

## Studies of crustal deformation due to hydrological loading on GPS height estimates

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**Abstract:** The paper deals with large-scale crustal deformation due to hydrological surface loads and its influence on seasonal variation of GPS estimated heights. The research was concentrated on the area of Poland. The deformation caused by continental water storage has been computed on the basis of WaterGAP Hydrological Model data by applying convolution of water masses with appropriate Green's function. Obtained site displacements were compared with height changes estimated from GPS observations using the Precise Point Positioning (PPP) method. Long time series of the solutions for 4 stations were used for evaluation of surface loading phenomena. Good agreement both in amplitude and phase was found, however some discrepancies remain which are assigned to single point positioning technique deficiencies. Annual repeatability of water cycle and demanding procedure for computing site displacements for each site, allowed to develop a simple model for Poland which could be applied to remove (or highly reduce) seasonal hydrological signal from time series of GPS solutions.

**Keywords:** GPS, PPP, hydrology model, surface loading

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### 1. Introduction

At the present level of space and satellite geodetic techniques accuracy the Earth cannot be regarded as rigid body. Temporal deformations on large scale are mainly due to tectonic movements, Earth tides, tidal and non-tidal ocean height changes, atmospheric and hydrological surface loading. The effects are changes of co-ordinates in terrestrial reference frame which often can be predicted accurately (e.g. Earth tides, tectonic movements, tidal ocean loading) and are usually implemented in GPS processing packages. Deformations caused by atmospheric and hydrological loading are currently not taken into account in GPS data analysis. Those displacements can be computed on the basis of pressure field (van Dam and Wahr, 1987, 1998; Sun et al., 1995) and water storage assessment (van Dam et al., 2001). Presented in the paper deformations due to continental water storage for the territory of Poland were computed and compared with height changes obtained from GPS observations for selected permanent sites. Section 2

presents computation of loading effect and hydrology data used in this study. It has also been indicated that consideration of global data set is indispensable. Section 3 gives summary of GPS processing strategy, while comparison of modelled and observed deformation is given in section 4. The last section is devoted to the development of a simple, hydrology induced, deformation model for the territory of Poland, based on observed annual harmonic repeatability of this phenomena in the considered area.

## 2. Crust deformation due to continental water storage

Hydrology deformation was computed on the basis of World GAP Hydrology Model (Döll et al., 2003; Güntner et al., 2007). This model contains an assessment of all kinds of water in the hydrosphere, i.e. the sum of canopy, snow, soil-water, surface water (rivers, lakes, wetlands, inundation areas). It provides global coverage with spatial resolution of  $0.5^\circ$  in latitude and longitude in monthly intervals. Among different global hydrology models this one has the advantage that it includes groundwater component. Deformation  $L$  was computed with the use of equation

$$L(r) = \rho \iint_{Earth} G(|r - r'|) \cdot H(r') \cdot dA \quad (1)$$

where  $\rho$  is a density of water,  $G$  is the integrated Green's function given by Farrell (1972) for PREM Earth Model,  $H$  is a height of equivalent of water and  $dA$  is an elementary surface. The analytic expression (1) which describes convolution of loading mass with Green's function was for computing purpose replaced by numerical integration. Figure 1 presents the example of modelled range of height changes due to water loading in Europe in 2002. These values confirm that hydrological loading cannot be neglected in precise positioning.

It should be mentioned that deformations caused by continental water storage are large scale effects. Computation cannot rely on local or regional water storage. The height changes during two years (2002-2003) were computed taking into account area of variable size. Figure 2a shows that realistic deformations due to hydrological loading can be obtained only when considering area of thousands of kilometres away from station. An example of the impact of using different distances in the Green's function on site displacement results for JOZE GNSS permanent station in Poland is presented in Figure 2b.

## 3. GPS measurement results

Four permanent Polish GNSS stations with long time series, namely Borowa Gora (BOGO), Borowiec (BOR1), Jozefoslaw (JOZE) and Lamkowko (LAMA) were chosen for the analysis (Fig. 3).

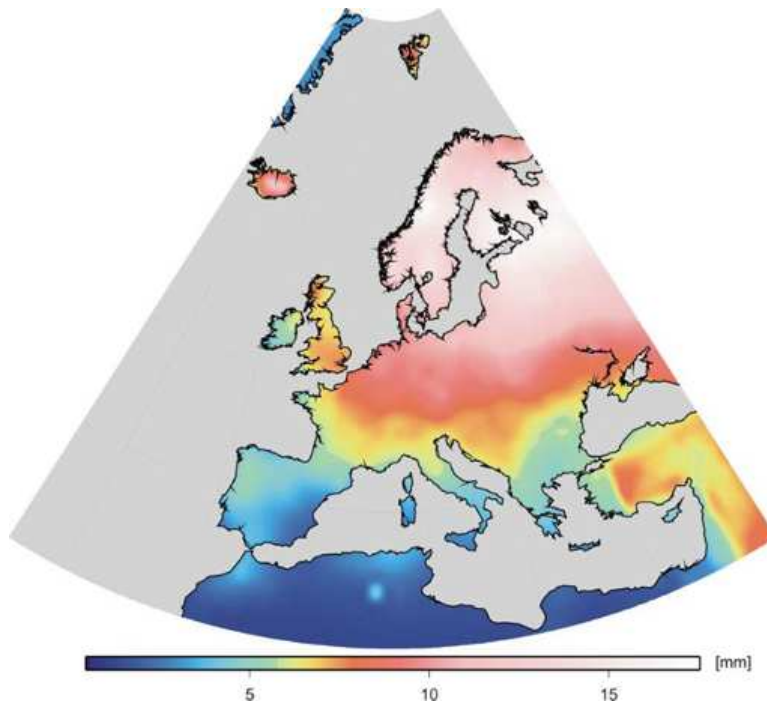


Fig. 1. Range of height changes due to hydrological loading in Europe in 2002

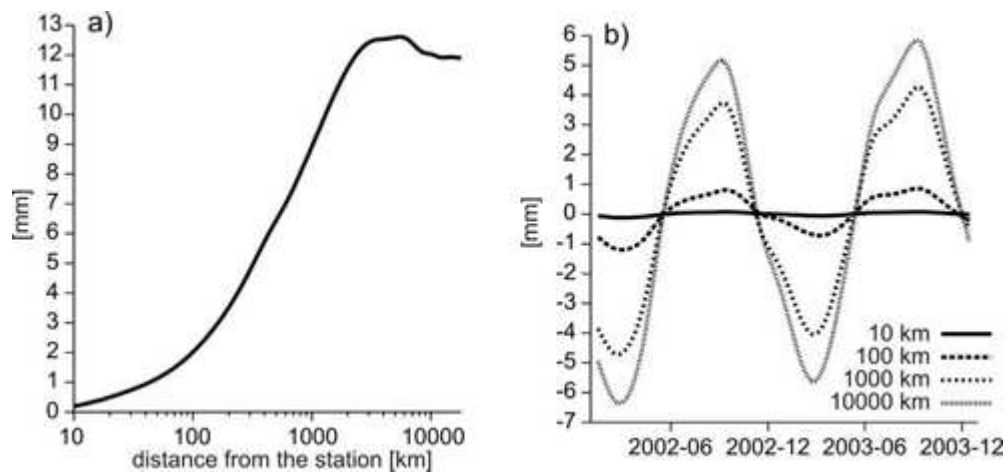


Fig. 2. Height changes range dependent on computation area (a) and modelled height variation for Jozefoslaw station depending on the area taken for computation in 2002-2003 (b)



Fig. 3. Location of GPS stations considered

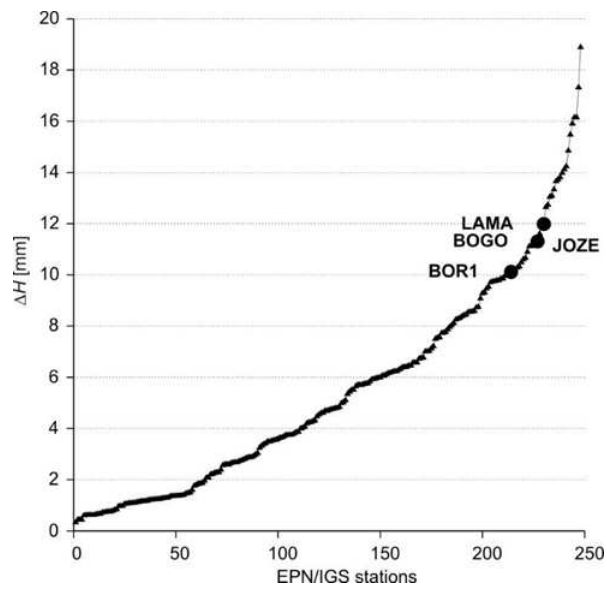


Fig. 4. Height change caused by surface hydrological loading for EPN/IGS sites in 2002

Figure 4 presents annual variation of height due to continental water storage for selected stations relative to 250 worldwide permanent GNSS sites operating within the International GNSS Service (IGS) or EUREF Permanent Network (EPN), ordered according to increasing height change. This graph presents only the range of annual variations of heights. This shows that water storage induced deformation in Poland are quite distinctive.

### 3.1. GPS data processing

GPS data from 10 years from 4 Polish stations listed in previous section (Fig. 3) were processed. Processing was conducted using the Precise Point Positioning (PPP) method as it is free of network constraints and expresses position purely relative to the geocentre. Consistent IGS products from first IGS Data Reprocessing Campaign (repro1) were used for data analysis. IGS Data Reprocessing Campaign aims at reanalysing of all GPS data collected by IGS since 1994 in a fully consistent way, using latest models and methodology.

GPS data in 24-hour blocks were processed using the Bernese GPS Software v.5.0 (Dach et al., 2007) with  $3^\circ$  elevation angle mask for observations. Tropospheric zenith delay was estimated every 1h with New Mapping Function (Niell, 1996). Ambiguities were estimated as real parameters. The atmospheric loading corrections were not applied.

## 4. Comparison of results

Figure 5 shows an overall good agreement for modelled and observed height changes. The scatter of daily PPP estimates is at the centimetre level but seasonal trend is clearly visible and is emphasized with fitted smooth Bézier curve. Some discrepancies between results can be observed. They can be explained by other geophysical loadings, e.g. due to pressure and non-tidal ocean level changes. Semi-annual period in time-series of height changes observed for each station investigated may be explained by GPS technique errors (orbit mismodelling, aliasing problem, etc) but still is not well understood (Penna and Stewart, 2003; Ray et al., 2007).

The fit in Figure 5 is also confirmed in terms of statistics. Evaluated standard deviation is only slightly smaller for corrected smoothed time series with modelled deformation (3.7 mm, 4.0 mm, 3.3 mm, 5.2 mm) than the one computed for smoothed time series itself (4.4 mm, 4.8 mm, 3.7 mm, 6.1 mm) for BOGO, BOR1 JOZE, and LAMA, respectively. This test is not well suited for this comparison due to high noise in GPS results. More convincing are correlation coefficients for smoothed GPS results with modelled deformation which reach as much as 0.6 for BOGO, BOR1 and JOZE, and 0.5 for LAMA site.

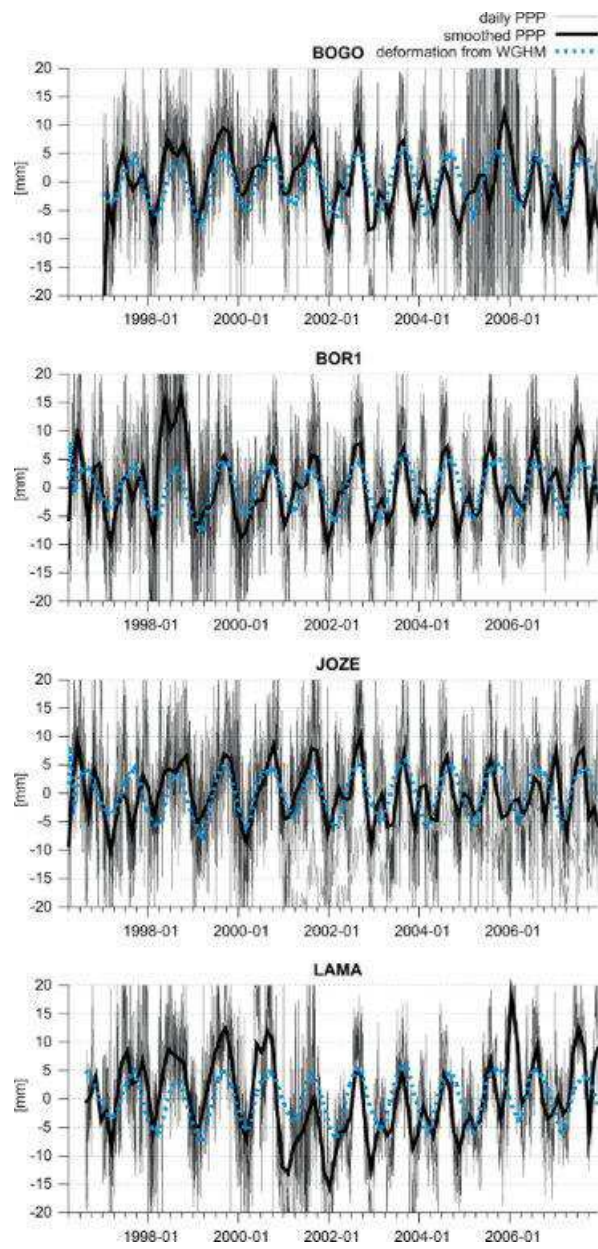


Fig. 5. Comparison of height residuals. Daily and smoothed estimation of heights from GPS measurements are compared with computed crustal deformation. Outliers were rejected, time series was detrended and centred

## 5. Simple deformational model

The amplitude and phase of surface deformation due to continental water storage in consecutive years repeats in very similar manner, despite of possible large changes of height of the equivalent of water between years. This characteristics allowed to model computed vertical displacements by using simple periodic function, given by equation

$$\Delta H = A \cdot \cos(\omega \cdot t - \varphi) \quad (2)$$

where  $A$  is the amplitude,  $\varphi$  is the phase and  $t$  is time. The period in angular frequency  $\omega$  was forced to be equal to one year (365.25 solar days). Figure 6 presents time series of height changes due to continental water loading during eleven years and fitted cosine function. The differences yield significant reduction of seasonal signal with the use of this simple two-parameters function.

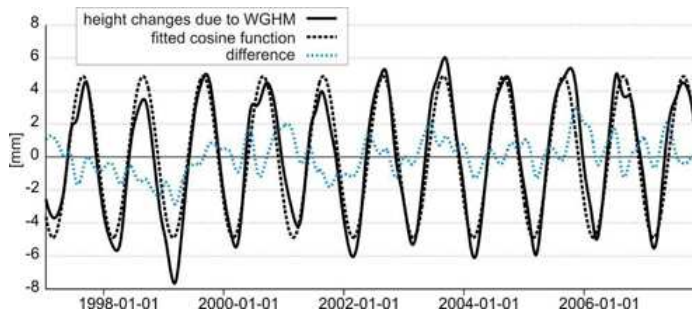


Fig. 6. Height changes due to continental water storage for Jozefoslaw

In the same manner those parameters were computed for dense grid ( $0.5^\circ$  resolution, both in latitude and longitude) for the territory of Poland. The graphical presentation of amplitudes and phases (where phase is given as day of year of maximum height, i.e. smallest storage of water in autumn) is given in Figures 7a and 7b. Smooth change in the amplitude from 4.4 mm in south-west Poland up to 5.4 mm in north-east corner of Poland can be observed. This reflects high variation of seasonal water storage in north-eastern Europe. It should be pointed out that the ocean cells on the west do not affect modelled loading. The phases reflect meteorological phenomena. There is a distinct change in temperature in different places in Poland (again along NE-SW line). The warm season occurs faster in Lower Silesia, thus the driest moment is observed there earlier as well.

The usefulness of the model developed is confirmed in terms of reduction of maximum height range computed for mentioned 11 years interval. Figure 8a presents modelled height range computed on the basis of WGHM output while Figure 8b shows the range of height change after applying simple two-parameters model. The reduction of height variation is clear. The developed simple cosine model for the territory of Poland could be used for subtracting major part of hydrological signal from GPS height time series.

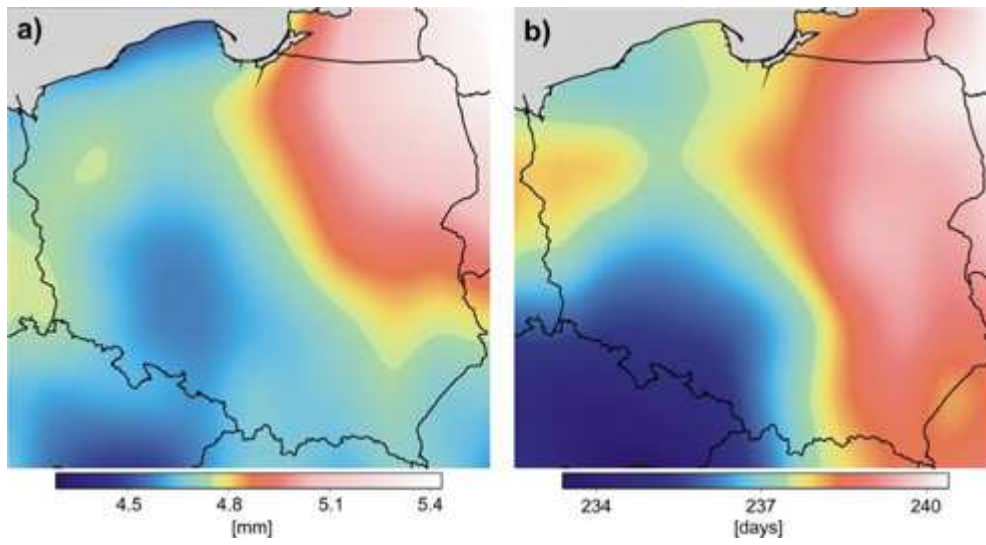


Fig. 7. Distribution of amplitudes [mm] (a) and phases [days of year] (b) for cosine model fitted in modelled deformation in 1997-2007 period

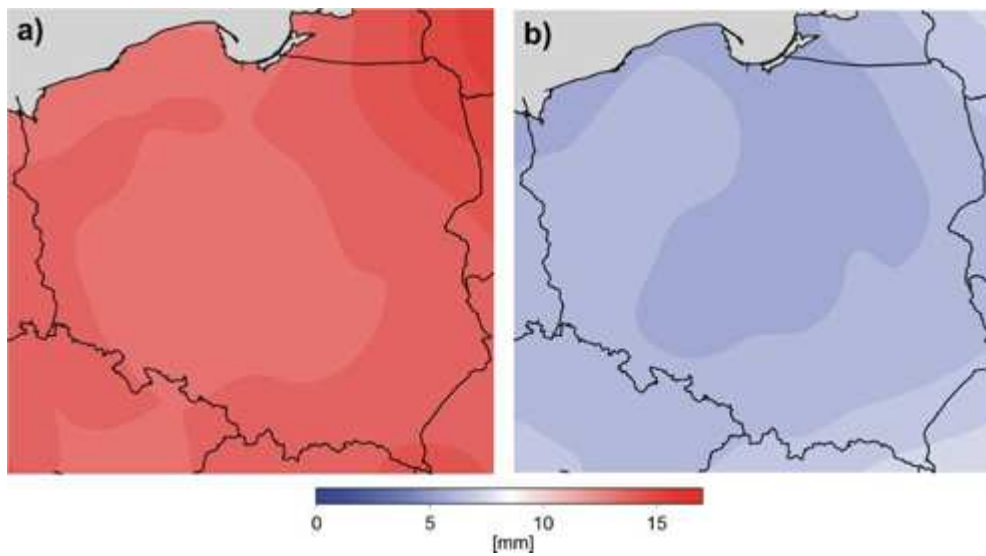


Fig. 8. Range of height change for deformations from WGHM model (a) and reduced with fitted cosine model (b) in 1997-2007



## 6. Conclusions

The analysis performed showed that crustal deformation due to continental water storage is one of the major components in annual apparent variation of position. This phenomenon is well observed in GPS heights even if single point positioning technique is used. Good agreement between modelled and observed height changes, which can reach 10 mm peak to peak, was presented both in the amplitude and phase. One should also be aware that large discrepancies also occurred in the comparisons performed and it requires more sophisticated studies. One possible reason could be connected to atmosphere loading effect containing also an annual signal which is, however, substantially weaker. Some of those discrepancies may be attributed to processing artefacts, mainly aliasing.

The crustal deformation due to continental water loading pattern allowed to apply a simple hydrological loading model for Poland. This can easily be used to reduce seasonal height variation for geodetic sites.

In this paper only height changes were considered, however horizontal position is affected as well with the same period but with much smaller amplitude (1-2 mm). This cannot be observed with PPP technique, however, later studies of the authors (not published yet) show that this horizontal changes can be fairly good resolved with differential results (global solutions).

Secular height changes which are negligible on the territory of Poland are not mentioned in the paper; for other areas they, however, could be essential and secular water storage changes should be taken into account to distinguish from other geophysical signals (post-glacial rebound, tectonic movement).

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### **Badanie wpływu deformacji skorupy ziemskiej powodowanych obciążeniami hydrologicznymi na wyznaczenie wysokości z pomiarów GPS**

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#### **Streszczenie**

Celem niniejszej pracy jest analiza wpływu zmian wielkoskalowych stosunków wodnych na deformację skorupy ziemskiej. Przedstawiona jest również możliwość monitorowania tego efektu przy pomocy geodezyjnych technik satelitarnych. Na podstawie zmiennego rozkładu mas hydrosfery lądowej (do tego celu wykorzystano model hydrologiczny WGHM) oraz wykorzystując informacje dotyczące właściwości skorupy ziemskiej (tzw. funkcje Greena) zostały obliczone modelowe zmiany wysokości wybranych punktów na terenie Polski. Wyniki te zostały porównane ze zmianami wysokości wyznaczonymi dla czterech stacji permanentnych GNSS, które dysponują długimi ciągami obserwacyjnymi, tj. Borowa Góra, Borowiec, Józefosław oraz Lamkówko. Do opracowania obserwacji GPS wykorzystana została metoda Precise Point Positioning (PPP), czyli obserwacje dla każdej stacji były opracowywane niezależnie. Pozwoliło to na odseparowanie sygnałów właściwych dla danej stacji pomiarowej i prawidłową interpretację geodynamiczną. Wyniki te dobrze zgadzają się co do amplitudy i fazy z modelowym efektem. Przyczyny widocznych rozbieżności również zostały przedyskutowane. Wyraźna, roczna powtarzalność deformacji wynikających ze zmiennego rozkładu mas wodnych, pozwoliła na skonstruowanie prostego dwuparametrowego modelu dla terenu Polski, który pozwala znacznie zredukować wpływ tego efektu bez konieczności złożonych obliczeń.