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GPS as a geodetic tool for geodynamics in northern Victoria Land, Antarctica

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Abstract: The VLNDEF (Victoria Land Network for DEFormation control) project started in 1999 with the aim of detecting crustal deformation in Northern Victoria Land (Antarctica) over an area that had never been surveyed by a dense GPS network before. After a brief summary of the Italian geodetic activities carried out since 1991, the paper presents the results obtained from the processing of data collected from 1999 to 2003. In particular, processing strategies were dealt with, in order to produce horizontal and vertical displacement maps through GPS observations. Absolute motions in a global reference frame have been investigated using a double approach, which allowed us to make considerable progress in detecting movements and standardizing the data analysis. The analyses provide absolute horizontal velocities ranging between 17 mm yr^{-1} and 8 mm yr^{-1}, with greater motions in the northernmost area. The subtraction of the rigid plate motion provides relative displacements, which may contribute to the understanding of neotectonics and geology, whereas the pattern of the vertical crustal motions detected, with average values of +1.3 mm yr^{-1}, is essential to detect the effect of Glacial Isostatic Adjustment (GIA) and other geophysical signals, and to redefine theory and numerical models used without any direct measurements.

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Introduction

The first experimental GPS geodetic network was setup in Antarctica during the Italian scientific expedition in 1990–1991, with the aim of detecting crustal motion and verifying the reliability of geodetic measurements for geodynamic purposes. The network, composed of 12 stations (see inset of Fig. 1) set into exposed bedrock, created a new reference frame for several scientific activities such as photo-grammetry, cartography and geology and contributed to the investigation of local geodynamic phenomena within the area of Terra Nova Bay, Victoria Land, East Antarctica (Capra *et al*. 1996). Moreover, to investigate deformation of the nearby Mount Melbourne, eight additional stations were monumented over stable outcrops around the volcanic edifice. Surveys and data processing performed since when the measurement began will not be dealt with in this paper, although they contributed to establishing of the most reliable processing strategy for GPS data, which is nowadays used for global or regional network analysis.

In 1998, a GPS permanent tracker (coded TNB1) was installed on a granitic hill close to the Mario Zucchelli Station at Terra Nova Bay (Fig. 1), to cover a gap in the distribution of GPS permanent stations in East Antarctica.

A subset of TNB1 data was used, in addition to others, in the framework of the SCAR (Scientific Committee for Antarctic Research) GPS epoch campaigns providing, since 1995, site coordinates and velocities for the stations involved, within an International Terrestrial Reference Frame (ITRF), and a detailed insight into the tectonic behaviour of the Antarctic plate (Dietrich *et al.* 2001, 2004). Subsequently, TNB1 data were included in the densification of the ITRF, epoch 2000 (Altamimi *et al*. 2002) to obtain its position and velocity within the global reference frame. Afterwards, when trying to determine the regional velocity in Northern Victoria Land (NVL), the data provided by TNB1 station were processed together with those from seven Antarctic IGS stations and eight peri-Antarctic stations. Results were comparable to those provided by the SCAR epoch project (Dietrich *et al*. 2001, 2004, Capra *et al*. 2004, Negusini *et al*. 2005).

The evolution in modern space geodesy techniques and the requests made by the scientific community for an extension of the area investigated by GPS observations led to deployment of a new network covering the entire NVL area: VLNDEF (Victoria Land Network for DEFormation control) was designed to measure horizontal and vertical displacements in the region for geodynamic purposes. In the southernmost area, VLNDEF sites partially overlap with 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).

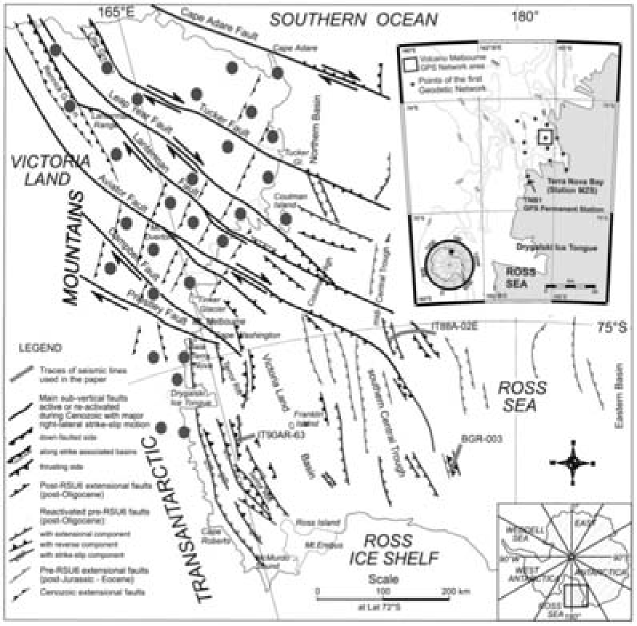

Fig. 1. Suitable spots (dark dot) chosen for GPS measurements on the Cenozoic Tectonic Map that represent the Ross Sea Region. From Salvini *et al.* (1997) with modifications. The inset in the upper right corner depicts a location map of the points belonging to the first geodetic network (dark dots) and its densification (within the dark frame) around the Mount Melbourne volcanic edifice. TNB1 represents the location of the GPS permanent station.

Geological setting and plate kinematics in NVL

The tectonic framework of the NVL region is dominated by NW–SE trending dextral strike-slip faults that represent the onshore expression of dextral transform shear along the Tasman Fracture Zone and Balleny Fracture Zone in the Southern Ocean. These intraplate faults reactivated the inherited, Palaeozoic custal discontinuities generated during the Ross Orogeny (Salvini *et al*. 1997, 1998, Salvini & Storti 1999, Storti *et al*. 2001). Cenozoic, N–S to NNE–SSW extensional faults developed in the crustal blocks between the strike-slip faults as a kinematic consequence of the transcurrent motion. The main extensional faults in the western side of the Ross Sea dip towards the east, segmented this region into a series of blocks with minor tilting. Strike-slip tectonics characterizes the Late Cenozoic time, and is responsible for N–S extensional, rather symmetrical faulting along transfer zones between major NW–SE transcurrent faults.

The morphological effects of the last tectonic event were the development of NW–SE and N–S depressions and the rapid growth of volcanic edifices, which influenced both the location and orientation of the main glaciers in northern Victoria Land and were responsible for their characteristic zigzagging (Storti *et al*. 2001). The distribution of VLNDEF GPS stations was planned to detect the expected displacements as derived from the assumption of Salvini and others in the NVL (Fig. 1).

So far, the plate kinematics and deformation status of Antarctica were obtained from the No-Net-Rotational NUVEL 1 model (Argus & Gordon 1991, DeMets *et al*. 1990) or could be based on the basis of a field surveys such as the investigation through static GPS methodology. Data acquired over a decade from more than 30 stations included in SCAR GPS epoch campaigns were processed, providing a regional solution as site velocities. The analyses indicated a general clockwise motion of Antarctica with a magnitude of 1–2 cm yr^{-1} (Dietrich *et al*. 2001), whereas the relative motion between the Antarctic Peninsula and the eastern Antarctica is not larger than 1–2 mm yr^{-1} (Dietrich *et al*. 2004). The result is consistent with the idea of a minimal amount of recent relative motion between East and West Antarctica in recent times. Vertical rates are much less precisely determined, but provide a valuable constraint on glacial isostatic adjustment models (GIA), once other geophysical signals are removed. Uplift values of about 10 mm yr^{-1} in the northern Antarctic Peninsula have been detected against lower values elsewhere in the Antarctic Peninsula (Dietrich *et al*. 2004).

Different uplift rates and patterns have been predicted from ice history models for Antarctica: ICE-3G (1991), ICE-4G (1994), ICE-5G (1998) and D91 (1998) showed different glacial history scenarios (Peltier 1994, 1998, James & Ivins 1998, Raymond *et al*. 2004, Ivins & James 2005, Kaufmann *et al*. 2005). The discussion of glacial isostatic phenomena resulting from GPS measurements in the NVL does not lie within the main scope of this paper, which is basically focused on methodology, but the resulting rates for each station are capable of providing a valuable constraint for GIA models and a validation of the rates provided by the numerical models.

VLNDEF: monumentation and survey

Position, height and stable outcrops needed to be suitable to GPS measurements, allowing us to detect crustal motions that could be expected based on tectonic hypotheses. During 1999–2000 and 2000–2001 expeditions 28 VLNDEF sites depicted in Fig. 1 were monumented (Capra *et al*. 2001, Mancini *et al*. 2004). A 3D steel benchmark with a fixed and levelled reference plane, for the setting up and orientation of the GPS antenna, was installed on the suitable outcrops (bedrock free from local strain or motions due to geological phenomena) by drilling and fixing a stainless steel pin in the hole with a little epoxy. Sites were described in field sheets together with some ancillary information regarding position, marker type, main morphological and geological features, helicopter approach path, map locality and suggestions for deploying GPS receivers, solar panel and battery pack. The first field operations around VLNDEF were performed by GPS receivers with moderate memory storage capability and, as a consequence, a detailed schedule of field operations and observations were carefully evaluated before starting the survey. The first complete survey of VLNDEF was carried out during the years 1999–2000 and 2000–2001, and was repeated during the 2002–2003 field activities.

Data analysis

In the following sections, data processing of VLNDEF campaigns will be discussed in two contexts; first of all the regional, or local, approach and, subsequently, a global approach to detect absolute motions within a global reference frame. The latter is the more complete and open strategy, dealing with the integration/combination of several solutions.

In the first approach, the GPS data were processed to obtain daily solutions, stored in Normal EQuations (NEQs as provided by the Bernese GPS package) and standard SINEX format, using a slightly constraints strategy, as described below. The adjustment procedure based upon the minimal constraints strategy allows us to detect relative motions within the VLNDEF geometry. The storage of a number of daily solutions, which could be combined together or with NEQs obtained by the processing of external data or networks (such as the IGS Antarctic stations or a peri-Antarctic network), is able to provide the absolute motions in a fixed reference frame and reference epoch (realization of a geodetic datum). In the second approach discussed in the data section, the NEQs - provided through the adjustment of the peri-Antarctic GPS, permanent stations - were combined with the constraints free VLNDEF solutions by using a certain number of common VLNDEF core stations. Constraining some IGS stations produces a final solution which is representative of horizontal and vertical velocities. These approaches were tested on 2002–2003 campaign data and successively applied to the data collected during the 1999–2000, 2000–2001 and 2002–2003 expeditions.

VLNDEF data processing: regional network approach

Data processing was performed by using Bernese GPS software V.4.2 (Hugentobler *et al*. 2001). The analysis strategy followed the well-known double difference approach. Baselines were processed after selecting of an independent set for each session of measurements and changing the geometry, in order to strengthen the final solution. The number of data collection days, used to calculate the baselines, was rather low during the first field season (three in the worst case) due to the instrumental capabilities and logistic problems. During the second survey, all the acquisition times were considerably longer. IGS precise orbits and the Earth Orientation Parameter file (EOP) were used. During the pre-processing stage, the data screening was checked in order to verify the quality of observation above the elevation mask of 13°, phase ambiguities were solved using the QIF (Quasi Iono Free) strategy.

The parameters were subsequently estimated using the L3 (ionosphere-free) linear combination of phase observations. Ambiguities and estimated ionospheric delays were previously estimated and, thus, not included in baseline estimation procedures. The tropospheric delay was modelled using the standard Saastamoinen model, estimating a correction factor every four hours, and observations were weighed using an elevation–dependent mapping function.

Ionosphere-free solutions, reducing or fully eliminating the ionospheric path delay of signal across the upper part of the atmosphere, are particularly suitable in polar regions where ionospheric activity is significant because of the vicinity to the geomagnetic pole. Ionospheric activity produces some significant effects on the GPS dual frequency signal. In particular, the effect known as "scintillation" causes a short-term variation in GPS signal amplitude and phase. The variation in amplitude consists of a continuous fading and enhancement of the signal strength towards the antenna phase centre. This will cause the signal level to drop below the threshold of the receiver, resulting in a loss of satellite tracking, and an increased number of cycle slips. Moreover, under these conditions the detection and repairing of cycle slips becomes critical. After baseline computation and final adjustment using a loose constraints procedure, solutions were produced and saved as daily NEQs. Normal Equation files do not contain observations

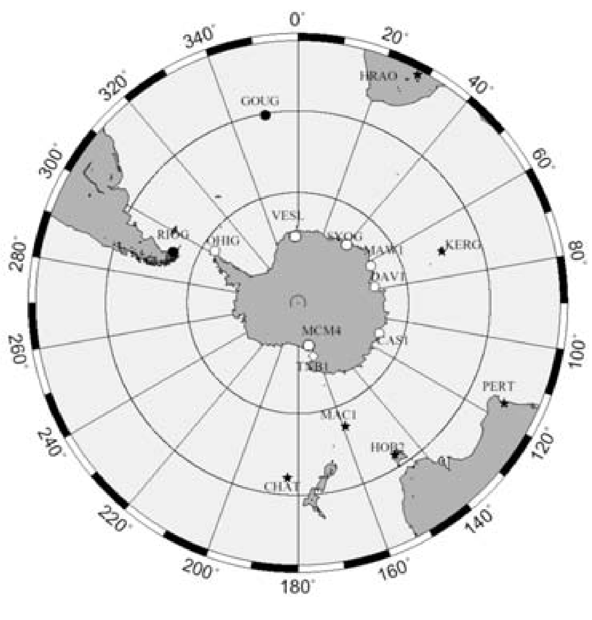

Fig. 2. Geographical distribution of Antarctic and peri-Antartic stations used in the analysis. Symbols used: white diamond = TNB1, white circles = the free IGS Antarctic stations, black circles = the free IGS peri-Antarctic stations, black stars = the fixed IGS peri-Antarctic stations in the peri-Antarctic analysis.

offering a significant improvement when multiple sessions have to be managed. Finally, weekly SINEX files were saved in order to stack solutions and share results with other packages or those provided by external GPS geodetic networks. As said before, the multi-temporal observations and comparison of solutions in a local approach can only provide relative motions. Due to the great improvements in the ITRF definition/stability and processing capabilities, a global approach is preferred to a constraint-free solution. Solutions provided by the VLNDEF data processing were therefore combined with an IGS peri-Antarctic network, to achieve global framing and absolute motions.

VLNDEF data processing: global network

With the purpose of linking the regional network to a global reference frame, two approaches were tested on the data collected within the 2002–2003 field activities.

First a classical network strategy was applied, using a large network including eight Antarctic stations, among which the TNB1 permanent station, in addition to eight peri-Antarctic IGS stations (Fig. 2) in order to constrain the solution into the ITRF2000.

The procedure has already been discussed in Negusini *et al*. (2005), where the velocities could be compared to those provided by the Precise Point Positioning (PPP) GIPSY approach (Stephen *et al*. 1996). During the analysis several problems had to be faced, long baselines and non-homogeneous distribution of permanent stations. Highly accurate *a priori* information was used for station coordinates, polar motion, precise IGS satellite orbits and IGS phase eccentricity file (elevation-dependent phase centre corrections for different antennas). Together with permanent station data, some selected VLNDEF stations were included in this analysis step, to be used as a link, when different networks would be combined.

When the solutions provided by the analysis of the global network were combined with the local NEQs, the coordinates of the stations in the global reference system were estimated by constraining six of the peri-Antarctic IGS with the most reliable *a priori* coordinates in the ITRF2000. In order to compare coordinates obtained through the local and global solutions, a 7-parameters Helmert transformation was applied to the dataset. Residuals of the transformation, reported in Table I, highlight a translation of the entire VLNDEF network, including TNB1, principally along the vertical component. Deformations of the network geometry are not apparent.

With the purposes of exploiting the solutions generated as standard SINEX files by the agencies involved in GPS services for data processing, a second approach was tried. It concerned the use of IGS weekly SINEXs combined with SINEXs obtained through peri-Antarctic network analysis

Table I. Residuals (mm) in the local system (north, east, up) of the 7-parameter Helmert transformation between the regional solution and the global solution. Tx = 0.5 ± 0.8 mm, Ty = 0.6 ± 1.2 mm, Tz = 0.1 ± 0.9 mm, rotational effects and scale factor are negligible.

Station	North	East	Up
TNB1	-0.5	1.8	29.7
VL01	-0.7	1.2	27.3
VL02	0.3	1.3	21.7
VL03	-0.4	2.1	24.5
VL04	0.1	1.3	26.5
VL05	-0.1	1.7	28.9
VL06	0.0	1.3	26.3
VL07	1.0	1.9	21.2
VL08	0.0	1.7	24.3
VL09	-0.1	1.6	23.5
VL10	0.2	1.7	24.3
VL11	0.5	1.8	21.2
VL12	-1.1	2.4	22.9
VL13	0.2	1.7	24.7
VL14	0.3	1.4	24.0
VL15	0.3	1.3	25.4
VL16	0.4	1.8	24.9
VL17	0.7	1.9	18.8
VL18	1.0	1.8	23.4
VL19	1.1	1.8	23.3
VL20	-1.2	2.1	25.5
VL21	-0.8	1.6	26.2
VL22	-1.0	1.9	25.9
VL27	-1.2	1.3	25.6
VL29	-1.0	1.8	25.9
VL30	-1.3	1.9	25.3
VL32	-0.6	1.5	25.7

Table II. Residuals (mm) in the local system (north, east, up) of the 7-parameter Helmert transformation between the regional solution and the global solution provided by the SINEXs combination. Tx = 18.2 ± 3.8 mm, Ty = 1.0 ± 4.9 mm, Tz = 19.9 ± 3.3 mm, rotational effects and scale factor are also detected.

Station	North	East	Up
TNB1	-0.3	0.8	9.4
VL01	-0.7	0.0	7.5
VL02	0.2	0.0	2.4
VL03	0.0	1.0	-2.7
VL04	1.2	-0.4	-6.2
VL05	0.0	0.4	8.4
VL06	0.6	-0.1	-14.0
VL07	1.1	0.8	1.2
VL08	1.0	0.4	-11.6
VL09	0.9	0.0	-5.5
VL10	0.2	0.2	0.8
VL11	0.7	0.5	-1.1
VL12	-1.2	1.3	3.3
VL13	1.1	0.3	-2.2
VL14	0.4	0.2	2.5
VL15	0.9	-0.7	-3.8
VL16	1.3	0.6	-6.7
VL17	0.8	0.7	-0.7
VL18	1.9	0.3	-10.5
VL19	1.7	0.3	-0.7
VL20	-1.7	1.5	-2.6
VL21	-1.3	-0.1	-5.5
VL22	-1.0	1.2	-18.9
VL27	-1.5	-0.2	-14.9
VL29	-1.9	1.1	8.2
VL30	-4.1	1.8	54.2
VL32	-0.9	0.4	2.0

and a regional approach. The combination was performed using the ADDNEQ program, part of the Bernese package, but some inconsistencies were encountered when combining the global IGS network with our solutions. In particular, it was not possible to constrain a couple of IGS stations (coordinates), without affecting the final accuracy level.

As in the first approach, a comparison between the regional and the IGS SINEXs-based solutions was performed through a 7-parameter Helmert transformation of the set of coordinates in the ITRF2000.The residuals of transformation (see Table II) do not show any systematic effect, but the general rms of transformation becomes higher and the overall reliability decreases.

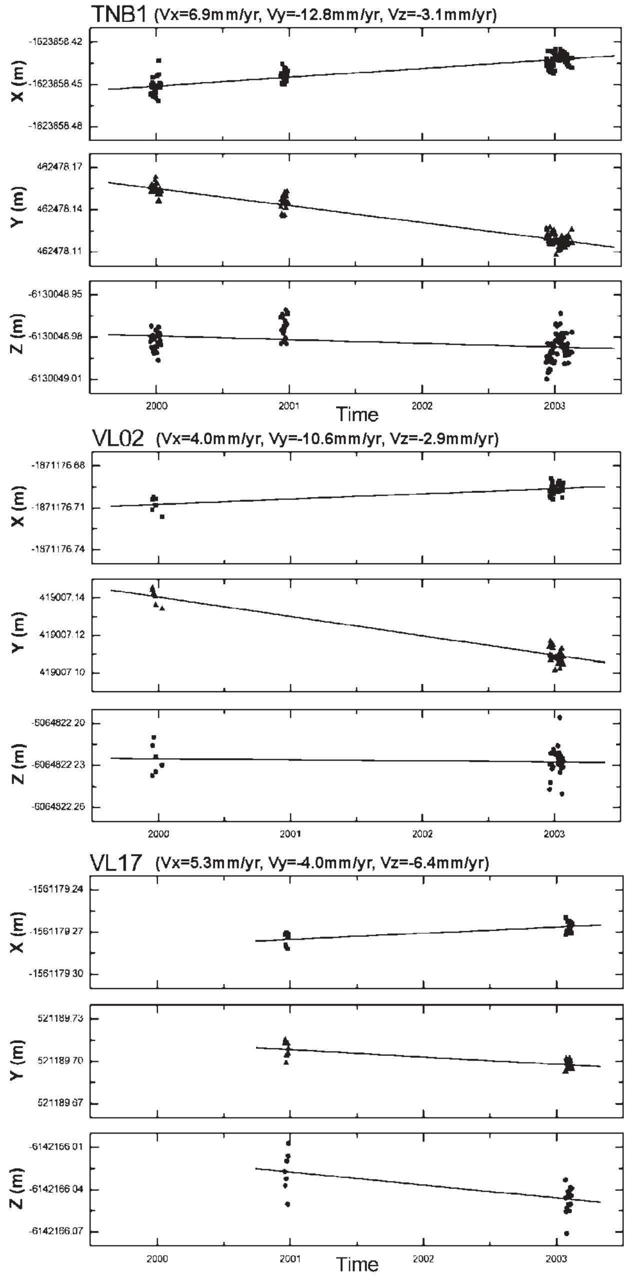

Fig. 3. Resulting characteristic data time series and velocities for TNB1, VL02 and VL17 (established during the 2000–2001 field season) sites. Coordinates and velocities, referred to episodic campaigns, are expressed in Cartesian components.

The higher and scattered values of Table II suggest that the first approach is the most reliable if global and regional solutions have to be combined. Moreover, as previously stated, the NEQs contain the full set of observation conversely to the SINEXs, which is a standard file for exporting solutions. Even if additional tests are necessary to select the best approach, the results discussed in the next paragraph will be therefore based on the first approach.

It must also be emphasized that the global framing approach, implemented by constraining peri-Antarctic GPS permanent stations, overcomes several problems related to the current status of the ITRF definition of Antarctica. Particularly, the uneven distribution of control stations for remote area could affect the reliability of the ITRF definition and, subsequently, have an impact on the solutions. In the proposed approaches, the data analysis is therefore based on a properly defined and accurate coordinates. Errors related to absolute and vertical velocities are indicative of the overall solution reliability, being generally lower than 4–5 mm yr^{-1}. Again, evolution and enhancement in the reference frames definition have to be carefully taken into account, as they are capable of improving the final combination procedure. In Fig. 3 some characteristic data time series are plotted.

The discontinuous nature of the time series hereinafter discussed, and therefore the inability to detect and remove seasonal signals that may impact the sites velocity, needs to be highlighted. Van Dam *et al*. (2001) showed that a bias may be induced on sites velocity by the hydrological and atmospheric loading. The bias entity potentially affects the precise site velocities estimation for plate tectonic study or reference frame investigation. The impact of unmodelled daily and sub-daily periodic effects was often considered mitigated or negligible when processing GPS data using a 24-hours session period. Conversely, recent studies about the superimposition of annual signals on velocities based on geodetic GPS data series demonstrate that artifacts arise in the GPS time series, due to the mismodelling of several effects, such as ocean tide loading (OTL), earth body tides and atmospheric pressure loading (APL). All these effects need to be considered when extreme accuracy (in terms of millimetres) must be achieved for determining the station position or site velocities. In particular, at VLNDEF latitudes both the atmospheric loading and solid earth tides may produce an annual signal in the vertical component up to 3 mm (Dong *et al*. 2002, IERS 2003). In our processing strategy, the tidal earth model IERS TN21 (conventions 1996) was applied. OTL and APL are currently under investigation and do not seem to have an impact on the site velocities above the mm yr^{-1} level. During the 1999–2003 time interval, only data from TNB1 were continuously acquired and a spectral signal processing is currently in progress to detect any unmodelled geophysical effect. As suggested by Blewitt & Lavallée (2002), a minimum data span of 2.5 years is recommended for velocity solutions intended for geodynamic purpose. Beyond that limit, the velocity bias (if any) related to non-geodetic signals becomes negligible.

Results and comments

After selecting the best approach for data analysis, this was applied to the other two VLNDEF campaigns, in order to obtain the velocities for the period. The processing allowed us to produce and store the daily NEQs for the 1999–2000, 2000–2001 and 2002–2003 field seasons. The combination of solutions through the ADDNEQ routine, was then performed by fixing the coordinates and velocities for the six well-known peri-Antarctic IGS stations, in order to obtain the tri-dimensional velocities over three years for all of the VLNDEF stations in the ITRF2000 reference frame. In the following sections, the detected horizontal absolute and relative bedrock motions will be discussed, in addition to the vertical displacements.

Absolute motions

Absolute horizontal crustal motions (Fig. 4) record several effects. The dominant is the regional displacement of the Antarctic plate in the global tectonics plate circuit and intraplate neotectonic motions. The latter are expected to occur, due to displacements on active faults, active volcanism and glacio-isostatic adjustment, as a response of the changes in the ice mass load.

Figure 4 shows that plate motion masks any other expected displacements from local deformation. Vectors follow a well defined pattern, with a dominant south-east direction, as detected also in Negusini *et al*. (2005) concerning the analysis of TNB1 long time series.

In Fig. 4, the formal errors, provided by the Bernese ADDNEQ procedure with a semi-axis of few tenths of mm, needed to be rescaled in order to obtain a more realistic error estimation. The scaling factor was derived from the comparison between formal errors and *a posteriori* sigma of unit weight, computed during the combination procedure. It is well known that the processing software underestimates the true errors, since systematic errors or mismodelled parameters are not part of the formal error computation strategy. A repeatability analysis of coordinates or long time series data processing suggests that the errors ellipses are comparable with those depicted in Fig. 4.

Relative motions

The subtraction of the dominant regional velocity from the pattern of Fig. 4 highlights the remaining horizontal local displacements (Fig. 5) which could be more strictly related to the recent neotectonic phenomena and crustal deformations in the NVL area. In particular, the dominant regional velocity was removed from the absolute field by subtracting the TNB1 velocity estimated from our data

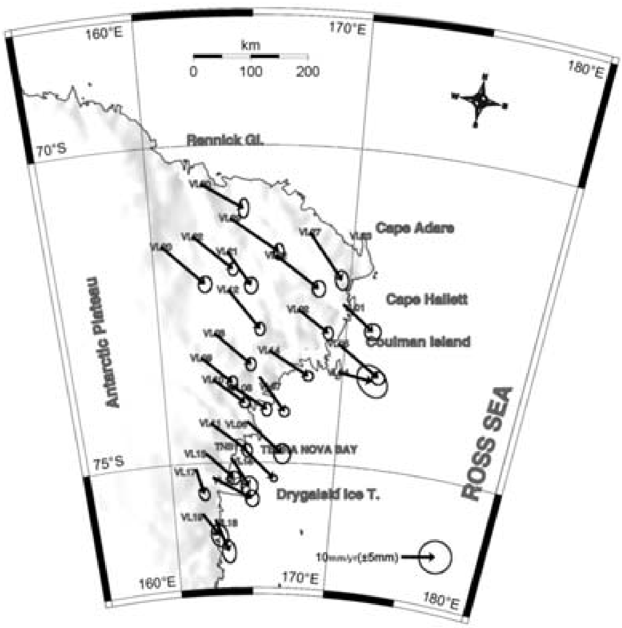

Fig. 4. Planimetrical absolute motions as observed by the analysis of data collected from December 1999 to January 2003. Values in mm $yr^{-1}$and error ellipses at the 95% level of significance.

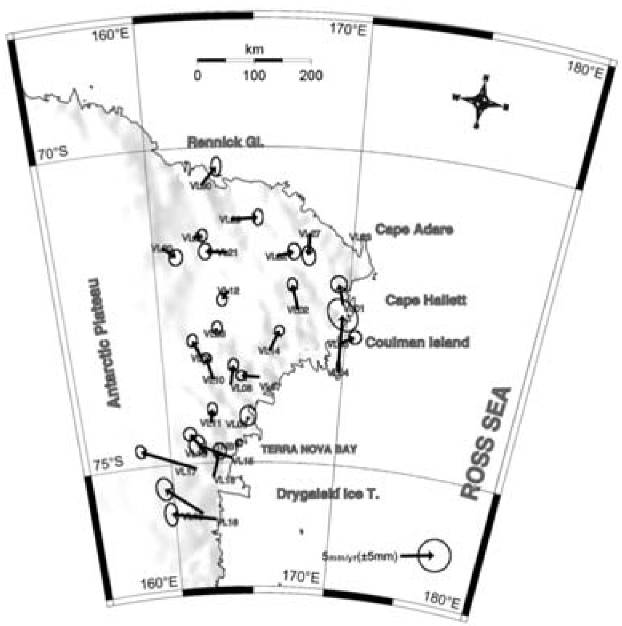

Fig. 5. Planimetrical relative motions as observed by the analysis of data collected from December 1999 to January 2003 expressed in mm yr^{-1}, with error ellipses at the 95% level of significance. Residual station velocities provided by the subtraction of the TNB1 average values: V_N = -10.6 mm yr^{-1}, V_E = +10.6 mm yr^{-1}, V_{UP} = +0.4 mm yr^{-1}.

analysis. At the moment, the TNB1 velocity is the more reliable of the East Antarctica's being the only one with a long time series available since 1998. The residual horizontal motion south of Terra Nova Bay latitudes are greater than those obtained to the north, revealing an area with different geological settings. As several long time series will be available for space-distributed VLNDEF stations, a more representative velocity of the NVL area will be considered to provide a geological context for enhanced detection of tectonic motions.

Local motions during the three year period from 1999–2003, are generally lower than 2–3 mm yr^{-1}, with values that reveal an increase in the southern part of the network and a slightly different vector orientation with a main pattern to the west.

Vertical motions

Absolute vertical displacements, as shown in Fig. 6, may provide measurements of isostatic bedrock motions in response to ice mass changes depending on the different time scales, superimposed to other geophysical signals acting on the vertical component of site velocities.

Figure 6 shows positive crustal vertical displacements in the western area and an eastward decrease with a neutral line positioned inland. Moreover, the uplift rates are greater in the northern sites and along the inner stations of the southern area. Negative values are encountered in the easternmost stations, that are closer to the coastal area and far from the Antarctic plateau, and this may be due to a relaxation phenomenon resulting from the uplift of the rebounding area. The vertical velocities revealed by the analysis range between +7 mm yr^{-1} to -4 mm yr^{-1} with vertical errors that are 2–3 times higher than those related to the horizontal velocities. This is due to poor satellite geometry over polar regions or less reliability of the ITRF definition along the up direction. Problems with calibration and orientation of old geodetic antenna series (adopted during the 1999–2000 survey) may be also encountered, especially for episodic campaigns. The complex pattern outlined in Fig. 6 could be related to several effects capable of producing vertical displacements such as glacio-isostatic adjustment, as a result of the changes in ice mass or tectonic phenomena. Even if the contributions are not easily separable, the GPS-determined uplift or sinking rates have the potential to constraint the predictions based on the available deglaciation models and improve an Antarctic ice mass balance estimation (Steig *et al*. 2001, Raymond *et al*. 2004). A new assessment of the Antarctic GIA model, according to Ivins & James (2005), predicts new values for vertical crustal motions over NVL, but a comparison with GPS observations is rather difficult. In addition to the seasonal and local noise affecting the vertical crustal motions provided by the GPS data analysis, there are some critical parameters to be deeply investigated in the modelling of GIA effects. The present-day mass balance, dominated by recession of ice mass, has been improved by the collection of field data and remotely sensed information, but GIA uplift rates rely on the viscosity model assumed. Assuming that the GPS-derived vertical motions are due to a glacial isostatic response, an average positive (uplift) velocity of +1.3 mm yr^{-1} was detected, which reflects the average value extrapolated from the GIA model (Ivins, personal communication 2005).

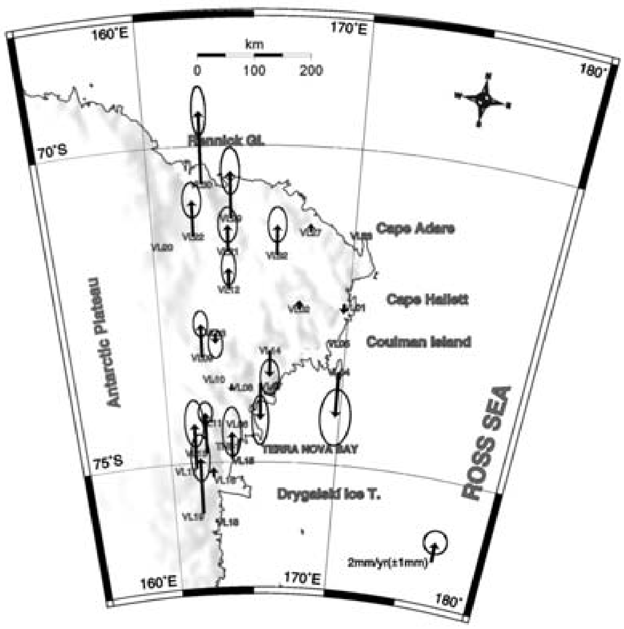

Fig. 6. Vertical motions occurred from December 1999 to January 2003 expressed in mm yr^{-1}. To avoid plotting misunderstanding for the reader, error ellipses at 95% level of significance are omitted for velocities minor than 1mm yr^{-1}.

Conclusions

Figures 4, 5 & 6 depict crustal motion measured by GPS within an area that had never been surveyed by dense GPS networks in the past. It should be noted that the detected horizontal and vertical displacements are related to several effects (i.e. glaciological or geological), all contributing to the resulting displacements. Moreover, the discontinuous GPS series include several seasonal effects (earth and atmospheric tides, ocean loading, etc.) that affect the analysis. A more exhaustive investigation of such effects needs a longer GPS time series with a dense network geometry. Therefore, further efforts should be focused on the deployment of additional remote permanent trackers into bedrock, in order to separate the seasonal contributions from the GPS-derived velocities. In the absence of tectonic phenomena producing crustal displacements in the vertical component, the resulting vertical motions play a particular role in the understanding of glacial isostatic adjustment effect. The availability of a reliable velocity field in NVL has the potential for contributing to the definition of boundary conditions in the deglaciation models, based upon field observations. The processing of new data gathered during the 2003–2004, 2004–2005 and 2005–2006 field activities by the strategy reported in this paper, in addition to the latest data collected by the first GPS remote permanent tracker in the NVL, will strengthen the historical series in order to achieve a more reliable result. Finally, the transition from bedrock displacements to deformation shall be the next frontier. A complete NVL geodynamic model is still a distant goal, but such accurate and reliable GPS observations, in combination with the geological and glaciological models developed, certainly have the potential for improving our knowledge about ongoing phenomena in NVL.

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