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Earth crust deformation in Poland: modelling and its implication for positioning with satellite based geodetic techniques

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Abstract. This paper gives the general overview of the effects which continuously deform our planet. The main aim is to give the picture of the temporal and spatial range of this phenomena and to indicate their importance in high precision positioning with space geodetic techniques. We present here the ranges of magnitude and pattern of earth tides, ocean tidal loading, atmospheric radiation tides loading, polar motion and its oceanic indirect effect, as well as the non-tidal ocean loading. We pay the special attention to loading effects due to atmosphere and continental water storage, which can cause significant changes in point position time series. Our study concentrate mainly on the territory of Poland. The Józefosław site was chosen as a representative example for the whole country. We present also here the impact of selected phenomena for relative geodetic measurements.

Keywords: geodynamics, Earth deformation, surface loading

1 Introduction

The earth is continuously changing its shape. There exists forces which can deform the crust as much as few tenths of centimetres. This cannot be neglected when the centimetre precision is required for site position in global reference frame. We present here the spatial and temporal pattern of the most important effects which results in site position variation. In this work we also discuss the importance of selected effects for space geodetic techniques used in differential mode when a region of few hundreds of kilometres is considered.

2 Tides

2.1 Earth Tides

The differential forces from external bodies play the most important role when one is interested in Earth deformation. We do not give here much theory referring to well known bibliography (e.g. Melchior, 1978). The features of tidal potential is very well known and the only unknown is the elastic (we neglect viscosity for the diurnal and sub-diurnal period) response of the Earth. Our knowledge permits us to have the appropriate algorithms for computing tidal deformation vector within 1 mm (Petit and Luzum, 2010b). We only give here an impression of the tidal deformation range which can reach as much as 0.5 m in height component at equatorial area. In tropics the dominant are semi-diurnal waves while in mid-latitude region the diurnal are dominant. On the poles we can observe only long period ones. Only a few so-called tidal waves are responsible for almost all deformation however in precise computation we must deal with hundreds of those. An example of deformation caused by Earth Tides (ET) in Józefosław is given in the Fig. 1(a) computed on the basis of HW tidal potential catalogue (Hartmann and Wenzel, 1995) and DDW tidal Earth model (Dehant *et al.*, 1999). The ET models are usually applied in processing software, so the short term deformation are usually excluded from space geodetic technique results. The appropriate conventional model can be found in IERS Conventions (Petit and Luzum, 2010b, sec. 7.1.1). However there still could be some problem with longer period through aliasing phenomena (Penna and Stewart, 2003).

2.2 Ocean Tidal Loading

The tidal potential causes spectacular ocean tides which causes the movement of huge amount of water. This leads to indirect effect, the so-called Ocean Tidal Loading (OTL). The variable loading of the water on the Earth crust causes the periodical crust deformation which can be observed even hundreds kilometres from seaside. The main periods of OTL are exact with those of ET but through complicated nature of ocean tides the phases are shifted and the amplitudes are strictly dependent of the tidal regime in nearest sea or ocean. The range of OTL phenomena can reach as much as a few centimeters. The example of OTL for Józefosław is presented in Fig. 1(b). The variations in height component can rich up to 2 cm peak-to-peak amplitude. Here we present the computation using SPOTL software package (Agnew, 1997) with TPXO ocean tides model (Egbert and Erofeeva, 2002)(for Józefosław station all modern ocean tides model gives similar results). The problem of appropriate modelling of OTL is given in IERS Conventions (Petit and Luzum, 2010b, sec. 7.1.2).

2.3 Atmospheric tides

The atmosphere undergoes periodical movement through tidal forces. The more pronounced phenomena is the radiation atmospheric tides which are triggered by insolation. The main waves has exact diurnal and semi-diurnal period, and have S_1 and S_2 codes respectively (Dai and Wang, 1999). The continuous changes of atmospheric pressure causes variable atmospheric tidal loading. This result in crust deformation. The effect are at the millimetre range and is the most important in equatorial region. Moreover for this frequencies the Inverted Barometer (IB) hypothesis is assumed to be valid, so there is no any pressure changes on the ocean bottom. The both harmonics have global pattern while for the diurnal we see strong amplitude dependency of land sea distribution (see graphics in Rajner, 2011).

We show here the time series of S_1 and S_2 atmospheric tidal loading for Józefosław computed on the basis of T. van Dam grids (`http://geophy.uni.lu/ggfc-atmosphere/`) prepared on the basis of atmospheric tide model given by Ray and Ponte (2003). Is is obvious that this phenomena in terms of deformation is of no importance in mid-latitude region. The treatment of atmospheric tidal loading is explained in IERS Conventions (Petit and Luzum, 2010b, sec. 7.1.3).

3 Polar motion

The pole of the Earth rotation changes its origin within Earth figure. While this subject is out of scope of our study, we are simply interested in deformation results of Polar Motion (PM). The change of position of the pole cause the change the change of centrifugal potential (we neglect small changes through variation of angular velocity of the Earth rotation). The elastic properties of our planet results in deformation. The IERS time series of pole position along with Love numbers where used to compute deformation in Józefosław utilizing equations given by Wahr (1985) – Fig. 1(e). The dominant frequency is 14-month Chandler period and the deformation can reach sub-centimetre amplitudes. The treatment of this effect is elaborated in IERS Conventions (Petit and Luzum, 2010b, sec. 7.1.4) and is usually modelled in professional space geodetic techniques processing software.

3.1 Ocean pole tide loading

The change of centrifugal potential cause the change of ocean heights which, in simplified assumption, adjust to new equipotential surface. The movement of water masses causes the variable load on ocean bottom which results in crust deformation called ocean pole tide loading (OPTL). The computing scheme for this effect is given in IERS Conventions (Petit and Luzum, 2010b, sec. 7.1.5) and is based on work of Desai (2002). For completeness the time series of OPTL is shown in Fig. 1(f) showing the unimportance of this effect in Poland.

4 Loading effects

In the last decade there is ongoing debate whether environmental loading should be incorporated in operational data processing.

Nowadays this topic is of great importance. Accessibility of environmental data sets and development of operational services for computation of crustal deformation lead to conclusion that it is only a matter of time when removing of loading effects will be yet another standard in positional space geodetic processing schemes. Currently there is no any resolution which advise removing loading effects from positioning results.

4.1 Atmospheric loading

The synoptic large scale variation of atmospheric pressure result in crust deformation. The computation of this effect utilize global air surface pressure fields along with crust properties. The IB hypothesis is usually applied. For the purpose of presentation we present here the results of atmospheric non-tidal loading (ATML) for three components in Józefosław – Fig. 1(g). The range of height variation is more than convincing when importance of ATML is discussed. The other significance is that ATML is undoubtedly recognized in position time series (van Dam and Herring, 1994, at least for height component). The ATML time series here were taken from model of Petrov and Boy (2004).

4.2 Continental water storage loading

The climate forcing can lead to significant variation in continental water storage. With the mass transport in the Earth system we can observe the side effect of the crust response due to loading and unloading (van Dam *et al.*, 2001). This effect of hydrology loading (HYDL) is quite important in Poland and can reach one centimetre of peak-to-peak amplitude with clear seasonal variation (loaded crust in early spring and unloaded in early autumn – Rajner and Liwosz, 2011). The time series given in Fig. 1(h) were computed on the basis of GLDAS model (Rodell *et al.*, 2004) and Greens function given by Farrell (1972). The procedure is described in Rajner and Liwosz (2011).

4.3 Non tidal ocean loading

For the sake of completeness the modelled variation of position in Józefosław through non tidal ocean height variation is presented in Fig. 1(i). The Ocean Bottom Pressure (OBP, from `http://grace.jpl.nasa.gov`) estimation from ECCO (Kim *et al.*, 2007) ocean model were used in this study. Using those values we take only an eustatic part of ocean height change, therefore we can treat this as a good approximation of real water masses loading on ocean bottom. This effect is significant only for coastal sites while in continental ones it is usually very small.

5 Differential geodetic techniques

The amplitudes of described effects are quite impressive. The values given in Fig. 1 show the movement relative to centre of the Earth. (We should aware that due to consistency of this review, we do not strictly differentiate whether it is centre of mass of whole planet or centre of the Earth figure. For discussion see e.g. Blewitt, 2003.) There is common way to mitigate many effects which affect positioning with space geodetic techniques. Differential measurement should diminish this effect considerably. Therefore we verify this assumption in Fig. 2. In this plots (the acronyms are the same as in Fig. 1) we show the maximal and minimal values of difference of respective phenomena between all points within the appropriate distance from Józefosław at the same time. We choose the extreme values for time span shown in Fig. 1 (horizontal axis for each phenomena). In other words we can read the plots in Fig. 2 as the extreme difference of deformation relative to Józefosław. This clearly shows that despite of global and continental character of described effects we cannot neglect their impact in relative mode. Thus, even in regional measurement the conventional models for crust deformation needs to be applied.

6 Conclusions

We presented here the main effects which continuously deform Earth's crust. The short glance at the values presented here can tell which one are important depending on spatial and precision criteria in specific geodetic task. One should keep in mind that even in differential mode some of this effects cannot be neglected in regional geodetic networks.

The aim of this study was to give spatial and temporal pattern with the typical amplitudes of select effects which can be presently modelled. We do not give any examples of verification of this models using space geodetic technique results. Those can be found in cited papers and references therein.

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The contribution of all agencies which provide geophysical data sets is greatly acknowledged. The ATML time series was provided by L. Petrov with his service `gemini.gsfc.nasa.gov/aplo/`. The animated presentation which was presented during the seminar is available through `www.geo.republika.pl`.

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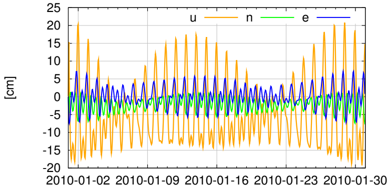
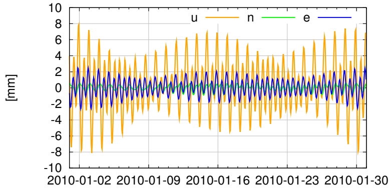
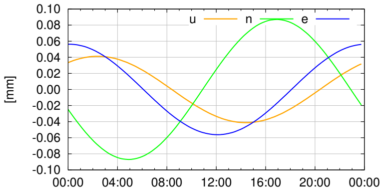


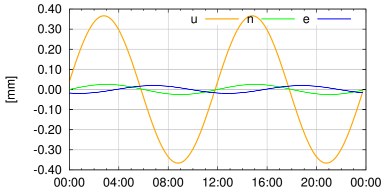
(a) ET



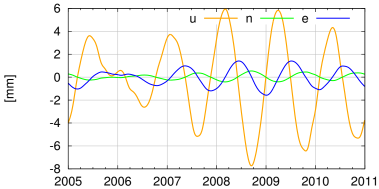
(b) OTL



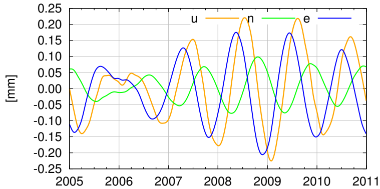
(c) S_1



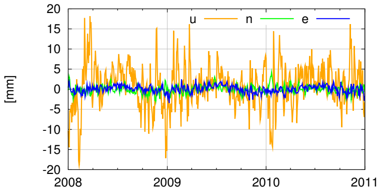
(d) S_2



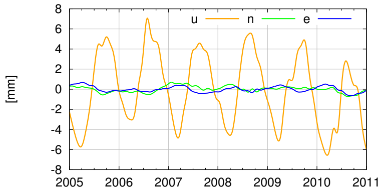
(e) PM



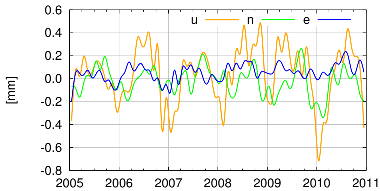
(f) OPTL



(g) ATML



(h) HYDL



(i) OBP

Figure 1. *Deformation time series in Józefosław for up, north and east component modelled for different phenomena*

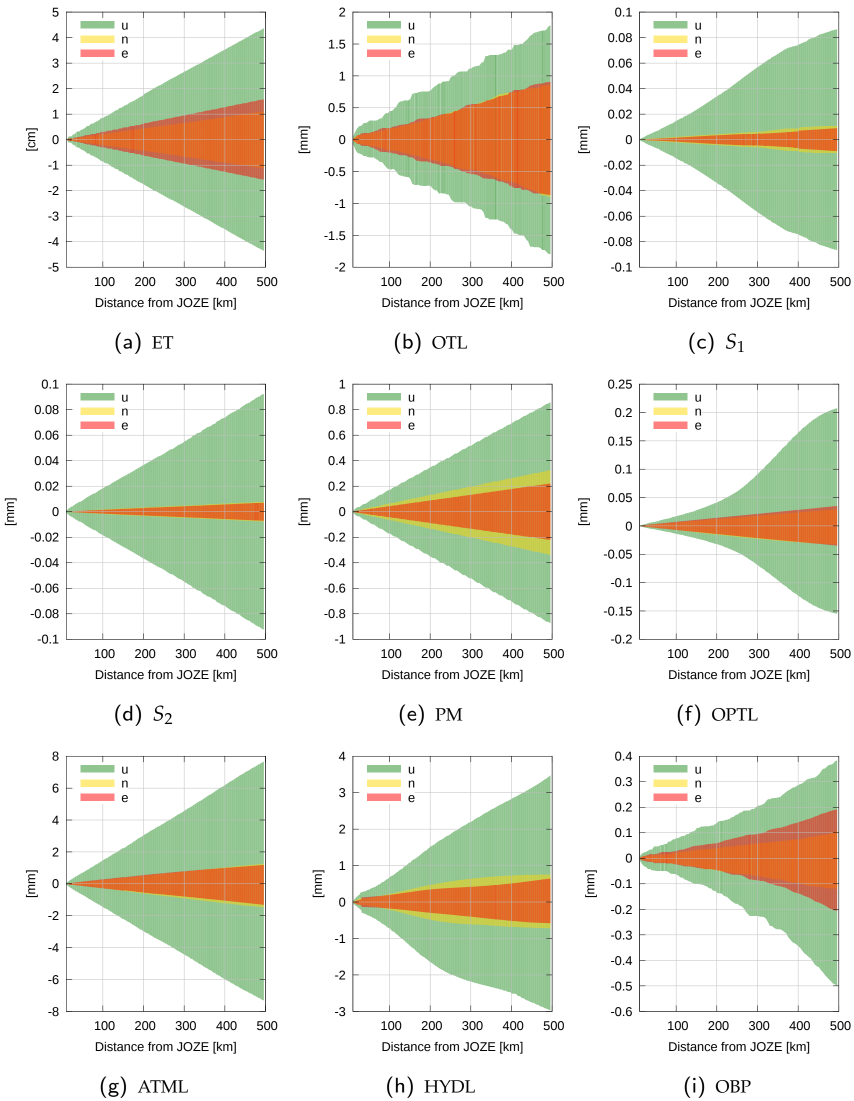


Figure 2. *Deformation time series in Józefosław for up, north and east component*

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