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Estimating atmospheric pressure loading regression coefficients from GPS observations

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Abstract The loading exerted by atmospheric pressure on the surface of the Earth causes deformations, mainly in vertical direction. Consequently, these deformations are also subject to pressure variations. At present this effect is only modeled by a few research groups in the post-processing of Very Long Baseline Interferometry (VLBI) and Global Positioning System (GPS) observations. As the displacements may clearly exceed the accuracy goals, we implement vertical pressure loading regression coefficients as a new estimable parameter type in the Bernese GPS software. This development is

applied to a network of 60 European permanent GPS stations extending from 35 to 79° northern latitude. The analysis comprises 1,055 days of observations between January 2001 and February 2004. During that period pressure variations as large as 80 hPa occurred at high latitude sites. A least squares solution including all observations and all relevant parameters yields significant regression coefficients for all stations but reveals also some critical issues with regard to the capability of this geodetic approach to verify results based on the geophysical convolution method.

Introduction

The surface of the Earth experiences periodical deformations, the largest ones being caused by the solid Earth tides; smaller effects are due to the loading caused by oceanic tides. Both phenomena can be modeled fairly well and are taken into account in the processing of high precision space geodetic observations such as Very Long Baseline Interferometry (VLBI), satellite laser ranging (SLR) and Global Positioning System (GPS) measurements. Other loading effects leading to mainly vertical deformations are terrestrial hydrological and atmospheric pressure loading. Pressure loading is not of periodic nature but seasonal dependencies may occur. The effect is not yet routinely modeled in VLBI, SLR and GPS analysis software packages, although the vertical site displacements may considerably exceed the accuracy goals.

The geophysical method for modeling atmospheric loading effects is based on the convolution of Green's functions with a global pressure field (e.g. Sun et al. 1995). An empirical approach consists of determining site-dependent pressure loading regression coefficients by fitting local pressure variations to vertical crustal motions derived from geodetic observations. During the past years several studies have applied the latter approach for detecting pressure loading signals in height estimates and for determining such loading coefficients in the post-processing analysis of both VLBI and GPS observations.

In case of VLBI examples of earlier studies are (MacMillan and Gipson 1994) and (van Dam and Herring 1994). More recently Haas et al. (2003) and Petrov and Boy (2004) have modeled pressure loading in the analysis of long series of VLBI observations. A first analysis of GPS data with regard to pressure loading

effects by van Dam et al. (1994) proved also clear correlations between height and pressure variations. Scherneck et al. (2003) studied atmospheric loading effects in the analysis of vertical crustal motions in Fennoscandia.

The aim of this contribution is to achieve further progress regarding the modeling of height variations due to pressure loading in GPS observations. We implement vertical pressure loading regression coefficients as a new solve for parameter type in a GPS post-processing software system. This development allows estimating the loading coefficients directly from the GPS observations along with all other relevant parameters. As an application regression coefficients for a network of European permanent GPS stations are estimated.

GPS data

The presently achievable repeatability of daily GPS height determinations in large regional and global networks is not better than $\sqrt{5}$ mm (e.g. Mao et al. 1999; Williams et al. 2004). Considering also that the vertical displacement caused by pressure loading is in the order of 0.5 mm/hPa or less, the effect can hardly be proven in regions of low-pressure variations. However, the European reference frame (EUREF) permanent network is a perfect candidate for demonstrating the ability to derive vertical loading regression coefficients from GPS observations. It 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 select a EUREF subset of 60 stations with a certain concentration in Fennoscandia. However, the network comprises also a large number of sites on Islands or at coastal locations where the geophysical modeling approach may perform worse than in inland regions. Nevertheless, the network covers the entire continent because we include some sites in the central part of Europe, part of them with the intention to serve as reference station for the datum realization. Further selection criteria are the on-line availability of the observations at the EUREF or global data centers and, as far as possible, data completeness and good tracking performance. A subset of stations was already included in a previous study (Kaniuth and Vetter 2005). We analyze the observations between January 2001 and February 2004. A very few stations do not cover the entire period but are included because of their particular location. The limit of 60 for the total number of stations is mainly set by the available computing resources. For a map of the network we refer to Fig. 2. The 4-character identifications are those used by EUREF and the International GPS service (IGS).

Pressure data

As most of the stations included in this analysis do not provide on-site pressure observations along with the GPS data, we use pressure data originating from the global data assimilation system (GDAS) of the U.S. National center for environmental prediction (NCEP). These daily data sets provide surface pressure values for a global $1 \times 1^\circ$ grid at 6-hour intervals (Schüler 2001). The reference heights of the grid points are given as geopotential heights, which for this analysis can be treated as orthometric heights. Unfortunately, during the analyzed period some of these daily files were incomplete or not available at all. Thus, in total 1,055 days of pressure data are at our disposal. We perform no specific analysis to assess the accuracy of these data. However, a validation by Schüler (2001) yielded an average agreement between GDAS based pressure values and precise local measurements at a number of globally distributed IGS sites. The procedure for generating for all GPS stations the pressure anomalies to be applied to the daily network processing comprises the following steps:

- Transformation of the orthometric heights of the grid points to ellipsoidal heights by applying the EGM96 geoid undulations (Lemoine et al. 1998); this transformation is done because all height related computations in the data processing refer to ellipsoidal heights.
- Conversion of the pressure values at the grid points to the approximate ellipsoidal heights of the GPS stations using a standard formula describing the pressure decrease with height (Hugentobler et al. 2001), and estimation of the surface pressure at the GPS stations by linear interpolation between the adjacent grid points.
- Generation of daily files of pressure anomalies with respect to the individual station reference pressure values at 0, 6, 12, 18, and 24 h UT. The reference pressure values are the averages over the 3-year period rounded to integer. The pressure variations during single days reach as much as 40 hPa in the northern part of Fennoscandia and 35 hPa on Iceland. They decrease southwards, and on the Iberian Peninsula or in the Mediterranean area they are in the order of 20 hPa. As the maximum daily pressure variations can be quite large, the modeling of the loading effects should reflect these daily pressure variations. Therefore, the modeling is based on the available six-hourly anomalies rather than on daily mean values. For two reasons we do not follow the recommendation given in the IERS Conventions 1996 (McCarthy 1996) to describe the loading displacements as a function of both the local and the regional pressure anomaly, the latter being representative for an area of about

1,000 km around the site. First, the regional pressure anomaly for many sites of the network would not be based on pressure data in land areas, but in ocean areas, which might respond quite differently to the loading. Second, this two parameter approach is not any more proposed in the new Conventions 2003 (McCarthy and Petit 2003), nor is it discussed within the recently established IERS Special Bureau for Loading (van Dam et al. 2003).

Typical examples of the local pressure anomaly distribution during the analyzed more than 3-year period are given in Fig. 1. The displayed sites cover the entire network and include also some exposed locations. The figure shows clearly the remarkably larger range of pressure anomalies at higher latitudes compared to the southern part of the network.

Analysis outline

The data analysis is done with the Bernese GPS software version 4.2 (Hugentobler et al. 2001). The principle characteristic of this software system is the processing of

phase observation differences between stations and satellites, the so-called double difference strategy. This double differencing eliminates satellite and receiver clock errors. The processing of the observations applies state of the art models and procedures. As regards the vertical position component and velocity, this holds in particular for the tropospheric path delay and the periodic site displacements due to Earth tides and ocean tide loading. As concerns the troposphere, the total dry and wet zenith delay for each site is estimated in the daily network processing as step function for 2-hour intervals from the GPS observations applying the Niell (1996) mapping function. These troposphere parameters are reduced from the daily normal equations. The ocean tide loading displacements are modeled for the vertical and horizontal position components based on the FES99 ocean tide model (Lefèvre et al. 2002) taking advantage of the automated ocean loading provider developed by Scherneck and Bos (2001). Not yet modeled are the displacements caused by atmospheric pressure loading.

The parameter types which can be estimated with the Bernese software include all geodetically relevant parameters and a few atmospheric parameters, but not those for atmospheric loading. Therefore, we implement

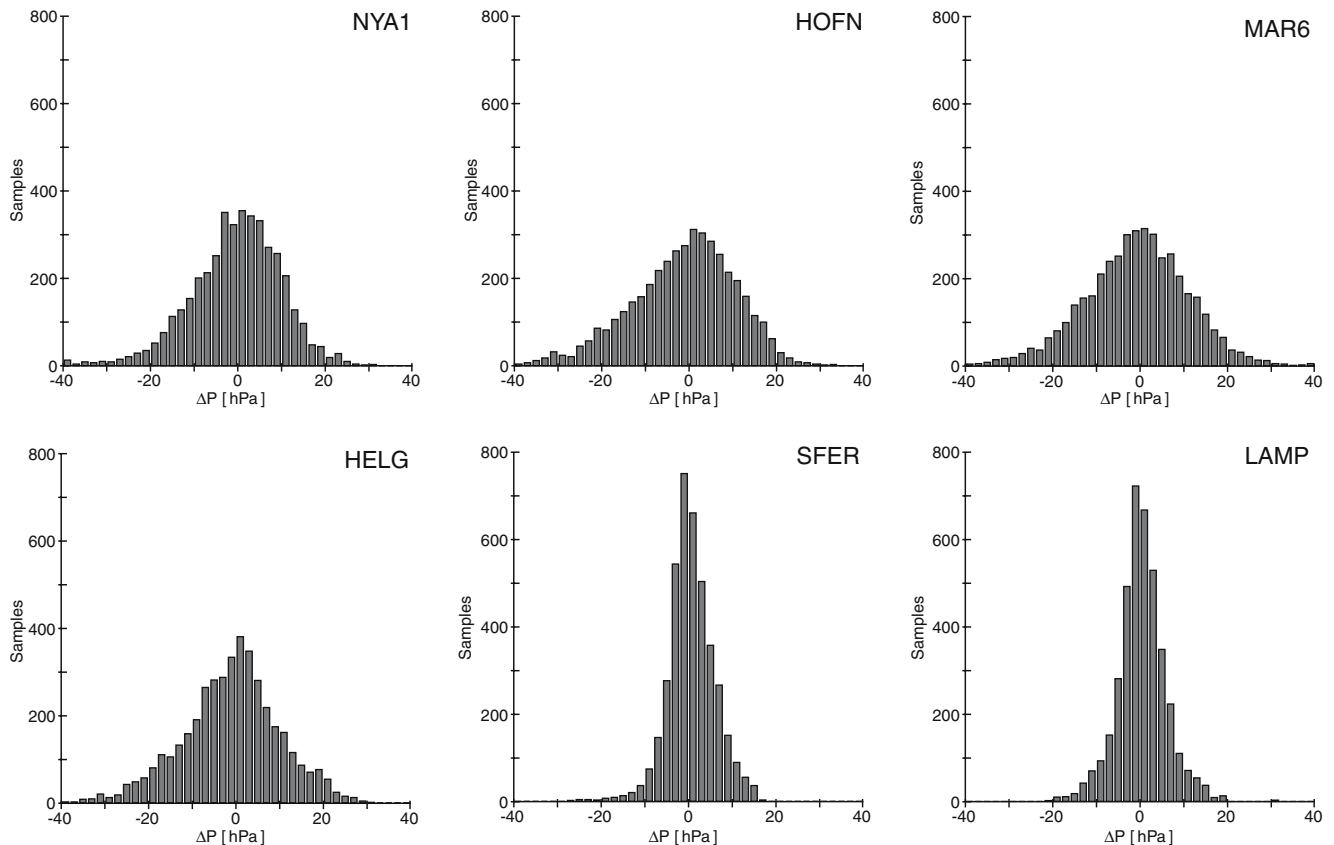
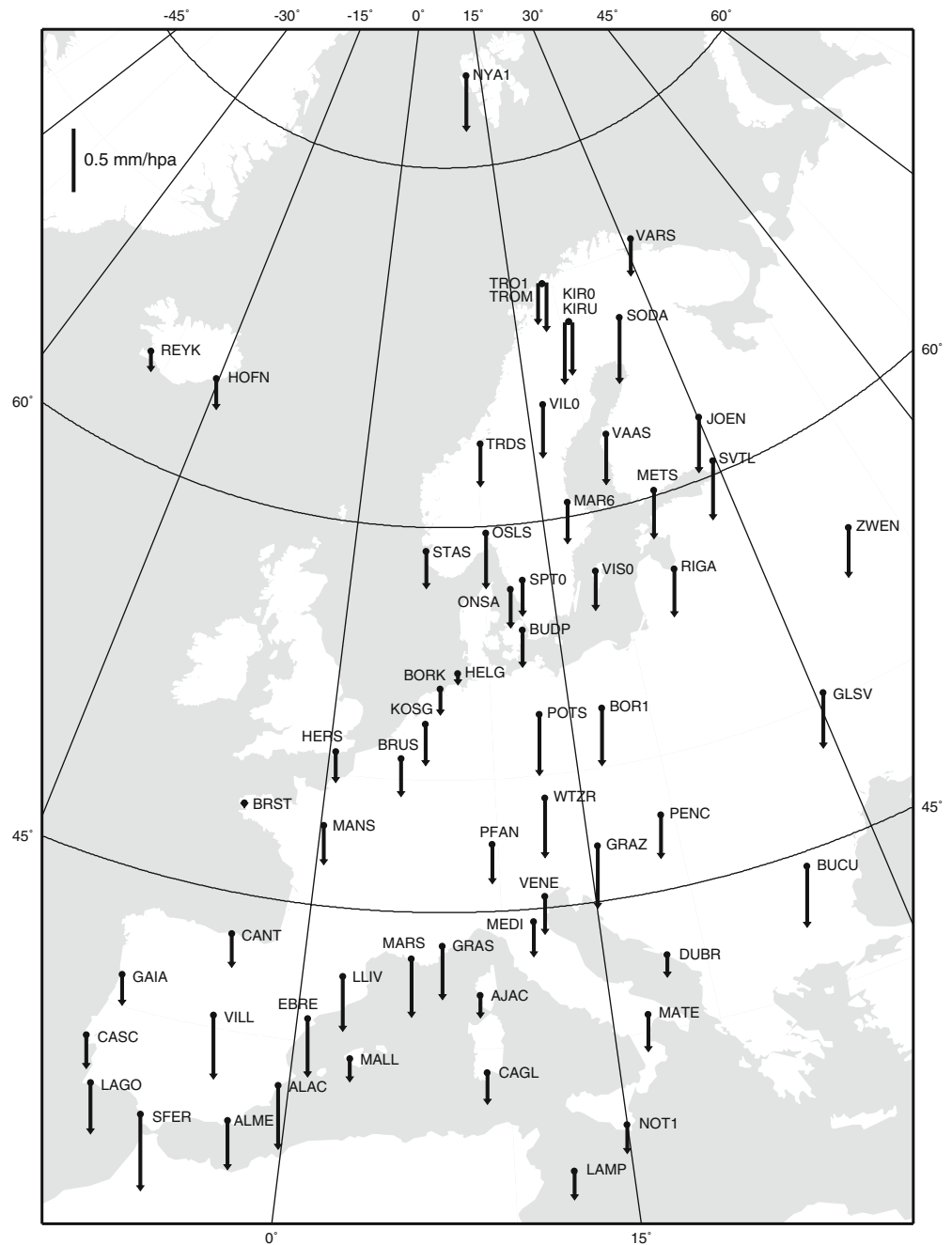


Fig. 1 Examples of local pressure anomaly distributions during the period January 2001–February 2004

Fig. 2 Estimated vertical pressure loading regression coefficients [mm/hPa]



vertical pressure loading regression coefficients as a new estimable parameter type in the network adjustment program GPSEST and also the capability of introducing site specific pressure anomalies. The realization comprises the formulation of the partial derivatives of the observations with respect to the vertical loading displacements and a proper parameter characterization, which is saved in the daily normal equations. The pressure anomalies are generated from the daily pressure files and the reference pressure values by linear inter-

polation between the six-hourly values. It should be noted that a single day solution can normally not separate the station height from its variation due to pressure loading because the sub-daily pressure variations are not large enough. In addition to GPSEST, the program ADDNEQ, which accumulates the daily normal equations and performs the combined adjustment, is modified to support the new parameter type.

The extended software is applied to the processing of the data sets described in the previous sections. The daily

network adjustments yield practically unconstrained normal equations, except that the combined IGS satellite orbits, satellite clock offsets and Earth orientation parameters are kept fixed. The only solve for parameters saved in these normal equations are station coordinates for each epoch and the vertical pressure loading coefficients. The accumulation of all daily normal equations and their combined adjustment using the modified program ADDNEQ can be briefly characterized as follows:

- Parameter transformation for replacing the daily station coordinates by positions at the reference epoch 2003.0 and linear site velocities;
- Accumulation of the site dependent vertical pressure loading coefficients over all available 1,055 days.
- Set-up of local height discontinuities to account for antenna modifications e.g. at HOFN and REYK.
- Identification of short period height biases e.g. at the Finnish station VAAS, presumably caused by snow accumulation on the antenna or its radome (see Jaldehag et al. 1996), and set-up of corresponding bias parameters.

Apart from a few stations the data span is sufficiently long as to avoid impacts of annual signals, which are often evident in GPS height time series (e.g. Dong et al. 2002), on the estimated linear velocities (Blewitt and Lavallée 2002). Although the satellite orbits and the Earth orientation parameters are fixed, the absolute frame is not well determined in a regional network. In order to establish a datum realization with respect to ITRF2000 (Altamimi et al. 2002) we solve in the final combined adjustment for 14 Helmert transformation parameters with respect to ITRF2000 positions at 2003.0 and the corresponding velocity field. The following stations are used for the datum realization: GRAS, GRAZ, HERS, MATE, METS, POTS, TROM and WTZR.

Results and discussions

The combined adjustment of all 1,055 days comprises 1,021 million double difference phase observations. The formal errors of the estimated parameters resulting from this solution are by far too optimistic. The reason is that the stochastic model applied in the GPS data processing does not take into account any physical correlations between the observations, which may e.g. be due to multipath or residual ionospheric and tropospheric effects. For a detailed analysis of the stochastic model of GPS phase measurements we refer to (Howind 2005). According to own experiences the autocorrelation

Table 1 Vertical pressure loading regression coefficients dh_P , ΔP = total range of pressure variations, comments on the standard deviations are given in the text

Stat. Id.	Lat. [°]	Days	ΔP [hPa]	dh_P [mm/hPa]
NYA1	78.9	1,032	73	-0.449 ± 0.029
VARS	70.3	1,012	78	-0.300 ± 0.019
TRO1	69.7	1,033	76	-0.326 ± 0.018
TROM	69.7	1,038	76	-0.390 ± 0.017
KIRO	67.9	1,044	74	-0.420 ± 0.017
KIRU	67.9	1,026	74	-0.493 ± 0.019
SODA	67.4	1,001	77	-0.528 ± 0.019
VIL0	65.0	1,043	70	-0.431 ± 0.016
HOFN	64.3	1,035	70	-0.247 ± 0.017
REYK	64.1	1,028	70	-0.166 ± 0.018
TRDS	63.4	1,023	70	-0.344 ± 0.016
VAAS	63.0	1,005	75	-0.405 ± 0.016
JOEN	62.4	1,026	76	-0.445 ± 0.017
MAR6	60.6	1,044	74	-0.334 ± 0.015
SVTL	60.5	869	69	-0.475 ± 0.026
METS	60.2	1,034	70	-0.388 ± 0.016
OSLS	59.7	1,031	67	-0.444 ± 0.016
STAS	59.0	1,031	70	-0.298 ± 0.015
SPT0	57.7	809	71	-0.286 ± 0.016
VISO	57.7	1,037	71	-0.319 ± 0.016
ONSA	57.4	1,039	70	-0.308 ± 0.016
RIGA	56.9	1,043	69	-0.384 ± 0.019
BUDP	55.7	404	63	-0.300 ± 0.025
ZWEN	55.7	616	62	-0.399 ± 0.028
HELG	54.2	1,033	68	-0.088 ± 0.016
BORK	53.6	1,043	66	-0.207 ± 0.016
POTS	52.4	1,041	60	-0.492 ± 0.019
BOR1	52.3	1,052	58	-0.462 ± 0.021
KOSG	52.2	1,033	63	-0.334 ± 0.018
HERS	50.9	970	65	-0.247 ± 0.018
BRUS	50.8	1,036	62	-0.304 ± 0.019
GLSV	50.4	1,046	56	-0.444 ± 0.022
WTZR	49.1	1,051	52	-0.478 ± 0.022
BRST	48.4	737	58	-0.039 ± 0.022
MANS	48.0	346	44	-0.317 ± 0.040
PENC	47.8	1,026	48	-0.352 ± 0.026
PFAN	47.5	1,007	51	-0.315 ± 0.022
GRAZ	47.1	1,008	48	-0.505 ± 0.026
VENE	45.4	1,028	43	-0.304 ± 0.026
MEDI	44.5	1,021	40	-0.284 ± 0.029
BUCU	44.5	1,053	46	-0.490 ± 0.027
GRAS	43.8	929	43	-0.427 ± 0.033
CANT	43.5	989	47	-0.273 ± 0.026
MARS	43.3	329	40	-0.467 ± 0.057
DUBR	42.6	729	42	-0.179 ± 0.041
LLIV	42.5	978	42	-0.443 ± 0.030
AJAC	41.9	578	44	-0.182 ± 0.037
GAIA	41.1	890	44	-0.246 ± 0.032
EBRE	40.8	1,009	44	-0.467 ± 0.031
MATE	40.6	1,045	44	-0.300 ± 0.031
VILL	40.4	955	43	-0.515 ± 0.034
MALL	39.6	1,050	47	-0.186 ± 0.028
CAGL	39.1	928	44	-0.256 ± 0.037
CASC	38.7	994	44	-0.271 ± 0.030
ALAC	38.3	1,030	44	-0.512 ± 0.031
LAGO	37.1	841	42	-0.413 ± 0.036
ALME	36.9	1,018	41	-0.393 ± 0.036
NOT1	36.9	1,023	41	-0.233 ± 0.039
SFER	36.5	990	43	-0.618 ± 0.040
LAMP	35.5	977	42	-0.231 ± 0.039

function of adjustment residuals in large networks tends to approach zero after about half an hour. Considering the sampling rate of 30 s in our solution, a rough guess would be that the formal errors should be multiplied by $\sqrt{60}$ in order to express accuracy. Applying this factor yields the error estimates given in Table 1 along with the estimated pressure loading regression coefficients themselves. The table documents for each of the 60 stations also the geographic latitude, the number of available observation days and the total range of the pressure anomalies during the 3 years. These are at high latitude sites about twice as large as on the Iberian Peninsula or in the Mediterranean area. Figure 2 shows the graphical representation of the estimated regression parameters.

The network includes two pairs of stations, which are very close to each other. TROM and TRO1 are at the same site at a distance of 51 m. Thus, both should experience exactly the same loading displacement, but our estimates differ by 0.064 mm/hPa. The TRO1 antenna is protected by a spherical radome, TROM is without radome. The stations KIR0 and KIRU are located at a distance of 4.5 km with a height difference of 107 m. Again one of the two antennas, namely KIR0, is equipped with a radome. The loading displacements should be very similar, but the coefficients differ by 0.073 mm/hPa. As documented in Table 1 these stations contribute between 1,026 and 1,044 days of data. As also the number of observations per day at the co-located stations is almost identical, we suppose that the differences between the regression coefficients are not due to differences in data distribution. In both cases the antenna with radome gets a smaller coefficient in absolute magnitude than the antenna without radome. This might be by chance, but there is also a vague guess of the reason. Depending on their size and shape, antenna radomes tend to bias both the height estimates and the tropospheric delay estimates. Thus, if the water vapor variations in the troposphere would be correlated with pressure variations, this could lead to apparent height variations, which are interpreted as loading displacement. If this were true, the applicability of the estimated loading coefficient would not only be restricted to the particular site, but also to the particular antenna configuration. As regards the entire network, we can summarize the results as follows:

- The regression coefficients for the inland sites in Fennoscandia, central Europe and the Iberian Peninsula reach maximum values in the order of -0.50 mm/hPa. Examples are SODA (-0.53 mm/hPa), BUCU (-0.49 mm/hPa) and VILL (-0.51 mm/hPa). The displacements tend to decrease to about -0.30 mm/hPa towards the coastlines.
- The sites in the Baltic Sea (VIS0 on Gotland) or along its coastlines, including the Gulf of Botnia, get only

slightly smaller displacement coefficients than the Fennoscandian inland sites. This includes ONSA located close to the shallow waters of the Kattegatt. Thus, the Baltic Sea as an enclosed basin is not clearly responding according to the inverted barometer hypothesis.

- The stations in the Mediterranean Sea experience much smaller displacements of -0.23 mm/hPa on the average. This value includes MATE and DUBR, but excludes MARS, which contributes less than 1 year of observations. The results suggest that the Mediterranean Sea is more likely following the inverted barometer hypothesis than the Baltic Sea.
- On the Iberian Peninsula the southernmost sites at the Atlantic as well as at the Mediterranean coast get surprisingly large loading coefficients with a maximum value of -0.62 mm/hPa at SFER. They decrease along the Atlantic coast towards north. We have no obvious explanation for the fact that the sites at the west- and northwest-coast of the Mediterranean Sea get larger loading coefficients than those farther in the east.
- The loading effects on the North Atlantic islands and the coastline including the North Sea look heterogeneous. The station NYA1 on the island of Svalbard gets a much larger coefficient than expected. The results for HOFN and REYK on Iceland of -0.25 and -0.17 mm/hPa would support the inverted barometer hypothesis. The stations along the Norwegian Atlantic coast experience slightly smaller deformations than the inland sites. HERS close to the English Channel and BORK offshore the North Sea coast are affected similarly with -0.25 and -0.21 mm/hPa. By far the smallest loading coefficients of -0.09 and -0.04 mm/hPa result for the small island of Helgoland (HELG) in the North Sea and for the exposed site BRST directly at the Atlantic coast.

Comparison with geophysical modeling

Both the empirical approach of estimating site dependent loading regression coefficients from GPS observations, as done in this analysis and the geophysical convolution method have particular advantages and shortcomings which are addressed in van Dam et al. (2003). For a first comparison of results from both approaches we select the period January/February 2004. During these 60 days the daily pressure files used in this analysis are continuously available. The following estimates of site displacements based on geophysical modeling are at our disposal:

- Time series from the Goddard VLBI group available at <http://gemini.gsfc.nasa.gov/aplo> (Petrov and Boy

2004); these series provide displacements with 6 h time resolution based on $2.5 \times 2.5^\circ$ NCEP pressure data.

- Time series provided by P. Gegout at the IERS Special Bureau for Loading (<http://www.sbl.statkart.no/products/research/>); there are series based on NCEP as well as ECMWF (European Centre for Medium-Range Weather Forecasts) pressure data, both for a $2.5 \times 2.5^\circ$ grid and 6 h time resolution.

In both cases the oceanic response is modeled according to the inverted barometer hypothesis. The reference levels of the estimated displacements are not explicitly documented. As an illustration, Figs. 3 and 4 show the vertical loading displacements for the two sites METS and KOSG from GPS modeling and the three geophysical series, two of them based on NCEP

and one on ECMWF pressure data. We do not distinguish between the three geophysical series because none of them fits really significantly better to the GPS estimates than the others. The average rms differences among the geophysical series are 0.9 and 1.5 mm between these and the GPS estimates. In case of the two sites there appears no obvious scale difference between the displacement estimates. We suspect that the deviations between GPS and geophysical modeling are mainly due to the different pressure data gridding of $1 \times 1^\circ$ compared to $2.5 \times 2.5^\circ$. Moreover, unlike the convolution method the GPS estimates are solely based on the local pressure anomalies. The agreements at these two stations are not representative for the entire network. Among the sites available for com-

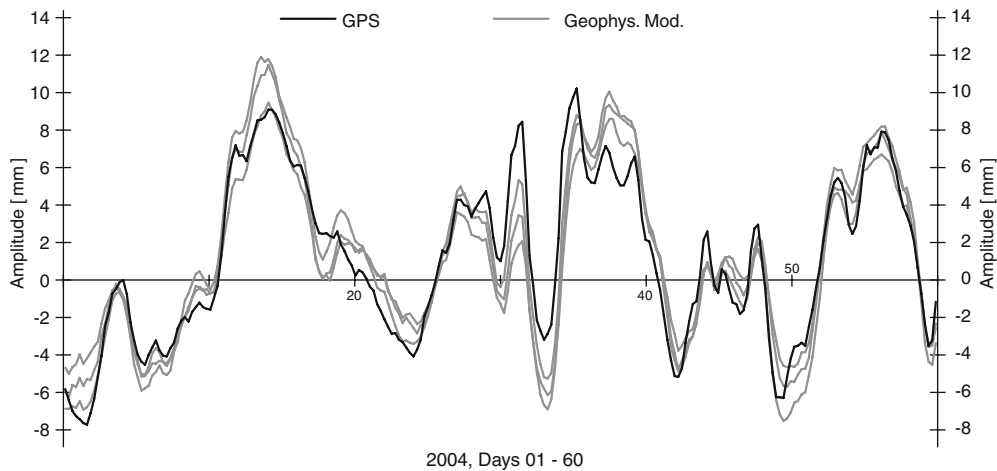


Fig. 3 Vertical displacement of METS due to pressure loading estimated from GPS and geophysical modeling; the GPS values are the local pressure anomalies multiplied by the estimated regression coefficient (further explanations are given in the text)

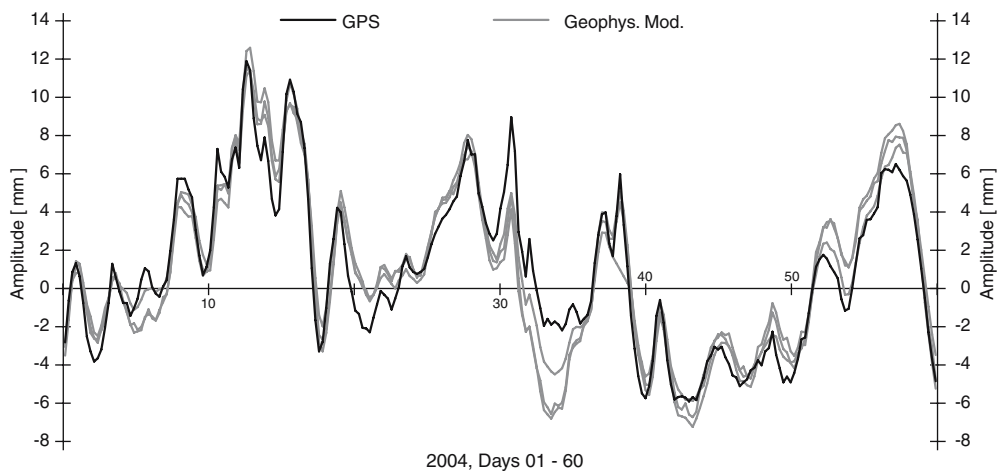


Fig. 4 Vertical displacement of KOSG due to pressure loading estimated from GPS and geophysical modeling; the GPS values are the local pressure anomalies multiplied by the estimated regression coefficient (further explanations are given in the text)

parison there are some where the agreement is worse. This holds for exposed coastal sites or GPS stations performing not well.

Conclusions

The main objective of this study was to establish in a widely used GPS processing software system the capability of estimating site-dependent vertical pressure loading regression coefficients in a common least squares solution along with all other geodetically relevant parameters directly from the GPS observations. This approach is novel and, compared to correlating time series of daily position estimates with time series of daily air pressure averages, it allows taking advantage of pressure observations with sub-daily resolution. The application to 3 years observations of a network of 60 European permanent GPS stations yields significant regression coefficients but reveals also some critical aspects as to the capability of this geodetic approach to serve as verification for the geophysical convolution method. First, we had to interpolate pressure values given on a global grid to the GPS locations because only very few of the involved stations provide regular meteorological observations. Thus, further applications of the approach should preferably be based on accurate local pressure measurements at each site. Second, our

strategy requires rather large data processing efforts and would therefore probably be restricted to selected sites.

Moreover, in order to ensure really unbiased estimates of the regression coefficients, any other loading effects such as continental or local water loading (van Dam et al. 2001, Munekane et al. 2004) should be taken into account, although this phenomenon is probably long-period in time. At coastal sites also wind induced loading could affect the results. The differences appearing at the two co-location sites indicate that the regression coefficients might absorb other small signals associated with the antenna configuration or its environment. If this were true, the regression coefficients would apply only to the particular station but not to the site. This poses the question whether or not the estimates would also be technique-dependent. The network did not include further co-located GPS stations because this effect showed up only at the final stage of the analysis. Therefore, further investigations should address this item and also the questions whether the regression coefficients vary with time or to what extent their application really improves the repeatability of daily position solutions.

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