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Non-tidal loading by the Baltic Sea: Comparison of modelled deformation with GNSS time series

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ABSTRACT

We study the influence of non-tidal loading by the Baltic Sea on GNSS daily coordinate time series. The momentary sea surface is estimated from hourly tide gauge recordings around the Baltic and the load is convolved with Green's functions to determine 3-D deformation, gravity, potential and tilt effects at 193 stations around the Baltic. This paper concentrates on 3-D deformation at a small number of continuous GNSS stations. Daily coordinate time series based on both Precise Point Positioning (PPP) and double differences (DD) were used. We find that for the east component of inter-station vectors crossing the Baltic, up to 56% of the variance can be explained by the Baltic loading. In the north and up components the Baltic loading is not well detectable. We think that for the north component this is due to station positions, and for the up component also to interaction with regional atmospheric loading.

1. Introduction

The loading effects of ocean tides are nowadays routinely removed from GNSS measurements, typically using the recommendations of the International Earth Rotation and Reference Systems Service (IERS) conventions [22]. In recent years there has been increased interest of the effects of the non-tidal variation in ocean loading. This concerns both the "normal" ocean circulation (e.g. [17-19,24,29] and special occasions like storm surges [12,13,17].

The variations in the sea level can be abrupt and large, for example during storms. The variable load may cause significant effects in geodetic measurements, especially near the coastline. This may cause problems in time-lapse measurements (e.g. GNSS campaigns, absolute gravity measurements) as well as in continuous time series. In GNSS time series 40% of the variation can be due to varying atmospheric, hydrological and ocean masses [9], which in turn makes the derived rate uncertainties larger than expected [6,7].

The seasonal loading signals, while typically smaller in size may distort the trend estimation, especially in shorter time series. This has been studied using daily [18,29], weekly [24] and monthly [7,19] time series of GNSS.

Most of the papers mentioned above treat vertical deformation only. The exception is Geng et al. [13] who detect the 3-D deformation during a storm surge event in the North Sea, with sub-daily resolution. We study the 3-D effect of the Baltic Sea loading in daily time series of GPS derived positions, but we have a time series of 1.5 years, which includes longer-period phenomena than the one-month time series of Geng et al. [13].

The relevant quantity for load calculations in ocean areas is the ocean bottom pressure (OBP), i.e. the sum of the load by the water column and the atmospheric pressure on the sea surface. However, in this study we are going to neglect the atmospheric pressure part. Can anything useful come out from such a computation?

Suppose that the atmospheric surface pressure anomaly is regionally near-uniform, i.e. it produces a near-uniform vertical deformation and near-zero horizontal deformations. When we then calculate the loading effect by the sea using only the water column part of the OBP, what comes out is not the total deformation but the deviation of the deformation from the regional common mode. The common mode in the GPS-derived coordinates can be eliminated by differencing. At the same time we difference the load corrections. Thus the Baltic loading could be studied using the differences, without knowledge of the common atmospheric mode. Note that the differencing also in part eliminates other regional common modes, like the annual hydrological load cycle.

The success of this approach obviously depends on the validity of the common-mode assumption. It will turn out that this assumption works for short vectors and horizontal deformation, and fails for long vectors and vertical deformation. While we

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neglect the atmospheric contribution to Baltic OBP in this study, we point out that this makes it easy to rigorously superpose our Baltic deformation results on atmospheric load calculations that use a neutral response of the Baltic instead of any inverse barometer type of behavior [15,31].

In what follows, we compute the loading effect of the Baltic Sea level variations using hourly sea level surfaces. We then difference both the computed deformation and the coordinate changes measured by GPS at selected station pairs around the Baltic Sea and compare them. We use two different daily time series of GPS-derived positions: the PPP (Precise Point Positioning) time series provided by the Jet Propulsion Laboratory and a double difference solution computed at the Finnish Geodetic Institute (FGI). The data and methods are described in Sections 2 (Baltic) and 3 (GPS). In the fourth section are the results of the loading and GPS comparison, fifth section contains the discussion and the last section is left for the conclusions and outlook.

2. Baltic Sea

The Baltic Sea is a well-monitored semi-enclosed sea in northern Europe. The level of the Baltic Sea level has been studied and recorded since 18th century (e.g. [10,20]). Nowadays a dense network of tide gauges monitors the Baltic Sea continuously and automatically, and also the satellite altimetry missions provide observations on the region. Thus, the Baltic Sea is suitable for testing and studying the effect of mass variations. The Baltic Sea water storage has been compared to GRACE analysis [26] and the mass variations and loading have been studied using gravimeters (e.g. [21,25] and GPS [19].

The mass variations of the Baltic Sea are mostly due to atmospheric pressure changes and wind, which redistribute the water within the basin and also govern the water exchange with the North Sea which determines the so-called fill level of the Baltic. Because the connection to the North Sea is via the narrow Danish Straits, the tides are small and the effect of local variations due to wind conditions is large.

Fig. 1 shows the magnitudes of 3D loading deformation calculated for a one by one degree grid. The load is a uniform fill level: one meter layer of water. The calculation methods are described in Section 2.2. The maximum vertical deformation near Gotland Island is about –21 mm and the horizontal maximums are about 4 mm. A variation in uniform fill level is in fact very close to the first Empirical Orthogonal Function (EOF) of Baltic Sea mass variation as determined by Wiehl et al. [28].

2.1. Sea level heights and surfaces

Previous studies of non-tidal ocean loading (e.g. [29]) typically rely on oceanographic models to estimate the load. However, in the Baltic we have a unique opportunity to estimate the momentary sea level directly from the more that 60 tide gauges that surround the sea at all coasts and provide hourly data in near real time through the Baltic Operational Oceanographic Service (BOOS, http://boos.org). We supplemented the BOOS data with Finnish tide gauges from the Finnish Meteorological Institute FMI. The hourly sea level surfaces were then created by interpolating between the hourly sea level heights at the tide gauges. Minimum-curvature-surface splines (routines in the IDL software library http://www.exelisvis.com/ProductsServices/IDL.aspx) were used. The number of tide gauges available varies in the computation. The data is near real-time and thus may suffer from gaps in data stream. The number of stations used in the interpolation varies from 40 to 60 stations. As the sea level is typically a rather smooth surface, this variation in the support points used does not appreciably influence the surface models created. The use of tide gauges instead of models is discussed in Section 5.

Steric effects are neglected in this preliminary study. The steric effects are primarily seasonal and about a one order of magnitude less than the effects in the variation of the water volume [26]. The tides in the Baltic Sea are only few centimetres in most areas and maximally 0.2 m (in the extremity of the Gulf of Finland). The tidal variation in the sea level is interpolated by our spline-interpolation between the tide gauges in the same way as the non-tidal variation.

2.2. Calculation of loading deformation

The sea surface derived from tide gauges, sampled at 0.2×0.1 degrees resolution (longitude $\times$ latitude) over the Baltic and coasts provides the model grid for the deformation calculation. The load response was computed using the program set SPOTL [1]. Green's functions for the Gutenberg–Bullen Earth model A (as described in [11]) are used. SPOTL overlays the land/sea mask on the model grid and resamples it to a new radial load grid centered on the computation point. The resolution for the coastline is 1/64 of degree. SPOTL also provides densities of surface sea water from the World Ocean Atlas [2]. In the Baltic they are typically 1003–1004 kg m^{-3}, though for the present purposes the calculation could just as well be made with nominal density values (say 1000 or 1027 kg m^{-3}).

The computation produces gravity change, potential change, deformation in three dimensions, tilt deformation in north and south and strain in north, east and shear. The center of mass of the solid Earth (CE) reference frame was chosen for the computation.

We have computed hourly time series for 193 stations in Fennoscandia, Baltic countries and on the south coast of the Baltic Sea. The time period is 27.2.2008–31.12.2012. Fig. 2 shows all components computed in the run for a single station. The output are hourly values (black in Fig. 2). For the comparison with GNSS time series daily values were computed (green in Fig. 2).

3. GNSS time series

We have used two types of GPS-derived coordinate time series. The first one has been computed at Jet Propulsion Laboratory (JPL, ftp://sideshow.jpl.nasa.gov/pub/JPL_GPS_Timeseries/repro2011b/post/point/, 8.3.2013), hereafter referred to as JPL time series. These time series are computed with Precise Point Positioning method using GIPSY-OASIS II software [32] fixing ambiguities [4]. While the preliminary products are non-fiducial, the daily results are transformed to IGS08. (http://sideshow.jpl.nasa.gov/post/tables/GPS_Time_Series.pdf). This is a global transformation; as such it could mask and smear regional loading phenomena in the coordinate time series, but not in the difference time series in a limited area which is what we are working with. These data are available for the whole period of Baltic Sea loading (February 2008 until end of 2012). Due to gaps and spikes in time series we have chosen a period of 671 days, starting in February 2008 and ending in December 2009.

The second time series has been computed at the Finnish Geodetic Institute (FGI, now Finnish Geospatial Research Institute FGI) using double differences and the Bernese GPS Software version 5.0 [8], hereafter referred as FGI time series. The original time series were produced for a regional test survey, and in that application the daily results were transformed to ITRF2008. Now this regional transformation could severely smear and mask the deformation signals we are looking for, even in the station differences. We therefore took the daily normal equations and instead of the