) demonstrated that reconstruction of all coordinates of the Earth rotation vector over the period of six weeks and the sub-arcsecond spatial resolution is possible. Tercjak (2021) concluded research on the interpretation of RLG observations by defending her PhD Thesis with excellent note.

2.3. The second Earth Orientation Parameters prediction comparison campaign

Predictions of EOP are needed for different operational activities like navigation of deep-space satellite missions or global satellite positioning and navigation systems. The first EOP Prediction Comparison Campaign (EOP PCC), run by Vienna University of Technology and Space Research Centre PAS in Warsaw (Kalarus et al., 2010, https://doi.org/10.1007/s00190-010-0387-1), considerably contributed to the assessment of different EOP prediction capabilities. The current need for improved EOP predictions prompted the establishment of the second EOP PCC under the auspices of the IERS. As in case of the 1st EOP PCC, the current campaign is again managed by SRC PAS with support from the GFZ Potsdam. So far, 28 institutions from 9 countries registered to the 2nd EOP PCC, and over 60 researchers have been delivering EOP predictions. The paper by Sliwinska et al. (2022) provided overview of the 2nd EOP PCC, including preliminary comparison of the IERS 14 C04 EOP reference series and selected EOP prediction solutions; see also the official campaign website https://eoppcc.cbk.waw.pl/ (accessed 29.03.2023). A more detailed validation of selected short-term forecasts of the universal time UT1-UTC and the length-of-day LOD collected by the EOP PCC was reported by Kur et al. (2022). Particular attention in this evaluation is paid to the forecasting methods based on the Effective Angular Momentum predictions.

One Polish research group from the AGH University of Science and Technology, Krakow, has been delivering EOP predictions to the 2nd EOP PCC. Michalczak et al. (2022) computed the ultra-short-term and short-term (up to 15 and 30 days into the future, respectively) predictions of polar motion coordinates (PMx, PMy) and LOD using geostatistical method of kriging and autoregressive integrated moving-average (ARIMA) method. Detailed description of the kriging-based predictions of polar motion can be found in Michalczak and Ligas (2021), while the application of kriging for LOD predictions was discussed by Michalczak and Ligas (2022). The authors concluded that the kriging-based short and ultra-short term prediction applied to both PM and LOD may compete with other existing prediction algorithms. Michalczak et al. (2022) stated also that ARIMA-based prediction is more accurate than kriging-based one for very short term prediction.

3. Geodynamics

3.1. Geodetic time series analysis

The main task of geodetic time series analysis is to discover significant and/or unknown oscillations inside the series, as well as to study the noise of the residuals after the deterministic model is taken into account.

Klos et al. (2020a) compared 6 different approaches to extract seasonal signals from the GPS-derived position time series. They analyzed results obtained using commonly applied Least Squares Estimation (LSE), Wavelet Decomposition (WD), Moving Ordinary Least-Squares (MOLS), Kalman Filter (KF), Singular Spectrum Analysis (SSA), and newly applied Adaptive Wiener Filter (AWF). The advantages or disadvantages of each method were described with an emphasis on Power Spectral Density (PSD) appearance after the extraction. First, the tests were performed on the synthetic database, created upon certain assumptions concerning seasonal signals, then real displacement time series reduced by environmental loadings were analyzed. The studies were followed by noise analysis using Hector software because the main purpose of the study was to investigate the use of such a method of eliminating seasonal curves that changes the nature of stochastic part of the series as minimum as possible. The SSA and AWF were found as appropriate methods that meet this condition to the greatest extent.

Klos et al. (2020b) adopted the GRACE-assimilating land surface model (CLM-DA) for separating the deterministic part of GPS (Global Positioning System) derived position time series from noise. They used data from 221 continuously operating stations of the EUREF (European Reference Frame) Permanent GNSS Network (EPN) located in Europe. The navigational data were processed at the ASI (Italian Space Agency) using the Precise Point Positioning (PPP). They confirmed, that a reduction of up to 60% of annual and semiannual amplitudes in position time series reduced by atmospheric and non-tidal loading comes from considering CLM-DA model in the series. The remaining part may come from draconitics or aliasing, being the systematic errors of GPS. They compared the results obtained to those recovered from the classical approach using harmonic functions, however, the latter cannot provide physical interpretations of the results since it was difficult to decouple each individual physical process that contributed to seasonal changes. Insufficient consideration of seasonal signals may induce an artificial change of the stochastic parts of the series, and resulting in mis-determinations of uncertainties of determined trends or amplitudes of seasonal signals. They concluded, that in the view of current and future International Terrestrial Reference Frames (ITRFs), including loading effects based on the GRACE data may contribute to a better realization.

Klos et al. (2021) examined the sensitivity of the GPS for environmental loadings. They used vertical displacements from 100 permanent stations being processed at the Nevada Geodetic Laboratory in the PPP mode. All selected stations were located in continental Eurasia with a minimal time span of 5 years each. Non-tidal loading models were delivered by the Earth-System-Modeling Group of Deutsches Geo-ForschungsZentrum (ESMGFZ). Non-tidal atmospheric (NTAL), non-tidal ocean (NTOL), hydrological loadings (HYDL), and barystatic sea-level changes (SLEL) were interpolated to GPS positions from the gridded crustal displacements using bicubic interpolation method. They used Wavelet Decomposition (WD) with a Meyer wavelet which enables signals to be acquired at various temporal resolutions. The analyzed data allowed the extraction of nine levels of details, and the final approximation. Using Pearson correlation coefficients between GPS-derived vertical displacements and displacements predicted from environmental models for different levels of decomposition concluded that improper recognition of the loading impact may significantly bias the determination of the velocities and amplitudes of the seasonal signals. Finally, they studied the impact of non-tidal loading on character of the GPS noise, noting that different loading effects have different impacts on the stochastic parts of the GPS-derived position time series.

Kaczmarek (2019) focused on the analysis of geophysical signal, in particular, the crustal deformation of the Earth induced by HYDRO, NTAL, and NTOL (non-tidal ocean) loads as well as the influence of these geophysical signal on the coordinate of permanent GNSS stations in Central Europe. The author analyzed time series of coordinates from BOR1, LAMA, WROC, PENC, GRAZ, GOPE, POTS, and JOZ2 permanent GNSS stations obtained from the CODE (Center for Orbit Determination in Europe). In order to identify whether deformations from geophysical signal on these stations are globally-or locally-related, he analyzed the correlation between GNSS time series coordinates of station selected and the Earth's surface deformations resulted from the aforementioned geophysical signal. Moreover, the author performed a coherence analysis to investigate whether similar seasonal deformations are observable within the GNSS time series coordinates of the GNSS stations investigated. He concluded that the crustal deformations of the Earth induced by NTAL have the major impact on temporal variations of GNSS time series coordinates. On a global scale, geophysical signal exhibited a clear impact on the Up component of GNSS time series coordinates analyzed. The horizontal components of GNSS coordinates may substantially be affected by local conditions surrounding the GNSS station, rather than geophysical signal. On the basis of coherence analysis, he found totally various seasonality in the North, East and Up components of GNSS stations investigated.

Karkowska and Wilde-Piorko (2022) presented a new concept of using the recordings of tidal gravimetric for, reliably, determining the Earth's structure in a regional scale. This concept is based on measuring and inversing the dispersion's curve of Rayleigh Surface Waves (RSW) of intermediate-periods (i.e. period 10–180 s). They analyzed time series data from tidal gravimeters and co-located broadband seismometers. These data were obtained from three gravimetric stations (two in Belgium and one in Germany) with estimated transfer functions (TF) and co-located with seismic stations. They proposed the deconvolution of the TF for pre-processing of gravimetric data. They also determine group velocities of fundamental-mode of RSW recorded by tidal gravimeters and co-located seismometers. They also applied a linear inversion algorithm to retrieve S-wave velocity models for Central and Southern Europe. As a conclusion, they reported that tidal gravimeters provide very reliable recordings of period 10-180 s surface waves, as good agreement between the outcomes from gravimeters and seismometers can be obtained. They also illustrated the potential of gravimeters, especially the superconducting ones, and seismometers for the determination of the Earth's structure on a regional scale.

Karkowska et al. (2022) analyzed the earthquake's tidal gravimeters recordings in the period of 10–1000 s. Three observatories, namely Membach and Rochefort in Belgium as well as Black Forest in Germany, in Western and Central Europe were chosen as a case study. They investigated over 10,000 traces of worldwide earthquakes recorded by tidal gravimeters and co-located very broad-band and very broad-band seismometers. The results obtained by them indicated that earthquakes' gravimetric recordings in the period of 10–1000 s and the corresponding ones from seismic data agree very well. The coefficient of correlations between the results obtained from seismometric and gravimetric data are ranging from –0.67 to –0.86. After elaborating the transfer function scheme, those coefficients of correlations became –0.9975 ± 0.0005. Moreover, they illustrated that for determining the greater depths of Earth's mantle structure, the recording of tidal gravimeters provides complementary information to their respective ones obtained from seismometers.

Rosat et al. (2020) compared time series of vertical displacements determined from GPS observations and gravity changes from superconducting gravimeters (SG). Due to the similar driving mechanism combining vertical and gravity changes, the transfer function of the Earth related to its rheological properties at various time-scales was able to be determined. The navigational data from 117 globally distributed permanent GPS stations were processed using GAMIT/GLOBK software including non-tidal atmospheric and oceanic effects with 9 of them being selected to the final analysis. Concerning SG observations, they used Level-3 products from the International Centre for Earth Tides (IGETS) cleaned from gaps, spikes and significant steps. For consistency, the same corrections for geophysical effects as in the case of GPS were implemented. With the use of these data, they determined the spectral coherency as well as gravity-to-height ratio, which is a real part of the transfer function between gravity reduced to the Earth's surface and height changes. They concluded that this ratio varies between analyzed stations significantly (from –5 to +1.1), which indicates a strong dependence on local mass fluctuations.

Ray et al. (2021) analyzed the correspondences between the annual oscillations of deformations determined with GPS and GRACE data. As a case study, they chose Nepal Himalaya and North-East India. This region is subjected to significant annual changes due to the monsoons. Thirty six GPS permanent stations as well as release 05 (RL05) GRACE-based Global Geopotential Models (GGMs) were chosen. Daily position time series expressed in ITRF2008 were obtained from navigational data processed using GAMIT/GLOBK software. The temporal variations of Equivalent Water Heights (*EWH*) were provided by the NASA MEaSUREs (Making Earth Science Data Records for Use in Research Environments) program with a root data in the form of spherical harmonics coefficients of RL05 GRACE-based GGMs. The seasonal deformations were determined using the CATS (Create and Analyse Time Series) software. Their results showed that almost 90% of the analyses series revealed positive correlation between seasonal deformations determined using both satellite methods in North component. Finally, they estimated the median value of Nash-Sutcliffe model Efficiency (NSE) to –0.01 and +0.28 for East and North components, respectively. This research confirmed, that seasonal horizontal deformations in the investigated area were mostly driven by local tectonics.

Nistor et al. (2021) investigated the seasonal signals, i.e. annual and semiannual oscillations, within the GNSS position time series. They considered the correlations between different types of geophysical events, namely volcanic activity, landslides, and earthquakes. The main aim of the research was to explore variation in amplitudes of the mentioned seasonal signals. The overlapping Hadamard variance (OHVAR) was applied to search for the presence of random walk and flicker noise. Moreover, the non-stationarity of the GNSS position time series was performed using continuous wavelet transform (CWT).

Lyszkowicz et al. (2021a) used the GipsyX software to investigate the position time series of the GNSS permanent network in Poland. They selected the time span of GNSS data used, covering the period from 2011 to 2018. They concluded that the velocities of the Polish permanent GNSS stations can be determined with an accuracy of 0.01 mm/yr.

Baselga and Najder (2019) presented an automated algorithm for the analysis of the position time series of the EPN stations neighboring an earthquake epicenter. This tool was named ADDquake (Automated Detection of Discontinuities in EPN stations due to earthquake events) which was developed using App Designer tool of Matlab release 2020b. Earthquakes data from the U.S. Geological Survey and GNSS time series coordinates provided for EPN stations were used as input for the ADDquake. As examples, the authors considered two significant earthquakes that occurred in Europe: L'Aquila (Mw 6.3) and Lorca (Mw 5.1) which took place on 6 April 2009 and on 11 May 2011, respectively. With the use of the ADDquak, they presented the analysis of time series of GNSS coordinates from ALBA, ALAC, and ALME permanent GNSS stations covering the period before and after these earthquakes. The authors made the ADDquak freely available for users via the website.

On the basis of SLR, DORIS and VLBI (Very Long Baseline Interferometry) station positions and velocities in ITRF2008, Jagoda et al. (2020a) determined the motion parameters of six chosen tectonic plates, i.e. the position of pole rotation (Φ, Λ) and the angular rotation velocity (ω). The least squares sequential adjustment approach was implemented to analyze the data from each technique (i.e. SLR, DORIS and VLBI) separately. The agreement between Φ, Λ and ω determined by them and the corresponding ones from the APKIM2005 (Actual Plate Kinematic and Crustal Deformation Model 2005) IGN (Institute of National Geography, France) model was at the level of 2° or better. However, they reported that the location of SLR, DORIS and VLBI stations is essential for the reliable resolve of Φ, Λ and ω.

Jagoda and Rutkowska (2020a) estimated and analyzed Eurasian plate motion and its parameters, i.e. Φ, Λ and ω, using ITRF2014 velocities and positions of 120 GNSS stations. For this purpose, four scenarios, with 30 GNSS stations each, were created considering the stable region and the boundary of the Eurasian plate. The results obtained revealed good agreement between estimated values of Φ, Λ and ω from these four scenarios, as for Φ and Λ the maximum differences were at the level of 0.31° and 0.24°, respectively, while there were no differences for ω. When analyzing all selected GNSS stations (i.e. 120 GNSS stations), they found that the estimated Eurasian plate motion parameters were $54.81^\circ \pm 0.37^\circ$ for Φ, $261.04^\circ \pm 0.48^\circ$ for Λ, and 0.2585°/Ma±0.0025°/Ma for ω which is consistent with the corresponding values published in the literature, e.g. the APKIM2005 IGN model.

Jagoda and Rutkowska (2020b) investigated the use of VLBI measurements for resolving of Φ, Λ and ω. For this purpose, velocities of positions in the ITRF2008 for VLBI stations distributed within six tectonic plates, i.e. EUAS, AFR, AUS, North NOAM, PACF and ANTC, were analyzed using sequential least squares adjustment procedure. The values Φ, Λ and ω determined from VLBI measurements were compared with those obtained from the APKIM2005 model. Overall, despite the inhomogeneous distribution of VLBI stations within major tectonic plates investigated, they found good consistency (i.e. discrepancies were within the level of 2°) between Φ, Λ and ω obtained from VLBI and APKIM2005 model.

Jagoda (2021) focused on the determination and analysis of Φ, Λ and ω of five selected tectonic plates. The author determined Φ, Λ and ω using ITRF2014 GNSS velocities stations positions. The author also proposed and applied the sequential least squares adjustment method to estimate Φ, Λ and ω. Then, those Φ, Λ and ω were compared with those from the No-net-rotation model of geologically current plate motions (i.e. NNR-MORVEL56) and the ITRF2014-PMM geodetic model. The results obtained indicated that the difference between parameters of the plate motion (i.e. Φ, Λ and ω) determined using the sequential least squares adjustment method and the corresponding ones obtained from the NNR-MORVEL56 and/or ITRF2014-PMM do not exceed the level of $\pm 3.88°$ for Φ, $\pm 6.95°$ for Λ, and $\pm 0.022°$/Ma for ω. The sequential method proposed by the author was beneficial to optimize the data volume required to obtain a stable solution as well as to identify stations that can corrupt the solution's quality and amplify the errors of the Φ, Λ and ω estimated.

With the use of SLR data from LAGEOS-1/2 satellites, Jagoda and Rutkowska (2019a) estimated the values of Love and Shida numbers (h_2 and l_2) which are connected to the tidal variations at the Polish SLR station located in Borowiec. These SLR data covered the period from January 1, 1999 to January 1, 2019. The sequential adjustment method was applied to estimate h_2 and l_2. They found that the values of h_2 and l_2 were equal to 0.7308 ± 0.0008 and 0.1226 ± 0.0003, respectively, which were significantly different (i.e. the difference reach up to 0.1230 (ca. 20%) for h_2 and 0.0379 (ca. 44%) for l_2) with the respective ones from the International Earth Rotation and Reference Systems Service (IERS) and from the previous research conducted by other scholars as well. The authors ascribed these differences to the length of data used in previous research (i.e. 2 years of SLR data) and the one used by them. Moreover, the coordinates of Borowiec station were determined using two sets of h_2 and l_2: (1) from Jagoda and Rutkowska (2019a) and (2) from the IERS. The authors found that the differences between X, Y, Z components determined using these different sets of h_2 and l_2 were –3.5, 3.3 and 4.2 mm, respectively. Furthermore, following the same procedure presented in Jagoda and Rutkowska (2019a), h_2 and l_2 for Riga SLR station were estimated using LAGEOS-1 and LAGEOS-2 satellite data covering the period of 01.01.2004-01.01.2019 (Jagoda and Rutkowska, 2019b). The results obtained by them revealed that the values of h_2 and l_2 for Riga SLR station were 0.6891 ± 0.0009 and 0.1043 ± 0.0004, respectively, which were differ by 0.0813 for h_2 and 0.0196 for l_2 from the values provided by the IERS. The differences between X, Y, Z coordinates determined with the use of h_2 and l_2 obtained by them and corresponding coordinates obtained from the ITRF2014 were 4.4, 4.7 and 6.9 mm, respectively.

Jagoda et al. (2019) assessed the effect of using different values of h_2 and l_2 on the determination of the coordinates of the selected SLR stations. With the use of SLR data from LAGEOS-1 and LAGEOS-2 satellites covering the period January 01, 2008-January 01, 2018, they estimated the values of h_2 and l_2 at these selected SLR stations. Then, on the basis of ITRF2014, the coordinates of SLR stations investigated were determined using the h_2 and l_2 estimated by them and the respective ones from the IERS. The comparison between the determined coordinates indicated that the use of different values of h_2 and l_2 can result in coordinate differences from –2.3 to 3.3 mm for X, from –2.7 to 4.1 mm for Y, and from –3.2 to 4.9 mm for Z coordinate.

Jagoda et al. (2020b) focused on the determination and analysis of local h_2 and l_2 values for Mount Stromlo and Yarragadee SLR stations. Data from LAGEOS-1, LAGEOS-2, STARLETTE, and STELLA covering the period January 01, 2014-January 01, 2019, were used. The authors implemented the sequential method to determine h_2 and l_2. Thereafter, the authors compared these h_2 and l_2 determined with the corresponding ones from the IERS. They reported that l_2 cannot be reliably determined from STAR-

LETTE and STELLA satellites data. On the biases of the combination of LAGEOS-1/2 satellites data, they found that for station Yarragadee were 0.5756 ± 0.0005 for h_2, and 0.0751 ± 0.0002 for l_2, which were differed by 5% and 11% from the corresponding values from the IERS, respectively. The combination of STELLA and STARLETTE satellites data indicated that h_2 was equal to 0.5742 ± 0.0015, and it differed by 6% from h_2 provided by the IERS. For station Mount Stromlo, the h_2 obtained by combining STELLA and STARLETTE satellites data was 0.5618 ± 0.0017, and it differed by 7% from the respective one of the IERS, while local h_2 and l_2 determined by combing LAGEOS-1/2 satellites data were 0.5601 ± 0.0006 and 0.0637 ± 0.0003, respectively, and there were differed by 8% for h_2 and 0.021 25% for l_2 from the respective ones given by the IERS. Moreover, they compared the coordinates (X, Y, Z) of Mount Stromlo and Yarragadee sites determined with the use of these local and IERS h_2 and l_2. The results of these comparisons indicated that using different estimates of Love and Shida numbers can induce coordinates discrepancies of approx. –3.5 ± 0.3 mm, 4.5 ± 0.5 mm and 5.3 ± 0.2 mm for X, Y and Z coordinates, respectively.

Cegla et al. (2020) investigated the use of a simplified approach based on: GNSS data and weather data from a numerical model and in-situ observations, to detect the volcanic plume over the area of Sakurajima volcano in Japan. Within the activity period of the volcano (i.e. during October 2014), zenith tropospheric delays (ZTD) were estimated using GNSS data from the a network in Sakurajima area. Moreover, ERA5 atmospheric data as well as eruption information and weather observations were utilized. They found that semblance analysis (i.e. time series analysis) of ZTDs from GNSS, ray-traced ERA5 and weather data were appropriate to reveal the effect of volcanic plumes. In a conclusion, the analytic approach implemented by them can reliably determine the volcanic plume activity over the area of Sakurajima.

Godah (2019) developed an open source scientific software, named IGiK-TVGMF, for the determination of temporal variations of gravity/mass functionals (TVGMFs) in the Earth's system using GRACE data as well as for analyzing and modelling TVGMF. This software was developed within the project entitled (European Plate Observing System-Poland)- task Gravimetric Observations Research Infrastructure Centre). The IGiK-TVGMF software was developed using the MATLAB R2017a App Designer. With the use of this software, thirteen TVGMFs can be computed using monthly RL05 GRACE-based GGMs developed by seven different computation centers. The results obtained from IGiK-TVGMF software were validated using the corresponding ones from the ICGEM (International Centre for Global Earth Models) interactive online tool and GRAVSOFT scientific software. This validation indicated good agreement, e.g. sub-mm in terms of temporal variations of geoid height, between TVGMFs values from IGiK-TVGMF software and the respective ones from GRAVSOFT and ICGEM interactive online tool.

3.2. Monitoring of the crustal movement with geodetic methods

For more than 20 years, GPS technology has been used effectively to investigate the dynamics of the Earth. Lately, the InSAR (Interferometric Synthetic Aperture Radar) technique has also been a prominent source of information to investigate the deformations of both the Earth's surface and man-made structures.

Bogusz et al. (2019) proposed a set of recommendations concerning GNSS-derived position time series to properly investigate dynamic effects of the Earth's crust. They perform a complex analysis of 469 European GPS vertical position time series from the Nevada Geodetic Laboratory (NGL) obtained through the PPP method. Sixty two of them were identified to have significant non-linearities, as a consequence the polynomial trend model (PTM) has been applied to properly describe the deterministic part. The ICE-6G_C (VM5a) and ICE-5G (VM2) models of Glacial Isostatic Adjustment (GIA) were used for comparison purposes. The vertical time series were then analyzed using Maximum Likelihood Estimation (MLE) method. For the stochastic part, the combination of white and power-law noise was assumed as optimal. Spectral indices were found to vary between –1.2 and –0.3, while maximum amplitude of the power-law noise was equal to 28.0 mm/yr$^{-k/4}$. Owing to this 297 out of 469 stations were found to have significant vertical rates and further analysis might be required. Comparison with present-day uplift predicted by the GIA models showed the differences reached 0.5 mm/yr on average. The assumptions they proposed should be employed to perform the GIA-oriented comparison, however, method is universal and applicable to the series recorded at each locations with strong geodynamical effects.

In recent years, the Military University of Technology (MUT) and Polish Geological Institute – National Research Institute (PGI-NRI) continued research on the neotectonics of Poland. Jarosinski et al. (2022) investigated the possibility of using geodetic satellite measurements to assess the magnitude of contemporary stress in an area of northern Poland. This is a relatively stable area, located on the East European Platform, the Paleozoic Platform and the Teisseyre-Tornquist Zone separating them. This study used GPS data from 63 stations of the ASG-EUPOS (Active Geodetic Network of the European Position Determination System) network, of which 35 remained after filtering. The strain rate was estimated using the least square collocation (LSC) method. The results published in this paper illustrated a high correspondence between the directions of the main strain rate and the stress directions determined from the boreholes. The main problem that arose in the study was the accuracy of the estimated strain rate. The strain rates obtained, ranging from 4.3×10^{-17}/s to 8.7×10^{-17}/s, are generally consistent with the strength of the lithosphere for each block. Unfortunately, the estimated strain rate error was between 4×10^{-17}/s and $10\text{x}10^{-17}$/s, depending on the local density of ASG-EUPOS stations. Thus, it may seem that the estimated deformations are not reliable. However, they were consistent with stress directions as well as strain magnitudes from other works, tectonic history and the current stress regime for considered area. The authors hypothesized that if station velocities exhibit some random residual instability, but are limited due to the prior filtering used, then with a model smoothing method (such as LSC method), this randomness can sufficiently be reduced which leads to a clear illustration of the tectonic signal.

Ligas et al. (2019) presented a method for approximating the planar deformation that consists of components of rotation and tensor. This method was based on the distance-weighted affine transformation model performed on regular and irregular grids generated with the use of the Swirl-like and Barrel-Pincushion deformations. The grid's area size selected was 500 m^2. The outcomes of this method were compared with the corresponding ones obtained using a simplified decomposition method. The results obtained by them indicated a good performance of the proposed method. For example, for ca. $\geq$ 90% of the grid's points, good agreements (e.g. measurements error range from zero to ca. ±0.0002, and correlation coefficients range from 0.82977 to 0.99925) between true and estimated strain components were obtained. However, the authors reported that unreliable results can be obtained from this simple method when there were small strain tensors and non-negligible rotation components.

Jozkow et al. (2021) assessed the prospect of Unmanned Aerial Systems (UAS) data: aerial photos and Light Detection and Ranging (LiDAR), for monitoring the terrain vertical deformations caused by underground mining in the Upper Silesia region. The UAS data used in their research were collected via three campaigns conducted with the period 2018–2019. Methods based on point cloud analysis and DTM of Difference (DoD) were implemented to handle these data. The terrain vertical deformations from ALS (Airborne Laser Scanning) data acquired in 2011 were also evaluated. They found a subsidence of 33 cm for the period 2011–2018, which results in a subsidence of ca. 5 cm/yr. For the period 2018–2019, depending on the investigated area within the Upper Silesia region, a subsidence of ca. 5 to 15 cm can be obtained.

Vertical deformations of the Earth's surface (VDES) at 25 sites of ASG-EUPOS in south-eastern Poland were studied by Godah et al. (2020a). For the period 2008–2013, monthly VDES were compued from: (1) release 06 (RL06) GRACE-based GGMs using the IGiK-TVGMF software, and (2) daily GNSS data processed with the GAMIT/GLOBK software. Then, comparisons between those monthly vertical deformations were conducted. The results obtained revealed good agreement between monthly VDES determined from GRACE data and the corresponding ones from GNSS data. Standard deviations of differences between these VDES are in ranging from 2.6 to 5.7 mm, while they are correlated to each other with corr. coef. range from 0.60 to 0.90.

Godah et al. (2020b) investigated the orthometric/normal heights change ($\Delta H/\Delta H*$) over 24 large river basins using GRACE data. These $\Delta H/\Delta H*$ were computed by combining time-varying of geoid/quasigeoid heights and ellipsoidal height changes estimated using the RL06 of monthly GRACE-based GGMs, load Love numbers based on PREM (Preliminary Reference Earth Model), and the IGiK-TVGMF software. The authors found that for the Amazon basin, $\Delta H/\Delta H*$ reach 8 cm, while $\Delta H/\Delta H*$ do not exceed ±1 cm in the case of the Orange basin. They also investigated the relation between the time-varying of equivalent water thickness (ΔEWT) and $\Delta H/\Delta H*$ over those 24 large river basins. They found that strong correlations between $\Delta H/\Delta H*$ and ΔEWT in 87% of river basin areas investigated with 45% reveal corr. coef. range from –0.97 to –0.70. Furthermore, they analyzed $\Delta H/\Delta H*$ determined over Amazon and Orange using the PCA/EOF (Principal Component Analysis/Empirical Orthogonal Function) method. The results of this analysis indicate substantial differences for $\Delta H/\Delta H*$ within subareas of the same river basin (e.g., ±2 cm in the Amazon basin). These substantial differences are highly dependent on different spatio-temporal hydrological phenomena (e.g. the precipitation, rainfall seasonality floods, and droughts, as well as the location of the downstream and upstream areas of the river basin) of the entire river basin.

Szafarczyk (2019a) discussed the landslides on the slopes of the Swinna Poreba dam reservoir in Poland. The author reported that heavy rainfall in May 2010 was one of the main reasons for the ongoing landslide that affected an area of 0.3 hectares. The magnitudes of landslides on the main slopes were estimated to 0.5–1.5 m, and do not exceed 0.5 m within the area of headwaters. In general, these landslides were located on the eastern side of the stream. The geological structure, erosional properties of the stream, and slope of the valley in addition to the rainwater were also contributed significantly to landslides on the slopes of the Swinna Poreba dam. Overall, she emphasized the need for ensuring the entire slopes of the stream in the area of the Swinna Poreba dam and their impedance for mass transport within the area of this dam.

Szafarczyk (2019b) focused on the use of GPS and GBInSAR (ground-based radar interferometry) technology for investigating the impact of kinematic mass variations on the determination of landslides. The author aimed to study the landslides placed in the selected open-pit mining area in Poland. She utilized 38 radarograms from GBInSAR data, as well as seventeen positions of points obtained using GPS RTK (real-time kinematic) technologies and total stations. The author illustrated that the determination of the landslide trend can be improved by eliminating the non-linear landslide in a 24-hour period. She also reported the advantage of GBInSAR technology for mentoring landslides, particularly, over inaccessible areas.

Szafarczyk et al. (2019) focused on the application of measurements using gyroscope in underground mining, in particular, the mines of Zofiowka and Borynia in Katwit. The orientations between these two mines as well as between each individual mine with respect to two GPS stations of the ASG-EUPOS network were obtained using the Sokkia model SX1 gyroscope. For this purpose, also angular-linear measurements as well as static GPS measurements and spirit levelling were also used. The authors compared the topographic azimuths of basic orientation obtained from strict levelling and the corresponding ones measured by the gyroscope. The results of these comparisons indicated that the differences between these topographic azimuths were in the range from -14^{cc} to 5^{cc}. Overall, they concluded that first results obtained from the application of gyroscope measurements in Zofiowka and Borynia in Katwit mines were very promising.

Blachowski et al. (2019) concentrated on the determination of the surface deformations for the period 1995–2010 over the Walbrzych Coal Basin (WCB) in south-west Poland. They used the European Remote Sensing satellite 1/2 (ERS 1/2) and Environmental Satellite (Envisat) radar data and the persistent scatterer InSAR (PSInSAR) method. They also analyzed the ground deformations induced by hydrogeological change. They utilized geological and mining data over this coal basin. The results obtained indicated a surface uplift of can reach +8 mm/yr for the period until 2002. This uplift can be caused by the process of the underground water table within the basins associated with the three adjacent coal fields. From 2002–2010 when the underground water table is stabilized, the ground deformations reach ±5 mm/yr, over WCB. These ground deformation activities are associated with the ground reaction to long-term shallow and deep mining. Overall, the results obtained by them illustrated the processes complication of ground deformations in post-mining areas. They emphasized the usefulness of SAR techniques to gain valuable historical information about ground deformation over mining areas and their relation with hydrological mass change.

Becek et al. (2021) focused on the use of freely available global digital elevation models (DEMs) and a simplified statistical method for determining the land deformations that resulted from mining and geodynamic processes over the central northern part of Turkey. They implemented the SBAS (small baseline subset) InSAR method to determine mining-induced land deformation, as well as to split the deformation and no-deformation over the region investigated. Moreover, they computed the difference between elevations from the recent Shuttle Radar Topography Mission (SRTM) and TanDEM-X DEMs. The results obtained reveal constant estimates of land subsidence from the SBAS InSAR method (–0.041 m/yr) with the one obtained from the differences between SRTM and TanDEM-X DEMs (–0.034 m/yr). They concluded that the approach based on the differences between DEMs of high accuracy can sufficiently be used to recognize land deformation caused by mining activities from the ones induced by geodynamic processes.

In order to analyze the transportation of rock raw materials and its effect on regional planning and development over the Lower Silesia, Blachowski and Buczynska (2020) assessed the scale of rails and roads used to transport the rock raw materials. They also proposed and applied multi-criteria scoring scheme to identify and select the operations related to the transport of the rock raw material that required to change road to rail or combined road and rail forms of transport. They reported that 70% of active mine productions were transported via road transports, which put substantial pressure on the road infrastructure condition, transport safety, as well as the environment surrounding these roads.

To identify the weaker areas that are susceptive to secondary land deformation and mine collapse, Blachowski et al. (2022) created a digital inventory of post-mining workings and mapped the underground rock mass. As a unique postglacial environment, the Friendship of Nations-Babina coal mine in western Poland was selected as a study area. With the use of GIS (Geographic Information System) data, a three-dimensional underground workings database from available historical mining documentations, ware developed. Furthermore, ERT (electrical resistivity tomography) geophysical measurements were performed. The primary outcomes obtained by them confirmed the fact that in complex and complicated glaciotectonic conditions, the coal mining of multi-level deposits can induce discontinuous of ground deformations.

To investigate landslide morphology and identify landslide features Pawluszek (2019) applied the high-resolution digital elevation model (HRDEM). She proposed a new method of identification of landslide feature mapping of the morphology with computer-aided techniques to enhance the interpretation of the elevation model. Morphological signatures of landslides were identified using the PCA on the basis of two landslides located in the South of Poland (namely, Roznow Lake and Grodek nad Dunajcem). Seven different derivatives of the HRDEM were applied to maximize the morphological information and to perform an enhancement of the visual interpretation. The proposed method is very promising since the conventional geodetic methods are time-consuming, however, this technique has its limitations which were also discussed in the paper.

Pawluszek et al. (2019) studied the possible detection of landslides with the use of object-based image analysis (OBIA) and data derived from LiDAR. Forested and agricultural areas located in the south of Poland (Outer Carpathians) were chosen for research, which are characterized by the specifically degraded landslide geomorphology. They considered the different aspects of degradation of OBIA accuracy, i.e. resolution of the applied Digital Elevation Model (DEM), feature selection, and scale of segmentation. The efficiency of this approach was presented with the use of 85% of overall accuracy and Kappa's index (KIA) reaching 0.6. Finally, they discussed the challenges and advantages of automatic approaches for detecting landslides.

Pawluszek-Filipiak et al. (2020) investigated landslides of two adjacent regions located in the south of Poland, namely "Lososina" and "Grodek", separated by the Roznow Lake and Dunajec River in order to develop an optimal method for mapping landslide susceptibility mapping (LSM). They performed a cross-modelling by creating various hydrological topographical, environmental, and geological landslide-conditioning factors (LCFs). Sentinel-2A data, DEMs, geological information as well as lake shapefile have been used for LCFs' generation. Then, the Seed Cell Area Index (SCAI) and Relative Landslide Density Index (RLDI) were used for checking and validating of the model. The applied methodology confirmed that with a lack of landslide inventory in the considered area, landslide susceptibility can be described based on inventory available for the adjacent area. Since landslide inventory is an expensive activity, this approach can be successfully used as an alternative.

Pawluszek-Filipiak and Borkowski (2020a) compared two approaches, namely PSI (Persistent Scatterer Interferometry) and DInSAR (Differential Interferometric Synthetic Aperture Radar) in order to assess their suitability for monitoring the subsidence caused by exploitation in the coal mining. Their case study was conducted upon the Rydultowy mine situated in the Upper Silesian Coal Basin (USCB) in SW Poland. The data used covered 62 ascending Sentinel-1 images. The comparison involved 6-day time-series deformation maps. They concluded that the results of DInSAR processing provide better information exposure comparing to PSI results because of the temporal baseline being always (with just few exceptions equal to 6 days). In addition, due to the deformation model used, the PSI could not cope with estimating displacements of more than 12 cm/yr, while the deformations in the case area reached even 1 m per year.

Pawluszek-Filipiak and Borkowski (2020b) used the same case area, but with the use of DInSAR and SBAS (Small BAseline Subset) techniques. The latter method requires a predefined deformation model, which is its disadvantage. However, the DInSAR accuracy is limited by correlations, either spatial or temporal, signal delays from atmosphere, and topographic or orbital errors. Therefore, they proposed to integrate those two techniques based on the geostatistical kriging prediction model to obtain the complete deformation pattern over the area of study. Moreover, they validated the proposed approaches with levelling data. Based on this validation the obtained minimum and maximum of the RMSE between displacements determined using DInSAR and levelling profiles were 0.9 and 3.2 cm, respectively. Unfortunately, SBAS processing is not suitable to monitor the subsidence in the area of maximum deformation rate. The final conclusion of the conducted research was that DInSAR is not the ideal technique when applied standalone and has to be supported by other geodetic measurements like GPS, LiDAR (Light Detection and Ranging) or classical spirit levelling.

Pawluszek-Filipiak and Borkowski (2021a) used a combination of classical PSInSAR approach and conventional consecutive DInSAR for investigating the deformation rates in the Rydultowy Mining located in the South-West part of Poland. This allows measuring very significant subsidence of even 1 m per year. The time span of used data covers the period from March 2018 to March 2019. The developed methodology made it possible to determine a complete deformation model, which was compared with the results of precise levelling. The RMSE of 22 mm with a maximum subsidence rate reaching 1.05 m per year confirmed the validity of the methodology used.

Pawluszek-Filipiak and Borkowski (2021b) applied the Object-Oriented Approach (OOA) and Digital Elevation Model (DEM) determined with the use of the Airborne Laser Scanning (ALS) data for the detection of landslides. Classical methods based on historical observations (e.g. precise levelling) are costly and time-consuming, so the future belongs to automatic methods. The vicinity of Roznow Lake (south of Poland) was taken as the study area. They concluded that even though some difficulties related to the smoothing of typical landslide features, automatic approaches are already very often used for these purposes, although as of today they are not yet fully able to replace the classical methods.

Pawluszek-Filipiak and Borkowski (2021c) used the PSI technique to update the intensity of the landslide in the area of Roznow Lake in Poland. Observations made with Sentinel-1 A and B satellites covering 2017 were used for this purpose. The PSI-based matrix approach was applied to assess the landslide state. A total number of 205 landslides were assessed for their activity demonstrating that the majority of them were evaluated as active.

Pawluszek-Filipiak et al. (2021) applied the PSI to verify the landslides in terms of their activity. Their test area covered Polish Flysch Carpathians (SE Poland). ALOS (Advanced Land Observing Satellite) PALSAR (Phased Array L-band Synthetic Aperture Radar) and Sentinel 1A/B data with different acquisition geometries were used. Line-Of-Sight (LOS) measurements were projected to the steepest slope to obtain the landslide intensity and expected maps of damages were created during field investigations. Forty-three of a total number of 50 investigated landslides were proved to be active, which was confirmed by in-situ measurements that have proved the applicability of the applied method for the assessment of landslide activity.

Milczarek (2019a) applied a Small Baseline Subset (SBAS) method to study the deformation of the Earth's surface caused by underground mining. Two large SAR datasets from Sentinel 1A/B satellites have been applied. For calculations, they determined atmospheric delay using Tymofyeyeva and Fialko empirical method and the Mogi model, which allowed simulation of underground mining exploitation as well as induced tremors. The observational data covered underground copper ore extraction in SW Poland. They concluded that this method is very useful, but only for regions where mining system produces displacements being relatively time-constant. Moreover, induced seismic events may be effectively monitored with this approach.

Grzempowski et al. (2020) investigated the Earth's surface deformations within the period 1995–2019 over Wroclaw as well as the potential factors causing these displacements. For this purpose, they used the PSI technique and data from ERS-2, Envisat, and Sentinel-1 satellites. The results obtained revealed that vertical and horizontal velocities over the area investigated reach up to 3 and 1 mm/yr, respectively. These results confirmed the linearity of Earth's surface deformations documented in historical geodetic data. They concluded that these displacements have a periodic subsidence pattern of 4–5 years and 2–3 years of stabilization or uplift. They reported that the area of Wroclaw is progressively decline in relation to the reference area, i.e. the area of the Fore-Sudetic Block.

Ilieva et al. (2019a) concentrated on the life cycle of the Earth's surface deformations resulted from extracting the coal over the area of Upper Silesian Coal Basin (USCB). They utilized InSAR data from Sentinel-1 satellite and the DInSAR method. The Earth's surface deformation results obtained from InSAR data and the DInSAR method were validated using levelling data from a local geodetic levelling network that was semiannually re-measured. They concluded that the Earth's surface deformation results obtained from InSAR data are sufficient enough for monitoring the subsidence induced by mine processes that can reach up to –1.65 m over one year. The standard deviation of the difference and the bias between these results and corresponding ones from levelling data are 18.3 cm and –4 cm, respectively. They revealed good agreement between the detected surface vertical change and the amount of the material extracted. For the following eight months of the extraction, the corr. coef. between detected surface vertical change and the material extracted can reach up to 90%.

Bazanowski et al. (2019) performed the study of the GNSS session durations to achieve the accuracy of several millimeters with 95% confidence level to monitor the subsidence of the Earth's surface due to mining of underground minerals. Their study area covered sylvinite mine in New Brunswick (East of Canada). Geodetic monitoring of the deformations contains GNSS measurements as well as precise levelling. The GPS observations have been carried out over the time of 18 days with 24-hour sessions. One baseline was selected for tests, the analysis of 58 3-hour long sessions indicated the accuracy in horizontal plane of 6 and 8 mm in Northing and Easting, respectively. Height component was determined with the accuracy of 8 mm. They concluded that to obtain several-mm accuracy of GNSS measurements for monitoring of the deformations in mines, the sessions should be at least 12-hour long.

Przylucka et al. (2022) monitored the subsidence of the mining area located in the Upper Silesian Coal Basin (USCB) (South Poland) using the PSI and DInSAR techniques. They combined 8 different data sets, derived using two different methods, from various sensors and the 12-year period (1992–2012). The map of subsidence of an area of 3045 km^2 was obtained using 81 different interferograms. Moreover, the change (development) of the subsidence of the area of study was determined. They concluded that combining different InSAR datasets may provide reliable large-scale and long-term information about negative impact of mining activities in SW Poland.

Dwornik et al. (2021) proposed an automatic procedure for the subsidence detection based on SAR interferograms. It makes use of analysis of spatial distribution of the interferogram phase, as well as its entropy and coherence. Sentinel-1 images were tested with the chosen mining areas located in south Poland that were considered as the test fields. The results were compared to those recovered with the use of circular Gabor filters. A significant improvement (34–83% of detection rate in comparison to 30–53%) has been observed, however, different numbers of false alarms for both methods were registered.

Bala et al. (2021) applied the circlet transform for automatic detection of subsidence areas. Advantage of the newly proposed method is the consideration of the finite data frequency. Additionally, the search shape is not restricted to the circle. The transformation does not require further edge detection or a binary segmentation as it operates directly on the image gradient. Sentinel-1A data were taken for testing over the Upper Silesian Coal Basing that was chosen as a test field. The study have shown a 20% improvement in the method's effectiveness.

Malinowska et al. (2019) used Envisat SAR images acquired between 2003 and 2010 to investigate the sinkholes caused by shallow submerged voids. They investigated an area in Upper Silesia (Poland) with 345 sinkholes that were identified between 1992 and 2013. The findings proved that the PSI technique is able to support the identification of zones with sinkholes and detect accelerated movements of the ground within 100 m of a single sinkhole.

Malinowska et al. (2020a) applied the PSInSAR method to determine the ground movement in the area of one of the copper ore and anhydrite mines in Poland. The main aim of this study was to develop a new methodology for uplift prediction using satellite data and correlate them with hydrogeological conditions and mine life. The results showed that the uplift will reach up to 12 mm/yr in the next 6 years.

Malinowska et al. (2020b) developed a new method for predicting surface deformations, generalized for the exploitation of various types of deposits. They presented a novel modification of the influence function method obtaining much more precise modelling of the ground movement for different types of minerals. They concluded, that each ground movements caused by different type of mineral reservoir exploitation can be predicted with this method.

Guzy and Malinowska (2020) performed an inclusive review of models used to predict displacements caused by aquifer drainage with recent advances. They also gave a summary of implementations of InSAR technique to support the process of modelling of the aquifer compaction.

Liu et al. (2019) described the capability of up-to-date ALOS-2 PALSAR data in observing the movement of the landslide of the test area in south China. According to the Authors either fast of slow movements can be captured, with different spatial or temporal baseline combination. The obtained results show that the L-band SAR data has its benefits in observing the landslide movements, especially in cloudy and rainy areas or in low latitudes.

Szczerbowski (2020) studied the problem of deformations of ground surface in the area of the Bochnia Salt Mine (SW Poland). Deformations observed by geodetic methods are of two origins, namely natural (Carpathian push) and anthropogenic (past mining activity). He recognized the abnormal zones of subsidence basins, since the long-term vertical displacement distribution revealed atypical geometry. The analysis of lines of constant vertical displacement rate revealed some additional driving mechanisms of the deformation processes in the considered area. He proposed polynomial approximation to determine and describe the anomalous areas. Szczerbowski and Gawalkiewicz (2020) applied geodetic methods to investigate the area of Inowroclaw town experienced by the halotectonic movement of salt diapir. They research on the vertical displacement of the set of benchmarks, which showed different characteristics depending on the distance from the reference benchmarks. As a result of the new approach, the points considered as reference were recognized as unstable, which is very important in the further study of the considered area. Szczerbowski and Niedbalski (2021) applied a combination of sonic probe extensometer in intact rocks surrounding the gallery of the Bochnia Salt Mine. The gallery has been in use for more than 800 years. They also provided the real accuracy of the applied instrument. Their study presents the process of rock salt flow into the gallery observed over a period of 3 years revealing of a specific distribution of strain over the gallery, not discovered before. They proved, that the additional tectonic push of the Carpathians provides a tectonic stress and causes the tectonic activity in the underground movements.

Maciuk et al. (2021) focused on the dynamics of European plate to assess their influence to the land boundaries. They analyzed the velocities of the selected permanent GNSS stations established in Poland and showed the differences in the velocities determined in IGS and ETRF (European Terrestrial Reference Frame) reference frames. They found, that within the next 25 years, the marks indicating borders may be shifted by 0.13 m due to tectonic movements and recommended verifications of cadastral data in Poland to be performed at least once every 15 years.

Maciuk (2021) summarized the practical research results from GNSS data for non-anthropogenic crustal deformations such as earthquakes, landslides, and tectonics. He described several measurement techniques. They were: real-time and post-processing of satellite navigation data in the absolute and relative positioning. At the end, he described the challenges related to the use of GNSS in future studies related to investigation of natural phenomena.

Wajs et al. (2021) proposed an active remote sensing based solution for fast and accurate inventory of open-pit Mines. As a case study, the authors selected the Mikoszow Granite Mine located in Lower Silesia, south-west Poland. Mobile LiDAR System (MLS) with a mobile mapping platform equipped with DMI (Distance Measurement Indicator) and IMU (Inertial Measurement Unit) sensors as well as GNSS and mobile laser scanners mounted on a vehicle. For data acquisition and localization, the Simultaneous Localization and Mapping (SLAM) approach was applied. Point clouds and positions over the whole area of the Mikoszow mine and its vicinity were recorded. The final results obtained by the MSL contained a set of 1,968,367 point clouds which can be post-processed in approx. 30 minutes. The accuracy of positions obtained from these MSL results was similar to RTK GNSS accuracy. They reported that the proposed solution based on MLS and SLAM approach can successfully be applied to the open-pit mine entire life cycle.

Kowalski et al. (2019) focused on studying the structural control of mass movements on slopes formed of magmatic and metamorphic rocks. The authors investigated the mechanisms and formation of landslides on the northern slopes of the dome-shaped, rhyolitic

Wielislawka Mt. located in the Kaczawa Foothills of the Western Sudetes, south-west Poland. A multidisciplinary approach based on data from geological and geomorphological field studies, terrestrial laser scanning (TLS) and LiDAR-based DEMs, for old adits and shafts in the landslide area, was applied. This multidisciplinary approach allowed the determination of the recent extent and origin of the landslides over the area investigated. The use of these data indicated that the observed initial stages of mass changes in the excavations, in particular, the area characterized by cover rocks of the rhyolitic massif, the old adits and shafts, were unique areas to study the landslide processes. The results obtained by them revealed that existing discontinuity surfaces within the rock massif have an essential contribution to the intensity, development and potential future evolution of the slope failures on Wielislawka Mt. Concerning the northern slopes of Wielislawka Mt., the morphology and further development of landslides were associated directly to riverine erosion and the formation of the deeper part of Kaczawa River. The authors reported that structural anisotropy and lithological of the massif have an essential impact on slope failure development.

Kowalczyk et al. (2020) evaluated the use of the co-kriging method to model the vertical deformations over Poland. They analyzed vertical movements of the Earth's crust from: (1) four precision levelling campaigns carried out in Poland within the period 1926–1937, 1953–1955, 1974–1982, and 1997–2003, respectively, (2) permanent GNSS stations data, and (3) the first alignment of vertical motion networks in Poland that include levelling (222 points) and GNSS (123 points) data. To process these data, methods based on variograms (semivariograms) were applied. The results obtained by them revealed that vertical deformations over Poland based on levelling data were anisotropic. They also indicated that vertical movements from GNSS data disagree with the respective ones from levelling data. This disagreement can be ascribed to data errors or external influences such as anthropogenic or geophysical factors. They concluded that co-kriging method allows the combination of numerous datasets, but the final model is considerably effected by initial dataset. This method is independent from the volume of data. They also confirm that co-kriging method is a numerically non-unique method, as the same input datasets can result in different models.

Kowalczyk et al. (2021a) focused on the need of creating a unified levelling network based on data from consistently campaigns of levelling measurements and permanent GNSS observations to increase the resolution of geodynamics models, in particular, the models of VDES, in space domain. For this purpose, they examined the scale-free network theory to obtain the most relevant common points in hybrid networks using the Euclidean's distance between points as a criterion. They utilized data from the UELN (United European Levelling Network) and EPN (European Permanent Network) networks. They identified 18 pseudo-nodal points with the highest number of links in this hybrid network. The Euclidean distance of 10 km was found as an appropriate criterion to identify these pseudo-nodal points as common points. Overall, they concluded that relative VDES can be estimated by aligning a hybrid network (UELN+EPN) using the scale-free network theory.

Fan et al. (2019) estimated the glacier displacement with the use of SAR image intensity information. They used six COSMO-SkyMed (COnstellation of small Satellites for the Mediterranean basin Observation) images obtained between July and December 2016 to study the movements of five glaciers. They are located in the central Himalayas. Their research provided evidence of the reliability of the measurements of the SAR data in addition to the analyses of RMSE of the velocity residuals in non-glacial zones. They compared the results with those obtained by terrestrial laser scanning and concluded that merging of those techniques should provide better information concerning the monitoring of the glaciers.

Glowacki and Kasza (2021) assessed the morphology change of the Werenskiold Glacier, south-west Spitsbergen and its end moraine. For this purpose, DEMs developed from aerial photogrammetry measurements for 1936, 1960, 1990, and 2011 as well as InSAR and GNSS data from GNSS RTK measurements for 2015 were utilized. The long-term analysis based on DEMs and with direct GNSS RTK survey revealed that the loss of rock and ice material disappeared from the end moraine of the glacier was about 200,000 m^3/yr. The short-term analysis of InSAR data covering the period between 2 August and 6 November 2015 indicated that this loss is at the level of 2000 m^3/day. They reported that the most essential morphology change was observed in the northern part of Werenskiold Glacier.

3.3. Investigation of seismic events

The progress in GNSS receiving equipment and processing of navigational data as well as new InSAR technology has led to considering these measurement techniques as very useful tools for the detection of co-seismic displacements and a source of information concerning the propagation of seismic waves.

Paziewski et al. (2020) validated the algorithms for automatic Galileo+GPS high-rate signals processing at medium and long-range baselines for seismic events' characterization. They used the Galileo foR Seismography System (GRaSS) which was elaborated previously for near real-time monitoring of anthropogenic seismic events at the area of a copper mine in SW Poland. This system contains 4 modules liable for automatic processing of high-rate navigation measurements and presenting the results. In their results, they used the relative geometry-based model, which was recognized to provide the most precise coordinate estimates with GNSS signals. They tested the elaborated algorithm on the case study of M3.8 seismic event which took place in January 2019 in the SW of Poland. GNSS permanent stations were located 1.2 and 4.0 km, respectively. In addition, they used accelerometer observations for comparison purposes by performing the integration of the obtaining position displacement. They found a very similar shape of the seismic waves, however, the displacements derived by accelerometer were two times lower than GNSS-derived ones. Moreover, they demonstrated an agreement in a frequency domain with the use of Fast Fourier Transformation (FFT) with the dominant frequency of 0.3 and 0.7 Hz in the north direction and 0.3 Hz in the east one. Finally, they validated the measuring system on the specially constructed shake table with simulated dynamic displacement. The validation results obtained indicated that maximal differences between GNSS-derived mean amplitude and the benchmark values were at the range of 0.2–1.9 mm.

Kudlacik et al. (2019) applied high-rate GPS PPP technique with a sampling frequency of 5 and 10 Hz to investigate the motion determined by GPS technique at permanent stations during three earthquakes. The seismic events took place in Nepal (Gorkha earthquake) and Italy (Visso and Norcia). The first one took place in April 2015 being a result of the thrust faulting and was successfully recorded by eight GPS permanent stations. The second and third events took place in October 2016 in the Apennines recorded by seven nearby permanent stations. First, the high-rate GPS data were processed with the RTKlib software in the kinematic PPP mode obtaining GPS-derived position time series. Then, tests of variuos types of digital filters were performed, with the conclusion that the 2nd order Butterworth band-pass filter adapted to each GPS station separately is an optimal filter for this study. They compared the GPS-derived results with those obtained using strong motion instruments (SM) obtaining GPS-SM absolute value of the average difference is 6 mm with GPS-SM distances within the range of 0.05 to 2.14 km although different measuring ideas (GNSS-derived displacement is absolute, while SM – relative). At the end, they found a significant relationship between those two types of data with correlation coefficients of 0.83 for the east, 0.95 for the north and 0.98 for up components, confirming the ability of GNSS for determining of the fault plane solution for earthquakes with magnitudes over 6. A similar methodology was applied by Kudlacik et al. (2021), but to a much less energetic (M3.7) event that occurred in January 2019 in the area of Legnica-Glogow Copper District (SW Poland). That was one of the first analysis of mining tremor using high-rate GNSS positioning. GNSS position time series were derived using either double differencing (DD) or PPP methods. Seismological data (accelerations and velocities integrated into displacements) served as the reference for validation. They found that the peak ground displacements (PGDs) calculated for two GNSS stations with the PPP-approach were very close to the same PGDs calculated on the basis of seismological data recorded at the stations co-located with GNSS ones. Coherence analysis was used to confirm the consistency of two types of data in the frequency domain. They concluded that with this methodology and instrumentation not only significant natural earthquakes may be sensed and analyzed, but also events of smaller magnitudes might be recorded when the epicentral distance is quite small.

Szczerbowski (2019) discussed the problem concerning the relations between seismic events of high-energy and regional scale deformations of the terrain surface. His test area covered the Legnica-Glogow Copper District (LGCD). He used position time series gathered from the GNSS stations of the ASG-EUPOS network that were located at the LGCD and adjacent areas were chosen. He investigated the temporal variation of distances between the chosen stations and evaluated the apparent strain, which was compared to the occurrence of tremors of high-energy, finding a significant correlation.

Kaczorowski et al. (2022) focused on geodynamic harmonic signals of the range 10^{-3}–10^{-4} Hz recorded by water-tube (WT) tiltmeters installed in the Space Research Center, Geodynamic Laboratory (GL) in Ksiaz, south-west Poland. The authors reported that the main components of these geodynamic harmonic signals resulted from post-seismic Earth's solid-body free oscillations and atmospheric pressure microvibrations. The period 2004–2012 was selected to study the viscoelastic vibrations of the solid Earth.

Within this period, two significant earthquakes: the Sumatra-Andaman on 26.12.2004 with a magnitude of M8.1, and the Tohoku-Oki on 11.03.2011 with a magnitude of M9.0, were occurred. To investigate harmonic signals induced by low-frequency atmospheric pressure microvibrations, different periods (e.g. June 6-21, 2010, February 2 to March 3, 2012) were considered. The authors found that amplitudes of air pressure microvibrations were in the range from ca. 0.15 to 0.50 mas. Overall, they concluded that amplitudes of harmonic signals induced by air pressure microvibrations were strongly dependent on the location of WT tiltmeters within the underground GL Ksiaz. For the harmonic signals generated by post-seismic free oscillations of the Earth, the location of WT tiltmeters did not play a significant role.

Przylibski et al. (2020) focused on the relationships between variation in activity concentrations of radon ^{222}Rn and seismic events recorded using WT tltimeters of the GL Ksiaz. The change of ^{222}Rn activity concentration in the underground tunnels at GL Ksiaz was obtained using 5 semiconductor SRDN-3 detectors operated within the period from May 18, 2014 to January 18, 2016, and one ionisation chamber of the AlphaGUARD instrument operated for the period March 21–28, 2014. Tectonic and seismic activities of the orogen at the GL at Ksiaz were measured for the same period of radon activity concentration changes using two WT tiltmeters. The comparison between changes of radon activity concentration and WT tiltmeters illustrated that radon data sinusoidal oscillations with an amplitude range from 1000 to 1500 Bq/m^3 and a phase of 12 months. The results obtained indicated that the coefficients of correlation between ^{222}Rn activity concentration and seismic events were within the range from 0.38 to 0.43. They reported that a vital conclusion concerning the relationships between the change of ^{222}Rn activity concentration and seismic events observed at GL Ksiaz can be drawn from the preliminary analysis of approximately two years of ^{222}Rn activity concentration observations.

Kaczorowski et al. (2019, 2021) focused on the deformation of the Swiebodzice Depression (SD) unit, which provide information concerning the deformation of the Fore-Sudetic Monocline (FSM). In particular, they concentrated on temporal variations of strong seismic events (i.e. magnitude ≥ 3.6) in the FSM using harmonic signals registered by WT tiltmeters in GL Ksiaz. Kaczorowski et al. (2019) concentrated, mainly, on strong seismic events that take place in 2016, while Kaczorowski et al. (2021) considered all strong seismic events occurred within the period 2013–2017. Either Kaczorowski et al. (2019) or Kaczorowski et al. (2021) reported that the comparison between the phases of tectonic activity of the SD orogeny and temporal variations of seismic events exhibited the presence of temporal dependency between these seismic events and the derivative of the tectonic activity (VTAF).

Chrapkiewicz et al. (2020) conducted intensive research concerning the inversion of the surface wave dispersion and teleseismic receiver functions data required to investigate the S-wave structure at a craton margin. They proposed a linearized method with a full solution to the inverse problem. In this method an ensemble of starting models covering the entire space of acceptable solutions was used. Rayleigh wave phase velocity dispersion and P-wave receiver function data from the so-called 13 BB Star (i.e. the passive seismic experiment in north-western Poland) were integrated into the inversion solution. They developed a workflow of multistep for the linearized inversion to obtain reliable models of S-wave velocity down to 300 km using receiver function and surface wave dispersion data. The results obtained by them revealed a very good fit between S-wave velocity data and their final models developed. This may indicate that using correct parameter optimization can, successfully, mitigate the ill-posed problem of the inverse problem. Moreover, they found a similar mantle over the area investigated, but rather high-velocity values (ca. 4.80 km/s) which are larger by 0.1–0.2 km/s compared to those estimated for other cratons. This may indicate that further investigations would be required to explain whether such high-velocity values are due to a local anomaly associated with the Earth's structure, or if they are a consequence of the simplification of the assumptions applied in the modelling procedures.

In order to assess the rapid response to the Samos M7.0 earthquake, Foumelis et al. (2021) combined historical seismicity of rupture areas with seismological and geodetic, e.g. GNSS and InSAR data as well as in-situ observation. They demonstrated that such a combination is very valuable to specify the rapid response requirements for assessing and preliminary interpreting the earthquake activity, even within the first 24 hours that proceeding the time of the earthquake. They also exhibited that in a period of less than a week, several constraints concerning the accessibility of data as well as the drawbacks of the techniques used can partially be recovered to provide more reliable results and interpretation. Furthermore, they highlighted the preparedness level of the rapid seismological solutions, systematic availability of open access Earth Observations (EO) data and on-demand online processing of both EO and GNSS data that were considerably improved over the past years.

Owczarz and Blachowski (2020a) investigated induced seismicity from anthropogenic activities in the mining areas of Poland. They analyzed surface displacements caused by eight induced tremors the area of Rudna copper mine (SW Poland). It is a region of moderate seismicity with no more than 100 induced shocks per year, mostly not felt by people. They used the DInSAR method with Sentinel-1 satellite imagery along with the geographic information system (GIS). They studied the vertical displacements derived from 37 calculated interferograms with 68 pairs of images being processed from November 2016 to February 2020 with eight events of magnitude greater than 2.7. They found that in the investigated region the average values of maximum vertical subsidence ranged from –44 to –119 mm depending on the induced shock with all analyzed vertical profile lines showing comparable subsidence properties. They also assessed the potential relations between maximum vertical displacements and the energy of tremors induced by underground mining activity, as well as energy and their spatial ranges in West-East and North-South directions with a strong positive relationship. In the paper by Owczarz and Blachowski (2020b) results of similar investigations were published, but for seismic events occurred between December 2016 and September 2018 for the same area. As the results, maps of the deformation resulting from the consecutive seismic events were shown and discussed in detail.

Pawluszek-Filipiak and Borkowski (2021d) investigated correlations between DInSAR-estimated deformations and mining tremors with the biggest amplitudes. For this purpose, they used data from Sentinel 1A and 1B ascending images. Fifty-one different interferograms in total have been processed. For correlation analyses, either time series in the center of subsidence basins or deformation profiles were taken. The result of their analysis was negative. For the earthquakes under consideration, they did not find correlations to attribute the deformation of the Earth's surface to a specific seismic event, probably due to the small magnitude (maximum 2.8) or the depth of extraction (1 km).

Milczarek (2019b) used SAR interferometry to determine the deformation of the Earth's surface due to the anthropogenic-induced earthquake. The area of study was located at the Legnica-Glogow Copper Belt (L-GCB) which reveals the highest level of seismic activity in SW Poland. Additionally, L-GCB is located at the FSM, which increases the likelihood of earthquakes. A total number of more than 1500 induced seismic events between 2000 and 2016 were recorded there. Data from Sentinel 1A and 1B satellites processed using DInSAR differential method covering 5 interferograms were used. Additionally, calculations using the SBAS time series method were also performed. Tremor that occurred in November 2016 was analyzed in detail. The displacements up to –80 mm in the radar Line-Of-Sight direction, were observed. They confirmed the ability of detecting surface displacement with small dimensions (few kilometers). Due to the lack of other geodetic observations within the period investigated, performing a comparative analysis was not possible.

Ilieva et al. (2019b) presented a combined seismological and geodetic study concerning the relationship between collapses resulted from mine processes and the ground response to seismic activities. They focused on the strongest seismic event that took place on 29 January 2019, in the area of Rudna Mine, Poland that is denoted as the M4.6 collapse. Seismic signal from the Legnica-Glogow Underground Mining INduced Earthquake Observing System (LUMINEOS) surface local seismic network, GNSS position time series as well as InSAR data from Sentinel-1 satellite mission were used. Daily-coordinates of high accuracy for the period of three months before and three months after the event, as well as oscillations of high-frequency in the horizontal and vertical coordinates, observed during the M4.6 collapse, were determined by processing GNSS observations collected at 10 Hz. In order to obtain surface deformation using InSAR data, a SBAS method for the slow-rate deformations and a conventional DInSAR method for fast-motion monitoring around the epicenter were elaborated. Through the analysis of GNSS and InSAR data, they confirmed the rapid decline of the ground. The analysis of InSAR data revealed that preceding the collapse by six days, a post-event rate of subsidence over an area of two km^2 was an increased. Overall, they concluded that in a very short time, shallow-induced seismic events with magnitudes of greater than M4 can result in a significant surface deformation.

Rudzinski et al. (2019) investigated the M4.0 earthquake in Wujek/Slask underground coal mine in Poland which was held on April 17, 2015. They used Sentinel 1-A data with a 12-day revisit time. To study the deformation before, during and after the earthquake they took three pairs of SAR images obtaining the subsidence pattern showing one cycle of deformation corresponding to approximately 2.8 cm of subsidence. Then, they compared the results of obtained deformations with the estimated source mechanism as a full moment tensor (MT) solution. The full MT inversions were performed with respect to the signals filtered between 0.13 and 0.16 Hz. They concluded that linkage of data from geodetic techniques with results of analysis of seismological information is able to provide very important insight into mine collapses.

Hejmanowski et al. (2019) discussed the effects of severe nearby mining-induced M4.7 and M4.8 earthquakes which took place in 2017 with 1.6 km distance between hypocenters. They applied InSAR technique to monitor the ground deformations caused by those two tremors. The earthquakes occurred in the area of "Rudna" Copper Ore Mine (SW Poland). A high level of seismicity in this region is caused not only by anthropogenic reasons, but also due to complex geological conditions. The ground movement was analyzed using Sentinel-1 data obtained from both, descending and ascending satellite orbits. The DInSAR method was applied for processing of the radar images with successful detection of the local dynamic subsidence troughs of a regular shape and a range of about 2 km induced by these tremors. They obtained the maximum vertical displacements of –84 and –116 millimeters depending on the tremor. The area affected by the earthquakes has reached the dimension of 1.2 km per 4.2 km. Finally, they found a very significant relationship between the magnitude of the mining-induced tremors and determined surface displacement.

Sopata et al. (2020) investigated the change in the shape of land surface after series of seven rock mass tremors of 2.3 to 2.7 magnitude which took place during the Spring of 2017 in the Upper Silesian Coal Basin (Poland). Using DInSAR method, the authors focused on vertical changes showing the applicability of the proposed methodology to study the deformations in large-scale areas.

3.4. Investigation of sea level changes

For decades, the study of sea level changes has been one of the important components of monitoring climate change in the Earth system. Fenoglio et al. (2019) investigated new altimeter missions equipped with Synthetic Aperture Radar (SAR) mode, which is to provide more accurate information about sea level heights. They used data from 2010 to 2018 gathered by CryoSat-2 and Sentinel-3A satellites, with the region of interest covering French and British Atlantic coasts as well as the coast of the North Sea. The results were compared to the in-situ measurements, by means of tide-gauges at 17 stations and 38 GPS stations located along the German coasts. In their research, they used two ocean models (operational model BSHcmod of the German Federal Maritime and Hydrographic Agency – BSH as well as NEMO-WAM being a part of the Geesthacht Coupled cOAstal model SysTem – GCOAST). The altimetry-derived sea level heights were referred to the WGS84 (World Geodetic System 1984) ellipsoid. Two GNSS solutions were taken, network solution processed in Bernese software in IGb08 (IGS Reference Frames 2008) reference frame and PPP solution from the Nevada Geodetic Laboratory. GNSS-derived velocities with realistic uncertainties were determined using CATS software. This comparison showed that the differences between altimetric and in-situ sea level determinations agree with GNSS-derived rates within 1.5 mm/yr at half of the investigated sites, with the uncertainty being larger than the error of the GPS rate by a factor bigger than two and more. The proposed methodology improved detection of the coastal sea level variability in the last 10 km from the coast.

The Mean Sea level (MSL) changes on the southern Baltic Sea coast were determined using data from five tide gauges (TGs) stations (Kowalczyk, 2019). Time series of MSL data from station Swinoujscie covering the period 1811–2015 were used, while for the remaining four TG stations data for the period 1951–2016 were utilized. In order to analyze vertical bias in time series that caused by using inconsistent reference levels, he used additional data from Stolpmunde and Gdynia TG stations. Furthermore, the author's own algorithm called Vertical Switching Edge Detection was utilized to reduce the MSL time series into a common reference level. For the determination of MSL change, methods based on linear regression, index decomposition, and Fourier function were implemented. He found slight increases in the MSL on the Polish coast of the Baltic Sea. These increases in MSL range from +0.8 to +2.4 mm/yr.

Kowalczyk et al. (2019) studied the vertical crustal motions (VCM) of the Polish coast of the Baltic Sea. They estimated secular variations of MSL using monthly average sea levels data from five TGs stations covering the periods of 1951–2017 and 1993–2017 as well as satellite altimetry (SA) data. Furthermore, for the period 2004–2018, they estimated the VCM at twelve permanent GNSS stations located in the north of Poland using the IGS08 (International GNSS Service 2008) reference frame. The results obtained by them indicated that the absolute VCM of the Polish coast determined from TG and SA data for the period 1951–2017 range from +2.20 ± 0.42 mm/yr to +2.68 ± 0.31 mm/yr. They found that the absolute vertical movements based on GNSS data range from zero to +1.30 mm/yr, which do not agree well with the corresponding absolute vertical motions obtained from TG and SA data. They ascribed this disagreement to several factors such as the time span and the continuity of the time series investigated, local movement of TG stations, anthropogenic activities, geophysical, geological and hydrological factors, the method elaborated to estimate the VCMs, as well as other unidentified movements of GNSS stations.

Kowalczyk et al. (2021b) analyzed the accuracy of VCM along the European coast estimated from SA, TG, GNSS and radar interferometry. Time series of daily and monthly MSL at 27 TG sites were obtained from SA and TG data. Moreover, daily VCM were acquired from GNSS data of permanent GNSS stations that co-locate with these TG sites. With the use of Sentinel-1A/B data from the Copernicus Open Access Hub, mean deformation velocity maps covering the locations of TG sites investigated were obtained. The time series of VCMs were decomposed. As a consequence of this decomposition, linear trends of VCM together with their standard errors were determined at all TG and GNSS sites investigated. For this purpose, they used the linear regression method and Fourier analysis. They reported that accuracies of VCMs estimated from TG, SA, GNSS and SAR data are different. In terms of the standard error of these VCMs from TG and SA data ranged from ±0.06 to ±0.21 mm/yr at a long-time span (i.e. TG data from 1856 to 2018) and from ±0.31 to ±1.59 mm/yr at a short-time span (i.e. TG data from 1993 to 2018). These standard errors are in the range from ±0.20 to ±0.49 mm/yr for SAR data, and from ±0.04 to ±1.92 mm/yr for GNSS data.

Pajak and Kowalczyk (2019) investigated seasonal variations of Baltic Sea level determined from altimetry and tide-gauge observations. They examined data between 1993 and 2015 with the aim of annual and semi-annual amplitudes comparison. They used the gridded (resolution of 0.25° per 0.25°)) daily sea level anomalies obtained from the Copernicus Marine and Environment Monitoring Service (CMEMS) along with the five tide-gauge stations located at the coast of the South part of the Baltic Sea. For comparison purposes altimetric grid points closest to the tige-gages were taken. Their assumed deterministic model consisted of the in-phase and out-of-phase annual and semi-annual terms along with the linear trend determined with the Least Squares Estimation (LSE). The amplitude of the annual oscillation they calculated ranged from 2.86 at the West coast to 5.49 cm at the East coast. They also found that the maximum of the annual cycle at the Polish coastline is in November/December. Maximum difference between techniques was 1.5 cm with a mean correlation coefficient between the satellite altimetry and tide gauge data being equal to 0.92.

Pajak et al. (2021) investigated vertical crustal movements with the use of differences between satellite altimetry (SA) and tide-gauge observations (TG) monthly sea level time series at each TG station along the Adriatic Sea coast. They used observational data from six tide-gauge stations co-located with nearby GNSS permanent stations. Satellite altimetry data were obtained from satellite multi-mission products in the form of the gridded (0.25° per 0.25°) sea level anomalies (SLA). To estimate trends in the MSL, they select two time periods. First, from 1993 to 2018 corresponded to the available satellite data. Second, from 1908 to 2018 based on the available tide-gauge records. They found the mean annual amplitude of +5.90 ± 1.15 cm from satellite altimetry data and +4.32 ± 0.90 cm from tide-gauge data. Finally, they used information about GNSS-derived displacements on permanent stations from the Nevada Geodetic Laboratory PPP solution to connect both types of sea level determinations. They concluded that in the area under study, quite coherent regional patterns of sea level change may be observed, with the trend +3.30 ± 0.32 mm/yr from the satellite altimetry data.

Klos et al. (2019) analyzed the relative and absolute sea level changes referenced to 38 tide-gauge stations located in the Western-North Pacific with the focus on a proper modelling of the Vertical Land Motion (VLM). A region with strong seismological effects was specifically taken to prove the thesis that stations affected by earthquakes still can be further useful for studying vertical changes of the Earth's crust. Therefore, they proposed a new mathematical description methodology for the nonlinear movement of GPS permanent stations with strong post-seismic deformations (PSDs). They also proposed, for the first time, the use of a combination of white and power-law noise for the determination of errors of linear trend and parameters of a nonlinear model determined in one run. Moreover, they analyzed differences in the pre- and post-seismic velocities (relaxation mode) finding very significant (of 15 mm/yr at maximum) differences. They concluded, that not accounting for non-linear vertical land motion in the tectonically unstable areas may lead to errors in estimating absolute sea level rise determined from tide-gauges of about 10 mm/yr. Finally, they found that altimetric determinations much better agree with tide-gauge data after the employment of the newly-proposed nonlinear VLM model.

Lyszkowicz and Bernatowicz (2019) investigated the changes in the Baltic Sea at 6 Polish tide gauge stations. All of them belong to the SONEL (Coastal Water Level Observation System) network. Moreover, they applied the TSAnalyzer software to analyze the vertical position time series from the co-located GNSS permanent stations. Assumptions concerning the deterministic part included annual and semi-annual oscillations plus linear trends. They concluded that geocentric changes of the Baltic Sean along its southern coastlines are between +2.6 mm/yr and +3.5 mm/yr.

3.5. International projects

EPOS (European Plate Observation System) is an infrastructure project aimed at integration of data, data products, and facilities in Europe (https://www.epos-eu.org/about-epos). Within EPOS-PL (EPOS-Poland; https://epos-pl.eu/) the information and measurement system for investigating dynamic events in the Upper Silesian Coal Basin (USCB) in Poland was recently established (Mutke et al., 2019). It's main aim is to carry out either continuous or periodic measurements in post mining and mining areas to show the relationships between underground mining, USCB geodynamics, surface flooding and subsidence, induced seismicity, and sinkholes. In situ observations include gravity monitoring, monitoring of seismicity by surface and underground stations, deformation of the Earth's crust by GNSS, groundwater table movements, as well as Earth's crust deformation monitoring using aerial and satellite (InSAR and PSI) observations. The research infrastructure within EPOS-PL is continuously extending. The proposed system is to investigate causal relations between mining and geodynamic processes taking place in Upper Silesia, but is universal and can be applied to any region of the world with increased anthropogenic seismicity.

In 2022, the construction of the GNSS Data Research Infrastructure Center was also completed, which included the start of a service providing access to GNSS data and products from the Polish GNSS observation infrastructure (Araszkiewicz et al., 2022). The portal (http://www.gnss.wat.edu.pl/cibdg/) presents also analysis of GNSS data quality, stations displacement and zenith troposphere delays.

Sousa et al. (2021) presented the report of the international Dragon 4 program project named "Landslide Identification, Movement Monitoring And Risk Assessment Using Advanced Earth Observation Techniques" (https://earth.esa.int/documents/163802/2550004/32365_PROJECT_SUMMARY.pdf) aimed at application of different geodetic techniques for wide application of remote sensing data, with special emphasis given to risk management, landslide hazard, and disaster prevention. They tested Multi-temporal InSAR, high-resolution image matching, SAR tomography, and data modelling with the aim to investigate the landslides and other geohazards. Moreover, the surface deformation of mountain slopes and glaciers, as well as subsidence, landslides and ground fissure were possible to be monitor with the use of the mentioned methods.

Space Research Centre of the Polish Academy of Sciences participates in the international project under the umbrella of European Space Agency "Geodetic SAR for Height System Unification and Sea Level Research" (Gruber et al., 2020; 2022). The main aim of this project is providing an integrated sea level observing system including commonly applied geodetic methods as GNSS of tide gauges, and introducing the SAR positioning in the Baltic Sea area. Within this project a new model of gravimetric quasi-geoid for Baltic Sea has been proposed (Lyszkowicz et al., 2021b). It has been calculated by applying Helmert condensation method with the use of high-quality dataset from Baltic countries including BNSS/levelling for verification.

4. Summary

In this review article an outline of researches concerning Earth rotation and geodynamics carried out by scientists from Polish scientific institutions from 2019 to 2022 is given. The main concern of the research works on Earth rotation was the estimation of the excitation of polar motion by surficial geophysical fluids using available data from GRACE and GRACE-FO experiments. Another important task was improvement of the quality of Earth rotation parameters estimated from the satellite techniques SLR, GNSS and DORIS. The studies concerning geodynamics were focused on the determination of the ground motion with geodetic methods with several aims. One of them was to monitor landslides and ground deformations caused by mining and seismic tremors. Another, determination of the vertical land motion for sea-level studies (relative sea level). All the results show the high activity of Polish research groups, commitment to scientific cooperation and activity in cooperation with leading international scientific units, conducting research related to Earth rotation and geodynamics.

Author contributions

Conceptualization: J.B., A.B., W.G., J.N.; original draft preparation, editing and reviewing: J.B., A.B., W.G., J.N.

Data availability statement

No datasets were used in this research.

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