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THE USE OF HYBRID DATA: PSINSAR, GNSS AND LEVELLING IN THE DEVELOPMENT OF A MODERN MODEL OF VERTICAL MOVEMENTS OF THE EARTH'S CRUST IN POLAND

The aim of this article is to present the first model in Poland of contemporary relative vertical movements of the Earth's crust, based on the integration of vertical movements determined from three sources: GNSS measurements (ASG-EUPOS), permanent PsInSAR scatterers from EGMS products, and double precise levelling measurements. Due to differences in the temporal and spatial resolution of the data, it was necessary to develop a consistent integration methodology. In the data merging process, an affine transformation was used to convert absolute vertical movements (GNSS and PsInSAR) to a relative system consistent with the levelling data. The InSAR data came from EGMS L2a products (after decomposition into a vertical component) and EGMS L3. The analysis showed that the optimal buffer radius for InSAR data in the study of micro-areas around GNSS stations is 0.3 km, and the use of the median as a representative value is statistically justified. The average transformation error for a single point was approximately 0.20 mm/yr. The final model was developed using the local polynomial method, and the results obtained provide a basis for further geodynamic studies and may be used in civil engineering and geological risk management.

Key words: hybrid data, data integration, vertical crustal movements, PsInSAR, transformation, micro-areas.

Introduction

Vertical movements of the Earth's crust are studied based on various data, such as geodetic, geological, tectonic, seismic and other measurements. Geodetic data includes satellite data such as Synthetic Aperture Radar Interferometry (InSAR), Satellite Altimetry (SA), Global Navigation Satellite Systems (GNSS) and data from ground measurements: Levelling (Lev) and Tide Gauge (TG).

Scientific literature presents attempts to determine vertical movements of the Earth's crust from both homogeneous data sets and their various configurations, which allows for mutual verification of results [Guo et al., 2019; Tretyak et al., 2024; Tretyak & Dosyn, 2015]. Satellite measurements enable the creation of absolute models, referenced to an ellipsoid, while ground-based data are used to construct relative models, referenced to the local sea level [Ballu et al., 2019].

Absolute models do not show the relationship between changes in surface area (land-ocean), but only determine changes in height over time in relation to a mathematical approximation of the shape of the Earth, i. e. they describe changes in height relative to a reference ellipsoid. From the point of view of assessing the risk of flooding or inundation in coastal areas [Le Gal et al., 2024], relative models are useful, as they relate land movements to local changes in sea and ocean levels.

Models of vertical movements of the Earth's crust can be local (e. g. Poland), regional (e. g. Europe) or global. In the case of global and regional models, various types of approximation, averaging and automation of computational processes are used [Kenyeres et al., 2019; Piña-Valdés et al., 2022]. This approach prevents detailed analysis of micro-areas around GNSS stations, levelling nodes or permanent InSAR scatterers. Local models allow the identification of often sub-millimetre changes, as well as the analysis of the relationship between ground movements and geological or anthropogenic factors.

Hybrid data integration faces challenges such as: different spatial reference systems, measurements not taken at the same points, different data processing methods, different measurement frequencies, different spatial resolutions of data, different expected accuracies. These problems are solved by: averaging data, interpolation and extrapolation methods [Del Soldato et al., 2021] at fixed grid nodes [Peifer, 2011], determining the so-called pseudo nodal point [Bednarczyk et al., 2018] or pseudo-PS [Ferretti et al., 2019], assessing the significance of points in hybrid networks [Kowalczyk A. M. & Bajerowski, 2020], adjustment geodetic hybrid networks [Kowalczyk K. et al., 2020] or transforming sets between different reference systems [Altamimi et al., 2002; Naumowicz and Kowalczyk, 2025].

The aim of this article is to develop a model of relative vertical movements of the Earth's crust in Poland based on hybrid data: tide-gauge, levelling, GNSS and InSAR. The reference data used were relative vertical crustal movements derived from levelling measurements [Kowalczyk K., 2005], vertical crustal movements of GNSS stations belonging to the Polish ASG-EUPOS network [Naumowicz et al., 2024], local changes in the Baltic Sea level [Kowalczyk K., 2019], and InSAR data from the Copernicus Land Monitoring Service available through the European Ground Motion Service (EGMS). The EGMS system provides three InSAR products for Europe: basic (L2a), calibrated (L2b) and orthogonal (L3), as well as a model of the Europe Permanent Network Densification (A-EPND) satellite positioning system used to calibrate L2b and L3 products (Del Soldato et al., 2021). A-EPND data are based on observations from approximately 2600 GNSS stations. Fig. 1 shows vertical movements in Poland from the EPND D2200 model.

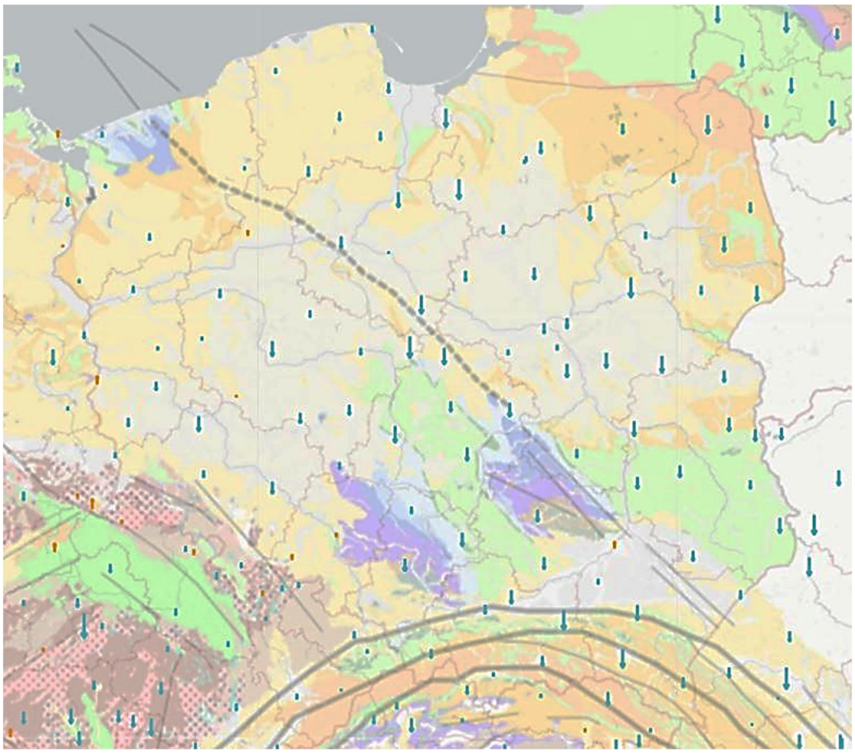

Fig. 1. Vertical movements from the A-EPND model against the background of bedrock and structural geology of Poland (source: https://epnd.sgo-penc.hu/velocities/): red arrows – positive vertical movement, blue arrows – negative vertical movement.

In A-EPND models, despite the use of averaging algorithms (Fig. 1), vertical movements opposite to the general trend (red arrows) were observed at some stations. This suggests the influence of anthropogenic or technical factors not taken into account in the overall analysis of the impact of tectonic plates.

Due to the significant number of InSAR measurement points compared to levelling points and GNSS stations, as well as the variation in vertical movement values, EGMS products cannot be directly used to construct a hybrid model. Therefore, the study was based on the verification of vertical movements at selected GNSS stations using InSAR data, the determination of absolute vertical movements in micro-areas from the EGMS L2a product, and the transformation of absolute vertical movements to a reference model. The verifycation of vertical movements and the location of selected GNSS stations was carried out in an experimentally determined buffer (micro-area) based on EGMS L2a and EGMS L3 products.

A novelty in this approach is the first-time use of vertical movements obtained from InSAR data to verify and supplement the model of vertical movements of the Earth's crust.

Data and methods

Poland is located on the European continent between the Baltic Sea and the Tatra Mountains, which are part of the Carpathians. It is characterised by slow sub-millimetre intra-continental deformation with little influence from Glacial Isostatic Adjustment (GIA). Deformations of the Earth's crust and its surface are mainly caused by various geological factors: uplift and subsidence of mountain ranges, loss of groundwater, melting of glaciers in Fennoscandia, and anthropogenic factors (mining, pressure from urban agglomerations). The authors presented a broad description of the area in the article [Naumowicz et al., 2024].

The first data set includes relative vertical movements of the Earth's crust based on two adjacent levelling campaigns conducted in 1974–1982 and 1997–2003, referenced to a tide gauge on the southern coast of the Baltic Sea [Kowalczyk K., 2005] (Fig. 2). These data were used as a reference. More recent levelling data are not available because another measurement campaign is currently underway in Poland, which is scheduled to be completed in 2027.

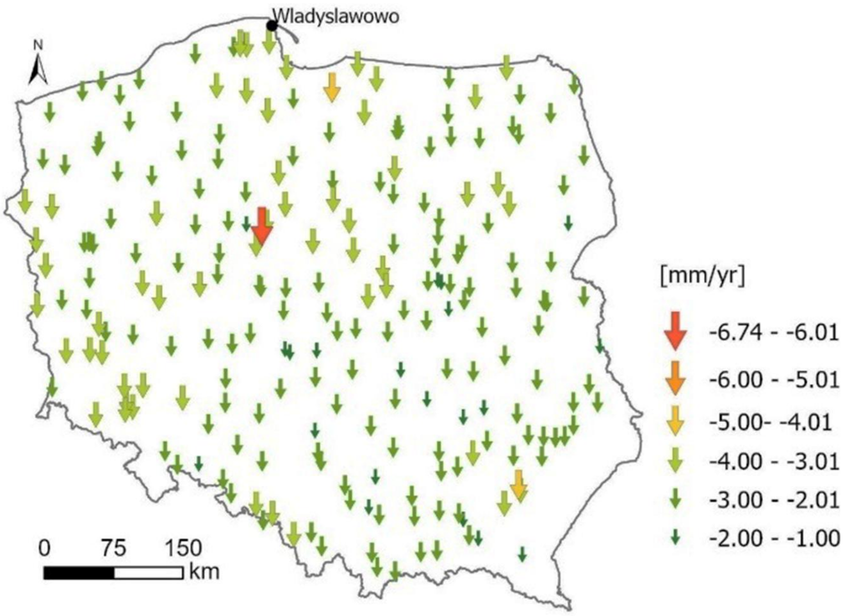

Fig. 2. Relative vertical movements at nodal points of the Polish levelling network [Kowalczyk K., 2005].

The second source of data is the vertical movements of the Earth's crust from observations at fixed GNSS stations of the ASG-EUPOS network from 2011 to 2021 (11-year observation period) using the PPP method – Precise Point Positioning [Łyszkowicz et al., 2021; Pelc-Mieczkowska, 2020] (Fig. 2). The use of long-term time series of coordinates ensures high reliability of results [Naumowicz et al., 2024].

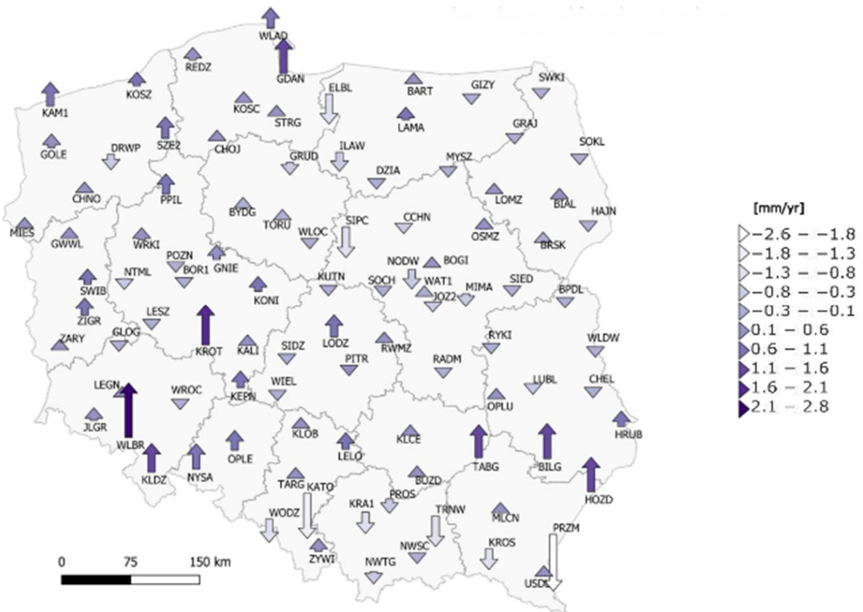

Fig. 3. Vertical movements at individual stations GNSS, mm/yr [Naumowicz et al., 2024].

The third dataset includes vertical movements of the Earth's surface obtained from the European Ground Motion Service (EGMS), which is part of the Copernicus programme (Fig. 3). The data comes from Sentinel-1 satellites equipped with C-band synthetic aperture radar (C-band SAR). Observations are conducted in Interferometric Wide Swath (IW) mode, with a spatial resolution of approximately 20 m in azimuth and 5 m in range. Data reliability is ensured by image redundancy resulting from the overlap of satellite tracks. Data comparison is based on pseudo-PS, i. e. sets of measurement points identified on regular 100×100 m patches of terrain. The EGMS L2a (Basic InSAR) product contains measurements of relative motion in the line of sight (LOS) between pairs of points on different acquisition dates, referenced to the ellipsoid. Each processing area has a local reference point, which makes direct comparison with other geodetic data difficult [Del Soldato et al., 2021].

The EGMS Ortho (L3) product, based on the decomposition of the calibrated L2b product, provides geospatial layers with vertical and east-west offsets in a 100×100 m grid. All measurement points belonging to the same grid cell and the same acquisition geometry are averaged to form a single time series of deformations [Ferretti A. et al., 2023]. For Poland, the EGMS L3 product contains over 4 million points (PS) (Fig. 4).

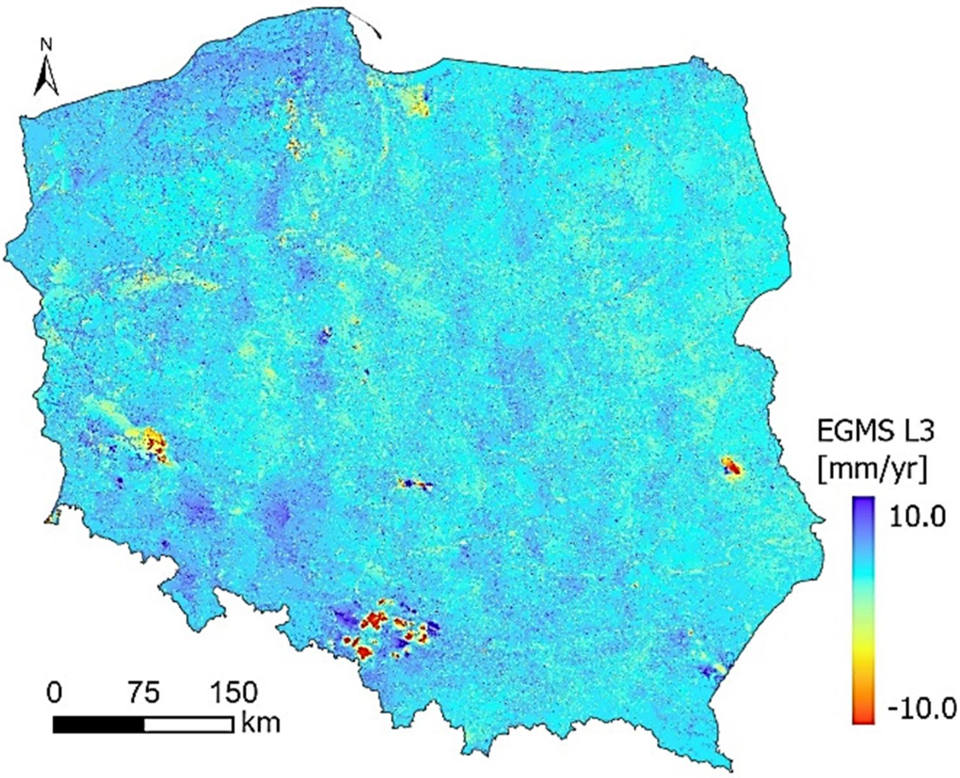

Fig. 4. Vertical ground movements in Poland based on the EGMS L3 model, scale from –10 mm/yr to +10 mm/yr (2018–2022).

A brief description of the data used is presented in Table 1.

Table 1

Characteristics of the data used

Data	Reference system	Spatial distribution	Number of measuring points	Data type	Epoch of measurement, yr
NIV (levelling)	relativ	1 pkt / 6 km	366	adjustment	1974–1982, 1997–2003
GNSS	absolute	1 pkt / 30 km	101	Time series	2011–2021
EGMS L3	absolute	13 pkt / 1 km	~ 4 mln	Time series	2018–2022

Qualitative assessment of vertical movements at selected permanent GNSS stations by comparison with InSAR data in an empirically determined micro-area

In Poland, the collection of PS points from the EGMS L3 product covers over 4 million points, and the L2a product contains even more. Statistically, there are between several dozen and several hundred PS points around each GNSS station.

GNSS stations that showed vertical movements different from the general trends in previous studies concerning the territory of Poland were selected for analysis [Naumowicz et al., 2024; Naumowicz & Kowalczyk, 2025; Piña-Valdés et al., 2022]. Table 2 contains a list of stations included in previous studies and, in the column “in this paper”, stations for which a different nature of vertical movements was found in this study. The detailed process of their identification is presented later in the article.

Table 2

GNSS stations where vertical motion differs from general models [Naumowicz et al., 2024; Naumowicz & Kowalczyk, 2025; Piña-Valdés et al., 2022]

Naumowicz et al., 2024	Piña-Valdés et al., 2022	Naumowicz & Kowalczyk, 2025	Naumowicz & Kowalczyk, 2025	in this paper
Not accepted into the model	Not accepted into the model	Outside the model	Not available in model EPND_D2200	Above the median
DRWP	ELBL	ELBL	DRWP	CHNO
KROT	KOSC	SIPC	GDAN	ELBL
WLBR	KROL	WLBR	JLGR	GDAN
WLDW	RWMZ	WODZ	KATO	GLOG
	WIEL	KATO	POZN	ILAW
		PRZM	PRZM	KATO
		KLDZ	WIEL	KOSZ
		NYSA	WLBR	KROL
		WROC	WODZ	LAMA
		WLOC		LEGN
		SOCH		LODZ
		NODW		MLCN
		CCHN		NYSA
		ILAW		RADM
		DRWP		SWKI
		TRNW		TABG
		KROS		WODZ
		BILG		ZYWI
		TABG		
		HOZD		

To identify these stations, a proprietary method was used to compare vertical movements from GNSS and InSAR data in micro-areas around the stations.

This procedure required the determination of the size of the micro-area (representative buffer). For this purpose, MP (measurement point) points from the EGMS L3 product were used, representing average values in 100×100 m GRID fields. The selection of the buffer around the station is not straightforward, as it may contain points with significantly different movement values, both positive and negative (Fig. 5). Buffers with radii of 0.1 km, 0.3 km, 0.5 km, 1 km, 5 km and 10 km were analysed using PS points from the EGMS L3 product (100×100 m grid).

In the literature, the size of the buffer selected around the measurement points varies and depends largely on the type of data used (levelling, GNSS, SAR). For example [Heiskanen & Moritz, 1967] they used a buffer of 40 km, [Bednarczyk et al., 2018] – 10 km and [Farolfi et al., 2019] – 1 km.

The levelling data analysis conducted in the article [Bednarczyk et al., 2018] showed that changes in vertical movements of the Earth’s crust in the 10 km buffer zone do not exceed 0.1 mm/yr. A similar buffer radius was used in the development of the EGMS model based on GNSS stations from the EPND database (Raport Copernicus land monitoring service.pdf v 1.01, 28/01/2020). In the case of SAR data, the literature assumes, among other things, a buffer: 1 km – [Farolfi et al., 2019], 0.25 km [Parizzi et al., 2020], 0.2 km [Catalão et al., 2009] or unspecified "in close proximity, with the same average speed MP – InSAR measurement point" [Bitelli et al., 2015].

Approaches to determining the representative value for the InSAR data buffer also vary. Both interpolation methods, e. g. IDV [Farolfi et al., 2019], or linear interpolation [EGMS-D3-ALG-006_v3.0.pdf] and statistical methods are used: average [Parizzi et al., 2020] or median [Catalão et al., 2009]. Due to process automation, the size of the areas and the large number of measuring points (MP), individual approaches that take into account additional information, e. g. geological, hydrological, tectonic, gravimetric, etc., are rarely used. This type of analysis is usually carried out for selected micro-areas [Trevoho et al., 2020].

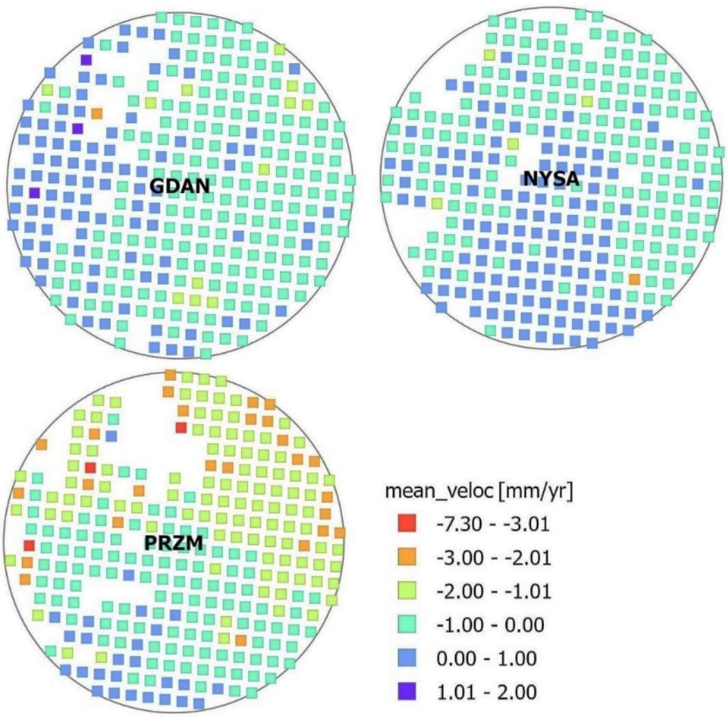

Fig. 5. Example of vertical movement from the EGMS L3 model around permanent GNSS stations (GDAN, NYSA, PRZM) in a 1 km buffer.

To determine the representative vertical movement from the EGMS model in the buffer around Polish ASG-EUPOS stations, the median was used, which allowed for limiting the impact of outliers. The results obtained were compared with the median calculated for a buffer with a radius of 0.1 km (Fig. 6).

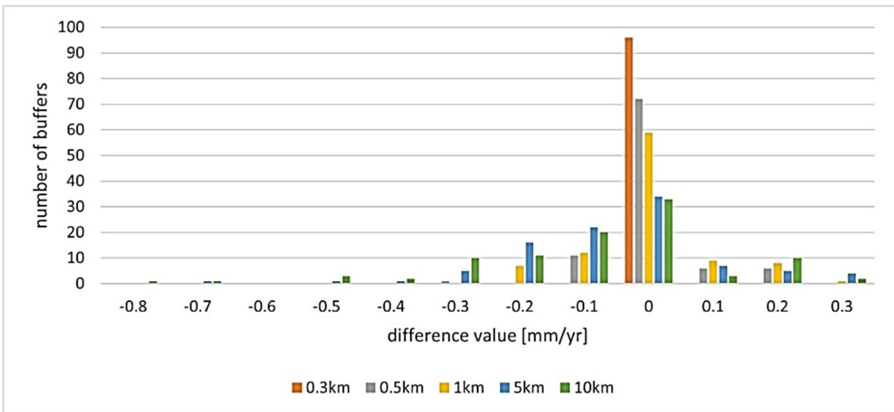

Fig. 6. Differences in median values in the analysed buffers relative to the buffer with a radius of 0.1 km.

The analysis showed the highest correlation for buffers with a radius of up to 0.3 km, with an RMSE error of 0.5 mm/yr (Table 3). Larger buffers (5 km, 10 km) were characterised by higher error values and lower consistency, indicating the need for additional analyses or more advanced statistical methods. Ultimately, in accordance with the literature [Catalão et al., 2009; Parizzi et al., 2020], a buffer of 0.3 km was selected.

Buffers with a radius greater than 1 km showed single areas where no consistency was found in changes to the Earth's crust around GNSS stations. These micro-areas require further verification. The highest consistency was observed for measurement points (MP) in micro-areas with a buffer radius of up to 0.3 km. Buffers of 0.5 km and 1 km also showed high correlation with buffers of 0.1 km and 0.3 km, with single micro-areas for which the differences were ±0.3 mm/yr. For 5 km and 10 km buffers, the overall fit to the median from the 0.1 km buffer remained good, but here too there were a few areas with differences above ±0.3 mm/yr. Micro-areas with median differences exceeding ±0.3 mm/yr (Table 2) were subjected to detailed analysis later in the study. The RMSE was also calculated for each data set (Table 3).

Table 3

RMSE summary for the analysed buffers

Bufferradius, km	0.1	0.3	0.5	1	5	10
RMSE	0.51	0.51	0.51	0.54	0.78	0.93

Based on the analysis of the median values in the buffers (Table 2) and a review of the literature, 23 stations were selected for which the vertical movements determined from GNSS and InSAR data in a 0.3 km buffer (25×25 m grid after decomposition) were compared. Fourteen stations (DRWP, GDAN, HOZD, JLGR, KATO, KROT, LAMA, NODW, POZN, PRZM, SIPC, WLBR, WLDW, WODZ) showed vertical movements unrelated to the movement of the Earth's crust, which excluded them from further processing in the development of a hybrid model of vertical movements in Poland. Fig. 7 shows the distribution of vertical movements around selected GNSS stations.

The decomposition of EGMS L2a data into a vertical component was performed according to the procedure used in the EGMS L3 (ortho) product, but using a denser 25×25 m grid and a buffer with a radius of 300 m [Renalt Capes & Emanuele Passera, 2023]. The conversion of the LOS movement into a vertical component was performed in accordance with the EGMS L3 procedure, using the decomposition formulas described in [Wieczorek, 2019].

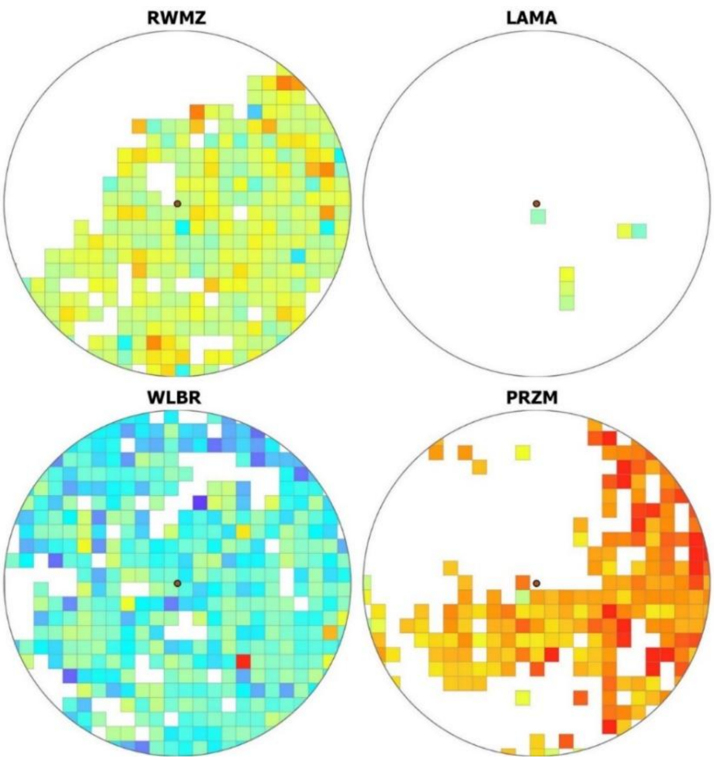

Fig. 7. Vertical motion distribution in the 0.3 km buffer around selected GNSS stations based on EGMS L2a data after decomposition.

The best agreement was obtained for the RWMZ, MLCN and NYSA stations. Clear negative movements were confirmed for the PRZM station, and positive movements for the WLBR station. The LAMA station is difficult to verify due to the lack of permanent diffusers in the micro-area.

Developing a model from hybrid data

The following data were used to construct a model of contemporary relative vertical movements of the Earth's crust:

Set No. 1: Relative vertical movements from levelling data referenced to the Baltic Sea level

Set No. 2: Absolute vertical movements at GNSS stations (ASG-EUPOS).

Set No. 3: Absolute vertical movements in micro-areas around 23 GNSS stations based on EGMS L2a data.

A proprietary data integration procedure was used (Fig. 8). The vertical movement values for 9 GNSS stations from sets 2 and 3 were averaged, and for 14 stations with different movements, the GNSS data was replaced with data from set 3. The median error rate was used as the compliance criterion.

Relative vertical movements from levelling data were taken as reference values.

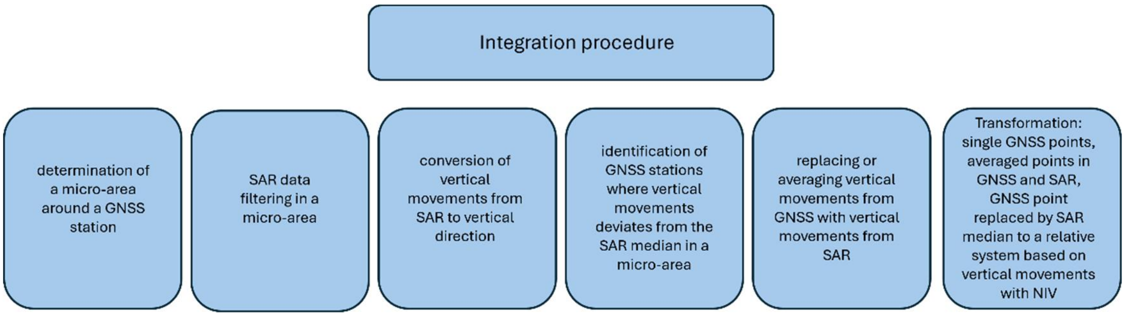

Fig. 8. Integration procedure.

Based on the literaturę [Naumowicz & Kowalczyk, 2025] on data merging, an affine transformation was applied while maintaining the consistency of the adjustment points, using 11 connection points. These points were defined as pseudo-nodal points [Bednarczyk et al., 2018] and determined based on the theory of scale-free networks [Kowalczyk A. M. & Bajerowski, 2020]. As a result of the transformation, a mean unit error of $m_o = 0.17$ mm/yr and a transformation error $m_t = 0.23$ mm/yr for a single point were obtained. The maximum error for a single point was 0.4 mm/yr and concerned 4 points.

Fig. 9 shows the final result of the work in the form of a model of contemporary vertical movements of the Earth's crust using hybrid data. A local polynomial was used to build the model [Fan & Gijbels, 2018].

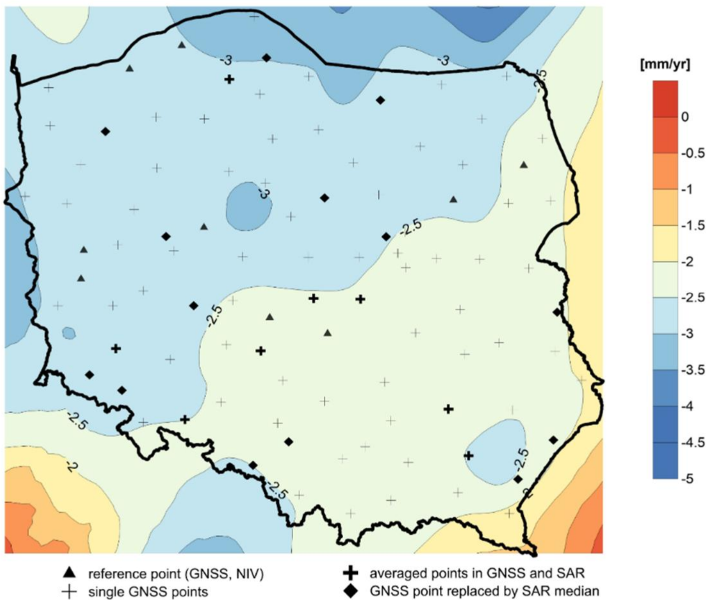

Fig. 9. Model of modern vertical crustal movements using hybrid data and the local polynomial method.

Conclusions

The conducted research has demonstrated that it is possible to develop a model of relative vertical movements of the Earth's crust based on the integration of data from levelling measurements, GNSS, and InSAR. The use of affine transformation as a method of combining vertical movements determined in different reference systems yielded very good results, with a transformation error of 0.2 mm/yr for a single point. The EGMS L2a product, after decomposition into a vertical component, proved to be reliable in the process of verification and supplementation of vertical movements at selected GNSS stations. It was confirmed that a buffer of 0.3 km is optimal for this purpose, ensuring high consistency of results. Due to the diversity of vertical movement values in micro-areas, the use of the median as a representative measure for the MP point set proved to be justified.

The analysis showed that in some GNSS station locations there are vertical movements related to anthropogenic factors, which requires their exclusion from the geodynamic model. Data from the EGMS L2a product can be used to create vertical movement models after decomposition. Further research should focus on the wider application of the EGMS L3 product, particularly for the correction of models taking into account geological components such as subsidence or tectonic movements.

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ВИКОРИСТАННЯ ГІБРИДНИХ ДАНИХ: PSINSAR, GNSS ТА НІВЕЛЮВАННЯ ПІД ЧАС РОЗРОБЛЕННЯ СУЧАСНОЇ МОДЕЛІ ВЕРТИКАЛЬНИХ РУХІВ ЗЕМНОЇ КОРИ В ПОЛЬЩІ

Мета цієї статті – навести першу в Польщі модель сучасних відносних вертикальних рухів земної кори, побудовану на основі інтеграції даних про вертикальні рухи, отриманих із трьох джерел: вимірювань GNSS (ASG-EUPOS), постійних розсіювачів PsInSAR із продуктів EGMS та подвійних високоточних нівелювань. Через відмінності у часовій та просторовій роздільній здатності даних виникла необхідність розроблення узгодженої методології інтеграції. Під час злиття даних було застосовано афінне перетворення для приведення абсолютних вертикальних рухів (GNSS та PsInSAR) до відносної системи, узгодженої із нівелірними даними. Дані InSAR походили із продуктів EGMS L2a (після декомпозиції на вертикальну складову) та EGMS L3. Аналіз показав, що оптимальний радіус буфера для даних InSAR під час дослідження мікрорайонів навколо станцій GNSS становить 0,3 км, а використання медіани як репрезентативного значення статистично обґрунтоване. Середня похибка трансформації для однієї точки становила приблизно 0,20 мм/рік. Остаточну модель розроблено методом локальних поліномів, а отримані результати є підґрунтям для подальших геодинамічних досліджень і можуть бути використані у цивільному будівництві та управлінні геологічними ризиками.

Ключові слова: гібридні дані, інтеграція даних, вертикальні рухи кори, PsInSAR, трансформація, мікрорайони.

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