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VLNDEF Project for Geodetic Infrastructure Definition of Northern Victoria Land, Antarctica

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Abstract Scientific investigations in Antarctica are, for many different reasons, a challenging and fascinating task. Measurements, observations and field operations must be carefully planned well in advance and the capacity of successfully meeting the goals of a scientific project is often related to the capacity of forecasting and anticipating the many different potential mishaps. In order to do that, experience and

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logistic support are crucial. On the scientific side, the team must be aware of its tasks and be prepared to carry out observations in a hostile environment: both technology and human resources have to be suitably selected, prepared, tested and trained. On the logistic side, nations, institutions and any other organisation involved in the expeditions must ensure the proper amount of competence and practical support.

The history of modern Italian Antarctic expeditions dates back to the middle 80's when the first infrastructures of "Mario Zucchelli Station", formerly Terra Nova Bay Station, were settled at Terra Nova Bay, Northern Victoria Land. Only a few years later, the first geodetic infrastructures were planned and built. Italian geodetic facilities and activities were, ever since, being constantly maintained and developed. Nowadays, the most remarkable geodetic infrastructures are the permanent Global Positioning System (GPS) station (TNB1) installed at Mario Zucchelli and the GPS geodetic network Victoria Land Network for DEFormation control (VLNDEF) entirely deployed on an area extending between 71°S and 76°S and 160°E and 170°E.

These facilities do not only allow carrying out utmost geodetic investigations but also posses interesting capacities on the international multidisciplinary scientific scenario.

In order to fully exploit their potentiality, management and maintenance of the infrastructure are crucial; nevertheless, in order to perform high quality scientific research, these abilities must be coupled with the knowledge concerning a proper use and a correct processing of the information that these infrastructures can provide.

This work focuses on the different methods that can be applied to process the observations that are performed with GPS technique in Northern Victoria Land, aiming at reaching the highest accuracy of results and assuring the larger significance and versatility of the processing outcomes. Three software were used for the analysis, namely: Bernese v.5.0, Gipsy/Oasis II and Gamit/Globk. The working data sets are (i) the permanent GPS station TNB1 observations continuously performed since 1998 and (ii) the five episodic campaigns performed on the sites of VLNDEF.

The two infrastructures can be regarded as neat examples of standard geodetic installation in Antarctica. Therefore, the technological solutions that were adopted and applied for establishing the GPS permanent station and the VLNDEF geodetic network as well as the data processing strategies and the data analysis procedures that were tested on their observation will be illustrated in detail. The results will be presented, compared and discussed. Furthermore, their potentials and role in geodetic research will be carefully described; their versatility will also be highlighted in the foreground of a multidisciplinary Antarctic international scientific activity.

1 Introduction and Motivation

The success of Antarctic scientific investigations is often related to the capacity of optimising the quality and quantity of the observations that can actually be performed. Difficulties of different nature may suddenly arise during an observing session or a field campaign. The ability of facing unforeseen occurrences is therefore mandatory in immediate terms. On the other hand, an equally large amount of difficulties may arise when long term or permanent observations are needed. Complications eventually increase when long time series of observations have to be recorded and securely stored at isolated and unmanned sites, where weather conditions as well as power supply can often place a serious limit on the capacity of confidently perform a set of observations.

The importance of existing (reliable and accurate) scientific records is therefore central to Antarctic research. Indeed, observations performed in Antarctica are often central to global mathematical models that describe the state and the evolution of the entire Earth system.

If possible, the number of data and observations should be constantly increased, keeping in mind that maximal versatility of observations is obtained through international actions aimed at coordinating the efforts, the financial investments and the needs of the entire scientific community. Sect. 2 is devoted to a description of the most important actions and of the recent developments that were undertaken in the field of Antarctic geodesy and geosciences.

Section 3 describes the geodetic Italian infrastructures in Antarctica and their role within the abovementioned international scenario. A detailed description of the practical solutions that were adopted for exploiting and maintaining these two geodetic facilities is given: they were designed, planned and established during the several Italian Antarctic scientific expeditions. They both are GPS based facilities which require different efforts and managing strategies; their contribution to geosciences and geodetic research is, in principle, different but, undoubtedly, complementary. Section 4 identifies the main scientific contributions that can derive from a proper management of these infrastructures.

In order to perform good scientific investigations and infer from results, the ability of properly process the available data sets is crucial: the procedures and the most efficient analysis strategies were identified and tested and are presented in Sect. 5. In particular, this latter Section presents the different scientific software that were used for processing (i) the seven years of continuous GPS observations performed by the permanent GPS station TNB1, installed at Mario Zucchelli station and (ii) the GPS data sets acquired by more than 28 stations episodically occupied during the five VLNDEF campaigns. Software's characteristics and their basic processing approaches are shortly summarized. The analysis strategies that were adopted for processing the two data sets are described in detail.

Section 6 is devoted to a critical discussion concerning the efficiency of each analysis strategy and to a detailed comparison of results.

2 Historical Background of Geodetic Infrastructure in Antarctica

The SCAR (Scientific Committee on Antarctic Research) GIANT (Geodetic Infrastructure of Antarctica) was established in 1992 for providing a common geodetic framework over Antarctica, as the basis for recordings of positional related science.

Some large scale GPS surveys over the Antarctic continent were planned within the SCAR WG-GGI (Working Group – Geodesy and Geographic Information) aiming at determining the rates of crustal deformation within the Antarctic tectonic plate and the relative motion between the Antarctic plate and the surrounding tectonic plates and micro-plates. The measurements were carried out in three campaigns: 1989–90, 1990–91 and 1991–92.

At the XXII SCAR meeting held in San Carlos de Bariloche, Argentina, 8–19 June 1992, the results of the SCAR GPS Antarctic Project 90–92 were assessed. It was also decided to further extend the GPS project to develop co-locations with other instruments and other observing techniques, such as VLBI, Absolute Gravity, DORIS and tide gauges. This was collectively identified as the Geodetic Infrastructure for Antarctica (GIANT), the coordinating program for Geodesy, initially chaired by Mr. J. Manning from Australia (Manning, 2005).

GIANT program objectives are:

- To provide a common geodetic and geographic reference system for all Antarctic scientists and operators;
- To contribute to global geodesy for the study of the physical processes of the earth and the maintenance of the precise terrestrial reference frame;
- To provide information for monitoring the horizontal and vertical motion of the Antarctic.

Since 1992 the GIANT program, has been revised and endorsed at each major SCAR conferences on a two years basis.

Several successful application of GPS surveys were performed in Antarctica; in particular GPS Epoch Campaigns based on series of summer GPS acquisitions started in 1995, within GIANT program (see e.g. http://www.tu-dresden.de/ipg/FGHGIPG/Aktuell-Dienste/scargps/database.html).

The SCAR GPS Epoch campaigns aim at establishing and maintaining an Antarctic GPS geodetic network framed within the International Terrestrial Reference Frame (ITRF); the densification of the IGS network established by the permanent GPS observatories (Fig. 1) is another operational goal. The observations acquired during the episodic campaigns are used for geodynamic as well as geodetic research (geodynamics, crustal deformation, reference frame definition).

SCAR GPS Epoch Campaigns are coordinated by Prof. R. Dietrich from TU-Dresden, Germany. The whole set of data comprises observations performed at numerous sites (Fig. 2) and is archived at the University of Dresden as ongoing collection devoted to scientific investigation; for the moment being, the entire set of data has been processed and re-processed several times (Dietrich et al., 2001, 2004; Steigenberger et al., 2006).

GIANT is giving a significant contribution to the work of other Antarctic earth scientists such as the newly formed ANTEC (Antarctic NeoTECtonics) group of specialists; its main research task is related to the development of a better understanding of the crustal dynamics process undergoing in Antarctica. In order to meet the ever increasing need of accurate observations for studying Antarctic geodynamic movements, the scientific community has planned to expand the geodetic network to provide a very stable Antarctic reference frame for geodynamics.

Fig. 1 GPS permanent trackers in Antarctica (2005), courtesy of SCAR website

A very interesting proposal which has been endorsed by the International Polar Year (IPY) 2007 Committee is POLENET (POLar Earth observing NETwork). This programme is an example of the most recent efforts that are undertaken by the scientific polar community to widen the perspective of operational scientific investigations towards the realization of multidisciplinary coordinated facilities and observations (Fig. 3).

POLENET aims at “[…] investigating the system-scale interactions within the polar earth system and polar geodynamics by deploying autonomous remote observatories […]”. The technical and scientific challenges that are going to be addressed are numerous. On the scientific side, the primary co-location of GPS systems (Fig. 4) and seismometers, possibly completed with meteorological sensors, geomagnetic observatories, tide gauges and bottom pressure gauges (Fig. 5), will realize a step towards the acquisition of coordinated geophysical observations of the Earth system and its processes.

POLENET can be regarded as a step toward a practical realization of IGOS (Integrated Global Observing System) guidelines (http://www.igospartners.org/over.htm) and as an effective contribution to GGOS (Global Geodetic Observing System) (see e.g. Altamimi et al., 2005; Rummel et al., 2005; Woodworth et al., 2005).

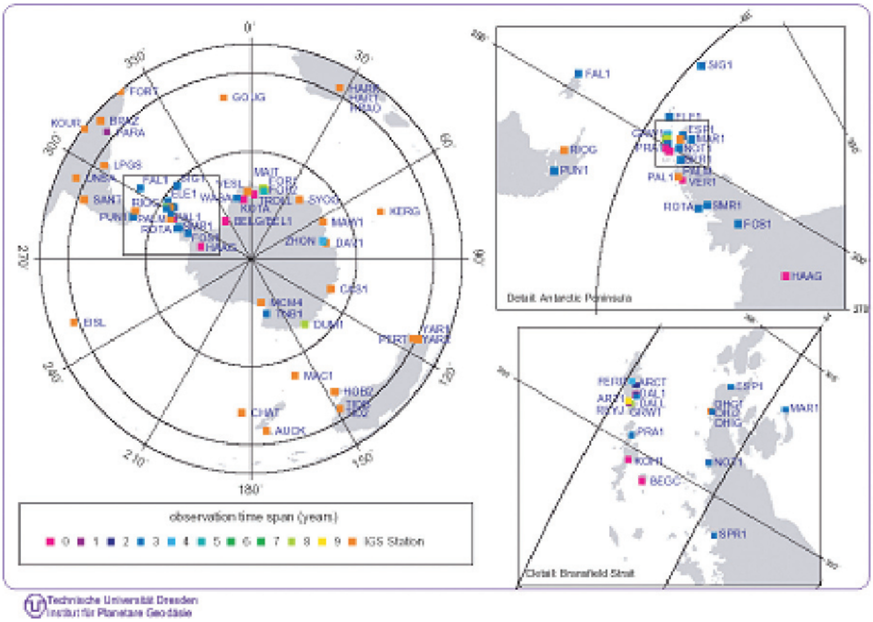

Fig. 2 SCAR GPS Epoch campaigns sites, courtesy of SCAR website

In particular, a continuous geodetic monitoring, exploited through GPS permanent stations, would accurately determine the 3-D motion of the crust. Besides all geodynamical applications, an accurate monitoring of vertical displacements will undoubtedly benefit the investigations related to cryosphere stability and ice mass balance, providing robust constraints on ongoing processes. Sea level change and post-glacial rebound are directly affected by modifications of the ice sheet; these investigations are particularly important as the modifications seem to occur at an unpredicted high rate of change. On the operational side, the efforts that must be made in optimising and ensuring highly accurate standardised performances of remote unmanned observing stations will be maximised by a coordinated effort in designing and planning the installations and the related technical solutions.

Several permanent GPS receivers have already been installed around the Antarctic continent; the global data set is thus continuously increasing. Although, not all observing sites are designed so as to provide observations' transmission in real time or with latency below one day. Furthermore, at remote sites the only suitable way to frequently retrieve experimental data is realized through a satellite link. The scientific instruments and all the hardware remotely installed need to be assisted by technological solutions capable of continuously supplying electric power. This is surely the case for GPS equipments at unattended and remote Antarctic sites. The lack of sunlight and the very low temperature characterising the dark Antarctic winters limit the use of solar panels and/or batteries. Technical solutions based on wind turbines and electric power generators are currently being investigated and developed:

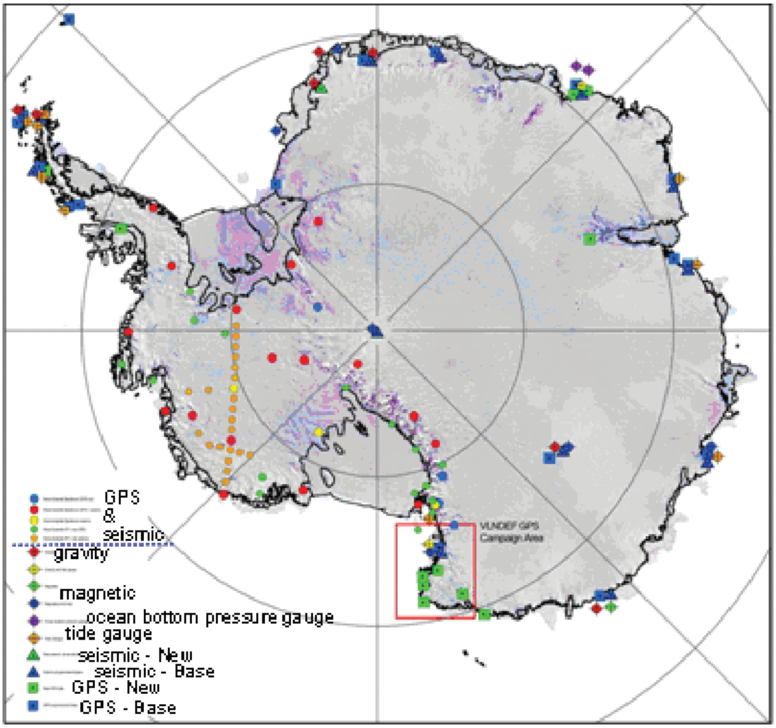

Fig. 3 Geodetic and Geophysical observatories in POLENET, courtesy of SCAR website

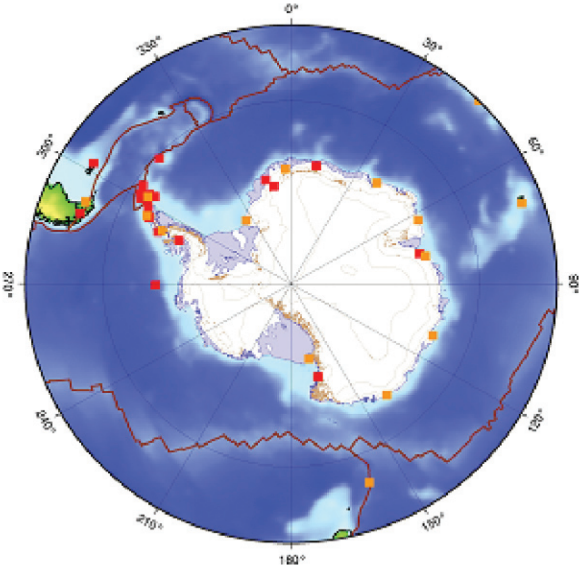

Fig. 4 GPS Observatories in POLENET, courtesy of SCAR website

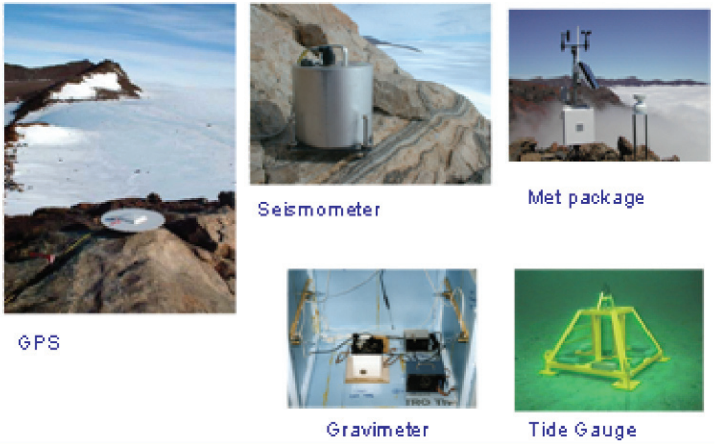

Fig. 5 Observation Techniques and related instrumentation to be co-located at remote polar observatories according to POLENET guidelines, courtesy of SCAR website

the different stages of the process are characterized by varying degrees of success. Ideally, such a remote observing station should be equipped with an inexpensive and reliable remote power unit and a satellite connection for data transmission. This remote operation technology is not quite proven and needs further development and testing to be ready for the International Polar Year in 2007, IPY07.

3 The Italian Geodetic Infrastructures in Antarctica

Geodetic applications of GPS technique in Northern Victoria Land (NVL), Antarctica, started during the 1988–1989 Italian scientific expedition. A local geodetic network was established aiming at creating an experimental GPS geodetic infrastructure that could be used as local geodetic reference frame as well as control network for local crustal motion and deformation detection purposes. In order to do that, 12 sites around the area of Terra Nova Bay (Victoria Land, East Antarctica) were carefully selected: geodetic benchmarks were monumented in suitable locations characterized by exposed and stable bedrock, thus creating a new local reference frame that could be adopted for geodetic, photogrammetric and geological surveys. Moreover, with the purpose of investigating deformations possibly occurring in the area nearby the Melbourne volcano, eight more stations were monumented over stable outcrops around the volcanic edifice (Gubellini & Postpischl 1991; Gubellini et al., 1994; Capra et al., 1996). The map shown in Fig. 6 depicts the location of the benchmarks belonging to the first GPS geodetic network and its densification around the Mt. Melbourne.

In 1998, a permanent GPS station (ITRF code: TNB1) was installed on a granite hill close to Mario Zucchelli Station at, Terra Nova Bay (see Fig. 6). The receiver

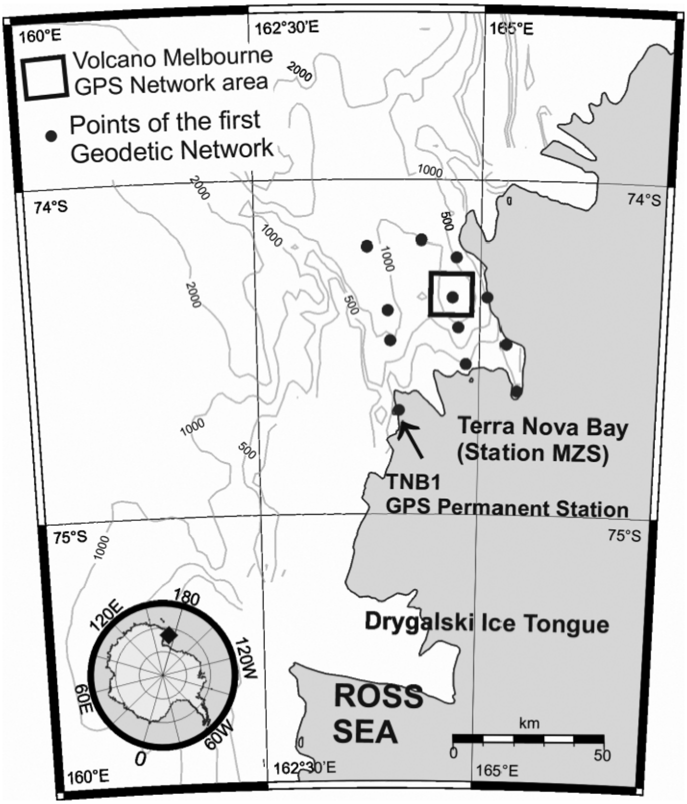

Fig. 6 Map showing the area around Terra Nova Bay: the sites that formed the first local geodetic network are represented with dark dots. The densification network around the Mount Melbourne volcano is situated within the dark square. The dark arrow indicates the location of the permanent GPS station TNB1

has, since, been continuously operating (its location with respect to Mario Zucchelli station and its monument and concrete pillar are shown in Fig. 7) (Capra et al., 2004).

In order to provide accurate estimates of site's positions, a stable monumentation of the geodetic benchmark is needed. The monument of the permanent GPS station TNB1 guarantees excellent technical solutions as well a very high stability. A concrete pillar was built on a well-preserved granite outcrop; it was materialized in 1988 (Gubellini & Postpischl, 1991) and its design and technical characteristics aim at ensuring high-precision measurements. The ITRF tracking point (DOMES number: 66036M001) is unambiguously and accurately identified by means of a forced centring system installed on top of the pillar. Three ex-centre markers were materialized close to the main ITRF tracking point; their positions were surveyed and estimated for maintaining and preserving the original location of the main tracking point in case of damages or inconveniences that might incidentally occur.

The GPS system that was chosen for and installed at Terra Nova Bay is composed by an ASHTECH Z-XII receiver and an ASH700936 Dorne Margolin antenna with

Fig. 7 The monument of TNB1 GPS permanent station. In the small upper-right inset, a black circle highlights the location of the GPS site in the vicinity of the Mario Zucchelli Station (MZS).

SNOW radome. The receiver and the ancillary electronic equipment are safely located in a box firmly anchored to the ground (see Fig. 7). The technology eventually installed and implemented greatly benefited by the numerous GPS surveys that were repeatedly performed in the area of Terra Nova Bay: this experience remarkably helped in selecting the receivers and antenna best suited to work in Antarctic conditions. TNB1 is permanently connected to a continuous and stable source of electric power: its location nearby MZS allows a direct connection to the engines that provide electricity to all the systems, instruments and equipments that must keep on working when the base is closed. Unfortunately, a lack of a cheap satellite connection does not only prevent a daily download of the observations performed during the closing period of the base: it also prevents the use of TNB1 observations to their full extent. They are stored on a personal computer and are downloaded every year, when geodesists arrive at MZS. Therefore, despite its extraordinary geodetic characteristics and its scientific potential, TNB1 cannot yet be part of the IGS network.

A successive fundamental step for Italian geodetic GPS-based activities in Antarctica is related to the monumentation of VLNDEF (Victoria Land Network for DEFormation control) network. This project aimed at planning, designing, establishing and maintaining a dense GPS network, deployed on solid bedrock, with the purpose of measuring horizontal and vertical crustal displacements. The network is nowadays formed by 28 sites (Fig. 8) which were monumented during the 1999–2000 and 2000–2001 field campaigns.

The benchmarks are stainless steel rods with a 5/8 inch screw thread that realize a 3-D forced centring set up and orientation of the GPS antenna (Mancini et al., 2004). Information of different origin had to be merged for properly designing the geometry of the network. Since one of the main scientific purposes was the realization of a geodynamic model of Northern Victoria Land (NVL), the main tectonic features of the area were taken into account and derived by the work of Salvini et al. (1997;

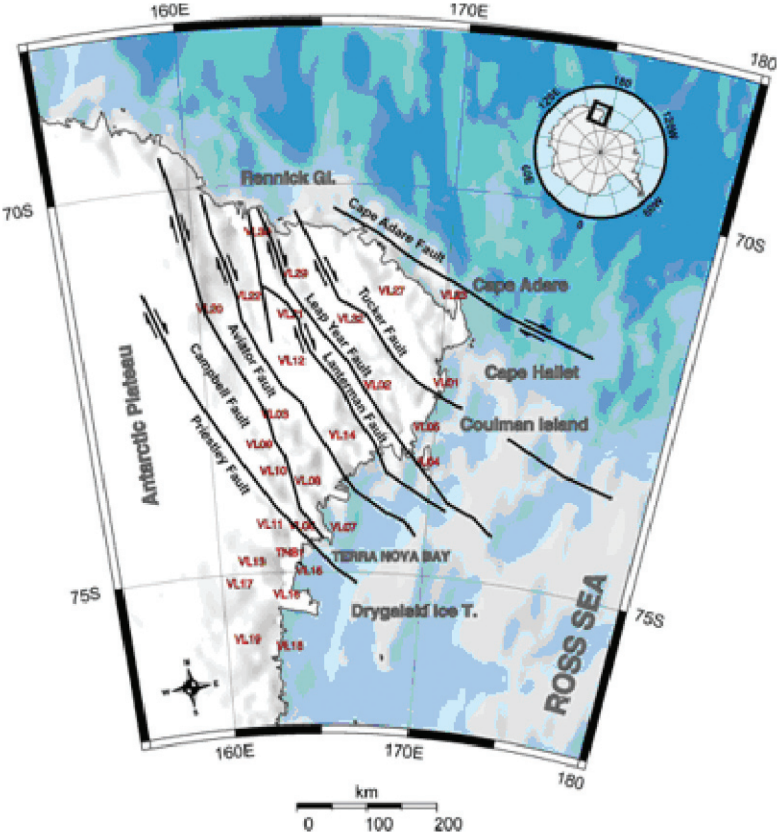

Fig. 8 VLNDEF sites geometry and proposed major strike-slip fault system as derived from the Cenozoic tectonic map of the Ross Sea region proposed by Salvini et al. (1997; see Sect. 4).

see Fig. 8). This led to the identification of the overall shape and extension of the network. In addition to these latter geometric aspects, derived by neotectonic hypothesis, several other requirements had to be evaluated in the planning phase; in particular, the geologic as well as rheologic properties of the bedrock where the monumentation could potentially be realized. Furthermore, the location of the sites had to be suitable for performing GPS measurements: this was a challenging task since the candidate spots needed to be characterized by further stringent properties. In practice, once the overall geometry and the potential area had been identified on a map, the site had to be surveyed by helicopter before taking a final decision and proceed with an immediate materialization of the benchmark. As a matter of fact, stable outcrops, characterized by solid and compact portions of rock are not very common in NVL. Furthermore, a wide open field of view, free from obstructions, obstacles and other limiting factors which might restrict the visibility of satellites during the GPS observations is an aspect that was also taken into account. All sites were described in log-files where all relevant information was summarized, such as position, main morphological and geological features, helicopter approach pathway, suggestions for a correct and quicker set up of the GPS receiver and related equipment (solar panel, battery pack). The first complete campaign-style survey of VLNDEF (1999–2000) was carried out, with limited memory storage capabilities, during the XV Italian Antarctic expedition, harmonising the monumentation of the network with the surveying operations. The following campaigns (2002–2003 and 2005–2006) led to the availability of a larger number of receivers which were also equipped with bulker memory devices (up to 1 Gb). VLNDEF sites are remote and not easily accessible; the observations can only be performed assuring a continuous source of electric power, which is usually provided by means of solar panels and batteries. Technological improvements of a few sites are currently under investigation, in order to meet the requirements that are needed for creating self-standing, unmanned, permanent and remote GPS stations (see Sect. 2).

The increasing redundancy of observations offers new opportunities concerning data processing strategies and long time series analysis. Results obtained by the last-generation GPS receivers have improved the ability to detect crustal deformation from GPS measurements and, when long time series of data are being acquired, to measure local (seasonal or periodical) non-geodetic effects which could affect the investigation.

It has to be highlighted that neotectonic features of Victoria Land are still under investigation both in the Northern as well as in the Southern part, where VLNDEF partially overlaps whit the United States project TAMDEF (TransAntarctic Mountains DEFormation network); this latter GPS network is managed by the Ohio State University and the United States Geological Survey (see Willis et al., 2006).

TNB1 and VLNDEF realize a remarkable Antarctic geodetic infrastructure, which can be view as a whole or as two separate facilities that can serve the whole international geoscience community. The scientific potentials are different as scientific applications are strictly related to the quantity and quality of observations, their duration and their main geodetic characteristic, principally, permanent vs. episodic observations. Maintenance, management, development, optimisation and full exploitation of these facilities imply the capability to approach similar and connected, though different, practical and theoretical aspects.

On one hand, TNB1 can be episodically considered as part of VLNDEF and a subset of its continuous observations are regularly processed along with the episodic observations performed during VLNDEF campaigns. The entire set of VLNDEF observations was processed applying different analysis strategies and different software with the purpose to achieve the most accurate and reliable results. Section 5.2 presents in detail the procedures that were applied while Sect. 4 focuses on the geodynamical potential of the network and its possible contributions to an understanding of the neotectonic features of the area. It is worth mentioning that a selected subset of TNB1 observations was used in the framework of the SCAR GPS epoch campaigns (Dietrich et al., 2001, 2004) (see Sect. 2) and in the densification of the ITRF2000 in the Antarctic and peri-Antarctic regions (Altamimi et al., 2002).

On the other hand, TNB1 is an Antarctic permanent GPS station and its continuous observations, despite the 12 months latency, can improve and support scientific investigations in a wide variety of fields, not only geodetic but multidisciplinary (see e.g. Sarti et al., 2008). The data processing approach, when dealing with TNB1 continuous observations, must be optimised searching, testing and applying the proper methods and the correct strategies to be adopted for continuous permanent GPS observations. Section 5.1 illustrates the detail of the processing strategies and solutions that were tested on seven years of TNB1 observations.

4 Geological and Geodynamical Settings of Northern Victoria Land

VLNDEF network extends on a wide portion of NVL, between 71°S and 76°S and 160°E and 170°E (Fig. 8). Its design (see Sect. 3) was planned according to the most recent information concerning the rheology, neotectonics and geodynamics of the area.

Most of the authors involved in offshore and onshore geology investigations of the Ross Sea region (Salvini et al., 1997; Salvini et al., 1998; Salvini, 1999; Storti et al., 2001) suggest that the tectonic framework revealed in the NVL region is dominated by a major right lateral strike-slip motion and a faults system with a dominant NW-SE direction. It represents the onshore side of the widest dextral transform shear which characterizes the Tasman Fracture Zone and the Balleny Fracture Zone in the Southern Ocean. Three main terrane that follow the NW-SE striking fault zone have been initially described by the GANOVEX TEAM (1987). From NE to SW they are: Robertson Bay Terrane, Bowers Terrane and Wilson Terrane. The Leap Year Fault divides the Robertson Bay from the Bowers Terrane whereas the Lanterman Fault separates the Bowers from the Wilson Terrane. Within the major NW-SE fault system five more faults have been mapped. From NE to SW they are the Cape Adare Faults, Tucker Faults, Aviator Faults, Campbell Faults and the Priestley Faults. Figure 8 shows the distribution of the 28 stations belonging to VLNDEF together with the deformation pattern along the NW-SE faults; it can be clearly noticed that the design of the network aims at detecting the deformations due to neotectonic phenomena and at confirming the strike-slip kinematics which is believed to control the Victoria Land basin.

All previous aspects will be further discussed in the next Sections after a short review of the plate kinematic and Glacial Isostatic Adjustment (GIA) in NVL as presented by several authors involved in the field of Antarctic geosciences.

4.1 Plate Kinematics in NVL

Since 1990, information about the plate kinematics of Antarctica was obtained from the No-Net-Rotation NUVEL 1 model (Argus & Gordon, 1991; DeMets et al., 1990). At the beginning of the 90's the IGS stations installed around the

Antarctic coast started to provide the first measurements of displacements derived from GPS observations. Since middle 90's, the SCAR GPS Epoch project (see Sect. 2), through a set of data episodically acquired by more than 30 IGS and non-IGS permanent stations, has been providing an accurate regional solution for sites' positions and velocities. The results obtained by SCAR GPS Epoch campaigns have highlighted a major clockwise motion of Antarctica with a magnitude somewhere greater than 1 cm/yr (Dietrich et al., 2001) whereas the relative motion occurring between the Antarctic Peninsula area and the eastern Antarctica is not larger than 1–2 mm/yr (Dietrich et al., 2004). These results have been recently confirmed by Negusini et al. (2005) processing a subset of GPS data recorded at 15 IGS Antarctic and peri-Antarctic sites to validate the reference frame stability. These displacements are consistent with the idea of a minimal amount of recent relative motion between East and West Antarctica. Besides that, the vertical rates of displacements are currently under considerations, in terms of accuracy and reliability, as a constraint in the available Glacial Isostatic Adjustment models. However, the analysis of vertical rates has to be combined with the study of other geophysical signals which could potentially affect the observations. It must be highlighted that vertical rates are less accurately estimated when compared to horizontal ones; nevertheless, values up to 10 mm/year were detected in the Northern Antarctic Peninsula (Dietrich et al., 2004) while smaller values were estimated elsewhere in the Antarctic continent.

Several GIA models predict uplift rates in Antarctica. ICE-3G (1991), ICE-4G (1994), ICE-5G (1998) and D91 (1998) show different scenarios of glacial history (Ivins et al., 2003, 2005; Kaufmann et al., 2005; Peltier, 1994; Peltier, 1998; Raymond et al., 2004). Even if this paper does not focus on a detailed discussion of GIA vertical rates as derived by GPS measurements, a first attempt to compare vertical rates (GIA vs GPS) will be discussed in the final part of this paper. The next Sections are devoted to an illustration of the different software and processing strategies applied to TNB1 and VLNDEF data and to a detailed description of the results.

5 GPS Data Sets and Related Analysis Approaches

Nowadays, the continuous observations performed with TNB1 form a 7-years data set; the VLNDEF data refer, instead, to observations performed and stored during five episodic GPS campaigns. In order to find a suitable processing strategy for these specific sets of data, different approaches and software had to be tested; the different tests aimed at obtaining the most accurate results out of the geodetic observations.

Taking into consideration the peculiar orographic and geographic features of Antarctica and its location with respect to the other continents, which distinguish Antarctica as a very remote and isolated site, the baselines that may be possibly formed with extra-Antarctic IGS network stations are characterized by very large moduli. Therefore, the effects of such a stringent constraint was investigated with (i) a classical double difference approach that was applied using Bernese GPS software, (ii) a classical distributed processing applied by means of Gamit/Globk data

Table 1 Some relevant information concerning the software packages and the parameterisation eventually applied to the GPS data sets

Software	Bernese 5.0	Gamit/Globk 10.2	Gipsy Oasis II 4.04
Producer	Astronomical Institute University of Bern (AIUB)	Department of Earth Atmospheric and Planetary Sciences, MIT	Jet Propulsion Laboratory
Orbits	IGS precise	Colombo (1986), Beutler et al. (1994)	FLINN
Antenna Phase Center Variation	IGS_05 – absolute	Antex.dat – relative	ant_info.003 – NGS – Relative
Satellite Phase Center Variation	Yes	No	No
Pole Tide	McCarthy (1996), McCarthy & Petit (2004)	McCarthy (1996)	Yoder (in Webb & Zumberge, 1995)
Solid Tide	McCarthy 1996, McCarthy & Petit (2004)	McCarthy (1996)	IERS2003
Ocean Tide	Matsumoto et al. (2000) Schwiderski (1980)	Scherneck (1991)	No
Tropospheric Mapping	Niell (1996)	Niell (1996)	Niell (1996)
Troposphere Function	Saastamoinen (1972)	Saastamoinen (1972)	Saastamoinen (1972)
Ionosphere correction	LC	LC	LC
Solution	Double difference	Double difference	Precise Point Positioning
Adjustment	Least Square	Least Square (Gamit) Kalman Filter (Globk)	Free net fiducial and 7 parameter transformation to ITRF00

processing package and (iii) Precise Point Positioning (PPP) applied by means of Gipsy/Oasis II. Table 1 resumes some relevant characteristics of each software as well as the specific models that were selected and applied in the analysis.

5.1 TNB1 Data Processing Approaches

In order to achieve an accurate estimate of TNB1 global position and velocity, eventually framed into ITRF2000, two different approaches were tested: a double difference approach, based on the analysis of a network formed by selected IGS permanent stations, by means of Bernese V.5.0 software and an undifferenced approach, based on the Precise Point Positioning strategy, applied with Gipsy/Oasis II software. The observations performed at TNB1 span, almost continuously, a seven-year period: from 1999 till 2006.

Sections 5.1.1 and 5.1.2 contain a short summary of the peculiarities, which characterise each solution; results are summarised in Sect. (5.1.3).

5.1.1 Bernese Carrier Phase Differenced Approach

Taking into consideration the peculiar orographic and geographic features of Antarctica, a relative positioning of TNB1 with respect to other IGS stations can be achieved using observations acquired at GPS sites located in Antarctica, on peri-Antarctic islands or in the nearest continents. In fact, this approach ensures a very high redundancy of observations: it is possible to select those IGS stations that have homogeneously and continuously acquired since 1998, being this latter the year when observations started at Terra Nova Bay (see Sect. 1). A network of GPS stations was therefore selected among the permanent IGS observing sites located both on Antarctica Plate (CAS1, DAV1, DUM1, KERG, MAW1, MCM4, OHIG/OHI2, SYOG e VESL) as well as on other tectonic plates (CHAT, GOUG, HOB2, HRAO, MAC1, PERT e RIOG, which constitute the so called peri-Antarctic network). The stations were chosen on the basis of several criteria: stability, availability of continuous observation series, data quality, availability of ITRF2000 positions and velocities as well as the geometrical shape of the network.

A traditional double difference approach was adopted in order to perform the analysis. Bernese GPS Software v5.0 (Dach et al., 2007) and the suite of scripts and programs named Bernese Processing Engine (BPE) were the processing tools. The analysis started from the observations files in RINEX (Receiver INdependent EXchange) format and aimed at producing and storing daily solutions in the SINEX V.1.0 (Software INdependent EXchange) format as well as Normal EQuation (NEQs).

A data sampling rate of 30 s, standard parameters such as precise orbits and Earth rotation parameters (ERP) provided by IGS were used. An elevation cut-off angle of 10° was adopted since it was considered the best compromise between quantity and quality of data available at the latitudes of the network.

A priori information about tropospheric delay, computed from a standard atmosphere (Berg, 1948), was estimated using Dry Niell mapping function for the dry part, while continuous piecewise linear troposphere parameters were estimated at 1-h intervals using the Wet Niell mapping function, in order to obtain the total zenith tropospheric delay.

The first order term of the ionospheric refraction was eliminated by forming the ionosphere-free linear combination (LC) of the L1 and L2 measurements.

Absolute phase antenna center variations (PCVs) for receivers (Menge et al., 1998) as well as block-specific values for the Block II/IIA and Block IIR satellites (Schmid & Rothacher, 2003) were used.

The ambiguity resolution on all baselines was performed adopting the Quasi-Ionosphere Free (QIF) strategy (Mervart, 1995) along with Global Ionosphere Models (GIMs), provided by CODE that were used as a priori information. The geodetic datum was defined by a No-Net Rotation (NNR) condition with a minimal constraint approach, fixing 6 peri-Antarctic stations which were considered as those having the most reliable a-priori coordinates into ITRF2000.

5.1.2 Undifferenced Precise Point Positioning Gipsy/Oasis II Approach

The Precise Point Positioning (PPP) approach (Zumberge et al., 1997), implemented in Gipsy/Oasis II V.4.04 developed at JPL (Jet Propulsion Laboratory), allows GPS data undifferenced processing of code and carrier phases observables acquired by one single receiver. PPP was run on a Linux Red Hat 9 platform using accurate orbits information and accurate satellite clock data as provided by the IGS or JPL.

PPP represents a major step towards the realization of high accuracy positioning based on stand-alone receivers. From a theoretical point of view, differentiate and undifferentiated approaches differ in clock bias and ambiguity modelling. When observations are differentiate, single, double and triple differences are formed and clock bias and ambiguity are thus removed. With the undifferentiated approach, clock bias and ambiguity are considered as unknowns and are estimated using a proper statistic model by a sequential filter: Square Root Information Filter (SRIF) (Blewitt, 1993). The SRIF filter is a modified Kalman filter, developed at JPL by Gerald Bierman. This filter includes the capability to assess effects from mismodelling by process noise. It allows parameters to have a stochastic behaviour: this is particularly useful for clock bias and tropospheric delay. The stochastic models that have been implemented are mainly a time-uncorrelated behaviour (white noise model) or a time dependent behaviour (random walk model); also unvarying model can be applied. A random walk model is explicitly used for evaluating wet tropospheric delay (Zumberge et al., 1998; Kouba, 2000); a white noise error model is then used for clock bias, since GIPSY doesn't solve double difference. The geodetic precision of PPP solution was demonstrated with the 'March 1985 High Precision Baseline Test' (Davidson et al., 1985; Beutler et al., 1986; Gouldman et al., 1986; Parrot et al., 1986).

The PPP strategy was also tested in remote regions, concluding that GPS daily solutions accuracy can be compared with traditional, differenced GPS positioning. The computation of orbits and satellite clocks solutions comes from the FLINN (Fiducial Laboratories for International Natural science Network) global network (it is a sub-network of the IGS): many of the FLINN stations are equipped with a hydrogen maser or a good quality rubidium or caesium clock. Thus a very stable time reference is available at the receiver site, crucial when estimating high-rate satellite clock corrections.

The orbits used for GIPSY processing have some peculiarities: for each day, JPL analysis center offers IGS-like fiducial orbits, for the current ITRF, and also non fiducial orbits, obtained by a fiducial free solution of the FLINN (Fiducial

Laboratories for International Natural Science Network) stations (Panafidina & Malkin, 2002; Heflin et al., 1992).

The analysis was carried out using non-fiducial orbits which were produced using poorly constrained ground stations. The relative geometry of all orbits is determined by GPS data only and the orbits will not be perturbed by any imperfect knowledge of station coordinate. After the non fiducial solution is obtained, a daily similarity transformation, also provided by JPL during the orbits downloading phase, was used to remove the uncertainty of the frame and to express the solution in ITRF2000.

All daily GPS solution were combined using a GIPSY utility (STAMRG) that use the station positions and the associate complete variance matrix, then the position and the velocity at 2003.0 epoch was calculated. The results were iteratively refined using a data snooping strategy with a 3 sigma tolerance. Default configuration and IGS antenna calibration parameters were also implemented. All the time series were processed using C-shell scripts in order to automate the processing procedure.

5.1.3 TNB1 Data Processing Results

The local geodetic velocity of TNB1 (North, East and Up components), as estimated using both the undifferenced (Gipsy/Oasis II) and the differenced (Bernese V.5.0) approaches, are shown in Fig. 9.

The results were obtained applying the software and the related analysis approach described in Sects. 5.1.1 and 5.1.2; Fig. 10 shows a flow diagram were the processing steps related to these two solutions are highlighted in yellow. Table 2 schematically shows the same results along with new estimates of TNB1 local geodetic velocity components that were obtained by means of Gamit/Globk software package (details can be found in Sect. 5.2.1). The working data set processed with Gamit/Globk differs from the one which was processed with Bernese V.5.0 and Gipsy/Oasis II: it is a subset of the whole 7-year observations set which was formed extracting the TNB1 data that overlap the VLNDEF episodic observations.

5.2 VLNDEF Data Processing Approaches

This Section illustrates the different tests that were performed on the data acquired during the VLNDEF campaigns. More than one strategy and combination of models are investigated, aiming at producing the most accurate final estimation and, at the same time, obtaining a comparable, homogeneous analysis strategy from each software.

The observations performed at VLNDEF sites were acquired during episodic campaigns (see Sect. 3). The large distances between the sites of the network and the external IGS stations as well as the limited duration of the observations on each site (lasting from a minimum of a few days to several weeks) prevent a straightforward application of a processing approach similar to e.g. the one described

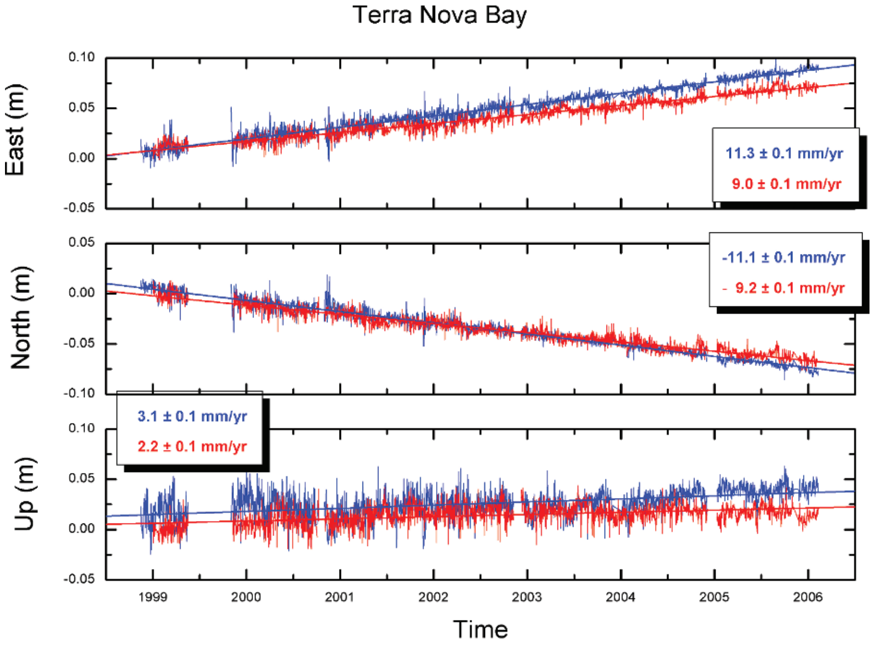

Fig. 9 TNB1 local geodetic coordinates time series derived with Bernese V.5.0 (*red*) and Gipsy/Oasis II (*blue*); the graph also shows the linear fit computed on the time series and the corresponding linear velocities

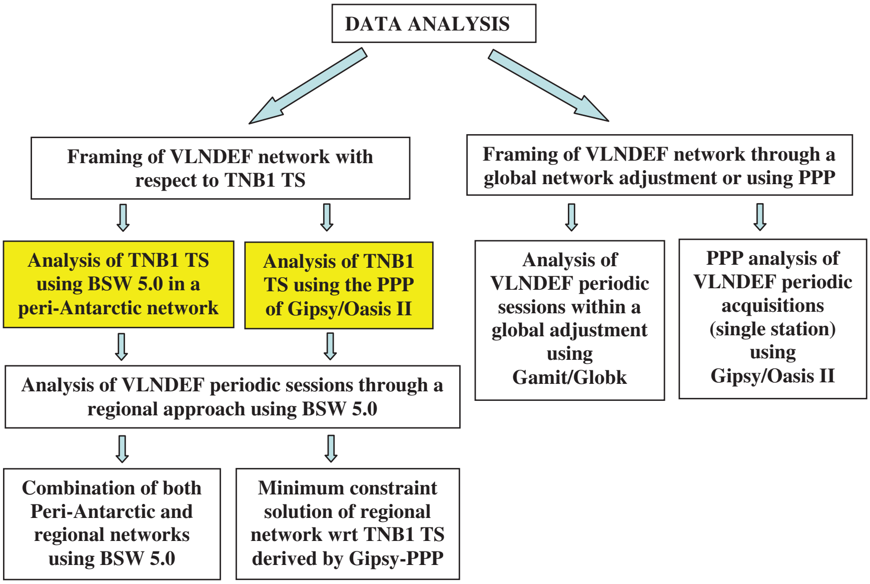

Fig. 10 Schematic flow diagram offering an overview of the strategies and the software packages that were adopted within each different analysis procedure

Table 2 TNB1 GPS permanent station velocities and errors expressed in the local geodetic reference frame

	East componentr (mm/yr)	North component (mm/yr)	Up component (mm/yr)
Bernese v. 5.0	9.0 ± 0.1	-9.2 ± 0.1	2.2 ± 0.2
Gipsy/Oasis II	11.3 ± 0.1	-11.1 ± 0.1	3.1 ± 0.2
Gamit/Globk	9.8 ± 0.2	-11.4 ± 0.2	1.6 ± 0.4

in Sect. (5.1.1). Nevertheless, the good quality and the duration of observations performed at each network's site as well as the their limited reciprocal distance (approximately 100 km) are sufficient to ensure an accurate relative positioning of the points of the network with respect to each others and TNB1. There is no unique analysis approach; therefore, in order to achieve accurate estimations of sites' absolute positions and velocities, eventually framed into ITRF2000, several processing strategies were applied and evaluated. The flow diagram of Fig. 10 resumes the different analysis approaches that were adopted and tested for estimating the most accurate positions' and velocities' solution for the sites of VLNDEF network.

The first approach is based on an accurate estimation of TNB1 coordinates and velocities within ITRF2000: both Bernese V.5.0 and Gipsy/Oasis II were used to estimate these parameters according to the approaches described in Sects. (5.1.1) and (5.1.2), respectively. The first analysis approach of VLNDEF observations was performed with Bernese V.5.0 in order to produce a set of Normal Equations (NEQ) that were successively combined with those produced and stored according to Sect. (5.1.1) procedure: an absolute framing of VLNDEF sites was therefore achieved (see Sect. 5.2.1). A second approach, which is also based on Bernese V.5.0, was adopted and evaluated (see Sect. 5.2.2): VLNDEF data processing was performed, tightly constraining the coordinates of TNB1 to the values estimated according to the procedure described in Sect. (5.1.2).

Two more processing strategies were applied to VLNDEF data and evaluated. A global approach is based on Gamit/Globk software (see Sect. 5.2.3) while the last and final approach that has been tested is based on Gipsy/Oasis II PPP (see Sect. 5.2.4). Final results are presented and discussed in Sect. (5.2.5).

5.2.1 VLNDEF Episodic Observations: Bernese V.5.0 Processing

This processing procedure had been successfully applied on the first and second VLNDEF campaigns to compute a set of coordinates and velocities for the sites of the network (Capra et al., 2007). It was therefore re-applied to the complete set of four VLNDEF campaigns, using the latest version of Bernese software (V.5.0) with similar strategy but a different approach for network framing. In order to take into account the effects of ocean tide on site coordinates, the model NAO.99b was applied at each VLNDEF station as computed by H. G. Scherneck, Onsala Space

Observatory. This ocean tide model is based on the same hydrodynamics as the Schwiderski model but uses TOPEX/Poseidon data given on a 0.5 by 0.5 degree grid (Matsumoto et al., 2000). In particular, station-specific amplitudes and phase of the eleven largest tidal terms for the vertical as well as for the horizontal station components were used; the IERS "standard" format was adopted, accordingly. A consistent set of coefficients was used for all VLNDEF stations.

Daily solutions were performed using the whole set of observations and NEQs were stored.

The final solution for VLNDEF network sites' coordinates (Table 3), properly expressed into ITRF2000, was produced by means of Bernese V.5.0 ADDNEQ routine: VLNDEF NEQs were combined with those produced and stored for TNB1 (5.1.1). Six peri-Antarctic stations (CHAT, KERG, MAC1, HOB2, HRAO, PERT) were used to define the geodetic datum of the site coordinates imposing a No-net translation condition.

Site velocities, estimated with the same ADDNEQ run, are shown in Table 4.

Table 3 VLNDEF sites positions expressed into ITRF2000 (epoch 2003.0) computed with Bernese/peri-Antarctic approach

	X (m)	Y (m)	Z (m)
TNB1 66036M001	−1623858.4319 ± 0.0001	462478.1171 ± 0.0001	−6130048.9861 ± 0.0001
VL01	−1898355.0792 ± 0.0001	344131.5796 ± 0.0001	−6059589.5961 ± 0.0002
VL02	−1871176.6926 ± 0.0001	419007.1067 ± 0.0001	−6064822.2174 ± 0.0002
VL03	−1793824.6435 ± 0.0001	550947.6384 ± 0.0001	−6077986.2946 ± 0.0002
VL04	−1786676.3872 ± 0.0001	323127.1023 ± 0.0001	−6095659.5976 ± 0.0004
VL05	−1833378.6460 ± 0.0001	336084.8236 ± 0.0001	−6079754.0536 ± 0.0002
VL06	−1665381.7116 ± 0.0001	455889.0590 ± 0.0001	−6122163.3470 ± 0.0004
VL07	−1731871.0228 ± 0.0001	451786.7821 ± 0.0001	−6103456.3734 ± 0.0002
VL08	−1717947.9199 ± 0.0001	501076.6043 ± 0.0001	−6104184.8502 ± 0.0003
VL09	−1747656.6838 ± 0.0001	562141.0904 ± 0.0001	−6090108.2408 ± 0.0003
VL10	−1716963.1572 ± 0.0001	532520.4138 ± 0.0001	−6101777.8056 ± 0.0002
VL11	−1644838.3637 ± 0.0001	517300.7456 ± 0.0001	−6122511.0323 ± 0.0004
VL12	−1870330.3720 ± 0.0001	545966.3540 ± 0.0001	−6054921.0795 ± 0.0002
VL13	−1592717.3243 ± 0.0001	511213.2531 ± 0.0001	−6135756.5247 ± 0.0003
VL14	−1791154.8186 ± 0.0001	449717.6339 ± 0.0001	−6086636.3236 ± 0.0002
VL15	−1596324.0004 ± 0.0001	466324.0209 ± 0.0001	−6136835.4752 ± 0.0003
VL16	−1555858.1899 ± 0.0001	489202.5719 ± 0.0001	−6145734.3337 ± 0.0003
VL17	−1561179.2635 ± 0.0001	521189.6915 ± 0.0001	−6142166.0340 ± 0.0002
VL18	−1487512.5303 ± 0.0001	466337.4687 ± 0.0001	−6164019.9253 ± 0.0004
VL19	−1490548.0456 ± 0.0001	490597.3284 ± 0.0001	−6162196.0181 ± 0.0004
VL20	−1909089.5266 ± 0.0002	677740.0492 ± 0.0001	−6029108.8684 ± 0.0006
VL21	−1932100.1091 ± 0.0001	563780.2301 ± 0.0001	−6033962.4198 ± 0.0004
VL22	−1938968.3244 ± 0.0001	628496.4975 ± 0.0001	−6023703.1621 ± 0.0003
VL23	−2017366.1617 ± 0.0001	344665.3680 ± 0.0001	−6021793.9214 ± 0.0004
VL27	−1999402.0838 ± 0.0002	432212.5222 ± 0.0001	−6022817.4305 ± 0.0006
VL29	−1985915.1837 ± 0.0001	573344.5455 ± 0.0001	−6015394.1881 ± 0.0004
VL30	−2027440.4130 ± 0.0002	638271.5344 ± 0.0001	−5994964.3005 ± 0.0004
VL32	−1947613.4119 ± 0.0001	479657.0732 ± 0.0001	−6036111.4515 ± 0.0003

Table 4 VLNDEF sites velocities expressed into ITRF2000 computed with Bernese/peri-Antarctic approach

	V_x (mm/yr)	V_y (mm/yr)	V_z (mm/yr)
TNB1 66036M001	5.9 ± 0.1	−11.1 ± 0.1	−5.1 ± 0.1
VL01	6.3 ± 0.1	−12.3 ± 0.1	−2.0 ± 0.1
VL02	6.7 ± 0.1	−10.7 ± 0.1	−2.5 ± 0.1
VL03	5.9 ± 0.1	−11.6 ± 0.1	−4.4 ± 0.1
VL04	8.0 ± 0.1	−10.3 ± 0.1	−1.1 ± 0.3
VL05	6.5 ± 0.1	−10.5 ± 0.1	−3.5 ± 0.1
VL06	5.5 ± 0.1	−10.5 ± 0.1	−3.1 ± 0.2
VL07	6.7 ± 0.1	−9.7 ± 0.1	−5.3 ± 0.1
VL08	5.1 ± 0.1	−11.2 ± 0.1	−5.0 ± 0.1
VL09	5.6 ± 0.1	−11.4 ± 0.1	−5.1 ± 0.1
VL10	5.4 ± 0.1	−11.2 ± 0.1	−4.7 ± 0.1
VL11	5.6 ± 0.1	−10.7 ± 0.1	−2.6 ± 0.1
VL12	5.6 ± 0.1	−10.9 ± 0.1	−6.0 ± 0.1
VL13	6.0 ± 0.1	−9.8 ± 0.1	−3.2 ± 0.1
VL14	6.7 ± 0.1	−11.8 ± 0.1	−2.1 ± 0.1
VL15	7.0 ± 0.1	−8.1 ± 0.1	−4.3 ± 0.1
VL16	5.3 ± 0.1	−11.8 ± 0.1	−3.6 ± 0.1
VL17	6.3 ± 0.1	−8.3 ± 0.1	−4.1 ± 0.1
VL18	6.9 ± 0.1	−8.9 ± 0.1	−4.8 ± 0.2
VL19	4.7 ± 0.1	−8.4 ± 0.1	−3.7 ± 0.2
VL20	6.7 ± 0.2	−13.8 ± 0.1	−6.6 ± 0.6
VL21	7.2 ± 0.1	−4.1 ± 0.1	−5.7 ± 0.2
VL22	6.5 ± 0.1	−12.5 ± 0.1	−4.5 ± 0.1
VL23	6.0 ± 0.1	−12.1 ± 0.1	−4.9 ± 0.2
VL27	11.3 ± 0.2	−11.4 ± 0.1	−6.3 ± 0.6
VL29	4.5 ± 0.1	−12.3 ± 0.1	−8.7 ± 0.2
VL30	4.0 ± 0.1	−11.8 ± 0.1	−6.5 ± 0.2
VL32	6.3 ± 0.1	−12.7 ± 0.1	−4.9 ± 0.1

Figure 11 shows the horizontal components of the absolute velocities of Table 4, properly transformed and expressed into the local geodetic frame (NEU).

5.2.2 Gipsy/Oasis II PPP and Bernese GPS Minimum Constraint Joint Solution

A second VLNDEF data processing strategy, based on a minimal constrained solution, was tested. The TNB1 coordinates time series, as estimated with the procedure described in Sect. (5.1.2) by means of Gipsy/Oasis II, was used in order to frame, into ITRF2000, the VLNDEF double-differences solutions produced according to Sect. (5.2.1). VLNDEF sites' positions, expressed into ITRF2000 at epoch 2003.0, are shown in Table 5.

Absolute velocities (expressed into ITRF2000) obtained with the same estimation process are shown in Table 6.

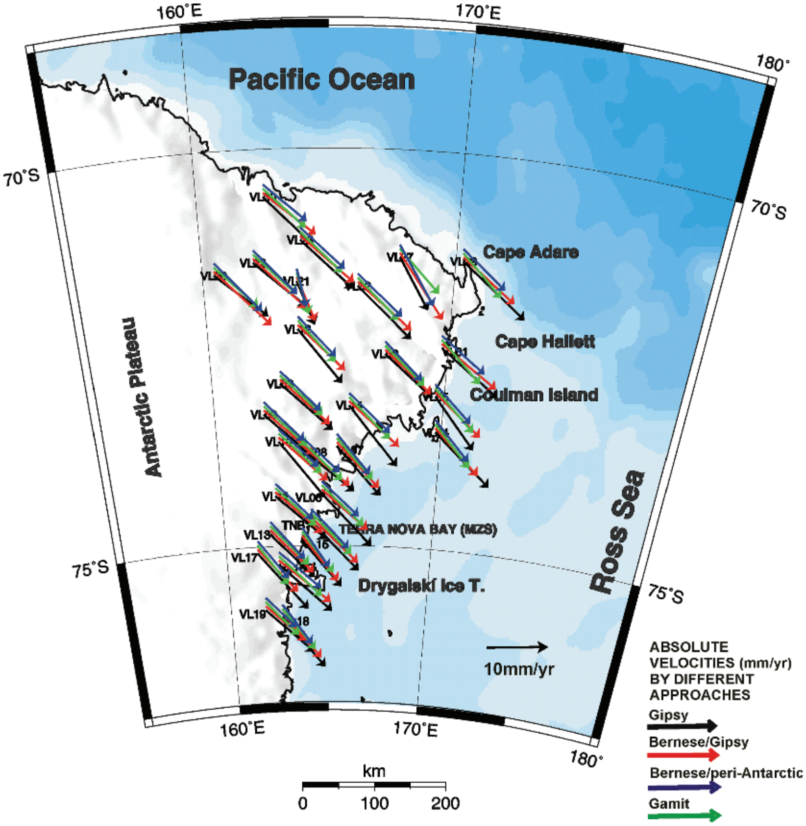

Fig. 11 Absolute velocities of the VLNDEF GPS sites in ITRF2000 computed by means of the three software and four solutions: Gipsy/Oasis (*black arrows*), Bernese/Gipsy (*red arrows*), Bernese/peri-Antarctic (*dark blue arrows*) and Gamit/Globk (*green arrows*)

This method, compared to a traditional approach based on larger networks of reference stations where positions are over-constrained (or loosely "over-constrained") at ITRF values, represents an interesting approach to deformation control: when accurate position(s) of the reference station(s) are available, the intrinsic geometry and orientation of the network is preserved, yielding datum definition while simultaneously maintaining the original characteristic of the regional solution.

5.2.3 Gamit/Globk Global Approach

The third processing strategy that was applied to VLNDEF data relies on the use of Gamit/Globk software package. The statistical model implemented in Gamit is based on weighted least squares. Gamit produces two or more solutions: a pre-fit solution is run in order to obtain a priori values of relevant parameters. Afterwards,

Table 5 ITRF2000 VLNDEF sites' coordinates (epoch 2003.0) estimated with a minimal constrained solution performed combining Bernese V.5.0 and Gipsy/Oasis II software.

	X (m)	Y (m)	Z (m)
TNB1 66036M001	−1623858.4374 ± 0.0001	462478.1120 ± 0.0001	−6130048.9968 ± 0.0001
VL01	−1898355.0840 ± 0.0001	344131.5745 ± 0.0001	−6059589.6055 ± 0.0003
VL02	−1871176.6972 ± 0.0001	419007.1022 ± 0.0001	−6064822.2267 ± 0.0004
VL03	−1793824.6482 ± 0.0001	550947.6334 ± 0.0001	−6077986.3041 ± 0.0004
VL04	−1786676.3925 ± 0.0002	323127.0975 ± 0.0002	−6095659.6071 ± 0.0009
VL05	−1833378.6511 ± 0.0001	336084.8188 ± 0.0001	−6079754.0631 ± 0.0003
VL06	−1665381.7163 ± 0.0002	455889.0542 ± 0.0001	−6122163.3562 ± 0.0007
VL07	−1731871.0270 ± 0.0001	451786.7776 ± 0.0001	−6103456.3816 ± 0.0004
VL08	−1717947.9245 ± 0.0001	501076.5994 ± 0.0001	−6104184.8594 ± 0.0005
VL09	−1747656.6889 ± 0.0001	562141.0851 ± 0.0001	−6090108.2502 ± 0.0004
VL10	−1716963.1612 ± 0.0001	532520.4087 ± 0.0001	−6101777.8129 ± 0.0003
VL11	−1644838.3685 ± 0.0001	517300.7410 ± 0.0001	−6122511.0410 ± 0.0005
VL12	−1870330.3769 ± 0.0001	545966.3488 ± 0.0001	−6054921.0892 ± 0.0003
VL13	−1592717.3293 ± 0.0001	511213.2496 ± 0.0001	−6135756.5343 ± 0.0005
VL14	−1791154.8233 ± 0.0001	449717.6289 ± 0.0001	−6086636.3328 ± 0.0003
VL15	−1596324.0050 ± 0.0001	466324.0166 ± 0.0001	−6136835.4843 ± 0.0006
VL16	−1555858.1942 ± 0.0001	489202.5669 ± 0.0001	−6145734.3419 ± 0.0005
VL17	−1561179.2677 ± 0.0001	521189.6883 ± 0.0001	−6142166.0423 ± 0.0005
VL18	−1487512.5347 ± 0.0002	466337.4643 ± 0.0001	−6164019.9351 ± 0.0006
VL19	−1490548.0500 ± 0.0002	490597.3237 ± 0.0001	−6162196.0278 ± 0.0006
VL20	−1909089.5314 ± 0.0005	677740.0443 ± 0.0003	−6029108.8780 ± 0.0010
VL21	−1932100.1140 ± 0.0002	563780.2254 ± 0.0001	−6033962.4295 ± 0.0006
VL22	−1938968.3293 ± 0.0002	628496.4928 ± 0.0001	−6023703.1707 ± 0.0005
VL23	−2017366.1668 ± 0.0003	344665.3634 ± 0.0001	−6021793.9310 ± 0.0008
VL27	−1999402.0887 ± 0.0005	432212.5175 ± 0.0002	−6022817.4404 ± 0.0014
VL29	−1985915.1887 ± 0.0002	573344.5406 ± 0.0001	−6015394.1972 ± 0.0006
VL30	−2027440.4181 ± 0.0002	638271.5296 ± 0.0001	−5994964.3101 ± 0.0007
VL32	−1947613.4171 ± 0.0002	479657.0683 ± 0.0001	−6036111.4609 ± 0.0005

post-fit solutions may be iterated until post-fit residuals are minimized in a least squares sense (King & Bock, 2000; Herring et al., 2006).

GPS phase observations equations are double differenced (Shaffrin, 1988; Serpelloni et al., 2006) and loosely constrained daily solutions are computed. These latter are stored in h-files and are based on a simultaneous estimation of the following parameters: coordinates, satellite orbits parameters, atmospheric corrections, integer-cycle ambiguities and variance-covariance matrices.

A short resume of the parameterisation adopted in the analysis follows (see Table 1). g-files precise orbit computed at Scripps Orbit and Permanent Array Center (SOPAC) and downloaded from the ftp site "ftp://lox.ucsd.edu" were used. An atmospheric zenith gradient was estimated for each station together with the zenith delay parameter; both atmospheric parameters are modelled by means of a piecewise-linear function (Chen & Herring, 1997). The default models that have been adopted to compute the hydrostatic (or dry) and wet, a priori, zenith delays are those described by Saastamoinen (1972), King and Block (2000), Herring et al. (2006). The dynamical models that were used in the initial conditions integration are taken

Table 6 Absolute velocities of VLNDEF sites expressed into ITRF2000, estimated with a minimal constrained solution performed combining Bernese V.5.0 and Gipsy/Oasis II software

	V_x (mm/yr)	V_y (mm/yr)	V_z (mm/yr)
TNB1 66036M001	6.4 ± 0.1	−13.6 ± 0.1	−5.9 ± 0.1
VL01	6.6 ± 0.1	−15.0 ± 0.1	−3.3 ± 0.1
VL02	6.9 ± 0.1	−13.5 ± 0.1	−4.0 ± 0.1
VL03	6.2 ± 0.1	−14.2 ± 0.1	−5.8 ± 0.1
VL04	8.2 ± 0.1	−12.9 ± 0.1	−2.4 ± 0.1
VL05	6.8 ± 0.1	−13.2 ± 0.1	−4.9 ± 0.1
VL06	5.8 ± 0.1	−13.2 ± 0.1	−4.5 ± 0.1
VL07	6.7 ± 0.1	−12.5 ± 0.1	−7.1 ± 0.1
VL08	5.3 ± 0.1	−13.8 ± 0.1	−6.6 ± 0.1
VL09	5.8 ± 0.1	−14.1 ± 0.1	−6.6 ± 0.1
VL10	5.5 ± 0.1	−13.8 ± 0.1	−7.1 ± 0.1
VL11	5.8 ± 0.1	−13.3 ± 0.1	−4.3 ± 0.1
VL12	5.9 ± 0.1	−13.6 ± 0.1	−7.4 ± 0.1
VL13	6.2 ± 0.1	−12.6 ± 0.1	−4.8 ± 0.1
VL14	7.0 ± 0.1	−14.5 ± 0.1	−3.6 ± 0.1
VL15	7.2 ± 0.1	−11.0 ± 0.1	−5.8 ± 0.1
VL16	5.4 ± 0.1	−14.5 ± 0.1	−5.5 ± 0.1
VL17	6.2 ± 0.1	−11.8 ± 0.1	−6.3 ± 0.1
VL18	6.9 ± 0.1	−11.7 ± 0.1	−6.2 ± 0.1
VL19	4.6 ± 0.1	−11.3 ± 0.1	−5.0 ± 0.1
VL20	7.1 ± 0.1	−16.5 ± 0.1	−8.0 ± 0.3
VL21	7.6 ± 0.1	−6.7 ± 0.1	−7.1 ± 0.1
VL22	6.9 ± 0.1	−15.4 ± 0.1	−6.1 ± 0.1
VL23	6.3 ± 0.1	−14.7 ± 0.1	−6.2 ± 0.1
VL27	11.6 ± 0.1	−14.0 ± 0.1	−7.6 ± 0.2
VL29	4.9 ± 0.1	−15.0 ± 0.1	−10.0 ± 0.1
VL30	4.4 ± 0.1	−14.5 ± 0.1	−7.9 ± 0.1
VL32	6.6 ± 0.1	−15.3 ± 0.1	−6.2 ± 0.1

from IGS/IERS 1992 standards (McCarthy, 1996). In particular, the tidal model that was used to take into account displacements of station coordinates originated by tides is the IERS/IGS standard model for diurnal, semi-diurnal and ter-diurnal earth tides (McCarthy, 1996). Finally, concerning pole tide corrections, the IERS standard model was adopted (McCarthy, 1996); pole tides affects station coordinates and pole tide model was also used during the GLOBK run (King & Bock, 2000; Herring et al., 2006).

Post-fit residuals were screened by means of an AUTomatic CLeaNing tool (AUTCLN) which is applied with the purpose to repair cycle-slips and eliminate outliers.

5.2.3.1 Data Combination, Stabilization and Computation of Velocity Field

VLNDEF solutions described in Sect. (5.2.3) were combined with the global solutions computed by SOPAC for the IGS global network stations using the GLRED tool of GLOBK package, treating them as quasi-observations (Dong et al., 1998).

A distributed session approach by means of sequential Kalman filtering procedures was followed, in order to preserve the uniformity of the reference frame definition and to reduce CPU usage (Hudnut et al., 1996; Dong et al., 1998; Mazzotti et al., 2003; Serpelloni et al., 2006). During the quasi-observation combination process, the goodness of fit of the model was estimated with the reduced Chi-Square estimator, whose values were always smaller than 2.

Adjusted coordinates and velocities were translated into ITRF2000, constraining positions and velocities of 54 stations belonging to the IGS Global Permanent Network and provided by SOPAC ftp site (ftp://lox.ucsd.edu) and obtaining the results shown in Tables 7 and 8, respectively.

Horizontal absolute velocities expressed in the local geodetic frame are shown in Fig. 11.

The overall Weighted Root Mean Square (WRMS) of the estimated stabilized station positions is between 1 and 2 mm for horizontal coordinates and 4–5 mm for

Table 7 ITRF2000 adjusted coordinates of VLNDEF network sites (epoch 2003.0) obtained with Globk, after the stabilisation process of 1999–2006 GPS episodic campaigns

	X (m)	Y (m)	Z (m)
TNB1 66036M001	−1623858.4330 ± 0.0004	462478.1236 ± 0.0004	−6130048.9910 ± 0.0010
VL01	−1898355.0800 ± 0.0007	344131.5863 ± 0.0006	−6059589.6060 ± 0.0016
VL02	−1871176.6890 ± 0.0008	419007.1132 ± 0.0007	−6064822.2280 ± 0.0020
VL03	−1793824.6430 ± 0.0007	550947.6454 ± 0.0006	−6077986.3050 ± 0.0018
VL04	−1786676.3870 ± 0.0010	323127.1064 ± 0.0008	−6095659.6060 ± 0.0026
VL05	−1833378.6500 ± 0.0004	336084.8323 ± 0.0004	−6079754.0680 ± 0.0010
VL06	−1665381.7120 ± 0.0006	455889.0620 ± 0.0005	−6122163.3580 ± 0.0015
VL07	−1731871.0240 ± 0.0006	451786.7872 ± 0.0005	−6103456.3830 ± 0.0017
VL08	−1717947.9210 ± 0.0008	501076.6108 ± 0.0006	−6104184.8650 ± 0.0022
VL09	−1747656.6850 ± 0.0008	562141.0966 ± 0.0006	−6090108.2550 ± 0.0024
VL10	−1716963.1570 ± 0.0006	532520.4202 ± 0.0004	−6101777.8110 ± 0.0012
VL11	−1644838.3660 ± 0.0006	517300.7526 ± 0.0005	−6122511.0520 ± 0.0019
VL12	−1870330.3750 ± 0.0005	545966.3580 ± 0.0004	−6054921.0880 ± 0.0011
VL13	−1592717.3230 ± 0.0009	511213.2602 ± 0.0007	−6135756.5370 ± 0.0029
VL14	−1791154.8190 ± 0.0005	449717.6398 ± 0.0004	−6086636.3350 ± 0.0011
VL15	−1596323.9990 ± 0.0008	466324.0257 ± 0.0007	−6136835.4870 ± 0.0026
VL16	−1555858.1900 ± 0.0006	489202.5783 ± 0.0005	−6145734.3440 ± 0.0018
VL17	−1561179.2630 ± 0.0007	521189.6953 ± 0.0006	−6142166.0410 ± 0.0018
VL18	−1487512.5310 ± 0.0007	466337.4738 ± 0.0006	−6164019.9360 ± 0.0024
VL19	−1490548.0460 ± 0.0006	490597.3336 ± 0.0006	−6162196.0300 ± 0.0018
VL20	−1909089.5270 ± 0.0026	677740.0542 ± 0.0023	−6029108.8750 ± 0.0052
VL21	−1932100.1100 ± 0.0009	563780.2380 ± 0.0007	−6033962.4280 ± 0.0023
VL22	−1938968.3240 ± 0.0009	628496.5050 ± 0.0007	−6023703.1720 ± 0.0023
VL23	−2017366.1650 ± 0.0010	344665.3744 ± 0.0008	−6021793.9340 ± 0.0020
VL27	−1999402.0870 ± 0.0029	432212.5283 ± 0.0024	−6022817.4420 ± 0.0062
VL29	−1985915.1840 ± 0.0009	573344.5532 ± 0.0006	−6015394.1980 ± 0.0021
VL30	−2027440.4130 ± 0.0012	638271.5411 ± 0.0009	−5994964.3110 ± 0.0028
VL32	−1947613.4120 ± 0.0006	479657.0799 ± 0.0005	−6036111.4620 ± 0.0016

Table 8 Absolute velocity components of VLNDEF sites expressed into ITRF2000, estimated with Globk

	V_x (mm/yr)	V_y (mm/yr)	V_z (mm/yr)
TNB1 66036M001	7.3 ± 0.5	−12.5 ± 05	−4.5 ± 0.7
VL01	7.6 ± 0.7	−13.8 ± 0.6	−2.5 ± 1.1
VL02	6.5 ± 0.6	−12.2 ± 0.6	−2.4 ± 1.2
VL03	6.0 ± 0.6	−13.1 ± 0.6	−4.3 ± 1.1
VL04	7.8 ± 1.0	−10.9 ± 0.8	−2.8 ± 2.1
VL05	8.3 ± 0.7	−12.7 ± 0.6	−0.8 ± 1.0
VL06	5.3 ± 0.7	−11.0 ± 0.7	−5.0 ± 1.5
VL07	8.5 ± 0.6	−11.6 ± 0.5	−1.1 ± 1.1
VL08	6.0 ± 0.6	−12.8 ± 0.6	−4.2 ± 1.4
VL09	6.2 ± 0.6	−12.8 ± 0.6	−4.8 ± 1.3
VL10	5.6 ± 0.6	−12.9 ± 0.6	−4.8 ± 1.1
VL11	6.1 ± 0.7	−12.2 ± 0.6	−1.0 ± 1.4
VL12	7.4 ± 0.6	−11.9. ± 0.6	−4.9 ± 1.0
VL13	5.7 ± 0.7	−11.6 ± 0.6	−3.9 ± 1.6
VL14	7.6 ± 0.6	−13.4 ± 0.5	−0.4 ± 1.0
VL15	6.8 ± 0.7	−10.0 ± 0.6	−4.0 ± 1.5
VL16	5.7 ± 0.6	−13.2 ± 0.6	−4.4 ± 1.3
VL17	6.3 ± 0.6	−9.8 ± 0.6	−6.3 ± 1.3
VL18	7.6 ± 0.7	−10.8 ± 0.6	−5.2 ± 1.6
VL19	4.8 ± 0.7	−10.0 ± 0.6	−4.1 ± 1.5
VL20	7.5 ± 2.0	−15.1 ± 1.5	−6.6 ± 5.1
VL21	8.4 ± 0.7	−5.5 ± 0.6	−6.0 ± 1.6
VL22	6.3 ± 0.7	−13.9 ± 0.6	−5.1 ± 1.3
VL23	7.4 ± 1.0	−13.8 ± 0.9	−4.5 ± 1.8
VL27	12.2 ± 2.6	−14.0 ± 1.6	−2.0 ± 6.3
VL29	5.3 ± 0.8	−13.7 ± 0.6	−8.7 ± 1.6
VL30	5.0 ± 0.8	−12.8 ± 0.6	−5.2 ± 1.6
VL32	7.2 ± 0.7	−14.1 ± 0.6	−4.3 ± 1.4

heights, depending on the number of daily sessions (varying between 5 and 10) and their duration.

GPS data error spectra are spatially correlated due to common orbital, earth rotational and regional atmospheric errors (Shen et al., 2000). In order to evaluate these effects, coordinates' time series were interactively edited using Tom Herring Matlab Utilities (Herring et al., 2006); outliers and discontinuities were evaluated along with time series common mode errors, seasonal signals and site per site Weighted Root Mean Square (WRMS). GPS time series' noise can be represented as a combination of white, flicker and random walk functions (Mao et al., 1999; Dixon et al., 2000; Mazzotti et al., 2003). Provided that a sufficiently large amount of data is given, the WRMS of the site coordinate time series is well correlated with the amount of white and colored noise. VLNDEF quasi-observations were re-weighted taking into account the WRMS of site coordinates time series.

5.2.4 Estimation of VLNDEF Sites' Positions Using the Gipsy/Oasis II PPP Approach

VLNDEF observations were processed with the PPP approach described in Sect. (5.2.1), with a c-shell scripting especially realized to achieve automatic data processing.

GPS daily sessions were processed independently; every solution was treated as part of a time series, from which positions (Table 9) and velocities (Table 10) were estimated.

The absolute velocities shown in Table 10, transformed and expressed into the local geodetic frame, are shown in Fig. 11; this latter figure also shows the estimated horizontal velocities obtained in Sects. (5.2.1) and (5.2.3).

Table 9 Positions of VLNDEF sites estimated with Gipsy/Oasis II software and expressed into ITRF2000 (epoch 2003.0)

	X (m)	Y (m)	Z (m)
TNB1 66036M001	−1623858.4378 ± 0.0002	462478.1111 ± 0.0002	−6130048.9959 ± 0.0005
VL01	−1898355.0857 ± 0.0003	344131.5745 ± 0.0003	−6059589.5989 ± 0.0008
VL02	−1871176.7022 ± 0.0004	419007.1021 ± 0.0003	−6064822.2633 ± 0.0009
VL03	−1793824.6495 ± 0.0005	550947.6313 ± 0.0004	−6077986.3151 ± 0.0011
VL04	−1786676.3936 ± 0.0011	323127.1006 ± 0.0009	−6095659.5932 ± 0.0026
VL05	−1833378.6580 ± 0.0003	336084.8160 ± 0.0003	−6079754.0701 ± 0.0008
VL06	−1665381.7196 ± 0.0007	455889.0539 ± 0.0006	−6122163.3506 ± 0.0017
VL07	−1731871.0292 ± 0.0005	451786.7774 ± 0.0004	−6103456.3973 ± 0.0012
VL08	−1717947.9246 ± 0.0006	501076.5988 ± 0.0006	−6104184.8703 ± 0.0016
VL09	−1747656.6869 ± 0.0005	562141.0847 ± 0.0005	−6090108.2575 ± 0.0012
VL10	−1716963.1666 ± 0.0007	532520.4080 ± 0.0006	−6101777.8046 ± 0.0016
VL11	−1644838.3713 ± 0.0007	517300.7426 ± 0.0006	−6122511.0562 ± 0.0018
VL12	−1870330.3822 ± 0.0003	545966.3461 ± 0.0003	−6054921.0899 ± 0.0008
VL13	−1592717.3281 ± 0.0006	511213.2483 ± 0.0005	−6135756.5400 ± 0.0015
VL14	−1791154.8304 ± 0.0005	449717.6299 ± 0.0005	−6086636.3306 ± 0.0013
VL15	−1596324.0039 ± 0.0006	466324.0145 ± 0.0005	−6136835.4869 ± 0.0015
VL16	−1555858.1967 ± 0.0005	489202.5655 ± 0.0005	−6145734.3474 ± 0.0015
VL17	−1561179.2733 ± 0.0006	521189.6925 ± 0.0005	−6142166.0424 ± 0.0015
VL18	−1487512.5365 ± 0.0006	466337.4638 ± 0.0006	−6164019.9389 ± 0.0017
VL19	−1490548.0516 ± 0.0007	490597.3276 ± 0.0006	−6162196.0308 ± 0.0019
VL20	−1909089.5387 ± 0.0015	677740.0379 ± 0.0014	−6029108.8760 ± 0.0035
VL21	−1932100.1119 ± 0.0008	563780.2237 ± 0.0008	−6033962.4288 ± 0.0019
VL22	−1938968.3420 ± 0.0006	628496.4951 ± 0.0006	−6023703.2235 ± 0.0014
VL23	−2017366.1762 ± 0.0014	344665.3665 ± 0.0012	−6021793.9336 ± 0.0032
VL27	−1999402.0914 ± 0.0011	432212.5133 ± 0.0010	−6022817.4345 ± 0.0025
VL29	−1985915.1915 ± 0.0008	573344.5385 ± 0.0007	−6015394.2060 ± 0.0018
VL30	−2027440.4214 ± 0.0009	638271.5284 ± 0.0008	−5994964.3107 ± 0.0020
VL32	−1947613.4191 ± 0.0006	479657.0635 ± 0.0006	−6036111.4637 ± 0.0015

Table 10 Components of absolute velocities of VLNDEF sites expressed into ITRF2000, estimated with Gipsy/Oasis

	V_x (mm/yr)	V_y (mm/yr)	V_z (mm/yr)
TNB1 66036M001	7.1 ± 0.1	−14.0 ± 0.1	−14.0 ± 0.2
VL01	6.7 ± 0.2	−16.1 ± 0.2	−16.1 ± 0.5
VL02	7.5 ± 0.2	−14.1 ± 0.2	−14.1 ± 0.4
VL03	6.2 ± 0.2	−14.9 ± 0.2	−14.9 ± 0.4
VL04	7.6 ± 0.6	−15.7 ± 0.5	−15.7 ± 1.4
VL05	10.0 ± 0.1	−12.4 ± 0.1	−12.4 ± 0.4
VL06	6.5 ± 0.3	−14.3 ± 0.3	−14.3 ± 0.8
VL07	7.9 ± 0.2	−13.1 ± 0.2	−13.1 ± 0.5
VL08	4.6 ± 0.2	−14.9 ± 0.2	−14.9 ± 0.6
VL09	5.3 ± 0.2	−14.3 ± 0.2	−14.3 ± 0.5
VL10	8.1 ± 0.3	−13.9 ± 0.2	−13.9 ± 0.7
VL11	5.9 ± 0.2	−14.4 ± 0.2	−14.4 ± 0.6
VL12	8.2 ± 0.1	−13.4 ± 0.1	−13.4 ± 0.4
VL13	5.8 ± 0.2	−12.8 ± 0.2	−12.8 ± 0.6
VL14	10.4 ± 0.2	−14.8 ± 0.2	−14.8 ± 0.6
VL15	6.6 ± 0.2	−11.7 ± 0.2	−11.7 ± 0.7
VL16	5.9 ± 0.2	−15.0 ± 0.2	−15.0 ± 0.6
VL17	7.6 ± 0.3	−14.7 ± 0.2	−14.7 ± 0.7
VL18	7.8 ± 0.2	−12.9 ± 0.2	−12.9 ± 0.7
VL19	4.7 ± 0.3	−13.4 ± 0.3	−13.4 ± 0.9
VL20	6.2 ± 0.9	−15.6 ± 0.9	−15.6 ± 2.0
VL21	7.5 ± 0.3	−6.6 ± 0.3	−6.6 ± 0.7
VL22	9.1 ± 0.2	−16.1 ± 0.2	−16.1 ± 0.6
VL23	8.0 ± 0.7	−17.8 ± 0.6	−17.8 ± 1.6
VL27	14.7 ± 1.0	−10.9 ± 1.0	−10.9 ± 2.4
VL29	6.6 ± 0.3	−15.2 ± 0.3	−15.2 ± 0.7
VL30	7.0 ± 0.4	−14.5 ± 0.3	−14.5 ± 0.8
VL32	7.7 ± 0.2	−15.6 ± 0.2	−15.6 ± 0.6

6 Combination of Results and Discussion

In order to compare the consistency of the solutions that were estimated adopting the four different approaches described in Sect. 5.2, a Helmert transformation between the results of Table 5 (derived with Bernese in Sect. 5.2.2) and the results of Table 3, Table 7 and Table 9 was performed. The transformation's residuals are shown in Table 11.

All the approaches that were adopted give similar results, both in terms of absolute and relative values. The comparison of the different solutions highlights biases that affect only a few points.

- Bernese (Sect. 5.2.2) vs. Gipsy: East and North components are similar while larger differences can be observed in the Up component. Two anomalous values

Table 11 Helmert transformation's residuals between the different solutions of Sect. 5.2.

	Gipsy/Oasis II (cf. Table 9)			Gamit/Globk (cf. Table 7)			Bernese (Sect. 5.2.1) (cf. Table 3)		
	ΔN (mm)	ΔE (mm)	ΔU (mm)	ΔN (mm)	ΔE (mm)	ΔU (mm)	ΔN (mm)	ΔE (mm)	ΔU (mm)
TNB1	−0.9	−1.2	0.8	−1.0	12.6	5.9	0.4	6.2	11.5
VL01	−4.0	−0.4	6.1	1.9	11.5	0.6	0.8	5.8	10.7
VL02	6.1	−1.1	−35.8	5.5	12.5	0.7	−0.3	5.8	10.4
VL03	2.9	−2.2	−10.6	1.5	12.9	−0.6	−0.4	6.0	9.3
VL04	−5.4	2.8	13.0	4.0	8.9	2.2	2.4	5.0	10.1
VL05	−4.0	−4.2	−8.5	0.2	13.0	−5.2	1.2	5.8	9.8
VL06	−5.1	−1.1	3.8	2.2	8.8	−1.5	0.0	5.9	9.4
VL07	2.6	−1.5	−14.9	0.9	9.5	−0.8	0.2	4.9	9.4
VL08	3.1	0.0	−10.6	2.1	12.6	−5.6	0.7	6.2	9.6
VL09	4.1	0.6	−7.1	1.6	12.6	−4.8	0.5	6.3	9.5
VL10	−7.5	−2.7	6.2	0.0	11.7	2.1	0.3	6.0	7.4
VL11	1.6	1.3	−15.1	2.3	12.3	10.8	0.7	6.3	9.5
VL12	−3.5	−4.3	−2.2	−0.9	9.2	0.8	0.5	6.2	9.6
VL13	2.8	−0.6	−5.5	3.1	12.3	−2.3	1.1	5.3	9.6
VL14	−7.3	−0.7	−0.1	1.7	11.6	−1.6	0.0	5.8	9.4
VL15	2.5	−2.6	−2.4	3.9	10.3	−2.1	1.2	5.2	9.6
VL16	−1.2	−1.9	−5.5	1.0	11.7	−1.8	0.2	6.0	8.3
VL17	−5.8	2.2	−1.5	2.2	8.2	1.6	0.4	5.1	8.4
VL18	0.0	−0.3	−4.1	1.0	10.7	−0.8	0.7	6.3	10.5
VL19	−2.3	3.2	−3.7	1.1	10.7	−1.8	0.0	5.1	10.3
VL20	−5.9	−8.3	0.1	−0.5	10.8	3.0	−1.2	6.1	10.1
VL21	1.8	−0.4	1.6	−0.4	13.6	2.0	0.1	6.2	10.6
VL22	4.6	−2.1	−54.4	1.3	13.0	−0.6	0.2	6.3	9.6
VL23	−8.1	2.4	−5.9	1.1	11.2	−2.8	0.7	5.8	10.8
VL27	−2.4	−5.3	4.5	0.5	10.2	−1.9	1.0	5.0	9.8
VL29	1.0	−3.7	−9.2	1.7	12.9	−0.5	0.3	6.2	9.6
VL30	−1.8	−2.8	−1.7	1.7	12.0	−0.5	0.4	5.3	9.7
VL32	0.0	−4.4	−3.2	2.2	12.8	−0.3	0.7	6.1	9.7
Mean	4.2	3.0	14.3	2.1	11.7	3.3	0.8	5.9	9.9

are found for a couple of points (VL02, VL22); these discrepancies must be understood and investigated further;

- Bernese (Sect. 5.2.2) vs. Gamit: the two solutions are in good agreement with respect to North and Up components; an exception is found for VL11. A systematic bias of one cm is found in the East component;
- Bernese (Sect. 5.2.2) vs. Bernese (Sect. 5.2.1): a constant bias of about one cm is found in the Up component, while a bias of half this value is found in the East component. These biases are probably originated by the initial values of the stations velocities used to constrain the final adjustment.

A formal inversion procedure was applied to the absolute velocity field obtained by means of the processing approaches described in Sects. (5.2.2) and (5.2.3) aiming at deriving the site relative velocities in a robust stable reference frame (Antarctic

Plate) (Argus & Gordon, 1991; DeMets et al., 1994; Altamimi et al., 2002). The relevant Euler Vector of the Nuvel-1A NNR global plate model relating stable Antarctic Plate ANTA to ITRF2000 (Altamimi et al., 2002) was applied; this procedure enabled a removal of the inherently rigid body rotation generally associated with a geodetic reference frame. This approach permitted to reduce the residual horizontal velocities of TNB1 and MCM4 sites to about some tenth of millimetres: this result highlights the consistency between the global reference frame and frame defined within the approaches described in Sects. (5.2.2) and (5.2.3) and adopted for solving the position and velocity of all VLNDEF sites.

A serious limiting factor that prevents the most accurate determination of the movements undergoing in NVL is originated by the lack of permanent remote GPS stations within VLNDEF. As it has been clearly stated before, all deformation results are obtained from episodic campaigns of ever increasing duration, with performances of increasing precision but not comparable to those achievable with permanent GPS stations. An optimal exploitation of the network is therefore tightly connected to the establishment of new remote observing permanent sites.

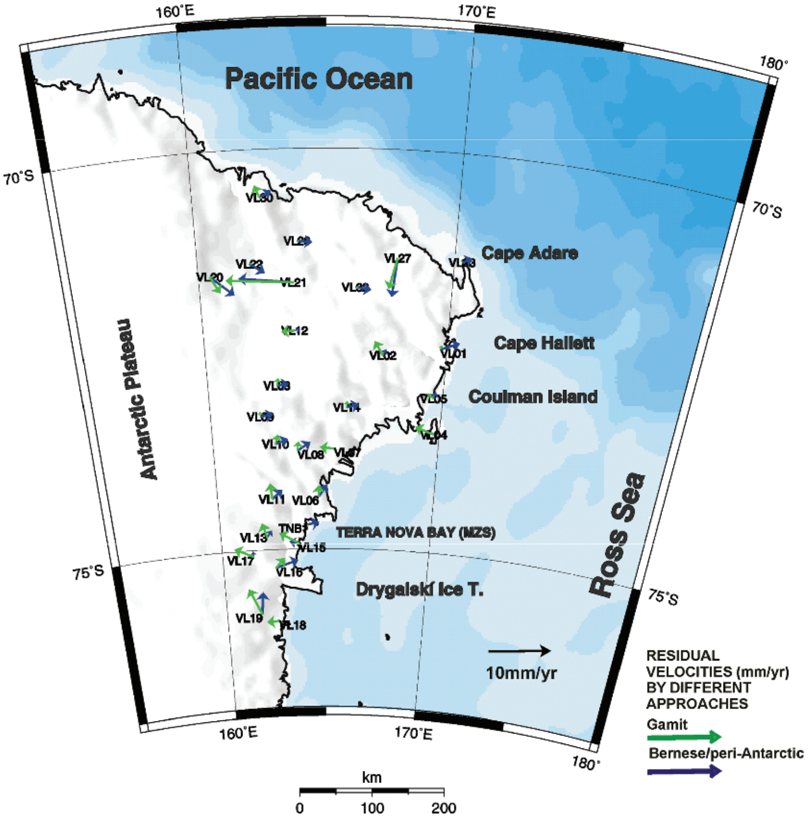

Fig. 12 Residual velocities obtained with Gamit/Globk (*green arrows*) and Bernese (*dark blue arrows*) after removal of the rigid clockwise Antarctic Plate rotation associated with the ITRF2000 reference frame

Relative horizontal velocities shown in Fig. 12 are very small and, within their own 95% confidence interval, do not highlight evident movements. The only exception is represented by the velocity of VL21, whose origin and magnitude are uncertain and should be further investigated.

Vertical velocities shown in Fig. 13 highlight a generalized positive trend of 2/3 mm/yr (1–2 in the Globk solution); this behaviour is particularly evident for the continental stations, being the estimated velocity increasing from the coast towards the Antarctic Plateau; a similar pattern of such vertical rates was already obtained by the processing of GPS data acquired up to the year 2003 (Capra et al., 2007).

The magnitude of the uplift is almost entirely consistent with most of the GIA models that are nowadays proposed to describe the vertical movements of NVL (Ivins et al., 2003, 2005); nevertheless, the uncertainties associated with our geodetic estimates are too large to draw any quantitative and final conclusion on the matter. According to most authors (Nakada et al., 2000; Hamilton et al., 2001;

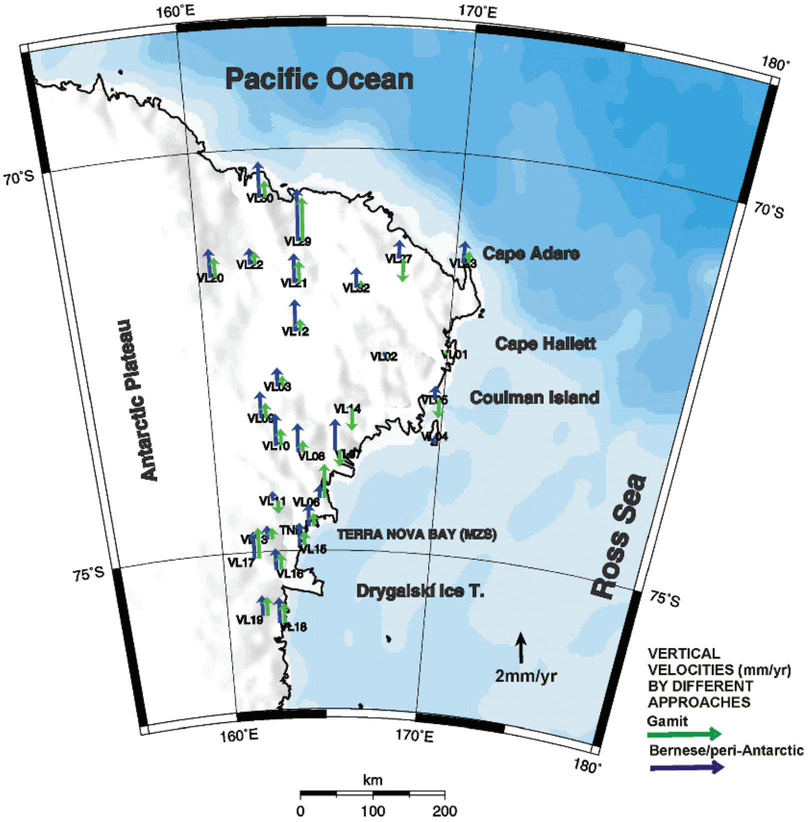

Fig. 13 Vertical velocities obtained with Gamit/Globk (*green arrows*) and Bernese (*dark blue arrows*)

Donnellan, 2004; Raymond et al., 2004; Ohzono et al., 2006), the Antarctic plate behaves as a coherent and rigid plate and our results, even if on a smaller area, are consistent with these conclusions.

This work demonstrates how geodetic Antarctic facilities, such as TNB1 and VLNDEF, can contribute to geosciences investigations in remote regions. Each facility needs special handling, management and maintenance and suitable processing strategies have to be identified, applied and evaluated.

Geodetic results are obtained testing different analysis approaches and processing tools and are framed within a wider scientific scenario, where geodynamics as well as neotectonics are the evaluating background and touchstone.

Therefore, the Italian geodetic infrastructures can be regarded as useful tools for the entire Antarctic scientific community as well as for global geosciences and their maintenance and their exploitation has to be planned, realized and performed as part of a wide, international scientific action.

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