Vertical motions in Northern Victoria Land inferred from GPS: A comparison with a glacial isostatic adjustment model

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Abstract Following the densification of GPS permanent and episodic trackers in Antarctica, geodetic observations are playing an increasing role in geodynamics research and the study of the glacial isostatic adjustment (GIA). The improvement in geodetic measurements accuracy suggests their use in constraining GIA models. It is essential to have a deeper knowledge on the sensitivity of GPS data to motions related to long-term ice mass changes and the present-day mass imbalance of the ice sheets. In order to investigate the geodynamic phenomena in Northern Victoria Land (NVL), GPS geodetic observations were made during the last decade within the VLNDEF (Victoria Land Network for Deformation control) project. The processed data provided a picture of the motions occurring in NVL with a high level of accuracy and depicts, for the whole period, a well defined pattern of vertical motion. The comparison between GPS-derived vertical displacements and GIA is addressed, showing a good degree of agreement and highlighting the future use of geodetic GPS measurements as constraints in GIA models. In spite of this agreement, the sensitivity of GPS vertical rates to non-GIA vertical motions has to be carefully evaluated.

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Introduction

The investigation of the dynamics of the Antarctic continent by GPS geodetic measurements began with the SCAR Epoch campaign (Dietrich et al. 2001, Dietrich et al. 2004) that provided a detailed insight of the whole Antarctic plate behaviour. Within that project, data provided by the Terra Nova Bay (TNB1) GPS permanent station, available since 1998, were processed and a first accurate evaluation of the Victoria Land (VL) regional velocity field established from geodetic measurements. Subsequently, TNB1 data were included in the densification of the ITRF (International Terrestrial Reference Frame), epoch 2000 (Altamimi et al. 2002), to better define the positional constraints over a region with poor network geometry. Other studies, relating Antarctic GPS stations with external (circum-Antarctic) networks, produced further information on the VL behaviour within the plate motion in the Southern hemisphere (e.g. Negusini et al. 2005).

In 1999, with the aim to investigate in detail the tectonic framework of the NVL and the dynamics of the Antarctic ice sheet in response to past and present ice mass changes, the VLNDEF GPS network was installed. It is composed of 28 stations with inter-site distance not longer than 70 km, and was monumented on bedrock and periodically surveyed up to 2006 (Capra et al. 2007). The deformation picture of the VL-Ross Sea region was extended by results from the TAMDEF (Transantarctic Mountains Deformation Network) GPS network, a joint OSU (Ohio State University) and USGS (United State Geological Survey) program to measure crustal deformation in Southern Victoria Land (Willis et al. 2006). Vertical motions in the Ross Sea region, and in particular in the Marie Byrd Land area (West Antarctica), have been detected by Donnellan and Luyendyk (2004). In addition, a new and wide WAGN (West Antarctic GPS Network) project has started. In the next sections, after a brief description of the VLNDEF data processing strategy, the GPS-based vertical motion detected over almost a decade of observation will be discussed and compared with the historical rates modelled in response to the ice mass loss.

Data processing and vertical motions

GPS data from the repeated observation campaigns, carried out from 1999 to 2006, were processed with Bernese version 5.0 (Dach et al. 2007). The first (1999-2000) surveys were carried out with poor instrumental capabilities and short observations (few days in the worst case) whereas from 2002 to 2006 the observation periods, and therefore the baselines involved, were considerably longer, with several months of acquisition at some core network stations. A continuous long time series is available for TNB1 for the whole period. The batch processing facilities included in the BPE (Bernese Processing Engine) were used in the data processing using a signal differentiation strategy. IGS precise ephemeris, Earth Orientation Parameters, Ocean Tide and Ocean Loading Model have been included in addition to the absolute antenna phase centre variations (IGS_05_1365.ATX antex file). Tropospheric delay was modelled using the Saastamoinen model (Saastamoinen, 1972) and Niell Mapping Function, NMF, (Niell, 1966; Niell, 2000). As reported by Boehm et al. (2006a and 2006b), the NMF has been demonstrated to be deficient at high latitude in the southern hemisphere and other Mapping Functions are currently under implementation in the Bernese package. As a consequence to this limitation a 13° cutoff angle was used to reduce the impact of NMF limitations towards the height estimation at the level of few mm (Niell and Petrov 2004). Some authors highlight the presence of a bias related to the use of a standard atmosphere (Tregoning and Herring 2006, Boehm et al. 2007) that could affect the station heights. However, a comparison between tropospheric delay and radiosounding data, available close to TNB1 station, did not show any bias attesting to the good quality of coordinates (Sarti et al., pers. comm., 2007). In addition, the improvement that could be achieved by the use of a Global Pressure and Temperature model, GPT, (Boehm et al. 2007) is under evaluation by comparison of the GPT model with locally measured pressure and temperature values. Daily parameters, including stations coordinates, were estimated using the L3 ionospheric free linear combinations, ambiguities fixed adopting the QIF (Quasi Iono Free) algorithm and Normal Equations (NEQ) stored on daily basis.

In order to obtain a time series of daily station coordinates in a global reference frame, the NEQs provided by the regional solutions have been combined with those provided by the analysis of 18 GPS reference stations, located both in Antarctica and on circum-Antarctic plates, to guarantee the connection between regional and global solution (see Figure 1 for station locations). The reference frame (ITRF2000) was finally fixed by a minimum constraint solution with a no-net-translation condition (Dach et al. 2007) on 6 more reliable circum-Antarctic stations.

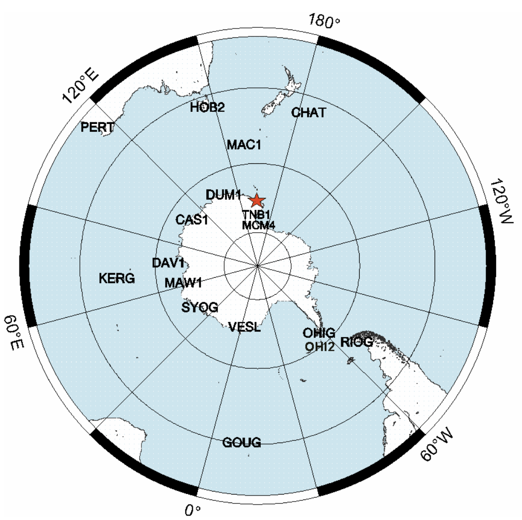

Figure 1 GPS permanent stations used as reference frame for absolute vertical rates computation. The star identifies the location of the VL area where the GPS sites were established.

The combination of episodic VLNDEF stations and continuous TNB1 solution with those provided by the external network, used as reference, yielded absolute heights (daily) and vertical velocities (mm/yr) from the time series. The discontinuity of the time series does not allow an evaluation of non-linear components of vertical motions. Non-linear trends should be detected from the analysis of the TNB1 8 years-long time series. However a non-linear trend is not clearly visible and, if present, would not be representative of the VL region. The atmospheric loading was not accounted for and its effect could potentially affect the time series with an annual bias added to the site velocities. However, this loading effect estimation might be not necessary for the 7-years long observation because of the decrease in the velocity bias beyond 4.5 years (Blewitt and Lavallée 2002). In addition, velocities produced by seasonal and repeated observations should not be sensitive to seasonal effects of fluid loading. The annual vertical rates of VLNDEF stations, within the ITRF2000 reference frame, are shown in Figure 2. Velocities and formal errors (at the 95% level of significance), provided by the ADDNEQ adjustment procedure in Bernese 5.0, are also listed in Table 1.

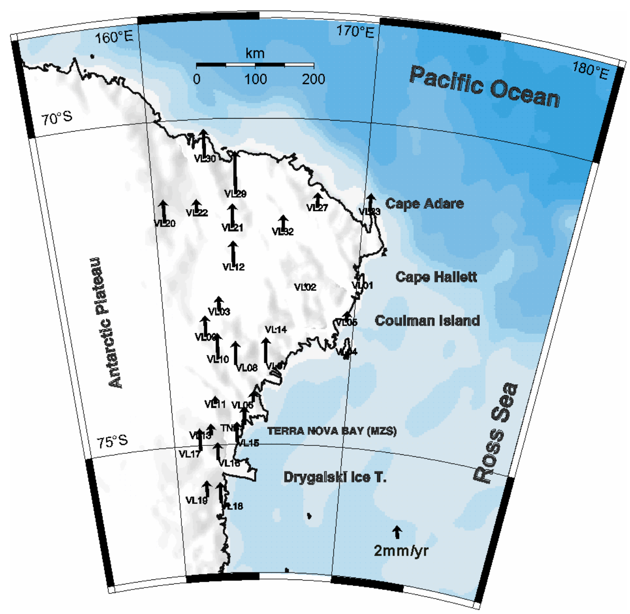

Figure 2 Vertical motions that occurred from December 1999 to February 2006 (mm/yr) in the VL area by GPS repeated observations.

Generally, in GPS data analysis the formal errors of sites velocity derived from the network adjustment are underestimated because of the uncorrected modelling of several parameters and systematic errors. A more realistic measure of the accuracy could be obtained from a more rigorous regression analysis of the long (periodical) time series. Errors from the regression line of the individual time series, which linearly models the vertical motion, are higher than the formal ones, but lower than 1mm/yr (95% level of significance) at 23 sites. An exhaustive investigation of errors affecting the VLNDEF site velocities has been made by Zanutta et al. (submitted).

Table 1 and Figure 2 highlight positive vertical displacements of the bedrock sites with exception of station VL04 that exhibits a negative, but very small, value. Velocities very close to zero are found at the easternmost stations and in the coastal area (VL01, VL02, VL05 and VL14).

Table 1 Vertical motions (mm/yr), and related formal errors from the network adjustment, detected within the period 1999-2006.

Station	Long. (dd.xx)	Lat. (dd.xx)	Up motion (mm/yr)	$2\sigma_{Up}$ (mm)
VL01	169.73	-72.45	0.1	0.2
VL02	167.38	-72.57	0.6	0.2
VL03	162.93	-72.95	2.3	0.2
VL04	169.75	-73.52	-1.0	0.6
VL05	169.62	-73.07	1.7	0.2
VL06	164.68	-74.35	1.6	0.4
VL07	165.38	-73.75	3.8	0.2
VL08	163.73	-73.77	3.5	0.2
VL09	162.17	-73.33	3.2	0.2
VL10	162.77	-73.68	3.9	0.2
VL11	162.53	-74.37	1.2	0.2
VL12	163.73	-72.27	3.9	0.2
VL13	162.20	-74.85	1.7	0.2
VL14	165.90	-73.23	0.2	0.2
VL15	163.72	-74.93	2.7	0.4
VL16	162.55	-75.23	2.6	0.2
VL17	161.53	-75.08	3.3	0.2
VL18	162.60	-75.90	3.1	0.4
VL19	161.78	-75.80	2.5	0.4
VL20	160.45	-71.55	3.5	1.2
VL21	163.73	-71.67	3.6	0.4
VL22	162.03	-71.42	2.0	0.4
VL23	170.30	-71.35	2.7	0.4
VL27	167.80	-71.35	2.3	1.2
VL29	163.90	-71.15	6.4	0.4
VL30	162.53	-70.60	4.4	0.4
VL32	166.17	-71.73	2.5	0.2

All others site exhibit vertical rates of 2-4mm/yr or more (VL29 and VL30). Absolute velocities of the same magnitude were obtained for VLNDEF stations using GAMIT/GLOBK software (Capra et al., pers. comm., 2007).

GPS versus GIA in the Northern Victoria Land

Prior to comparing GPS and predicted GIA vertical rates, basic differences between the types of data have to be highlighted. The GPS-derived vertical displacements are related to several effects (i.e. glaciological or geological), all contributing to the resulting displacements. Moreover, the discontinuous GPS series could be affected by seasonal effects or mis-modelling of atmospheric and ocean loading contributions. The time series produced by periodical surveys for VLNDEF station is not able to separate out the different contributions. The GIA models, on the other hand, refer to displacements under several assumptions related to the lithosphere state, and several vertical uplift rates have been predicted from global or regional isostatic models for Antarctica: ICE-3G (1991), ICE-4G (1994), ICE-5G (1998) and D91 (1998) showing different glacial history scenarios (Tushingham and Peltier; 1991, Peltier, 1994; Peltier, 1998; James and Ivins, 1998; Raymond et al. 2004; Kaufmann et al. 2005; Ivins and James, 2005). A comparison between vertical rates based on the GIA model from James and Ivins (1998) and geodetic GPS vertical rates was also accomplished by Scheinert et al. (2006) in Dronning Maud Land. As the present paper is mainly focused on the comparison between geodetic and modelled vertical rates for the VL area, a recent GIA model produced from Ivins and James (2005), hereafter referred to as IJ05, is considered. The uplift rates (mm/yr) for Antarctica were computed assuming uniform ocean loading and that deglaciation occurred from 21 kyr to 1 kyr B.P. and without a Melt Water Pulse. In addition, an elastic lithospheric thickness of 100 km is adopted with a lower mantle viscosity: $8*10^{22}$ Pa*s and an upper mantle viscosity: $7*10^{20}$ Pa*s. During 3.2 to 1 kyr B.P. the average uplift rate in NVL, from the model of Ivins and James (2005), is 0.3 mm/yr. A visual comparison between the IJ05 vertical rates and the uplift rates measured by GPS observations is shown in Figure 3.

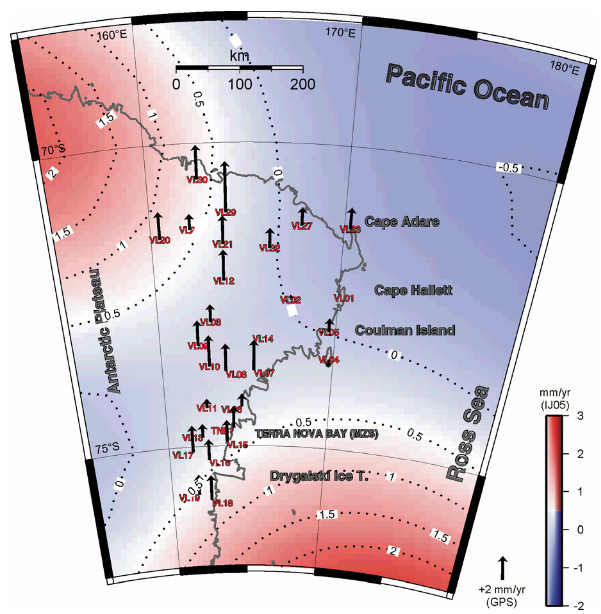

Figure 3. Comparison between the uplift rates (mm/yr) predicted by the ice model IJ05 (Ivins and James 2005) and the vertical rates from GPS geodetic observations.

In the NVL area the computed vertical rates range between +6 and -1 mm/yr (negative rate at VL04). Seaward, the IJ05 ice model predicts negative (but close to zero) values. Positive GPS-vertical rates are visible in the figure with an E-W oriented trend of increasing values, whereas the ice model depicts over almost the entire area, positive but lower rates.

The GIA model provides the average uplift rate of bedrock mostly related to the post-glacial rebound effect that occurred since 20 kyr BP, whereas the present-day GPS geodetic measurements could be affected by several geological, glaciological, local or seasonal phenomena acting on short spatial and temporal scale. Although the latter contributions are not easily separable, the relatively long GPS time series increases the reliability of vertical crustal motions and, when a continuous dataset is available, allows the detection of local, seasonal and/or mis-modelled effects affecting the measurements. Therefore, a straight correlation between GIA and GPS vertical rates is difficult.

Discussion and conclusions

As discussed in the previous sections, the repeated GPS measurements are able to provide a reliable picture of the vertical deformation pattern over the NVL area. Although the vertical rates detected along the VLNDEF stations are not exclusively related to glacial isostatic phenomena, the dominant uplift value (around 2 mm per year) has the potential to constrain the regional trend in vertical displacement. The relationship between the vertical displacements detected by GPS measurements and the values based on the available GIA models has to be addressed very carefully because of errors involved in the analysis. Moreover, the assumptions made in the ice model used have to be verified for NVL. When comparing the GPS-derived uplift with the GIA vertical rates other factors have to be taken into account. Ice models use other evidence such as gravity or geoid anomalies and the Relative Sea Level (RSL) fluctuations during the last 20 kyr (Late Pleistocene and Holocene). As discussed by several authors, the RSL variation is strongly dependent on the ice sheet advances and retreats and is poorly sensitive to the mantle viscosity (Mitrovica and Vermeersen 2002). Thus the combination of GPS–based vertical rates, which are mainly sensitive to the mass balance of the ice sheet as well as to the viscoelastic response of the Earth, with the RSL measurements could help in the future to separate the influence of mantle viscosity on ice models and GIA. Moreover, a dense GPS network is more likely to be sensitive to the three-dimensional deformations produced by the GIA. A simulation made by Wahr and Davis (2002) on the BIFROST network geometry (BIFROST Project, 1996), suggested that a geodetic network with inter-site spacing of 100 km is needed to determine the mantle viscosity, at various depth, from horizontal and radial motions. An analysis made by Johansson et al. (2002) demonstrated a correlation between geodetic measurements and predicted GIA velocities (for such networks). The study made by Johansson et al. (2002) indicated for geodetic measurements that an accuracy better than 1 mm/yr is required to yield useful constraints on the viscosity profile.

In spite of the low annual vertical rates provided by the regional VLNDEF data analysis, the length of the time series should be considered in assessing accuracy. An accurate and definitive evaluation of the errors affecting the GPS time series is needed for a reliable comparison of GPS uplift rates with the ice models and possible constraints on these models. The stability of GPS periodical solutions (as station velocities) has been confirmed by analysis made by other software (GAMIT-GLOBK), and velocities for the TNB1 permanent station are confirmed also by the PPP processing strategies (Negusini et al. 2005, Zanutta et al. submitted). In addition, notwithstanding the deficiency of periodical time series in detecting non-linear phenomena, a dense GPS network is able to separate out local and regional vertical displacements.

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