Modelling Vertical Site Displacements due to Atmospheric Pressure Loading with the Bernese Software ! A Demonstration Using EUREF Data !

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Abstract

The observations collected by the EUREF permanent network are almost exclusively processed with the Bernese GPS software 4.2. For obvious reasons the software does not yet model atmospheric pressure loading effects. However, in case of the EUREF network the vertical displacements due to pressure loading at high northern latitudes may reach centimetres and may thus exceed the accuracy goals. Therefore, we have implemented in the Bernese software the capability of estimating site dependent vertical pressure loading coefficients. This development is applied to selected EUREF data sets. A common adjustment of all data yields significant loading coefficients for the majority of analysed sites. Both, the estimation of loading parameters as well as their application in the network processing is described.

1. Introduction

The Earth!s crust experiences displacements due to various loading phenomena. Common to all these phenomena is that the main displacement of a point on the surface of the Earth is in vertical rather than in horizontal direction. The dominant effect is due to ocean tides which may amount to as much as ±7 centimetres at sites on the European Atlantic coast. These displacements with primarily near diurnal and semi-diurnal periods are modelled in state of the art GPS software systems. Other loading effects caused by atmospheric pressure, snow and ice coverage or water storage and their variations are not yet regularly accounted for in the GPS data processing. Unlike ocean tide loading the displacements are not periodic but they may show seasonal characteristics. Whereas the latter two effects do not exceed the one centimetre level, pressure variations may cause height changes of up to a few centimetres (SUN et al. 1995).

Several analyses aiming at detecting pressure loading signals in height estimates and at determining loading coefficients have been performed during the past years. In case of VLBI VAN DAM and HERRING (1994) proved high correlations between pressure variations and inter-site distance changes on long baselines; MAC MILLAN and GIPSON (1994) as well as HAAS et al. (1997) estimated vertical loading coefficients for a number of sites directly from VLBI measurements and surface pressure data. A first analysis of GPS data with regard to pressure loading effects by VAN DAM et al. (1994) yielded not as definite results due to the higher noise level of the GPS height estimates.

The EUREF Permanent Network (EPN) extends to high northern latitudes which are, compared to the central and southern part, exposed to large pressure variations. Thus, the EPN height estimates might be considerably affected by pressure loading. Therefore, a first attempt to prove the loading effect consisted of analysing a 17 stations EPN subnetwork during a 32 days period of large pressure changes in early 2000 (KANIUTH and HÄFELE 2002). Subsequently this network has been extended in terms of number of stations and processed days. A common adjustment of all data based on daily height estimates and their full variance / covariance matrix yielded significant loading coefficients for the majority of sites (KANIUTH and HUBER 2003). Continuing, site dependent vertical loading coefficients were implemented as a new parameter type in the Bernese GPS software, and a further extension to 32 stations and 126 days of data lead to improved results. As the EPN processing is almost exclusively done with the Bernese software, the present contribution discusses mainly the related software developments for estimating as well as applying vertical pressure loading coefficients and demonstrates their performance.

2. Software Development

The adjustment program GPSEST of the Bernese software version 4.2 (HUGENTOBLER et al. 2001) is capable of solving for more than twenty different parameter types. The definition of all parameters actually to be estimated is given in an array "locq" which contains all relevant information such as the type of each parameter, the station number and the coordinate component concerned, the period of validity etc..

Defining site dependent vertical pressure loading coefficients as a new parameter can be realized either by extending the list of parameter types or by replacing an existing but not used parameter. We have chosen the latter option and accommodated the pressure loading parameters in place of local troposphere models, a parameter type which is anyhow not supported by the menu. Besides the station number "locq" contains then the individual reference pressure to which the estimated station height will refer. As the parameter list is also stored in the normal equation file a consistency check of the applied reference pressure values can be done when accumulating many normal equation systems.

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The pressure data sets, containing the actual local pressure and the station individual reference pressure, are introduced as soon as the adjustment program has read the observation period and the names of all involved stations. The observation equations set up in the subroutine SNDIFF are extended by the partial derivatives of the observations with respect to the loading coefficients. Several other modules needed modifications in order to support the new parameter type. The normal equation format itself has also been modified accordingly.

When not estimating loading parameters in the adjustment but introducing already available coefficients into the data processing, the time dependent site displacements are modelled like solid Earth tides ocean tides loading effects. Figure 1 displays a simplified flow chart of the Bernese adjustment program and indicates the modified modules as well as the stage of introducing the pressure data.

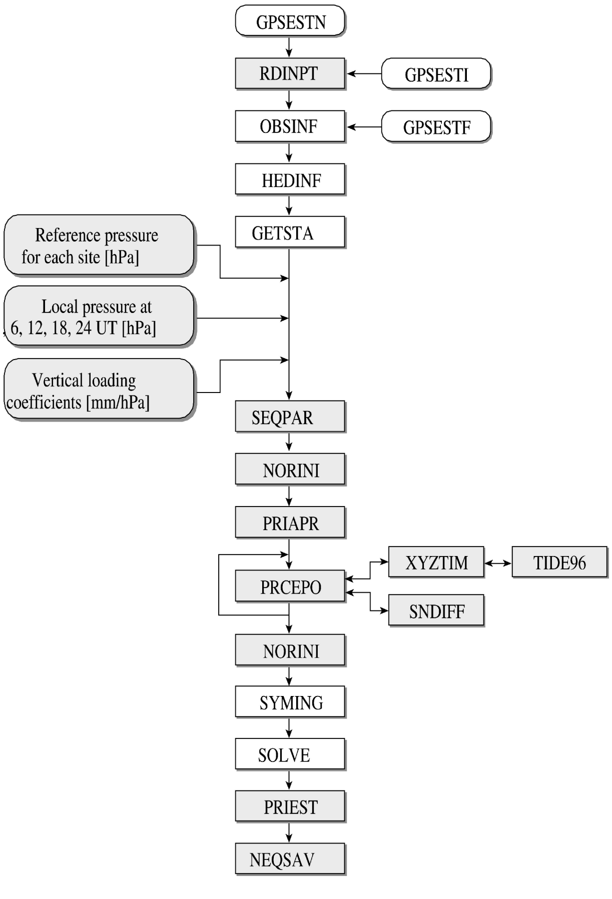


Fig. 1: Generalized flow chart of the Bernese adjustment program GPSEST; modified modules and new data files are underlayed in grey.

Some modifications were also necessary in the normal equation accumulation program ADDNEQ. These relate mainly to the subroutine reading the normal equations (GETNEQ) as a consequence of changing the format and to the modules performing the least squares solution (COVEST) and printing the results (PRNERS).

3. GPS Data

Considering firstly, that the presently achievable repeatability of daily GPS height determinations in regional or global networks is not better than ± 5 mm, and secondly, that the vertical displacement due to pressure variation is on the order of 0.5 mm/hPa or less, the design of the network to be analysed and the selection of data periods to be processed is rather important. As regards the first issue, the EUREF Permanent Network (EPN) is a perfect candidate for demonstrating the ability to derive vertical loading coefficients from GPS observations using the modified Bernese software. The EPN extends with a rather dense station distribution to beyond 70/ northern latitude, and in particular the high latitude sites are exposed to large pressure variations. Therefore, we have selected a network of 32 stations with a concentration at higher latitudes, but including also a number of more southernly sites experiencing relatively small pressure variations. Figure 2 displays the station distribution; the identifications are those used by EUREF. It should be mentioned that NOT1 and TLSE replace former setups NOTO and TOUL. The stations STAS, TRDS and VARS were earlier in operation under the identifications STAV, TRON and VARD.

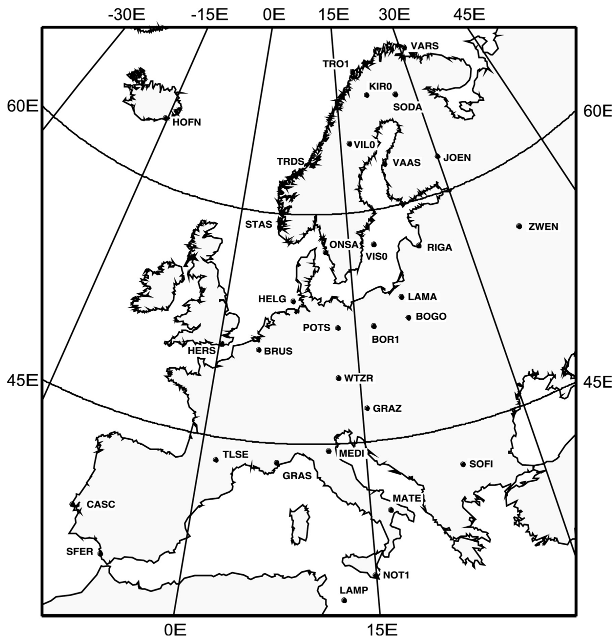


Fig. 2: EPN stations included in the analysis

As concerns the second issue, the selection of proper periods to be processed, the following criteria were considered:

! Inclusion of periods of large pressure anomalies as well as days of rapid pressure variations;

! Proper distribution of the selected periods over a sufficiently long time span in order to enable also the estimation of vertical velocities primarily of sites in Fennoscandia which are subject to post-glacial uplift;

! As far as possible, data completeness and good tracking performance at the majority of involved stations.

Following these criteria we have selected eleven periods between March 1999 and February 2003, covering in total 126 days of data. The temporal distribution of the analysed data sets is given in Table 1.

Table 1: Analysed data periods and number of involved stations

Year	Days	Stat.	Year	Days	Stat.
1999	074 ! 082	30	2002	053 ! 060	32
1999	328 ! 335	32	2002	078 ! 085	32
2000	023 ! 054	31	2002	244 ! 254	32
2000	268 ! 278	28	2003	019 ! 024	32
2001	037 ! 049	31	2003	027 ! 035	32
2001	273 ! 283	32			

4. Pressure Data

The pressure data used in this analysis originate from the Global Data Assimilation System (GDAS) of the National Center for Environmental Prediction (NCEP) being part of the U.S. National Oceanic and Atmospheric Administration (NOAA). Besides auxiliary information these daily data sets comprise surface pressure for a global 1/ × 1/ grid at six hours intervals, starting at 0 hrs UT (SCHÜLER 2001). The reference heights of the grid points are given as geo-potential heights which can for this study be treated as orthometric heights. The generation of pressure anomalies to be introduced into the GPS network adjustment consisted of the following steps:

! Transformation of the orthometric heights of the grid points to ellipsoidal heights by applying the EGM 96 geoid undulations (LEMOINE et al. 1998);

! Conversion of the pressure values at the grid points to the approximate ellipsoidal heights of the GPS stations;

! Estimation of the surface pressure at the GPS stations by linearly interpolating between the adjacent grid points;

! Generation of daily files of pressure anomalies with respect to the individual station reference pressure values at six hours intervals.

The reference pressure values were calculated by propagating the sea level pressure of 1013.25 hPa to the approximate ellipsoidal station heights and accounting for geoid undulations. Figure 3 displays the pressure anomalies in the area of the network for one out of the 126 analysed days; it is obvious that relative anomalies of 80 hPa may occur. The total range of the pressure anomalies at each involved site during the processed periods is shown in Figure 4. The stations are arranged according to their latitude from left to right in order to indicate the latitude dependence of the size of the pressure anomalies. As can be seen the reference pressure of sites at higher latitudes does not match the mean value during the 126 days. This is simply due to the fact that during most of the selected winter periods Fennoscandia was dominated by pressure lows. Typical examples of the local pressure anomaly distribution during the analysed periods are given in Figure 5 for two stations, one of them located in Fennoscandia and the other one in the Mediterranean Sea. The figure shows again the remarkably larger range of the pressure anomalies at higher latitudes compared to the southern part of the network. The pressure records indicate also that the sub-daily variations mainly at northern sites may be large. Examples of the anomaly variations during two seven days periods for five stations at different locations are displayed in Figure 6. Thus, in order to account for such daily variations, the modelling is based on the available 6 hours anomaly values rather than on only daily mean values.

It should be mentioned that at this stage we did not follow the recommendations of the IERS conventions 1996 (MCCARTHY 1996) to describe atmospheric loading effects as a function of both the local and the regional pressure anomaly, the latter being representative for an area of about 1000 km around the site. The reason is that the regional pressure anomaly for many sites of the analysed network would not be based on pressure data in land areas but in ocean areas which might respond quite differently to the loading.

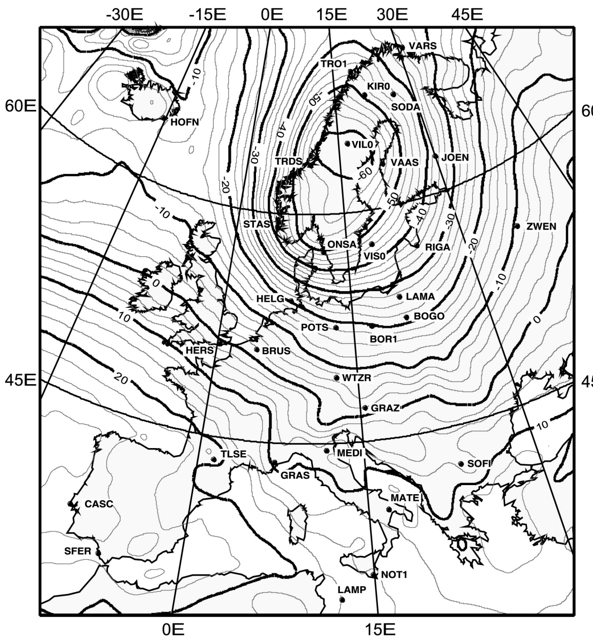


Fig. 3: Pressure anomalies in the network area on January 30, 2000, at 0 hrs UT [hPa]

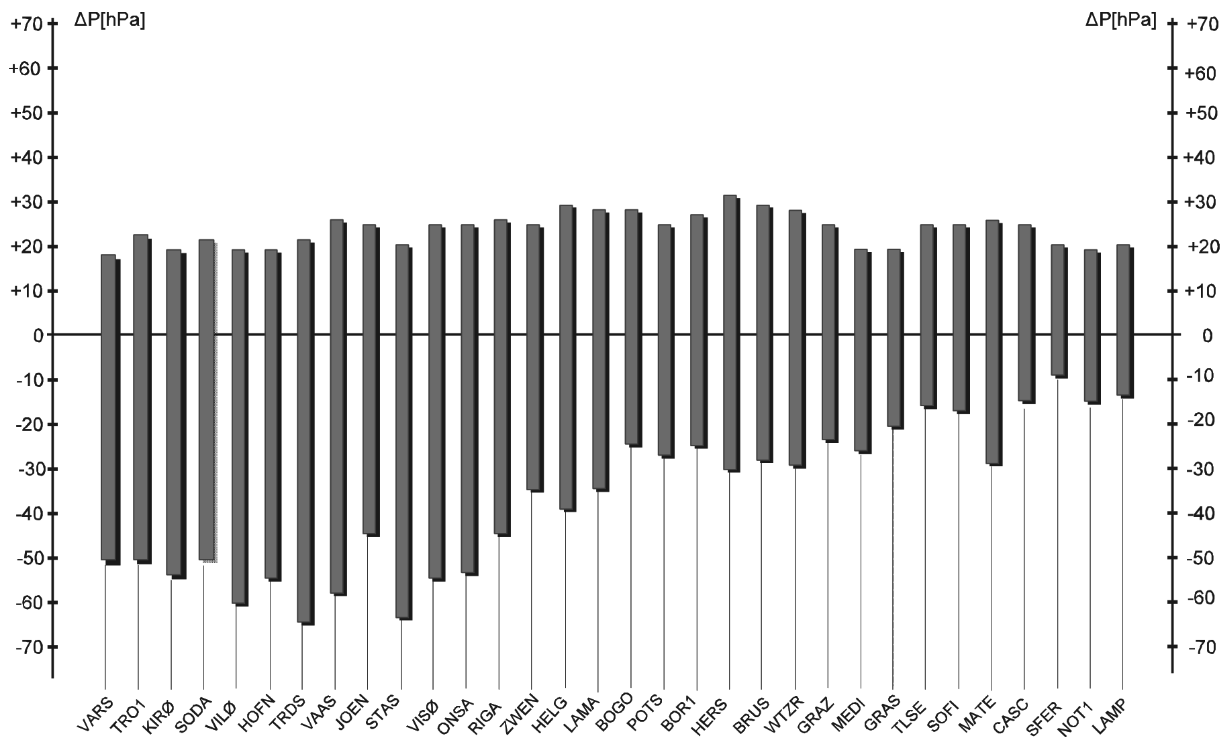
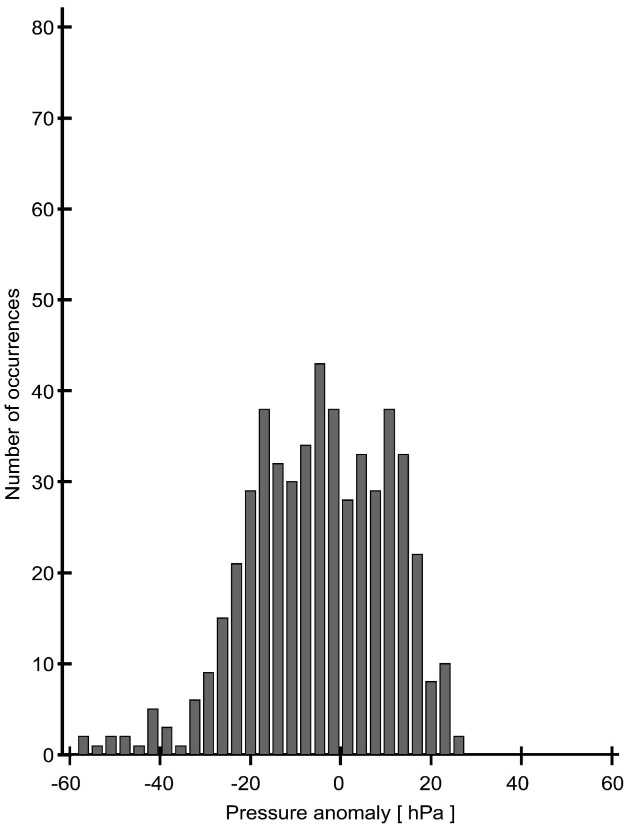


Fig. 4: Range of pressure anomalies at each involved site during the analysed periods



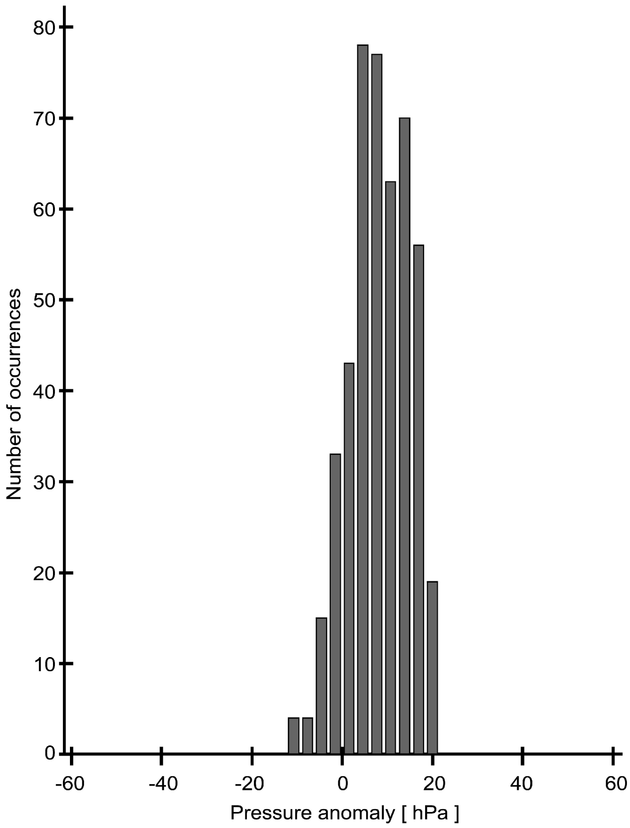


Fig. 5: Distribution of pressure anomalies at VISØ (left) and LAMP (right)

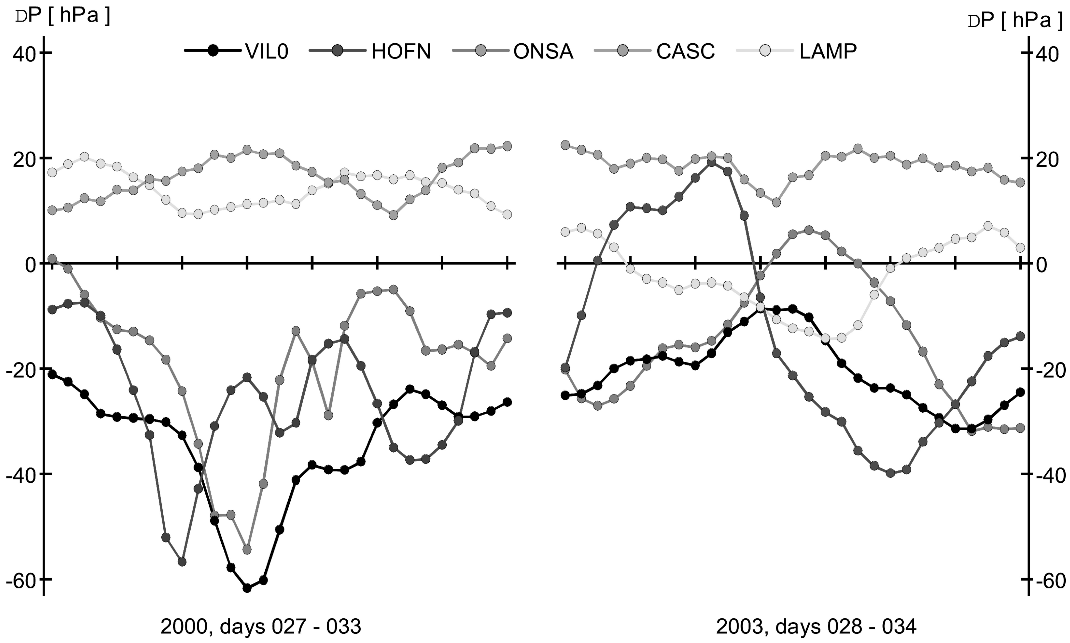


Fig. 6: Pressure anomaly variations at selected sites during two seven days periods

5. Processing

The main characteristics of the daily network adjustments performed with the modified program GPSEST can be briefly summarised as follows:

Satellite orbits, satellite clock offsets and Earth orientation parameters fixed to the combined solutions of the International GPS Service (IGS);

- Data sampling rate and elevation angle cutoff set to 30 seconds and 10/ respectively;
- No elevation dependent weighting applied in order to achieve a good de-correlation of height and troposphere estimates;
- No tropospheric delay prediction but unconstrained estimation of the total zenith delay applying the NIELL (1996) mapping function;
- Modelling of the site displacements due to ocean tide loading based on the FES95.2 model (LE PROVOST et al. 1998);
- Phase ambiguities resolved using the Quasi Ionosphere Free (QIF) strategy;
- No automatic outlier rejection, instead, if suggested by repeatability checks, editing of the adjustment residuals for identifying possibly unrepaired cycle slips.

The normal equations saved from these daily adjustments contain only the station coordinates at the epoch and the site dependent loading coefficients; all other parameters were reduced. The accumulation of all 126 normal equation system and their combined solution using the modified program ADDNEQ provides then the final results. Besides the vertical loading parameter) H_P for each involved site these include station coordinates at a reference epoch set to 2001.0 and linear velocities. We solved also for local eccentricities at three sites to account for antenna shifts at NOT1 and TLSE and for a height change due to antenna and radome replacement at HOFN. The velocities of these sites before and after the modifications were constrained to identity.

In order to establish a datum realization with respect to ITRF 2000 (ALTAMIMI et al. 2002) we solved in the final adjustment for Helmert transformation parameters with respect to ITRF 2000 position at epoch 2001.0 and the corresponding velocity field. The following six stations were used for this datum transformation: HERS, GRAS, MEDI, ONSA, POTS and WTZR.

6. Results

Table 2 gives the vertical velocities of the six stations used for the datum realization from both the ITRF2000 and our adjustment solving for Helmert transformation parameters with respect to ITRF2000. It must be noted that the standard deviations of ITRF2000 can be considered accuracy measures derived from the combination of various solutions based also on different space techniques.

Table 2: Vertical velocities from ITRF2000 and from this adjustment after solving for Helmert transformation parameters with respect to ITRF2000 [mm/yr]

Station	ITRF2000	This study
HERS	! 0.6 ± 0,3	! 1.7 ± 0,1
GRAS	! 0.8 ± 0,4	! 1.4 ± 0,1
MEDI	! 4.1 ± 0,4	! 4.9 ± 0,1
ONSA	2,6 ± 0,4	3,1 ± 0,1
POTS	! 1.3 ± 0,4	! 0.2 ± 0,1
WTZR	! 0.9 ± 0,3	! 0.1 ± 0,1

On the other hand, the standard deviations of our solution are precision estimates resulting from an adjustment with the Bernese software including more than 50 million phase observations. These estimates are very small due to the extremely high redundancy, and they are known to be by far too optimistic. This fact and the ITRF uncertainties can easily explain the differences remaining after the transformation.

The vertical pressure loading coefficients)H_P and their standard deviations from the combined adjustment of all 126 days of data are given in Table 2 for all those stations whose loading coefficients result significantly on the 99 % level, based on the quoted standard deviations. However, these are again the too optimistic formal errors from the adjustment and are listed mainly for indicating the precision differences among the stations. The table documents also the number of days available for each station. The five stations not included in the table are CASC, MATE, NOT1, SFER and SOFI, all situated in the southern part of the network. The results for these stations suffer from the following facts:

- The amount of data available during the processed periods was smaller than for the average of the other stations;
- The data quality was sometimes poor compared to the overall performance of the network;
- The range of the local pressure anomalies was considerably smaller than at higher latitude sites.

The latter circumstance increases also the correlation between estimated mean height and loading coefficient. It should be mentioned that the correlations between estimated tropospheric zenith delays and loading coefficients are small, typically in the order of 0.2 only. The reason simply is that the partial derivatives of the observations with respect to vertical loading are cos z (z = zenith distance) whereas they follow approximately 1/cos z in case of the tropospheric zenith delays.

Table 3: Vertical pressure loading coefficients)H_P [mm/hPa] resulting from the combined adjustment

Station	Days	)H_P	Station	Days	)H_P	Station	Days	)H_P
VARS	96	!0.59 ± 0,009	STAS	98	!0.39 ± 0,006	BOR1	126	!0.42 ± 0,009
TRO1	93	!0.57 ± 0,009	VISØ	126	!0.43 ± 0,005	HERS	125	!0.13 ± 0,008
KIRØ	126	!0.54 ± 0,006	ONSA	123	!0.35 ± 0,006	BRUS	115	!0.29 ± 0,008
SODA	122	!0.71 ± 0,007	RIGA	124	!0.54 ± 0,008	WTZR	126	!0.40 ± 0,009
VILØ	126	!0.62 ± 0,006	ZWEN	119	!0.35 ± 0,009	GRAZ	125	!0.30 ± 0,011
HOFN	120	!0.11 ± 0,008	HELG	113	!0.14 ± 0,006	MEDI	123	!0.62 ± 0,013
TRDS	98	!0.51 ± 0,006	LAMA	125	!0.32 ± 0,007	GRAS	125	!0.36 ± 0,016
VAAS	122	!0.79 ± 0,006	BOGO	126	!0.44 ± 0,009	TLSE	117	!0.25 ± 0,014
JOEN	118	!0.55 ± 0,007	POTS	125	!0.39 ± 0,007	LAMP	108	!0.18 ± 0,021

7. Conclusions

It should be mentioned that some of the periods processed for this analysis were selected such as to include large pressure variations. This holds for the months between November and March. During this time antennae at high latitudes might have been covered by snow which could affect the height estimates (JALDEDAG et al. 1996). Another effect which is not yet modelled are displacements due to water loading (VAN DAM et al. 2001). Fortunately, the latter phenomenon is long-periodic in time and space and should therefore not affect our solution. Apart from this, the obtained results demonstrate that the modified software is capable of determining local vertical pressure loading coefficients directly from GPS phase observations in a common adjustment along with other geodetic parameters. Significant loading parameters could be derived from 27 out of 32 sites. The most precisely determined coefficients result in stations at high northern latitudes which were exposed to large pressure variations reaching as much as 80 hPa. Extreme loading values of up to !0.7 mm/hPa appear at sites in the centre of the Fennoscandian postglacial uplift area. Although the correlations between the estimated vertical velocity and loading parameters are generally small this phenomenon should be analysed further.

The loading coefficients resulting in a number of island or of coastal stations are considerably smaller in absolute magnitude or even almost zero. This applies in particular to HOFN (Iceland), HELG (North sea), HERS (English channel) and LAMP (Mediterranean Sea). This could be regarded as supporting the oceanic "inverted barometer" hypothesis: atmospheric pressure variations are compensated by motions of oceanic masses, so that no pressure load is transferred to the sea-bottom. However, there are also results contradicting this assumption: VARS, TRO1, TRDS and STAS got loading coefficients of about !0.5 mm/hPa although they are situated close to the Atlantic coast and thus closer to deeper waters than the sites mentioned above. The stations ONSA (Kattegatt) and VISØ (Baltic Sea) are located close to shallow waters, and their coefficients are in the order of !0.4 mm/hPa. There are also Central European inland sites showing smaller effects than some of the coastal stations. Unfortunately, at this stage there is no explanation for some evident discrepancies. However, it should be stressed again that the standard deviations resulting for the loading coefficients are by far too optimistic and cannot be regarded as realistic accuracy measures.

The EPN comprises much more stations at exposed island or coastal locations than those included in this study. Therefore, much more efforts should be dedicated to the analysis of pressure loading effects in the EPN. Besides an extension in terms of number of stations and processed data periods further investigations could also include alternative strategies such as the two parameter approach recommended in the IERS conventions.

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