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INFLUENCE OF GEOPHYSICAL SIGNALS ON COORDINATE VARIATIONS GNSS PERMANENT STATIONS IN CENTRAL EUROPE

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ABSTRACT: This article presents an analysis of the extent of the impact of deformations of the earth's crust resulting from geophysical models on changes in the coordinates of Global Navigation Satellite System (GNSS) stations. The author presents the results of analyses of the spatial correlation coefficient of deformation components for the non-tidal atmospheric loading (NTAL), non-tidal ocean loading (NTOL) and hydrological loading (HYDRO) models of geophysical deformation. In addition, the author calculated the correlation coefficients between station's coordinate series to determine whether the deformations of the earth's crust have a more global, large-area (regional scale) or local-range (local scale) impact, limited to the nearest of stations. In addition to correlation coefficients, the author analysed the similarity in periodic components between station coordinates by calculating the coherence between them. The results of the analysis showed that for the height components (Up), we observe the global range of deformation models, and the NTAL deformation has the greatest influence on the change in them. The lack of correlation between coordinate signals for horizontal components may result from specific local conditions in the place of the station, low-resolution of geophysical models and small amplitudes of these signals in relation to noise. An analysis of the coherence coefficients showed that each station coordinates shows completely different periodic components in the North, East and Up directions.

Keywords: GNSS time series, model deformation of the Earth's Crust, coherence signal, correlation coefficients.

1. INTRODUCTION

The time series of coordinates (north, N; east, E; and up) of the Global Navigation Satellite System (GNSS) are used to analyse, amongst other things, global or local geodynamic processes. The appropriate interpretation of coordinate changes in time series is extremely important for this purpose. Coordinate changes result not only from global geophysical processes occurring on the surface of the earth's crust but also from specific local conditions at the station. The earth's crust is also subjected to tidal phenomena with half-day and daily oscillations in GNSS station positions that interfere with the correct determination of its long-term components (Penna and Stewart, 2003). The presence of these signals has been well described by Lambert et al. (1998) and Dong et al. (2002). Deformations of the earth's surface crust influence not only the geodynamic determination of the area but also the realisation of the reference system in the world. Crétaux et al. (2002) showed that geocenter motion can be determined based on the surface loads caused by atmospheric pressure, hydrological changes (water storage) and ocean loads. Deformations of the earth's crust also affect the changes in the external gravitational field because of the direct attraction of moving masses, which is related to the induced surface load. In the past 30 years, slight changes in gravity caused by surface loads have been observed (Yoder et al., 1983; Ivins et al., 1993; Cheng et al., 1999, 2004; Cox et al., 2002; Hughes and Stepanov, 2004), and gravitational changes affect the local geoid models. In turn, Dragert et al. (2000) showed the inclusion of deformation correction for the Western Canada Deformation Array (WCDA) station network, which is the subject to oceanic tidal deformations in the lithosphere. The application of ocean load corrections diminished the correlation between WCDA deformations and oceanic loads. It should be noted that taking into account global or local deformations of the earth's crust at the stage of observation development is extremely important for the correct interpretation of geodynamic phenomena as well as for the realisation of the global reference system.

In this article, the author focused on analysing the models of deformation of the earth's crust caused by non-tidal atmospheric loading (NTAL), non-tidal ocean loading (NTOL) and hydrology (HYDRO) in terms of the extent of influence of deformation on GNSS station coordinates time series. Besides, the author performed a correlation analysis between the coordinates of selected GNSS stations, as well as between the coordinates and the deformation components of individual deformation models, to determine whether the deformations from geophysical models are global or local. Besides, the coherence between coordinate signals of GNSS stations was also calculated.

2. MOTIVATION

Kaczmarek and Kontny (2018a) analysed the impact of the deformation of the surface of the earth's crust (estimated based on the geophysical models) on changes in the coordinates of GNSS stations at the station's location. A strong correlation was demonstrated between modelled crust deformations and coordinate changes only for the height component. Horizontal components are poorly correlated with crust motion, and periodic are often shifted in phase. The amplitudes of periodic changes in horizontal coordinates are small (up to ±1 mm) and, in principle, do not exceed the noise level, which clearly shows the nature of coloured noise (Kaczmarek and Kontny, 2018b).

Deformations of the surface of the earth's crust caused by geophysical factors (NTAL, HYDRO and NTOL) are probably of considerable scope because of the global models being estimated. The analysis of the extent of deformation and their impact on coordinate changes will allow to assess if the extent of changes in the GNSS station coordinates are caused by global and local geophysical factors.

2. INPUT DATA AND STRATEGY

The time series of coordinates of GNSS permanent stations from the development of the Center for Orbit Determination in Europe (CODE) Repro2013[1] were used for the analyses. These data were selected because of the lack of consideration of geophysical models of surface deformation of the earth's crust at the stage of developing strict GNSS observations.[2] Kaczmarek and Kontny (2018a) allowed the use of the same data (coordinates and

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[1] International GNSS Service, 2nd Data Reprocessing Campaign. Available online: http://acc.igs.org/reprocess2.html (accessed on 18 March 2019).

[2] INTERNATIONAL GNSS SERVICE, CODE Analysis Strategy Summary for IGSrepro2. Available online:ftp://ftp.aiub.unibe.ch/REPRO_2013/CODE_REPRO_2013.ACN (accessed on 18 March 2019).

deformations) to maintain consistency with the analyses in question. They used the online[3] service for the interpolation of deformations from geophysical models for specific GNSS stations. However, in these investigations, the deformations were interpolated (linear interpolation) from the Global Geophysical Fluid Centre (GGFC) deformation models available in the Federal Agency for Cartography and Geodesy in Germany/Bundesamt für Kartographie und Geodäsie (BKG) centre in the Network Common Data Form (NetCDF) format with a spatial resolution of 2.5° × 2.5°.

The computational strategy consisted of the determination of the Pearson correlation coefficient (*R*) between the earth's crust deformations for the GNSS station and the nodes of the deformation model grid and then the development of isolation coefficient maps of *R*. Besides, periodic components for coordinate residuals were analysed. The *R* for the North, East and Up components between the analysed GNSS stations (Fig. 1) was also examined.

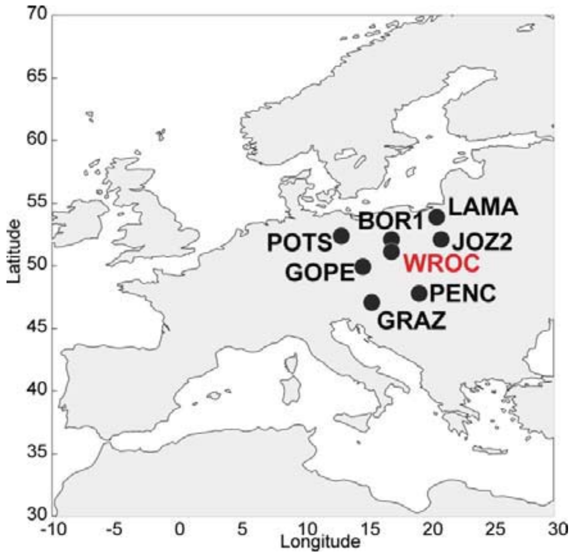

Fig. 1. Localisation of the analysed GNSS stations.

3. ANALYSIS

3.1 ANALYSIS OF SPATIAL CORRELATION COEFFICIENT FOR GEOPHYSICAL DEFORMATION MODELS

The analysis of the spatial *R* was aimed at investigating whether the extent of deformation of the earth's crust determined from geophysical models is more local or global. For this purpose, individual components of the deformation model were analysed: NTAL, NTOL, HYDRO and the sum of all deformities (SUM). Figure 2 shows the spatial distribution of the NTAL deformation *R*, relative to the location of the WROC station. It can be noticed that the extent of NTAL deformation relative to the WROC (Poland) station is significant and global. Besides, the largest changes in the *R* for the horizontal north component occur in the north direction, whereas for the horizontal east component, they occur in the east direction. However, for the height component up, the distribution of the deformation *R* relative to the WROC station decreases with an increase in the distance from the station without showing any significant anisotropy.

[3] http://ida.bkg.bund.de/refsys/ (accessed on 18 March 2019).

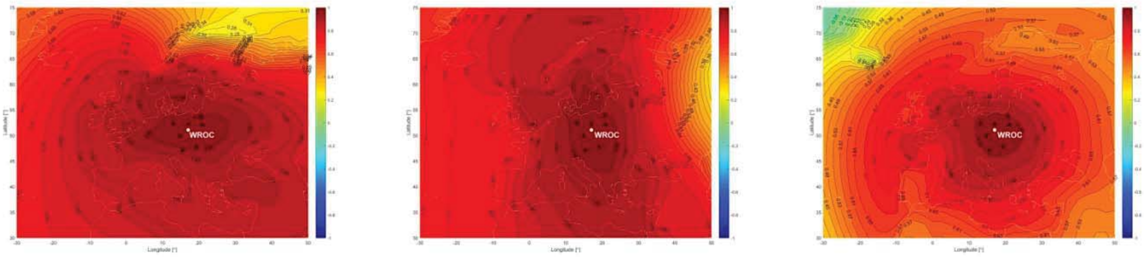

Fig. 2. Distribution of NTAL deformation correlation coefficient relative to the WROC station (Poland): from left, North, East and Up (for a high-resolution picture, refer to Appendix 1).

Figure 3 shows the spatial distribution of NTOL deformation, with respect to the WROC station. Here we are dealing with the global character of the deformation distribution. It can be seen that for the horizontal east component, the gradient of the *R* is unequivocally oriented meridionally. As we move away from the WROC station towards the west, the *R* decreases rapidly, whereas towards the east, the *R* decreases. The northern component of horizontal NTOL deformation diminishes concentrically, and its *R* is high even at large distances from the station. For the height component (up), the largest decrease in the *R* occur along the coasts of the seas and the Atlantic Ocean ($\Delta R \approx 0.4$).

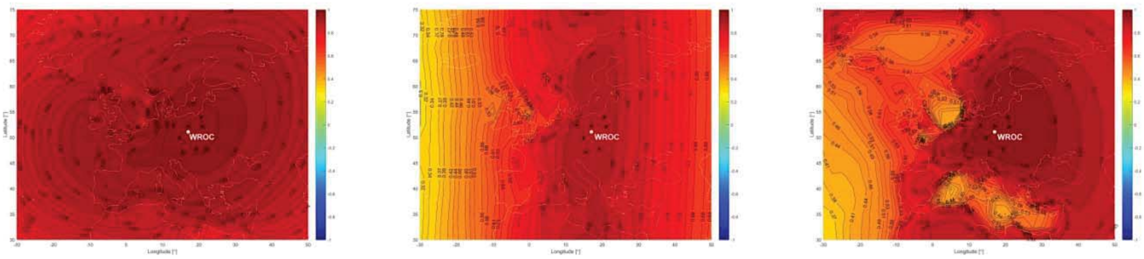

Fig. 3. Distribution of the NTOL deformation correlation coefficient relative to the WROC station (Poland): from left, North, East and Up (for a high-resolution picture, refer to Appendix 1).

In turn, Figure 4 presents the spatial distribution of the *R* of the earth's crust deformation caused by HYDRO, which diminishes rapidly in the north–west direction for all the components. The reason may be that hydrological models are not very accurate in this region. Similar to the previous ones, the HYDRO model shows also the global nature of surface deformation of the shell.

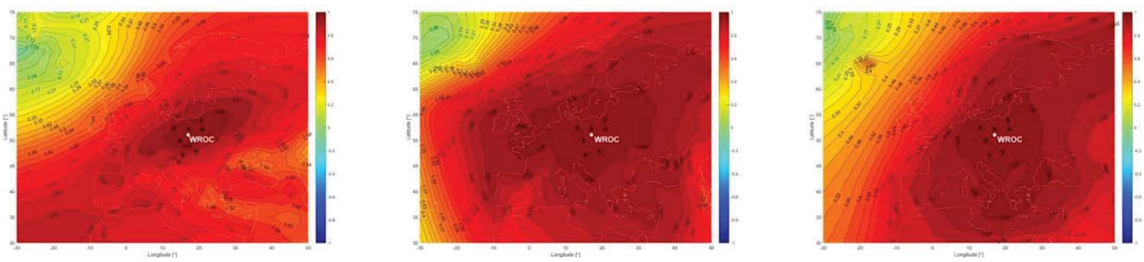

Fig. 4. Distribution of the deformation correlation coefficient HYDRO relative to the WROC station (Poland): from left, North, East and Up (for a high-resolution picture, refer to Appendix 1).

The distribution of the *R* for the sum of all the analysed sources of deformation was also analysed (NTAL, NTOL and HYDRO; Fig. 5).

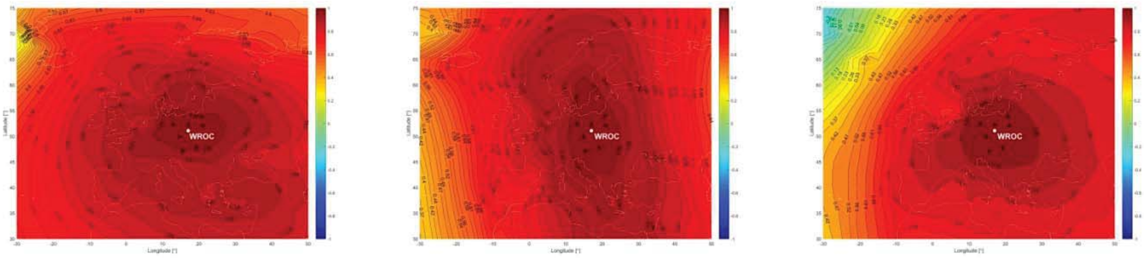

Fig. 5. Distribution of the deformation correlation coefficient of the SUM relative to the WROC station (Poland): from left, North, East and Up (for a high-resolution picture, refer to Appendix 1).

For all components (north, east and up), the *R* shows a roughly concentric, isotropic distribution and decreases slightly with increasing distance from the WROC station. At further distances, the change in the *R* for the east component is strictly directed to the east–west direction. The greater the distance from the WROC GNSS station, the greater is the change in *R*. For the up component, the largest decrease in *R* gradient (≈0.4) is towards the Atlantic Ocean (NW).

3.2. ANALYSIS OF THE CORRELATION COEFFICIENT BETWEEN THE COORDINATES OF THE ANALYSED GNSS STATIONS

In Section 3.1, the author showed that the impact of deformation of the earth's crust on the changes in the coordinates of the analysed stations (a large range and smooth model of *R* coefficient changes). Besides, to determine whether the global influence of deformation on changes in the N, E and Up components is similar for the analysed stations and whether it is of decisive importance, *R* was calculated. The *R* between the central GNSS WROC station and neighbour stations was calculated. The *R* was calculated for the N, E and Up components, and the results are presented in Figure 6. Besides, the significance of the *R* was calculated using the Student's test (95% significance and degrees of freedom >3,000). The significance of the *R* was represented in green in Figures 6 and 8 and was formatted in bold in Table 1.

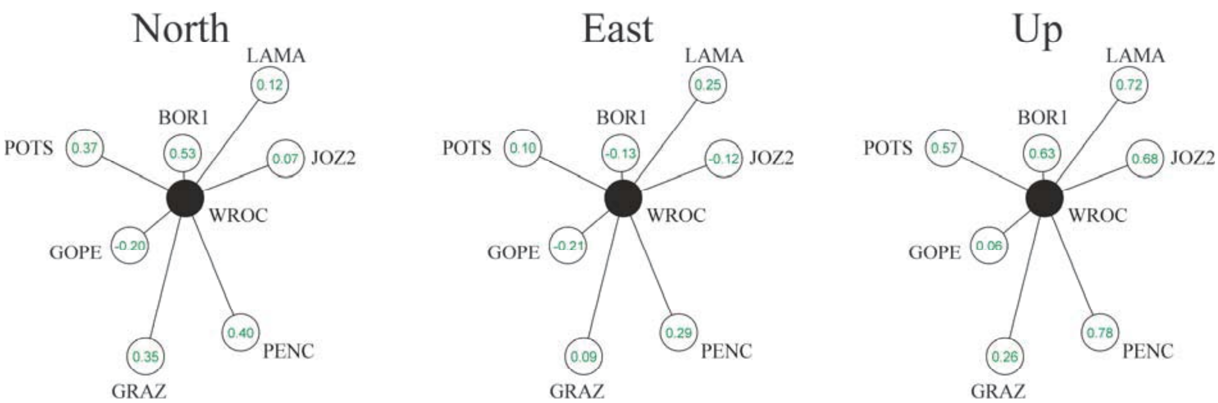

Fig. 6. Spatial distribution of correlation coefficients between coordinates of the WROC station and coordinates of the neighbour GNSS stations (green colour represents statistically significant *R* coefficients).

By analysing Figure 6, it can be seen that for horizontal components, the *R* between coordinates is small. However, for the height component (Up), we can see that the value of the correlation *R* is much greater than that for the horizontal components. In addition, it can be concluded that the global extent of influence of deformation is registered in this area by the analysed GNSS stations, and the *R* between the coordinates of the height components is the same as between coordinates and the sum of deformations at the location of the GNSS station (Kaczmarek and Kontny, 2018a). Small correlation for horizontal components may be caused by the small amplitude of their periodic changes in relation to the noise level (Kaczmarek and Kontny, 2018b). Local conditions, which are different for each station, may have a large influence on the value of the *R* between stations and their significance for coordinate variations are difficult to estimate.

In the next step, the stations for which the amplitude of the earth's surface deformation (SUM) signal amplitude are similar or greater than that of coordinate changes for the analysed GNSS stations were selected (for detail, the signal modelling is presented in Kaczmarek and Kontny, 2018a). Only the height component (Up) was selected for analyses because of the high value for *R* between coordinate changes and deformations. The stations BOR1, LAMA and WROC were selected (Fig. 7).

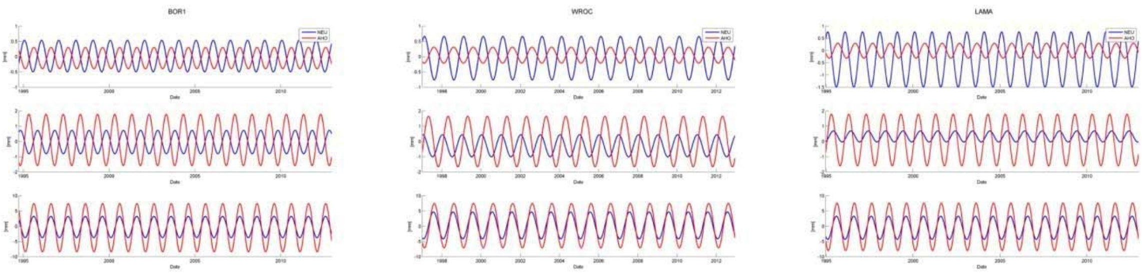

Fig. 7. Models of oscillations in GNSS coordinates and deformations of the earth's crust for selected GNSS stations (from the left: BOR1, WROC and LAMA; blue represents coordinates and red deformation; for a high-resolution picture, refer to Appendix 1).

The high values for *R* between the height coordinates of GNSS stations are show in Figure 8.

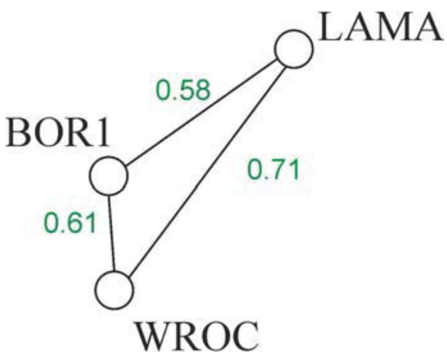

Fig. 8. Correlation coefficients between the Up components of the coordinates of selected GNSS stations (green represents statistically significant *R* coefficients).

3.3 ANALYSIS OF THE CORRELATION COEFFICIENT BETWEEN COORDINATES AND ANALYSED MODELS

In order to identify the most influential geophysical factors, a correlation analysis was carried out between the GNSS station coordinates and surface deformations of the earth's crust estimated independently from particular geophysical models: NTAL, NTOL and HYDRO. Table 1 presents the comparison of *R* for the analysed stations.

Table 1. Values of correlation coefficients between coordinate changes and deformations for particular geophysical models (values in bold are statistically significant *R* coefficients).

Station	HYDRO			NTAL			NTOL		
	N	E	Up	N	E	Up	N	E	Up
WROC	−0.16	−0.01	0.05	−0.12	−0.15	**0.46**	0.05	−0.02	0.27
BOR1	0.03	−0.26	0.31	−0.15	−0.08	**0.65**	0.10	−0.02	0.22
JOZ2	−0.23	−0.12	0.35	−0.06	−0.07	**0.57**	0.06	0.07	0.33
GRAZ	−0.15	−0.04	**0.49**	−0.11	−0.14	**0.43**	0.02	0.05	0.36
PENC	−0.09	−0.07	0.22	−0.03	−0.27	**0.54**	0.03	−0.01	0.28
GOPE	−0.18	−0.17	**0.44**	−0.08	−0.08	**0.40**	−0.03	0.00	0.28
LAMA	−0.27	0.02	−0.02	−0.11	0.02	0.35	0.03	−0.02	−0.01
POTS	−0.26	−0.03	0.24	−0.06	−0.12	**0.50**	−0.05	0.00	0.16

In Table 1, it can be seen that the largest values of the *R* between coordinate changes and deformations occur in the Up component of the NTAL model as it was previously noticed by Kaczmarek and Kontny (2018a) in the case of Up component and the SUM of all deformation models. Differences in *R* (NTAL from Table 1 and Kaczmarek and Kontny, 2018a) for deformations from the NTAL model and SUM deformations are within the range of −0.06 to 0.16, so they are not very significant.

3.4. ANALYSIS OF PERIODIC COMPONENTS OF COORDINATE RESIDUALS

The analysis of periodic components of coordinate residuals after subtraction of the trend and the annual periodic component for the analysed stations showed that the amplitudes of signals occurring in these residuals are very small in relation to the original signal. The iterative least square estimation (iLSE) method discussed by Kaczmarek and Kontny (2018a) was used for the analysis of periodic components in the coordinate residuals. The sample results for the WROC station are outlined in the form of charts in Figure 9.

The charts clearly show that the modelled annual period has been removed from the coordinate series for North, East and Up components. In addition, it can be noticed that in the coordinate residuals, there are other periodic components related to, for example, a draconic periods Global Positioning System (GPS) orbits modelling (approximately 351.4 days), semi-annual period of the tropical year and harmonics period of GLONASS satellites and other unidentified periodic components. The mentioned periodic components may affect the type and size of noise in the coordinate ranks on the measurement stations and result from local conditions. Confirmation of the influence of local conditions may be the fact that each measurement station frequently registers various periodic components (although, in the analyses presented above, the effect of global deformations of the earth's crust on coordinate changes was found).

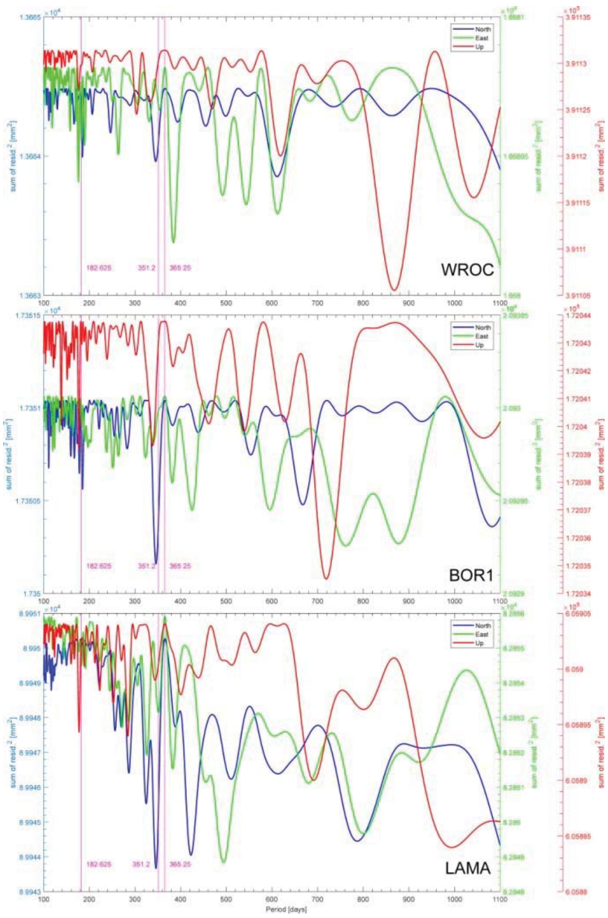

Fig. 9. Distribution of GNSS station coordinate signals residual after removing the linear trend and the annual periodic signal using iLSE approach (for a high-resolution picture, refer to Appendix 1).

3.5 COHERENCE COEFFICIENT ANALYSIS BETWEEN COORDINATE SIGNALS OF GNSS STATIONS

The analysis of the coherence coefficient as a function of the oscillation period was performed in order to check whether similar periodic signals are present the analysed stations coordinates (Fig. 1). For this purpose, the function of coherence analysis in the MATLAB environment was used. Coherence analysis did not assume a specific period in the time series. Raw signals of the coordinate time series for N, E and Up components were analysed.

Studies have shown that each of the analysed stations shows different periodic components (Table 2) with values for a coherence coefficient greater than 0.50: 341.3, 107, 58, 49 and 186 days (harmonic period: 372 days) and components with periods 1–3 days. Tseng et al. (2017) also showed a periodic component of 341.3 days but in the Z component of geocenter motion, which is close to the draconic period of GPS (about 351.4 days). However, for too short a time series, it is not possible to separate the draconic year oscillation from the annual one. Besides, the recited values of periodic components do not occur for all analysed stations. Each station has its periodic components and different components for individual North, East and Up components. The occurrence of such significant differences (despite the global impact of the deformation of the earth's crust) confirms that a very significant impact on periodic components as well as on station coordinate variations have local conditions that are difficult to identify and estimate.

Table 2. Periodic components with coherence coefficients for station pairs.

Station pairs	North (coherence)	North (period in days)	East (coherence)	East (period in days)	Up (coherence)	Up (period in days)
WROC–BOR1	0.60	341.3			0.93	341.3
	0.57	157.5				
	0.50	107.7			0.60	107.7
	0.55	89.0			0.73	89.0
	0.68	70.6	0.61	73.1	0.55	70.6
	0.82	58.5	0.77	56.9		
WROC–JOZ2					0.92	341.3
			0.54	204.8	0.72	204.8
	0.66	170.7	0.55	102.4	0.81	170.7
	0.63	51.2	0.54	51.2		
WROC–GRAZ	0.74	341.3	0.57	682.7	0.91	341.3
	0.51	204.8	0.50	292.6		
	0.75	157.5				
	0.63	113.8				
	0.81	89.0				
	0.76	70.6				
	0.80	49.9	0.67	49.9		
WROC–PENC	0.53	341.3	0.89	409.6	0.95	341.3
	0.70	186.2	0.80	227.6	0.91	89.0
	0.65	102.4	0.67	113.8		
			0.71	70.6		
			0.73	49.9	0.81	49.9
WROC–GOPE	0.68	341.3	0.61	341.3	0.86	341.3
	0.52	186.2			0.75	136.5
	0.72	113.8				
	0.85	49.9	0.56	49.9		
WROC–LAMA	0.54	341.3	0.54	341.3	0.81	341.3
					0.54	186.2
					0.63	70.6
					0.77	51.2
					0.73	45.5
WROC–POTS	0.76	409.6			0.98	341.3
	0.66	186.2				
	0.81	113.8			0.86	113.8
	0.84	58.5	0.62	58.5		
	0.84	49.9	0.70	49.9		

4. CONCLUSION AND DISCUSSION

Summarising the above analyses, it can be concluded that the deformations of the earth's crust caused by NTAL have the greatest influence on the GNSS station coordinates variations. This is confirmed by the values of the *R* between station coordinates and NTAL deformations and between station coordinates and the sum of deformations (SUM) for the Up component as shown by Kaczmarek and Kontny (2018a). Differences in this *R* are between −0.06 and 0.16.

Besides, it was shown that vertical deformations of the earth's crust caused by geophysical factors have an impact on the Up component of analysed stations with a significant global range determined from GNSS measurements. This is confirmed by the high value of *R* between the GNSS station coordinates (Fig. 8). It should be noted that the relatively small *R* for horizontal components may result from the small amplitude of horizontal geophysical deformations in relation to the measurement noise and a significant phase shift between coordinate signals and deformations, demonstrated in the article by Kaczmarek and Kontny (2018a). Owing to the low spatial resolution of global geophysical models, they do not regard significant local phenomena, which can significantly affect the variations in station coordinates. To know better the causes of the variations in the GNSS station coordinates, high-resolution local geophysical models are needed. Coherence analysis for coordinates of GNSS stations has shown that stations often register different periodic components. In addition, these components do not appear in all time series of North, East and Up components.

GNSS stations record various periodic components (e.g. annual and semi-annual oscillations, GPS draconic year, Z geocenter motion oscillation of 341.3 days, draconic of GLONASS constellation of 107 days) despite the global impact of deformations on the surface of the earth's crust.

The author indicates that local conditions are very difficult to be modelled and can have a significant impact on the variability of time series of coordinate components used for geodynamic tests as on recorded periodic components by the GNSS station. The aim of the work has been achieved but requires further analysis by taking into account the influence of local conditions on coordinate changes.

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REFERENCES

Cheng, M., Tapley B. D., 1999, Seasonal variations in low degree zonal harmonics of the Earth’s gravity field from satellite laser ranging observations, J. Geophys. Res.,104, 2667-2681.

Cheng, M., Tapley B. D., 2004, Variations in the Earth’s oblateness during the past 28 years, J. Geophys. Res.,109, B09402, doi:10.1029/2004JB003028

Cox, C. M., Chao B. F., 2002, Detection of a large-scale mass redistribution in the terrestrial system since 1998, Science, 297, 831–833.

Crétaux J. F., Soudarin L., Davidson F. J., Gennero M. C., Bergé-Nguyen M., & Cazenave A., 2002. Seasonal and interannual geocenter motion from SLR and DORIS measurements: Comparison with surface loading data. Journal of geophysical research: solid earth, 107(B12), ETG-16.

Dong D., Fang P., Bock Y., Cheng M. K., & Miyazaki S. I., 2002. Anatomy of apparent seasonal variations from GPS-derived site position time series. Journal of Geophysical Research: Solid Earth, 107(B4), ETG-9.

Dragert H., James T. S., Lambert A., 2000. Ocean loading corrections for continuous GPS: A case study at the Canadian coastal site Holberg. Geophysical research letters, 27(14), 2045-2048.

Hughes C. W., Stepanov V. N., 2004, Ocean dynamics associated with rapid J2 fluctuations: Importance of circumpolar modes and identification of a coherent Arctic mode, J. Geophys. Res.,109, C06002,doi:10.1029/2003JC002176

Ivins E. R., Sammis C. G., Yoder C. F., 1993. Deep mantle viscous structure with prior estimate and satellite constraint. Journal of Geophysical Research: Solid Earth, 98(B3), 4579-4609.

Kaczmarek A., Kontny B., 2018a. Estimates of seasonal signals in GNNS time series and environmental loading models with iterative Least-Squares Estimation (iLSE) approach. Acta. Geodyn. Geomater. 15, 131–141.

Kaczmarek A., Kontny B., 2018b. Identification of the Noise Model in the Time Series of GNSS Stations Coordinates Using Wavelet Analysis. Remote Sens. 10, 1611.

Lambert A., Pagiatakis S. D., Billyard A. P., Dragert H., 1998. Improved ocean tide loading corrections for gravity and displacement: Canada and northern United States. Journal of Geophysical Research: Solid Earth, 103(B12), 30231-30244.

Penna N. T., Stewart M. P., 2003. Aliased tidal signatures in continuous GPS height time series. Geophysical Research Letters, 30(23).

Tseng T. P., Hwang C., Sośnica K., Kuo C. Y., Liu Y. C., Yeh W. H., 2017. Geocenter motion estimated from GRACE orbits: the impact of F10. 7 solar flux. Advances in Space Research, 59(11), 2819-2830.

Yoder C. F., Williams J. G., Dickey J. O., Schutz B. E., Eanes R. J., Tapley B. D., 1983. Secular variation of Earth's gravitational harmonic J2 coefficient from Lageos and nontidal acceleration of Earth rotation. Nature, 303(5920), 757.

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Appendix 1:

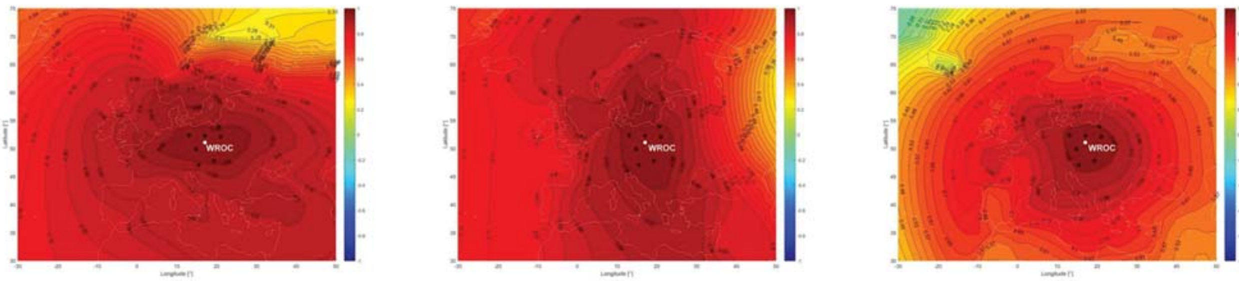

Fig. 2. Distribution of NTAL deformation correlation coefficient relative to the WROC station (Poland): from left, North, East and Up.

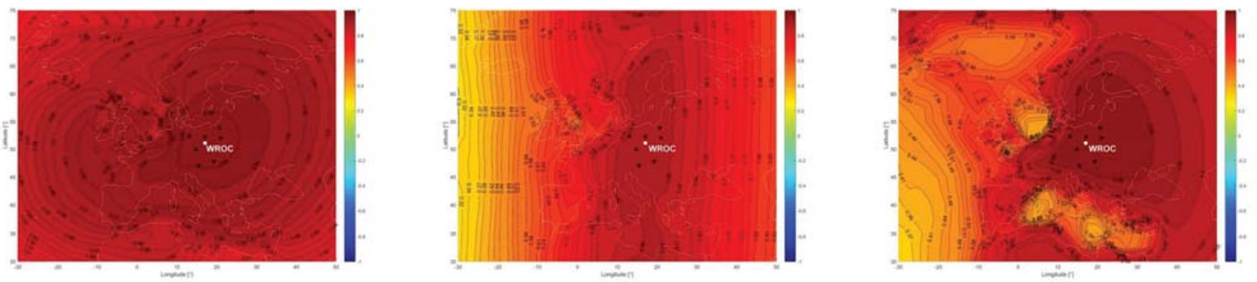

Fig. 3. Distribution of the NTOL deformation correlation coefficient relative to the WROC station (Poland): from left, North, East and Up.

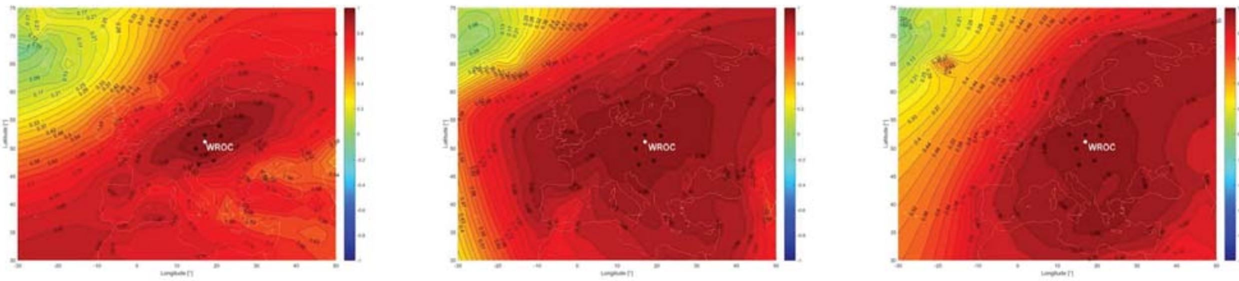

Fig. 4. Distribution of the deformation correlation coefficient HYDRO relative to the WROC station (Poland): from left, North, East and Up.

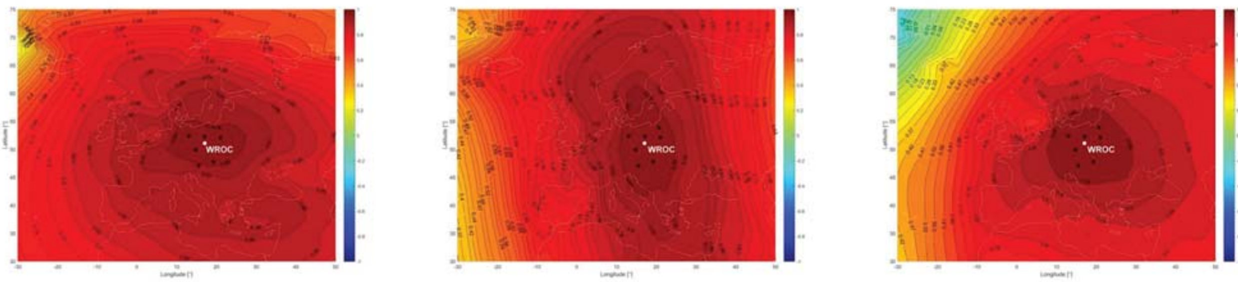

Fig. 5. Distribution of the deformation correlation coefficient of the SUM relative to the WROC station (Poland): from left, North, East and Up.

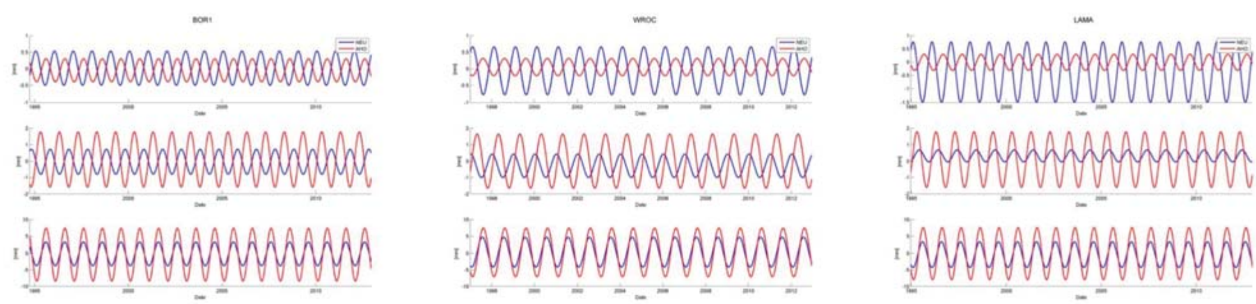

Fig. 7. Models of oscillations in GNSS coordinates and deformations of the earth's crust for selected GNSS stations (from the left: BOR1, WROC, LAMA; blue represents coordinates and red deformation).

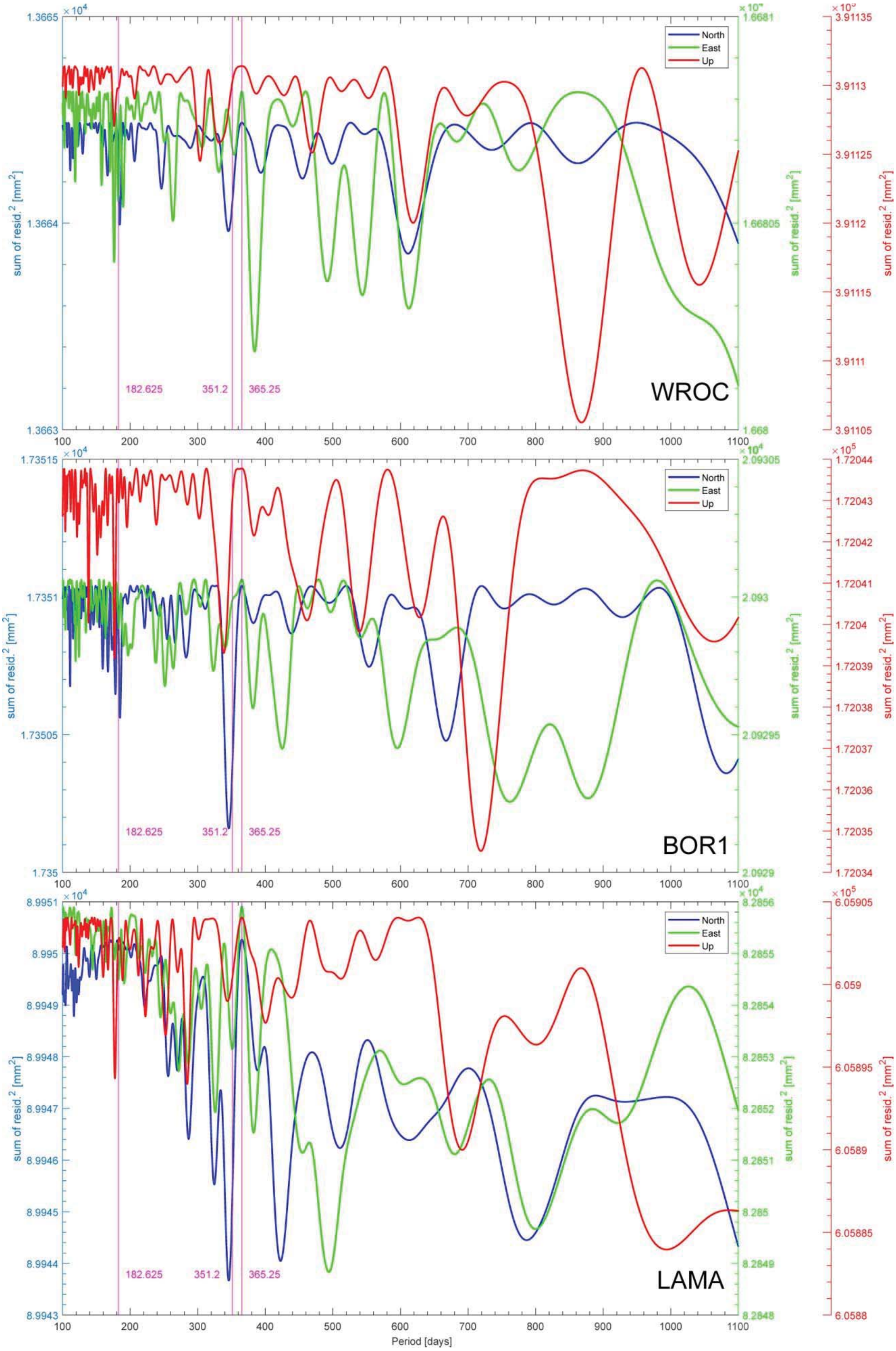

Fig. 9. Distribution of GNSS station coordinate signals residual after removing the linear trend and the annual periodic signal using iLSE approach.