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ORIGINAL ARTICLE

A PPP kinematic application on historical GPS data: the reprocessing of the ITASE98-99 Antarctica mission height profiles

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Abstract

The analysis of altimetric profiles in Antarctica and their evolution over the years is a sensitive topic for the scientific community since it helps understand the effects of climate change that the continent undergoes. Different geomatic techniques, including the GNSS technology, can be employed to obtain altimetric profiles. However, the GNSS differenced approaches, such as the Post Processing Kinematic, are hardly usable to define long profiles in Antarctica because of the low number of CORS stations. In these conditions, the Precise Point Positioning (PPP) approach is a valid alternative to avoid processing very long baselines. The aim of this article is to define a standard procedure for the processing of historical GPS data, thanks to the availability of a dataset from the International Trans-Antarctic Scientific Expedition, which took place between 1998 and 1999 (*ITASE98-99*). This expedition focused on mapping the Antarctic territory, subdividing it by nations of influence, using geophysical and geodetic technologies, including GPS. The altimetric profiles had already been calculated in 2002 by the Geomatics group of the University of Bologna using the Gipsy-OASIS II software. In this work, the new version of the JPL software, GipsyX, is used to apply the newly implemented models and reprocessed products. The calibration of the processing parameters leading to the final PPP solution is described in the paper, including details on the implementation of a post-processing filtering procedure. The average a posteriori elevation error is 4.6 cm, while 99% of them are within 27 cm. The comparison of the new results to both the previous processing and the REMA elevation model shown that about double the number of solutions are now available, meter-level elevation spikes have been avoided, and a half meter bias is now reduced to a few centimeters. Given the almost 15 years difference between the 1999.0 expedition epoch and the REMA reference epoch, the obtained results can be used to study accumulation/erosion effects on the Antarctica ice sheet.

Keywords GPS · Precise point positioning · GipsyX · Antarctica · Altimetric profiles · Digital elevation model REMA

Introduction

The *ITASE98-99* expedition was carried out in 1998 as part of a project (the International Trans-Antarctic Scientific Expedition (Vittuari et al. 2004), with the aim of studying the paleoclimate of the Antarctic continent. The activities involved ice core, geotechnical and geophysical investigations, and determining the altimetric profiles based on data acquired from several GPS (Spilker Jr. et al. 1996) receivers mounted on moving tracked vehicles. The paper focuses on the computation and analysis of the altimetric profiles (Mayewski et al. 2005) related to the Italian-French expedition (Fig. 1).

Given the size of the Antarctic continent, the very low density of permanent GNSS reference stations, and the impossibility of having stable benchmarks, the computation of kinematic baselines between a reference receiver and rover receivers is made difficult by distance separations that are often very long. In particular, in year 1998, 7 GPS permanent stations were located on the Antarctic continent (CAS1, DAV1, MAW1, MCM4, OHIG, SYOG, VESL) (Negusini et al. 2005). The MCM4 station is the closest to the *ITASE98-99* path, with a distance ranging from 330 to 1150 km. To overcome these limitations, the most appropriate data processing method was identified as the

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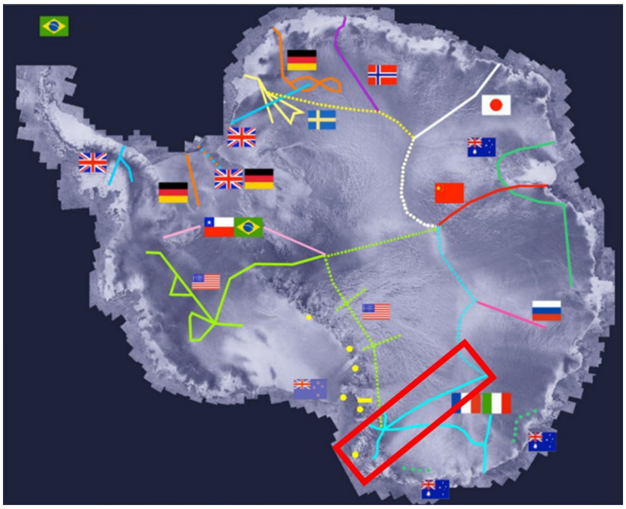

Fig. 1 Antarctica map showing areas of influence of different national scientific programs (Mayewski et al. 2005). The red box indicates the area covered by the Italian-French ITASE98-99 expedition

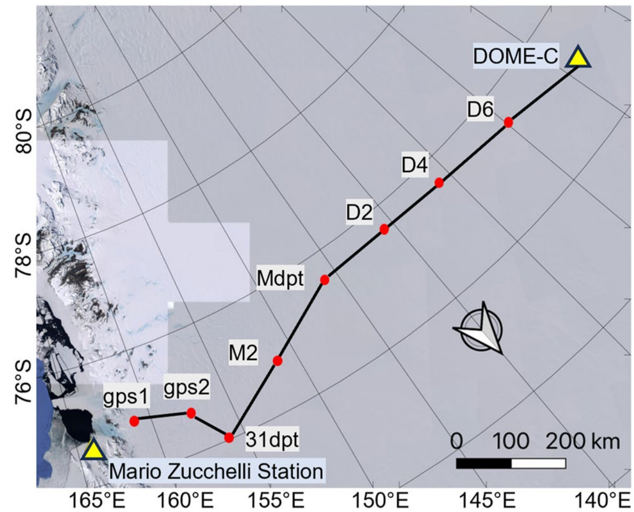

Fig. 2 Details of the track of the Italian mission connecting the starting point (gps1) on the plateau close to the M. Zucchelli station, and the Concordia station (DOME-C)

Precise Point Positioning (PPP) in kinematic mode(Geng et al. 2010; Zumberge et al. 1997).At the time of the expedition, the Gipsy-OASIS II (Webb and Zumberge 1997) software developed by the Jet Propulsion Laboratory of NASA (USA) was the only scientific package implementing the PPP approach. Indeed, this software was employed for the first processing of the acquired dataset carried out by the Geomatics group of the *DICAM* Department of the University of Bologna in 2002. Since then, the evolution in the calculation of the ancillary parameters and correction models typical of the PPP approach (EOP, tides, atmospheric corrections, satellites clocks and bias corrections) (Kouba and Héroux 2001), together with algorithms enabling phase ambiguity fixing (Bertiger et al. 2010; Ge et al. 2008), have resulted in an improvement in the accuracy of PPP. In addition, a new version of the JPL software, GipsyX (Bertiger et al. 2020), has been developed and made available to the research community.

This work describes the reprocessing of the dataset from the ITASE98-99 expedition, focusing on the altimetric component and the analysis of the differences with the old solutions generated by the previous software version, highlighting the impact of 21 years of PPP model and algorithm improvements. The article presents a detailed analysis of the GipsyX package for kinematic processing, including a discussion about the most suitable parameters, the different models, and the best strategies to use. Moreover, a post-analysis strategy is described for the identification of the outlier solutions to filter the altitude profiles, thus obtaining reliable estimates of the height of the Antarctica surface along the mission track. Finally, the two PPP solutions are compared with the REMA (Reference Elevation Model Antarctica) Digital Elevation Model (Howat et al. 2019) in order to assess their reliability in describing the geomorphology of the surveyed area. In addition, some evaluations of the climatic evolution of the area are presented, based on the comparison between the GPS-derived heights and the REMA ones, which are related to the epoch of 2014.

Dataset and materials

Different countries have been involved in the international expedition ITASE98-99, covering different areas of the Antarctic territory, as shown in Fig. 2. The paper focuses on the data acquired by the Italian-French expedition concerning the trajectory connecting the stations *Mario Zucchelli* (near Terra Nova Bay) and *Concordia* (Dome-C). The entire route from Zucchelli to Concordia Stations includes a portion of territory approximately 1200 km long with an overall height difference of about 2000 m, surveyed using several tracked vehicles that followed almost the same trajectory. Due to the long distances involved, the trajectory has been divided into several spans, with a series of stops where other glaciological and geodetic investigations have been carried out (Frezzotti and Flora 2002).

The analyzed dataset comes from three GPS receivers mounted on two vehicles. Two receivers, hereafter called ITK1 and ITK2, were mounted on the same vehicle and rigidly connected to each other (Fig. 3a), while the third station was mounted on a second vehicle, and will be called ITR1 (Fig. 3b). All antennas were Trimble model T4000ST, the ITK receivers were Trimble 4000SSE, while model Trimble 4000SSI was used for ITR1. The dataset consists of 25 RINEX

Fig. 3 Vehicles carrying the two ITK1 and ITK2 antennas (**a**) and the ITR1 antenna (**b**)

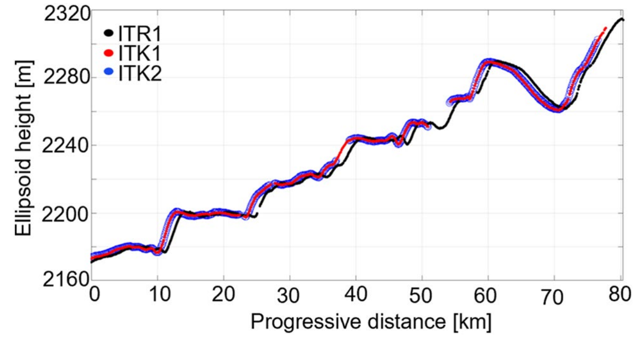

Fig. 4 Height profiles from the old Gipsy-OASIS II solution as a function of the progressive track distance. Detail of the 31dpt—M2 section

files generated by ITK1, 22 by ITK2 and 18 acquired from ITR1, for a total of 65 files. All files contain dual-frequency (L1 and L2) GPS carrier phase and pseudo-range measurements, and were provided in format RINEX 2.11.

The REMA DEM has been used to estimate height evolution after almost 15 years since the GPS surveys (https://www.pgc.umn.edu/data/rema/). REMA is a high-resolution high-quality map that covers about 95% of Antarctica. The height model results from the combination of different imagery sources, collected over a period of several years (2007–2014), under different seasonal conditions. The REMA mosaic version2, at 2-m resolution has been chosen, which is available as 50 km × 50 km tiles in the Geotiff raster format. The elevation model has been built from thousands of individual stereoscopic DEMs at high spatial resolution (2 m). Each individual DEM was vertically registered to satellite altimetry measurements from CryoSat-2 and ICESat (Ice, Cloud, and land Elevation Satellite), resulting in estimated absolute height uncertainties of less than 1 m, and relative uncertainties at the decimeter-level (Howat et al. 2019).

Historical data computation using Gipsy-OASIS II

The first elevation profile from the ITASE98-99 expedition was analyzed in 2002 by DICAM at the University of Bologna using the Gipsy-OASIS II software. Figure 4 shows an example of the obtained results for a single span of the survey. GPS solutions were computed using JPL Flinn orbits, thus aligning the survey to the ITRF2000 (Altamimi et al. 2002). Even though the receiver data sampling was set to 5 s, the processing was carried out using the 300 s data sampling corresponding to the ephemeris data, since precise orbit interpolation was not possible because "Selective Availability" was still enabled. The Niell Mapping Function (NMF) (Niell 1996, 2001) was used to apply tropospheric corrections and the iono-free linear combination of the observables was exploited to limit the impact on the coordinate solutions of the ionospheric delay.

The coordinate solutions were then interpolated to retrieve a denser profile at 5 s intervals, after having removed spikes due to outlier solutions. Nevertheless, detailed information about that processing is no longer available, making it difficult to discuss certain details about the processing strategies and their impact on the differences found with respect to the new GipsyX computations.

Methods

This section provides a description of the strategies used for the ITASE98-99 reprocessing, focusing on both the GPS data computation and the post-processing strategies used to retrieve a reliable altimetric profile of the track. First, the RINEX files were pre-processed using the TEQC software (Estey and Meertens 1999) to detect the presence of jumps in the receiver clock errors and to fill in (when possible) missing observations. Then several tests were performed to optimize the PPP kinematic computation, and Perl scripts were used to automate the processing.

Kinematic PPP using GipsyX/2.0

As already mentioned, the GipsyX version 2.0 was used for data processing. At the time of the survey (between 1998 and 1999), Selective Availability (SA) was still applied, with noise introduced by the US Department of Defense to prevent precise single-point positioning for non-military users of the GPS service (Adrados et al. 2002; Leick 2000).

A consequence of SA was the impossibility of interpolating satellite clock error data, thus forcing the position computation to be performed at the JPL product sampling rate. Furthermore, since HighRate orbits products were not available for the considered period, the JPL's "Final" products (https://gipsyx.jpl.nasa.gov/index.php?page=data) have been used for the processing, which have 300 s sampling rates.

By default, the *GipsyX* software implements parameters to perform static PPP processing (Gandolfi et al. 2016) based on an extended Kalman filter algorithm. Any change in the default parameters, including the switch to kinematic processing, requires substantial modifications to the main file containing the processing instructions, the so-called *rtgx input tree* (text file). Kinematic processing exploits the same extended Kalman filter algorithm, whose parameter tuning has been the subject of specific tests and studies performed to optimize the processing (Bertiger et al. 2020).

In GipsyX, the python script used to manage the whole data processing is called gd2e.py, which is also defined by an input file called gd2e input tree. The first parameter to be modified to properly manage data acquired in the Antarctica region for kinematic processing is the so-called *SanRMS,* which does a quality control check on the raw observations. Since at Antarctica latitudes the GPS satellite elevations are low, the signal travel path is longer than usual and hence the impact of atmospheric biases increases considerably, it has been necessary to reduce the SanRMS parameter to let the software process as much of the measurement data as possible. According to JPL recommendations, available through the GipsyX user forum, the parameter was changed to the value of − 0.12. Moreover, according to Graffigna et al. (2019),the estimation of the tropospheric asymmetry (ATD) parameters has been eliminated for kinematic applications.

Three sequential computations were carried out starting from the same GPS data to overcome the limited redundancy in the kinematic PPP processing (Li and Zhang 2014). In a first run, the single-point positioning (SPP) solution is computed based on pseudo-range observations, so as to provide a-priori coordinates. This initial step improved dramatically the quality of the final solutions. Then, the *rtgx input tree* is set up to perform two iterations of the PPP processing so as to exploit in the second run the both the estimated coordinates and the wet ZPD obtained from the previous iteration. Further iterations have been tested but have shown negligible variation of the estimated parameters.

Some tests were performed to tune parameters such as the process noise and the weight of the a priori SPP coordinates. Since the SPP kinematic processing dataset had shown significant spikes in the solutions, easily detectable on the height component given the known morphology of the area, which is almost flat, the a priori sigma to be used in the PPP processing related to these coordinates was increased from 10 to 100 m. Actually, the impact of such parameter on the final coordinates is mostly negliegible when two PPP runs are applied in the loop: after testing, only few solutions have height differences at the decimeter level, being te most of the discards under the mm level.

As for the process noise, which has dimensions $\left[\frac{\mathrm{m}}{\sqrt{\mathrm{s}}}\right]$, should be tuned according to the expected speed of the tracked receiver, taking value 1.4 in our case. Anyway, tests were performed to assess the impact of this parameter on a kinematic processing structured in three iterations on a terrestrial vehicle like those used for the expedition: values 0.001, 1, 1.4 and 10 led to the same results. Only applying values like 0.00001, which means almost static conditions, this parameter significantly impacts on the final coordinates. In other words, the algorithm is very flexible and adaptive to the dinamic of a receiver moving at terrestrial speeds, at least when a SPP processing is performed to provide the a priori for the PPP iterations, therefore we chosen to set the process sigma at the value of 1.

Table 1 summarizes the main computation parameters that have been modified with respect to the GipsyX default ones to estimate the GPS coordinates from the expedition dataset.

As for the tropospheric mapping function, tests were performed comparing NMF, GMF (Global Mapping Function) (Niell 1996), and the VMF-1 (Vienna Mapping Function) (Kouba 2008). The average difference in height of the solutions obtained by using GMF and VMF-1 with respect to those given by the NMF are 0.7 mm and 1 mm respectively. Moreover, biases below the tens of mm were found between the everage vaule of all the solutions computed using different mapping function. Such a small impact of the tropospheric mapping function is likely due to the dry environment of the Antarctica reagion due to the low air temperatures. Therefore, to allow a direct comparison with the old results computed using the Gipsy-OASIS II software, the NMF for the troposphere was used.

Corrections for the ocean load cannot be directly applied through gipsy for a kinematic processing. Nevertheless, the impact of such phenomena on the height componenet has been tested on the locations of the start-point and end-point of the traverse, namely gps1 and DOME-C, by retreaving ad hoc parameters of GOT4.8 model from the Chalmers "free ocean tide loading" service (http://holt.oso.chalmers.se/loading/). The maximum amplitude of such tidal effect was found to be 3.4 cm over gps1, closer to the coast, and 2.1 cm at DOME-C. For those applications actually requiring the cm level accuracy, height variations could thus be applied in post-processing to account for the ocean loading effect.

Furthermore, even though GipsyX allows the use of uncombined observations, the ionospheric-free linear combination was used by default in the software. Second-order ionospheric effects were not considered since their impact is negligible for this specific application (Zhang et al. 2020). In all computations, the cut-off GPS satellite elevation angle was fixed at 7°. Finally, PPP ambiguity fixing was enabled

Table 1 GipsyX processing parameters modified from the default values

File/command line	Parameter	Default value	New value	Action
gde.tree	*SanRMS*	3	−0.12	Loosen observations' quality threshold
gd2e.py command line	*−subIterations*	1	2	Enable 2 PPP iterations
rtgx input tree (ppp_0.tree)	Pos (line 184)	ConstantAdj 10	StochasticAdj <A priori *sigma*> <*Process sigma*> GLOBALDATARATE RANDOMWALK	Move from static to kinematic processing
	A priori *sigma* [m]	10	100	Loosen the weight of the a priori coordinates
	Process sigma $\left[\frac{m}{\sqrt{s}}\right]$	–	1	Consider the expected kinematic of the receiver
rtgx input tree (ppp_0.tree)	*Troposphere gradients* (line 202–205)	On	–	Disable the ATD estimation
rtgx input tree (ppp_0.tree)	*OceanLoad* (line 208)	On	Off	Disable the Ocea Load model (mandatory for moving receivers)
rtgx input tree (ppp_0.tree)	*Global/input* (line 100)	Station\..*\.Trop.*	Station\..*	Use both positions and troposphere estimates as a-priori in the subsequent PPP iterations

by using WLPB products (Bertiger et al. 2010). All solutions are inherently aligned to the frame IGS14 by using the JPL "fiducial" orbits available for the expedition' epoch. The main products used for the computation and models implemented in GipsyX are listed in Table 2.

Post-processing strategies

This section describes the strategies used to eliminate outlier solutions and to assess the quality of the coordinate solutions obtained from the PPP processing. Advantage was taken of having two co-located antennas, namely ITK1 and ITK2, on the same vehicle. In this way the relationship between real errors and the 3D formal error output by GipsyX could be used to filter the kinematic solutions. Indeed, the antenna set up shown in Fig. 2a supports the assumption that the ITK1 and ITK2 solutions at common epochs should have very similar elevations and to consider the distance between the two antennas as invariant over time.

The formal error of a kinematic solution is given by GipsyX running the *tdp2llh.py* script, in terms of 3D error, hereafter referred to as σ_{3D}. The full covariance matrix is not available for such kind of processing as it is for the static ones. In a first step, each ITK solution is coupled to a common epoch, thus defining (1) the error in the Up direction as the difference between the two ellipsoid heights, and (2) the planimetric error as the difference in the distance between the two receivers (calculated using Latitude and Longitude values and the known distance between the antennas). In addition, the a-posteriori error of each pair of solutions is computed by applying variance propagation as:

$$\sigma_{ITK} = \sqrt{\sigma^2_{3D,ITK1} + \sigma^2_{3D,ITK2}} \quad (1)$$

Table 2 Products and models implemented in GipsyX and used in computation

Product	Source	File
Orbits	https://sideshow.jpl.nasa.gov/pub/JPL_GNSS_Products/Final/../.	*YYYY-MM-DD.pos.gz*
Clock		*YYYY-MM-DD.tdp.gz*
Bias		*YYYY-MM-DD.wlpb.gz*
Sat. Attitude	Implemented in the default rtgx input tree for GPS	
Rec. antenna calibration	https://sideshow.jpl.nasa.gov/pub/gipsy_files/gipsy_params/etc/antennaCalsGNSS/	igs14_1958.atx
Sat. Antenna calibration		igs14_1958.xyz
Phase center mass correction		igs14_1958.pcm
EOP, Solid and Pole Tides	IERS 2010 conventions (Techincal note 36), Chapter 7	

where $\sigma_{3D,ITK1}$ is the 3D formal error for the ITK1 receiver and $\sigma_{3D,ITK2}$ is the same GipsyX output for ITK2. Then, a threshold value for σ_{ITK} is defined so as to eliminate all the solution pairs having a higher formal error. Given that some blunders indicate errors up to tens of meters can be eliminated by applying a loose threshold on the σ_{3D} of 1 m, Fig. 5 shows some statistics on the real errors as the threshold value for σ_{ITK} varies.

A significant drop in terms of real error can be observed for thresholds lower than 10 cm. However, applying such a filtering value results in the percentage of rejected solutions being above 10%, thus eliminating a significant amount of information from the track profile. 20 cm was therefore considered to be a suitable threshold value of σ_{ITK}, which leads to saving 97.4% of the PPP solutions, which are then characterized by an average real error in the Up direction of 4.6 cm, with 99% of the values within 27 cm, and a maximum error of 40 cm. Moreover, by applying such a threshold 95% of solutions have errors smaller than 13.4 cm. As expected, better results can be observed for the planimetric components. These might have led to a different choice in terms of σ_{ITK} threshold value, but the goal of this work was to provide altimetric profiles of the ITASE98/99 mission, thus the focus was on the height results.

As a consequence, two different strategies to coherently set thresholds for outlier rejection were applied: one suitable for PPP solutions of single receivers, namely the ITR1, or the ITK1/ITK2 solutions, which cannot be coupled at common epochs to compute the real error (5% of the cases), and one to filter the ITK pair of solutions. The PPP solutions from single receivers were filtered by applying a threshold value based on their formal error as:

$$\sigma_{3D} \leq \sqrt{\frac{1}{2}\sigma^2_{ITK,th}} \cong 14 \text{ cm} \tag{2}$$

where $\sigma_{ITK,th}$ is the 20 cm threshold value discussed above. In contrast, for coupled solutions allowing us to compute a real error, it was decided to reject those whose difference in height is greater than 27 cm, which resulted in the rejection of only 1% of solutions (according to Fig. 5). For the remaining pairs of coordinates the average of their ellipsoid height was used as the final result to define the altimetric profile.

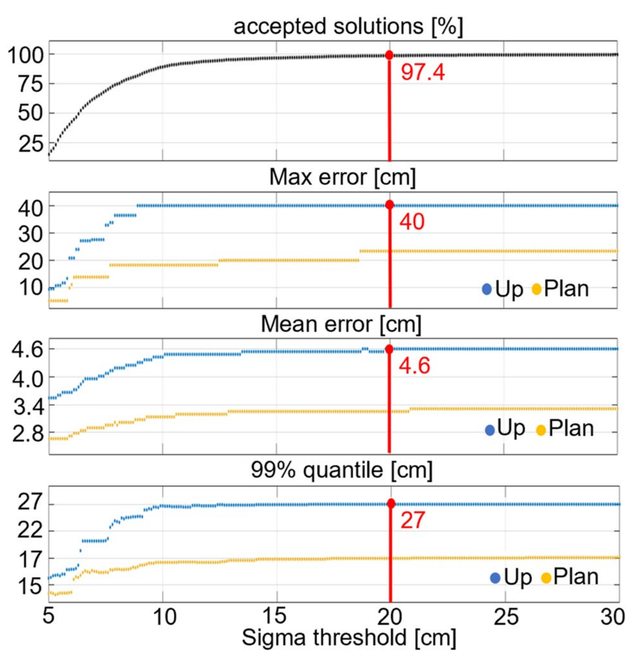

Fig. 5 Statistics on the height errors obtained by comparing ITK1 and ITK2 coordinates as a function of the sigma threshold [cm] used as filtering parameter

Results

In this section, the main numerical results are presented and discussed, providing comparisons between the GipsyX derived altimetry profiles of the ITASE98-99 mission and those computed almost 20 years ago using the GIPSY-OASIS II software, as well as using the REMA elevation model as an external height information source for further comparisons.

The total number of PPP solutions from the GipsyX processing are 1819, 1817 and 1784 for the ITK1, ITK2 and ITR1 receivers, respectively. By applying the above-described filtering process, the percentage of epochs for which the height values were rejected is 1.1% for the profile defined by the vehicle carrying the ITK receivers and 6.3% for ITR1.

Figure 6a, b show the two altimetric profiles expressed in the form of ellipsoid height. These are the main output of the work and indicate a height increase from the starting point, close to the coastline, to the Concordia Station of about 2003 m over a travel path almost 1200 km long. The path is steeper in the initial part, 0.35%, and it flattens in the inner part of the Antarctica Plateau, where the incline is about 0.02%. The density of surveyed points is approximately one every 750 m, based on the assumption that the average speed of the vehicle was almost 8 km/h and the solutions were computed every 300 s. By comparing the two profiles an average height difference of 2 cm can be found, which mainly depends on the fact that the two vehicles ITK and ITR1 did not exactly follow the same path, but it could also be due to small errors in the measurement of the receiver antenna offsets.

The height profiles calculated using the GipsyX software were compared to the old results computed using the GIPSY-OASIS II package. Note that the available old solutions were

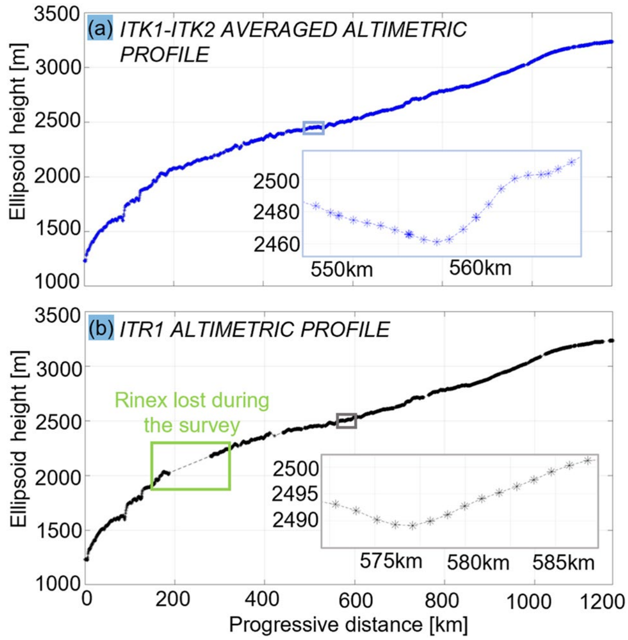

Fig. 6 Height profiles computed by GipsyX from the ITK1-ITK2 (**a**) and the ITR1 (**b**) data. Elevations are expressed as a function of the progressive distances covered by the two vehicles

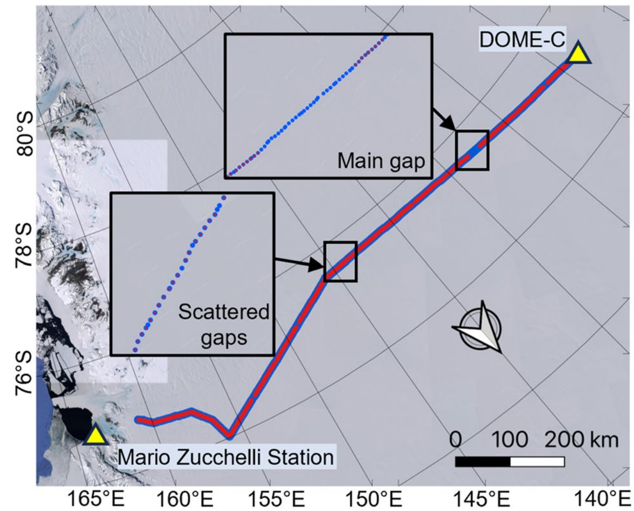

Fig. 7 Averaged trajectory of the ITK receivers. Blue marks are the new GipsyX solutions, red dots represent those from the older Gipsy OASIS II processing. The zooms highlight the higher consistency of the new solutions with respect to the old ones

interpolated at a 5-s rate. However, the results were decimated at the epochs corresponding to the orbit sampling so that only results directly related to those of the new computation were compared. By doing this, the number of solutions actually computed successfully using the old software is about 51% of the ones now available from the GipsyX processing considering the ITK receivers, and 54% for ITR1. Figure 7 gives an indication of the location of the main gaps in the previously available data, even though many missing solutions are also randomly scattered along the track and cannot be perceived at this map's scale.

Given that the number of GIPSY OASIS II solutions is much smaller than the GipsyX solutions, a direct comparison between the two in terms of heights is possible only for the 922 and 966 common epochs for ITK and ITR1, respectively. Figure 8 shows the height differences between the REMA elevation model, here used as independent height benchmark values, and the two PPP solutions. The height differences are related to the ITK solutions, where spikes of up to 16 m, with clusters of values above the meter level can be seen. After removing them, the bias between the two profiles is 48 cm. The bias value between the ITR1 solutions is 39 cm, with the residuals showing similar behavior. From Fig. 8 it is evident that the larger residuals between height values are mainly for the old GIPSY-OASIS II coordinates, thus allowing us to assume that the new solutions also improve the quality of the coordinate results. The average bias between the PPP solutions and REMA is – 46.9 cm and 1.1 cm for the old and new solutions, respectively, considering the ITK profile. While these values are – 49.9 cm and – 1.1 cm for the ITR1 receiver, thus supporting the conclusion that there is an improvement in the accuracy of the new results. The different reference frames used to define the orbit products, namely ITRF2000 and ITRF2014 (Altamimi et al. 2016), should impact on the height component at the 2–3 cm level at the considered latitudes, thus not enough to explain the 48 or 39 cm bias. Factors positively impacting the PPP accuracy, possibly leading to the bias reduction in the new processing, may include the computation of new corrective models and geodynamic parameters, the enabled fixing of the phase ambiguities, in addition to the evolution of the algorithms (now a kalman filter) implemented in the software.

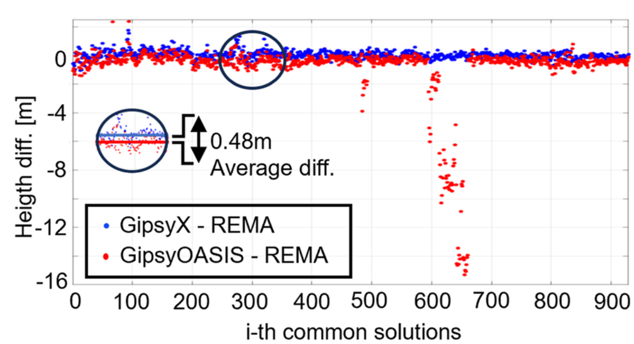

Fig. 8 Elevation differences between the PPP solutions and the REMA DEM. Residuals of the old Gipsy OASIS II solutions are in red, while the ones related to the new GipsyX solution are in blue. The 48 cm bias between the averaged values is highlighted

Finally, the REMA model was compared with all the solutions computed in this work. The average difference between the DEM and all the GPS heights is negligible, being − 0.2 cm. Nevertheless, splitting the dataset for the ITK and ITR1 profiles, the average differences to the REMA model are 1.3 cm for the former and − 1.8 cm for the latter. Such a difference is probably caused by small errors in the definition of the antenna offsets, or minor factors such as the different weights of the two vehicles, or the slight difference in the GPS receiver or antenna models. The overall standard deviation of the residuals to the DEM is 27 cm, their mean absolute value is 20 cm, and residuals range from − 1.23 and 1.35 m.

Figure 9 shows details of the height differences between the ITK profile and the REMA model. It is possible to identify the larger values grouped into clusters, while there are wider areas characterized by smooth variations from negative to positive values. Considering the reference epoch of the REMA product (the year 2014), which is almost 16 years after the GPS survey epoch, some preliminary conclusions about surface accumulation (positive values) and erosion (negative values) along the track can be drawn. Traversa et al. 2023 already performed a similar analysis of the ice surface by comparing GPS elevation data from the ITASE98-99 expedition and the REMA DEM for some transects (few tens of km in length) of the megadune around 300 km from Dome C to estimate the change in surface morphology due to the sedimentological migration of the megadunes (Frezzotti et al. 2002). The GPS data computation was performed using the GPSGeotracer (V.1.03, V2.25, and V.2.28) software and an algorithm implemented for kinematic processing (Urbini et al. 2001). Traversa et al. 2023 observed an almost stable elevation in correspondence with the glazed surface/leeward flank of the megadune, whereas the maximum difference in elevation (from 1.2 to 1.9 m, with an average maximum value of 1.4 m) always occurs in the snow accumulation/upwind flank of the megadune on the correspondence of the trough. The glaciological interpretation of data used in this work is beyond the scope of this paper and will be the subject of further studies. Nevertheless, considering the almost flat area (Frezzotti and Flora 2002), the spatial density of the GPS derived data can be considered sufficient for such investigations. Also, the consistency of the GPS heights shown in Fig. 5 compared to the statistics on the residuals with respect to the DEM, listed above, indicate that the computed data are accurate enough for glaciological applications aimed at improving knowledge on the Antarctica elevation.

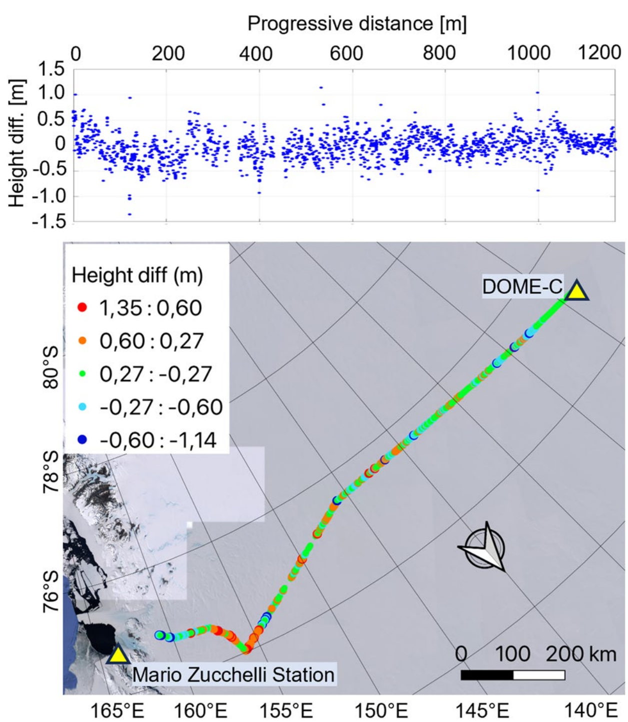

Fig. 9 Height differences between the GipsyX ITK averaged profile and the REMA DEM along the entire trajectory. The top panel shows values as a function of the progressive distance, while the bottom map indicates possible accumulation and erosion areas along the track

Conclusions

In this work, GPS data acquired from three receivers during the *ITASE98-99* Antarctic expedition were processed using the Precise Point Positioning (PPP) approach in kinematic mode. The GipsyX-2.0 software, developed and maintained by the JPL, was used. We first identified the best workflow and calculation parameters for the implementation of the kinematic processing, defined ad hoc for the geographical location of the surveyed area and the specific period (before 2001) when Selective Availability was still enabled. In particular, choices as (1) reducing the SanRMS parameter, (2) run a SPP processing using pseudo-ranges to provide a-priori for PPP, and (3) set two PPP iterations also using positions as input for the second run, played a key role to make the processing effective. A post-processing procedure was developed to identify the best filtering of the raw height solutions to reduce gross errors and to generate the most reliable altimetric profiles.

The newly computed results were then compared to those obtained almost 20 years earlier on the same dataset by computing PPP solutions using the Gipsy-OASIS II software package and the geophysical models available at the time. The comparison between the two solutions shows that the reprocessing using the new software, new products, and new parameters led to: (1) an improvement in the consistency of the kinematic solutions, being almost double that obtained in the old computation, (2) a strong reduction in the presence of spikes in the height solutions, and (3) the elimination of an almost 40 cm bias between the PPP-derived ellipsoid heights and the REMA reference elevation model. Therefore, the specific parametrization of GipsyX used in this work could be a benchmark for the reprocessing of GPS data acquired in Antartica during the many international expeditions that tool place before year 2001.

The comparison between GipsyX solutions and the REMA model, whose reference epoch is about 14 years different from the GPS data collection, shows an overall consistency at the centimeter-level, but is also open to analysis in terms of the time evolution of the ice level on the Antarctica continent.

Author contributions All authors contributed to the study conception and design. Cappuccio M. reorganized the data, performed the GipsyX processing and implemented the post-processing strategies. Tavasci L. supervised the PPP processing, provided guidelines for the post-processing strategy and analyzed the results. Enrica V. took care of the comparisons with the REMA DEM. Frezzotti M. and Gandolfi S. personally took part in the ITASE98-99 expedition and supervised both the computations and the paper writing. The first draft of the manuscript was written by Cappuccio M. and Tavasci L. All authors read, commented and approved the final manuscript.

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Data availability The data on which this research is based are available from the corresponding author exclusively for fully justified scientific purposes.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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