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The Use of National CORS Networks for Determining Temporal Mass Variations within the Earth's System and for Improving GRACE/GRACE-FO Solutions

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Abstract: Temporal mass variations within the Earth's system can be detected on a regional/global scale using GRACE (Gravity Recovery and Climate Experiment) and GRACE Follow-On (GRACE-FO) satellite missions' data, while GNSS (Global Navigation Satellite System) data can be used to detect those variations on a local scale. The aim of this study is to investigate the usefulness of national GNSS CORS (Continuously Operating Reference Stations) networks for the determination of those temporal mass variations and for improving GRACE/GRACE-FO solutions. The area of Poland was chosen as a study area. Temporal variations of equivalent water thickness ΔEWT and vertical deformations of the Earth's surface Δh were determined at the sites of the ASG-EUPOS (Active Geodetic Network of the European Position Determination System) CORS network using GRACE/GRACE-FO-based GGMs and GNSS data. Moreover, combined solutions of ΔEWT were developed by combining ΔEWT obtained from GNSS data with the corresponding ones determined from GRACE satellite mission data. Strong correlations (correlation coefficients ranging from 0.6 to 0.9) between detrended Δh determined from GRACE/GRACE-FO satellite mission data and the corresponding ones from GNSS data were observed at 93% of the GNSS stations investigated. Furthermore, for the determination of temporal mass variations, GNSS data from CORS network stations provide valuable information complementary to GRACE satellite mission data.

Keywords: equivalent water thickness; GNSS; GRACE/GRACE-FO; temporal mass variations within the Earth's system; vertical surface deformation

1. Introduction

The determination of temporal mass variations in the Earth's system with high accuracy as well as high spatial and temporal resolutions using space geodetic data is one of the main scientific problems in the Earth science-related disciplines. Since the last decade, the Gravity Recovery and Climate Experiment (GRACE; [1]) satellite mission operated between March 2002 and October 2017, brought a unique opportunity for the determination of temporal mass variations within the Earth's system. Its concept, including theoretical background as well as impressive scientific results, has widely been demonstrated by many authors (e.g., see the review given by [2]). The tremendous success achieved from the mission emphasized the need of launching a GRACE-type mission for a sustainable long-term monitoring of temporal mass variations within the Earth's system. The GRACE Follow-On (GRACE-FO; https://gracefo.jpl.nasa.gov/) satellite mission of a designed life of five years has been launched in May 2018. The GRACE and GRACE-FO missions, without any doubt, are a state-of-the-art space geodetic technique for monitoring temporal mass variations within the Earth's system. They have

clearly revolutionized research in many disciplines of Earth sciences. Besides GRACE-type satellite missions, the Global Navigation Satellite System (GNSS) has proven itself as one of the most powerful space geodesy tools for the determination of temporal mass variations in the Earth's system and related geodynamic processes. It is successfully used to study the elastic ground loading deformation in response to the Earth's hydrological mass variations. Since the beginning of this century, numerous studies on the relation between the mass loading and the Earth's surface deformations obtained from GNSS data have been conducted on a global scale (e.g., [3–7]), on a continental scale, e.g., South America [8]; and Europe [9], as well as on a local/regional scale, e.g., Japan [10]; the Amazon basin [11]; Bangladesh [12]; Greenland [13]; the West Africa [14]; North America [15–18]; China [19–22]; Tibet [23,24]; Poland [25,26]; and the East Africa [27]. Except van Dam et al. [9] that indicated poor correlation between the annual vertical crustal deformation from GRACE and GPS at 36 GPS sites over Europe, all those studies revealed very good agreement (correlation coefficient >0.6) between the Earth's surface deformations obtained from GNSS data and the corresponding ones determined from GRACE data. In addition to GNSS and GRACE data, other space geodetic techniques, e.g., the very long baseline interferometry (VLBI), indicated that the vertical crustal deformations due to continental water loading reach up to 15 mm [28].

The latest official GRACE/GRACE-FO level-2 products, i.e., RL06 (release 6) GRACE/ GRACE-FO-based Global Geopotential Models (GGMs), developed by GFZ (GeoForschungsZentrum), CSR (Center for Space Research) and JPL (Jet Propulsion Laboratory) centers (cf. [29–32]) are currently available for scientific users. In addition to GRACE/GRACE-FO-based GGMs, global mass concentration (mascon) products of NASA (National Aeronautics and Space Administration), GSFC (Goddard Space Flight Center), JPL and CSR have also been released to the scientific community [33–35]. On the other hand, national GNSS CORS (Continuously Operating Reference Stations) networks are rapidly growing and being continuously expanded around the world. Currently, national GNSS CORS networks are in operation in Australia, North America and almost all European countries (e.g., networks of the EUPOS multifunctional reference stations) as well as in some countries in Africa, Asia and South America. National GNSS CORS networks are regarded as a multifunctional precise positioning system that provides very valuable information for: (1) static and Real-Time Kinematic (RTK) positioning; (2) monitoring crustal deformations; (3) definition and realization of global, regional and national geodetic reference frames; (4) atmosphere related studies; etc. Besides national GNSS CORS networks, a number of dense regional/local GNSS CORS networks have been established for a specific scientific research, e.g., the PBO H₂O (Plate Boundary Observatory Studies of the Water Cycle) established to study the 3D strain field resulting from deformation across the active boundary zone between the Pacific and North American plates in the western United States as well as remotely measured changes in soil moisture content, snow depth, water content of the troposphere, and ground motions related to changes in the water table (e.g., [36]).

The coarse spatial resolution of GRACE/GRACE-FO products is one of the main weaknesses of GRACE-type missions. Moreover, GRACE/GRACE-FO level-2 products (e.g., GRACE/GRACE-FO-based GGMs) as well as GRACE-based mascon products being the results of a complex processing of GRACE mission data, are released to scientific users with a delay of a few months. On the other hand, temporal mass variations can be obtained using GNSS data in real or near real time, but they represent the local effect for a very limited area within the radius of a few kilometers from a GNSS station. Furthermore, coordinate variations obtained from GNSS data are affected by many errors, e.g., the draconitic error that systematically affects the seasonal periods in GNSS series (e.g., [37]). However, investigation concerning the use of national GNSS CORS networks to study temporal mass variations within the Earth's system is essentially needed. The main objective of this study is to investigate the use of national GNSS CORS networks for monitoring temporal mass variations within the Earth's system on a regional/local scale determined from GRACE/GRACE-FO satellite missions' data. The study area and data used are described in

Section 2. In Section 3, the methods implemented for the determination of vertical deformations of the Earth's surface Δh and temporal variations of equivalent water thickness using GRACE/GRACE-FO satellite mission and GNSS data as well as the determination of ΔEWT combined solutions using these data are specified. The results obtained are presented and analyzed in Section 4. Moreover, in Section 4, the improvement of ΔEWT determined from GRACE satellite mission data when adding ΔEWT determined from GNSS data is illustrated. Finally, in Section 5, discussions and conclusions concerning the usefulness of GNSS data from CORS network stations for the determination of Δh and ΔEWT as well as for improving GRACE/GRACE-FO solutions are given.

2. Study Area and Data Used

The area of Poland has been chosen as a study area. A national GNSS CORS network in this area, called the Active Geodetic Network of the European Position Determination System (ASG-EUPOS), consists recently of 102 GNSS stations apart from each other by about 70 km; http://www.asgeupos.pl, are operating since 2008. Daily GNSS data from 96 ASG-EUPOS stations covering the period 2008–2018 were used within the course of this study. Figure 1 illustrates the study area as well as the ASG-EUPOS sites used.



Figure 1. Study area and the location of Global Navigation Satellite System (GNSS) stations used.

Beside the GNSS data from ASG-EUPOS stations, CSR RL06 GRACE/GRACE-FO-based GGMs were utilized in this study. In order to reduce the noise included in RL06 GRACE/GRACE-FO-based GGMs, the DDK3 (decorrelation 3) filter (cf. [38]) that indicates a good performance over the area investigated [39], was applied. Moreover, CSR RL06 GRACE/GRACE-FO-based GGMs developed as monthly solutions obtained from GRACE/GRACE-FO satellite missions were truncated at d/o 60 that corresponds to the spatial resolution, i.e., $3^{\circ} \times 3^{\circ}$ at the equator.

The WaterGAP Global Hydrology Model (WGHM) Version 2.2d (e.g., [40,41]) was used for the evaluation purposes. This hydrological model represents the terrestrial hydrological cycle with a

spatial resolution of 0.5 degree. Within the context of the investigation conducted in this study, monthly variations of equivalent water thickness for the period 2008–2016 were obtained at the ASG-EUPOS sites from the WGHM.

3. Methods

The methods implemented for the determination of monthly vertical deformations of the Earth's surface and monthly variations of equivalent water thickness from GRACE/GRACE-FO-based GGMs and GNSS data are described in Sections 3.1 and 3.2, respectively. In Section 3.3, the method applied to determine combined solutions of monthly variations of equivalent water thickness $\Delta EWT_{m-CombSol}$ is presented. In Section 3.4, uncertainties of monthly variations of equivalent water thickness determined from GNSS and GRACE/GRACE-FO satellite missions' data as well as their combined solutions are estimated. The general steps of the method implemented within this investigation are summarized in Figure 2.



Figure 2. General steps of the method implemented to determine combined solutions of ΔEWT and evaluate monthly variations of equivalent water thickness from Gravity Recovery and Climate Experiment/GRACE-Follow-On (GRACE/GRACE-FO)-based Global Geopotential Models (GGMs) and GNSS data.

3.1. The Determination of $\Delta h_{m-GRACE}$ and $\Delta EWT_{m-GRACE}$

Monthly vertical deformations of the Earth's surface $\Delta h_{m-GRACE}$ and monthly variations of equivalent water thickness $\Delta EWT_{m-GRACE}$ were determined at the sites of the ASG-EUPOS CORS network using GRACE/GRACE-FO-based GGMs as follows [9,20,42,43]:

$$\Delta h_{\text{m-GRACE}} = a \sum_{n=0}^{N_{\text{max}}} \sum_{m=0}^{n} P_{nm}(\sin\varphi) \frac{h_n}{1+k_n} (\Delta C_{nm} \cos m\lambda + \Delta S_{nm} \sin m\lambda)$$
(1)

$$\Delta EWT_{m-GRACE} = \frac{a \times \rho_{avg}}{3\rho_w} \sum_{n=0}^{N_{max}} \sum_{m=0}^{n} P_{nm}(\sin\varphi) \frac{2n+1}{1+k_n} (\Delta C_{nm} \cos m\lambda + \Delta S_{nm} \sin m\lambda)$$
(2)

where φ , λ are spherical geocentric coordinates of the computation point, *a* is the radius of the Earth (semi-major axis), ρ_w is the water density, ρ_{avg} is the Earth's average density, *k* and *h* are load Love numbers of degree *n* based on the Preliminary Reference Earth Model (PREM; [44]) obtained from [45], ΔC_{nm} and ΔS_{nm} are the differences between fully normalized spherical harmonic coefficients from monthly RL06 GRACE/GRACE-FO-based GGMs and the corresponding ones obtained from a reference GGM, P_{nm} are the fully normalized Legendre functions of degree *n* and order *m*, and N_{max} is the maximum degree applied.

The $P_{nm}(\sin\varphi)$ are determined using a recursive algorithm as follows (e.g., [46]):

$$P_{00}(\sin \varphi) = 1.0$$

$$P_{11}(\sin \varphi) = \sqrt{3} \cos \varphi$$

$$P_{nn}(\sin \varphi) = \sqrt{\frac{(2n+1)}{n}} \cos \varphi P_{(n-1)(n-1)}(\sin \varphi)$$

$$P_{nm}(\sin \varphi) = \sqrt{\frac{(2n-1)(2n+1)}{(n-m)(n+m)}} \cos \varphi P_{(n-1)m}(\sin \varphi)$$

$$-\sqrt{\frac{(2n+1)(n+m-1)(n-m-1)}{(2n+3)(n+m)(n-m)}} \cos \varphi P_{(n-2)m}(\sin \varphi)$$
(3)

In this study, $\Delta h_{m-GRACE}$ and $\Delta EWT_{m-GRACE}$ were determined using CSR RL06 GRACE/GRACE-FO-based GGMs specified in Section 2 and the IGiK-TVGMF software [43]. These GGMs were obtained from the International Centre for Global Earth Models (ICGEM; cf. http://icgem.gfz-potsdam.de/series). The degree-1 and degree-2 spherical harmonic coefficients of these GGMs were replaced by the corresponding ones obtained from the solution described in [47] and from Satellite Laser Ranging (SLR) observations [48], respectively. The monthly estimates of these degree-1 and degree-2 spherical harmonic coefficients are available via GRACE TN-13 (GRACE Technical Note 13; https://podaac-tools.jpl.nasa.gov/drive/files/allData/ grace/docs/TN-13_GEOC_CSR_RL06.txt) and GRACE TN-11 (GRACE Technical Note 11; cf. https://podaac-tools.jpl.nasa.gov/drive/files/allData/ grace/docs/TN-11_C20_SLR.txt), respectively. The EGM2008 (Earth Gravitational Model 2008; [49]) was used as a reference GGM and the WGS84 (World Geodetic System 1984) was chosen as a geodetic reference system.

3.2. The Determination of Δh_{m-GNSS} and ΔEWT_{m-GNSS} from GNSS Data

Daily vertical deformations of the Earth's surface Δh_{d-GNSS} for the period 2008-2018 were determined first at the location of 96 sites of the ASG-EUOPS CORS network using daily GNSS observations data processed by the GAMIT/GLOBK software version 10.7 [50,51]. The TEQC (Translation, Editing, and Quality Checking) software developed by UNAVCO [52] was used to check the quality of GNSS data from 96 stations of the ASG-EUPOS network. The linear combination of L1 and L2 was implemented to eliminate the signal delay caused by first-order ionospheric refraction. The delay induced by second- and third-order ionospheric refraction of the carrier wave was also removed using daily IONEX (IONosphere EXchange) files provided by the Centre for Orbit

Determination in Europe (CODE; [53]). These IONEX files represent the ionosphere in the form of global maps of the Vertical Total Electron Content (VTEC). The troposphere delay was estimated using the Vienna Mapping Function (VMF; [54]) with a priori hydrostatic delay estimates based on the global pressure and temperature (GPT2) model [55]. The troposphere delay was estimated for every 2 h from GNSS data acquired at ASG-EUPOS sites investigated. The Atmospheric Loading Model (ATML; [56]) at the observation level provided by the MIT (Massachusetts Institute of Technology) was applied to remove deformation caused by atmospheric loading. The Finite Element Solutions 2004 tidal model (FES2004; [57]) was used to remove deformations induced from oceanic tidal loading.

From the GAMIT software, the daily loosely constrained solutions were obtained. These solutions were combined with global solutions provided by the MIT using the GLOBK software. In this step of processing, the GLORG was used to define the reference frame. Time series of daily vertical deformations of the Earth's surface were tight to the ITRF2014 (International Terrestrial Reference Frame 2014; [58]). Daily vertical deformations of the Earth's surface that exceed the daily repeatability within the same month were considered as outliers. These outliers were detected using GAMIT/GLOBK MATLAB TOOL [50] and subsequently removed. Finally, all daily vertical deformations of each month were averaged to estimate monthly vertical deformations of the Earth's surface Δh_{m-GNSS} . Time series of daily and monthly vertical deformations for an exemplary ASG-EUPOS station KLCE are shown in Figure 3. Then, Δh_{m-GNSS} were inverted into monthly variations of equivalent water thickness ΔEWT_{m-GNSS} using the Green's function elastic half-space model (cf. [59]).

$$\Delta EWT_{m-GNSS} = \Delta h_{m-GNSS} \cdot \left(2\rho_w \cdot R_0 \cdot g \cdot \left(\frac{1-v^2}{E} \right) \right)^{-1}$$
(4)

where R_0 presents the radius that has been estimated on the basis of the spatial resolution of GRACE/GRACE-FO satellite missions' data (i.e., 167 km), *g* denotes the gravity value (estimated to 9.81 Gal), *v* is the Poisson's ratio, *E* is the Young's modulus. It should be noted that on the basis of the review of the literature (e.g., [59]), the Poisson's ratio and the Young's modulus used in this study were estimated to 0.25 and 70 Gpa, respectively.



Figure 3. Time series of daily and monthly vertical deformations for the KLCE station of the Active Geodetic Network of the European Position Determination System (ASG-EUPOS) network.

3.3. The Detrmination of $\Delta EWT_{m-CombSol}$

Combined solutions of monthly variations of equivalent water thickness $\Delta EWT_{m-CombSol}$ were developed for each (*i* = 1, 2, 3, ..., *q*) GNSS station of the ASG-EUPOS CORS network:

$$\Delta EWT_{m-CombSol}^{i} = \frac{w_{GNSS}^{i} \cdot \Delta EWT_{m-GNSS}^{i} + w_{GRACE}^{i} \cdot \Delta EWT_{m-GRACE}^{i}}{w_{GNSS}^{i} + w_{GRACE}^{i}}$$
(5)

where *q* denotes the total number of GNSS stations of the ASG-EUPOS CORS network investigated and w_{GNSS} and w_{GRACE} are weights for ΔEWT determined from GNSS and GRACE/GRACE-FO satellite missions' data, respectively. These weights were estimated as follows:

$$w_{\text{GNSS}}^{i} = \left(\sqrt{\frac{\sum\limits_{t=1}^{k} \left(\left(\Delta E W T_{\text{m-GNSS}}^{i}(t) - \Delta E W T_{\text{WGHM}}^{i}(t) \right) - \overline{\left(\Delta E W T_{\text{m-GNSS}}^{i}(t) - \Delta E W T_{\text{WGHM}}^{i}(t) \right)}^{2}} \right)^{-1} \right)^{-1} \left\}$$

$$w_{\text{GRACE}}^{i} = \left(\sqrt{\frac{\sum\limits_{t=1}^{k} \left(\left(\Delta E W T_{\text{m-GRACE}}^{i}(t) - \Delta E W T_{\text{WGHM}}^{i}(t) \right) - \overline{\left(\Delta E W T_{\text{m-GRACE}}^{i}(t) - \Delta E W T_{\text{WGHM}}^{i}(t) \right)}^{2}} \right)^{-1} \right\}$$

$$(6)$$

where (t = 1, 2, 3, ..., k) denotes the month, k is the total number of months investigated, ΔEWT_{m-WGHM} are time series of monthly variations of the equivalent water thickness obtained from the WGHM and the overbar operator presents the average over all k months.

3.4. Estimation of $\Delta EWT_{m-GRACE}$, ΔEWT_{m-GNSS} , and $\Delta EWT_{m-CombSol}$ Uncertainties

Monthly variations of equivalent water thickness determined from GNSS data and GRACE/GRACE-FO-based GGMs as well as their combined solutions determined with the use of methods specified in Section 3.1, Section 3.2, Section 3.3, were evaluated using ΔEWT_{m-WGHM} . The differences

$$\delta \Delta EWT^{i}_{m-GRACE} = \Delta EWT^{i}_{m-WGHM} - \Delta EWT^{i}_{m-GRACE}$$

$$\delta \Delta EWT^{i}_{m-GNSS} = \Delta EWT^{i}_{m-WGHM} - \Delta EWT^{i}_{m-GNSS}$$

$$\delta \Delta EWT^{i}_{m-CombSol} = \Delta EWT^{i}_{m-WGHM} - \Delta EWT^{i}_{m-ComSol}$$

$$(7)$$

were determined and standard deviations of these differences were computed. Moreover, correlations between equivalent water thickness obtained from the WGHM and the corresponding ones determined from GNSS and GRACE/GRACE-FO satellite missions' data as well as the combined solutions $\Delta EWT_{m-CombSol}$ developed were estimated.

4. Results

4.1. Monthly Vertical Deformations of the Earth's Surface

Time series of monthly vertical deformations of the Earth's surface Δh at the stations of the ASG-EUPOS network obtained from GNSS data Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ determined from GRACE/GRACE-FO satellite missions' data are illustrated in Figure 4.

20 10 0 -10 -20							
20 10 0 -10 -20	BUZD	BRSK		ELBL	GOLE	нгив	WINCOC
20 10 0 -10 -20	BILG	BUZD	снио	GDA1	GRAJ		
20 10 0 -10 -20	Bogi	BYDG	снол	GIZY		JLGR	
20 10 0 -10 -20		СВКА		GLOG	GWWL		
20 10 0 -10 -20		PROS		SKSV	Swki MMMMM		
ne Earth's surfa 0 -10 -10	osmz MMMM	PRZM		SOCH	SZE2		NWSC
eformation of th 0 0 0 0 -10				SOKL			Mies
02 Vertical de 0 -10 -20		RWM1	sksk			WIEL	
20 10 0 -10 -20		RYKI	SKSL	SWIB		WLBB	KRA1
20 10 0 -10 -20	KAM1	KLOB	KROS		MLCN	NWT1	
20 10 0 -10 -20	KATO		KUTN		Mysz Myy	MANNA A	
20 10 0 -10 -20		Kosc MMMMC					
20 10 0		KOSZ		MIEL		2008 2012 2016 2 Time	008 2012 2016 [year]
-10 -20 20	08 2012 2016 2	2008 2012 2016 2	008 2012 2016 2	2008 2012 2016 2	008 2012 2016	GRACE GNSS	/GRACE-FO

Figure 4. Time series of monthly vertical deformations of the Earth's surface determined from GNSS and GRACE/GRACE-FO satellite missions' data at the stations of the ASG-EUPOS network.

The results presented in Figure 4 exhibit a seasonal pattern over the area investigated. It is observed that maximum values of Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ occur during the summer–fall seasons and minimum values during the winter–spring seasons [26]. This pattern can be attributed to the change in the mass loading caused by seasonal variations in the water mass with maximum values in March and minimum values in July–September [26,60]. For all GNSS stations investigated, the phase difference between Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ is less than one month, which can be considered negligible. Statistics

of peak-to-peak variations of the seasonal pattern of the monthly vertical deformations are given in Table 1.

Δh	Min	Max	Median	Std
$\Delta h_{\rm m-GNSS}$	10.2	38.2	21.7	4.0
	13.8	21.4	20.0	1.6

Table 1. Statistics of peak-to-peak variations of Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ [mm].

The results presented in Table 1 indicate that although the medians of peak-to-peak variations of the seasonal pattern in Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ are in a good agreement, the dispersion and the standard deviation of those variations for Δh_{m-GNSS} with respect to the corresponding ones obtained from $\Delta h_{m-GRACE}$ are higher by a factor of approx. 3.5, and approx. 2.5, respectively. The higher dispersion and standard deviation of peak-to-peak variations in Δh_{m-GNSS} may reveal that monthly vertical deformations obtained from GNSS data include the local deformation signal which cannot be detected from GRACE/GRACE-FO satellite missions' data. The sources of such local deformation signal may be (i) thermoelastic deformation of the monuments caused by seasonal variation of the Earth's temperature [61] and (ii) poroelastic deformations caused by large variation of the water table [62]. Besides these geophysical sources, systematic errors in GNSS observations such as mismodeling of daily and subdaily tidal signals [63], presence of GPS draconitic signal [37,64] as well as the variation in the phase center and the local multipath, can also induce the specific Δh_{m-GNSS} pattern for a station [65].

Furthermore, along with the seasonal pattern of Δh obtained from GNSS and GRACE/GRACE-FO satellite missions data illustrated in Figure 4, there are also linear trends in the monthly vertical deformation of the Earth's surface (Figure 5). Statistics of these linear trends are given in Table 2. It should be mentioned that due to limited GNSS data at SKSL, SKSK and SKSV stations of the ASG-EUPOS network, linear trends of Δh have not been estimated at these sites. The results presented in Figure 5 and Table 2 indicate positive linear trends for $\Delta h_{m-GRACE}$ at the ASG-EUPOS sites, ranging from 0.67 mm/year to 1.86 mm/year. These trends can be ascribed to the annual water depletion over the territory of Poland, observed beyond the extreme land hydrology events, i.e., flooding and increased precipitation, occurred in 2010–2011 (e.g., [66]). It should be noted that magnitudes of linear trends estimated from $\Delta h_{m-GRACE}$ depend on both the covering period and number of months used. The Δh_{m-GNSS} reflects variable linear trends ranging from -1.47 mm/year to 2.16 mm/year. The reasons for these different linear trends can be attributed to the unstable monument [67], anthropogenic factors such as subsidence of mining areas and over exploitation of groundwater [68] and the presence of diverse geological structures such as Eastern European Precambrian platform, young western and middle Paleozoic platform as well as Carpathian region [69]. As the factors causing linear trends in $\Delta h_{\text{m-GNSS}}$ and $\Delta h_{\text{m-GRACE}}$ are different, the distinctive mismatch between linear trends of $\Delta h_{\text{m-GNSS}}$ and $\Delta h_{m-GRACE}$ for some ASG-EUPOS GNSS stations such as PRZM, SWKI occurs. The linear trends in $\Delta h_{m-GRACE}$ in the case of ASG-EUPOS GNSS stations PRZM, SWKI can primarily be attributed to the manifestation of the elastic response of the water depletion over the area. On the other hand, the corresponding linear trends in Δh_{m-GNSS} can be ascribed to the monumental instability of the ASG-EUPOS GNSS station, anthropogenic activity and water mass change occurring in limited spatial scales, e.g., few kilometers, as well as the presence of geological features. The uncommon linear trends in $\Delta h_{\text{m-GNSS}}$ and $\Delta h_{\text{m-GRACE}}$ may result in disagreements between vertical deformations of the Earth's surface determined from GNSS and GRACE/GRACE-FO satellite missions' data. Time series of $\Delta h_{\text{m-GNSS}}$ and $\Delta h_{\text{m-GRACE}}$ were thus detrended for further analysis.



Figure 5. Linear trends of vertical deformation of the Earth's surface estimated at ASG-EUPOS sites using GRACE/GRACE-FO satellite missions and GNSS data.

Table 2. Statistics of linear trends of vertical deformation of the Earth's surface estimated at ASG-EUPOS sites (except sites SKSL, SKSK and SKSV) using GRACE/GRACE-FO satellite missions and GNSS data [mm/year].

Δh	Min	Max	Median	Std
$\Delta h_{ m m-GNSS}$	-1.47	2.16	0.07	0.58
$\Delta h_{ m m-GRACE}$	0.67	1.86	0.83	0.25

In order to compare monthly vertical deformations of the Earth's surface Δh determined from GNSS and GRACE/GRACE-FO satellite missions' data, correlations and standard deviations of the differences between (1) $\Delta h_{\text{m-GNSS}}$ and $\Delta h_{\text{m-GRACE}}$, and (2) detrended $\Delta h_{\text{m-GNSS}}$ and detrended $\Delta h_{\text{m-GRACE}}$ were computed. Figure 6 depicts coefficients of correlations between Δh obtained from GNSS data and the corresponding ones obtained from GRACE/GRACE-FO satellite missions' data at the locations of the ASG-EUPOS stations investigated. Statistics of these correlation coefficients are given in Table 3. The results presented in Figure 6 and Table 3 reveal that at 68% of the ASG-EUPOS GNSS stations investigated, strong correlations (correlation coefficients ranging from 0.60 to 0.90) between Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ were obtained. Moderate/weak correlations (correlation coefficients ranging from 0.30 to 0.59) between $\Delta h_{\text{m-GNSS}}$ and $\Delta h_{\text{m-GRACE}}$ were observed at 30% of the stations investigated. At two ASG-EUPOS GNSS stations (PRZM and NWT1) correlations coefficients between Δh_{m-GNSS} and $\Delta h_{\text{m-GRACE}}$ were found to be 0.13 and 0.29, respectively. After detrending $\Delta h_{\text{m-GNSS}}$ and $\Delta h_{\text{m-GRACE}}$, strong correlations between Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ were obtained at 93% of the GNSS stations investigated. At 7% of the stations, moderate/weak correlations between Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ were obtained. Thus, values of correlations coefficients have clearly improved after detrending. For the ASG-EUPOS stations PRZM the value of the correlation coefficient increased to 0.71 after the removal of linear trends from $\Delta h_{\text{m-GNSS}}$ and $\Delta h_{\text{m-GRACE}}$ (cf. Figures 4 and 5). On the contrary the value of

the correlation coefficient at the station NWT1 does not change much despite removing the linear trend. However, it should be noted that the value of the coefficient of correlation between Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ in the case of NWT1 can be less reliable because of the shorter time span and gaps in Δh time series. Overall, the results presented in Figure 6 show strong correlations between Δh obtained from GNSS data and corresponding ones determined using GRACE/GRACE-FO data. Strong correlations between Δh suggest that surface mass loading effects are the dominant contributor to the vertical deformation of the Earth's surface over the area investigated and also indicate consistency of the GNSS and GRACE/GRACE-FO satellite missions' data in monitoring surface mass loading effects. The cases of weak correlations between Δh obtained from GNSS data and the corresponding ones determined using GRACE/GRACE-FO satellite missions' data in monitoring surface mass loading effects. The cases of weak correlations between Δh obtained from GNSS data and the corresponding ones determined using GRACE/GRACE-FO satellite missions' data may be attributed to variety of reasons such as local temporal variations of water masses and GNSS station dependent errors. However, in this study the values of correlation coefficients got improved after removing the linear trends and there are only two ASG-EUPOS stations (NWT1 and WIEL) for which values remain under 0.5. The case of NWT1 has already been stated above, and regarding WIEL the authors believe that the value of the correlation coefficient may get improved with the use of the longer data span.



Figure 6. Coefficients of correlation between vertical deformations of the Earth's surface determined from ASG-EUPOS and GRACE/GRACE-FO satellite missions' data.

Table 3. Statistics of correlation coefficient values presented in Figure 6.

Δh	Min	Max	Mean
GNSS-GRACE	0.13	0.91	0.64
GNSS-GRACE (detrended)	0.31	0.83	0.72

The standard deviations of the differences between Δh obtained from GNSS data and the corresponding ones obtained from GRACE/GRACE-FO satellite missions' data were illustrated in Figure 7. Statistics of these standard deviations are given in Table 4. They reveal that the mean value

of standard deviations of the differences between Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ decreased by ca. 18% (i.e., from 4.2 to 3.4 mm) after removing the linear trend of Δh specified in Figure 5. The reduced value of standard deviations of Δh differences after removing linear trend in Δh signifies the reduction of amplitude discrepancy between detrended Δh_{m-GNSS} and detrended $\Delta h_{m-GRACE}$ in relation to that of $\Delta h_{m-GRACE}$. Overall, the improvement, in terms of correlation coefficients (Figure 6) and standard deviations of the Δh differences (Figure 7), obtained after removing linear trends in Δh is observed. The results also indicate that although Δh obtained from GNSS and GRACE/GRACE-FO data agree well, linear trends in Δh can vary significantly. Therefore, detrended Δh_{m-GNSS} are further used for estimating ΔEWT .



Figure 7. Standard deviations of the differences between vertical deformations of the Earth's surface determined from ASG-EUPOS and GRACE/GRACE-FO satellite missions' data.

Δh	Min	Max	Mean
GNSS-GRACE	2.6	7.3	4.2
GNSS-GRACE (detrended)	2.5	5.2	3.4

Table 4. Statistics of standard deviation values presented in Figure 7 [mm].

4.2. Monthly Variations of Equivalent Water Thickness

Monthly variations of equivalent water thickness $\Delta EWT_{m-GRACE}$ and ΔEWT_{m-GNSS} were determined with the use of Equations (2) and (4) as well as data from GRACE/GRACE-FO satellite missions and GNSS data from the ASG-EUPOS CORS network, respectively. Moreover, monthly variations of equivalent water thickness ΔEWT_{m-WGHM} were obtained from the WGHM. In order to be consistent with the detrended ΔEWT_{m-GNSS} , linear trends in $\Delta EWT_{m-GRACE}$ and ΔEWT_{m-WGHM} were also removed. Then, combined solutions $\Delta EWT_{m-CombSol}$ were determined using Equation (5) with the weights w_{GNSS} and w_{GRACE} estimated by Equation (4) and ΔEWT determined from GRACE/GRACE-FO and GNSS data. The ratio between these weights (i.e., $w_{GNSS}:w_{GRACE}$) is illustrated in Figure 8.

The maximum (i.e., 0.73) and minimum (i.e., 0.14) values of this ratio were observed at the GNSS stations CHOJ and SIDZ, respectively. For ca. 72% of GNSS stations investigated (i.e., 69 GNSS stations of ASG-EUPOS network), the ratio between w_{GNSS} and w_{GRACE} is at the level of 0.46 ± 0.13. Time series of $\Delta EWT_{m-GRACE}$, ΔEWT_{m-GNSS} and $\Delta EWT_{m-CombSol}$ as well as the corresponding ΔEWT_{m-WGHM} obtained from the WGHM are illustrated in Figure 9. It is observed from the results presented in Figure 9 that likewise Δh , there is also a seasonal pattern in ΔEWT . This seasonal pattern can be attributed to seasonal mass variations related with the hydrological cycle over the territory of Poland. Statistics of peak-to-peak variations of the seasonal pattern of the monthly equivalent water thickness variations are given in Table 5. From the values of medians and standard deviations, it is clear that overall $\Delta EWT_{m-CombSol}$ are in better agreement with ΔEWT_{m-WGHM} than those of ΔEWT_{m-GNSS} and $\Delta EWT_{m-GRACE}$.



Figure 8. The ratio between the weights w_{GNSS} and w_{GRACE} (i.e., w_{GNSS} : w_{GRACE}).

30 20 10 -10 -20 -30	BART	MMMM BPDL	CCHN	AMAMAAA	GNIE	HAJN	WLDW
30 20 10 -10 -20 -30	BIAL	BRSK	CHEL	AND HOM	GOLE	HRUB	WINC
30 20 10 -10 -20 -30	BILG	BUZD	CHNO CHNO	GDA1	GRAJ	Ambypp	MA MANA
30 20 10 -10 -20 -30	BOGI	BYDG	сној	GIZY	GRUD	JLGR	
30 20 10 -10 -20 -30	BOR1	СВКА	DRWP	GLOG	GWWL	Jozz Jozz	
30 20 10 -10 -20 -20	OPNT	PROS	SIDZ	SKSV	swki	TRNW	
. Thickness [cn 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,	OSMZ	PRZM	SIED	SOCH	szez	USDL	NWSC
uivalent Water	PITR	RADM	SIPC	SOKL	TABG	WAT1	MIES
ы 30 20 10 -10 -20 -30	POZN	RWM1	SKSK	STRG		WIEL	
30 20 10 -10 -20 -30		RYKI AMAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA	SKSL	SWIB		WLBR	KRA1
30 20 10 -10 -20 -30	KAM1	KLOB	KROS	LODZ	MLCN	NWT1	KLDZ Malay Maga
30 20 10 -10 -20 -30	КАТО	KONI	KUTN		Mysz Am Mygy I	NYSA MADANAA	KALI
30 20 10 -10 -20 -30		Kosc	LAMA		NODW	OPLE	
30 20 10 -10 -20 -30	KLCE	Kosz		MIEL	MAN MAN	2008 2010 2016 2 Time [year] GNSS	008 2010 2016 Time [year] NGHM
2	2008 2010 2016 2 Time [year]	008 2010 2016 2 Time [year]	008 2010 2016 2 Time (year)	008 2010 2016 2 Time [year]	008 2010 2016 Time (year)		

Figure 9. Time series of monthly temporal variations of the equivalent water thickness ΔEWT determined from GNSS data ΔEWT_{m-GNSS} , GRACE satellite mission data $\Delta EWT_{m-GRACE}$ and their combined solutions $\Delta EWT_{m-CombSol}$ as well as the corresponding ΔEWT_{m-WGHM} obtained from the WGHM.

Table 5. Statistics of peak-to-peak variations of ΔEWT_{m-GNSS} , $\Delta EWT_{m-GRACE}$, $\Delta EWT_{m-CombSol}$ and ΔEWT_{m-WGHM} [cm].

ΔEWT	Min	Max	Median	Std
ΔEWT_{m-GNSS}	11.1	56.9	38.5	8.5
$\Delta EWT_{m-GRACE}$	11.1	22.2	18.7	3.2
$\Delta EWT_{m-CombSol}$	6.7	28.4	22.2	4.3
ΔEWT_{m-WGHM}	5.7	37.1	21.4	4.9

In order to assess the performance of GNSS data from ASG-EUPOS CORS network for the determination of ΔEWT as well as for improving ΔEWT determined from GRACE/GRACE-FO satellite missions' data, correlations between (1) ΔEWT_{m-GNSS} and ΔEWT_{WGHM} , (2) $\Delta EWT_{m-GRACE}$ and ΔEWT_{m-WGHM} , and (3) $\Delta EWT_{m-CombSol}$ and ΔEWT_{m-WGHM} have been estimated (Figure 10 and Table 6). Strong correlations (correlation coefficients ranging from 0.60 to 0.70), between ΔEWT_{m-GNSS} and ΔEWT_{m-WGHM} were obtained at 32% of GNSS sites investigated; moderate/weak correlations (correlation coefficients ranging from 0.30 to 0.59), were obtained at 56% of the GNSS sites investigated; at about 12% of GNSS sites investigated, no correlations (correlation coefficient ranging from -0.41to 0.29) have been obtained. In terms of correlations between $\Delta EWT_{m-GRACE}$ and ΔEWT_{m-WGHM} , strong correlations (correlation coefficients ranging from 0.60 to 0.79) have been obtained at 57% of the stations investigated; moderate/weak correlations (correlation coefficients ranging from 0.30 to 0.59) were obtained in the case of 38% of the stations investigated; at the remaining 5% of the GNSS sites investigated correlation coefficients range from -0.04 to 0.29. It is clear that the obtained correlations between $\Delta EWT_{m-GRACE}$ and ΔEWT_{m-WGHM} are much stronger than the corresponding ones between ΔEWT_{m-GNSS} and ΔEWT_{m-WGHM} . The reason for this may be ascribed to the fact that $\Delta EWT_{m-GRACE}$ is obtained directly from the monitoring of the gravitational effect of mass variations within the Earth's system, while ΔEWT_{m-GNSS} is determined by inverting the response of the Earth's surface to the mass variation at a point. The response of the Earth's surface to the mass variation depends upon the underlying crustal properties. Moreover, ΔEWT_{m-GNSS} is sensitive to the local signal and the presence of any such signal could affect the ΔEWT_{m-GNSS} . At 83% of the GNSS sites investigated, strong correlation (correlation coefficients from 0.60 to 0.80) between $\Delta EWT_{m-CombSol}$ and ΔEWT_{m-WGHM} were obtained. At 16% of the GNSS stations investigated, the correlations are moderate/weak. For the remaining 1% of the GNSS stations investigated (one station) the correlation coefficient is 0.27. The values of coefficients of correlation between $\Delta EWT_{m-CombSol}$ and ΔEWT_{m-WGHM} have evidently been improved at 85% of the GNSS stations in comparison to values of coefficients of correlation between $\Delta EWT_{m-GRACE}$ and ΔEWT_{m-WGHM} . Furthermore, combining ΔEWT obtained from GNSS data with the corresponding ones determined from GRACE/GRACE-FO satellite missions' data does not change, however, the correlation coefficients' values at 3% of the GNSS stations investigated. At 12% of the GNSS stations, the addition of GNSS data worsen the ΔEWT in terms of correlations with the ΔEWT_{m-WGHM} . The good agreement, in terms of correlations, between $\Delta EWT_{m-CombSol}$ and ΔEWT_{m-WGHM} , indicates that GNSS data from CORS network stations provides in general valuable information to improve GRACE/GRACE-FO solutions for monitoring mass variation within the Earth's system.



Figure 10. Coefficients of correlation between ΔEWT_{m-GNSS} and ΔEWT_{m-WGHM} (red bar), between $\Delta EWT_{m-GRACE}$ and ΔEWT_{m-WGHM} (black bar), and between $\Delta EWT_{m-CombSol}$ and ΔEWT_{m-WGHM} (cyan bar).

ΔΕ₩Τ	Min	Max	Mean
GNSS	-0.41	0.71	0.51
GRACE	-0.04	0.79	0.58
Combined solution	0.27	0.83	0.67

Table 6. Statistics of correlation coefficient values presented in Figure 10.

With the use of Equation (7), the differences $\delta \Delta EWT_{m-GNSS}$, $\delta \Delta EWT_{m-GRACE}$ and $\delta \Delta EWT_{m-CombSol}$ were determined. Standard deviations of these differences were depicted in Figure 11. Statistics of these standard deviations are given in Table 7. The results presented in Figure 11 and Table 7 reveal that the mean values of standard deviations of differences $\delta \Delta EWT_{m-GNSS}$, $\delta \Delta EWT_{m-GRACE}$ and $\delta \Delta EWT_{m-CombSol}$ are 7 cm, 5 cm and 4 cm, respectively. The values of standard deviations of $\delta \Delta EWT_{m-CombSol}$ decreased at 44 sites of the ASG-EUPOS CORS network in comparison to standard deviations of $\delta \Delta EWT_{m-GRACE}$. At 48 sites of the ASG-EUPOS CORS network, standard deviations of $\delta \Delta EWT_{m-CombSol}$ remained the same as the values of standard deviations of $\delta \Delta EWT_{m-GRACE}$. There are only 4 sites of the ASG-EUPOS CORS network where standard deviations of $\delta \Delta EWT_{m-CombSol}$ increased in comparison to that of the $\delta \Delta EWT_{m-GRACE}$. Although there are improvements in the median values of standard deviations of $\delta \Delta EWT_{m-CombSol}$ in comparison to the corresponding ones of $\delta \Delta EWT_{m-GRACE}$, they are limited to only 46% of GNSS sites investigated. This can be attributed to the amplitude differences, due the fact that GNSS data present ΔEWT at points, while GRACE/GRACE-FO satellite mission data and the WGHM present ΔEWT over an area. Furthermore, amplitude differences between $\Delta EWT_{m-GRACE}$ and ΔEWT_{m-WGHM} may be due to (i) the coarse spatial resolution of the GRACE/GRACE-FO satellite missions data (ca. $3^{\circ} \times 3^{\circ}$ at the equator), and (ii) the spatial resolution of the WGHM (ca. $0.5^{\circ} \times 0.5^{\circ}$), as well as uncertainties of the WGHM related to modeling of storage capacity, fluxes, and human

intervention [70]. As the data from GNSS, GRACE/GRACE-FO satellite missions and the WGHM characterize with differences between each other, so incorporation of ΔEWT_{m-GNSS} to $\Delta EWT_{m-GRACE}$ may not reduce standard deviations of $\delta \Delta EWT_{m-CombSol}$ in comparison to that of $\delta \Delta EWT_{m-GRACE}$. Since, there are only 4 GNSS stations where the addition of ΔEWT_{m-GNSS} to $\Delta EWT_{m-GRACE}$ increase the standard deviation values of $\delta \Delta EWT_{m-CombSol}$, addition of ΔEWT_{m-GNSS} to $\Delta EWT_{m-GRACE}$, in general, either reduced or did not change the values of standard deviations in comparison to the corresponding ones of $\delta \Delta EWT_{m-GRACE}$.



Figure 11. Standard deviations of differences $\delta \Delta EWT_{m-GNSS}$ (red bar), $\delta \Delta EWT_{m-GRACE}$ (blue bar) and $\delta \Delta EWT_{m-CombSol}$ (cyan bar).

ΔEWT	Min	Max	Mean
GNSS	0.03	0.12	0.07
GRACE	0.03	0.07	0.05
Combined solution	0.02	0.06	0.04

5. Conclusions and Discussions

In this study, monthly vertical deformations of the Earth's surface Δh as well as temporal variations of equivalent water thickness ΔEWT were determined using GNSS data from the ASG-EUPOS CORS network as well as the CSR RL06 GRACE/GRACE-FO-based GGMs over the area of Poland. Combined solutions of ΔEWT were developed by combining ΔEWT obtained from GNSS data and the corresponding ones determined from GRACE satellite mission data. The ΔEWT obtained from GNSS data, GRACE/GRACE-FO satellite missions' data and from the determined combined solutions of ΔEWT were evaluated using the corresponding values obtained from the WGHM hydrological model. The main findings reveal:

Over the area investigated, the seasonal patterns in Δh determined from GNSS data of the ASG-EUPOS CORS network Δh_{m-GNSS} are in a good agreement with the corresponding ones determined from GRACE/GRACE-FO satellite missions' data $\Delta h_{m-GRACE}$. The maximum and minimum values of Δh occur during the summer–fall and winter–spring seasons, respectively. Linear trends in the time series of Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ are, however, not fully consistent. It is found that $\Delta h_{m-GRACE}$ show positive linear trends which can be related with water depletion over the territory of Poland. In the case of Δh_{m-GNSS} , the nature of linear trends significantly differs at the sites of the ASG-EUPOS CORS network. These differences in linear trends of $\Delta h_{\text{m-GNSS}}$ can be due to monumental instability, anthropogenic activity, and geological features. Strong correlations between Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ were obtained at 68% of GNSS sites investigated. When removing the linear trends in Δh_{m-GNSS} and $\Delta h_{\text{m-GRACE}}$, the number of stations with strong correlations between detrended $\Delta h_{\text{m-GNSS}}$ and detrended $\Delta h_{m-GRACE}$ increased to 93% of GNSS sites investigated. Median values of standard deviations of differences between Δh_{m-GNSS} and $\Delta h_{m-GRACE}$ as well as between detrended Δh_{m-GNSS} and detrended $\Delta h_{m-GRACE}$ are 4.1 mm and 3.4 mm, respectively. Overall, removing the linear trends in $\Delta h_{\text{m-GNSS}}$ and $\Delta h_{\text{m-GRACE}}$ results in clear improvements of the fit, in terms of both correlations and standard deviations of the difference between Δh determined from GNSS data of the ASG-EUPOS CORS network to the corresponding ones determined from GRACE/GRACE-FO satellite mission data.

Furthermore, ΔEWT determined from GRACE/GRACE-FO satellite missions' data ($\Delta EWT_{m-GRACE}$) and from GNSS data of the ASG-EUPOS CORS network (ΔEWT_{m-GNSS}) as well as their combined solutions $\Delta EWT_{m-CombSol}$ are also in a good agreement with the ΔEWT_{m-WGHM} obtained from the hydrological model WGHM. Strong correlations between (1) ΔEWT_{m-GNSS} and ΔEWT_{m-WGHM} , (2) $\Delta EWT_{m-GRACE}$ and ΔEWT_{m-WGHM} , as well as (3) $\Delta EWT_{m-CombSol}$ and ΔEWT_{m-WGHM} were obtained at 32%, 57% and 83% of the GNSS sites investigated, respectively. It has been found that the combination of ΔEWT_{m-GNSS} and $\Delta EWT_{m-GRACE}$ improves the determination of ΔEWT , in terms of correlations coefficients, at 85% of GNSS sites investigated in comparison to the one obtained with the use of GRACE/GRACE-FO satellite missions' data only. The median values of standard deviations of differences ΔEWT_{m-GNSS} , $\Delta EWT_{m-GRACE}$, and $\Delta EWT_{m-CombSol}$ with respect to ΔEWT_{m-WGHM} are 7 cm, 5 cm and 4 cm, respectively. The improvements, in terms of standard deviations of the differences, obtained for $\Delta EWT_{m-CombSol}$ in comparison to $\Delta EWT_{m-GRACE}$ are limited to 46% of the GNSS stations investigated, however, there are only 4% of the GNSS sites where standard deviations of the difference between $\Delta EWT_{m-CombSol}$ and ΔEWT_{m-WGHM} (i.e., $\delta \Delta EWT_{m-CombSol}$) are larger than the corresponding ones obtained from the differences between $\Delta EWT_{m-GRACE}$ and ΔEWT_{WGHM} (i.e., $\delta \Delta EWT_{m-GRACE}$). In general, the combination of ΔEWT_{m-GNSS} and $\Delta EWT_{m-GRACE}$ either reduce or do not change standard deviations of $\delta \Delta EWT_{m-CombSol}$ in comparison to the corresponding ones of $\delta \Delta EWT_{m-GRACE}$.

Although linear trends in Δh estimated from GNSS data of the ASG-EUPOS CORS network and the corresponding ones determined from GRACE/GRACE-FO satellite missions data are not fully consistent, the agreement in the seasonal pattern of Δh and ΔEWT obtained from these both data types demonstrates the capability of using stations of the ASG-EUPOS CORS network as sensors for the determination of temporal mass variations within the Earth's system. Moreover, incorporation of ΔEWT_{m-GNSS} to $\Delta EWT_{m-GRACE}$ provides improved solutions for sensing mass variation of the Earth's surface. The $\Delta EWT_{m-CombSol}$ developed from this incorporation can be thought as optimization of the determination of mass variations using GNSS data from the ASG-EUPOS CORS network and GRACE/GRACE-FO satellite mission data. This is due to the coarse spatial resolution of GRACE/GRACE-FO satellite mission data while GNSS provides local information about mass variations. Thus, ΔEWT_{m-GNSS} and $\Delta EWT_{m-GRACE}$ are complementary to each other.

Overall, the results obtained indicate that although national GNSS CORS networks are mainly developed for precise positioning related applications, they evidently provide a valuable information complementary to the one obtained from satellite data for the determination of temporal mass variations within the Earth's system. Data from the ASG-EUPOS CORS network in Poland improve models of temporal mass variations within the Earth's system obtained from GRACE/GRACE-FO satellite missions'

data. However, the use of other national GNSS CORS networks operated worldwide for determining temporal mass variations within the Earth's system as well as for improving GRACE/GRACE-FO satellite missions' solutions is a subject of future investigation.

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